Collaborative Research: A Mooring for Cabled Ocean Observatories

Project Summary

Sustained observations are required to advance ocean science. The NSF Ocean Observatories Initiative expects to provide the basic backbone infrastructure of junction boxes on the seafloor for power and communications. To obtain spatial extent, a sensor network infrastructure is necessary to distribute the power and communications capability to other platforms and the science sensors. For a large fraction of the oceanographic community, the capability must be extended into the water column. This five-year project will design, build, and deploy a prototype ocean mooring system for cabled ocean observatories, including the software needed for real-time data management, data quality control, information product generation, and public outreach. The participating institutions are the Universities of Hawaii, Maine, and Washington.

The initial mooring deployment will be in mid-2005 at the recently NSF-funded ALOHA Observatory (AO) 100 km north of Oahu, where the Hawaii Ocean Time-series program has now provided nearly 14 years of sustained time-series data. Subsequent deployments of similar moorings are envisioned at the Hawaii-2 Observatory in the mid-Pacific, at DEOS buoy/seafloor junction box sites around the world, and on the planned NEPTUNE observatory on the Juan de Fuca Plate.

The mooring backbone infrastructure will supply observatory power, communications, and timing throughout the water column. Two primary junction boxes will be located at the bottom of the mooring and on the subsurface float (200 m). Two mobile secondary J-boxes are attached to these: the winched profiler (0–200 m) and a McLane moored profiler (crawls along the mooring wire, 200–4800 m, with docking station inductive power/communications transfer). Energy storage (ultra-capacitors) will supply high peak power demands on the backbone power supply. The basic mooring will be designed with the goal of a 10-year life; components on the mooring will be serviceable in place using a remotely operated vehicle.

Multiple sensors on the mooring will measure profiles of physical and biogeochemically-relevant variables. The combination of these collocated sensors will give a continuous, long-term, high-resolution picture of the processes responsible for the distribution of particulate and dissolved materials throughout the water column. Mixed-layer responses to local and remote atmospheric forcing, full water column mixing, eddies, high-salinity intrusions, and cold bottom water overflow events will be studied with the high resolution data. A particular objective of the AO is to observe and understand the biogeochemical response to these physical forcings; the proposed mooring will be the backbone for pursuing this objective.

The mooring infrastructure we develop will be used to acquire the high-resolution, long time-series data that are critical for understanding the essential elements of climate and biogeochemical cycles, and their broad impacts on society. Providing reliable streams of real-time data will document the present ocean climate, encourage creation and refinement of ocean climate models, and support experimental predictions. Information products developed from the mooring data streams and from models will support education and outreach. A post-doctoral investigator, along with graduate and undergraduate students, will learn essential skills to work with moored ocean observing systems, and will contribute to the workforce needed to build a sustained ocean observing system for operational purposes.

Project Description

Results from Prior NSF Support

PI: **Bruce M. Howe**

Grant Number: OCE-0116750; $1,943,183; 1 October 2001 – 31 March 2004

Grant Title: **Development of a Power System for Cabled Ocean Observatories**

This grant is supporting the design and prototype of a 100-kW parallel DC power system for cabled ocean observatories. The design will support regional ocean observatories such as NEPTUNE on the Juan de Fuca Plate offshore of the Pacific Northwest (see http://www.neptune.washington.edu). NEPTUNE with 3000 kilometers or more of fiber optic cable for power and communications may have thirty or more nodes, each capable of complex sensor systems. The power system is being designed in collaboration with JPL and the NEPTUNE Engineering Team. A recent Concept Design Review was held with a panel of internationally recognized experts with favorable results. See papers (Schneider et al., 2002; Howe et al., 2002; Kirkham et al., 2001a, b) and the Web site http://neptunepower.apl.washington.edu (username neptune, password neptune). Four graduate students are involved in the project.

PI: **Roger Lukas**

Grant Number: OCE-9811921; $896,172; 1 October 1998 – 30 September 2001

Grant Title: **A Time Series Investigation of Climate-Related Processes in the Subtropical North Pacific Ocean**

This grant supported physical observations for the Hawaii Ocean Time-series project at Station ALOHA. Objectives include documenting seasonal and interannual variability of water masses; relating water mass variations to gyre fluctuations; and developing a climatology of short-term variability. The physical component of HOT provides critical CTD/rosette sampling to the biogeochemical component of the program (cf. Karl et al., 2001), to many ancillary investigations, and for development of new instrumentation (http://hahana.soest.hawaii.edu/hot provides a comprehensive bibliography). Data are made available rapidly, generally within a month for CTD-based measurements (http://imina.soest.hawaii.edu/HOT_WOCE). Coherent T-S variations in the upper pycnocline at ALOHA occur on decadal time scales apparently related to rainfall variations over the mid-latitude North Pacific through subduction at the Subtropical Front (Lukas, 2001). During El Niño events, this front moves southward and active ventilation occurs at ALOHA (Lukas, 2002a). The mixed layer at ALOHA shows distinct impacts of variable freshwater fluxes, with ML salinity varying by as much as 1 psu, while ML temperature varies by only about 2°C (Lukas, 2002b). Eddies transport waters of distinctly different character to ALOHA, contributing a portion of the turbulent diffusion that balances advection to produce the mean water mass distribution. An extreme water mass anomaly event observed during January 2001 is attributed to a sub-mesoscale apparently spawned by the 1997-98 El Niño, carrying salty, O_2-depleted mid-thermocline waters from Baja California to Hawaii (Lukas and Santiago-Mandujano, 2001). More typically, eddies bring somewhat fresher thermocline waters to ALOHA (Figure 2) from a genesis region about half way between Hawaii and Mexico (Lukas et al., 2002). These eddies significantly impact biogeochemistry at ALOHA (Letelier et al., 2000). Cold, salty overflows from the Maui Deep to the Kauai Deep occur episodically, creating pronounced anomalies in the lowest 300 m, especially in temperature (Lukas et al., 2001). A time- and depth-varying eddy diffusivity model fit to observations of the thermal relaxation of the Kauai Deep yielded peak eddy diffusivities of 40–50 $cm^2 sec^{-1}$ near the sill depth for a month or more. Finnigan et al. (2002) independently confirm estimates of this enhanced near-bottom mixing at Station ALOHA.

1. Motivation and Objectives

Long-life sensor networks with real-time communications and necessary power will be a crucial part of sustained research ocean observatories and operational ocean observing systems. Our general long-term goal is to develop the required sensor network infrastructure that can attach to seafloor junction boxes, as envisioned by the NSF Ocean Observatories Initiative (OOI; http://www.geo-prose.com/projects/ooi.html). This infrastructure will expand the coverage away from "backbone" junction boxes providing power and communications, to cover the three-dimensional ocean and seafloor beneath. Here we address one aspect of the sensor network infrastructure, ocean moorings. The work will be done in the context of the science of the Hawaii Ocean Time-series program (HOT); robust physical, chemical, and biological (optics) oceanographic sensors will be used to address multidisciplinary problems.

The specific objectives of this proposal are:

- Develop and integrate the mooring infrastructure, including connection to the seafloor junction box, an electro-optical-mechanical mooring cable, junction boxes distributed along the mooring, an upper ocean winched profiler, a docking station with inductive power/communications transfer for a moored profiler, and energy storage for peak loads.
- Integrate existing sensors onto the mooring, including the winched profiler and moored profiler.
- Deploy, test, operate, and service the mooring at the ALOHA Observatory (AO; http://kela.soest.hawaii.edu/ALOHA) 100 km north of Oahu, Hawaii (Figure 1).
- Develop required software systems for real-time data management, data quality control, and information distribution.
- Investigate, in collaboration with HOT Program participants, and in conjunction with HOT cruises, scientific topics, including eddies, vertical mixing, advection and their impacts on the carbon cycle.
- Provide for the transition of the mooring to operational status as part of the AO.

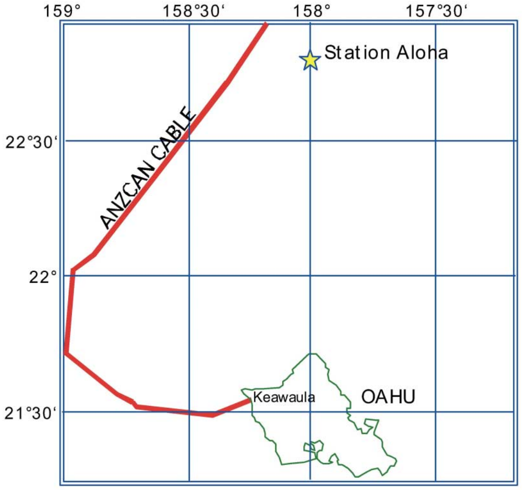

Figure 1 ALOHA Observatory (AO) located at 22°45′ N, 158° 00′ W, 4750 m. The ANZCAN cable will be re-routed to the ALOHA site and a junction box attached.

1.1 Programmatic context

The recent NSF-sponsored report, *Ocean Sciences at the New Millennium* (Ocean Sciences Decadal Committee, 2001), emphasizes the need for long duration Eulerian observations. The challenge for acquiring sustained *in situ* observations is supplying the required power while also retrieving the data in real time. The solution is either a dedicated submarine cable or a semi-permanent moored buoy with on-board power generation and satellite telemetry connected to a seafloor junction box (e.g., DEOS; Orcutt and Schultz, 1999). These facilities are referred to as ocean observatories. The NRC report, *Illuminating the Hidden Planet* (NRC, 2000), makes a compelling scientific case for such seafloor observatories and enumerates the benefits and risks. We will not quote from the report, but it is appropriate to paraphrase the recommendations, namely (p. 108-111): the need for basic observatory infrastructure and sensor development (#5), the need for a framework for evaluating proposals for sustained observations (#6), the encouragement of individual scientists to convert their instruments to community assets (#7), high priority for public outreach and education (#8), the necessity of information dissemination (#9), and coordination on an international scale (#10).

Ocean observatories will greatly expand the capability to observe physical and biological processes. Fitting the definition of an enabling technology, they provide an opportunity to acquire understanding in ways previously unthinkable. Observatories enable the exploration of spatial variability of ocean thermal structure and currents on multi-year (climatic) time scales. There are few multi-year datasets with which to study episodic, high-frequency as well as long-period, sub-surface ocean variability. Observatories enable the collection of data about shorter timescale phenomena (eddies, Rossby-topographic waves, internal tides, etc.) to not only produce statistical reliability of estimates of mean properties (e.g., energy levels and fluxes, interaction with the "mean" currents) but also to examine the long-time-scale modulation of these phenomena that are suspected to have important roles in redistributing energy throughout the oceans, supplying energy to mixing processes, and forcing biogeochemical variations. The last century of oceanography is a story of sampling: starting very poorly and improving (Munk, 2002).

For all the reasons cited above, as well as others, NSF has undertaken the Ocean Observatories Initiative (OOI). "The proposed system 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 re-locatable deep-sea observatories based around a system of buoys, and 3) an expanded network of coastal observatories" (Clark, 2001).

Fixed, cabled observatories such as AO, H2O (Petitt et al., 2002), LEO-15 (Schofield et al., 2002), and the planned NEPTUNE system (NEPTUNE Phase 1 Partners, 2000), which permit the long-term deployment of instrumentation with power, real-time command-and-control, accurate time distribution, and data acquisition over a specific region are acknowledged to be an essential complement to more traditional observing schemes. (See Edson et al., 2002, for a special issue of *IEEE Oceanic Engineering* on this topic.) The AO is a variant of OOI element 2, i.e., a deep-sea junction box; it is with this system that we envision our proposed sensors and mooring network infrastructure being deployed, tested, and operated. We must prepare the latter so they are ready when the AO and other observatory infrastructure are installed in late 2004 and after.

We intend the proposed work to take place within the OOI structure, which includes the DEOS and SCOTS efforts hosted by CORE (Dynamics of Earth and Ocean Systems, Scientific Cabled Observatories for Time Series, Consortium for Oceanographic Research and Education; for all see http://www.coreocean.org). Specifically, the science will be coordinated through the HOT program, and the infrastructure developed through the NEPTUNE program. The goal of the latter is to "wire" the Juan de Fuca Plate for science – anticipating OOI element 1 above. Several parts of NEPTUNE are funded: 1) power, communications, and system engineering funded by NSF and NOPP, 2) the Monterey Assessable Research System (MARS; a testbed system, http://www.mbari.org/mars) funded by NSF, 3) the Victoria Experimental Undersea System (VENUS, http://142.104.11.31/venus.html) in the straits of Georgia and Juan de Fuca funded by the Canadian Foundation for Innovation (CFI), and 4) the northern part of NEPTUNE, also funded by CFI (http://neptunecanada.com). These funded projects provide a framework for the proposed development.

1.2 The Hawaii Ocean Time-series (HOT) Program and ALOHA Observatory (AO)

The HOT Station ALOHA (A Long-term Oligotrophic Habitat Assessment) has been supported by NSF under the JGOFS and WOCE programs, with approximately monthly sampling since October 1988 (Karl and Lukas, 1996). During nearly 14 years of comprehensive observations, significant responses of the water column physics, chemistry, and biology to episodic and climate variations have been observed and studied (Karl et al., 2001). The El Niño/Southern Oscillation has a strong influence on mixing and stratification at ALOHA, and thus on nutrients and biology (Karl et al., 1995; Karl 1999). Decadal variations of mixing, circulation, and biogeochemistry appear to fundamentally reorganize the ecosystem. HOT observations have provided great insights into the functioning of the North Pacific subtropical gyre and its ecosystem, challenging some of the most closely held assumptions in ocean biogeochemistry. Some of the most significant biogeochemical features are: 1) the variations in the mechanisms of nutrient supply, especially the ecological consequences of pulsed nutrient delivery (e.g., via eddies; cf., Figure 2, and Letelier et al., 2000), and the nutrification of low-latitude regions in the absence of turbulence (e.g., enhanced N_2 fixation [Karl et al., 1997; Karl, 1999]), 2) the relationships between ocean physics and biology, especially for community structure and trophic dynamics (cf. Cullen et al., 2002), and 3) the resultant physical and biological controls on the ocean's carbon pump. The decoupling of production, export, and remineralization processes in time and space, and the detection of decade-scale, climate-driven ecosystem perturbations and feedbacks combine to reveal time-varying biological and biogeochemical complexities (even on time scales as short as a day to a few weeks) that are just now becoming evident in these independent ocean time-series data sets (e.g., Dickey and Falkowski, 2002). These variations in ecosystem structure have important implications for carbon dioxide sequestration, as well as the productivity of higher trophic levels (e.g., fish and micronekton) in the North Pacific subtropical gyre.

These insights will be followed with research focused on guiding the development of the sustained, high-frequency, long-term ocean observing system components needed to quantify these variations and feedbacks accurately, and to support assessment and prediction efforts. Thus new objectives for HOT include: 1) continuing critical time series measurements, and enhancing them with high frequency and spatial sampling; 2) improving our understanding of critical physical and biogeochemical processes for improved predictive modeling capabilities; 3) identifying the most important variables (and their time and space scales) for sustained observations to quantify carbon cycling; 4) testing advanced sensors for measuring these variables and integrating them into observational systems; and 5) testing advanced ocean analysis and prediction capabilities. The strategy for approaching these objectives is to conduct *in situ* perturbation experiments to test hypotheses regarding controlling factors for primary production and carbon cycling and sequestration, to develop improved ecosystem model parameterizations based on these results, to integrate autonomous measurements with ship-based *in situ* observations, and to develop and test model-based data analyses and predictions in conjunction with intensive process studies as part of national and international research programs. **It is intended to evolve the ongoing intensive shipboard observational strategy of the Hawaii Ocean Time-series to one that relies on continuous autonomous time series with less frequent shipboard work. The autonomous measurements will be made from moorings to provide critical time series, and using AUVs, gliders, tomography, and other platforms and techniques to provide essential spatial context.**

The goal of the NSF-funded ALOHA Observatory project (AO) is to establish cabled observatory infrastructure at Station ALOHA for the next generation of the Hawaii Ocean Time-series. The AO seafloor junction box will be deployed in late 2004; it will provide power to scientific equipment and real-time two-way communication between sensors and scientists for at least the next ten years. Continuous measurements will then enable scientists and students to detect trends and variations that are not well observed by standard ship-based observations. AO is designed for maximum flexibility, with the ability to support a wide range of experiments, from simple listening devices to vertical arrays with ports for removable sensor systems. With the proposed mooring, observing systems from the deep ocean floor to the ocean surface will benefit from AO. At the end of the mooring development, the hardware and software systems will be transitioned to "operational" status as part of the AO backbone.

The AO will be an important contribution to the integrated ocean observing system, providing sustained *in situ* observations of key ocean variables beyond temperature and salinity, and resolving shorter time and space scales than can be achieved by satellites and the Argo float array. An important motivation for this element of the integrated ocean observing system is that it provides the co-located multivariate and multidisciplinary observations required by interdisciplinary scientific objectives (Send et al., 2001). AO will be embedded within the basin-scale observing system (including remote sensing from space), and its observations will provide an important benchmark for basin-scale, model-based ocean analyses. It will also help to provide the observational basis for research linking ocean-state assessments and predictions on the basin scale with those of island coastal regions. In addition, AO will provide a high quality testbed for development of novel sensor technologies to observe key ocean variables, such as proposed here.

2. Science Opportunities at ALOHA

The present ~monthly shipboard observations at Station ALOHA include 36-hour burst sampled $CTDO_2$ profiles to resolve the strong internal tides. Other than oxygen and fluorescence measurements, there are no biogeochemical variables that resolve high-frequency variations while on station. Transient episodic events (e.g., plankton and Trichodesmium blooms, eddies) are observed only serendipitously. Variations on time scales from 2 days to 2+ months are not resolved, aliasing the time series, and making it difficult or impossible to observe time scale interactions. High temporal resolution requires moored measurements, and high vertical resolution requires profiling capability. Motor driven profilers require significant power. Real-time two-way communications capability is important to detect and react to unusual events by allowing control of the sampling strategy during such events. Communications capability is also important to sustain high quality observations, as it enables detection of sensor/systems failures and scheduling of timely servicing.

2.1 Physical oceanography

Observations show that advective and diffusive processes are occurring on many time scales at ALOHA. These processes interact with each other in ways that are not well understood, and they force biogeochemical systems and ecosystems in ways that have not been well observed. Upper ocean mixing is forced by synoptic weather systems such as cold fronts, but this is subject to large spatial and year-to-year variability (Lukas, 2002b), with important remote consequences as well (Alford, 2001). Water mass intrusions appear intermittently (Kennan and Lukas, 1996; Lukas, 2002a), and the processes that control their generation and their fate are not well known. Slow variations in upper thermocline stratification associated with subducted North Pacific water mass anomalies may influence vertical turbulent fluxes of nutrients, and thus impact the biogeochemistry of overlying waters at ALOHA. Eddies generated by circulation instabilities within and external to the North Pacific subtropical gyre clearly impact biogeochemical processes (Letelier et al., 2000), but the relative importance of vertical circulation, vertical mixing, and horizontal advection are not known. Figure 2 shows that along-isopycnal advection of anomalous waters within eddies is significant, and must be considered along with local upwelling anomalies associated with eddy passage. These eddies have varying vertical structures and horizontal scales, and while they appear intermittently, their statistics are apparently modulated by slow ocean climate variations (Lukas and Santiago-Mandujano, 2001).

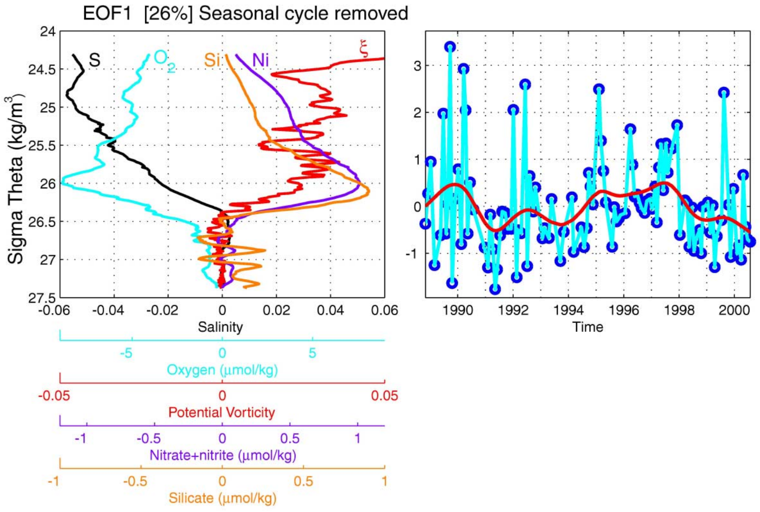

Figure 2 Multivariate EOF of HOT hydrographic profiles in potential density space (left). Red line in the time series panel (right) is a spline fit to the individual cruise values (blue dots). Intermittent appearance of anomalous water masses associated with mesoscale eddies is associated with extreme values of the EOF time series.

Strong internal tides have been observed near the Hawaiian Ridge, with vertical displacements of the upper thermocline by as much as 50 m, apparently enhancing vertical turbulent exchanges (Finnigan et al., 2002). These internal wave enhancements vary considerably in space (Egbert and Ray, 2000; Merrifield et al., 2001) and time, and certainly contribute to so-called "background" vertical fluxes of nutrients. The ability to observe physical variability over the entire water column with high vertical and temporal resolution is critical to making advances in understanding these complex interactions. Research into such interactions is a high priority for improving ocean climate models, and is vital for deciding appropriate sampling strategies for the profilers on the mooring.

2.2 Particles and dissolved organic material dynamics: a biogeochemical link

The production of biogenic material in the upper ocean and their fractional removal to the deep sea determines to a large degree the distribution of the biogeochemical elements in sea water (Ittekkot, 1996). Here we propose to measure the distribution of particulate and dissolved materials with high temporal and vertical resolution using robust optical instrumentation, with the necessary physical measurements to provide context. Doing so will provide us with:

1. Description of the particulate and dissolved constituents in higher resolution than available to date.
2. Quantification of the contribution of episodic events to the vertical flux of particulate material and its rate of conversion to dissolved material.
3. Quantification of the cross-correlation of physical and optical variables so that we better understand the interaction between physics and biogeochemical fields and their contribution to particulate fluxes.

Our efforts will contribute directly to carbon science as outlined in the Ocean Carbon Transport, Exchanges and Transformations report (http://www.msrc.sunysb.edu/octet/Workshop_Report.html). For example, transmissometer measurements have already shown the importance of the 'twilight zone' (100–1000 m) to the recycling of carbon. The addition of oxygen measurements as well as CDOM (as proposed here) will provide evidence for the transformations incurred by particulate organic carbon. The combined high spatial and temporal resolution measurements of physical and optical variables will allow us to compute eddy-correlation terms, which are needed to quantify and understand the role of physics in fluxes of dissolved and particulate material.

Traditional moorings using instruments that burst sample at fixed depths suffer from two problems when trying to achieve the above goals. The vertical resolution is coarse and there is significant uncertainty in calibration. Cross-calibration between the instruments is usually performed only at the beginning and end of each deployment forcing the user to assume a linear drift.

The mooring suggested in this proposal is a significant improvement for measuring dissolved and particulate properties with high temporal-vertical resolution. The power and communications requirements of commercial optical instrumentation, which measures several times a second, can be easily accommodated. The use of the profilers insures high vertical resolution, particularly in areas of high vertical gradients such as the top of the bottom boundary layer and at the base of the surface boundary layers. In addition, a better degree of cross-calibration between the sensors is achieved as sensors (nearly) overlap in the vertical during profiling, insuring higher quality measurements. Periodic HOT cruises to the mooring location will contribute to the goal of absolute calibration throughout the deployment.

The selection of optical instrumentation is based primarily on maturity of the technology, its biochemical link, and its price. As other novel technology matures and becomes available commercially we will incorporate them in the mooring. For example, measurements of particulate size distribution (e.g. Sequoia's LISST) will provide crucial information regarding particle aggregation dynamics. Novel optical nutrient sensors (e.g. Ken Johnson's nitrate sensor) will relate the particulate field to the underlying nutrient dynamics, a cornerstone for biogeochemical interpretation.

The suite of optical properties we propose to measure, and the biogeochemical properties they are related to, is as follows:

1. Beam attenuation at 660 nm – particulate organic carbon in many areas of the open ocean (e.g. Bishop, 1999) and total suspended material in the bottom boundary layer (Spinrad et al., 1983).
2. Chlorophyll fluorescence – chlorophyll concentration (e.g., Cullen, 1982).

3. Colored dissolved organic matter (CDOM) fluorescence – dissolved organic material (DOM; e.g., Blough and Green, 1995, Blough and Del Veccio, 2002).
4. Backscattering at 660 nm – particulate organic carbon (POC; e.g., Stramski et al., 1999); with beam attenuation it provides a proxy for the backscattering ratio that is a good indicator of the composition of the particulate material (Twardowski et al., 2001).
5. Profiling upward looking irradiance sensor and downward looking radiance sensor – reflectance, diffuse attenuations (for both measurements), and photosynthetically available radiation for the upper 200 m. These measurements have been used to estimate inherent optical properties such as absorption by phytoplankton and CDOM (Nahorniak et al., 2001). A by-product of this measurement is a validation measurement for satellite ocean color.

The relationships between optical variables and biogeochemical parameters is not unique and can vary with the composition and size distribution of the material investigated. We have investigated the relationships between beam-c and POC, and chlorophyll fluorescence and chlorophyll concentration at HOT (Fennel and Boss, 2002) and found them to be close to linear through several years of the HOT program (Figure 3). For the other variables (e.g., the CDOM-DOM relationship) the data collected as part of HOT will provide the needed relationship and its variability in time and space.

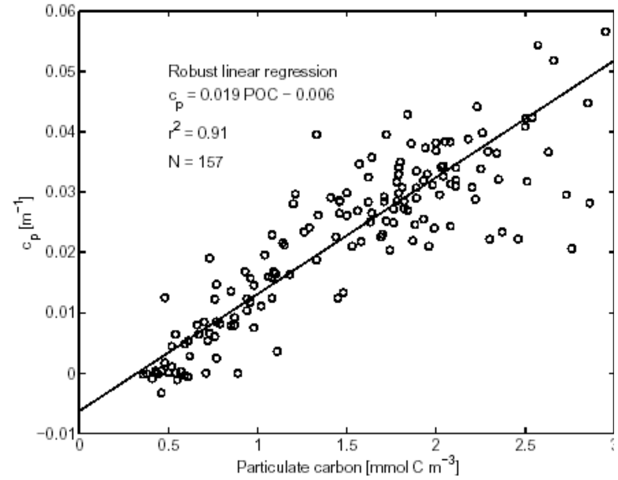

Figure 3. Beam attenuation coefficient vs. POC bottle concentration at Station from August 1991 to July 1995 (figure from Fennel and Boss, 2002). c_p represents the value of beam attenuation measured minus the average value of c_p between 250-300m. This is done in order to account for drift in transmissometer calibration.

From 1997 through 2000, a surface mooring (HALE-ALOHA) was maintained not far from Station ALOHA to capture high frequency, episodic variations. The temporal resolution was 10 minutes, while the vertical spacing was 25 m and larger. This mooring has been instrumental in highlighting the importance of mesoscale and mixed-layer processes in the distribution and fluxes of dissolved and particulate properties (R. Letelier, personal communication, 2002). Unfortunately, this effort was discontinued.

The optical/physical measurements proposed here will supplement and complement the HOT program by resolving both vertically and temporally the frequency domain most contributing to variability at the site. We will replicate the HALE-ALOHA radiance measurements by including two radiometers on the winched profiler, insuring that the necessary parameters for primary production studies at the site are measured. These radiometers will have the added benefit of validating ocean color algorithms at the site.

The high vertical and temporal resolution will enable us to quantify the role of mixed layer dynamics (strongly forced on diel and atmospheric weather time scales) in the redistribution of biogeochemically relevant material in the upper ocean. Upwelling of nutrients, flux of cells below the euphotic depth, and bleaching of organic material are just a few of the processes affected by the mixed layer dynamics, with important consequences for particulate and dissolved material fluxes and distributions. Contribution of horizontal processes will be assessed from ocean color images, horizontal velocity measurements, and local measurements.

3. Technical Approach

We propose to integrate a suite of moored sensors for measuring physical, chemical, and bio-optic oceanographic variables. Our chosen sensors residing on various platforms will provide information that is representative of the full water column, including crucial near-surface data. The mooring and sensors will be robust and long-lived for connection to cabled ocean observatories. The mooring sensor network infrastructure will be a direct extension of seafloor sensor network infrastructure; indeed, the mooring can be regarded as a vertical cable network with connections available at various points. This infrastructure is integral to this proposal. The network infrastructure will be compatible with the NEPTUNE interface (400 V, 100 Mb/s Ethernet, timing) and adapted here for the AO instrument interface (48 V, RS-422). It will easily support other sensor interfaces and future expansion.

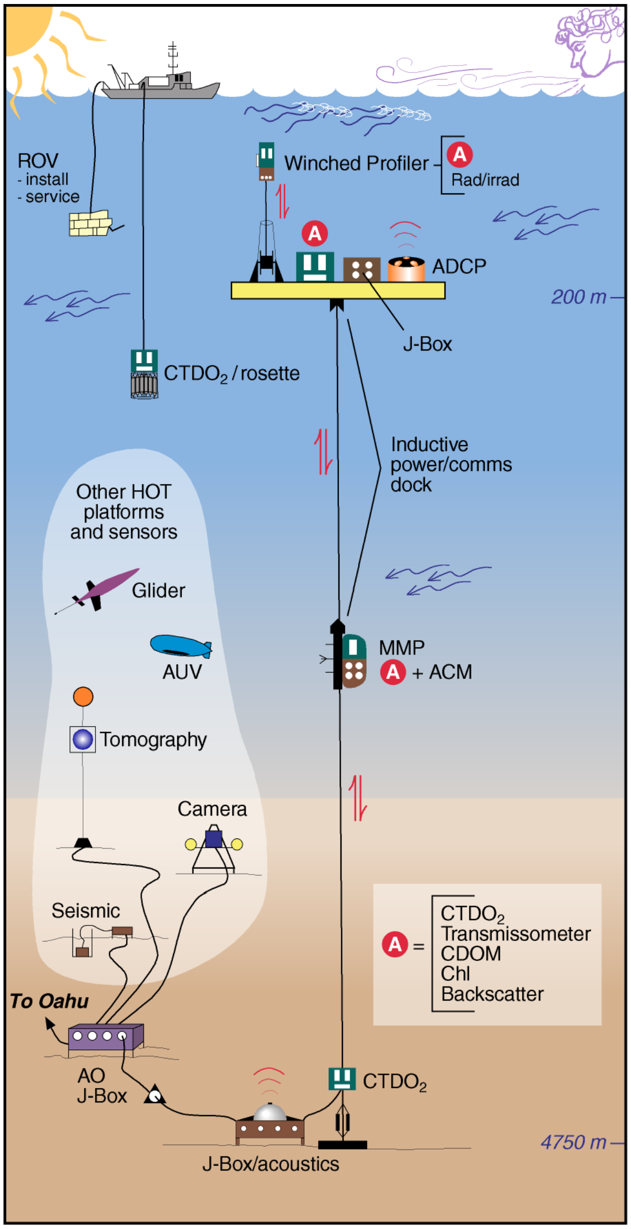

Figure 4 The ALOHA Observatory mooring system.

Figure 4 depicts the configuration of instrument packages, platforms, and junction boxes on the mooring. Other possible future components to the ALOHA Observatory are also shown. The various components of our proposed effort are shown in Figure 5.

3.1 Instrumentation

3.1.1 Sensors The sensors we have chosen are robust, long-lived, and have a proven record of performance. With them we expect to continue the high standards of measurement set by the HOT program. A limited number of different types of sensors makes this demonstration project manageable with higher probability of scientific success. While some investigators may take issue with the specific sensors we have chosen, they will have the opportunity to use the infrastructure we create to add others in the future. We have intentionally not called for dual sensors (and platforms) to control cost; these trade-offs (amount of service, impact on calibration, etc.) are best made after experience is gained.

We tentatively plan to use Seabird CTDs (FastCat or ALACE style on the winched profiler and MicroCats on the subsurface float and at the bottom; all with Paro-Scientific pressure sensors) except on the MMP which, uses a Falmouth Scientific CTD and acoustic current meter (ACM). A Seabird dO$_2$ sensor will be used on all platforms. An RDI 75-kHz LongRanger acoustic Doppler current profiler (ADCP) will be used on the subsurface float. For the optics, we plan to use WET Labs CDOM and chlorophyll pucks and C-Star transmissometer and an OBS backscatter sensor; the upper ocean ones will have copper shutters. On the winched profiler will be Satlantic radiance and irradiance meters.

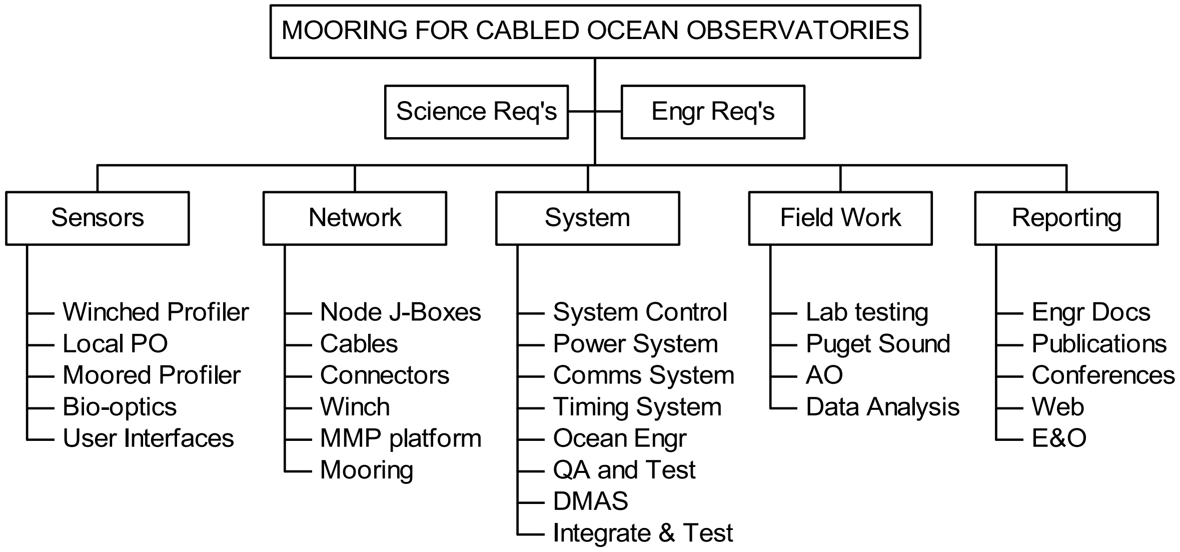

Figure 5 Project tasks.

3.1.2 Winched profiler We are using a winched profiler as opposed to a surface mooring to sample the uppermost ocean to minimize the detrimental effects of being at the surface for long periods: high wave energy with associated mechanical stresses and heave, adverse bio-fouling of sensors and platforms, frequent servicing, ship strikes, and vandalism. The profiler sensors are shown in Figure 4. The profiler will be configured as a secondary junction box, with external (dry mateable) connectors for other sensors. The profiler can be serviced with a ship in dynamic positioning mode by spooling out additional cable by command through the communications system. It will then be possible to recover the profiler, connect to the mooring network and then run the entire mooring from the ship for diagnostic purposes.

3.1.3 Subsurface float The disc-shaped syntactic foam float at 200 m will serve as the platform for the winched profiler, the ADCP, CTDO$_2$, the optical sensors, and the junction box (Figure 4). We note that with plentiful power, the ADCP can be run nearly continuously. The instrument mounts on the float will permit the easy addition, removal, and servicing of sensors and the other components.

3.1.4 Moored profilers One McLane moored profiler (MMP) will be used with the sensors shown in Figure 4. It can travel at speeds up to 0.4 m/s, which is necessary to prevent tidal signal aliasing over the ~4500 m of mooring cable (6 W average; the normal MMP travels at 0.25 m/s drawing 2 W); this is one example where the capability to obtain power from the mooring infrastructure AO is crucial). Working with McLane, we will modify the profiler to mate with a dock for inductive power and communications transfer (using electric car technology; this will be a challenge, as there will likely be some degree of mechanical alignment necessary); install a secondary node controller to be the interface between the McLane control system, the sensor payload, and the inductive power/communications transfer; switch from lithium to rechargeable batteries; and make the MMP and docking station replaceable using an ROV. The latter will permit servicing without mooring recovery, as well as make it easy to add new sensors over the long expected lifetime of the mooring. *In-situ* calibration of sensors can be done with an ROV fitted with a similar sensor payload during service calls. There should be little bio-fouling because the MMP will be greater than 200 m deep and can be parked deep between profiles. In the future, the profiler can be easily modified to carry other transducers, such as an acoustic transducer for tomography, communications, and other purposes.

3.1.5 Anchor A CTDO$_2$ will sit at the base of the mooring. A 10-kHz general purpose acoustic transducer will be used as an inverted echosounder, as an ambient sound receiver (wind rain, marine mammals, shipping, tomography signals), and for acoustic communications and navigation (this transducer sits in the gray area between a science and an infrastructure element).

3.1.6 Other In the future, we expect additional instruments to be added to the system (facilitated by the junction box/ROV servicing capability). One example is a bottom-mounted ADCP to measure bottom boundary layer velocity in conjunction with the periodic MMP profiles along the mooring, relevant to understanding the Kauai-Maui overflow current. A second example is turbulence measuring ADCPs on the winched profiler and the subsurface float, relevant for studying storm induced mixing. Another example is a small spar extension to the winched profiler to allow measurements above the air-water interface. These might include air temperature, pressure, velocity, radiation, and GPS; the latter provides an integral measure of precipitable water in the surrounding atmosphere (Chadwell, 2000, Goody et al., 2002).

3.2 Infrastructure

3.2.1 Winch Our provisional design calls for a 0.5 m/s profiling speed, requiring 145 W peak power (assuming 50% efficiency). The budgeted average power of 25 W will allow one profile every 40 minutes. The main buoyancy element will be syntactic foam (0.5 m diameter by 0.4 m high) with the instrument frame above. The cable will be approximately 5 mm diameter, include 4 #24 conductors, have greater than 500 lb breaking strength with steel armor wires to protect it against fish bite, and have a jacket (similar to Rochester A-H-181A). The drum will be 0.25 m diameter with 0.5-m diameter flanges and 0.1 m wide. A fairlead 2 m out will keep the fleet angle <1.5º. The winch will have to generate 145 N of tension when reeling in, 36 N-m of torque at 20 rpm. Oil-filled submersible slip rings will carry the electrical signals across the winch.

3.2.2 Primary junction boxes Junction boxes will be placed on the subsurface float and on the seafloor immediately adjacent to the mooring. The junction box provides access via ROV-mateable connectors to the 400 V / 100 Mb/s mooring network backbone. To be consistent with future systems such as NEPTUNE, a time distribution channel will also be included (with AO 1 ms, in the future 1 μs). On each primary J-box, 4 ROV-mateable connector ports (or more, as needed or anticipated) will be provided. The same ports will be used for linking the backbone system as well as for sensors. If attached to sensors, ports will also provide 48 V and RS-232 options. An embedded micro-controller will be used for controlling the junction box and communicating with the shore power and communication control systems. For communications, a high reliability commercial Ethernet switch will be used that takes 8 input/outputs and sends the packets to the appropriate locations, whether commands to instruments or data going to the data archive and scientist on shore. Sensors that are "observatory-ready" (Ethernet interface, metadata storage, 48VDC or other suitable voltage) may be plugged in to the J-box directly. Other sensors (typically RS-232) will need to connect through a single or multiple channel SIIM (see below). If external sensors using serial communications protocols are expected, RS-232-Ethernet servers exist that take 8 devices, assign each a unique IP address, and convert to Ethernet protocol for connection to the Ethernet switch. The controller will have the ability to add instrument metadata if necessary, e.g., for instruments using the RS-232 ports. As a matter of policy, we will require all data on the backbone to have metadata attached. The user 48 and 400 V power supplies will have ground fault and overcurrent protection. Because the AO junction box can only supply a relatively limited amount of power (100 W), energy is stored in "smart" ultra-capacitors banks (http://www.powercache.com) that are charged from the 400 V bus and are able to buffer energy to meet peak power demands. The ultra-capacitors will connect to a junction box just like a feeder from another power source (auctioneering diodes permit this); they will be distributed through the system as appropriate to minimize cable I^2R losses when high instantaneous power is required.

We emphasize that much of the engineering, hardware, and software, will directly carry over from the MARS (http://www.mbari.org/mars) and NEPTUNE (http://neptune.washington.edu) development efforts, in which we are intimately involved.

3.2.3 Science instrument interface modules The components that lie between instruments and the backbone system are collectively called science instrument interface modules (SIIMs) in the MARS/NEPTUNE engineering jargon; they are called out explicitly in the MARS NSF grant as a required component, but one which will be designed in an external effort, e.g., as proposed here. Such sensor network infrastructure will be needed for any ocean observatory, whether at a single DEOS buoy/seafloor junction box or a complete regional observatory such as NEPTUNE envisions. There are two types of SIIMs that will be used here. One is a very small (postage stamp size) chip that converts a single RS-232 device to/from Ethernet, allows metadata to be stored or retrieved, and uses a small dc-dc converter to provide the desired voltage to the sensor, given the 48 or 400 V from the backbone. These components will be housed in very small pressure cases in-line with the instrument cable. The second type of SIIM is a small multiplexer that combines multiple RS-232 data streams (e.g., a hub), contains a microcontroller to store the metadata for the multiple sensors, and provides power, for instance to the suite of optical sensors. With this type of SIIM, only one port on a junction box is necessary to service all the sensors. Simple and easy to use SIIMs are crucial to observatory success; our work will be coordinated with NEPTUNE development.

3.2.4 Mooring cable The mooring cable has 4 #18 conductors with polyethylene insulation, 4 fibers in a 2-mm diameter steel tube, Kevlar strength member, armor wires (above 1500-m water depth for fish bite protection) enclosed in a polyurethane jacket, and an overall diameter of 25 mm. The subsurface float provides 2000 lb of buoyancy to provide a taut mooring to minimize horizontal and vertical motion. All mooring components are selected for a 10-year life; titanium and non-metallic materials are used where necessary.

3.2.5 Other The AO junction box is designed for ROV underwater mateable electrical connectors. An "observatory interface" will connect to the AO junction box and will step up the 48 V power to 400 V (100 W) and convert the data stream format from the AO RS-422 protocol to/from 100 Mb/s Ethernet on fiber, necessary for the 2 km distance to the mooring (clearance for ROVs). This 2-km electro-optical cable will be deployed in a cable pack at the AO J-box, unspooled using an ROV to the base of the mooring and then connected to a junction box that is in turn connected to the connector at the base of the mooring.

3.3 System

All active elements of the mooring (i.e., everything except the cable, float, and hardware) can be added or removed for service by an ROV. We stress again how crucial ROVs, and the ships that support them, are to the success of this mooring concept specifically, and to observatories in general. NSF and the community must act expeditiously so that ROV availability does not become a bottleneck. The experience we gain from this effort will help us determine the optimal balance between servicing (involving an ROV, for instance) and the number of dual/redundant sensors and platforms (e.g., 2 MMP docks, 2 MMPs, dual sensors, etc.).

The estimated power budget for the instrumentation and infrastructure is 50 – 60 W, well within the 100 W available, and with sufficient margin for future expansion. Date rates are modest and will not stress the system.

We have kept individual sensors separate because they may fail; distributed sensor units that can be unplugged are more appropriate. To the extent possible, frames and pressure housings will be made of non-corrosive materials (e.g., plastics and titanium) to minimize cost and risk of corrosion and stray galvanic electric fields that may contaminate measurements.

3.3.1 Command and control At the most basic level, the observatory control system will monitor voltages, currents, ground faults, etc., throughout the mooring infrastructure system. It will flag out-of-range values and take corrective action if necessary, such as opening a breaker on a particular junction box connector. Given power contracts with the different users, it will determine if there are conflicts; this will be especially important in coordinating the operation of the winched profiler, the MMPs, and the ultra-capacitor energy storage, given the finite amount of power available.

Instrument command and control capabilities are essential for realizing the observational power of the proposed mooring. Real-time information, along with command and control capabilities, will be used to conduct experimental sampling to determine the most appropriate "operational" sampling. These capabilities will also be critical to contingency sampling when important intermittent events are detected. Real-time sensor status will be essential for monitoring the MMP performance, and the ability to change the profiler programming will be used to diagnose, possibly even overcome, profiler system crises (e.g., fouling of the mooring line). Sensor/system failure detection will trigger alerts with AO/mooring managers and PIs.

The present design for the NEPTUNE Data Management and Archive System (DMAS; http://www.hia.nrc.ca/pub/CADC/NEPTUNE/) specifies a virtual instrument server (a software entity in the DMAS) be associated with every instrument. A scientist would communicate to his/her instrument via this server. All commands, data, and metadata are logged by the DMAS. The same server handles interactions between the user, the instrument, and the infrastructure system. For example, if a user wants to cycle power to an instrument, he can ask that power to the appropriate connector be turned off and on. We will be working with the DMAS development staff to construct the instrument server software for these particular sensors, so that they can be used as templates for others. This virtual instrument server supports the engineering and experimental modes of interacting with the mooring. Among other things, this server will facilitate experiments with the MMPs and winched profiler to help determine appropriate sampling strategies to capture all relevant signals and to avoid aliasing. In addition, this experimentation will help to decide what latitude exists in the "operational" profiling mode to support contingency sampling (e.g., when an eddy is detected.)

3.3.2 Information management To support routine automated quality control, scientific analysis, and education/outreach functions, a real-time data management system will be built. Raw data (Level 1) will be held online in an accessible format for as long as possible, and then ported to optical media. Calibration and quality control will be conducted in two modes. Level 2 data will be available with the minimum delay associated with the modes of sampling and automated processing. Level 3 data will be delayed-mode, involving retrospective calibration and quality control procedures that will use all other information that is available within a reasonable time frame (e.g., laboratory calibrations, other *in situ* measurements). All levels of data will be archived, and Level 2 and 3 data will be accessible online along with all metadata. Designated federal oceanographic data archives will be able to access the data and products on schedules that are convenient for their staff.

To support scientific analysis and curiosity-driven browsing, we will set up a live action server based on readily available public domain software. (An example is found at the PMEL/TAO web site: http://www.pmel.noaa.gov/tao/. This will enable direct Internet access to the information contained in the datasets through online plotting, as well as the ability to subset and download data.

4. Work Plan

The timeline for the project is:

Year 1	2003	Workshop
		Develop the winch profiler system
		Develop junction boxes
		Develop the MMP system (integrate J-boxes, new sensors, battery charging, dock)
		Web site development, quality control software engineering
Year 2	2004	Observatory interfce development
		Sensor integration and software testing
Year 3	2005	Full system integration and testing on land
		Deployment
Year 4	2006	Analyze data, service mooring, education and outreach
Year 5	2007	Analyze data, service mooring, education and outreach, transition to operation

We intend to mitigate engineering risk on this project by having three formal design reviews with independent experts. To insure good coordination, representatives from the AO, HOT, and NEPTUNE development programs will attend. While we have been somewhat specific in describing the proposed sensors and systems here, we recognize that it will be essential to coordinate this effort very closely with HOT scientists in particular as well as the community in general, in order for the science and engineering results and lessons learned to be optimized and applicable to cabled observatories in general. To this end, we are proposing an open workshop the second week of January 2003 in Hawaii. We anticipate that as NSF's OOI develops the Ocean Observatories community will organize annual workshops to address common issues such as governance, management, education, and public outreach. We will contribute organization expertise as well as the benefits of our experiences to these workshops.

4.1 Tasks

4.1.1 Development and testing What we expect to be the most difficult tasks will be tackled first: the winch design because it is a new mechanical system with moving parts; the MMP because it is a mechanical system that must be adapted for our use and also interfaced with a commercial entity/product; the primary and secondary J-box development because of the software including the command and control and interfacing to the DMAS. After 6 months the Concept Design Review (summer 2003), prior to prototyping, will be held to assure ourselves and others we are on the right track. In the second half of the first year, we will build the first prototypes and, in parallel, research the integration of all the sensors. The Preliminary Design Review will be held at the end of the first year with tested prototypes and detailed plans for sensor integration.

4.1.2 Integration and test The second year is devoted to interfacing/integrating all the various sensors, as well as continued testing of the critical elements above. At the end of year 2 (December 2004) we will hold the Critical Design Review, just prior to full system integration and testing. The latter will then take place in the first half of year 3 (2005) in preparation for deployment in the summer. Full system integration means the entire mooring system with all sensors is connected together on land (after pressure testing) with a realistic (accelerated) sampling schedule so that the winched profiler and MMPs are moving, data is flowing to the DMAS, and so on. Extensive wet tests of the winch system and MMP will be made in both the UW's test pool and in Puget Sound in depths to 200 m. Both sub-systems will be deployed and allowed to run attended for days to weeks with changes made and deployments repeated, as necessary. During this period a safety review will be held to review the deep water deployment plans. These essential steps towards deployment will be documented on the project Web site, allowing the scientific community and others to participate, either actively or vicariously in this complex process.

4.1.3 Deployment and servicing Deployment of the mooring will be in summer 2005 using ROV *Jason-2*. A special purpose winch will be used for the deployment of the mooring cable. The mooring will be deployed float first; the anchor will be lowered on a release as the mooring is towed and flown into the chosen location using the ROV and acoustic navigation net. The *Jason-2* will be used to deploy and connect the bottom cables, the AO interface, and J-box. We expect to spend several days to a week inspecting and debugging the mooring and sensors. This cruise will be coordinated with other AO activities that require the deep ROV. We will plan to make available real-time video of the shipboard and underwater activities through the project Web server. While not as visually exciting as a Space Shuttle launch, there will be educational value in this pioneering process of extending the Internet to the seafloor at 5000 m and then back up to the surface.

This mooring system is new and complicated so it is prudent to budget service calls. During the normal monthly (eventually quarterly) HOT cruises, the winched profiler (and possibly gear on the subsurface float) can be serviced by a surface ship by spooling out extra cable. A shared cruise in summer 2006 is planned. Major service with an ROV will take place in summer 2007; the present plan is to leave the mooring in place, as we assume the process of transitioning it to an operational state will have occurred (see below). Service vehicles may be a medium-depth ROV or the manned submersible PISCES, or a deep ROV if needed.

4.1.4 Data analysis Physical and optical oceanographic data analysis supporting the development of mooring sampling strategy will be undertaken with existing observations prior to deployment, Data from sampling experiments conducted after deployment will be analyzed to support choices for ongoing operational observations. A high priority for data analysis both before and after deployment is to develop the software for data quality control. This requires the prior experience with HOT observations in terms of distinguishing signals from noise, as well as anticipating modes of possible sensor failure. Close scrutiny of sensor characteristics and data streams after deployment will be required on a continuing basis, and adaptation of software developed prior to deployment will be needed. Finally, we will analyze the QCd data from the mooring to advance science objectives outlined earlier in this proposal. This will require integration with data streams from other platforms, such as the HOT cruises, Argo floats, and satellite altimetry. This will be pursued through collaborations with data assimilation efforts such as ECCO.

In addition to direct comparions with similar sensors used during HOT cruises, the optical data will be regularly inter-compared with biogeochemical variables (e.g. POC, DOC, chlorophyll, nutrients). This will allow us to evaluate how accurately we can invert optical measurements to obtain biogeochemical parameters at the ALOHA site and provide a context for with which to interpret the observed particulate and dissolved matter dynamics.

4.1.5 Instrument calibration In order to insure the retrieval of usable and high quality data, a specific effort will be mounted that will focus on:

1. Pre- and post-deployment calibrations.
2. Cross-calibration of sensors on the mooring when the MMP is parked either at the top or bottom of the mooring. This will require a deliberate sampling strategy that includes these inter-calibration episodes.
3. Cross calibration of sensors on the mooring with measurements obtained in conjunction with HOT (optical sensors used in HOT are calibrated every 6 months; R. Letelier, personal communication, 2002).

The design of the mooring will thus insure a vertical structure of high precision (through internal cross calibration). The accuracy will depend on the possibility to cross calibrate with accurate instruments, in particular those of HOT. There is a difficulty associated with comparing measurements from a vertical cast with those of an adjacent mooring; horizontal distance has to be maintained to avoid tangle resulting in a spatial difference of O(1 km). However, the instrument on the vertical cast will be compared to several cross-calibrated in-situ sensors, some of which will travel a significant vertical distance within the time Aloha Station is occupied. Minimization of the differences between the HOT and mooring sensors will provide the information needed for an absolute calibration of the mooring sensors and an error estimate associated with the calibration. Additionally, data-comparison obtained at the less variable portions of the water column will be weighted more in the minimization procedure.

4.1.6 Education and outreach Education and outreach activities will be conducted as part of the UH effort under this project. AO data will be made available in near real-time via the Internet, and we will work with colleagues in the Curriculum Research Development Group of the UH College of Education to obtain funding for their participation in developing educational products that are most useful for K-12 education. Sights and sounds in the ocean (observed by a hydrophone and video camera module attached to the junction box) will attract interest to displays that include information from our other observations. In addition to the undergraduate and graduate students that presently participate in HOT, we will seek to also involve UH community college students with the AO, both in the classroom and at sea. We will also network with the new NSF Centers for Ocean Science Education Excellence (http://www.nsf.gov/pubs/2002/nsf01173/nsf01173.html), and also with CORE and UCAR, organizations that have developed relevant science education programs. Local outreach will be achieved through a variety of partnerships, including the Waikiki Aquarium and the new Science Education Center at the Bishop Museum. At APL, an ocean engineering summer intern will be hired.

4.2 Project organization

The project will be lead by B. Howe. Assisting him are co-PIs Boss (optics), Gobat (ocean engineering), Lukas (physical oceanography, data/information management, education and outreach), McGinnis (engineering), and Mercer (cabled systems). As this is a substantial development effort, T. McGinnis has been designated project engineer and manager and will interface with the NEPTUNE engineering efforts (he is on the NEPTUNE system engineering team and is the system engineer for the NEPTUNE Power System development project). In addition to informal weekly meetings, there will be formal quarterly project meetings including personnel as appropriate. As mentioned, design reviews will figure prominently as milestones.

Interaction with the larger community will occur on several fronts. Sufficient travel funds have been requested to attend and present work-in-progress and results at engineering and scientific meetings, as well as to visit specific engineers. Documentation and dissemination of information is an important element of this project. We expect to publish in conference proceedings as well as technical journals. A Web page describing the project and providing electronic versions of publications and engineering documents will be maintained to inform the wider community.

During the January 2003 workshop we anticipate the establishment of an advisory body for the AO that is closely coordinated with the HOT program. We will work with them closely to insure the integration of our system, as well as its transition to an operational science tool.

5. Significance and Broader Impacts

The ALOHA Observatory, and the development work proposed here, will help the HOT program attain the long-term goal of reducing cruise time by increasing the use of real-time on-site systems. The latter will enable modes of sampling that will allow investigators to view their subject in new and different ways. Further additions and extensions might include direct chemical and biological sampling, small-scale turbulence and mixing studies from the bottom boundary layer to the air-sea interface, and drifters, gliders, AUVs, and tomography to extend the HOT footprint, for instance. Our goal is to make it as easy as possible for new investigators to use this infrastructure and to be able to painlessly add their particular sensors and obtain the data and related information products in a seamless way. Then, with experience, we will be better able to judge long-term service issues and costs: how should we balance frequency of ship visits with calibration needs and sensor/platform reliability? As systems like this are envisioned in one form or another at many sites around the world, this will serve as a useful first case.

Ocean observatories are established but fledgling components of our ocean science world. They are growing and multiplying, an expansion fueled by the science being done. Whether via the NSF Ocean Observatories Initiative or by other means, ocean observatories and the science they perform are clearly fundable in the competitive NSF environment.

Our sensors and mooring network infrastructure will be designed emphasizing reliability and long life. The effort is aimed at the regional and global observatories and is intimately linked with the associated engineering development efforts. These are the building blocks to conduct the oceanographic science reviewed here. This science will provide the essential, coherent context for improving our understanding of the complete ocean system.

NSF has two merit review criteria. The intellectual merit of the proposed work lies in the planned and potential scientific use of the instrumentation and infrastructure that is being developed. Long-term, reliable time series will clearly be an immediate and on-going benefit; the topics discussed in Section 2 fall into this class. But the primary premise and promise of ocean observatories is that new and different ways of doing ocean science will result. An observatory is inherently *coherent.* The change in approach is likely to be a large leap, rather than an incremental step. We believe this work directly supports the leap.

The broader impact of the proposed work is the enhancement of "the infrastructure for research and education, such as facilities, instrumentation, networks, and partnerships" (NSF Grant Proposal Guide, 2002). It will directly contribute to advancing techniques for distributing power to, and communicating with ocean and seafloor sensors. The proposed work will contribute to graduate and undergraduate education/training, preparing the workforce for deployment, maintenance and use of the Integrated Ocean Observing System. Further, by extending Internet connectivity (a general NSF-wide goal) to sensors and platforms on ocean observatories and the archives, students, the public, and all citizens will have access and can share in the process of scientific research.

References

Alford, M. H. and M. C. Gregg, 2001: Near-inertial mixing:modulation of shear, strain and microstructure at low latitude. *J. Geophys. Res.,* 106, 16,947-16,968.

ATOC Consortium, 1998: Ocean Climate Change: Comparison of Acoustic Tomography, Satellite Altimetry, and Modeling, *Science,* 281**,** 1327-1332.

Baringer, M.O., and J.C. Larsen, 2001: Sixteen years of Florida Current transport at 27 N. *Geophys. Res. Lett.*, 28, 3179-3182.

Bishop J. K. B., 1999. Transmissometer Measurement of POC. *Deep-Sea Res. I.* 46(2) 353-369.

Blough, N. V. and R. Del Vecchio, 2002. Chromophoric DOM in the Coastal Environment. In: Biogeochemistry of Marine Dissolved Organic Matter (D. A. Hansell and C. A. Carlson, eds.), Academic Press, pp.509-540.

Blough, N. V. and S. A. Green, 1995. Spectroscopic characterization and remote sensing of non-living organic matter. In: The Role of Non-living Organic Matter in the Earth's Carbon Cycle (R. G. Zepp and C. Sonntag, eds.), John Wiley & Sons Ltd, pp.23-45.

Campbell, L., H. Liu, H. A. Nolla and D. Vaulot, 1997: Annual variability of phytoplankton and bacteria in the subtropical North Pacific Ocean at Station ALOHA during the 1991-1994 ENSO event. *Deep-Sea Re. I*, 44, 167-192.

Cornuelle, B. D., B. Dushaw, D. Stammer, D. Menemenlis, and the NPAL Group (J. A. Colosi, B. D. Cornuelle, D. D. Dushaw, M. A. Dzieciuch, B. M. Howe, J. A. Mercer, R. C. Spindel, and P. F. Worcester), Acoustic remote sensing of large-scale temperature variability in the North Pacific Ocean, *Symposium on the Global Ocean Data Assimilation Experiment*, Biarritz, France, 13-15 June 2002

Chadwell, C.D., and Y. Bock, 2001: Direct estimation of absolute precipitable water in oceanic regions by GPS tracking of a coastal buoy, *Geophys. Res. Lett., 28*, 3,701-3,704.

Clark, H.L., New sea floor observatory networks in support of ocean science research, *Proceedings of the Oceans 2001 MTS/IEEE Conf., Honolulu, Hawaii, November 5–8*, 2001.

Cullen, J. J. 1982. The deep chlorophyll maximum: comparing vertical profiles of chlorophyll a. Can. J. Fish. Aquat. Sci. 39: 791-803.

Cullen, J.J., P.J.S. Franks, D.M. Karl and A. Longhurst, 2002: Physical influences on marine ecosystem dynamics. In The Sea, vol. 12, A. Robinson, J.J. McCarthy and B.J. Rothschild, Eds., John Wiley & Sons, Inc. New York, pp. 297-336.

Dickey, T. and P. Falkowski, 2002: Solar energy and its biological-physical interaction in the sea, eds. In The Sea, vol. 12, A. Robinson, J.J. McCarthy and B.J. Rothschild, Eds., John Wiley & Sons, Inc., New York, 401-440.

Dushaw, B.D., B. M. Howe, J. A. Mercer,R.C.Spindel, and the ATOC Group, Multimegameter-Range Acoustic Data Obtained by Bottom-Mounted Hydrophone Arrays for Measurement of Ocean Temperature, *IEEE J.Oceanic Engin.,* 24, 202-214, 1999.

Dushaw, B.D., D. B. Chester,P.F.Worcester,A Review of Ocean Current and Vorticity Measurements using Long-Range Reciprocal Acoustic Transmissions, In OCEANS '93: Engineering in Harmony with the Ocean, New York: IEEE. pp. I-298 to I-305, 1993.

Dushaw, B.D., Inversion of Multimegameter-Range Acoustic Data for Ocean Temperature, *IEEE J.Oceanic Engin.,* 24, 205-223, 1999.

Dushaw, B., G. Bold, C.-S. Chiu, J.Colosi, B. Cornuelle, Y. Desaubies, M. Dzieciuch, A. Forbes, F.Gaillard,

J. Gould, B. Howe, M. Lawrence, J.Lynch, D.Menemenlis, J. Mercer, P.Mikhalevsky,W.Munk, I. Nakano, F.Schott, U. Send, R. Spindel, T.Terre, P.Worcester, C. Wunsch, Observing the ocean in the 2000's: A strategy for the role of acoustic tomography in ocean climate observation, Proceedings of the First International Conference on the Ocean Observing System, San Rafael, France, 18-22 October 1999, in: *Observing the Oceans in the 21st Century*, C.J. Koblinsky and N.R. Smith (eds), Bureau of Meteorology, Melbourne, Australia, 2001.

Edson, J. B., A. D. Chave, M. D. Dhanak, and F. D. Duennebier, Guest editorial on cabled Ocean observatories, *IEEE J. Oceanic Engineering*, 27, 145, 2002.

Egbert, G.D. and R.D. Ray, 2000. Significant dissipation of tidal energy in the deep ocean inferred from satellite altimeter data. *Nature,* 405: 775-778.

Fennel, K. and E. Boss, 2002. Subsurface maxima of phytoplankton and chlorophyll--Steady state solutions from a simple model. Submitted to Limnology and Oceanography.

Finnigan, T.D., D.S. Luther and R. Lukas, 2002: Observations of enhanced mixing near the Hawaiian Ridge. J. Phys. Oceanogr., in press.

Goody, R., J. Anderson, T. Karl, R. B. Miller, G. North, J. Simpson, G. Stephens, and W. Washington, Why monitor climate? *Bull. Am. Meteorological Soc.,* 873-878, June 2002.

Howe, B. M., H. Kirkham, and V. Vorpérian, Power system considerations for undersea observatories, *IEEE J. Oceanic Engr.*, **27**, 267-274, 2002

Ittekkot, V., 1996. Particle flux in the ocean: introduction. In: Particle flux in the ocean (V. Ittekkot, P. Schafer, S. Honjo, P. J. Dpetris, eds.), John Wiley & Sons Ltd, pp.1-6.

Karl, D.M, 1999: A sea of change: Biogeochemical variability in the North Pacific subtropical gyre. *Ecosystems* 2, 181-214.

Karl, D.M. and R. Lukas, 1996: The Hawaii Ocean Time-series (HOT) Program: Background, rationale and field implementation. *Deep-Sea Res. II*, 43, 129-156.

Karl, D. M., R. Letelier, D. Hebel, L. Tupas, J. Dore, J. Christian and C. Winn, 1995: Ecosystem changes in the North Pacific subtropical gyre attributed to the 1991-92 El Niño. *Nature,* 373, 230-234.

Karl, D. M., J. R. Christian, J. E. Dore, D. V. Hebel, R. M Letelier, L. M. Tupas and C. D. Winn, 1996: Seasonal and interannual variability in primary production and particle flux at Station ALOHA. *Deep-Sea Res. II* 43, 539-568.

Karl, D., R. Letelier, L. Tupas, J. Christian, and D. Hebel, 1997: The Role of Nitrogen Fixation in Biogeochemical Cycling in the Subtropical North Pacific. Nature, 388, 533-538.

Karl, D.M., J.E. Dore, R. Lukas, A.F. Michaels, N.R. Bates and A. Knap, 2001: Building the long-term picture: The U.S. JGOFS time-series programs. Oceanography, 14, 6-17.

Kennan, S.C. and R. Lukas, 1996: Saline intrusions in the intermediate waters north of Oahu, Hawaii. Deep-Sea Res. II, 43, 215-241.

Kirkham, H., B. M. Howe, V. Vorpérian, and P. Bowerman, The design of the NEPTUNE power system, Proceedings of the Oceans 2001 MTS/IEEE Conf., Honolulu, Hawaii, November 5–8, 2001.

Kirkham, H., V. Vorpérian, and B. M. Howe, Parallel Power for Undersea Application: The Basic Considerations, SubOptic 2001, The Fourth International Convention on Undersea Communications, Kyoto, Japan, May 2024, 2001.

Letelier, R.M, D.M. Karl, M.R. Abbott, P. Flament, M. Freilich, R. Lukas and T. Strub, 2000: Role of late winter mesoscale events in the biogeochemical variability of the upper water column of the North Pacific

Subtropical Gyre J. Geophys. Res. Vol. 105, No. C12, p. 28,723-28,740.

Lukas, R., 2001: Freshening of the Upper Thermocline in the North Pacific Subtropical Gyre Associated With Decadal Changes of Rainfall. Geophys. Res. Lett., 28, 3485-3488.

Lukas, R., 2002a: Variability of the T-S Relationship Observed in the Hawaii Ocean Time-series. manuscript in preparation.

Lukas, R., 2002b: Mixed layer variability in the Hawaii Ocean Time-series. Manuscript in preparation for submission to Deep-Sea Res.

Lukas, R. and F. Santiago-Mandujano, 1996: Interannual variability of Pacific Deep and Bottom Waters observed in the Hawaii Ocean Time-series. Deep-Sea Res. II, 43, 243-255.

Lukas, R. and F. Santiago-Mandujano, 2001: Extreme Water Mass Anomaly Observed in the Hawaii Ocean Time-series. Geophys. Res. Lett., 28, 2931-2934.

Lukas, R., F. Santiago-Mandujano, F. Bingham and A. Mantyla, 2001: Cold bottom water events observed in the Hawaii Ocean time-series: Implications for vertical mixing. Deep-Sea Res. I, 48 (4), 995-1021.

Lukas, R., F. Santiago-Mandujano, and L. Zamudio, 2002: Eddy transport of anomalous waters in the Hawaii Ocean Time-series. Manuscript in preparation for submission to J. Geophys. Res.

Merrifield, M.A., P.E. Holloway, and T.M.S. Johnston, 2001: The generation of internal tides at the Hawaiian Ridge. *Geophys. Res. Lett.*, 28, 559-562.

Munk, W.H., 2002: The evolution of physical oceanography in the last hundred years. *Oceanography*, 15, 135-141.

Nahorniak, J. S., M. R. Abbott, R. M. Letelier, and W. S. Pegau, 2001. Analysis of a method to estimate chlorophyll-a concentration from irradiance measurements at varying depths, J. Atmos. Ocean. Tech., 18, 2063-2073.

National Research Council (NRC), *Illuminating the Hidden Planet: The Future of Seafloor Observatory Science*, National Academy Press, Washington, D.C., 2000.

NEPTUNE Phase 1 Partners (University of Washington, Woods Hole Oceanographic Institution, Jet Propulsion Laboratory, Pacific Marine Environmental Laboratory), 2000 *Real-time, Long-term Ocean and Earth Studies at the Scale of a Tectonic Plate: NEPTUNE Feasibility Study* (prepared for the National Oceanographic Partnership Program), University of Washington, Seattle. See also http://www.neptune.washington.edu.

Niiler, P.P., and C. J. Koblinsky, 1985: A local time-dependent Sverdup balance in the eastern North Pacific Ocean. *Science*, **229**, 754-756.

Ocean Sciences Decadal Committee, P. Brewer and T. Moore, co-chairs, *Ocean Sciences at the New Millenium*, University Corporation for Atmospheric Research, 2001.

Orcutt, J., and A. Schultz, Working Group Co-Chairs, *DEOS Global Working Group Report: Moored Buoy Ocean Observatories*, 1999. See DEOS web page and links at http://www.coreocean.org.

Petitt, R., D. W. Harris, B. Wooding, J. Bailey, J. Jolly, E. Hobart, A. D. Chave, F. D. Duennebier, R. Butler, A. Bowen, and D. Yoerger, The Hawaii-2 observatory, *IEEE J. Oceanic Engineering*, **27**, 245-253, 2002.

Schneider, K., C-C. Liu, T. M. McGinnis, B. M. Howe, and H. Kirkham, Real-Time Control and Protection of the NEPTUNE Power System, *Proceedings of the Oceans 2002 MTS/IEEE Conf.*, Biloxi, Mississippi, October, 2002.

Schofield, O., T. Bergmann, P. Bissett, J. F. Grassle, D. B. Haidvogel, J. Kohut, M. Moline, and S. M. Glenn, The long-term ecosystem observatory: an integrated coastal observing system, *IEEE J. Oceanic*

Engineering, **27**, 146-154, 2002.

Send, U., R. Weller, S. Cunningham, C. Eriksen, T. Dickey, M. Kawabe, R. Lukas, M. McCartney, and S. Osterhuis, 2001: Oceanographic time series observatories, Observing the Ocean for Climate in the 21st Century, eds. C.J. Koblinsky and N.R. Smith, Australian Bureau of Meteorology, 376-390.

Spinrad, R. W., J.R.V. Zaneveld, and J. C. Kitchen, 1983.A study of the optical characteristics of the suspended particles in the benthic nepheloid layer of the Scotian Rise. *J. Geophys. Res*. 88 (C12): 7641-7645

Stramski, D., R. A. Reynolds, M. Kahru, and B. G. Mitchell. 1999. Estimation of particulate organic carbon in the ocean from satellite remote sensing. *Science*, 285, 239-242.

Twardowski M., E. Boss, J. B. Macdonald, W. S. Pegau, A. H. Barnard, and J. R. V. Zaneveld, 2001. A model for estimating bulk refractive index from the optical backscattering ratio and the implications for understanding particle composition in case I and case II waters. *J. Geophys. Res*., 106, 14,129-14,142.

Budget Justification

In this 5-year project we will integrate a suite of sensors on a mooring for measuring oceanographic variables, adapting existing components or developing new ones, as necessary. The mooring network infrastructure that is required to link an array of these instruments to the cabled ALOHA Observatory is integral to this proposal. This is a collaborative research proposal with three institutions: UW Applied Physics Laboratory (Howe et al.; $3,347K), University of Hawaii (Lukas; $522K), and University of Maine (Boss; $281K). Here we describe the UW part; please see the other respective Budget Justifications. The total requested amount for all institutions is $4,150K.

A major part of this project's expenses are in equipment fabrication (including salaries associated with development) that does not carry indirect cost overhead (17% at APL-UW). Major fabrication items include the winched profiler, the modified moored profiler with dock, junction boxes, mooring cable, and float. The NSF budget sheets combine non-fabrication and fabrication together. The non-fabrication part of the budget (includes science, management, and most travel, for instance) amounts to $1,106K, spread roughly uniformly over time. The fabrication portion amounts to $2,237K, heavily weighted in the first years.

Within the fabrication budget, equipment in the normal sense (sensors, pressure cases, electronics, cables, etc.) is listed under supplies, accounting for $852K of the $2,237K total. The former amount could be regarded as an estimate of the replication or recurring parts cost, and the difference, $1,385K, can be regarded as an estimate of the labor costs. We estimate that about $250K of this labor cost is what it would take to replicate the mooring, not including sea trips. The major development items are the winched profiler, the modified MMP, and the junction boxes; the first two involve mechanical systems. The following tables summarize the fabrication and non-fabrication portions of the project.

Summary of Fabrication Effort (parts, $K; labor, man months)

	Year 1		Year 2		Year 3	
Fabrication Item	Parts	Labor	Parts	Labor	Parts	Labor
Winched Profiler	31	6.0				
Profiler Sensors	47	0.5				
Winch	31	2.0		4.0		
Float Infrastructure		5.5	35	2.2		1.0
Float Sensors	89	0.5				
Moored Profiler	200	10.3		1.0		
Junction Boxes		9.5	67	1.5	67	1.0
Observatory Interface			50	3.0		
Anchor, Cables & Connectors			212		9.5	
Anchor Sensors			15	0.5		
Testing				7.7		
Deployment Cruise						4.5
Assembly		6.0		5.6		2.5
Total	**$397K**	**40.3**	**$379K**	**25.5**	**$77K**	**9.0**

Summary of Non Fabrication Effort (man months)

	Year 1	Year 2	Year 3	Year 4	Year 5
Admin/Management	3.0	2.5	1.3	0.7	0.7
Science,Coordination	4.5	5.0	7.0	4.5	5.3
Cruises (Non Fab)	0.3			0.5	1.0
Support (intern)	3.8	3.6	4.0	3.6	3.5
Total	**11.5**	**11.1**	**12.3**	**9.3**	**10.5**

Personnel and Roles

The major personnel and their roles and responsibilities are as follows:

Bruce Howe, project PI. Howe will be responsible for overall coordination of this project, coordination within the NSF OOI effort and NEPTUNE, and the analysis of the ambient sound data. He is currently PI on the NSF-funded NEPTUNE power system design project, and on the NEPTUNE Program Office staff.

Jason Gobat will be responsible for the mooring and winched profiler design analyses, and integration of the physical and optical sensors into the infrastructure framework, including interfacing the MMPs. He has extensive experience in the design of innovative oceanographic moorings, including both mechanical and hydrodynamic forcing aspects and integration of complex sensor and telemetry suites.

Tim McGinnis, project engineer and manager, will contribute to all aspects of the development work. He recently joined APL-UW specifically to work on ocean instrumentation and sensor network infrastructure for cabled ocean observatories. He is presently system engineer for the NEPTUNE power system project and is a member of the NEPTUNE system engineering team.

Jim Mercer (APL-UW) will work with Fred Duennebier (UH, ALOHA Observatory) as our primary point of contact with the AO. He is currently building a shore power supply for the similar IRIS H2O cable system and has over 30 years of experience with underwater cable systems and acoustic technology.

Others at APL: Mike Kenney will be responsible for hardware/software work associated with the various micro-controllers and for the instrument server software providing the interface between the sensors and the scientists; he is working on similar topics for the NEPTUNE power system. Vern Miller will be responsible for mechanical engineering, including the winch, MMP docking, and mooring designs.

Emmanuel Boss (UMaine) will lead the moored optical data analysis and supervise a post-doc who will devote six months per year to this project. The post-doc will interface with APL's engineers to insure proper integration and deployment of the optical sensors. See the UMaine Budget Justification for detail.

Roger Lukas (UH) is the co-founder of the Hawaii Ocean Time-series, and has studied the ocean around Hawaii for nearly 30 years. He will be responsible for the development of the information management system, including real-time data management and quality control, product generation, and distribution via the Web. He will work with other groups to pursue education and outreach objectives for the AO. He will lead the moored physical data analysis, in conjunction with analysis of other physical measurement at and around Station ALOHA. See the UH Budget Justification for detail.

Equipment

The estimated costs for the various elements are:

Year 1 – Winched profiler ($31K, includes secondary junction box, flotation, frame); winched profile sensors ($47K; Seabird CTDO$_2$, $15K; Optics, $32K); winch ($31K); subsurface float sensors ($89K; ADCP $50K, CTDO$_2$, $15K; Optics, $18K); moored profiler ($200K; basic MMP, $54K; McLane NRE, $50K; Falmouth CTD and ACM, $21K; O$_2$, $5K, Optics; $18K; secondary junction box, $19K; batteries, dock, ultra-capacitors and controller, $34K). Optics breaks down as follows: CDOM, $4K; transmissometer, $4K; chlorophyll, $4K; backscatter, $6K; and radiance/irradiance (on winch profiler only), $14K. The total for Year 1 is $397K.

Year 2 – Anchor, cables and connectors ($212K; mooring cable $120K; connectors: dry $60K, wet $26K), Observatory Interface ($50K); subsurface float parts ($35K; float; $18K; hardware, $7K; ultra-capacitors, $10K); subsurface float junction box ($67K), anchor sensors (Seabird CTDO$_2$, $15K). The total for Year 2 is $379K.

Year 3 – Anchor junction box ($67K; includes acoustic transceiver, $21K); Anchor ($10K).

The total cost of the sensors (no platforms) is $237K.

Travel

Funds are requested to attend science and engineering meetings, visit engineers associated with existing ocean observatories, provide coordination with on going ocean observatory development efforts, provide travel for consultants for the three design reviews, sea trips (including one HOT cruise the first year to gain familiarity with the program), and to brief program officers at NSF. The total travel request is $86K, of which $22K is for the deployment cruise, within the fabrication budget. Per diem rates used at specific locations are set by the state of Washington.

Services and Supplies

A total of $60K is allocated for compensation and costs for design review consultants (this is based on the recent Power System Concept Design review mentioned in the Results from Prior NSF Support section). Various other services include journal page charges, communications, computer services, test tank rental, pressure testing, APL utility boat charges, shipping, and machine shop; the last three make up most of the fabrication services.

General Notes:

Section B: Other Personnel The amount budgeted for administrative, clerical, or secretarial support will cover services directly related to the grant/contract. APL-UW is considered a “major project,” and thus such charges are in full compliance with OMB Circular A-21, Section F.6.b. Reference 30 Sept. 1994 letter (ser 4330/247) from June Hawley, Administrative Contracting Officer, Office of Naval Research, Seattle Regional Office, to William Bakamis, APL-UW General Manager, Business and Finance.

Section C: Fringe Benefits The benefit and leave rates included in the budget are in accordance with UW’s negotiated rates approved by HHS and UW policy on proposal budgets.

Section G-6: Other Included in this section are services and APL-UW Prorated Direct Costs (PDC). The University Indirect Cost rate applied to APL-UW is lower than the rate elsewhere on campus (17% vs 52%) and does not recover the Laboratory's central costs. These are recovered by applying PDC to total salaries. PDC includes such expenses as salaries and employee benefits for central service employees, administrative data processing, communications, and some facilities costs. APL-UW’s PDC has been reviewed and accepted by the Navy’s resident administrative contracting officer. Reference 24 Oct. 01 letter (ser 4330/247) from C. C. Everley, Administrative Contracting Officer, Office of Naval Research, Seattle Regional Office, to David Low, Dept. of Health and Human Services, San Francisco, CA.

Summary of Other Charges ($K)

	Year 1	Year 2	Year 3	Year 4	Year 5
Non Fabrication PDC	37	37	43	32	39
Fabrication PDC	144	85	29	3	3
Computer Service	2	2	3	1	1
APL Machine Shop	63	63	16	16	16
Communications	2	2	2	1	1
Other *	0	24	33	0	6
Total	**$247K**	**$212K**	**$123K**	**$52K**	**$65K**

*Other: Year 2: Testing costs (Pressure testing $3.6K utility vessel $19.5K & test tank $1.2K
Year 3: Deployment costs (Shipping $22.5K, sensor calibration $5K & pier services $5K)
Year 5: Shipping $6K

Section I: Indirect costs APL-UW’s negotiated indirect rate is 17% of Modified Total Direct Costs (MTDC). Other departments at UW have an indirect rate of 52% MTDC. MTDC includes all direct costs less equipment, and the amount of sub awards above the initial $25K. **Indirect charges are not applied to cost associated with equipment design and fabrication for equipment for which the UW will retain title.**