Electrical Impedance Tomography of the Loihi Underwater Volcano

R/V Roger Revelle, July 1-5, 2006

Cruise Report

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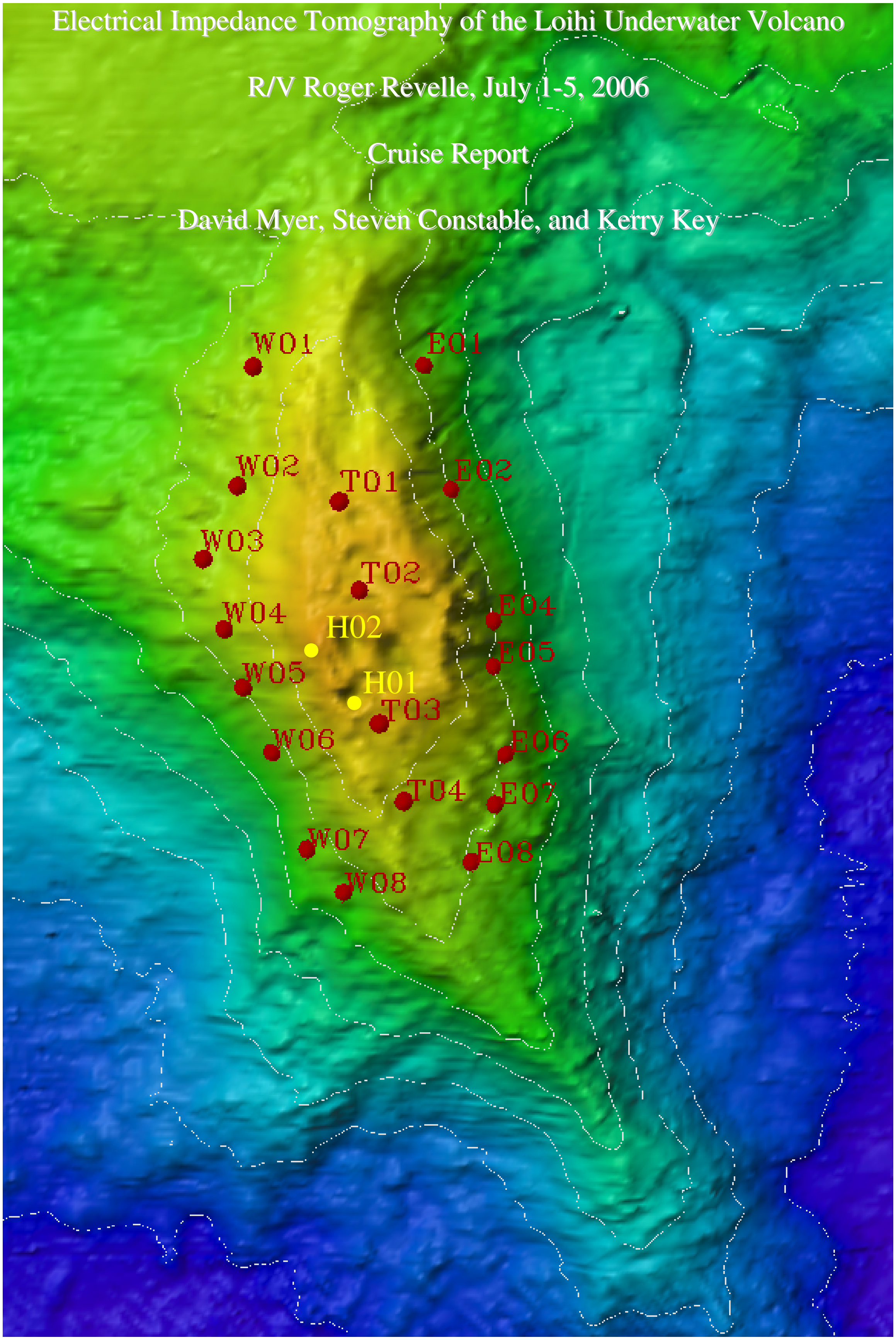


Objectives & Summary

The purpose of this experiment is to map the internal structure of an active underwater volcano; the Lo'ihi seamount. The Lo'ihi seamount is the newest Hawaiian island, rising on the lower flank of Mauna Loa about 40 km southeast of the big island of Hawaii. Though it is presently 1000m below the sea surface, it stands roughly 3500m tall and is comparable in size to the Mount St Helens volcano in Washington State. "Lo'ihi" is a Hawaiian name meaning "long", which reflects its abnormally elongated shape: 30km x 15km.

Lo'ihi is an interesting target of study for several reasons. First, it is the newest island in the 6000km long Hawaiian-Emperor Island chain and is speculated to be in transition from pre-shield alkalic lavas to shield-building tholeiitic lavas. The shield building stage produces 95% of the bulk an intraplate volcano and should be heralded by recharge of the magma plumbing system and, potentially, shallowing of the deep magma chamber. Second, after a dramatic peak collapse in 1996 accompanying a seismic swarm of ~1000 events during which the upper magma chamber is thought to have drained, Lo'ihi lay dormant until a new, smaller swarm (~100 events) at the end of 2005 indicated that magma recharge has possibly begun. Third, the abnormal shape makes Lo'ihi an interesting target of study because it is neither conical nor star-shaped like most volcanic seamounts. The structural reasons for this elongation are unknown.

Traditionally, seismic waves passing through a body are used to create a 3D model based on wave refraction and the difference in travel time velocity through various materials. However, seismic studies of Lo'ihi are complicated by a lack of seismometers in the area and the proximity of the actively erupting Kilauea volcano whose island building activities create a noisy seismic environment.

In this study we are taking an entirely new approach and using electromagnetic fields rather than seismic waves to build a tomographic image of the internal structure of Lo'ihi. For this experiment, we are using the controlled-source electromagnetic (CSEM) exploration method and had hoped to augment it with any serendipitously collected magnetotelluric (MT) data. The MT data was unattainable, however, due to the weakness of the MT signal source (i.e. variations in the Earth's magnetic field).

The CSEM method involves deep-towing an electromagnetic source above or around a target geologic structure and recording the resulting fields at a number of fixed receiver locations. As the electromagnetic fields travel through the ground, they are attenuated more by conductive features than resistive features. Measurements of field strength and phase are then used to determine the resistivity structure of the material through which the fields passed. This method is ideal for use on a submarine volcano because of the conductive nature of interconnected melt in magma chambers.

Field attenuation is frequency dependent, so CSEM studies usually try to tune the broadcast frequency of the transmitter to suit the target geology. In the case of Lo'ihi, we decided to fill the spectrum with many frequencies to increase the resolution of our tomography. Consequently we modified our transmitter to rotate through a set of three frequencies on a five minute schedule. The three frequencies plus the odd harmonic frequencies generated by broadcasting a square wave yielded 21 measured frequencies. This is an unprecedented filling of the spectrum in CSEM research. When combined with approximately 30km of tow and 18 sites of data, we expect to be able to derive a well-constrained tomographic model of the seamount. This work will be David Myer's PhD dissertation.

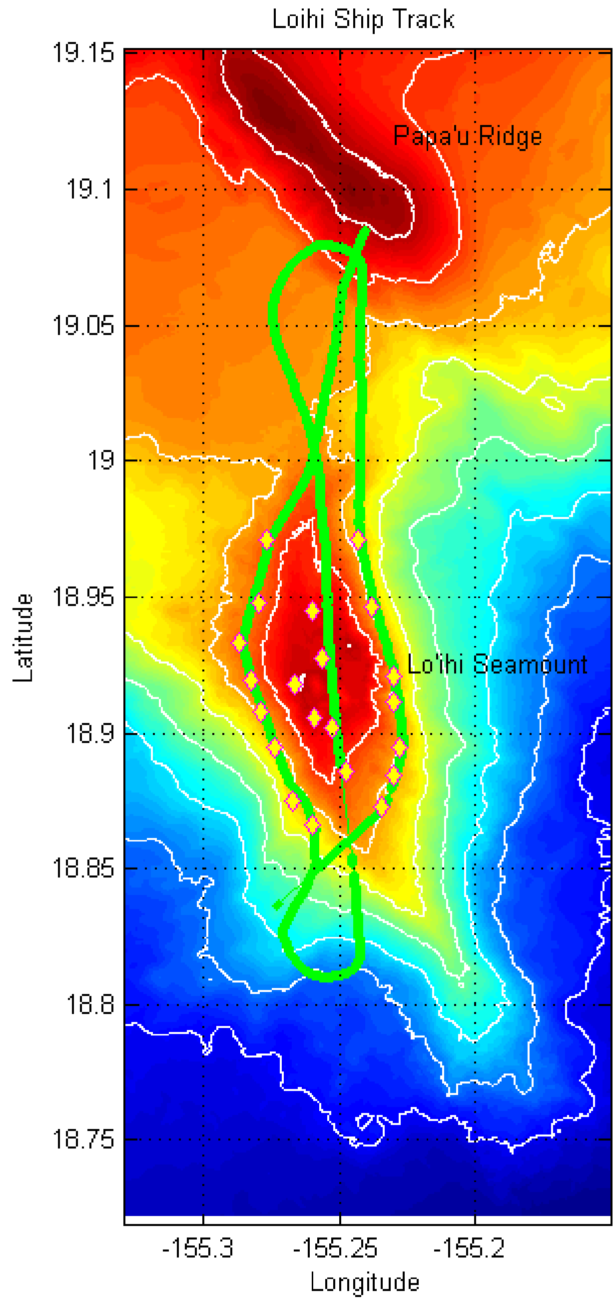
Mobilization & Logistics

This cruise was opportunistic, taking advantage of a brief time window in the R/V Revelle's Amat expedition schedule between an experiment off the coast of Hawaii and transit back to home port in San Diego. The Marine Sciences Subcommittee on Research carved out time for us to undertake the experiment as a student cruise. Consequently, S. Constable recruited volcanologist H. Staudigel to join the cruise and the two established a graduate level class at IGPP/SIO. Twelve graduate students from a variety of fields joined the cruise to learn about EM methods, ship operations, and volcanology. Five of the students had never been on a cruise before.

Approximately twelve tons of equipment was shipped to Honolulu and loaded onto the ship. Due to time constraints, equipment was left onboard for the return to home port and offloaded in San Diego. Because of poor placement of a cruise liner in the Hilo port, there was no room for the R/V Revelle to tie up to dock at the end of the cruise. Instead, science personnel were ferried to shore in one of the Revelle's deck boats. Below is a brief summary of events:

Local HI time	Activity	Elapsed time
08:00 June 29	Revelle arrives in Honolulu	-
08:00 June 30	Load and secure equipment	32 hours
16:00 July 1	Depart Honolulu	1 hour
17:00 July 1	200 mile transit to station at 8 kts; Seabeam turned on and set at 65°.	21 hours
14:00 July 2	Deploy 20 EM instruments & 2 temperature + water sample instruments.	16 hours
06:00 July 3	Transit to south to begin tow, navigating instruments on the way. Site E3 not at bottom. Search finds it at surface 0.5km from drop point. Instrument recovered & transit resumed.	4 hours
10:00 July 3	Deploy transmitter & perform in-water tests of system.	3 hours
13:00 July 3	East transmitter tow at 2kt; SUESI at 305 Amps; encountered seamount at ~15:15	7 hours
20:00 July 3	Tow over top of seamount at 4kt.	3 hours
23:00 July 3	West tow at 2kt	6 hours
05:00 July 4	Recover & secure transmitter	4 hours
09:00 July 4	Navigate & recover 22 instruments	18 hours
03:00 July 5	Transit ~60 mi to Hilo; anchor off-shore & transfer science personnel to shore.	-
July 6-7	Chief scientists hold field volcanology class in Hawai'i Volcanoes National Park, including an excursion to an active lava flow.	-

Twenty-two instruments were deployed on this cruise. Two of the instruments (H1 and H2; see title-page map) were temperature & water sample instruments deployed in Pele's Pit and just west of Pisces Peak on the top of the seamount. These instruments were left in situ at the end of the cruise and retrieved in Oct 2006. They are part of an ongoing experiment being carried out on seamounts by H. Staudigel.



The twenty remaining instruments were Mark II Scripps EM broadband receivers deployed around and on top of the seamount. Site E3 "bounced" off the seafloor and was successfully located at the sea surface nearly ½ km from its drop location. Site T3 stopped recording data after 24 hours. All other receivers functioned properly. All sites were successfully recovered.

Operations were carried on 24 hours a day through two 12 hour shifts. There were fifteen students and postdocs on board, 5 of whom had never been to sea before. All were trained in deck operations and rotated in and out of various jobs on instrument deployment. Recovery is slightly less controlled than deployment because of the difficulty associated with bringing the 10m arms of the instruments back onboard while the instrument is suspended from a crane over the side of the moving ship. So for safety reasons, student rotations were stopped and people were assigned specific tasks to assume for the duration of their shifts.

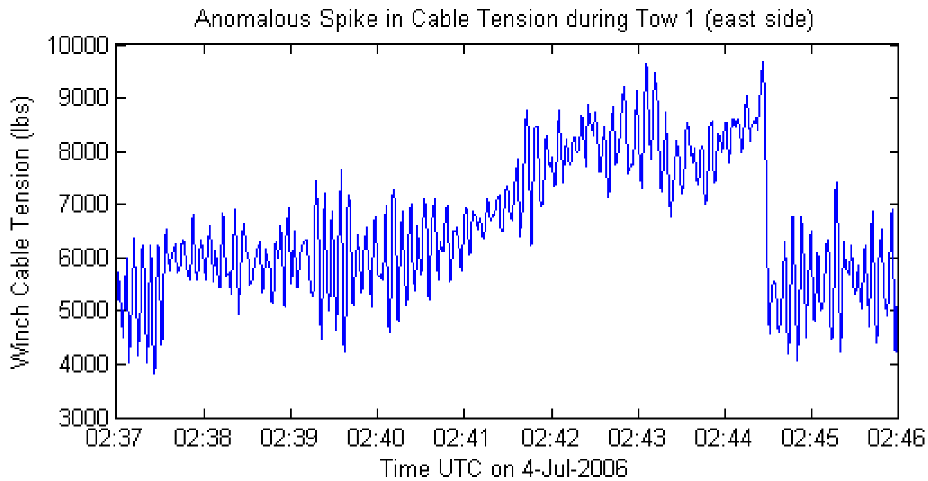
SUESI-500 performed nearly flawlessly during the towing phase of the expedition. Operator error temporarily locked up the command interface, requiring a hard-reset to fix at the end of tow 2. The transmitter continued functioning properly throughout the incident.

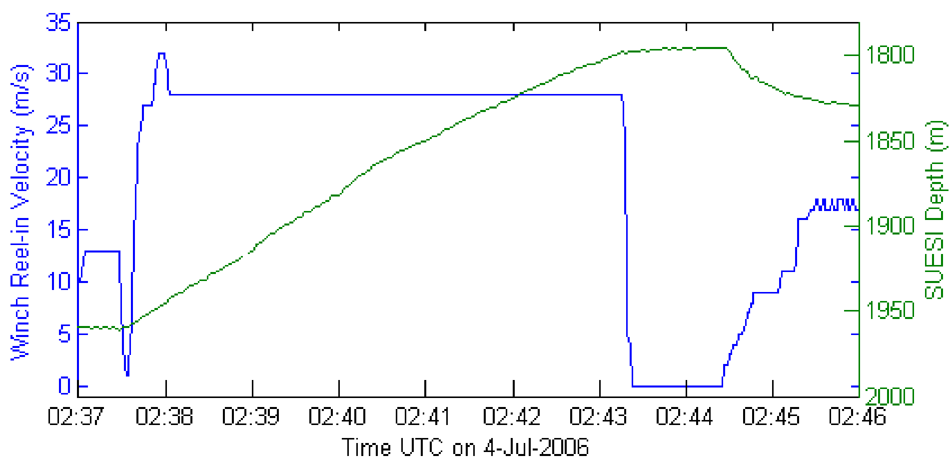
SUESI's downward-looking sonar would not function when the transmitter output was set to 10Hz. This was normally not a problem because our frequency rotation pattern (0.1Hz for two minutes, 1Hz for two minutes, and 10Hz for one minute) allowed the sonar to work for every 4 minutes out of 5. However, the highly variable topography on the east flank of Lo'ihi caused the transmitter antenna to touch the bottom during tow #1 immediately after one of these one minute blackouts because there was insufficient time to winch SUESI to a safe height. The body of the transmitter itself only approached to within 5.7m.

SUESI made three passes by the seamount. Tow #1 began in the southwest, crossed the southern rift zone and passed up the steep east side of the volcano. The transmitter was reset just after the crossing the southern rift zone to deal with a time drift (tag slipped to 0.119 from 0.95405; new tag after reset: 0.1815 – which moved to 0.509 almost 2 hours later). After a wide sweeping turn in the north, tow #2 ran southward across the top of the seamount. The transmitter was reset at the end of to #2 to correct the interface lockup (new time tag: 0.07158). Another wide sweeping turn in the south brought SUESI around for her final tow up and around the west side. Tows #1 & 3 were executed at 2 knots. Constant winch operations attempted to keep SUESI at ~200m above the seafloor (the limit of SUESI's bottom-sensing sonar). However the extreme topography made this difficult, so in practice SUESI was kept between 100 & 200m. Tow #2 was not originally planned. During the cruise, we noted the strong south-westerly currents and judged that trying to tow southward along the western side of the seamount would be too difficult – SUESI would most likely be pushed westward too far away from the seamount. So we improvised a high-speed tow across the top of the seamount to line up for the western tow. Consequently, we ran tow #2 at 4 knots. At this speed, we judged that SUESI would kite upwards so much that the decreased wire angle would make it difficult to control SUESI's altitude above the seafloor. So we ran at a constant depth of ~900m to avoid all bathymetry – the seamount's summit platform is at 1100-1200m depth.

A mystery occurred with the winch at the end of tow 1. On 4-Jul-2006 at ~02:37:30 UTC the winch cable average tension jumped from 5200 lbs to 6000 lbs. Simultaneously, the winch reel-in velocity dropped briefly almost to zero (see the figure on next page). We were, at the time, shallowing SUESI in preparation for making a 180° turn and had been reeling in steadily for two minutes. The ship was located at 19.00N, 155.24W, heading almost due north, SUESI was at a depth of 1959m, and we had 3938m of cable out. This places SUESI about 3400m behind the ship, at 18.97N, 155.24W. SUESI was approximately 280m above the seafloor and continued to rise ~150m during the incident, so we are certain that we did not bottom the instrument. The initial jump in cable tension may be due to the sudden change in winch velocity. It is possible that the actual anomaly of interest is around 2:40:30 when the tension began to climb rapidly to a mean of about 8000 lbs. (Note: at 2 knots, this is ~360m north of the locations sited above.) Six times during the next 3.5 minutes the tension peaked above 9000 lbs. Two of these peaks approached the cable tension limit of 10,000 lbs. Between these two peaks, cable reel-in was halted. Tension was observed to step down then rise continuously, so it is unlikely that the winch was causing the tension increase. After the final high peak (9666 lbs), the cable tension suddenly dropped back down to the 5500 lbs range, and reel-in operation continued normally.

We speculate that SUESI had snagged the abandoned HUGO observatory fiber optic cable either at 2:37:30 or three minutes later. Although a rough map of the cable location (see http://www.soest.hawaii.edu/HUGO/about_hugo.html) shows it to be about 5 km from our tow track, we cannot be certain of the exact location of the cable. Private communication with Dave Clague in 2006 indicate that the original cable was poorly laid. Direct observation from the Pisces submersible finds it laying in coils in some locations and suspended tens of m above the seafloor in others. It seems incredible (unlikely?) that the cable was suspended 280m above the seafloor (where SUESI was positioned at the time) unless a large (several km) loop of it hung eastward off the northern rift and SUESI had navigated under it.





Interestingly, if SUESI had snagged a cable, we would be expect SUESI to be pulled towards the bottom as tension rose. Yet the figure shows that SUESI continued to rise whenever the winch was reeling in. This does not seem indicative of hooking a cable. It should be noted, however, that the cable strain relief at the connection point between SUESI and the 0.680 wire was observed to be destroyed when SUESI was hauled in at the end of the cruise. This would indicate that something was trapped between the tow cable and the steel stop on SUESI's frame. Note also that the HUGO cable is an unarmored fiber-optic cable with an unshielded coaxial core and it is not unreasonable that 3000 lbs of force would separate it.

Inspection of the wire-out log from when SUESI was strapped to deck and the cable pulled tight show no difference between the beginning and end of towing, so the winch cable was apparently unstretched by the episode.

Instrumentation

Receivers

Twenty Mark II Scripps EM broadband receivers (aka "loggers") were deployed for this experiment. Each instrument was configured with a pair of horizontal, orthogonal magnetic field sensors and a pair of horizontal, orthogonal 10m electric dipoles. The instruments were configured to record at a sampling rate of 62.5Hz with low gain on all channels. More detailed specifications for this receiver can be found at the lab website: http://marineemlab.ucsd.edu/instruments/receiver.html.

Four new options were tested on this cruise: external compass, external temperature sensor, GPS-equipped strayline ball, and tripod anchor feet.

The logger has an internal compass which is, unfortunately, affected by the surrounding electronics and batteries. An external compass is being developed that will be mounted to the outside of the equipment frame. Six external compasses were tested on sites E1, E3, E4, E5, T1, and T3. Only the compasses on E1, E5, and T3 collected usable data due to battery problems. The orientations recorded by these compasses are being checked.

The external temperature sensors were attached to E2, E5, T2, and W6. These sensors performed properly. Data is being analyzed to search for temperature fluctuations associated with tidal signature around the seamount. Deep water tides are greatly exaggerated versions of surface tides – the relatively small differences in temperature & density at depth mean that small buoyancy changes have a greater affect on tide amplitude than at the surface where temperature & density vary greatly.

GPS-equipped strayline balls were tested on four instruments: W1, W4, W7, and E2. The original strayline ball is only equipped with a radio pulse beacon and a strobe light. This means that to find the instrument you have to listen for the radio beacon then scan the sea with binoculars – the radio beacon carries no information. The new GPS-equipped balls carry a GPS receiver and broadcast their location via radio. A receiver on the ship picks up the signal and displays the location, making recovery much faster. Additionally, the strobe has been replaced by a tower of super-bright white LEDs to reduce power consumption. The GPS balls performed well, though not flawlessly. There are a few issues to resolve with signal directionality. The super-bright LEDs were observed to be brighter than the old strobe.

The anchor feet were designed to keep an instrument from sliding on a high angle slope and to reduce rocking in the event an instrument might land on rocks. Since Lo'ihi has both rocky and high angle slopes in the landing sites, we decided that this would be a good test of the feet. No difference in the instrument signal was observed between instruments with and without feet. The feet appeared to work fine, but were not needed.

Scripps Undersea Electromagnetic Source Instrument (SUESI-500)

This was the second deployment of the new SUESI-500 EM deep-tow transmitter. This is the third and most powerful transmitter created by the lab. SUESI-500 can support square wave zero to peak current of 500 amps, compared with the previous transmitter whose current is 200 amps. SUESI-500 uses standard 0.680" UNOLS copper coaxial cable for power and telemetry.

The tow frame has space for a variety of additional devices and for this cruise was outfitted with downward-looking sonar for seabed ranging, front-looking sonar for ranging to the receivers, and a Valeport SVXtra. The Valeport reports depth, local sound speed, and conductivity. All the external devices report to the transmitter which buffers the data and forwards it to the ship every three seconds through serial communications on the 0.680" cable.

Appendix

Cruise Personnel

Steve Constable	SIO	Chief Scientist
Hubert Staudigel	SIO	Chief Scientist
Kerry Key	SIO	Postdoc
James Behrens	SIO	Postdoc
Yuguo Li	SIO	Postdoc
John Souders	SIO	Engineer
Allen Nance		Engineer
Chris Armerding	SIO	Technician
Patricia Cheng	SIO	Technician
Garth Engelhorn	SIO	Technician
Cambria Colt	SIO	R/V Revelle Restech
Eddy Kisfaludy	SIO	R/V Revelle Restech
David Myer	SIO	Student, SIO
Karen Weitemeyer	SIO	Student, SIO
Ashley Medin	SIO	Student, SIO
Joseph Ribaudo	SIO	Student, SIO
Deborah Kane	SIO	Student, SIO
Dan Cartamil	SIO	Student, SIO
Fernando Gonzalez	SIO	Student, SIO
Achintya Madduri	SIO	Student, SIO
Lora Van Uffelen	SIO	Student, SIO
Sylvain Barbot	SIO	Student, SIO
Chris Takeuchi	SIO	Student, SIO
Trevor Wilkey	UH	Student, UH
Arnold Orange		Observer
Margit Orange		Observer
Charlie Nance		Observer

Pre-cruise Support

Jacques Lemire	SIO	Lab Manager

Site Locations

Site	Name	Amp Boards	Nav Latitude	Nav Longitude	Nav Depth	Temp Sensor	GPS Ball	Tripod Feet
E01	Quokka	BF/BE	18.97129	-155.24326	-2146			X
E02	Tazz	BF/BE	18.94666	-155.23826	-2037	3327	X	
E03	Quindal	BF/BE	--	Bounced	--			X
E04	Cass	BF/BE	18.92058	-155.23006	-2006			
E05	Bullant	BF/BE	18.91148	-155.23025	-2061	4001		X
E06	Devil	BE/BE	18.89430	-155.22783	-2005			
E07	Possum	BF/BE	18.88424	-155.22998	-2030			
E08	Glider	BE/BE	18.87292	-155.23477	-2041			
T01	Emu	BF/BE	18.94465	-155.25994	-1176			X
T02	Fruitbat	BF/BE	18.92754	-155.25626	-1180	3292		
T03	Dingo	BF/BE	18.90170	-155.25258	-1223			
T04	Bogong	BE/BE	18.88595	-155.24796	-1559			
W01	Wobby	BF/BE	18.97115	-155.27669	-1725		X	
W02	Echidna	BE/BE	18.94775	-155.27998	-1763			X
W03	Joey	BE/BE	18.93347	-155.28691	-1767			
W04	Lerp	BE/BE	18.91972	-155.28274	-1756		X	X
W05	Dugite	BE/BE	18.90797	-155.27931	-1944			
W06	Magpie	BF/BE	18.89474	-155.27381	-2171	3049		X
W07	Galah	BF/BE	18.87525	-155.26711	-2199		X	
W08	Spit	BF/BE	18.86651	-155.26001	-2297			X
H01	--	--	18.90585	-155.25917	-1269			
H02	--	--	18.91769	-155.26628	-1057			

Note: at Lo'ihi's location (UTM area 5), the fifth decimal place in lat & lon is equivalent to one meter: (specifically 1m : 0.000009145 deg latitude & 0.00000937 deg longitude).

Acknowledgements

We gratefully acknowledge the Marine Sciences Subcommittee on Research for creating the window of opportunity and allocating funding for this cruise. The captain & crew of the R/V Revelle created a wonderful work environment for us and we are thankful for their tireless efforts.