The ALOHA Cabled Observatory

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Abstract

The ALOHA Cabled Observatory (ACO) is located at Station ALOHA about 100 km north of Oahu, Hawaii at 4728 m water depth. Station ALOHA is the field site of the Hawaii Ocean Time-series (HOT) program that has investigated temporal dynamics in biology, physics, and chemistry since 1988. HOT conducts near monthly ship-based sampling and makes continuous observations from moored instruments to document and study climate and ecosystem variability over semi-diurnal to decadal time scales. The cabled observatory system will provide continuous, interactive ocean sampling with adequate power and communications, enabling entirely new measurements as well as a new mode of ocean observing that integrates ship and cabled observations.

The ACO is a prototypical example of a deep-ocean observing system that uses a retired fiber optic telecommunications cable. The ACO architecture uses highly reliable existing transoceanic cable systems to provide power and communications bandwidth. This paper reviews the observatory engineering, results from initial deployment, modifications for deployment in 2011, research directions, and the current status of this observatory, the deepest operating one in the world.

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Introduction

Sustained observation of the ocean is difficult. Ocean science requires new and varied ways to observe the ocean, each with its own strengths and weaknesses, in order to advance our understanding and lay the foundations for predictive models and their applications. Recent technological advancements, such as autonomous mobile platforms (floats, gliders and AUVs), satellite transmission and acoustic data links are providing new data acquisition methods, but sensors, instruments and platforms requiring high power, high data rates or continuous access to the water column and seafloor are as yet out of reach of these technologies. Cabled observatories – such as the ALOHA Cabled Observatory (ACO) – provide remote interactive instrument control, continuous real-time data streams and large amounts of electric power. Cabled and autonomous technologies are complementary in that the cable systems can provide the power and communications interface to subsurface autonomous fixed and mobile platforms using docking stations and acoustic communications, without the routine use of ships, thus significantly increasing the spatial footprint and efficiency of the overall observing system.

Submarine cable systems have been used for science since the 1960s, with much work in Japan since the 1970s. In the 1990s, scientists in the United States began using cables to support their instrumentation and several systems were installed, e.g., LEO-15, ATOC, HUGO, and H2O (Forrester et al., 1997; ATOC et al., 1995; Duennebier et al. 2002; Petit et al., 2002; an historical account is given by Howe et al., 2012). Two technologies opened the door for these observatories: remotely operated vehicles (ROVs) with power, high-resolution video, manual dexterity, heavy lift capability, long continuous work time at the ocean floor, and wet-mate electrical and optical connectors allowing instrumentation to be attached to the observatory by the ROVs. These developments and projects, and the associated planning efforts have led to many of the ocean and earth observing systems that are described in this volume.

As the design of new cable systems progress (Favali and Beranzoli, 2006) and experience with test bed systems accumulates, the realities of the design, cost, and complexities – as well as advantages and disadvantages – of such cable systems are becoming clearer. The full-scale new cable systems coming on line, NEPTUNE Canada, RSN (Regional-scale Nodes of the NSF Ocean Observatories Initiative), and the Japanese DONET, will provide important contributions to cabled observatory efforts. At the same time the re-use of existing cables provides a cost effective complementary path to the deep ocean with minimal compromise in capability.

The ACO is a prototypical example of a deep ocean system that uses a retired fiber optic communications cable. The ACO architecture uses highly reliable existing transoceanic cable systems to provide power and communications bandwidth. The cables are terminated on land at existing cable stations that contain the infrastructure required to power and control the observatories and transmit commands and data. Since the cable is already in-place and is designed to operate for well beyond its commercial lifetime, costs of converting retired cable systems to scientific use are substantially lower than for design and installation of new systems.

In the following section the background of the ACO is presented. This is followed by a description of the ACO infrastructure. The next section discusses current and future science and engineering topics that the ACO has or can address. Concluding remarks follows this and includes an epilogue briefly describing the recent installation of the complete node and the current operating status.

Background

The ACO is located at Station ALOHA (22°45'N, 158°W; see Figure 1), about 100 km north of Oahu, Hawaii. Since October 1988, the Hawaii Ocean Time-series (HOT) program has investigated temporal dynamics in biology, physics, and chemistry at Station ALOHA, a deep-ocean field site in the nutrient poor North Pacific Subtropical Gyre (NPSG). HOT conducts near monthly ship-based sampling and makes continuous observations from moored instruments to document and study NPSG climate and ecosystem variability over semi-diurnal to decadal time scales (Karl and Lukas, 1996; Karl et al., 2001). The recent work of Dore et al. (2009) on ocean acidification trends and dynamics at ALOHA stands out. Understanding the impacts of climate forcing on the ecosystem (Bidigare et al., 2009) is only possible by having long time-series observations coupled with constantly evolving and improving ocean models.

Long term change in parameters such as salinity and rare and episodic temperature events at Station ALOHA (Lukas et al., 2001; Lukas and Santiago-Mandujano, 2001; Alford et al., 2011) can be better observed with the new capabilities of the ACO because sustained real-time detection of events will support adaptive sampling within and around the observatory.

In 2002, the ACO had been funded as a Major Research Instrumentation project by the US National Science Foundation (NSF) and was in the process of obtaining permission to use the retired ANZCAN coaxial cable that ran near Station ALOHA. Teleglobe, Inc., the main owner, went into bankruptcy and negotiations failed. HAW-4, a newer first-generation optical cable system, was then retired and made available for the ACO by AT&T. A meeting of cable engineers at Rutgers University in 2003 led to a specific design for cable hardware that would provide data transport through first-generation optical cable systems (Tremblay and Duennebier, 2006). A test of the production hardware in 2006 demonstrated the capabilities by sending 100

Mb/s data from the Makaha Cable Station on Oahu to a cable station in California where it was looped-back to Oahu and recorded error-free, a round-trip path of more than 8,000 km.

Installation of the ACO was organized in two phases. During the first phase, the HAW-4 cable was cut, both ends terminated, and 20 km of cable was relaid to Station ALOHA. This operation was accomplished in February 2007 using the cable ship USNS *Zeus* (Figure 1). The cable termination was lowered to the ocean floor with a set of electronics, a hydrophone, and pressure sensor (the “Proof Module”) to provide proof of concept and assurance that the system would operate as designed (Figure 2). Data began flowing to Oahu shortly after the sensors were in the water and ran continuously (except for brief, planned outages) until the package was recovered in October 2008.

During Phase 2, a cruise to install the ACO general-purpose observatory node planned for October 2007, had to be canceled because of late delivery of faulty (i.e., obviously cracked) titanium pressure cases for the observatory electronics. A rescheduled cruise in October 2008 recovered the proof module and deployed the ACO node (Figure 3), but failure of optical dry-mate connectors between the junction box and the observatory module forced its immediate recovery. The plan had been to install the main ACO infrastructure, two hydrophones, an absolute pressure sensor, two acoustic Doppler current profilers (ADCPs), a vertical thermistor string, two temperature/conductivity sensors (CTDs), and an acoustic modem supplied by Woods Hole Oceanographic Institution (WHOI). The thermistor string was deployed in an autonomous mode, to record temperatures with sampling for up to three years, but the other systems could not be installed.

Phase 3 consisted of observatory upgrades, testing and deployment. Upgrades were based on lessons learned (e.g., connectors) and new technology (e.g., precise timing). Testing was extensive, facilitated by special test connectors and system modularity. Deployment was based again on the capabilities of ROV *Jason*, with several new instruments including a camera system and a secondary node with a fluorometer and additional CTDs with oxygen sensors.

Infrastructure

The ACO is based on the technology used in the HUGO and H2O observatories, with improvements based on lessons learned from both (Duennebier et al., 2008), as well as from the October 2008 attempted Phase 2 deployment. In the following subsections we describe the Phase 3 system elements (Figure 4), making brief reference to changes relative to Phase 2. Phase 3 modifications occurred in 2009-2011 and deployment in May-June 2011.

Shore station and cable

At the AT&T Makaha shore station, the shore power system supplies the single conductor sea cable with a constant 1.6 A at a (negative) voltage that varies depending on load, up to 1280 V for the present observatory configuration. Because the cable is single conductor, the sea water is used as the second electrical conductor, with a cathode (positive) just offshore of the shore station and an anode (negative) at the most seaward end of the electrical system. AT&T communications equipment provides the interface between the cable system and the Internet through the University of Hawaii (UH) via a dedicated 3 Mb/s line. The interface includes access to the supervisory functions, such as repeater status. A grandmaster clock synchronized to GPS time provides system time at the sub-microsecond level using the precision time protocol (described below). At the seaward end of the cable is a titanium and fiberglass frame with the cable termination, an Ocean Design, Inc. (ODI) hybrid electro-optical wet mateable connector.

Junction Box

In the junction box, an AT&T SL560 regenerator is used to interface to the cable optical fibers and convert between optical and electrical signals. A custom multiplexer ("muldex") board is used to interface these electrical signals with 100 Mb/s optical Ethernet. In essence, the muldex samples the lower data rate Ethernet signal at a higher data rate suitable for the SL560, and vice versa. Details are presented in Tremblay and Duennebier (2006). In Phase 3, the optical Ethernet is connected to a managed industrial Ethernet switch with electrical ports connected to the observatory module and a local time server.

Precise and accurate time is obtained using the IEEE-1588v2-2008 precise time protocol (PTP) that provides sub-microsecond accuracy and precision over Ethernet. Switches following this protocol append packets to the Ethernet stream that contain the measured time-varying latency within the switch. Further, the drifts of all clocks in the system are monitored and delays through the system are measured many times a second. A PTP client connected to the Ethernet switch provides 1-PPS and IRIG-B signals.

The Ethernet, 1-PPS, and IRIG-B are provided on a 12-pin ROV wet mate connector. Normally this is connected to the observatory module (as shown in Figure 4), but it can also be connected, for example, to the hydrophone experiment module (HEM) so the combination becomes a "proof module" as in Phase 1.

Three power modules based on Zener diodes supply local power for the regenerator/muldex, the Ethernet switch/PTP, and 20 W at 48 V. The high voltage is passed through, provided on a 4-pin ROV wet mate connector. Normally this is connected to the observatory power supply followed by the anode (seawater electrode) to complete the series circuit. If the junction box is operated by itself or with the HEM, then this is connected to the seawater electrode. The 48 V is supplied on the 12-pin connector, which then has the standard "observatory configuration" (see below).

Power System

Submarine commercial telecommunications cables, such as HAW-4, are single conductor, use the low resistance seawater as the return path, and are double-end powered by shores stations on each end. They operate in constant current, constant power mode for several reasons: robust immunity to single electrical ground faults, and power supplies are simple because loads (the repeaters) are constant.

After the cable was cut for scientific use, the power system is supplied from only one end and voltages vary depending on the requirements of the observatory. To deliver power to an experiment at the ocean-end of such a cable as for ACO, the power available from the cable needs to be converted in two ways: 1) the power delivered to the experiment must be isolated from the voltages on the cable and 2) the power delivered to the experiment must match the amount required. Such conversions are very common in electronic design. The power required and the source voltage define the converter operating point (input voltage and current).

In the more usual (terrestrial) constant voltage configuration, with the converter close to the source, the input voltage is fixed and the input current adjusted as necessary (e.g., Howe et al., 2002). If the convertor requires more power at a fixed voltage, more current is drawn from the source, up to the power handling limits of the converter and delivery capability of the source. Such converters operate as constant power devices. They are designed to handle a relatively wide range of input voltages (2:1 or more) and a much wider range of output currents up to a maximum amount of power. These convertors are quire stable when supplied from a voltage source.

But this constant power mode produces a stability problem when the input power is supplied in the form of a constant current. Assume that the convertor is operating at an input voltage and current and thus power that supplies the needed output power, and are within the limits of the convertor. If the needed power increases slightly, the input power must also increase. So the input current tries to increase. The current increase can be supplied for a short period by discharging the capacitance but this soon results in a drop in the input voltage to the converter. This, in turn causes the converter to try to draw even more current from the cable and the voltage rapidly collapses to a low voltage at the constant current.

This instability can be managed by using active current shunts that consume the excess power if the load power decreases. Sensing the input voltage to the converter controls the amount of power consumed by the shunts. If the voltage is higher than desired, the current to the shunts is increased to return the voltage to the correct level. The power consumed by the shunts is converted into heat and passed into the ocean water around the observatory.

An active shunt can be thought of as a resistor and a field effect transistor (FET) in series. The observatory hotel and user load is in parallel with the active shunt. The FET can be (relatively) instantaneously controlled so the total current going through the observatory load and through the active shunt (FET + resistor load) is the required constant amount. ACO uses several of these shunts in parallel to distribute the heat and provide redundancy. The active shunts must be designed to be able to consume all the power that can be delivered by the converter when the experiment is turned off or not connected (FET "open" fully conducting). The maximum power available to the experiment occurs when the current shunts are consuming zero power (FET "closed" non-conducting). Any attempt to draw more power will result in the voltage collapse described above.

When the input current is fixed, as it is in our case (because of in-line repeaters), the input voltage must increase to increase the available output power. Most commercially available modules, however, are limited to ~200 W. To increase the available power, we use multiple convertor modules. The inputs are connected in series to increase the voltage drop along the current loop to 800 V, which increases the power that can be delivered from the cable to 1280 W (at 1.6 A). The outputs are connected in parallel and operated at a constant voltage. To be able to connect all the outputs in parallel, of course, the outputs must be isolated from the inputs (Figure 5).

With the outputs properly connected in parallel, the convertor sharing circuitry will ensure that each converter delivers the same amount of current as the others. Since the same current passes through the input of each module, each module converts the same amount of power as the others. The ACO power supply uses 8 convertors, each with a 100 VDC nominal input and a regulated 48 VDC output. Each convertor is capable of 200 W.

The parallel output reduces the effect of power consumption changes in any one experiment by summing all the experiment currents. It also allows the design of low voltage current shunt regulators to enable a stable operating point. See Harris and Duennebier (2002) for more details on the design of a constant current power supply of this type.

Although the 48 V now is a stable source of power for the experiment modules, other converters are used to provide isolated power to each experiment. Each of these isolated outputs is further protected by circuit breakers programmable to disconnect the experiment power if it exceeds the current specified by the system operator. Because the main power supply can deliver only 1280 watts maximum (8 stacks × 100 V × 1.6 A), any one experiment can obtain the rated power but not every user can get the maximum power (see following).

Observatory Module

The observatory module has eight science channels or ports supplying power (2 ports at 400 V/300 W, 5 ports at 48 V/150 W, and 1 port at 48 V/500 W), 100 Mb/s Ethernet (or other selectable serial protocol such as RS-232 or RS-485), and 1-PPS and IRIG B timing to science users. The associated connectors are identical to the one on the junction box, and to those used on MARS, NEPTUNE Canada, DONET, and planned for RSN, so that experiments should be interchangeable. (This informal, de-facto connection interface “standard” was arrived at by consensus during numerous meetings of the various planning and engineering groups over the last decade or more.) From the power supply 48 V user bus, the power on each channel goes through separate, controlled dc-dc converters to provide isolation and on/off switching.

Both sides of the 48 V are monitored by the system to determine possible ground faults. As long as the voltages are near +24 V and –24 V with respect to the Observatory pressure case, none of the supplied circuits are connected to seawater. Multiple microprocessors, each connected to the Ethernet, are used to control the power and communications associated with the individual channels.

Other system aspects

Based on the experiences from the October 2008 deployment attempt, three modifications or upgrades have been performed. The first change is to modularize the mechanical system, separating the junction box pressure case from the observatory frame. With this configuration, the highly reliable junction box can remain in place with the proof module (or any other low power experiment) if the observatory node needs to be recovered. If expansion of the system is required, a new observatory/power supply module can be inserted between the current junction box and the observatory frame without recovery of any in-place modules. Further, testing is simplified.

Secondly, by converting the optical Ethernet (the output of the muldex) immediately to electrical form in the junction box, the need for downstream optical connectors is eliminated. The third change makes use of the new PTP capability (mentioned above) that greatly simplifies system time distribution.

Lastly, several other problems associated with cable and connector assemblies were experienced during the 2008 cruise. One was difficulty in the physical mating of the hybrid optical-electrical connector, connecting the junction box and the sea cable termination.. The manufacturer has now provided alignment guides to mitigate this problem. Once the connection is made between the junction box and the sea cable, the connection should (ideally) never need to be broken again, thereby reducing future risk. Further, since 2005 when the original cable/connector assemblies were made, the manufacturer has instituted new practices and testing procedures that will reduce overall risk associated with cable and connector assemblies.

All exposed metal components of the observatory are titanium. In most cases, bulkhead connectors on pressure cases are dry mate. Pressure balanced oil filled (PBOF) hoses are used to connect these dry mate bulkhead connectors to flange mounted ROV wet mate connectors, as well as between wet mate connectors on the observatory frame, the junction box frame, and the sea cable termination. This modularity permits parallel independent testing of the various components.

Data management and archiving, along with interactive control to facilitate adaptive sampling, are essential elements of an ocean observatory and will be developed for ACO during Phase 3. Our experience to date indicates that the efforts associated with data management, archiving, processing, and scientific quality control and product presentation should not be underestimated.

Research

The motivation for deploying the ACO infrastructure is to conduct research that cannot otherwise be accomplished in the abyssal and overlying ocean. Compelling scientific research questions have been posed that only measurements from the ACO can uniquely and cost-effectively address. There are also engineering research and development issues that can be addressed within the framework of the ACO, some related to observatory infrastructure and some related to sensors. The scientific questions and engineering issues that will be raised by the exploratory measurements made via the ACO are equally important.

Research with Core Measurements

Because the effort and resources that are required to deploy the ACO are significant, it is essential that there be initial research returns from that effort. Given the long lead time for designing, proposing, obtaining funding, and the ship and ROV scheduling needed to add experiments to the ACO, a “core” set of measurements will be made as part of the ACO deployment. These core measurements will serve the multiple purposes above, and will also provide a long time-series context for subsequent observatory-based experiments. The core measurements are summarized in Table 1. An example of what might be expected for the basic core measurement of salinity and temperature is given in Figures 6 and 7 (updated from Lukas and Santiago-Mandujano, 1996). In Figure 6, the increasing trend in abyssal salinity as measured by the HOT program is shown along with the high frequency variations around the trend. The relatively recent freshening of this water mass (Nosse et al., 2012) may be related to Rossby waves associated with the 2007–2009 La Niña. Figure 7 shows large amplitude (for the abyss) cold events with sudden onsets. Lukas et al. (2001) attributed these events to episodic flow of abyssal waters from the Maui Deep over the shallower ridge of the Nuuanu Seamounts into the Kauai Deep, where Station ALOHA is located. The long recovery time from cold events is due to relatively slow vertical turbulent diffusion of heat. Note there is no obvious correspondence of salinity variations (Figure 6, triangles) with the cold overflow process. The high frequency sampling of the observatory will allow filtering out of internal wave noise in the salinity record that can not be resolved by the sparse shipboard sampling.

The ACO node frame is deployed with two upward looking ADCPs and a MicroCAT CTD connected to the µSEM (micro science experiment module) that is dry-mate connected to the main observatory node pressure case. There are two co-joined 200-m high-cabled components (on separate experiment ports) integrated into the thermistor array/acoustic modem (TAAM) mooring system. One cabled component is a ten-element thermistor array plus one fluorometer, all self-powered with batteries for at least two years but communicating in both directions through the ACO via an inductive modem; the second provides power to and two-way communications with a 10 kHz WHOI micro-modem system. The acoustic micro-modem will communicate with nearby autonomous systems such as the NSF-funded HOT profiler mooring installed in 2012.

The original hydrophone/pressure proof module was reconfigured to use the standard 12-pin connector, so it can connect either to the junction box as a proof module or to an experiment port on the observatory node (the hydrophone experiment module, HEM). It now has two hydrophones separated by 1.2 m with combined effective bandwidth of 0.01 Hz to 40,000 Hz; sampling rate can be remotely selected up to 192 kHz. A secondary node with two CTDs with oxygen sensors and a fluorometer will sit next to the node. An Ethernet video camera with lights and another hydrophone also sits nearby on a tripod.

An example of an engineering issue to be addressed is the utility of acoustic Doppler measurements to obtain estimates of abyssal current profiles. We simply do not know the concentration climatology of the backscattering particles needed to obtain reasonably accurate deep ocean currents, and thus how far above the seafloor such profiles can be obtained. The two ADCPs will allow us to conduct exploratory measurements for the design of future abyssal current measurements. Optical measurements will help quantify the backscattering particle density, which may be variably related to near-surface productivity events and to strong near-bottom current events that suspend sedimentary materials.

Another engineering issue concerns the calibration stability of conductivity sensors deployed near the bottom. Can the relatively small, but important, salinity signals that are observed in the abyssal ocean (Figure 6) be observed with high fidelity via the ACO? Will the accumulation of sediments be an important factor?

An important engineering unknown for future observatory design that needs to be explored is the range and fidelity of acoustic modem communications in the abyssal ocean. By placing an acoustic modem sufficiently far above the seafloor, we can listen to the received signals with the dual hydrophones that we propose as part of the core sensor suite, while the micro-modem can receive direct signals from other sources, such as ships, gliders and moorings, without the complication of bottom and observatory infrastructure reflections.

The ACO core measurements should be of broad interest, not just related to a current scientific hypothesis; it is intended for these exploratory core measurements to inspire new hypotheses that may motivate new experimental proposals. Given the need to site an acoustic modem above the seafloor, the cost-effective addition of inductively communicating temperature sensors to the riser cable will provide the vertical structure of temperature variations around the ACO increasing the spatial footprint of measurements. The cold overflow events observed by the HOT program will be continuously monitored, with the possibility of measuring the full spectrum of thermal responses to overflow events which are likely important (e.g., Figure 7; Lukas et al., 2001; see more recently Alford et al., 2011). Given that these sensors are battery powered, their effective and efficient use will require commanding hibernation and awakening adaptively for event sampling, a compelling topic of research in itself.

Bio-optical sensors on the riser cable and on the ACO itself will help to quantify the scattering particle density, which will aid the interpretation of ADCP return intensity variations, and will help understand the CTD calibration changes due either to particle fall events that may be associated with near-surface productivity blooms, or to resuspension of bottom sediments during strong flow events. Video frame grabs will support categorization of particles and enable estimation of currents as the particles are advected within the field-of-view. Particle export events to the abyss will be observed, and their relationship to near-surface productivity blooms will be studied (see Figure 8).

The dual hydrophones will provide redundancy and some level of directionality to the acoustic measurements that have already been shown to be of interest to widely separated scientific communities. Along with absolute pressure measurements, the variations of sea level will be measured directly, and the acoustic spectrum will provide useful constraints on the sea surface elevation spectrum. Signals from earthquakes, tsunamis, and human activities will provide information about the solid earth that will be exploited. Marine mammal acoustic signatures are already the focus of several research groups using the data obtained from the proof module deployment (Oswald et al., 2009, and Ou et al., 2012).

Because the acoustic data collected during Phase 1 has proven to be exceptionally rich, we provide some detail here. Data were collected for ~20 months from February 2007 to October 2008. 1.5-minute time samples of 24 kHz were sampled from the data every 5 minutes to provide power spectral densities of the acoustic data from 0.0114 Hz to 10 kHz (6 decades in frequency, 20 octaves). The 12 spectra obtained each hour were averaged to provide hourly spectra. The statistics of the ambient sound and the dependence on wind speed using these spectra are given in Figures 9 and 10, respectively.

The acoustic data span more than 150 dB in energy level. The log of the number of samples at each frequency with a particular energy level ("sample density") is contoured in Figure 9, allowing visualization of measurements from a single hourly observation in the 20-month period to over a thousand observations. The highest energy levels are observed at the microseism peak near 0.2 Hz. Note the relatively low range of spectral values between 2 and 6 Hz compared to other frequency bands. A sharp increase in the range of spectral levels above 16 Hz continues to at least 4 kHz. A peak near 16 Hz may be associated with blue whale vocalizations (Diachok and Duennebier, 2009). While the general trend of spectral levels decreases between 14 Hz and 5 kHz, the median level is stable at near 60 dB. Resonances above 2 kHz are the result of the physical size of the sensor being close to the acoustic wavelengths. The ambient background level is above instrument noise level from below 0.02 Hz to about 4 kHz, where the system noise floor is roughly 30 dB re $\mu Pa^2/Hz$.

The hourly-averaged acoustic spectra were sorted by wind speed into 0.5 m/s bins, and the median spectral levels at each wind speed were determined and plotted in Figure 10. Higher acoustic levels are generally associated with higher winds except for the noise hole around 0.04 Hz. The maximum range of the median acoustic level with wind speed (about 30 dB) is observed near 2-4 kHz, with acoustic levels correlating with wind speeds as low as 1 m/s. The variation of acoustic level with wind speed is largest near 10 Hz at wind speeds between 7 and 15 m/s, changing at a rate of about 4 dB/m/s. Noise unrelated to the wind speed puts a floor under acoustic levels at lower wind speeds. Detailed analysis of noise levels between 50 and 500 Hz recorded in 1975 by Gaul et al., [2007] shows a strong correlation with high wind speeds that is limited by shipping noise at wind speeds below 2.5 m/s. Their analysis yields acoustic levels that are within 2 dB of those presented here near 500 Hz but their noise floor is lower at low wind speeds. This difference may be the result of their selection for times when local shipping is absent, while the data presented here have not been selected.

Figure 11 shows a representative sample of ambient sound, including various whales, shipping, and a rain event. Research will continue on the surface wave-wave inter-actions that are observed in the hydrophone data (Farrell and Munk, 2008; Duennebier et al., 2012), as well as seismic signals from various sources (Figure 12).

Examples of Future Research Directions

While we do not know the full variety of innovative ideas that will be proposed to take advantage of the ACO infrastructure in the future, we provide some examples of viable future experimental research activities that have been extensively discussed. They illustrate the transformative nature of the observatory approach to deep ocean research.

Mooring sensor systems. A mooring sensor network with profiler has been designed and tested in shallow water (ALOHA-MARS mooring (AMM); Howe et al., 2010). A similar if not identical mooring system will be proposed for installation at ACO to address numerous science goals (Figure 13). In the meantime, the “HOT Profiler” mooring project has installed an autonomous battery powered (two 0.8-m steel spheres with alkaline batteries) mooring system with a profiler, using an inductive power transfer system similar to the AMM. This mooring was deployed in June 2012 with enough on-board energy to run the profiler and other systems continuously for half a year. It has several means to communicate. First is an acoustic modem that can “talk” to with the ACO acoustic modem and hydrophones as well as with the ship during routine ALOHA-HOT visits. The second is via a small, slack tethered surface buoy with GPS, Iridium and FreeWave radio. Ultimately, the cabled mooring system in Figure 13 will enable high-resolution vertical profiles of physical, chemical, and biological quantities over the entire water column. This will eventually allow shifting some of the burden of the routine HOT sampling to this automated system (with much improved sampling), freeing the human and ship resources to focus more on new, more difficult and challenging sensors and sampling.

Tsunamis. The absolute pressure sensor in the Phase-1 system had a resolution of better than 5 mm of equivalent sea level, enough to detect a small tsunami, although none were observed during the recording period. A potential problem of using pressure sensors for tsunami detection is that the pressure signal from seismic Rayleigh waves generated by tsunamigenic earthquakes recorded at the ocean floor can be several centimeters of equivalent ocean depth in amplitude at the expected time of arrival of a tsunami. Obscuration of the tsunami pressure signal could lead to mis-identification of signals and possible false alarms. Tsunami detection might be improved with near-bottom current measurements, since the horizontal motion of the water column (above the benthic boundary layer) is expected to be far larger than the vertical motion during a tsunami. This hypothesis is one of the motivations for installing both a pressure sensor and ADCP at the ACO.

Hydrophone array. One of the most useful and robust sensor systems that can be installed at the ACO is a hydrophone array. In addition to surface environmental studies discussed above, it would be used for tracking whales, ships, and moving acoustic sources near the ACO. Although the bottom is below the critical depth of the SOFAR channel (varies seasonally between 0 and 200 m off the bottom), we are able to hear ships from as far away as 160 km and T-phases from earthquakes around the Pacific Rim. During the initial 20 months of recording, the calls of fin, blue, humpback, minke, and sperm whales and as well as porpoises were identified (Figure 11). A suitable array is under consideration; but in the meantime the two hydrophones that are already installed can provide crude directionality information.

Concluding remarks and epilogue

Since writing the main body of this paper in 2010, the ACO node was successfully installed in June 2011 and is currently operating. Details of the installation can be found in Howe et al., 2011. The comprehensive web site provides a complete description of the system and real-time data and plots (aloha.manoa.hawaii.edu).

Figure 14 is a composite image of the installed system on the bottom as observed by ROV *Jason*. Shown are the various components that have been described above. The main infrastructure elements are working flawlessly, however, there is mixed success with the sensors and sensor network infrastructure. Sensors delivering data in real time are: temperature, conductivity and ADCP on the OBS frame and two hydrophones (HEM- hydrophone experiment module) on the JBOX frame. The temperature and conductivity sensors on the OBS are (as expected) occasionally contaminated by heat from the electronics beneath. The pressure sensor after a year began to exhibit large step changes and drift. One ADCP is exhibiting excessive noise. The video camera is working, but the lights failed after a few weeks (we suspect a control circuit and a power supply) and the associated hydrophone is not functioning. The ten-element thermistor array extending 200 m into the water column is recording data internally but with no connection to the observatory because a dry-mate connector failed during deployment. Ground faults have disabled the WHOI acoustic micro-modem and the AMM secondary node, and thus the science instrument interface module (SIIM) with the 2 pumped $CTDO_2$s and the fluorometer. The replacement/repair of the non-functional instruments will take place over the next year or so. Learning from these problems will be all-important as we and the community move forward with deep sea cabled observatory systems.

While too early for science results using the current data, it is clear there is a wealth of information in the data now being collected. For instance, in the one month of video data, roughly 400 events involving 15 or more species of visible macro fauna occurred; the most exciting one was of a deep-sea lizard fish attempting to capture an aristeid shrimp (J. Drazen and A. Fleury, personal communication). ADCP data over the observed 23 – 70 m depth range reveal strong internal tides. The acoustic data continue to reveal a very rich soundscape including earthquakes, shipping, sonars, wind and wave effects, and especially marine mammals.

The value of long, sustained time-series of ocean observations only increases with length. The exceptional record from HOT at Station ALOHA is the perfect example of this. HOT is successful because it maintains the continuity and is constantly improving the high quality base time series, and thus it acts as a magnet for projects with tremendous synergy, e.g., the WHOTS meteorological/upper ocean mooring, the Center for Microbial Oceanography: Research and Education (C-MORE) which uses Station ALOHA as its primary field site, and the ALOHA Cabled Observatory. Over the long-term, the ACO will provide the infrastructure necessary to continue and improve the base time series, while enabling the expansion of the spatial and temporal sampling needed to address ever more difficult questions.

With the successful deployment of the ACO node, the community is expected to respond with new designs for experiments to use the system. A benthic monitoring system to make long-term sediment flux and benthic ecology studies has been proposed by K. Smith (MBARI). The authors and colleagues will be proposing to extend the spatial footprint of the node and mooring systems using bottom HPIES (horizontal electric field (barotropic velocity), pressure, and inverted echosounder) and gliders; the latter will not only sample the ocean directly, but provide "data mule" service for the HPIES and other autonomous instruments in the area. Active and passive acoustics will also be proposed to extend the footprint to basin scale a la the Acoustic Thermometry of Ocean Climate (ATOC) project (Dushaw et al., 2009).

In the longer timeframe we envision the AUV docking stations mentioned in the introduction, with vehicles performing maintenance tasks as well as science missions. For acoustics, the precise and accurate timing will be essential in simultaneously serving navigation, communications, and science needs. Further, the observatory will be used in education and outreach to the public; the real time data including video and audio are expected to be very useful in this regard.

The ACO will be one of the few sites in the global ocean that can provide sustained low-maintenance observations, and the only one at such water depth, 4728 m. As already said, sustained observation of the deep ocean is difficult and the past and continuing problems with connectors are just one reflection of this. Having such a facility, not only for science use, but also as an engineering test bed for deep-sea operations is essential.

The ACO is a proof-of-concept system for cable re-use. The existence of 10s of thousands of kilometers of in-place retired or soon-to-be-retired first-generation fiber optic and other commercial cable systems are a potential resource for marine science. Several of these cables go through regions of interest, such as south of the Aleutian Islands, and across the equator to New Zealand, where they could be effectively utilized in place. In many cases, the precise location is less important than the supply of reliable power and communications. These systems offer potentially lower operational costs and far more data bandwidth and electrical power than autonomous buoy observatories and should be considered by the research and operational oceanography communities.

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References

ATOC Instrumentation Group: B. M. Howe, S. G. Anderson, A. Baggeroer, J. A. Colosi, K. R. Hardy, D. Horwitt, F. Karig, S. Leach, J. A. Mercer, K. Metzger, Jr., L. O. Olson, D. A. Peckham, D. A. Reddaway, R. R. Ryan, R. P. Stein, K. von der Heydt, J. D. Watson, S. L. Weslander, and P. F. Worcester, Instrumentation for the Acoustic Thermometry of Ocean Climate (ATOC) prototype Pacific Ocean network, *Proceedings, Oceans '95, MTS/IEEE, October 9–12, San Diego, CA*, 1483–1500 (IEEE, New York, 1995).

Alford, M. H., R. Lukas, B. M. Howe, A. Pickering, and F. Santiago-Mandujano, Moored observations of episodic abyssal flow and mixing at station ALOHA, *Geophys. Res. Lett.*, 38, L15606, DOI: 10.1029/2011GL048075, 2011.

Bidigare, R. R., F. Chai, M. R. Landry, R. Lukas, C. C. S. Hannides, S. J. Christensen, D. M. Karl, L. Shi and Y. Chao, 2009: Subtropical ocean ecosystem structure changes forced by North Pacific climate variations. *J. Plankton Res*., **31**, 1131-1139.

Diachok, O., and F. Duennebier, Blue whale vocalizations and the seasonal variability of ambient noise levels at the Aloha Observatory, *J. Acoust. Soc. Am*. 127, 1784, 2010.

Dore, J. E., R. Lukas, D. W. Sadler, M. J. Church, and D. M. Karl, 2009: Physical and biogeochemical modulation of ocean acidification in the central North Pacific, *Proc. Nat. Acad. Sci.* USA, 10.1073/pnas.0906044106.

Duennebier, F. K., D. Harris, J. Jolly, J. Caplan-Auerbach, R. Jordan, D. Copson, K. Stiffel, J. Babinec, and J. Bosel, HUGO: The Hawaii Undersea Geo-Observatory, *IEEE J. Ocean Engineering*, V 27, # 2, pp 218-227, April 2002.

Duennebier, F., D. Harris, and J. Jolly, ALOHA Cabled Observatory will Monitor Ocean in Real Time, *Sea Technology*, 49, 2, 51-54, February 2008.

Duennebier, F. K., R. Lukas, E.-M. Nosal, J. Aucan, and R. A. Weller, Wind, waves, and acoustic background levels at Station ALOHA, *J. Geophys. Res*., 117, C03017, 21 pp., doi:10.1029/2011JC007267, 2012.

Dushaw, B. D., P. F. Worcester, W. H. Munk, R. C. Spindel, J. A. Mercer, B. M. Howe, K. Metzger, Jr., T. G. Birdsall, R. K. Andrew, M. A. Dzieciuch, B. D. Cornuelle, and D. Menemenlis, A decade of acoustic thermometry in the North Pacific Ocean, *J. Geophys. Res.*, **114**, C07021, 24pp, doi:10.1029/2008JC005124, 2009.

Farrell, W. E., and W. Munk, What do deep sea pressure fluctuations tell us about short surface waves? *Geophys. Res. Letts.*, 35, L19605, 2008.

Favali, P., and L. Beranzoli, 2006: Seafloor Observatory Science: a review. *Annals Geophys*., 49, 515-567.

Forrester, N. C., R. P. Stokey, C. von Alt, B. G. Allen, R. G. Goldsborough, M. J. Purcell, and T. C. Austin, The LEO-15 long-term ecosystem observatory: Design and installation, *Proc. IEEE Oceans'97*, 2, 1082–1088, 1997.

Harris, D. W., and F. K. Duennebier, Powering Cabled Ocean-Bottom Observatories, *IEEE J. Oceanic Engineering*, 27, 202-211, 2002.

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

Howe, B.M., Y. Chao, P. Arabshahi, S. Roy, T. McGinnis, A. Gray, A Smart Sensor Web for Ocean Observation: Fixed and Mobile Platforms, Integrated Acoustics, Satellites and

Predictive Modeling. *IEEE J. of Selected Topics in Applied Earth Observations and Remote Sensing*, doi: 10.1109/JSTARS.2010.2052022, 2010.

Howe, B. M., R. Lukas, F. Duennebier, and D. Karl, ALOHA cabled observatory installation, *OCEANS 2011*, 19-22 Sept. 2011.

Howe, B. M., F. K. Duennebier, R. Butler, R. B. Lukas, Scientific uses of submarine cables: Evolutionary development leading to the ALOHA Cabled Observatory, *Mains'l Haul, J. Pacific Maritime History*, 48, 100-119, 2012.

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

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

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

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

Nosse, C. T., F. Santiago-Mandujano, R. B. Lukas, J. E. Dore, R. A. Weller, and A. J. Plueddemann, Recent strong interannual variation disrupted pycnocline and abyssal salinity trends at Station ALOHA, *Eos Trans. AGU*, Ocean Sci. Meet. Suppl., PosterID: A0189, 2012.

Oswald, J. N., W. W. L. Au, and F. Duennebier, Minke whale (Balaenoptera acutorostrata) boings detected at the Station ALOHA Cabled Observatory, *J. Acoust. Soc. Am*. 129, 3353-3360, DOI:10.1121/1.3575555, 2011.

Ou, H., W. W. L. Au, and J. Oswald, A non-spectrogram-correlation method of automatically detecting minke whale boings, *J. Acoust. Soc. Am*., 132, 4, EL317-EL322, DOI:10.1121/1.4747816, 2012.

Petitt, R., D. Harris, B. Wooding, J. Bailey, J. Jolly, E. Hobart, A. Chave, F. Duennebier, R. Butler, A.D. Bowen, and D.R. Yoerger, The Hawaii-2 Observatory, *IEEE J. Ocean Engineering*, V 27, # 2, pp 245-253, April 2002.

Tremblay, M. D., and F. K. Duennebier, Format and bit rate independent communications over regenerated undersea fiber optic cable systems, *Proceedings of the Scientific Submarine Cable 2006 Conference*, 182–185, Marine Institute, Dublin Castle, Dublin, Ireland, 7-10 February 2006.

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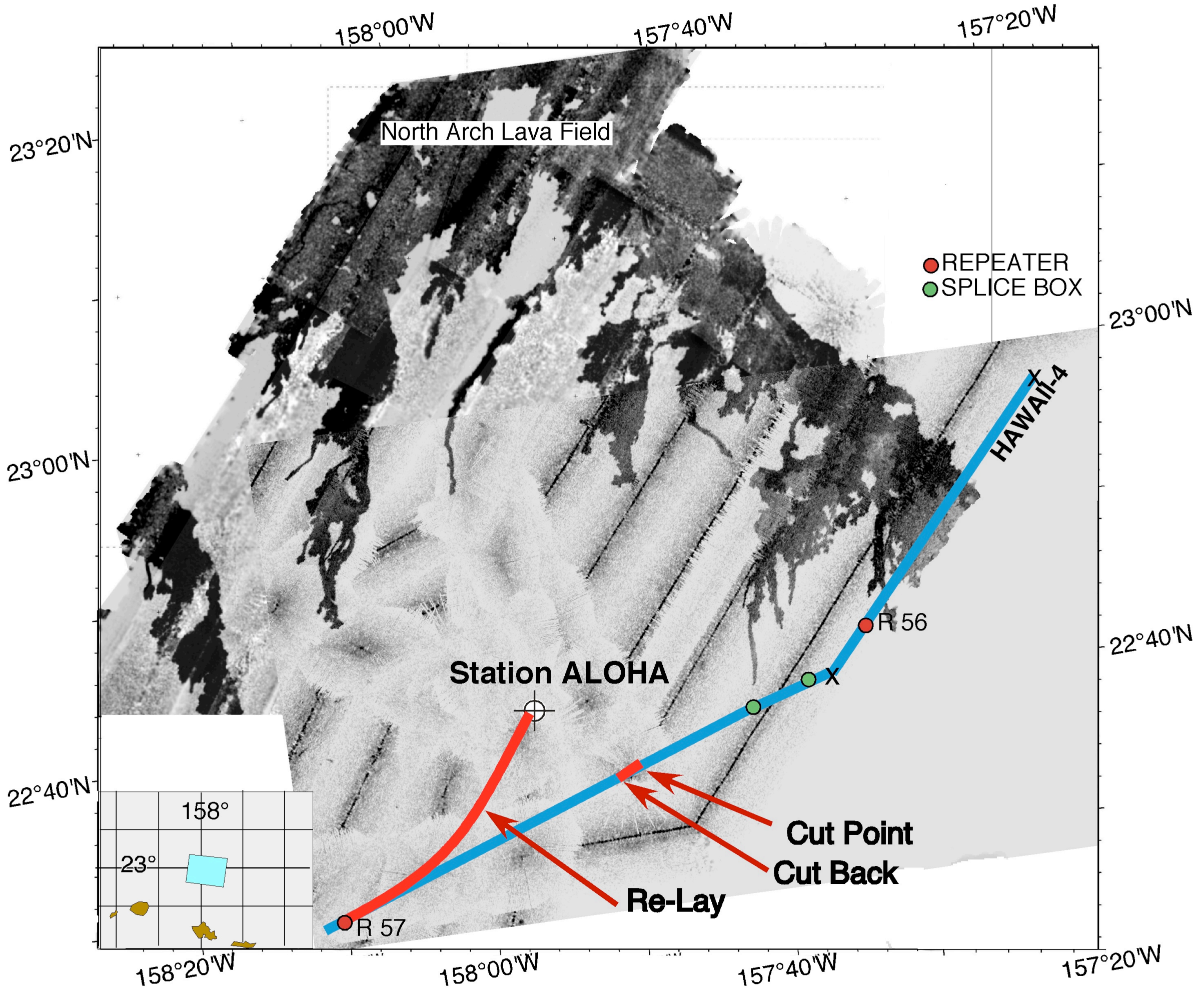
Tables

Table 1. ACO Core Measurements

Platform/Sensor suite	Sensors	Comments
Thermistor array/acoustic modem (TAAM) mooring from seafloor to 200 m	Seabird SBE37 thermistors 10 equally spaced (2 w/pressure) Wetlabs FLNTU fluorometer (chlorophyll) and backscatter (turbidity) WHOI 10 kHz micro-modem	A physically coupled dual mooring. Battery-operated thermistor array and one fluorometer communicate with the ACO using Seabird inductive modem. The thermistors also record internally. The modem is directly connected to the observatory.
Camera frame CAM	AXIS 214 PZT color video camera 2 LED Multi SeaLites lights Hydrophone	Internet surveillance camera in 17-inch polished glass sphere.
Observatory node OBS	Conductivity/temperature CT Seabird 37 (un-pumped) 2 Sontek 250 kHz ADCP	On top of node frame; CTD swings outboard for some horizontal separation from the electronics.
Hydrophone experiment module (HEM)	Two hydrophones, bandwidth 0.01-5,000 Hz and 24-40,0000 Hz Digiquartz pressure, 16 Hz	On separate sled, can work directly off junction box (as proof module during deployment), or standard science connector on node (switched over after node deployment).
AMM secondary node	2 Seabird 52/43MP CTDO$_2$ Wetlabs FLNTU	Primary sensors Connected to a SIIM, AMM node and then to the OBS.

Figures



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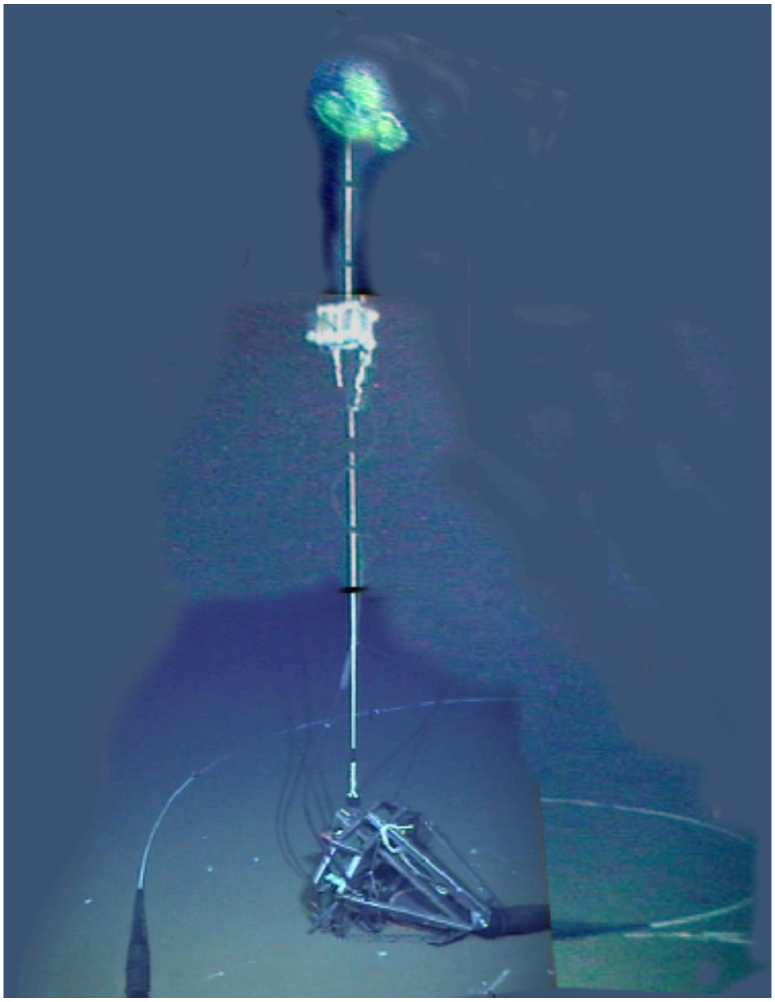

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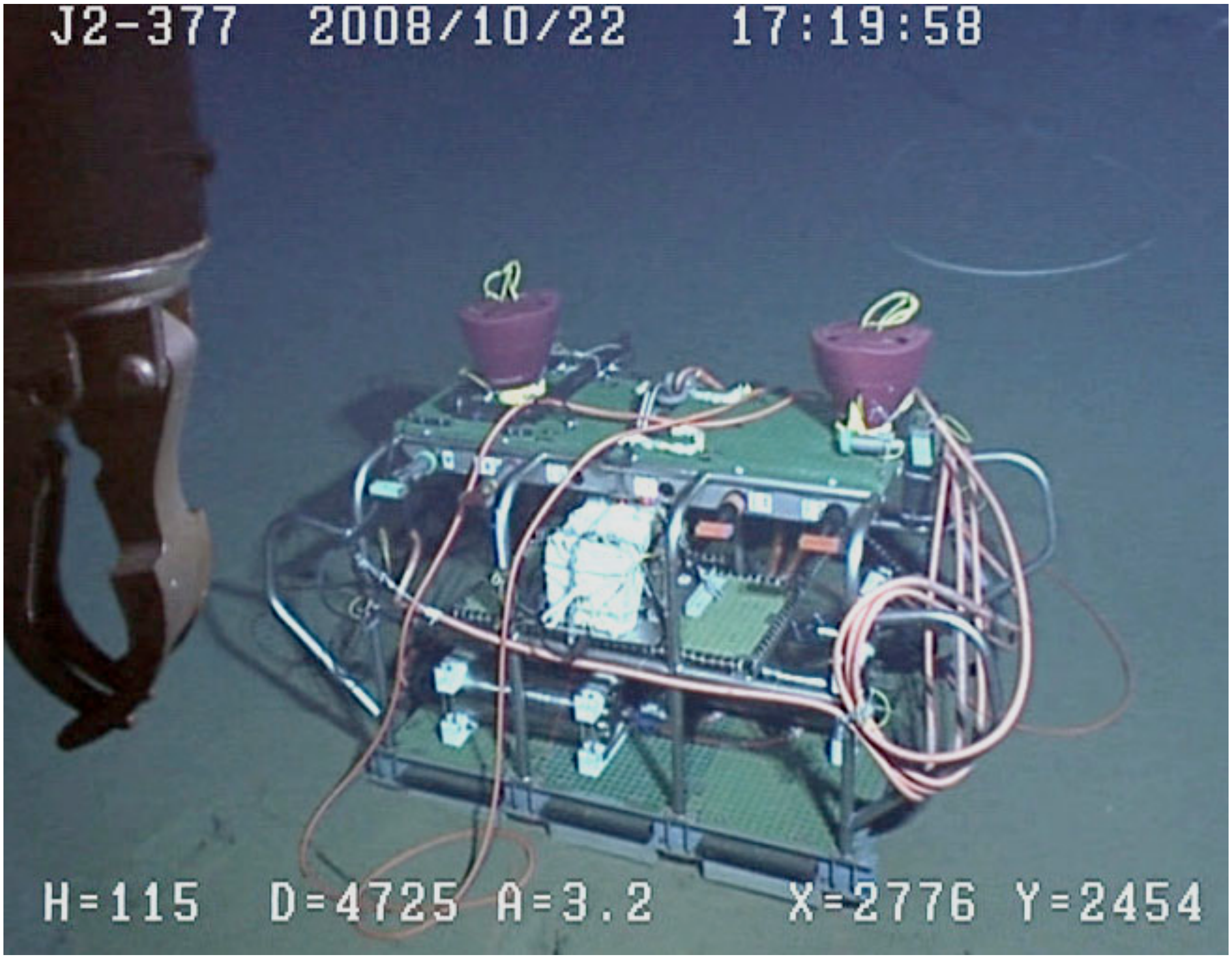

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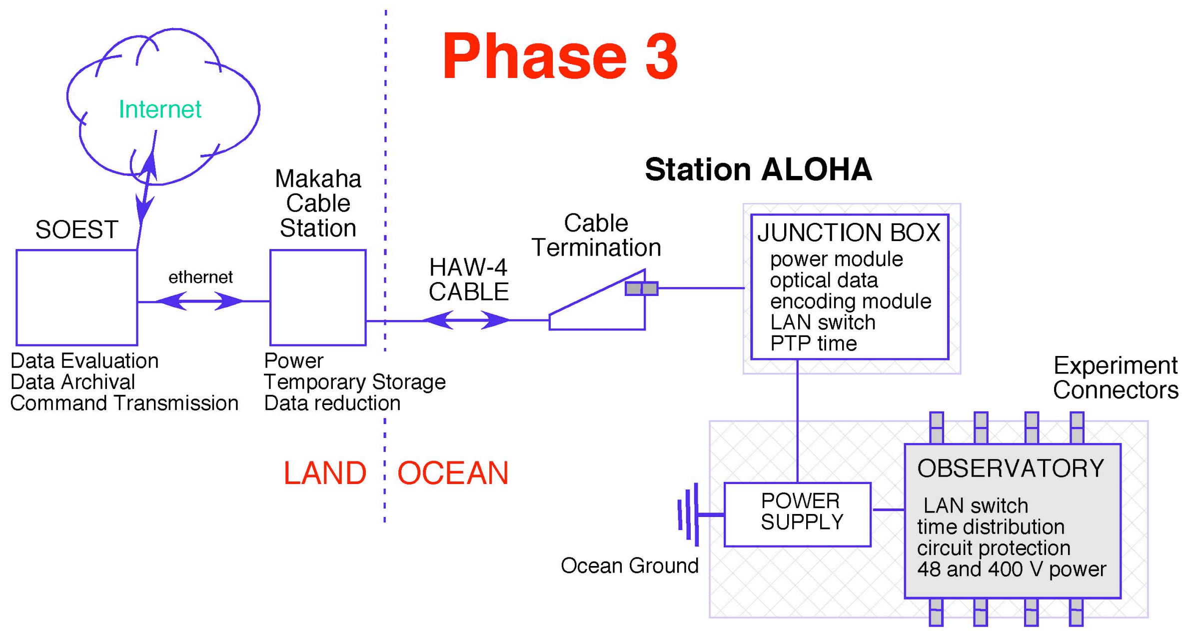

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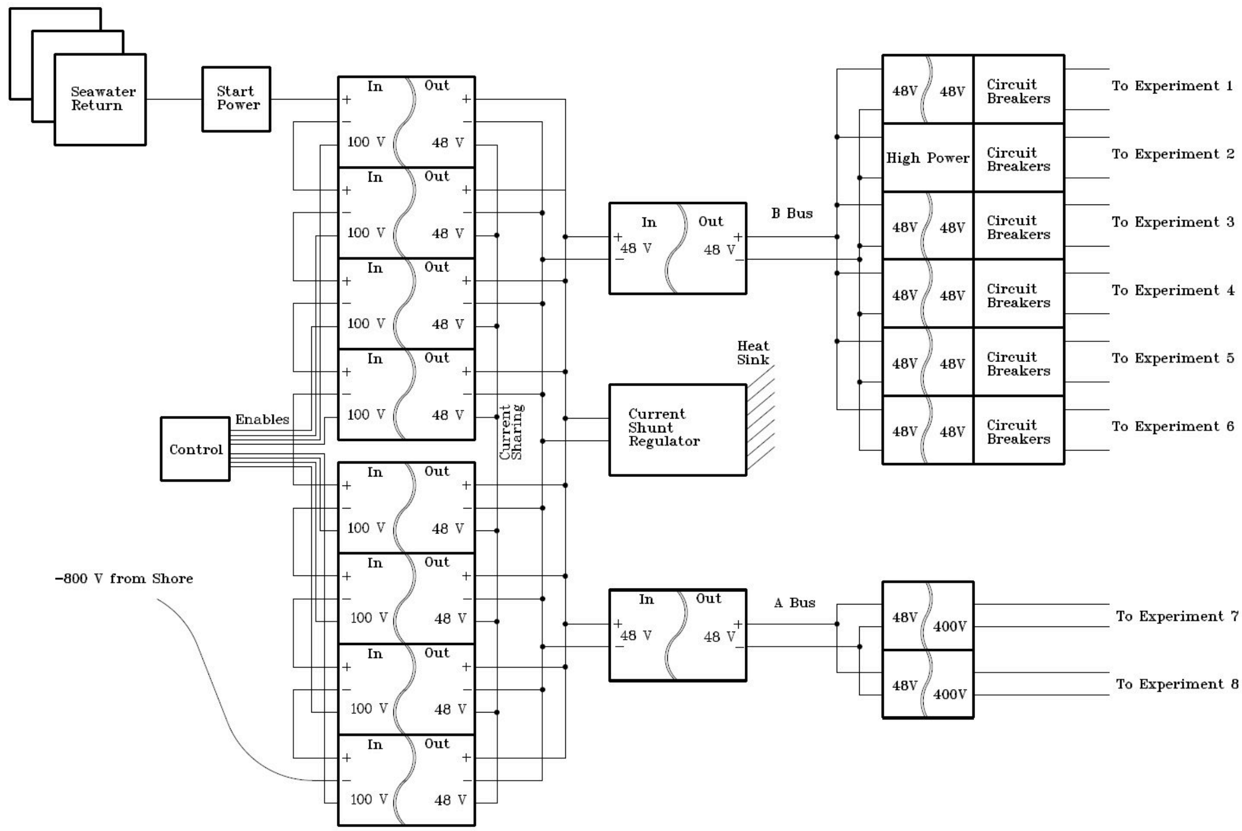

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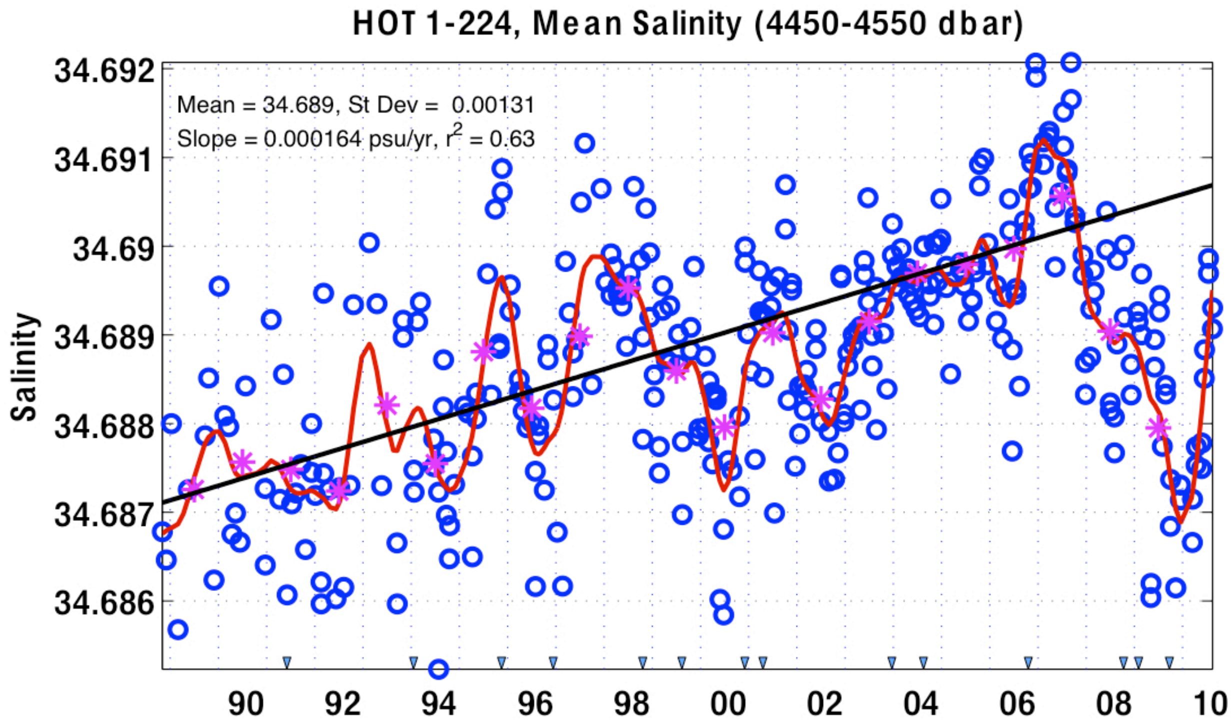

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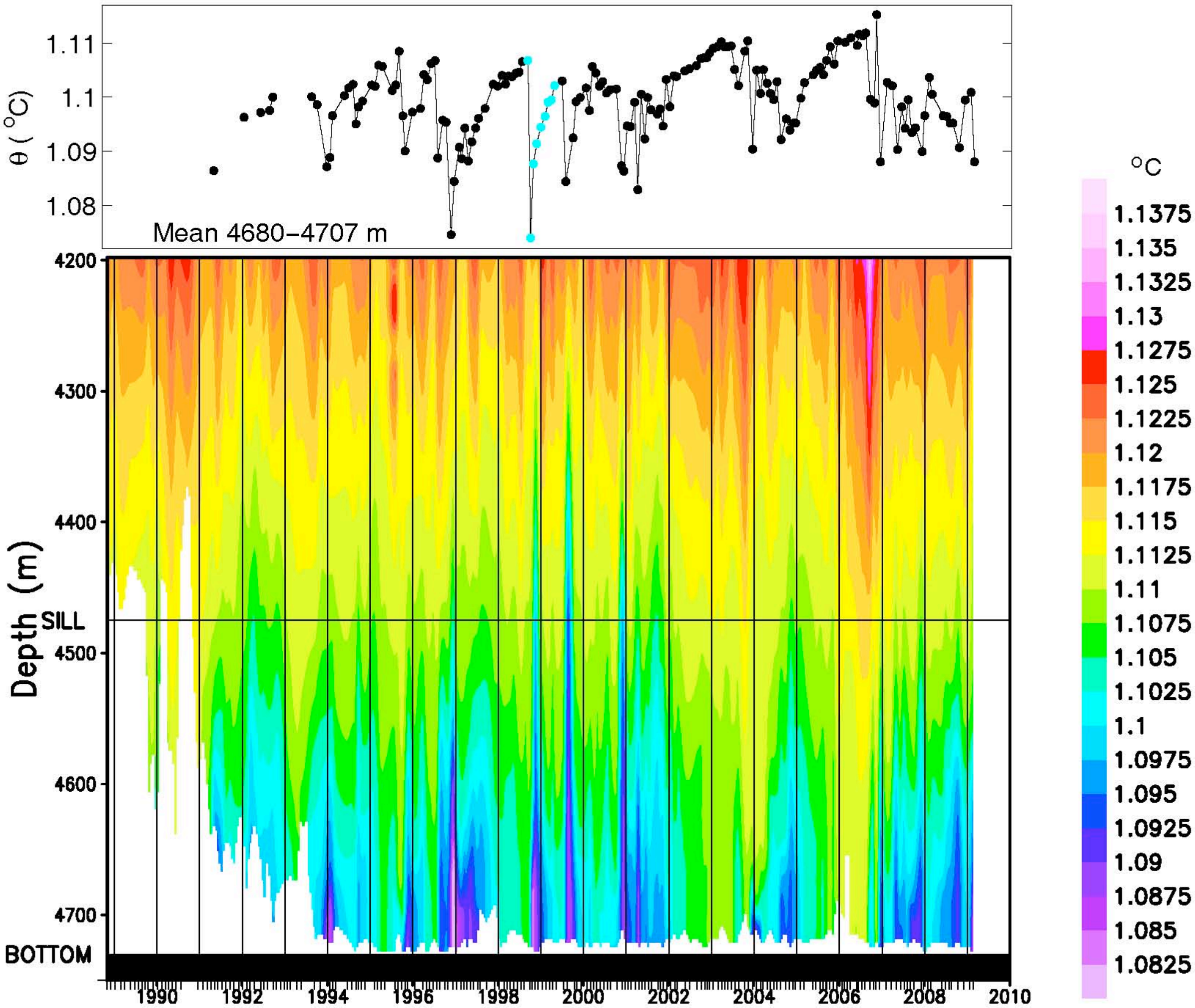

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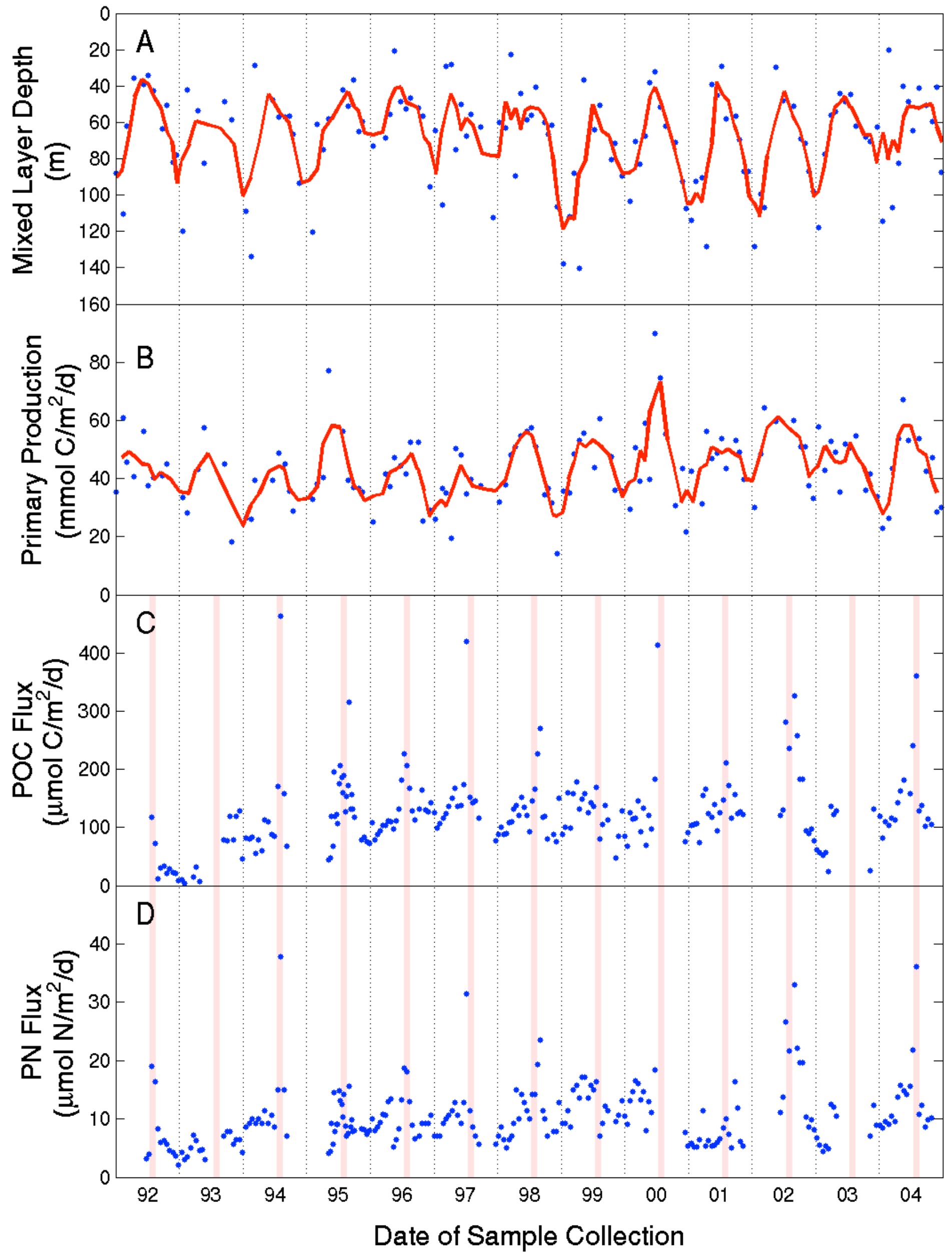

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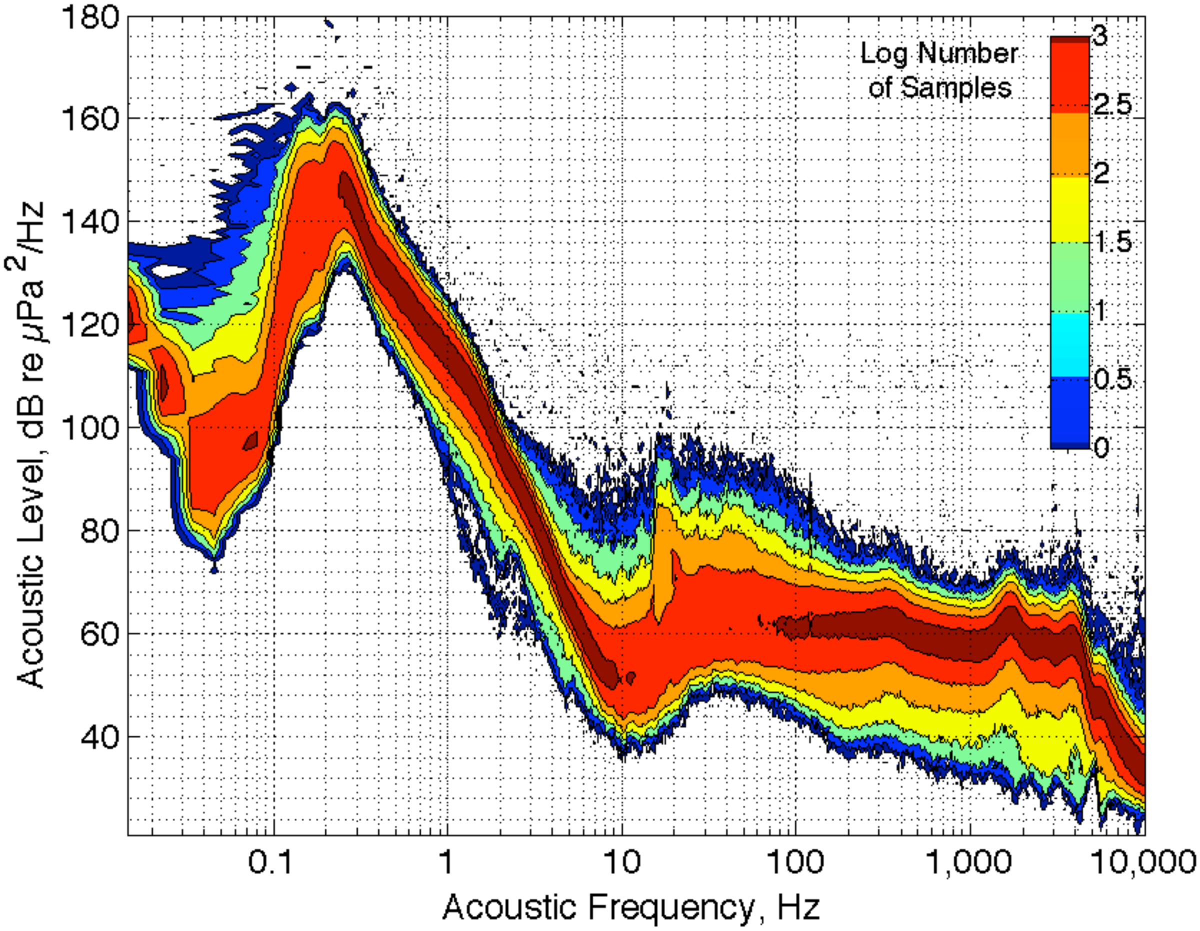

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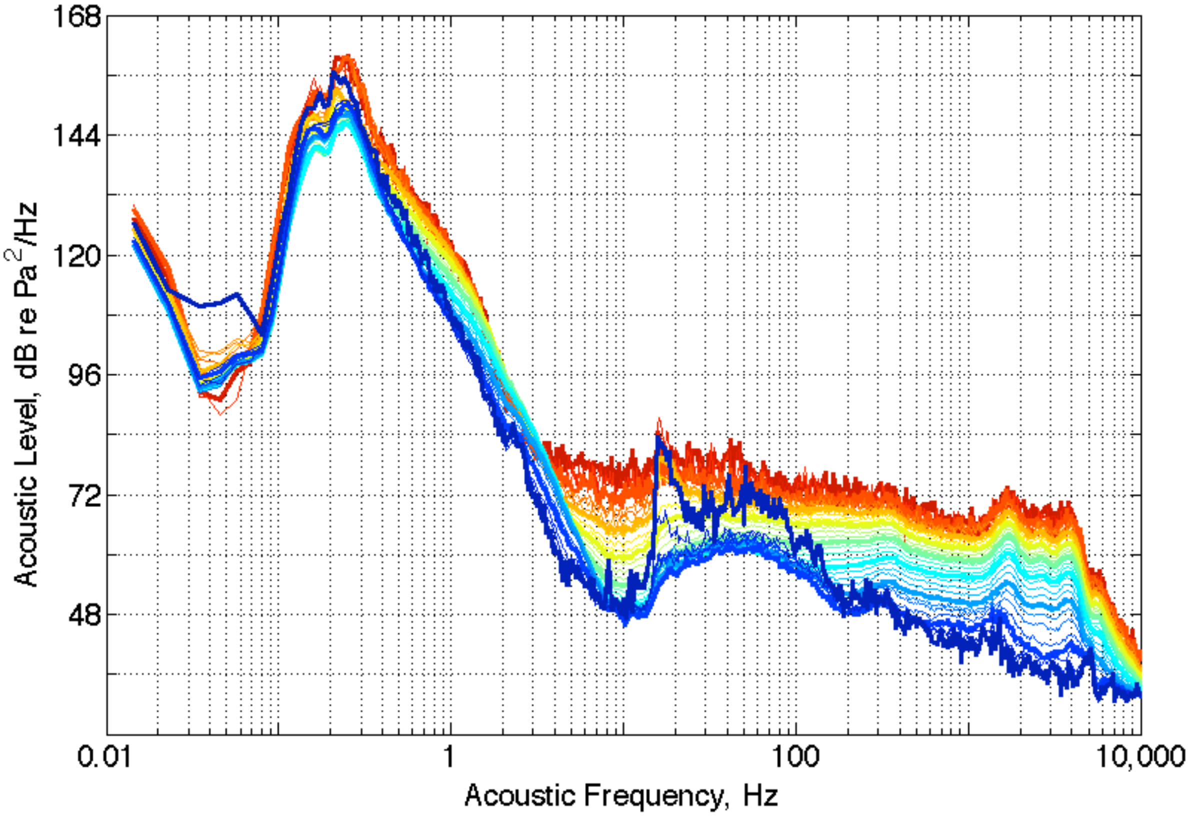

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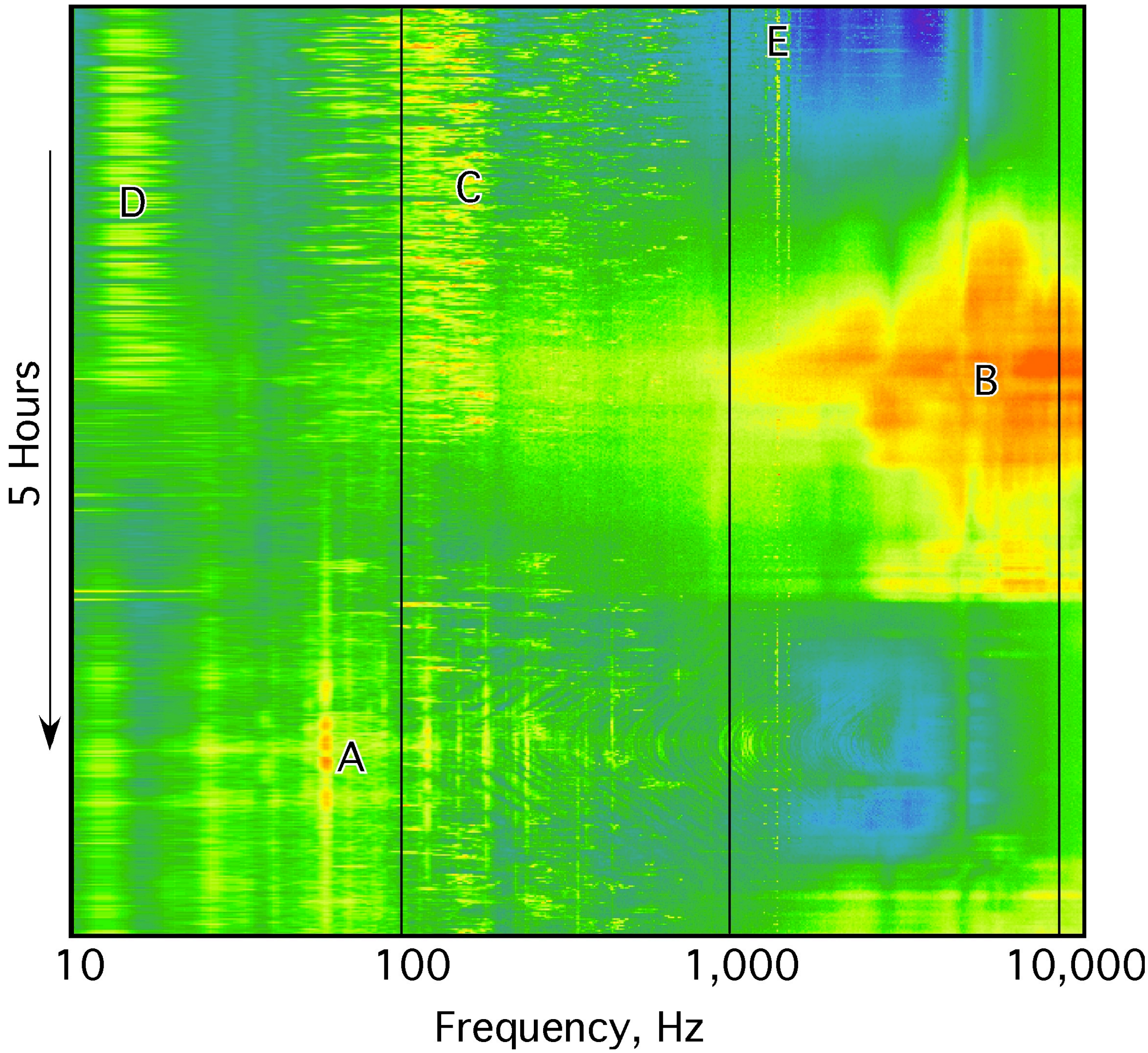

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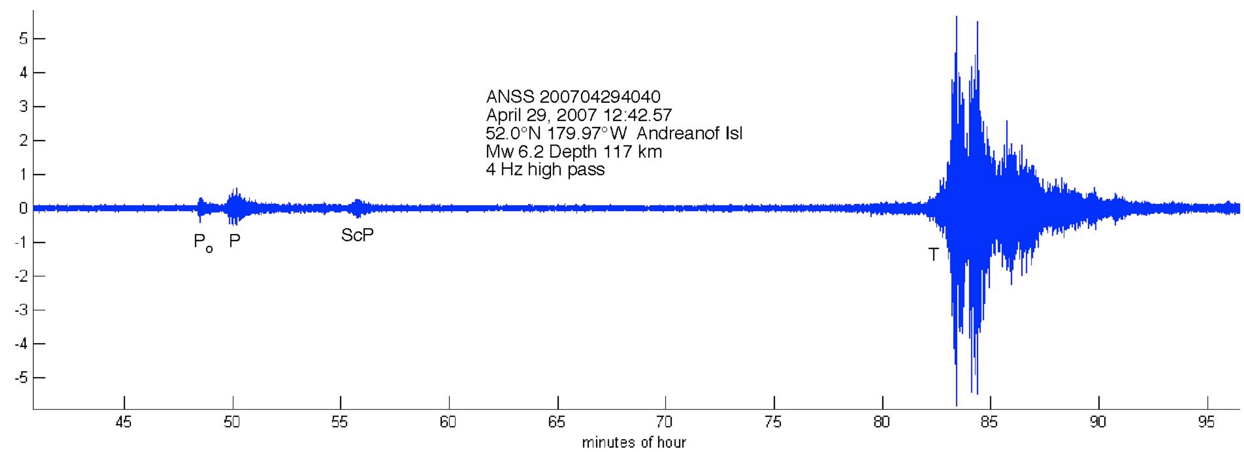

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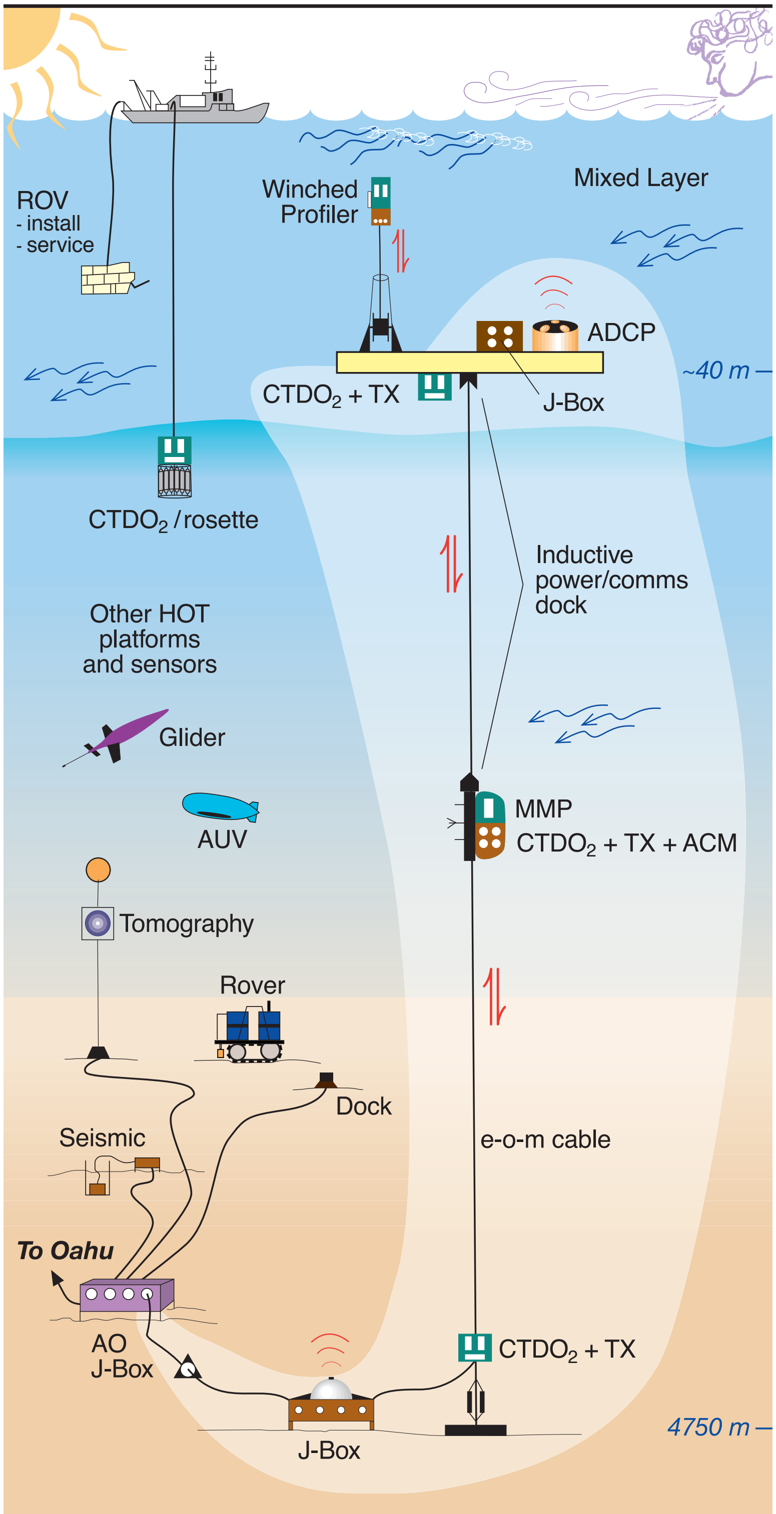

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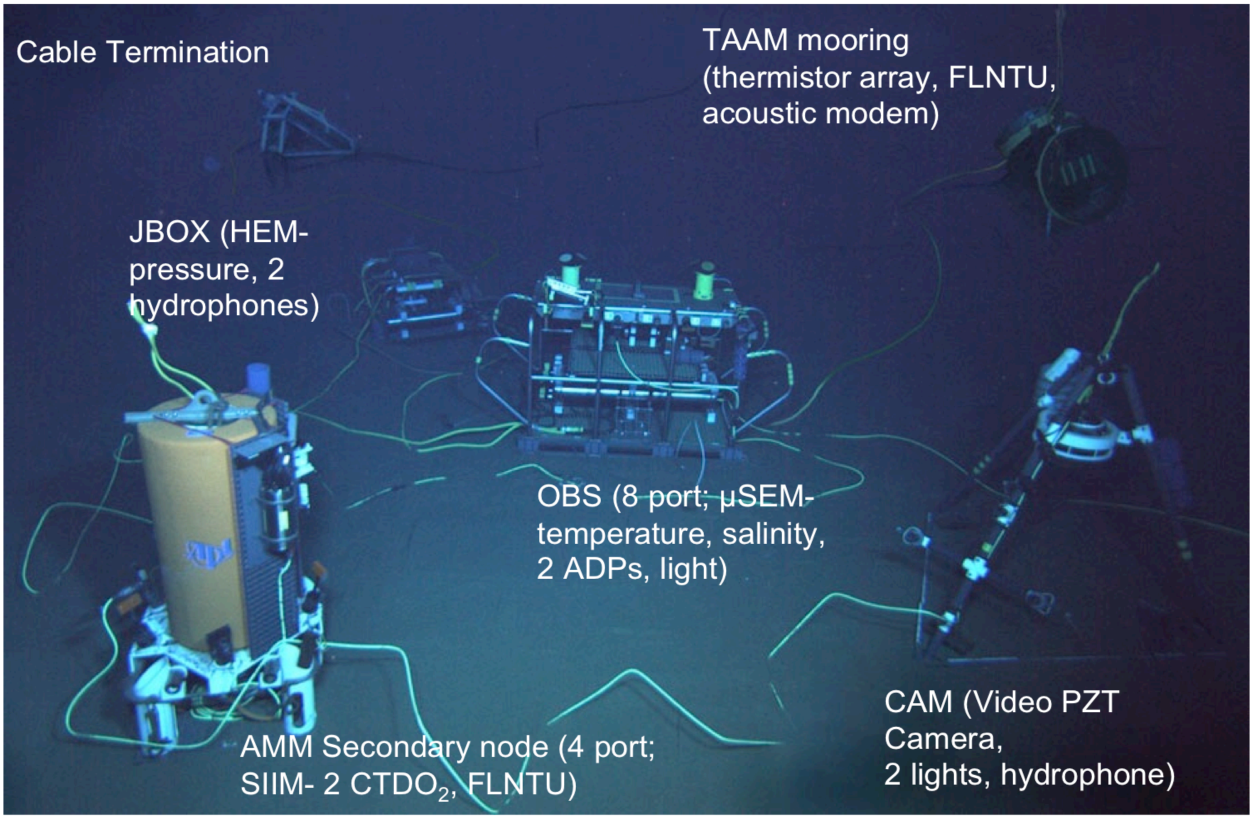

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