

## The Hawaii-2 Observatory (H2O)

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Beneath 5,000 meters of water midway between Hawaii and California, the Hawaii-2 Observatory (H2O) rests on the seafloor (Figure1). The dream of a deep-ocean scientific observatory is a reality. Telemetry and power comes via a retired telephone cable—Hawaii-2—donated by AT&T to the IRIS Consortium for the benefit of the scientific community. H2O is the first Global Seismographic Network (GSN) station on the seafloor, and with a suite of wet-mateable connectors on a junction box (j-box), offers marine scientists a new opportunity to deploy and operate remote instrumentation in the middle of the ocean.

Although Earth is mostly covered by ocean, nearly all of the long-term (> year) geophysical time series have been collected on land. The near-total absence of long-term geophysical data from the seafloor starkly contrasts with the century-long record of land-based seismic and geomagnetic observations. Deployment of instrumentation in the ocean and on and below the seafloor has been limited by the availability of ships, battery capacity, corrosion problems, and data storage

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technology. The re-use of retired undersea telephone cables offers the scientific community the opportunity to install equipment for long-term studies by bringing electrical power to the seafloor and by providing a means for two-way communication in real time. The scientific driver for H2O was primarily seismology, but there are new opportunities for geomagnetism, tsunami studies, biology, and physical oceanography among other fields.

Seismology's need for good global coverage has been the impetus for the IRIS Global Seismographic Network. Many GSN stations are sited on islands. However, islands are not in general representative samples of the oceans and vast areas of the oceans are without islands. The Hawaii-2 Observatory fills one of these important gaps in the northeast Pacific and will provide important control in studies of earthquake sources in Hawaii, the western United States, and Alaska. Furthermore, since the data are recorded in real-time on Oahu via the Hawaii-2 cable and made immediately available to the seismological community via the IRIS Data Management System, data from H2O can be incorporated into epicenter and focal mechanism determinations made within tens-of-minutes following an earthquake. Figure 2 shows H2O seismic data from a California earthquake. Tsunamis generated by large earthquakes with epicenters from the Gulf of Alaska to Central America will be recorded at H2O 30 minutes to 2 hours prior to their arrival in the Hawaiian Islands. The H2O data may eventually be incorporated with operational data for the tsunami warning networks.

The structure of the Earth's mantle can be strongly constrained by studies of seismic waveforms. Seismic rays turning and reflecting in the upper mantle illuminate and constrain the mantle structure. Located between the seismicity in California and Hawaii, the H2O site will yield the first direct evidence of the nature and variability

of the 400 km discontinuity beneath the northeastern Pacific. Furthermore, the extensive seismicity in the western United States will provide coverage of deeper structure in the upper mantle as well. The data from H2O will enhance existing data sets of multiply reflected body waves such as  $ScS_n$ ,  $SS$ ,  $SSS$ ,  $PcP$ , etc., which sample the Earth between earthquake source and receiver, by broadening GSN coverage with unique, new paths and reflection bounce points. Finally, the observation of shear-wave splitting at H2O will be diagnostic of anisotropy in the mantle beneath the site.

Seismic data from H2O will enhance our understanding of elastic and anelastic structure and anisotropy in the lithosphere and asthenosphere of the northeast Pacific. High-frequency Pn and Sn waves, which propagate in the older, western Pacific lithosphere but heretofore have not been observed in the younger, northeast Pacific, may be observable at H2O from Hawaii and California earthquakes. Analyses of long-period (>15 sec) surface wave recorded at H2O will yield true, pure-path oceanic data for studies and will afford a perspective of the wave propagation without the complications of ocean–continent boundary effects or island effects that have implicitly been part of all previous studies. In global surface wave tomographic studies, the H2O site will substantially enhance the coverage of the eastern Pacific.

For geomagnetism and other marine sciences, the H2O site offers a new platform for making long-term, scientific measurements in a deep-ocean setting without constraints imposed by low-power, internally-recording, temporary deployments. The H2O site offers the same advantage to geomagnetism as for seismology—improved global geographic distribution of geomagnetic observatories.

In 1987, Shozaburo Nagumo of the University of Tokyo approached the Incorporated Research Institutions for Seismology (IRIS) to collaborate on re-using the Trans-Pacific Cable-1 (TPC-1) that was soon to be retired from telephone service as newer fiber-optic cables came online [Nagumo *et al*, 1981]. Recognizing the opportunity for permanent stations on the seafloor, in 1991 a section of TPC-1 from Guam to Japan was transferred from AT&T and Japan's KDD to IRIS and the University of Tokyo. With National Science Foundation (NSF) funding to IRIS for the work at the cable terminus on Guam in 1992, the Japanese spliced a short-period seismic package into TPC-1 300 km south of Tokyo in 1996 [U.S Cable Steering Committee, 1992; Kasahara *et al*, 1998].

With the success and experience in re-using TPC-1, U.S. efforts focused on the Hawaii-2 cable (Figure 1) as the best, deep-ocean location to improve global coverage and provide for regional studies near the United States. Three enhancements were sought and achieved in re-using Hawaii-2 relative to TPC-1: • a conventional, large oceanographic vessel was used instead of a specialized, commercial cable ship, • a junction box connected to the cable with underwater wet-mateable connectors gave the capability to add and change scientific instruments, and • a broadband seismometer was buried beneath the seafloor to meet GSN standards. With the donation of the Hawaii-2 Cable, IRIS obtained NSF funding for the H2O project in 1995. The Hawaii-2 Observatory was installed in September 1998, and revisited for maintenance and repair in September 1999, by the R/V Thomas G. Thompson and remotely operated vehicle (ROV) Jason.

The Hawaii-2 submarine telephone cable system (HAW-2) uses vacuum tube SD cable technology developed by AT&T around 1960. This is a second-generation

seafloor telecommunications system also used in TPC-1 and numerous other civilian and military cables around the world. The deep-water SD cable is an armorless coaxial cable, about 3-cm diameter, with an internal strength member. Power is supplied (about 3300 volts with a constant system current of 370 mA) to the cable center conductor from the Makaha cable station. Repeaters are spaced at 20 nm intervals along HAW-2. The technical standards applied to SD repeater construction were very stringent, and in more than 30 years of service on numerous SD cable systems, no repeater has ever failed. Although the SD repeaters were designed for a 25 year service life, there is little question but that these repeaters, and hence the HAW-2 cable, will be usable for at least twice that interval. For example, an AT&T SD repeater retrieved from the seafloor after more than 25 years of service and sent to Bell Labs for check out passed all of the tests required for its initial delivery.

From the outset, it was deemed necessary to design a seafloor installation that minimizes the cost of instrument connection and which provides a simple mechanical and electronic interface for many scientific users. The approach uses a seafloor junction box (Figure 3) into which scientific users can simply plug their instruments using standard deep submergence assets, and which provides a standard digital communications interface as well as DC power.

The HAW-2 cable itself is terminated at a small frame with a wet-mateable connector to which the main junction box is linked by a short (~30 m) tether cable. All links between the components use wet-mateable underwater connectors. This allowed the HAW-2 cable and j-box to be lowered separately to the seafloor during installation, and permits the j-box to be retrieved, repaired, and re-deployed without recovering the cable.

The junction box houses the power system, communications and control interface, and connectors. All wet components of the H<sub>2</sub>O system use titanium alloys and plastic, thus avoiding corrosion problems. The j-box has eight ROV-compatible, wet-mateable connectors situated well clear of the seafloor for easy access by a generic ROV. Each connector provides an RS-422 communications interface and 48-volt power for external instruments. The system is terminated by a sea ground deployed far enough from the j-box to eliminate corrosion concerns.

The electronics system for the H<sub>2</sub>O junction box was designed to meet a number of criteria: • make efficient use of the available bandwidth on HAW-2, • accommodate both low and high data rate users, • provide a digital interface between plug-in instruments and the j-box, • protect HAW-2 and the j-box from interference or damage by users, • provide accurate time and a down-link capability to control j-box and user instrument functions, • use commercial hardware whenever possible to minimize engineering costs, • use high-reliability design principles with fail-safes and fallbacks in case of partial failures. About 400 watts are available to power both the j-box electronics and user instruments. The power converter accommodates changes in load by extracting a fixed amount of power from the constant-current SD system for the j-box or instruments, dissipating the remainder as heat. The communications system consists of an FDM interface and a set of five PC104 computers, each connected to four high-speed telephone modems. Each of the computer/modem stacks provides a full-duplex serial connection of up to 115 KBPS, which can be routed to any of the connectors. The data arriving from instruments are packetized, time stamped, and distributed among four modems. Time is synchronized to a GPS time standard at the shore station. Seven individual modems are also available to users with more modest

data rate requirements. The digital communications system requires about 270 of the available 400 kHz, leaving the remaining spectrum for future expansion of the junction box.

Scientific instruments are currently using two of the eight ports on the H2O system. A multi-sensor seismo-acoustic (ULF) package designed and built at the University of Hawaii occupies the first port. A set of 4 Benthos hydrophones in series occupies the second port. Both systems are housed in titanium. The Ocean Drilling Program has scheduled the drill ship to visit the H2O site in late 2001 to drill a borehole into basement at the site, for the emplacement of a broadband borehole seismometer.

The ULF sensor system consists of two sections (Figure 4). Connected by cable to the j-box, the Acoustic Sensor Package (ASP) sits on the seafloor, housing most of the digital electronics, power conditioning, pressure sensors (a broadband Cox-Webb differential pressure gauge and crystal hydrophone), a thermal sensor, and 2-component current meter. The Ground Motion Sensor Package (GMSP) is deployed 6 meters from the ASP and contains the seismic sensors plus a compass, thermal sensors, and a sensor stage that can be leveled by command from shore. The sensor stage contains tilt meters, a set of Guralp CMG-3ESP broadband seismometers, and three orthogonal 4.5 Hz geophones. Sensor calibration and coupling tests may be performed on command. By burying the GMSP in the sediment 0.5 m beneath the seafloor and isolated from bottom currents, good seismic noise conditions and coupling to the ocean floor are achieved.

The ULF System digitizes seismic and acoustic channels at up to 240 samples/sec with 16-bit resolution, and 32 samples/sec on the environmental and calibration

channels. The Guralp seismometers, which are the primary GSN sensors at H2O, the geophones and the differential pressure gauge are sampled at both high and low gains, effectively increasing the dynamic range to 24 bits. The Benthos hydrophone system is sampled at 2,000 samples/sec with 16-bit resolution. All sensors are under remote-operator control from the surface—e.g., sample rates and other parameters may be changed, and software may be remotely downloaded.

All data from H2O flows up the cable to the Makaha Cable Station (space leased by IRIS from AT&T) and is transmitted to a data collection center at the University of Hawaii. H2O j-box and sensor system functions and state of health can be controlled and monitored directly via the Frame link to UH and the Internet. Data flows via the Internet to the IRIS Data Management Center in Seattle and directly to users.

Installation and maintenance of H2O makes use of conventional oceanographic assets. Starting from an initial bathymetric survey and a cable track based on 1960's navigational accuracy, the HAW-2 cable was located using the ROV Jason. From the selected observatory location, Jason then traversed 5,000 m along the cable toward California, and cut it. Returning to location, the cable was recovered with a grapnel attached to R/V Thompson's trawl wire. HAW-2 was then pulled up to the ship, with 5,000 m of cable draped over each edge of the grapnel hook. After testing, the cut section was dropped, and the continuous section to Makaha was spliced to the cable termination frame. With power and telemetry from Makaha, the H2O j-box electronics were equalized to SD repeater specifications, and then end-to-end tested with the ULF sensor package—all coordinated with a shore team at Makaha.



While beginning to lower the termination frame attached to HAW-2 from the ship, a chain broke and the entire unit fell to the bottom. Fortune smiled, for it landed upright and undamaged, about 2 km from the intended site. The j-box was lowered on the trawl wire to the site using the ship's dynamic positioning system and acoustic transponder navigation. ROV Jason plugged the system together. The j-box failed initially after 12 hours, and was unplugged and retrieved by the Jason ROV system. Repaired on site, the j-box was returned and reconnected two days later. The ULF system was then lowered using a buoyancy package, maneuvered to H2O by Jason and plugged in. After Jason buried the seismic sensor in the seafloor, GSN and other data began to flow to Makaha.

After two months operation, a failure in a water current meter corrupted the seismic data, necessitating a maintenance visit. During this cruise the Jason ROV system unplugged and retrieved the ULF system for repair and the j-box for upgrade. The systems were then re-deployed and plugged in, as before. An additional hydrophone was also deployed. Using passive positioning at the end of the ship's trawl wire, the j-box can be relocated within a few meters of its previous position.

The H2O project was created and coordinated within the IRIS Consortium with funding from the U.S. National Science foundation. The junction box communications system was developed and built by Woods Hole Oceanographic Institution (WHOI). The seismo-acoustic sensor package and j-box power supply were developed and built by the University of Hawaii (UH). The re-engineering of the cable station power system and cable splicing were accomplished by Margus, Inc. WHOI and Margus performed the cable recovery, and WHOI accomplished the re-deployment. Ocean operations were carried out by WHOI and UH using the

University of Washington R/V Thomas G. Thompson and the WHOI Deep Submergence Laboratory Operations Group ROV Jason.

The technology employed for re-using the Hawaii-2 cable can be adapted for other retired cables, including both telephone cables and Navy SOSUS arrays. There are a number of opportunities in the Northern Hemisphere, but not in the southern oceans where islands are few and seismological coverage by the GSN is sparse. There is currently an active effort by our Japanese colleagues in re-using the TPC-2 cable from Guam to Okinawa. However, to achieve truly global coverage with undersea observatories, a combination of cabled, autonomous, tethered-buoy observatories will be required.

IRIS, the U.S. Cable Steering Committee, and the National Science Foundation welcome interest in deploying new scientific sensors at the Hawaii-2 Observatory. Interested parties may contact the authors. Further information may be obtained from the H2O web site at [www.iris.washington.edu/GSN/](http://www.iris.washington.edu/GSN/).

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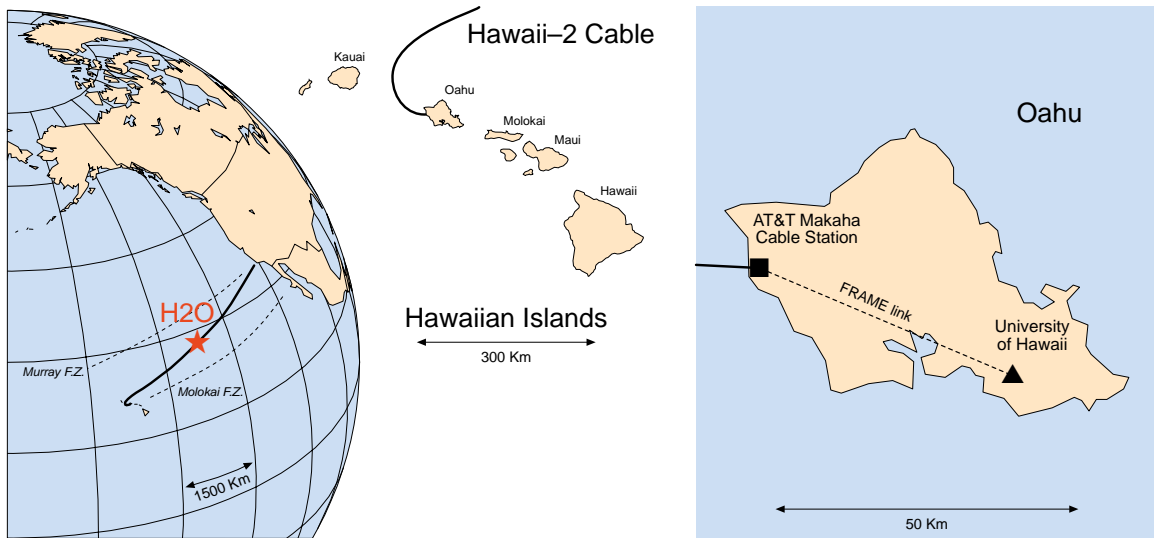


Figure 1. (Left) The Hawaii-2 Observatory at  $27^{\circ} 52.916' N$ ,  $141^{\circ} 59.504' W$  is sited 1750 km east-northeast of Honolulu. The site lies between the Murray and Molokai Fracture Zones at 4979m depth on about 100 m of predominantly terrigenous, pelagic clay. The oceanic crust is of Eocene age (45–50 m.y.) and is normal but fast spreading with a spreading half rate of 7 cm/y. (Center) The path of the Hawaii-2 Cable runs between Oahu and Kauai, then heads northeast toward California. (Right) The AT&T Makaha Cable Station on western Oahu is connected via a leased 256 KBPS Frame Relay circuit to the University of Hawaii for data transmission to a data collection center and the Internet.

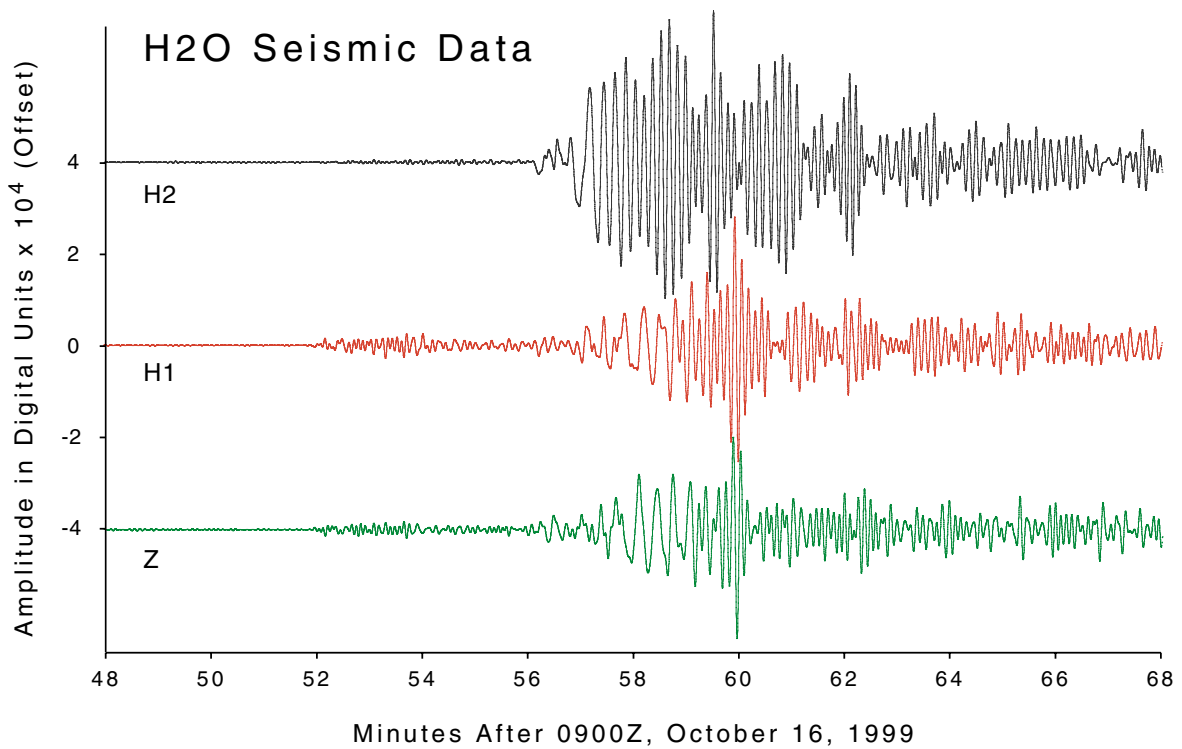


Figure 2. The magnitude 7.0 Hector Mine earthquake on October 16, 1999 in southern California recorded at the H2O site at 2550 km distance. Two orthogonal horizontal and the vertical (Z) components are shown, low-pass filtered at 0.2 Hz. Fortuitously, the H1 component is aligned nearly radially along the great circle from the earthquake, showing the compressional body waves and Raleigh wave similar to the vertical. The transverse H2 component shows shear waves and the Love wave.

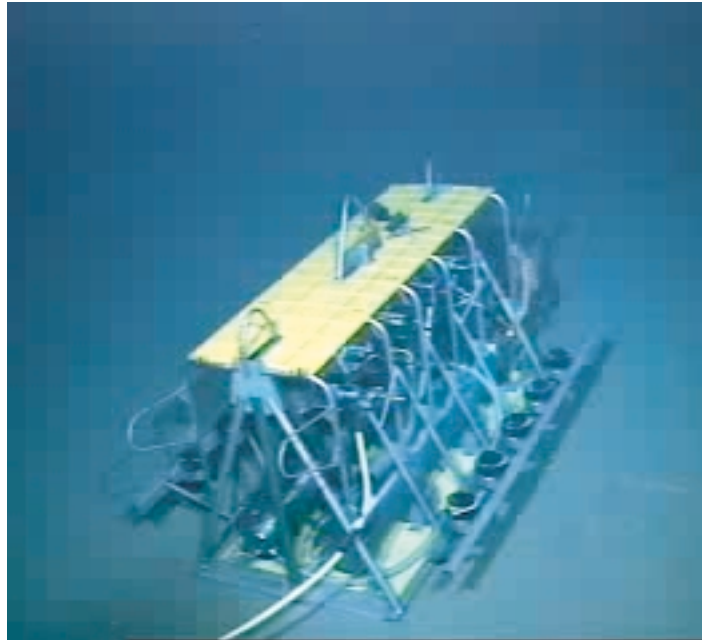


Figure 3. View of the H2O junction box from ROV Jason during installation on the seafloor. The yellow cable tether connects the junction box to the HAW-2 cable.

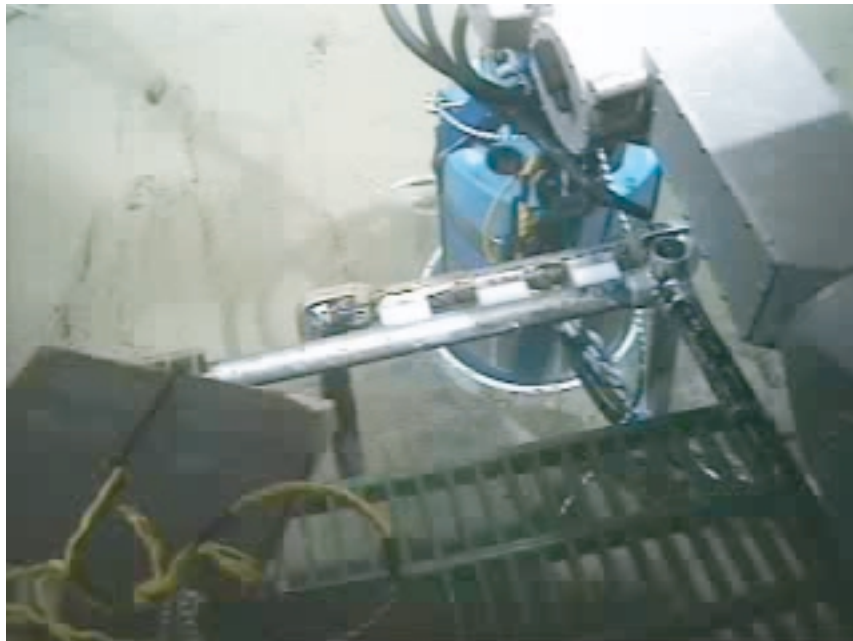


Figure 4. View of the GSN seismometer from ROV Jason. Using its manipulator arm, the sensor package is being lowered into a caisson set in the seafloor. Cabling runs to a nearby acoustic sensor package that is connected to the H2O junction box.