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HUGO:The Hawaii Undersea Geo-Observatory

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HUGO: THE HAWAII UNDERSEA GEO-OBSERVATORY

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ABSTRACT :

The Hawaii Undersea Geo-Observatory, HUGO, was installed with the intent of supplying infrastructure for experimenters interested in studies of undersea volcanism and associated phenomena at Loihi, the newest volcano of the Hawaiian chain. Much like an astronomical observatory, HUGO is a facility where scientists can perform experiments while sharing resources with others. The main components of HUGO are the Shore Station, supplying power and recording data on site; the Main Cable - an electro-optical cable connecting the Shore Station to the summit of Loihi; the Junction Box - the power distribution and data collection point on Loihi; Multiplexing (Mux) Nodes – secondary distribution points; and Experiments supplied by scientists. HUGO can potentially supply electrical power, command capability, and real-time data service to more than 100 experiments connected and removed on the ocean floor by submersible or ROV. HUGO was installed on October 11, 1997, but the Main Cable developed an electrical short circuit to sea water on April 26, 1998, and a new cable must be obtained and installed before routine operations can continue.

Despite the failure, Several important tasks have been accomplished, including 1) the successful small-ship lay of the 47-km electro-optical cable from the Island of Hawaii to the summit of Loihi submarine volcano; 2) installation and servicing of the Junction Box; 3) successful operation of electro-optical connectors on the ocean floor by submersible; 4) installation and removal of experiments on the ocean floor; 5) transmission of power and commands from shore to experiments installed at HUGO; 6) transmission of high-rate, high-fidelity data from the summit of Loihi to shore in real time; and 7) recording of volcanic, earthquake, biological, ocean wave, and ship noises for a period of three months. This paper provides a general description of the HUGO system and its history of operation.

INTRODUCTION

Astronomical observatories provide telescopes and ancillary equipment that scientists can share to study the heavens. Similarly, ocean floor observatories can provide shared infrastructure, such as electrical power and communications to shore for studies in this remote and hostile environment. Previously, our incursions into the deep-ocean environment have been for very short periods in manned vehicles and ROVs or by autonomous instruments largely limited by low power and data storage capacity. These experiments provide scientists with only snapshots of the phenomena and processes occurring there. However, while there is considerable science pressure for long-term and power-hungry experiments on the ocean floor, there is often a wide diversity in required data rates, power and data storage requirements, and, most importantly, a lack of consensus on where the observatories should be located. Regions of high potential for scientific return on the ocean floor are often dispersed to the point where a single site will not satisfy enough users to justify the expense of installing an observatory. In addition, many sites of interest are remote and/or in the deep ocean where the logistics of installing and maintaining an observatory become formidable. Loihi volcano, located 30 km SE of the Island of Hawaii offers an observatory site of interest to many research fields that is in relatively shallow water, close to shore, close to port and research facilities, and within U.S. territorial waters.

Nearly all of what we have learned about submarine volcanism is from short-term observations and by monitoring eruptions from distant stations. Until the routine acquisition of submarine acoustic data for scientific use [1], [2], deep submarine volcanic activity was virtually unknown. Even now, close observation of this activity requires a research vessel and autonomous instruments, recording data for limited periods of time and requiring periodic replacement. Permanent cabled observatories have several advantages over autonomous internally powered instruments, namely power, data, and command capability. As power is supplied to experiments from shore, and data and commands can be transferred to and from shore in real-time, there is no need to service instruments on a routine basis. The availability of underwater mateable connectors allows submersibles and ROVs to install and remove instruments when necessary on the ocean floor, without disrupting other experiments, and advances in optical fiber technology allow experiments to transmit high rates of data to shore. While suitable cable can be very costly (roughly $10,000 per km) and require a large ship for installation, the benefits of cables over autonomous instruments in the long run will certainly outweigh the initial cost for sites within a reasonable distance to shore.

While much of the effort being expended in study of submarine volcanism is at spreading centers, hotspot volcanoes, such as Loihi, offer several advantages for such studies. Loihi is the classic submarine hotspot volcano located above the classic deep-mantle plume. It is the youngest volcano in the Hawaiian chain, likely to become the next Hawaiian island in about 100,000 years. The likelihood of volcanic activity per square km per year is probably higher at Loihi than at any other region on the ocean floor, with the possible exception of other submarine hotspot volcanoes, all of which are more difficult to instrument and are less well studied. Hotspot volcanoes are nearly point sources of magma, rather than line sources (spreading centers), and eruptive activity is confined to a small focused area. Hotspot submarine volcanoes are often near islands, and thus logistically easy to reach compared to spreading centers. Loihi is particularly accessible, less than a day’s transit from Honolulu and less than 20 miles from the shore of Hawaii Island. It’s summit volcanism occurs at only about half the depth of most spreading centers. The “weather window” for Loihi is year-round, although winds of 20 kts can be encountered at any time of year. These same benefits also make an observatory on Loihi an excellent site for testing sensors and systems for eventual use at other observatories.

The goal of the HUGO Project is to provide scientists and students with relatively simple access to the deep-ocean environment for experimentation in submarine volcanology and other related phenomena. HUGO will also be available as a fixed station for physical oceanographic, biological, and geo-acoustic research, taking advantage of Loihi's summit location 200 m below the SOFAR channel axis with a unobstructed acoustic view of more than half of the Pacific Ocean, - or nearly 1/4 of the world ocean.

The surface of Loihi is one of the best surveyed areas in the ocean, with numerous swath bathymetric surveys, deep tow surveys, and more than 50 submersible dives. Since the realization of Loihi as a separate Hawaiian volcano [3], seismic swarm activity, indicative of magmatic events, has been detected by the Hawaiian Volcano Observatory seismic array about every few years, with more frequent swarms recently [4]. Earthquake swarms last from a few days to several months, with one of the largest swarms ever recorded at any Hawaiian volcano recorded from Loihi during mid July and August, 1996. The impact of this activity was documented by several cruises to Loihi in August and September, 1996 [5], [6]. Submersible dives and mapping expeditions have discovered recent volcanic products and features, including fresh lava flows, a new pit crater, and active hydrothermal venting (**FIGURE 1**), [7], [8]. The summit is characterized by pillow basalt flows, talus slopes, volcanic muds, and three major pit craters. When activity is occurring, the water is often turbid with bacterial floc, and white "snow" apparently blown out of the ocean bottom. Venting of hot water has been observed [9], although no macro vent fauna, such as are common on the mid-ocean ridges, have been observed. Loihi provides a scientifically significant natural laboratory at a location and depth that make it a primary site for an ocean bottom observatory.

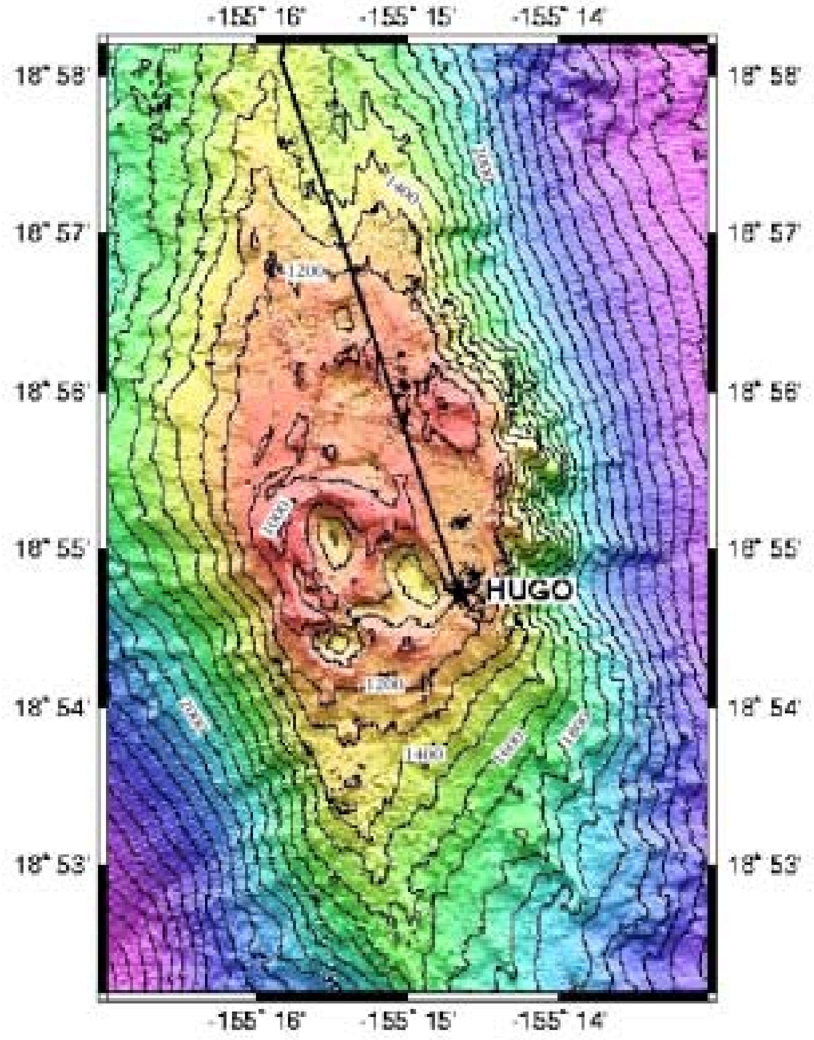

Figure 1. Loihi Volcano Summit. Contours are every 100 m.

The Loihi environment is both similar enough to mid-ocean ridge environments to make valid comparisons and to use identical instrumentation, and different enough to warrant observatories in both settings. The location and depth of Loihi make the cost of establishing a cabled observatory there at least an order of magnitude less than the cost of a similar observatory at a spreading center such as Juan de Fuca. The areal extent of the summit region is only about 3 by 5 km, making it possible to reach many sites of possible volcanic activity from a single observatory. Roughly 80% of the scientific studies elucidated in various RIDGE workshop reports could also be conducted at Loihi, and HUGO should be an excellent proving ground for experiments being developed for spreading center use.

In addition to volcanic studies, Loihi provides an excellent site for study of the deeper crust and upper mantle. A seismic array on Loihi, coupled to the Hawaiian Volcano Observatory array will help a great deal in improving the accuracy of earthquake epicenters at Loihi and in offshore regions such as the submarine south flank of Kilauea volcano [4]. These seismic data will help a great deal in improving models of the structure of the volcanic edifices, the crust and its deformation, and possibly the current location of the hot spot and mantle plume.

Loihi’s summit is only about 200 m below the axis of the SOFAR channel, and sound velocity is nearly constant at the summit depth. This condition makes it ideal for reception of natural and man-made sound sources such as employed by ATOC [10]. The summit area is acoustically visible to earthquake source areas from California and around the Pacific to the south to the Solomon Islands. Earthquake T-phases from distant earthquakes are common in the HUGO hydrophone data (**FIGURE 2**) [11]. The constant-velocity condition makes possible “line of sight” communications over large areas of the summit to distances of up to 8 km. With the rapid improvement of acoustic data telemetry [12], it should soon be possible to transmit data from autonomous experiments to the HUGO system acoustically, rather than running cables across the summit. This will be accomplished with high frequency carriers so that the quality of lower frequency geo-acoustic data are not compromised.

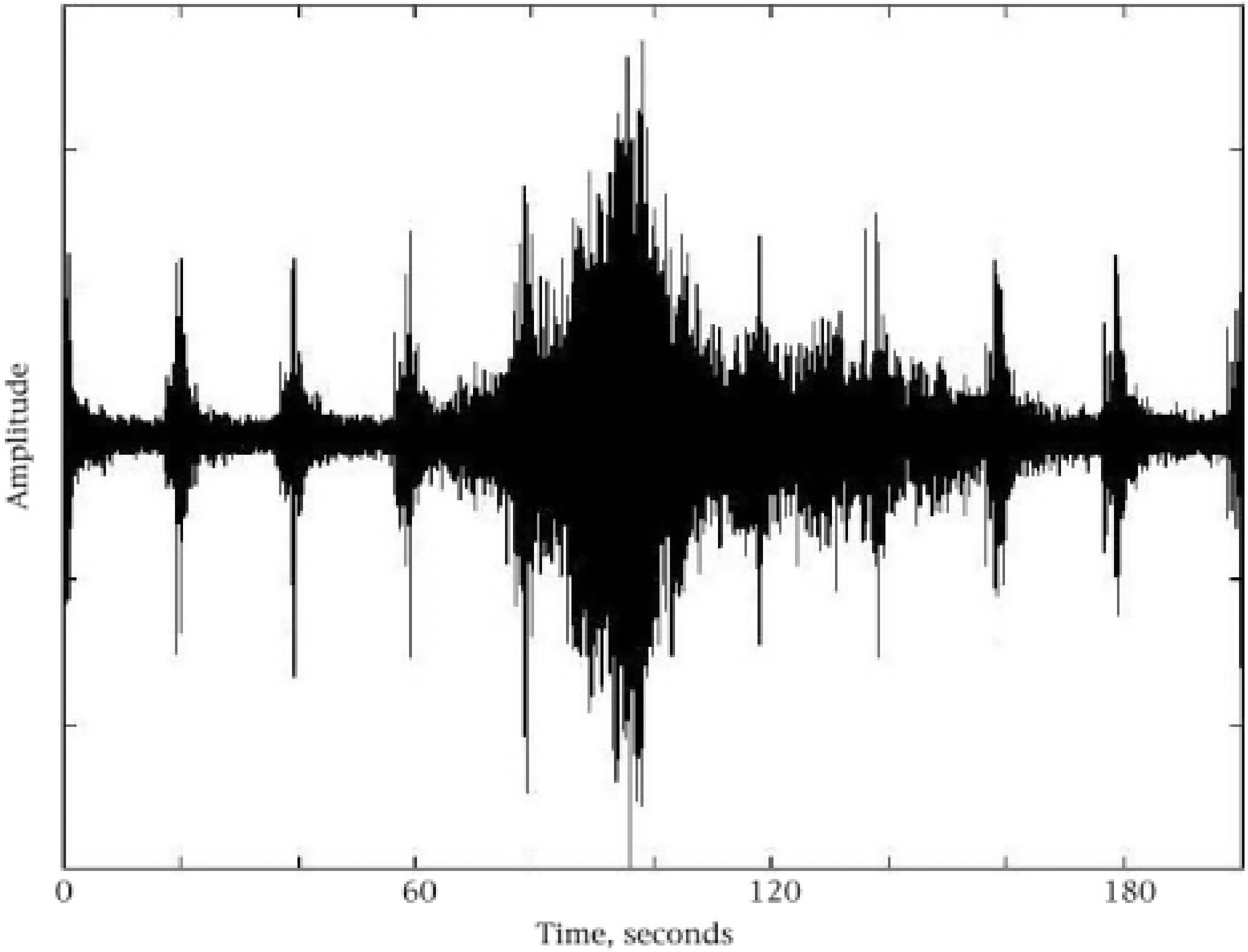

Figure 2. T-phase from an earthquake off Chile superimposed on air gun sounds from the *R/V Maurice Ewing*.

Measurement of deformation of the edifice is an experiment of particular interest. Rather than use noisy short-baseline tilt meters, we envision an array of pressure sensors on the bottom that would measure the ocean depth with a precision of better than 0.05 m. Water depth changes as the volcano deforms, and tilts of 10 µrad can be resolved between two pressure sensors placed 1000 m apart. As tilts of more than 100 µrad are common in Kilauea events [13], an array of pressure sensors should yield particularly interesting data on the deformation associated with seismic and magmatic activity [14] . As these sensors are sampled at a relatively low rate, they would be excellent candidates for acoustic telemetry to a central collection node on the summit. Long-term drift of these pressure sensors is a problem for events with periods of months and greater, but events with durations of weeks or less are expected, where drift should not be a factor. With depth gauges and transponders for measuring horizontal deformation, a network can be installed that will monitor the summit region continuously, tracking deformation in real-time.

Theory of Operation:

The design philosophy of HUGO is to provide the maximum possible power and data capability to users, with high reliability and considerable flexibility in experiment design and location. Data transmission and power delivery should be transparent to the users, who are required to pay only cost of operation and experiment installation. Towards this end, HUGO was designed to be extremely versatile, with a variety of possible data rates and power consumption options, plus the ability to expand the system in terms of number of experiments and spatial coverage as required by demands of the users. Plans and documentation for relatively easy incorporation of experiments from all interested students and scientists are available [15].

Data from experiments are transmitted directly to shore through dedicated optical fibers. The delays from data generation to reception on shore (latency) are minimal and invariant from each node. This fixed latency means that there is no need to include a time stamp with data on the ocean floor. All timing is done on shore. All nodes, however are synchronized to a very stable oscillator, so that the time for a particular sample can be determined to within about 100µs relative to GPS time. A planned hardware timing circuit should reduce this value to a few µs.

The availability of submersible assets to perform routine installations and maintenance of ocean bottom observatories is particularly important. HUGO, while funded by the NSF, is truly a joint venture with NOAA. We are very fortunate to have the *PISCES V* submersible operated by the NOAA NURP HURL group at the University of Hawaii. The submersible and its support ship (*R/V Kaimikai-o-Kanaloa*) have their home port in Honolulu and have pledged support for the HUGO Project (see HURL Science Plan RFP 2001). Having this facility available is critical for efficient operation of HUGO.

Experiments on Loihi are connected by cable to Multiplexing Nodes, which are in turn connected to the Junction Box. The Junction Box is the termination of the Main Cable connecting Loihi to the Shore Station on the Island of Hawaii (**FIGURE 3**). A functional description of these components follows.

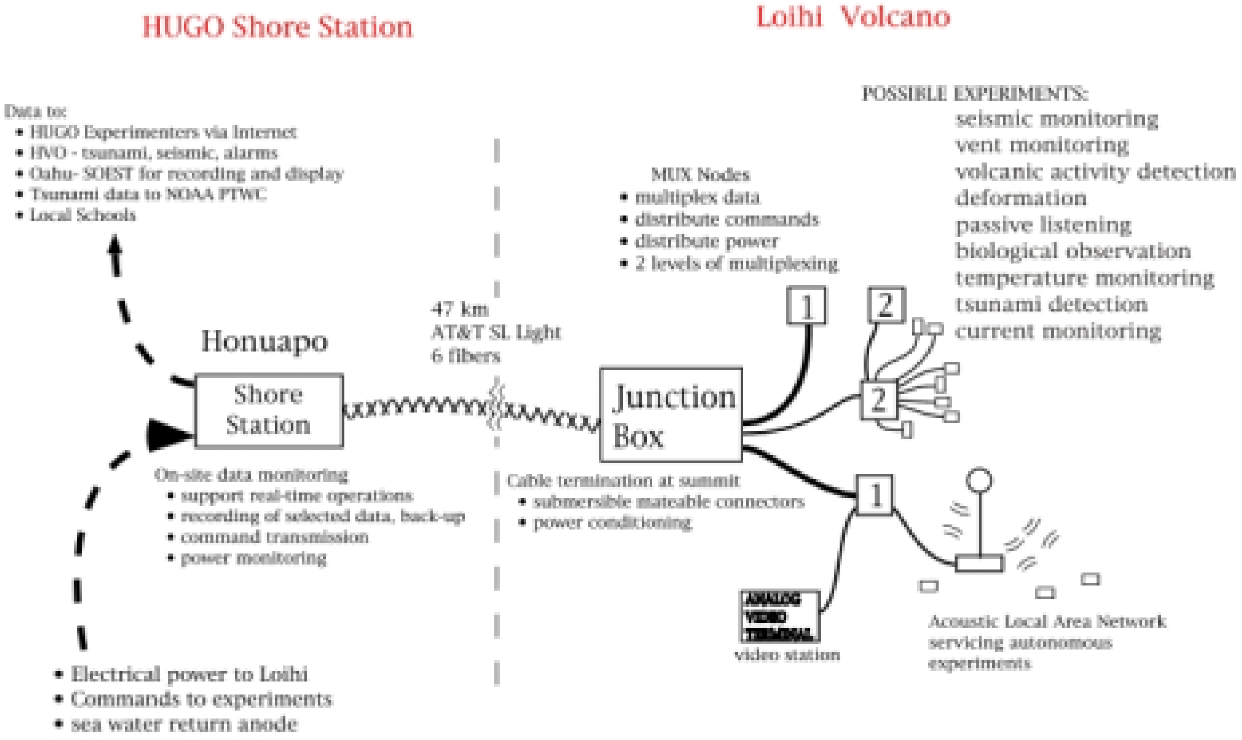

Figure 3. Functional Schematic of the HUGO System

Experiments are user-supplied sensor systems to which HUGO supplies electrical power and provides communications to shore. Experiments may be high or low power, and high or low data rate, but there will be more capacity for low power and low data rate experiments. It is possible to change the configuration of experiments as desired by command from shore. Experiments are installed on the ocean floor by submersible or ROV, connecting the experiment to a Multiplexing Node. One experiment might be an acoustic node (Figure 2) which collects data from many autonomous sensors that are not directly connected to HUGO by cable.

Multiplexing Nodes parse power and commands to eight channels, one of which is used to operate the Multiplexing (Mux) Node itself and any internal experiments. For example, each Mux Node will likely contain a programmable transponder for use in navigation of vehicles and for measuring horizontal deformation, a pressure sensor for depth measurement, and a thermister for monitoring changes in water temperature. Data and power can be distributed to two levels of multiplexing, the upper level (Level 1 Mux) has a data rate of 5120 kBd, and all data from a single Level 1 Mux are sent to shore on a single fiber channel. Normally, a Level 1 Mux would be located near an area of particular interest, and connected to the Junction Box by a secondary cable. The distance experiments can be located from the Junction Box is limited by the power desired and the resistance of the cables involved. Each Level 1 Mux can be further divided into up to seven Level 2 Muxs, each provided with 640 kBd of data capacity. Level 2 Muxs can in turn support up to 7 experiments with an eighth channel reserved for operation of the Mux Node. Each Level-2 channel supports up to 16 kBd of band width. With this system, a typical 4-channel 32-bit word seismic experiment might sample at 500 samples per second per channel and use 20 W of electrical power, using only 1/7th of the capacity of a Level-2 Mux, or less than 1/100th of the capacity of the HUGO system. Alternatively, a high data rate experiment can utilize a complete Level-1 Mux channel, and a very low rate experiment can share an experiment channel with other low-rate experiments.

Junction Box: The HUGO Junction Box is the termination of the Main Cable at the Summit of Loihi, located in the “Thousand Fingers Field” east of East Pit Crater. The Junction Box regulates electrical power, parses commands to experiments, and passes data to the optical fibers in the Main Cable. The Junction Box also contains a built-in Level-1 Multiplexer and a programmable pinger/transponder. Five of the six fibers in the Main Cable can support up to two Level-1 Muxes by frequency division multiplexing, and one fiber is dedicated to command “uplink”. The 10 fiber channels available to Level-1 experiments can be programmed to three of the ten underwater mateable connectors. Each of these connectors has two duplex fiber circuits for support of two Level-1 Muxs. The remaining connectors are assigned to a built-in Level-1 Mux in the Junction Box, and to the Power Regulator.

Power: Electrical power is supplied to the HUGO Main Cable through a dc Power Supply at the HUGO Shore Station at Honuapo, on the SE shore of the Island of Hawaii. A maximum of 1000 dcV at 20 A can be supplied from shore to the cable, delivering about 5 kW of usable power at the Junction Box. This power is regulated to 350 V by a shunt regulator at the Junction Box, dumping excess power into a resistor stack, which can be replaced on the bottom if necessary. This regulation is critical because of the negative dynamic input impedance of the typical dc-dc converter [16]. The circuit is completed through the sea water, with an electrode at the Junction Box and electrode in the ocean at the Shore Station. Power is distributed to nine underwater mateable connectors in the Junction Box. Should a connector fail, the power supply is protected by programmable circuit breakers. The amount of power supplied to each connector can also be regulated according to demand. Care must be taken when installing experiments to ensure that the shore voltage is increased to accommodate the experiment and its appropriate turn-on and operating transients. A diode in the

Junction Box prevents current from flowing the wrong way up the cable. In this way, a battery package or power-only cable can supply electricity to the Junction Box in the event of an electrical failure of the Main Cable.

Commands to experiments are generated in the Shore Station Computer, although they may originate at a remote site and be transmitted to the Shore Station over the Internet. Commands are addressed by MUX level and number, and then by experiment. Each Mux hears all commands, but reacts only to commands with the appropriate address. Command formats allow nearly any command to be sent from simple gain changes and downloading software updates to a system sync command that resets all sample times to a fixed reference.

Main Cable: The HUGO Main Cable is a 45-km section of SL-Light standard trans-oceanic telephone cable donated by AT&T (now TYCO Submarine Systems International). The cable was spliced to a 700 m double-armored Shore Section, and an additional 1000 m of “Fish Bite” protected cable. The 45 km main section of the cable is roughly 2.7 cm in diameter with no armor. This cable contains six single-mode optical fibers. As discussed later, this cable was not robust enough for the volcanic Loihi environment, and it failed six months after installation with an electrical leak to sea water.

Shore Station: The HUGO Shore Station, located in two 20’ vans at Honuapo, Hawaii, feeds power and commands to the Main Cable, and transmits and archives data from experiments. The site is located at an elevation of about 25 m to avoid most tsunamis. As more users are involved, the Shore Station will be capable of transmitting data packets to experimenters and processing commands using the Internet. As the station is at the “bitter end” of the power and telephone grid in Hawaii, losses are expected and back-up power and data storage requirements are anticipated. The station is normally unmanned, but the HUGO Shore Station Manager lives about 100 m from the site.

System management: HUGO is available to all experimenters with appropriate instrumentation. HUGO engineers are available for help in developing such instruments, and the HURL group is available to help in mechanical design and installation options. HUGO is currently managed at the School of Ocean and Earth Sciences (SOEST) at the University of Hawaii. As the user base increases, a committee of users and outside observers will be formed to recommend changes in the system and to ensure that management provides fair and efficient access to the HUGO system with maximum reliability.

DESIGN and CONSTRUCTION:

Design and construction of HUGO began in earnest late in 1991 with funds from the National Science Foundation. Initial Design efforts and planning made it clear that an electro-optical cable was required, and such a cable was donated to the University by AT&T for the HUGO Project. A primary technological challenge of HUGO was the goal of installing and servicing the system on the ocean floor, requiring underwater mateable electro-optical connectors. At the time, no such connectors were available commercially, and some electrical connectors that were tested did not operate at depths of greater than a few hundred meters. As a result, we developed our own hybrid connectors for HUGO. These connectors utilize standard Ocean Dynamics Inc. electrical connectors coupled with optical connectors that transmit the optical beam through a water path between two SELFOC lenses embedded in the ends of the connector (**FIGURE 4**). The connectors are unique in that the cable-side of the connectors is active, with the capability of re-generating the optical signal in the connector for transmission down the cable and into the Junction Box, rather than transmitting any losses incurred across the connector. The SELFOC lenses greatly ease the mechanical tolerances in the alignment of the connector. There are only a few thousandths of an inch of water between the lenses, which actually improves the optical coupling by reducing surface reflections.

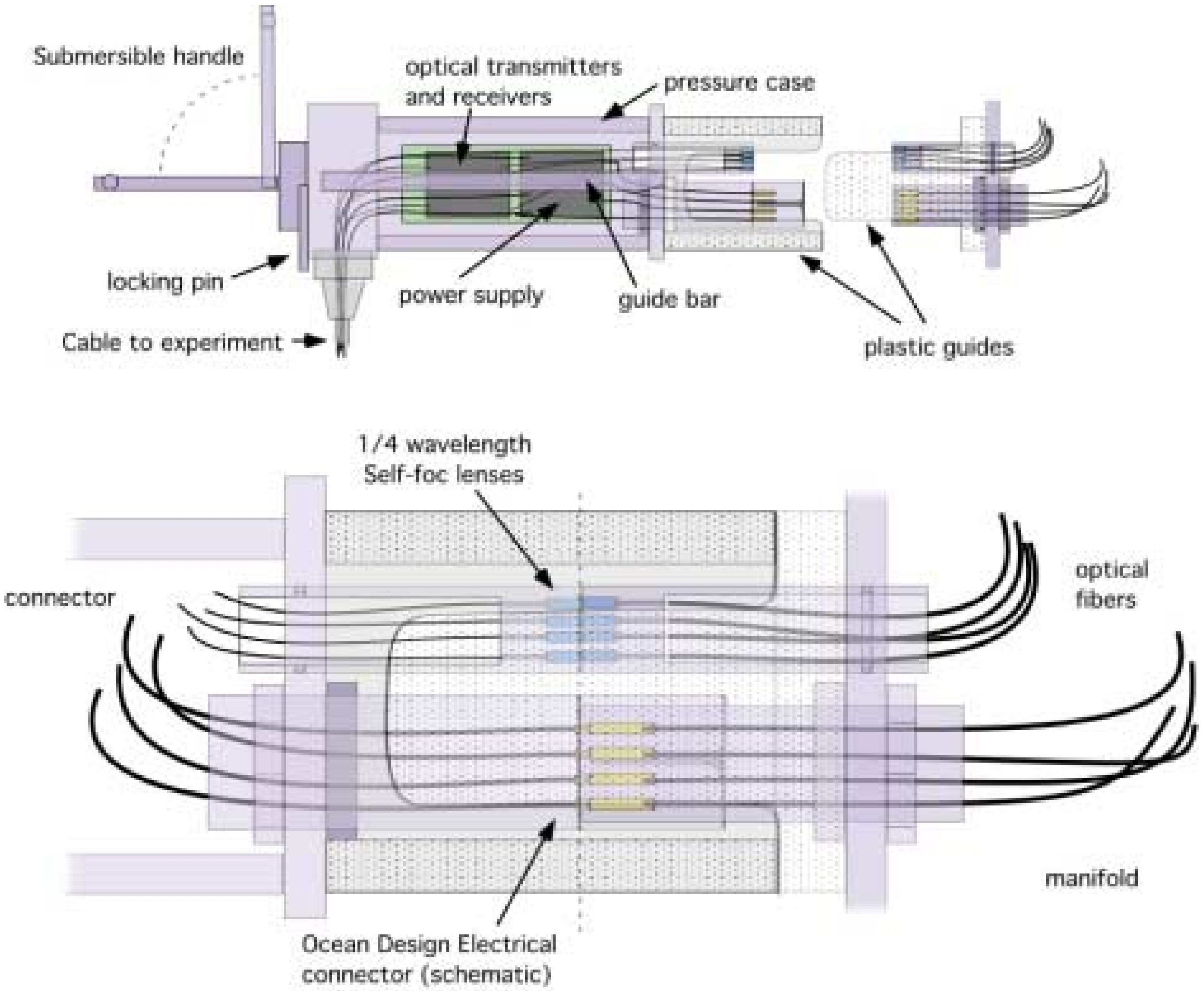

Figure 4. The HUGO Connector. This hybrid connector has two duplex optical circuits and two electrical circuits. The optical signals are regenerated in the connector to diminish optical losses across the connector. The bottom figure is an expanded view of the upper figure.

In the first two years of design, we also settled on dc power transmission with a sea-water return and constant-voltage regulation at the Junction Box. Use of ac power, such as in the land power grid, would require cable with multiple conductors and higher voltages due to the voltage drop in the return. The dc system gives good flexibility, allowing the power at the Shore Station to increase as loads from experiments increase. The 350 V bus voltage is switched to the individual connectors by programmable circuit breakers. The trip level for each connector can be programmed to safely handle the startup surge of a given load while still providing reasonable protection from excess fault currents.

Because the system was to operate on the ocean floor for at least ten years, all mechanical components were designed to minimize corrosion (titanium and plastics) or be easily replaced, and all electronics were designed to be as redundant and high-reliability as possible. The primary single-point failure path is the Main Cable itself (and that is what eventually failed).

Another design challenge was the interface between the submersible and HUGO. Connectors and deployment devices had to be designed taking into account the capabilities and limitations of mechanically-challenged manipulators. One of the first lessons was that the connectors should not require rotation, since some manipulator arms have a difficult time stopping rotation, and can destroy a connector by rotating too far. The likelihood that many cables would eventually be plugged into the Junction Box also required planning of cable approaches to the Junction Box, and the necessity to keep the sides of the Junction Box free of cables for safe submersible operations.

A primary consideration was that some data would be collected from the Junction Box during and after emplacement, rather than wait for construction of a MUX Node and experiments. Towards this end, a Level-1 Mux was built into the Junction Box to provide direct experiment access. Two “proof experiments", a seismic package and a high-rate hydrophone were also added. The seismic package contains a pressure sensor, tilt meters, a thermister, and a hydrophone with an orthogonal geophone sensor package that could be deployed away from the Junction Box and buried. A second hydrophone was built that was plugged directly into one of the Mux Connectors on the Junction Box. This hydrophone was sampled at 64 kHz with a signal bandwidth of 0.01 Hz to 20 kHz. The hydrophone is actually a mini-mux node in itself, with the ability to sense what rate it is allowed to send data at, and adjust its rate accordingly. In addition, a permanently installed programmable pinger was installed that can be commanded to transpond or ping at programmable frequencies and ping rates. The HUGO Junction Box was finally complete and tested in shallow water in August, 1997.

The Shore Station site is located at Honuapo, Hawaii on land leased from Kau Agribusiness. Planning for HUGO required an environmental assessment, since the cable was to run over a State pier, through protected beach area, and through a county park. In the end, eighteen months were required for permitting, and more than 15 agencies and entities had to give their approval before the plan could move forward. The shore station was prepared for landing of the main cable by installing a temporary walkway and running conduit over a derelict pier at Honuapo. A land extension to the cable was run 500 m from a cable junction vault near the pier, in buried conduit through a county park, and up on poles to the Shore Station at an elevation of 25 m. Two 20-foot vans were installed at the Shore Station to house recording, telephone, and power equipment. Two 7 m deep holes were drilled near the shore and lined with perforated pipe to house the sea water return electrode.

A detailed near-bottom survey of the summit region and most of the cable route was conducted during June, 1997, using a deep-towed RESON swath mapping system operated by SAIC. The map resulting from these and other data provided coverage of all areas shallower than 1800 m with aerial and depth resolution of about 5 m (**FIGURE 5**). The *PISCES V* submersible surveyed the intended Junction Box site and part of the cable route in August, 1997. While the intended landing site was found to be adequate over an area about 300 m by 600 m, the cable route is extremely rough with no “safe” path, particularly on the north end of Loihi. In response to these surveys, a study was made of the possibility of armoring the main cable, but the total cost would have been well over $600,000 (which was not available), more than doubling the value of the cable. Addition of armor would also have delayed installation of HUGO by more than a year.

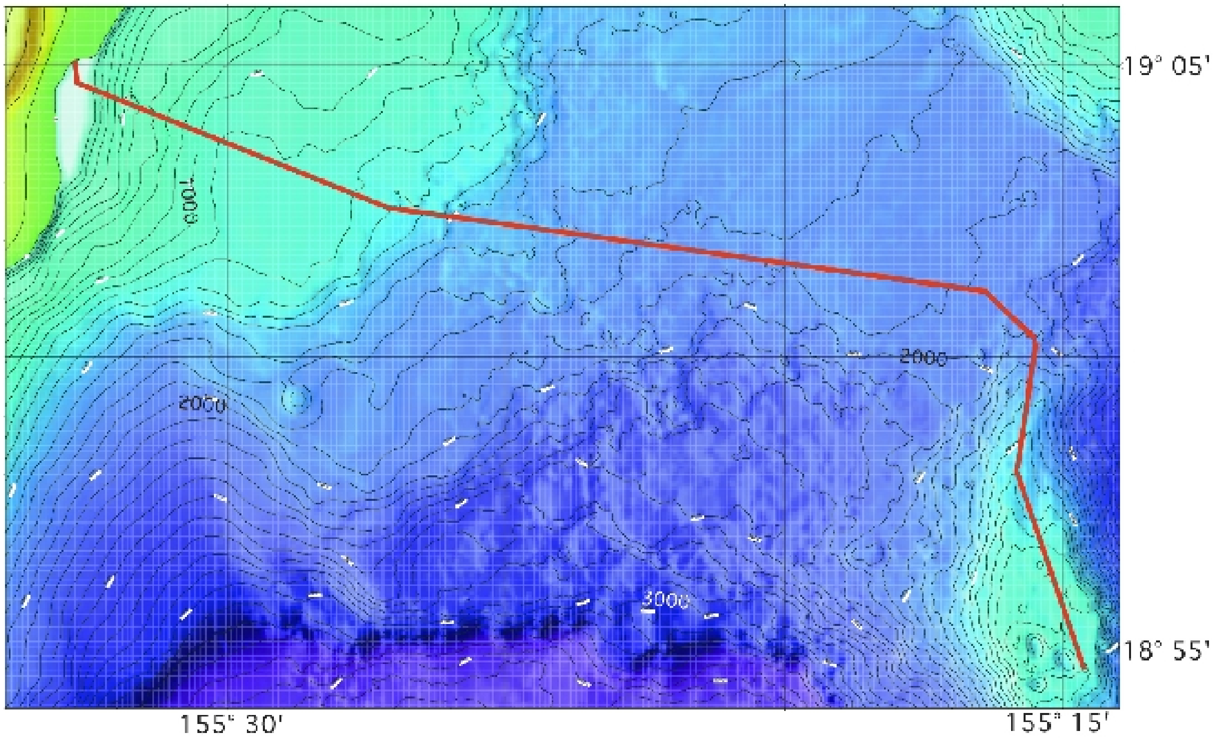

Figure 5. HUGO Cable Route. Depths are in meters.

INSTALLATION

We were very fortunate to obtain the use of the *R/V Independence* for installation of the HUGO Junction Box and main cable. The ship was in Hawaiian water for installation of other cables, and had the expert SAIC MARIPRO cable-laying team and equipment on board to accomplish the operation. The cable was loaded into a pan on the *Independence* from a cable pan at the AT&T yard in Honolulu harbor, passing the cable over the *C/S Longlines*, where splices were made to the Junction Box termination and to the shore cable by AT&T personnel. Loading the cable required 24 hours of continuous spooling (**FIGURE 6**). Recording gear loaded on the *Independence* allowed us to test and monitor the Junction Box and its sensors during the 20 hour transit to Loihi and during installation of the cable. The ship sailed for Loihi on October 10, and laying operations began at 6 PM on October 11, 1997. The cable was laid from the summit of Loihi towards shore.

Figure 6. Loading the HUGO cable on the R/V Independence. 24 hours were required to load 47 km of cable.

An anchor consisting of two Danforth anchors and 500 lbs. of chain were first lowered, followed by 150 m of steel cable and the Junction Box. Power was applied to the system as soon as it was in the water, and the pressure sensor was monitored to obtain package depth. The ship began transiting along a pre-set path and a rate determined by the SAIC MARIPRO cable laying team that supervised this operation. Once the Junction Box was on the bottom at 1204 m depth, the tilt meters and geophones verified that the attitude was well within limits, and cable was paid out. About 30 minutes after touchdown, the geophones became very noisy and the Junction Box tilt increased from nearly flat to down 6° in the pull direction, indicating that the cable was dragging the Junction Box. Cable pay-out rate was increased, and no further motion of the package was observed. All during the cable lay, the high-rate hydrophone on the Junction Box recorded continuous explosive activity and occasional roaring sounds.

Approximately 7 hours after beginning the lay, the cable reached a shallow terrace above the steep slope on Mauna Loa volcano, and an additional anchor was laid to prevent the cable from sliding down the steep slope. The end of the cable was disconnected from the recording system after eight hours of recording, and passed to the Shore Station to be winched through the conduit to the junction vault. The lay was complete less than 11 hours after beginning, and the *Independence* returned to Honolulu.

The connection from the main cable to the shore cable leading to the Shore Station was completed on October 19, 5 days after deployment. While the system was working, we were soon greeted by a series of failures. The seismic experiment was lost three days later, and the hydrophone signal was lost the following week. The 350 V circuit to the connector the hydrophone was plugged into was shorted, and, since the hydrophone does not use that circuit, we concluded that the hydrophone pressure vessel was flooded. Serial data from the Shunt Regulator was lost about two weeks after deployment, although the shunt regulator continued to operate and regulate power normally. Testing of the electrical circuits to each of the connector ports showed that the only inoperable ports were those in use, thus bringing us to the conclusion that all of the plugged-in connectors had flooded, but that the Junction Box was still functional.

On November 7, 1997, the system failed and could not be brought back to life, with the main Shore Station circuit breaker tripping whenever power was applied to the HUGO cable. We knew that the Junction Box electronics were still intact, however, since a diode in the power electronics which prevents current from flowing “backwards” in the system was operational. Had the Junction Box been flooded, or the cable compromised, the diode would not have been visible. The reason for the failure of the connectors was found to be slow creep of the adhesive used to seal the optical lenses into the connectors. The mating connectors on the Junction Box side did not fail, since they are located in an oil-filled pressure-compensated housing and there is little pressure differential across the lens. The problem was solved in new connectors by using a different adhesive. It was also determined that the system could operate without regulation (at relatively low power) if the flooded connector to the Shunt Regulator was removed. Thus, two additional hydrophones and a new cable and connector for the Seismic Experiment Package were constructed in anticipation of bringing the system back to life.

A series of four NSF-funded *PISCES V* dives for HUGO were scheduled for January, 1998, to service the Junction Box, test the connector ports, install the new sensors, and to survey the cable. On the first dive, the main cable was located without difficulty and followed to the Junction Box. The front of the Junction Box was found to be buried about 30 cm in mud, apparently pulled forward and down during installation. Other than that, the system appeared normal (**FIGURE 7**). Whenever the submersible touched the bottom, however, a cloud of mud would blow up, reducing visibility to zero and forcing operations to stop until the cloud cleared ten to fifteen minutes later.

Figure 7. The HUGO Junction Box on Loihi. A hydrophone is connected in one of the instrument bays. The front of the package is buried about 30 cm in the mud.

When the Shunt regulator was disconnected, power was immediately restored to the system as expected. The faulty hydrophone was replaced, allowing the Shore Station to listen to submersible operations at the Junction Box (Voice communication between the submersible and the support ship can be heard at :http://www.soest.hawaii.edu/~fred/sounds/sounds.html). The sea water return electrode, which completes the DC electrical power circuit, was deployed away from the Junction Box, and the cable connecting the Junction Box to the deployment anchor was cut. All of the underwater mateable connector ports on the Junction Box were tested, and, despite some severe attenuation of optical signals, all but three were operable.

About three km of the HUGO cable was surveyed to the north of the Junction Box in terrain that appears relatively flat in the contour maps. However, even in this relatively benign area, the cable is suspended over valleys in several spots for lengths of about 100 m. No surveys of the cable on the north slope of Loihi, where there is steep rougher terrain, have been conducted.

On completion of the dive series, HUGO was running with the hydrophone, pressure sensor, thermister, and a programmable pinger operating. The pinger had been used during the dives for navigating the submersible, and later for determining the water depth by detecting pings reflected from the ocean surface. Early in February, 1998, the *R/V Maurice Ewing* conducted an extensive reflection survey on the east side of Hawaii, including three lines that went directly over the HUGO Junction Box. Analysis of the resulting refraction data recorded on the HUGO hydrophone is the subject of another paper [17]. At this point, HUGO was ready to accept new experiments.

During the period from re-start until early April, 1998, a large amount of natural activity was observed on the hydrophone, including teleseismic and local earthquake body waves, surface waves, earthquake T Phases, volcanic explosions, volcanic roars and hisses, humpback whale song, and other unidentified marine mammals. With only one hydrophone, it is difficult to locate the source of these events, although some help will be provided by data from the NOAA equatorial hydrophone array [18], the Hawaiian Volcano Observatory Seismic Array, and the various earthquake catalogues. The vast majority of the detected events, however, were observed only at HUGO. Analysis of these signals is the subject of another paper [11].

On April 26, 1998, the system failed and could not be restarted. Testing showed that the diode which prevents “backwards” current in the Junction Box was no longer operating, indicating a short to seawater either at the Junction Box or in the HUGO cable. Subsequent testing of the optical fibers showed that all are intact up to the Junction Box with no detectable degradation since installation. A tear in the cable insulation could easily have caused the short without loss of the optical fibers. Impedance tests implied that the short is near the Junction Box end of the cable, and possibly within the Junction Box.

HUGO was again brought to life on October 26, 1998, when a battery pack was plugged into the Junction Box by the PISCES V submersible, confirming that the electrical fault was in the cable, rather than in the Junction Box. During the ensuing eight hours data were transmitted to shore through the optical fibers in the main cable. The system has not been operated since this time.

Unexpectedly, mud turned out to be a significant problem at the HUGO Junction Box. A 1.8 meter long probe pushed into the mud below the Junction Box met no resistance over its complete length, raising the question of the source of the mud, which had not been observed prior to the 1996 event. The Junction Box site, known as the Thousand Fingers Field, had been an area where a large number of hydrothermal vent pipes extended above the bottom. The area is believed to be very young, probably less than 100 years old, since no gorgonian corals (common on the older outcrops) are found in the area [19], thus the presence of thick mud is unexpected. A microprobe analysis shows that the mud is largely volcanic and that it contains volcanic glass fragments from Loihi (Mike Garcia, personal communication). If the Junction Box had sunk an additional 10 cm, some of the connector bays would be in the mud and unusable. The mud can pose a severe problem to submersible operations, since so much time is lost to poor visibility. A possible solution is to provide landing points for vehicles on the structures so that the vehicles can stay off the bottom. This solution was used in the Hawaii-2 Observatory Junction Box [20].

Data Recording

Four periods of data recording have been made for a total of about three months of data: 1) during the cable lay from the ship, 2) prior to the failure in November, 1997, 3) from late January, 1998, until the electrical failure at the end of April, 1998, and 4) with the battery package connected in November, 1998. As the seismic system failed early, the analysis has centered around the data from the high-rate hydrophone. Some data from the pressure and temperature sensors have been examined, but only tidal variations are observed.

The high-rate hydrophone was recorded continuously at 512 samples per sec, and from 5 Hz-11 kHz on DAT tape on demand. Interesting signals have been copied from the DAT tapes, and a sample of these signals are available for listening at: http://www.soest.hawaii.edu/~fred/sounds.html. Sounds include natural explosive sounds and roars, the R/V Ewing air gun, submersible activity and voice transmissions, and a serenade by a humpback whale. Recorded sounds have excellent fidelity, and are well worth listening to on a system with a good speaker. Continuous recording for three months resulted in over 8 GB of data. Analysis of these data continues, but a quick look shows local and teleseismic earthquakes, T-phases, ship sounds, and eruptive noise from Kilauea [11]. Loihi volcano appears to have been quiet during the entire recording period.

The use of a high-rate hydrophone has made it possible to observe events that have not been previously documented (**FIGURE 8**). The

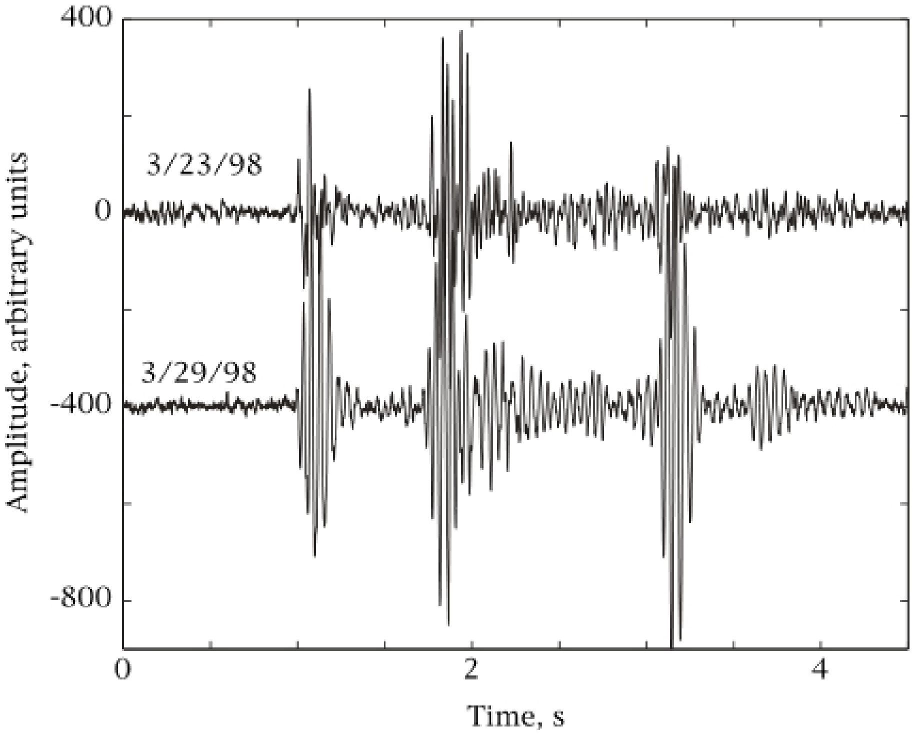

Figure 8. Volcanic explosions recorded by the HUGO hydrophone. While these events have a wide variety of frequencies, nearly all show the same separation between peaks, implying that they come from nearly the same source.

explosive sounds vary in frequency from below 30 Hz to above 1 kHz, with nearly all signals consisting of a sharp first arrival followed by a diffuse second arrival about 0.75 sec later. Our initial assumption that the first arrival is a direct arrival and the 2nd is a surface reflection placed the volcanic source is at a distance of about 1.7 km from the junction Box. A likely site for this eruption site was to the north of the HUGO Junction Box, but a submersible dive to that area observed no signs of recent eruptive activity. Sonobuoys were dropped from the *R/V Kaimikai o Kanaloa* to record some of the explosive sounds while the battery was connected to the Junction Box in November, 1998, to triangulate on the source. It was thus determined that the explosions were not generated at Loihi, but where lava from Kilauea volcano was entering the water 50 km to the north [11]. Although we were surprised and somewhat disappointed that the sounds were not indicating a Loihi eruption, the high volume and fidelity of signals imply that Loihi eruptions, when they occur, will be very well recorded by HUGO.

Another common event is the “roar/hiss” signal (**FIGURE 9**), building slowly first at 20-50 Hz to a roar while a hissing sound is building at higher frequencies. These events are observed several times per day, often accompanied by increased explosive activity. Correlation with observed lava bench collapses suggests [21] that these events are the sounds of submarine landslides at the Kilauea ocean entry.

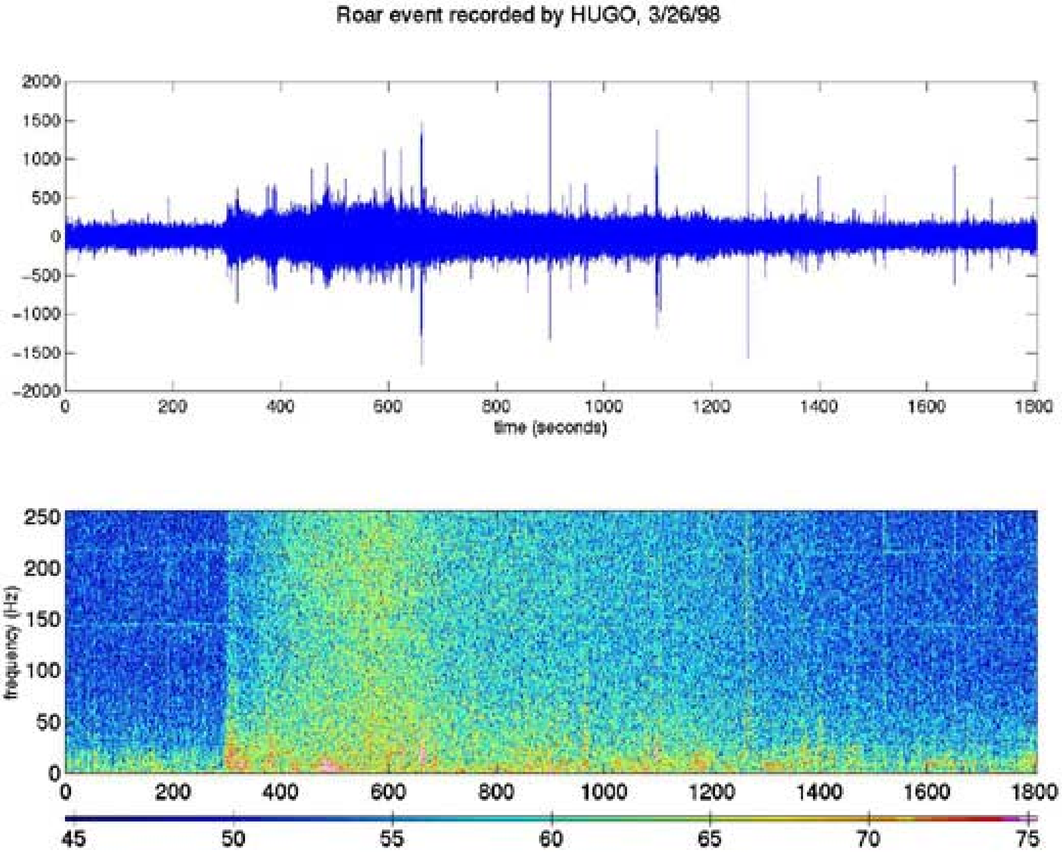

Figure 9. Roar/hiss event recorded by the HUGO hydrophone on March 26, 1998. These events appear to be generated by submarine landslides near the site where lava from Kilauea volcano is entering the ocean. The upper figure is the time series, and the lower is a spectrogram with energy plotted vs. frequency and time. Color bar units are dB.

FUTURE:

To bring the HUGO system back into operation will require a new cable, at a cost of roughly $1,500,000 installed. The cost reflects the necessity of armoring the complete cable to prevent a failure similar to the one experienced, plus the cost of implementing improvements based on lessons learned.

In addition to a new cable, we will recover the HUGO Junction Box and make several changes to improve its reliability and functionality. Improvements include replacing all optical components in the underwater mateable connectors with electrical connectors. The optical connectors are not as reliable as we would have liked, and, while commercially available electro-optical connectors are now available, they are expensive, and not required for the relatively modest data rates of the HUGO system. It may be necessary to transmit data optically from remote Multiplexing Nodes to the HUGO Junction Box, however, and this will be accomplished by installing optical transmitters and receivers in the connector housings. A cable termination, similar to that used in the H2O system [20] will be installed between the Junction Box and the main cable to make it possible to replace the Junction Box (or the cable) without disturbing the rest of the system.

The existing cable poses a navigation hazard to submersibles and ROV's where it is suspended off the bottom, and we will request several submersible dives to cut the cable over these spans to reduce this hazard. The cable will also be pulled away from the shore station and released in deep water.

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