Project Description

Background

We propose to develop a hardware/software interface system that will allow the acquisition of scientific data from the seafloor in observatory mode, using seafloor cables to provide power and communications. The proposed prototype cabled observatory should be viewed in the general context of national and international efforts to acquire scientific data from the seafloor, such as, for example, the cabled observatories being planned as part of the Ocean Observatories Initiative (OOI). The prototype system development will take advantage of the existing seafloor seismic observatory MOBB (Monterey Ocean bottom Broad Band project), and the opportunity we have to connect it to the MARS cable due to be deployed in Monterey Bay, CA, in the Fall of 2006.

The main objective of this proposal is to provide a system, based as much as possible on off-the-shelf technology, that will allow the following seafloor-to-cable capabilities:

- Connection of scientific instruments that are not in the immediate vicinity of a cable node and therefore require an extension cable.
- Connection of multiple sensors with different interfaces (analog and digital), data rates, and other requirements to the extension cable.
- Data acquisition as part of an existing continuous and real time monitoring system (in our particular case, the Northern California Earthquake Monitoring System (Gee et al., 1996; 2003).

In the context of the Ocean Observatories Initiative (OOI; Isern, 2005), two types of cabled observatories are planned: a regional cabled observatory in the Pacific Northwest, loosely coordinated with the funded NEPTUNE-Canada cabled observatory, as well as several coastal observatories. A variety of geophysical, oceanographic and biological sensors will eventually be deployed near these cables, and will rely on the cable for their power as well as for data transmission to shore, and for remote sensor control. In some cases, auxiliary sensors will also be deployed near the primary sensor. And in some cases, one or a suite of independent sensors will be deployed close to each other, but not in the immediate vicinity of the cable node, and, to be reached, will require an extension cable of length up to several kilometers. These various sensors will have different requirements. For example, some will come with analog interfaces and some, with digital interfaces. Some will require very accurate time references, and for some, data acquisition in real time will be important.

From the technological point of view, an opportunity presents itself at present, with the conjunction of : 1) the planned installation of the MARS cable (Monterey Accelerated Research System; http://www.mbari.org/mars), now scheduled for the Fall of 2006. The MARS project, funded by NSF, is a test bed for cabled observatories such as NEPTUNE; and 2) the proximity of the MARS cable path to the existing ocean floor broadband seismic MOBB station (Monterey Ocean bottom Broad Band observatory), operated cooperatively by the Monterey Bay Aquarium Research Institute (MBARI) and the Berkeley Seismological Laboratory (BSL).

The multi-sensor MOBB system, which will be described in more detail below, has now been in operation in autonomous mode for over 4 years, and presents a high level of complexity and technological requirements. While MOBB represents only one category of sensors that could benefit from the proposed development, its requirements for timing accuracy, real-time continuous data acquisition and two-way communications are among the most demanding, making it a good starting point for the development of such a prototype system. The planned MARS cable route is down the center of Smooth Ridge and with a termination and junction box approximately 2.96 km from the MOBB site (Figure 1), which is within reach of the cable-laying capability of the MBARI ROV Ventana (the maximum reach is 4km). In addition, the relative proximity of MOBB to shore (and to MBARI) allows recurrent visits, during which system improvement can be performed.

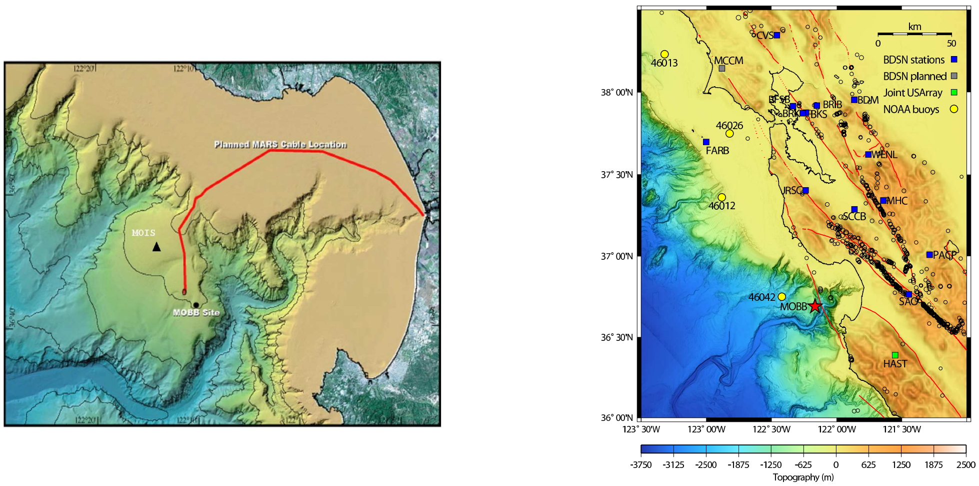

Figure 1: *left*: Location of the MOBB and MOISE stations in Monterey Bay, California, against seafloor and land topography. The 1997 MOISE experiment, in which a similar system was deployed in a similar manner for a period of 3 months, was a cooperative program sponsored by MBARI, UC Berkeley and the INSU, Paris, France (Stakes et al., 1998; Romanowicz et al., 1998; Stutzmann et al., 2001). During the MOISE experiment, valuable experience was gained on the technological aspects of such deployments, which contributed to the success of the present MOBB installation. The planned location of the MARS cable is also indicated, with its termination close to the present MOBB site. *Right*: Location of the MOBB (red) and the BDSN seismic stations(Blue) shown against the seafloor and land topography. Background seismicity (ANSS catalog, 1968-2006, M3.5+) is shown in black. Locations of the NOAA buoys closest to the MOBB are shown in yellow. Fault lines from the California Geological Survey's database are shown in red.

Furthermore, there is already existing extensive infrastructure on land to acquire seismic data in real time in the context of the Northern California Earthquake Notification System operated jointly by UC Berkeley and the US Geological Survey in Menlo Park (USGS/MP). Contributing the data from MOBB will allow us: 1) to test the feasibility and quality of real-time data acquisition from a complex cabled ocean floor observatory requiring an extension cable, and 2) to acquire useful data, for the duration of the experiment, to complement broadband data acquired on shore to characterize earthquakes occurring in this portion of the North America/Pacific plate boundary. Indeed, MOBB is uniquely located on the west side of the seismically active San Gregorio fault - which is capable of M 6 and larger earthquakes. Also, the central California portion of the San Andreas Fault (SAF) is poorly illuminated from the west side, as the Farallon Islands are the only available islands providing on-land sites for broadband seismic installations.

Finally, an on-line archive exists at the Berkeley Seismological Laboratory, the Northern California Earthquake Data Center (NCEDC, http://www.ncedc.org). The NCEDC archives and distributes data from the Berkeley Digital Seismic Network (BDSN), the Northern California Seismic Network (NCSN) operated by the USGS and other geophysical stations in northern California. Making the data from the cabled-observatory available to the community, once it is acquired onshore, is therefore an already resolved problem and will allow us to demonstrate how data from the seafloor - no matter what discipline - can be merged continuously and in real-time with land-acquired data.

The Regional Cabled Observatory Network Design for ORION's Ocean Observatories Initiative includes a core seismic suite of instruments at each of the five main nodes. Each suite consists of a broadband seismometer, a hydrophone, and a pressure sensor. To our knowledge, no existing off-the shelf system is available for the purposes described above without additional software development.

There are many good examples of the re-use of retired commercial early generation optical and coaxial undersea cables, such as H20 (e.g.Chave et al., 2002), GeO-TOC and VENUS (e.g. Kasahara et al., 1995; 2000). However, the node and shore station technology (containing high-power and voltage, direct-current generation, network and science experiment management, and standardized interfaces) is not readily transferable to the current generation of commercial optical cables (e.g. Favali and Beranzoli, 2006). The Antarès broadband seismic system in France is piggy-backing on a neutrino detector experiment and has currently limited capabilities (e.g. Aguilar et al., 2006; Anne Deschamps, *pers. comm.*). The system we are proposing offers flexibility which will be needed in practical scenarios, where optimal siting and availability of a suite of complementary data streams is necessary. Neptune-Canada is exploring possible solutions for the connection of their broadband seismic and other sensors to their cable, but the specifications of the system they are pursuing are not yet available and they remain interested in our development. On the other hand, a proposal to install a *borehole* broadband seismic sensor in Monterey Bay and connect it to the MARS cable has been deferred indefinetely, because the permit to drill the IODP hole was not secured. The borehole installation may have provided a lower noise environment, and therefore higher quality seismic data, than the buried seafloor installation, but it will not be available in the time frame required for the MARS or the OOI cabled observatory experiments that need such a device. Also, the buried seafloor system is more closely related to at least the first of the planned deployments on the OOI cabled observatory.

The present MOBB autonomous observatory

The ocean-bottom MOBB station was deployed in April 2002 and comprises a three-component seismometer package, a current-meter, and a recording and battery package. In addition, a differential pressure gauge (DPG) with autonomous recording (Cox et al., 1984) was installed in Fall 2002. The seismic package contains a low-power (2.2W), three-component CMG-1TD broadband seismometer system, built by Guralp, Inc., with a three-component 24-bit digitizer, a leveling system, and a precision clock. It is mounted in a cylindrical titanium pressure vessel 54 cm in height and 41 cm in diameter, custom built by the MBARI team and outfitted for underwater connection. Because of the extreme sensitivity of the seismometer, air movement within the pressure vessel must be minimized. In order to achieve this, after extensive testing at BSL, the top of the pressure vessel was thermally isolated with two inches of insulating foam and reflective Mylar. The sides were then insulated with multiple layers of reflective Mylar space blanket, and the vessel was filled with argon gas (e.g. Uhrhammer et al., 2002; Romanowicz et al., 2006; Dolenc et al., 2006). The current-meter is a Falmouth Scientific 2D-ACM acoustic current meter. It is held by a small standalone fixture and measures the magnitude and direction of the currents about 1 meter above the seafloor. The recording system is a GEOSense LP1 data logger with custom software designed to acquire and log digital data from the Guralp system and digital data from the current meter over RS-232 serial interfaces. The seismic data are sampled at 20 Hz, current-meter and DPG data at 1 Hz, and all are stored on a 3 GB, 2.5 in disk drive. All the electronics and the sensor packages are powered by a single 10 kWh lithium battery.

Prior to the instrumentation deployment, the MBARI team manufactured and deployed a 1181 kg galvanized steel trawl-resistant bottom mount to house the recording and power systems, and installed a 53 cm diameter by 61 cm deep cylindrical PVC caisson to house the seismometer pressure vessel. The bottom mount for the recording system was placed about 11m away from the caisson to allow the future exchange of the recording and battery package without disturbing the seismometer. This bottom mount can be re-used to house the interface to the MARS cable. Prior to deployment, the seismometer package was tested extensively at BSL, then brought to MBARI where its internal clock drift was calibrated in the cold room against GPS time.

The deployment itself occurred over 3 days (04/09-04/11/02). On the first dive, the seismometer package was lowered into the PVC caisson (Figure 2a), and its connection cable brought to the site of the recording unit. On the second dive, the recording package was emplaced in its trawl-resistant mount (Figure 2b), and connected to the seismometer package. Tiny (0.8 mm) glass beads were poured into the caisson until the seismometer was completely covered, to further isolate it from water circulation. The seismometer package is now buried at least 10 cm under the seafloor. On the third dive, the ROV buried the cable between the seismometer and recording packages, then connected to the seismometer through the recording system (Figure 2b), levelled and recentered the seismometer and verified that it was operational.

The system design and configuration (including seismometer shielding and testing) were replicated for the three broadband ocean bottom stations that were deployed on the Juan de Fuca plate, as part of the KECK project (Wilcock et al, 2004; McGill et al., 2004). The Keck instruments operated for a full 12 months in an autonomous mode signalling their capability to perform in a cabled environment.

Figure 2: left: Installation of the seismometer package inside the PVC caisson. This was later completely covered by glass beads. Right: Trawl-resistant enclosure for the recording and battery packages. This snapshot was taken as the ROV Ventana was bringing the cable from the seismometer package in order to connect it onto the recording package. The first time such a remote underwater connection was attempted during the MOISE experiment, it took 2.5 hours to succeed and led to a redesign of the geometry of the instrument packages. The ROV operators are now able to do this routinely in less than 5-10mn.

The station has been recording data autonomously for over 4 years. The site is revisited every 3-4 months, at MBARI's cost. During these dives, dataloggers and battery packages are exchanged, seismometers recentered, and Guralp clock compared to GPS time. Seventeen visits have occurred during the time period 04/10/02 to 06/15/06. The data are archived and available at the on-line Northern California Earthquake Data Center (NCEDC, Romanowicz et al., 1994; http://www.ncedc.org), along with those of the Berkeley Digital Seismic Network (BDSN).

Illustration of results from the analysis of MOBB data

While the main motivation of this proposal is to develop technology reaching beyond seismology to any type of continuous data acquired on the sea-floor, the data from the specific set of sensors comprising MOBB is unique in several ways: 1) it is the only seismic broadband station located west of the seismically active San Gregorio fault, providing a unique view from the west of earthquakes on this fault as well as the other active faults of the San Andreas system in central California; while a single broadband station cannot solve all the issues related to the unbalanced distribution of seismic stations around the plate boundary, it can contribute significantly. 2) The accumulating long term database of background seismic noise data, combined with auxiliary pressure and current data, is allowing us to demonstrate the effectiveness of noise reduction methods to enhance signals from earthquakes. Finally, the long term acquisition of these data has proven useful for the study of various wave-climate related phenomena, in particular in the infragravity wave band. In what follows, we illustrate some of the findings from MOBB.

Earthquake observations

Figure 3a shows the records, deconvolved to ground velocity, for a M3.63 regional event which occurred on 04/23/2002 on the San Andreas Fault (SAF) at a distance of 53.4 km from MOBB. The very large S wave pulse on the horizontal components as well as the subsequent ringing are likely due to site response, and this could be removed by post-processing, as described in a forthcoming section. On the vertical component, the water reflection of the P wave is clearly seen 1.3 sec after the P wave (e.g. Ward, 1979; Blackmann et al., 1995). In spite of these strong site effects, and because of the low noise notch between 10-30 sec (see section on background noise), these data can be used in moment tensor studies, as performed routinely in real-time in northern California (Gee et al., 1996; 2002). Figure 3b shows the results of a moment tensor inversion using the time domain whole waveform methodology (Dreger and Romanowicz, 1994; Dreger, 1997) which is used in operational mode in the joint UCB/USGS northern California earthquake notification system. A robust solution is obtained using data from 5 stations, including MOBB (and 4 land-based stations of the Berkeley Digital Seismic Network, BDSN). The waveform fit at MOBB is outstanding with a 92.8% variance reduction. This example serves to show that the MOBB data are well calibrated and have potential for providing valuable constraints in moment tensor studies of events of other types, such as reverse fault events in the Coast Ranges or strike-slip events on faults closer to the shore or offshore. To further demonstrate the consistency of the MOBB data, we also show the results of a single station moment tensor inversion using only MOBB, and the comparison of the corresponding synthetic predictions with the actual data at the four other BDSN stations. The single station solution results in a nearly identical focal mechanism, but a slightly larger CLVD component and scalar moment, which is not unlike other single station inversions based on land-acquired data.

Background noise observations

One of the key issues regarding installation of broadband seismic systems on the ocean floor is the high level of background noise that is typically experienced. We have therefore put significant effort into understanding and minimizing the sources of noise in the MOBB system.

Before and during the initial deployment of the MOBB package in Monterey Bay, a number of steps were taken to minimize the instrument-generated background noise as well as the noise induced by water flow around the seismometer. Prior to deployment, the seismometer system was extensively tested at BSL to obtain the best insulation and minimize the long-period noise due to the sensitivity of the instrument to air movement within the titanium pressure vessel (e.g. Uhrhammer et al., 2003; Dolenc et al., 2006). By not allowing convective air currents within the pressure vessel, these steps significantly reduced noise that was observed on all three components in the 10-100 sec period range (noise reduction was over 20dB, Dolenc et al., 2006). Steps taken during the deployment, as described earlier allowed the noise from eddies that could be generated from the different components of the system to be minimized. The remaining long-period background noise observed at MOBB is primarily due to pressure forcing from infragravity ocean waves (e.g. Dolenc et al., 2005).

Infragravity noise

Infragravity waves are ocean waves in the frequency band $\sim 0.002 - 0.05$ Hz. They are a strong and always present source of long-period noise in ocean floor deployments. A comparison of the power spectral density (PSD) at MOBB and three other land stations of the BDSN for a quiet

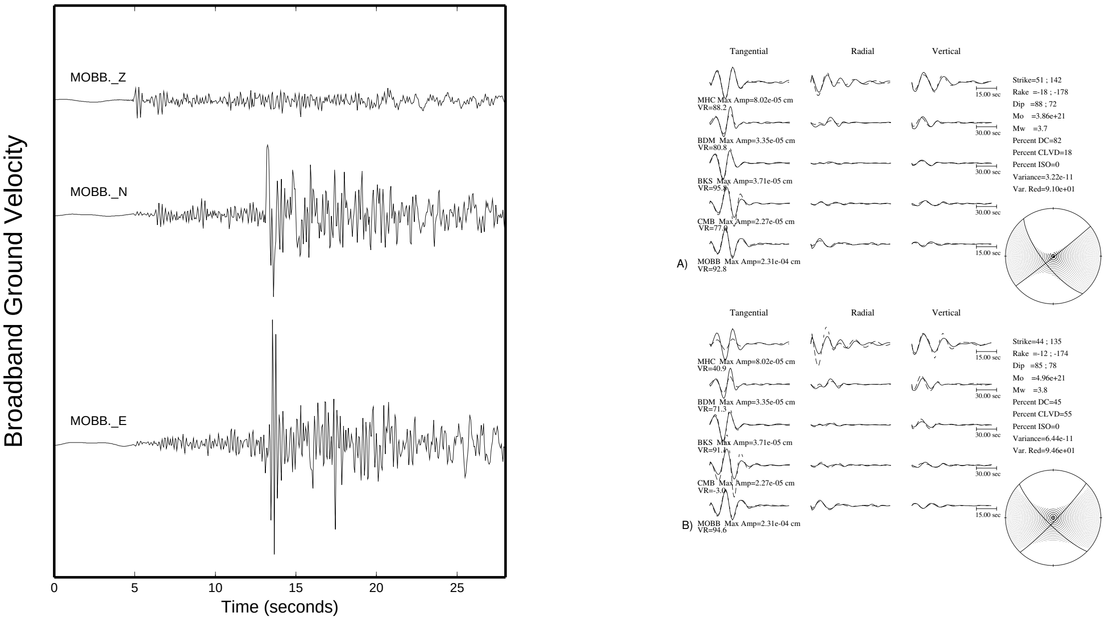

Figure 3: Left: Three component deconvolved ground velocity records at MOBB of the 04/23/2002 Mw 3.63 San Andreas fault event (lat = 36.866, lon = -121.61, depth = 9 km). Right: Results of moment tensor inversions for the M 3.63 regional event shown on left. Top: inversion using 4 stations of the BDSN and MOBB (BDM,BKS,CMB are bandpass filtered between 0.02 and 0.05 Hz; MHC and MOBB, between 0.05 and 0.10 Hz). Bottom: results of inversion using only MOBB, showing the good fits of the single station solution to the other BDSN waveform data.

and a stormy day without significant earthquakes show that a noise "hump" is always observed on MOBB, but not on the stations located inland (Figure 4). The "hump" occurs in the period range 20-200s during the quiet day, and becomes stronger and wider (20-500 s) on the stormy day, when it can actually also be observed at the Farallon Islands station FARB. The fact that only linear waves with wave numbers comparable or smaller than the inverse of the water depth can generate a detectable pressure signal at the seafloor (Webb, 1998) results in the sharp short-period cutoff observed at 20 s in the spectrum for the vertical component at MOBB on a stormy day (e.g. Dolenc et al, 2005; Romanowicz et al., 2006). On the horizontal components, the infragravity peak is observed only on the stormy days, indicating that this signal is primarily generated by vertical pressure on the seafloor. The stronger signal at FARB on the horizontal components (stormy day) may be a combination of direct atmospheric effects (tilts) and conversion of infragravity waves to horizontal elastic motion. The shape of the noise spectra in the infragravity wave band measured at MOBB agrees with theoretical predictions (Araki et al., 2004) as well as with observations from other shallow buried seismometer deployments (Stephen et al., 2003; Araki et al., 2004).

Because the infragravity noise is continually present in a bandpass critical for the detection and analysis of seismic surface waves, it is important to try and remove it. This is where the pressure signal from the locally recorded DPG becomes useful. A simple method for the removal of this noise is to subtract the pressure-correlated part of the MOBB signal. To achieve this, we have experimented with two approaches. In the first one, we assume that there is a frequency independent linear scaling factor between the pressure and the vertical seismic data in the time domain, a method previously applied to remove atmospheric pressure noise from gravimeter observations of earth tides (e.g. Warburton and Goodkind, 1977) and later vertical seismic data on land (Zürn and Widmer, 1995). Figure 5 (left) illustrates the result for a 5.5-hour period, presented in the

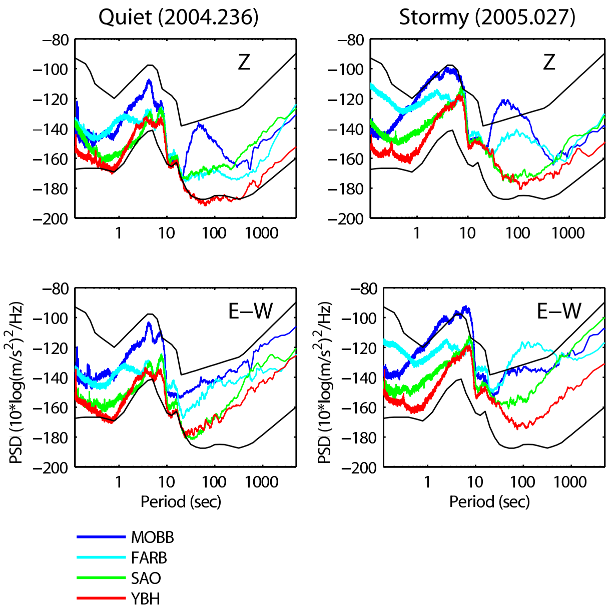

Figure 4: Comparison of vertical component (top) and N/S component (bottom) noise recorded at MOBB and 3 other stations of the BDSN network, on two days in 2004-05 when no significant earthquake signals were recorded: a "quiet day" (236,left), and a "stormy" day (2005/027,right), as assessed by the mean wave height recordings at a nearby NOAA buoy, located in Monterey Bay. Spectra were calculated using 4 hours of data. The USGS high- and low-noise models for land stations are shown in black (*Peterson*, 1993). Increased noise levels for periods 20 to 300 sec are observed at MOBB on both quiet and stormy days, as well as at the island station FARB (Farallon Islands) on the stormy day. The noise level at MOBB between 10 and 20 sec is comparable to the land station YBH, one of the quietest stations of the BDSN. Note how the height and also the width of the infragravity noise band increases on the vertical component on stormy days.

frequency domain to show the successful removal of the infragravity "hump". A second approach is to compute a transfer function between the vertical seismic and pressure recordings and predict the corresponding vertical component deformation signal, which is then removed from the seismic data either in the frequency or time domain (e.g. Webb and Crawford, 1999; Crawford and Webb, 2000). The transfer function is calculated from records during times without earthquakes. Since it is only a function of structure at the MOBB location, it does not change with time and can be applied to all data from this site. The method only works when coherence between the two channels used to compute the transfer function is high in the period of interest. Figure 5(right) illustrates the result of this approach. An example of the long-period background noise removal for a period that included an earthquake is shown in Figure 6, using the same transfer function as computed from the data shown in Figure 5(right). The result shows that the method successfully recovers the seismic phases that were previously hidden by the long-period background noise. Such a method can be systematically applied to MOBB and similar data.

Signal-generated noise

The other type of noise observed at MOBB is signal-generated noise. It is due to reverberations of seismic waves in the shallow sedimentary layers and is particularly strong following the arrival of sharp and strong phases that are often characteristic of large deep teleseismic events. An example of such signal-generated noise observed at MOBB is shown in Figure 7(left). The waveforms in the 0.03-0.08 Hz passband show the arrivals of the P, pP and PP phases which look similar for all

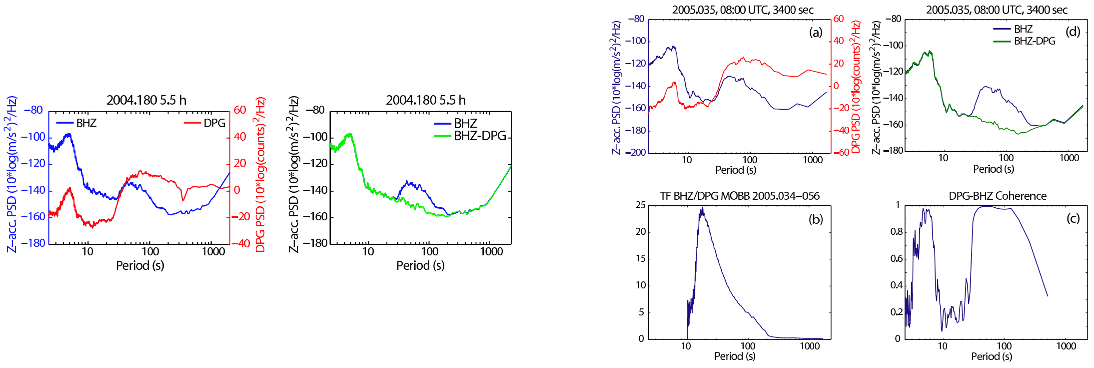

Figure 5: *left*: Power spectral density (PSD) calculated for a 5.5 hour period without earthquakes for the vertical seismic channel (blue) and the DPG (red). At periods longer than 20s the infragravity "hump" is observed for both datasets. (b) PSD for the vertical seismic channel before (blue) and after (green) the time-domain subtraction of the DPG signal. Most of the infragravity "hump" has been removed from the seismic data. *Right*: Example of the transfer function method to remove noise from the earthquake-free vertical data (a) PSD for 1-hour period without earthquakes for the vertical seismic channel (blue) and DPG (red). (b) Transfer function between vertical seismic and DPG signal calculated from 144 1-hour long data windows within the time interval 2005.034-056. (c) Coherence between the vertical seismic and DPG channel for the selected 1-hour period; (d) PSD for the vertical seismic channel before (blue) and after (green) the noise removal using the transfer function shown in (a).

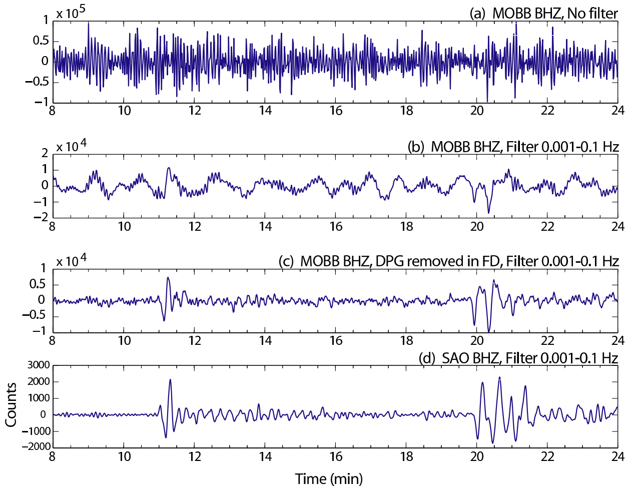

Figure 6: Example of long-period background noise removal for the 12/06/2004 M_w6.8 Hokkaido Japan earthquake using the transfer function shown in Figure 7b. (a) Original MOBB vertical data; (b) MOBB data bandpass filtered between 0.001 and 0.1 Hz. (c) MOBB data after removal of the coherent DPG signal and bandpass filtered between 0.001 and 0.1 Hz; (d) SAO data bandpass filtered between 0.001 and 0.1 Hz.

four stations. When compared in a wider passband (0.03-0.3 Hz), a strong signal-generated noise can be observed at MOBB, but not on the land stations. This type of noise may be unavoidable in shallow buried ocean bottom installations. However, it can also be removed by post-processing, using either an empirical transfer function obtained from a nearby land station, or a synthetic transfer function obtained by modelling the response of the shallow structure at MOBB. Figure 7(right) illustrates the results obtained using both approaches for the Fiji Islands earthquake. In particular, the 4th panel shows the case where the transfer function was estimated using a different event, with a different back azimuth, indicating that a transfer function can be computed using a

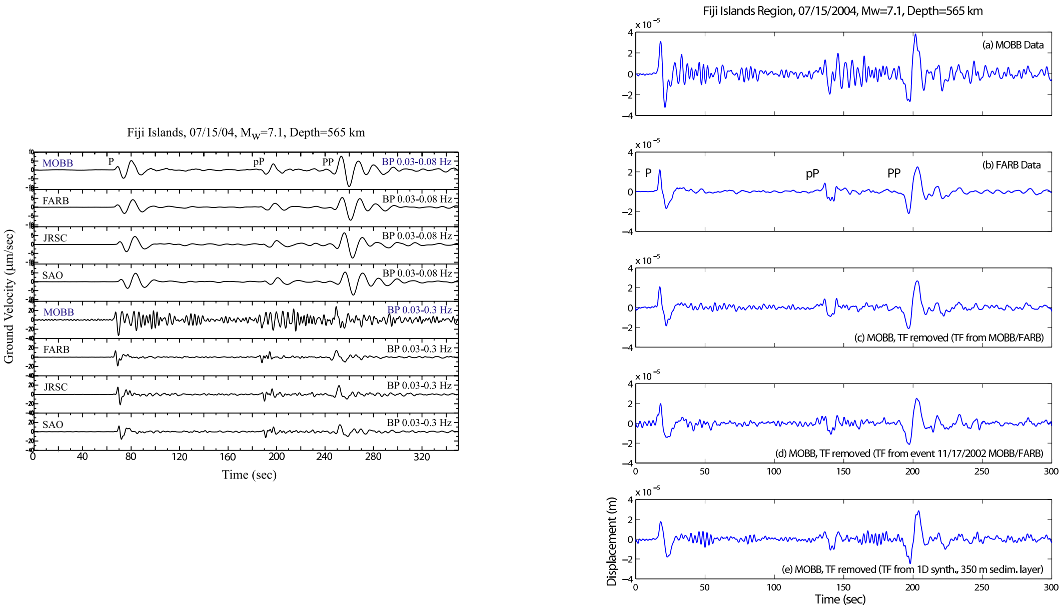

Figure 7: *left* :Comparison of the vertical component records at stations MOBB, FARB, JRSC and SAO for the 565 km deep M_w7.1 Fiji Islands earthquake of 07/15/2004. The data are shown in two pass-bands: 0.03-0.08Hz and 0.3-0.3 Hz, to emphasize the narrow-band character of the signal-generated noise in the MOBB P-wave data. Clearly identifiable in the lower frequency band are the P,pP, and PP arrivals. *Right*:Two examples of deconvolution of the signal-generated noise at MOBB for the Fiji Islands event shown in Figure 9. (a) Original MOBB data; (b) Original FARB data; (c) MOBB data after removing empirical transfer function constructed using MOBB and FARB data. (d) Same as (c) except that the empirical transfer function obtained from the M_w7.3 Kurile Islands event of 11/17/2002 was used; (e) MOBB data after removing a synthetic transfer function obtained by 1-D modeling of the shallow structure with a 350m sedimentary layer with $v_p = 0.324$ km/s, $v_s = 0.196$ km/s and $\rho = 1.3\ g/cm^3$. The synthetic transfer function was computed using a propagator matrix approach (Kennett and Kerry, 1979) applied to a 1-D crustal model for the region (Begnaud, 2000) augmented by a stack of slow sedimentary layers, of 1km thickness and elastic parameters as estimated from a USGS velocity model (Jachens et al., 1997) constructed to represent the San Francisco Bay shallow sediments. The sedimentary structure was then perturbed to obtain an optimal result.

stronger event, and then applied to smaller events regardless of their azimuth. From these results it is clear that the background noise levels due to both infragravity waves and sediment reverberations can be systematically reduced by post-processing.

Ocean and Infragravity wave observations

While infragravity wave noise is high on the ocean floor and needs to be removed, as much as possible, for the study of earthquake signals, the study of the time variation of the infragravity wave signal, and its correlation with weather as well as ocean surface wave height and direction data from a nearby buoy may help understand better where and when the infragravity waves are generated, which is of interest not only for seismologists, but also to oceanographers. The band-limited character of the infragravity related noise "hump", whose observation is made possible by the very-broadband characteristics of the CMG-1T seismometer (low frequency corner of 360 sec, is qualitatively in agreement with theoretical predictions of loading of the seafloor by infragravity waves (e.g. Araki et al., 2003). We have documented that its change in width and height is correlated with environmental parameters, and in particular wave-height, during the passage of storms in Monterey Bay (Dolenc et al., 2005). Figure 8 shows a comparison of PSD (power spectral

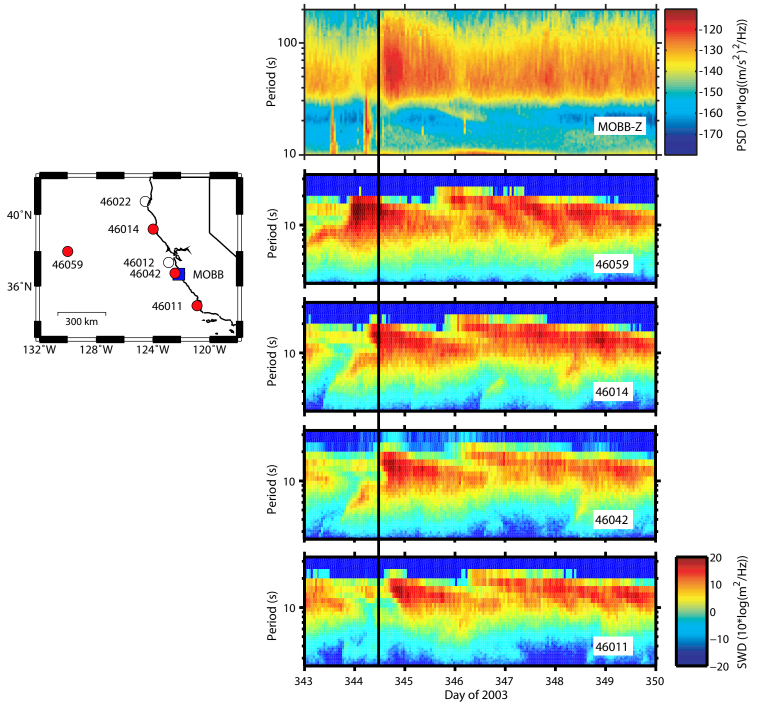

Figure 8: Comparison of spectrograms of MOBB vertical component data and nearby ocean buoy data for a period of 7 days marking the passage of a storm (days 343 to 350 in 2003). The vertical black line marks the onset of strong infragravity wave energy at MOBB(top). It also coincides with the time at which the storm reaches Monterey Bay(4th panel). Note the different period scale on MOBB and the ocean buoys. Large narrow vertical peaks of noise in the period range 10-30sec correspond to earthquakes.

density) plots as a function of time, for a 7 day period in winter 2003, for the vertical component at MOBB, and ocean wave-height as measured at several buoys off shore central California. The results indicate that the infragravity waves observed at MOBB are generated locally and may have some bearing on the issue of how energy is transferred from ocean storm to the ocean floor to produce the earth's "hum" (e.g. Rhie and Romanowicz, 2004, 2006).

Proposed Work

The components of the cabled observatory

The MOBB seismic station has been operating in Monterey Bay for over four years as an autonomous, battery operated system. This project will define, design, fabricate, and install the interfaces necessary to have MOBB installed on the MARS cable to fully exploit the power of the existing instrumentation and the benefits provided by MARS. The components developed will then be available for connecting other seafloor sensors to MARS. Likewise, the system can be replicated on other cables. Figure 9 illustrates all the components of the cabled observatory.

MARS cable

The MARS science node is in the final stages of fabrication at this time. The installation of the cable itself will take place in October, 2006. Installation of the seafloor science node and start-up is currently scheduled for the first half of 2007. The six-month commissioning phase should be completed by mid-2007.

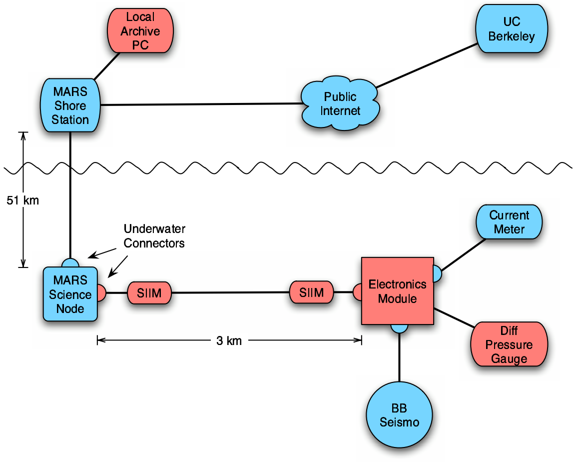

Figure 9: Components of the cabled observatory: the proposed MOBB system integrated into the MARS network. Existing or MARS-provided components are shown in blue, and components to be installed or modified by the proposed project are shown in red.

Extension Cable

The MOBB site is just less than 3 km away from the planned location of the MARS science node, and so an extension cable will be required to connect MOBB to the network. The extension cable can be divided into three components: the electro-optical cable, the ODI connectors, and the SIIM (Science Instrument Interface Module). The extension cable will bring the power, Ethernet communications, and precision timing from the MARS node to the MOBB instrument site. The science port connectors on the MARS node are 12-pin ODI (Ocean Design Incorporated) underwater-mateable connectors providing copper Ethernet, a precision 1 pulse-per-second timing signal, 48 VDC, and 400 VDC. Ethernet can only be communicated on twisted-pair wire for about 100 m from the primary node, so the kilometer distances require that the protocol change to optical transmission at one end of the cable and then back to copper at the other end. One SIIM at each end of the extension cable contains the required electro-optical media converters to convey the network data and precision timing signals. Copper conductors running the entire length of the extension cable carry 400 VDC current to power the experiment. The SIIM closest to the MOBB system contains a voltage regulator that converts the 400 VDC cable voltage down to 12 VDC. The SIIM outputs a single voltage that is selected when the SIIM is built, so other voltages, such as 24 or 48 VDC, can be provided as required by other experiments. MBARI has nearly completed the design of the SIIM ($http://www.mbari.org/mars/new/node_{d}escription.html$), and it will be ready for use in 2007. MBARI has also developed a cable-laying toolsled for its Remotely Operated Vehicles (ROVs), which will be used to install the cable between the MARS and MOBB sites. The toolsled contains a large reel holding up to 4 km of cable that is paid out as the ROV transits between the two sites. The terrain on Smooth Ridge is flat and muddy, and presents no hazards to the cable.

One great advantage of the MBARI SIIM is that it is an intelligent device, i.e. the media adapters contain microprocessors that can monitor network traffic and provide diagnostic information. This capability is critical for the installation and maintenance of the extension cable. During installation with the cable-laying toolsled, the cable can be monitored for data integrity. Any problems, such as a kink in the cable, can be discovered as soon as possible. Even after the extension cable is installed and working, if communications with the MOBB instruments are lost, it is a simple matter to discern if the problem lies in MOBB instrumentation or in the extension cable itself. This can greatly reduce ROV maintenance dive time and the unnecessary recovery of working equipment.

For experiments located less than 100 m away from the MARS science node, an extension cable is not required. The AUDL (Advanced Underwater Data Logger) can be connected to the MARS node with copper cable, utilizing the Ethernet and timing signals directly, and powered from the 48 VDC provided. This arrangement would still provide all the data transport and buffering, and experiment management benefits of the proposed work, without incurring the cost of the extension cable.

Electronics Module

The MOBB system is currently running autonomously, and will require some changes to interface to the cable. The MOBB electronics, with the exception of the buried Guralp seismometer and the free-standing current meter, are housed in a removable frame that is protected by an 1800 kg steel trawl-resistant bottom mount. The module contains the data logger, a 10 kwh battery, and a DPG. To service the autonomous system, the electronics module is removed by an ROV every four months, and then replaced with an identical electronics module containing fresh batteries and empty data disks. To transition to a cabled system, the electronics module will have to be modified. The most important change will be to replace the current autonomous data logger, a GEOSense LP1, with a GEOSense Advanced Unified Data Logger (AUDL) to provide the hardware and software interfaces necessary for cabled operation. The other change will be to replace the Differential Pressure Gauge. The current unit is an early prototype, with little documentation, and is no longer supported by its developer, Scripps Institute of Oceanography (SIO). SIO has since developed newer DPGs with more modern electronics and documentation.

Some aspects of the electronics module will remain the same. We will refurbish and reuse the ODI underwater mateable connectors that allow the Guralp seismometer and the Falmouth current meter to be disconnected during electronics module installation and removal. We will also maintain the existing battery system, as this will provide up to 4 months of standby power in the event of cable network interruption. Uninterrupted operation is important for two reasons: (1) the locking mechanism in the Guralp seismometer can be damaged by excessive power cycling, forcing retrieval and repair of the buried sensor; (2) continuous data sets improve the quality of the science, reduce the amount of manual intervention in processing the data, and guarantee data recording during the most interesting times, i.e. during and after an earthquake when the cable power is most likely to fail. If autonomous recording is forbidden by the US Navy for national security reasons, then the system can simply be deployed without a battery, although this would place the Guralp sensor at a slightly higher risk of mechanical failure if this happens frequenty. Alternatively, the MOBB software could be easily modified to disallow buffering of data while the cable power is off.

As in the current MOBB system, we propose to build two identical electronics modules, always maintaining one at sea and one on shore. This has proven to be a very effective strategy, as it allows the system to be serviced either in normal operation, or in the case of a hardware or software failure, in a single ROV dive. It also allows troubleshooting and development work to continue after the system is deployed, as there is a complete duplicate of the at-sea system running in the laboratory. NASA has used this same approach with great success for their orbiters and landers.

Data Logger

We propose to use GEOSense's Advanced Unified Oceanographic Data Logger (AUDL) to acquire, store, and telemeter the MOBB data in near-real-time to shore-based computer systems. The AUDL is being developed by GEOSense as an NSF-sponsored Small Business Innovative Research

(SBIR) development project specifically for cabled and autonomous applications. The AUDL utilizes a commercial-off-the-shelf (COTS) PC-104 computer running the Linux operating system. It uses extremely low power Analog Measurement Modules (AMM) and Serial Measurement Modules (SMM) with their own microprocessor and memory to acquire data from analog or serial devices independently from the main processor. The data are transferred on a user-configurable basis over a high-speed USB port from the measurement modules to the the PC-104 computer where they are stored on a local disk, and are available for telemetry to remote computers over a TCP/IP connection. The system will use Network Time Protocol (NTP) and pulse-per-second provided by the MARS cable interface to provide long-term stability for an embedded Real Time Clock (RTC) module that will be used to control data acquisition and timestamp data. The AUDL will provide the necessary hardware and software interfaces to acquire data from the RS-232 digital Guralp broadband seismometer and digital Falmouth Scientific current meter, and the analog DPG. The AUDL will also transmit the pulse-per-second signal from the MARS cable and generate the appropriate NMEA time message to sent to the Guralp digitizer through a second serial interface. This will allow the Guralp digitizer to assess the drift rate of its own internal precision clock used to timestamp the data from its digitizers, and to log the drift rate and true time offset of its clock. This clock offset information can optionally be used in near-real-time on-shore and during the data archiving to correct the timetags for the Guralp data, to account for the internal clock drift of the Guralp precision clock with respect to true time.

For normal cabled operation, the PC-104 Linux computer will be running continuously, and can provide data in near-real-time to shoreside computers over the cable network. However, one unique and critical feature of the AUDL is its ability to dynamically switch operation between "cabled" mode and "standalone" mode, where the PC-104 computer is powered up only periodically to receive data from the measurement modules and log the data to disk. The AUDL will monitor power from the cable, and will automatically switch between cabled and autonomous mode, thus providing the best of both worlds - acquire and telemeter data in near-real-time when the network and power are available, and generate complete and continuous data sets by continuing to acquire and log data locally when external power and network are unavailable. Since local undersea power is normally supplied from non-chargable batteries, low power operation during cable power outages is a highly desireable feature. Data logged to disk during network and power outages can be transferred to shore using FTP or similar methods when cable power and network are restored. The system will incorporate a 10 KWh external battery system which will operate the AUDL and provide power to the Guralp seismometer package and other sensors during cable power outages. In these circumstances, the Guralp will be the largest consumer of power (2.2 watts), while the AUDL itself should consume less than 50 mW. Development and testing will be done using a Guralp simulator and one of the KECK instruments while not deployed at sea (see letter attached).

The data collection and on-shore distribution software environment for this system will be based on the open source package "freeorb" originally developed by the NSF-funded IRIS Joint Seismic Project. The principal component of the freeorb is the orbserver process which uses several memory-mapped disk files to implement an Object Ring Buffer (ORB) used to store and retrieve arbitrary data objects. The orbserver provides a TCP/IP socket interface that allows client programs either on the same computer or on remote computers to connect to the server, insert and retrieve objects from the ring buffer, and obtain status information about the server and other clients. Each object inserted by the orbserver into the ring buffer has 2 tags provided by the inserting client: the srcname (a string), and a timetag. This allows applications to retrieve object either in FIFO order or select and sort by srcname tag and time. Although the orbserver does not enforce any restrictions on the srcnames used, commonly conventions are used to represent sitename, data channel, data type, and data format which allows client to select the objects of interest to them. This will allow us to easily represent the different data types acquired by this system, such as analog data, Guralp seismic data packets, and current meter data (and other data as needed). It may be desireable to operate an orbserver on the AUDL to facilitate data collection and telemetry and minimize possible network outages between the AUDL TCP/IP software interface and the freeorb software. We have already ported the freeorb software to the Linux OS and processor used by the AUDL, and have verified its operation in this environment.

We will operate an orbserver on the shore computer that acquires and logs all data received from the AUDL. We will develop an orb client that utilizes the TCP/IP data interface of the AUDL to receive tag, and insert the near-real-time data packets from the AUDL into the orbserver. We will develop another client that will convert the AUDL-specific raw data packets into industry-standard MiniSEED timeseries packets, thus allowing the data to be easily used by the seismic community. We will develop an orbserver client that logs all raw AUDL data packets to disk for permanent archive. Using an existing orb-to-orb copy client program, we will transfer all data to orbservers at UC Berkeley and to MBARI. The data at UC Berkeley will feed directly into the real-time DART (Data Available in Real Time) data distribution service at the Northern California Earthquake Data Center (NCEDC) and will be immediately available to the entire user community. We will maintain a permanent copy of all data at the NCEDC, and will maintain a significant ring buffer of data at the shore-based computer at the MARS operation center and on the AUDL itself. The freeorb package and all software developed for this project will be open-source and freely available to the user community. The NCEDC can make also the MOBB data available to any interested users in near-real-time using the freeorb system.

The freeorb software is currently used by the BSL, the USGS, and the NCEDC for ingesting and transmitting over 10 GBytes/day of seismic data to the NCEDC. It provides a simple and well-documented interface for developing new clients, and its open source ensures that other users will be able to utilize the capabilities developed by this project.

In conclusion, we stress that the proposed system, when combined with the MOBB instruments, will highlight its flexibility, and demonstrate how the components can be used in a wide range of cabled experiments. We will demonstrate data acquisition from:

- a) analog devices (DPG),
- b) simple serial devices (current meter).
- c) complex serial devices (Guralp digitizer).

Configuring the AUDL to interface with simple instruments such as the serial current meter will be handled by user configuration of the standard AUDL software. The Guralp digitizer implements a more complex bi-directional protocol that utilizes compressed packetized data with data integrity checks. This will require specialized programming of the serial acquisition module of the AUDL, but will demonstrate the flexibility of this system to handle complex protocols. We will demonstrate how digital instruments can be added or replaced using undersea mateable connectors. The extension cable is a separable component of the system, and thus can be used when needed, or omitted for experiments close to the cable node. The components developed here will be available for connecting other seafloor sensors to MARS and for replication on other cables: in addition to the commercially available datalogger, we expect that the SIIM will be freely available to other researchers, while the software for data telemetry and shore-based acquisition and data distribution software based on Freeorb will be freely open and available.

Note that the present proposal represents a **convergence of NSF-funded technologies**:

- Seafloor cable: MARS, implemeting organization: MBARI

- Data Logger: AUDL, implementing organization: GEOSense
- Software: FreeORB (Open source Object Ring buffer: IRIS Joint Seismic Project
- MOBB Guralp CMG-1 Seismometer: joint UCB/MBARI

Project Timeline

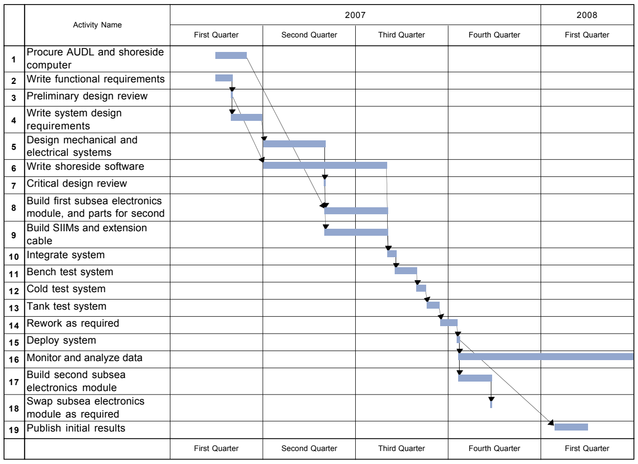

Figure 10: Work schedule for the first year. The second year will be spent acquiring, processing, analyzing and distributing data. During the second half of the second year, at least one of the ports will be made available to other PI's to try out other sensors (e.g. Spahr Webb, see attached letter), for example by disconnecting the current-meter.

Results from prior NSF support

B.Romanowicz (P.I.) "Instrumentation for the Deployment of a Permanent Ocean Floor Broadband Seismic System in Monterey Bay, in Cooperation with MBARI" , NSF/OCE-9911392, $159,896, 08/01/00-12/31/02.

This grant has supported the seismometer acquisition, packaging and testing for the deployment of a long-term ocean bottom broadband seismic station, in Monterey Bay, Ca (MOBB, Monterey Ocean Bottom Broadband project), as described at the beginning of this proposal. The MOBB deployment itself, the costs of auxiliary instrumentation and software development, as well as subsequent operation, have been supported by funds to MBARI from the Lucile and David Packard Foundation, and UC Berkeley funds to BSL. The MOBB deployment and data have been described in the following publications: Dolenc et al. (2005, 2006; Romanowicz et al. (2003, 2006).

Broader Impacts

The cabled observatory system developed in this proposal, based on commercially available components and freely available additional software, will serve 1) for the connection of the MOBB and later other prototype sensors to the MARS cable and 2) for replication in future cabled observatories in the context of the OOI. The data acquired during this project will be openly available for future analysis through the NCEDC; more generally, the networking protocols and data archives already exist for the land-based arrays such that the data will be immediately available for the research community.