A Vertical Hydrophone Array Coupled via Inductive Modem for Detecting Deep-Ocean Seismic and Volcanic Sources

H. Matsumoto[1], D. Bohnenstiehl[2], R. P. Dziak[1], L. Williams[3], R. Gliege[4], C. N. Meinig[5] and P. Harben[6]
[1]Oregon State University, 2115 SE OSU Dr. Newport, OR 97365
[2]North Carolina State University, 2800 Faucette Drive, Rm. 1125 Jordan Hall, Raleigh, NC 27695-8208
[3]Massatusetts Institute of Technology, 70 Amherst St., Cambridge, MA 02142
[4]University of Washington, 3737 Brooklyn Ave. NE Box 355672 Seattle, WA 98105
[5]Pacific Marine Environmental Lab, National Oceanic and Atmospheric Administration, Bldg 3, 7600 Sand Point Way NE, Seattle, WA 98115
[6]Lawrence Livermore National Laboratory, MS L-208,7000 East Ave., P.O. Box L-208,Livermore CA 94551-0808

***Abstract*-A vertical autonomous hydrophone (VAUH) array useful for a long-term low-frequency underwater acoustic propagation study was developed at Oregon State University (OSU), North Carolina State University and the National Oceanic and Atmospheric Administration's (NOAA) Pacific Environmental Lab (PMEL). To analyze the arrival structure of the hydroacoustic signals in deep water, we needed a multichannel vertical hydrophone array with relative timing accuracy of as good as 10 ms/year where no GPS or Network Time Protocol (NTP) is available. A new scheme takes advantage of Inductive Modem Modules (IMM® from Sea-Bird Electronics) and a low-power accurate clock (QT2001® from Q-Tech Corporation). With the master unit sending an accurate 1-PPS pulse train once a day to slave instruments over a single wire inductive modem/mooring cable, it synchronizes the other slaves' clocks and keeps the timing errors among the instruments less than 10msec. As compared to the timing synchronization methods based on three-wire serial or NTP network interface, it only requires an insulated single wire mooring cable using seawater as a return. It is robust, low power and useful for long-term time synchronization of multiple instruments serially connected. As a trial, an array consisting of three vertical autonomous hydrophones (VAUH) was deployed in the Lau Basin from December 2009 to April 2010 at 21° 25'12.60"S, 176° 12'45.50"W. Each unit was fastened on a 1000-m long 5/16" jacketed cable with a 500 m of separation. All three VAUHs recorded continuously the low frequency acoustic signal at 250-Hz sampling rate and maintained a relative timing accuracy of less than 10 ms. The acoustic record shows that the entire region is active with seismicity and submarine eruptions. The results of the four-month long monitoring and comparison with other single hydrophone moorings in the area are discussed[1].**

I. INTRODUCTION

For the last 15 years, the NOAA-OSU acoustics group has successfully operated and maintained autonomous hydrophone (AUH) arrays for monitoring hydroacoustic activity in areas of the world's ocean where no historical data exists [1, 2]. The arrays' low regional detection threshold of m_b 1.5-3.0 is due to the low attenuation properties of ocean-sound propagation [3, 4 and 5]. The AUH is a battery-powered single-element hydrophone with multiple hard-disks data logging system. The sampling rate is programmable from 100 Hz to 5 kHz. With an internal clock error of less than ±1sec/year, the AUH array has been a valuable tool for accurately locating low frequency acoustic events in the deep ocean. The 16-bit data resolution affords a large dynamic range that is useful for estimating earthquake magnitudes and the source level of marine mammal calls [6]. The rugged construction of the system and the -20°C to 50°C temperature tolerance makes the AUH suitable for extreme the oceanographic conditions [7]. Although made robust, it is a single-element omni-directional hydrophone and is not sufficient for the studies investigating modal propagation or utilizing matched field processing techniques, which require a multi-element hydrophone array.

A vertical hydrophone has been commonly used to improve signal to noise ratio for ambient noise monitoring [8, 9], seismic refraction surveys, acoustic tomography, low frequency propagation [10]. One of the issues of the large scale array is the length and costs associated to the multi-conductor cable. A typical vertical hydrophone array consists of six or more hydrophones with spacing of ~λ/2 of the acoustic signals of interest. For low-frequency study (e.g., T-wave spectral content <25 Hz), however, as the wavelength becomes longer, sending analog signals by a multi-conductor cable over a long distance becomes problematic as a result of increased cable weight and capacitance. Such an array has to be carefully tuned among multiple elements to produce an equal amplitude and phase response over the frequency of interest. Because of its size, often a kilometer long, and fragileness of the cable, deployment and recovery procedures are often cumbersome and cables are prone to damage. If the signals are digitized however, synchronizing multiplexed multichannel records also is challenging.

The array described here uses three self-contained battery-operated vertical autonomous hydrophones (VAUHs). Instead of multi-conductors or multiplexing to send the data, each unit digitizes and stores the data independently while intra-instrument timing synchronized to the 1-PPS calibration pulse sent from the master unit over the inductive modem and single-wire modem/mooring cable. A vertical hydrophone array was deployed at SOFAR channel depth in the Eastern

[1] This study was funded by NSF grant #0825295.

978-1-4244-4333-8/10/$25.00 ©2010 IEEE

Lau Spreading Center (ELSC) from the R/V *Roger Revelle* (in red in Fig. 1) in December 2009. VAUH is a part of a much larger array network consisted of 13 other single AUH mooring which included five in the northern Lau (WM_W, WM-N, WM_E and WM_S and M10) near the recently discovered most active submarine volcano, West Mata. It also included central Lau Basin AUH moorings, M1, M2, M3W, M3N, M3E, M3S, M4, M5 and M6.

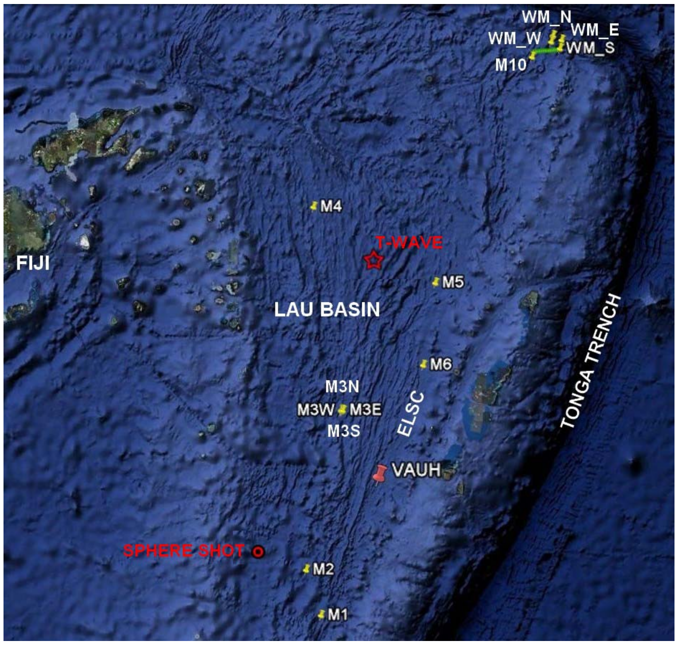

Figure 1. Mooring locations of VAUH (red thumb stack) and 13 regular single AUH moorings in the Lau Basin during the 2009-2010 acoustic monitoring. VAUH mooring was deployed at 21°25'12.60"S-176°12'45.50"W for four months. T-wave and glass sphere implosion shot discussed here are plotted on the same map.

The three-year program is to 1) study the tectonics of the Basin, 2) identify sites of submarine volcanism along the back-arc ridge systems and volcanic arc, and 3) provide constraints on seismic activity that may impact hydrothermal systems along the ELSC. The monitoring phase was completed after 15 months of operation, and all AUH and VAUH moorings were recovered in April 2010 by the R/V *Kilo Moana*.

Sending/receiving over a single-wire inductive modem/ mooring cable has been successfully implemented for off-shore platforms [12, 13, 14] to send CTD and Doppler current sensor data to a surface buoy for a real-time data transmission. This paper describes a new application of the inductive modem technology for a timing synchronization of multiple instruments connected on the inductive modem/mooring line. The T-wave data observed by VAUHs during the acoustic monitoring experiment are discussed and compared with other single element AUH data. We will discuss the acoustic data of glass sphere implosion during the 2010 April cruise as a ground truth.

II. System Descriptions

A. *Vertical hydrophone mooring*

Fig. 2 is a schematic of vertical hydrophone array mooring used during the Lau Basin hydroacoustic experiment in 2009-2010. From top to bottom, the mooring is consisted of two syntactic foam floats which suspend the entire mooring in mid-water depth, three VAUHs were fastened on a single wire modem/mooring cable (5/16" dia. jacketed steel line) at the water depth of 500 m, 1000 m and 1500 m. Two glass floats and an acoustic release were attached near the bottom. Each VAUH independently digitized the acoustic signal using its internal A/D timing signal and recorded the files on to its own hard disk. The master VAUH sent timing pulses to other slave units so that all signals are synchronized by the same timing pulse distributed over the inductive modem cable. .

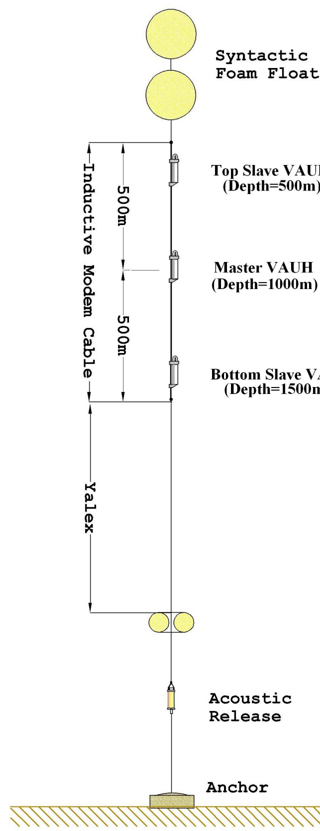

Figure 2. Mooring diagram of the vertical hydrophone array deployed in the Lau Basin.

B. *VAUH System*

As compared to the single hydrophone predecessor developed at PMEL, each VAUH instrument is smaller and lighter (Fig. 3). The 4" ID and 2000-m rated pressure housing is made of titanium alloy and weighs 18.5 kg in the air (versus 55 kg of AUH) and 8 kg in the water. The unit is directly fastened by two plastic clamps to the modem/mooring cable making servicing the unit relatively easy for a quick turn-around. Similar to the predecessor, it is a portable acoustic data logger with the timing accuracy of ~1 sec/year. It can also communicate with other serial VAUHs through the inductive modem cable. With the current configuration, only the master unit transmits serial timing data and the slaves listen. Each unit consists of a single-element hydrophone, an inductive coupler, a data logger, a 40-GB hard disk with accurate internal oscillator powered by a single lithium battery pack.

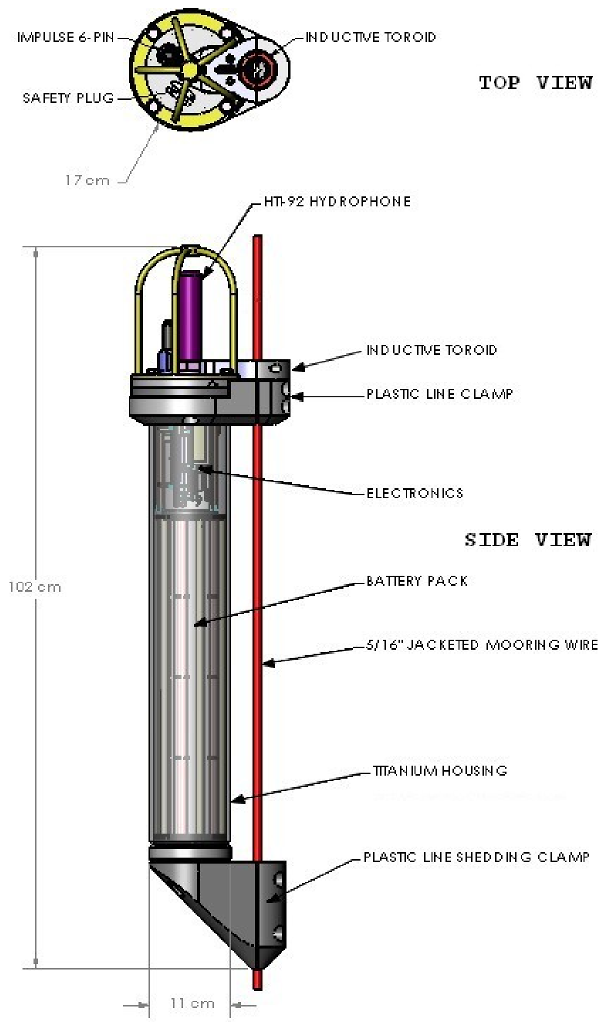

Figure 3. Assembly drawings of VAUH. A battery-operated electronics includes multi-processor data acquisition board with an inductive modem module, an 1.8" hard disk and an internal clock which is accurate to 1 sec/year. Multiple VAUHs can be stringed together up to 1 km of separation from the master on the modem/mooring cable.

The hydrophone is HTI-92 hydrophone from High Tech Inc., which has a nominal sensitivity of -175dB *re* 1V/1μPa. The omni-directional hydrophone is directly mounted on the titanium end plate and protected by cage. The hydrophone has a built-in pre-amp with a 1-pole high pass filter at 5 Hz. With the pre-amp's filter response, it applies a pre-whitening filter optimum for a typical deep ocean ambient noise spectrum between 1 Hz to 12 kHz. A 12-V lithium battery has approximately 180-AH capacity. The battery life is ~1.5 years with sampling rate at 250-Hz and 16-bit data resolution. An external toroidal coupling inductor with a sealed 20-turn coil is connected to the internal Inductive Modem Module (IMM®) on the data acquisition board (DAQ). Through the inductive coupler and single-core mooring cable, it sends/receives the serial data to/from the remote units as far as 1000 m of distance [15].

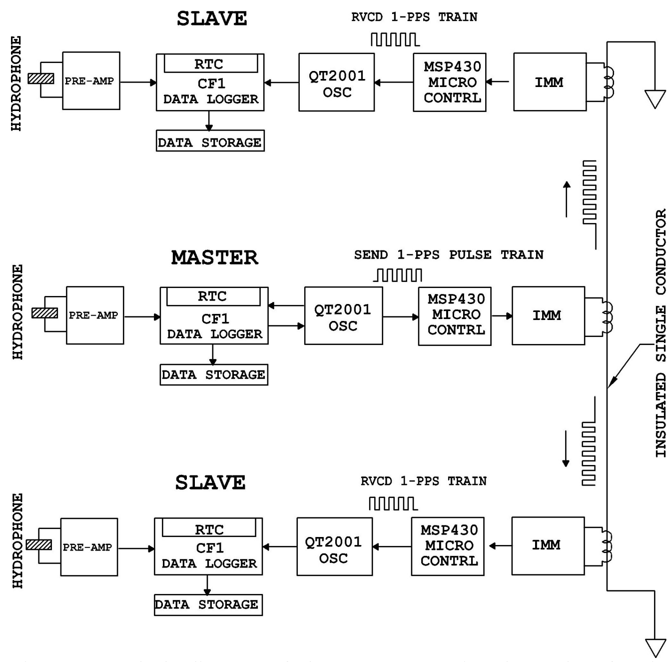

Figure 4. Block diagram of three VAUHs stringed together for time synchronization.

Fig. 4 is a block diagram of the three VAUH units connected in series via a serial inductive modem link. The internal electronics consist of a CF1® computer (Persistor Instrument) for data logging, QT2001® oscillator clock (Q-Tech Corporation), MSP430®-based timing controller and IMM® modem. The QT2001® is a low-power, microprocessor-controlled,temperature-compensated oscillator which has a long-term stability of ~$3x10^{-8}$ with nominal power consumption of 35 mW. In this configuration, the master IMM® unit sends 15 consecutive host-wake-up command text string (*IMFlags*) at a precise interval of 1 second to the other units via inductive serial link at 1200 bps. All these sub-components including the CF1®, QT2001® and IMM® drain very little current and are useful for a long-term deep-water mooring operation. The power consumption of CF1 at 250Hz sampling rate was 75 mW, MSP430 controller 5 mW in sleep mode and pre-amp including the hydrophone consumed 65 mW.

The VAUH is also a stand-alone system and once synchronized to accurate clock source, e.g., GPS NMEA time and 1-PPS output, it maintains timing accuracy equivalent to 1 sec/year or 3 ms/day. Although 1 sec/year drift may be adequate to differentiate the arrivals of P- or T-waves using a long-baseline hydrophone array with element spacing of 100s of kms, it is not accurate enough for beam forming or acoustic mode propagation studies. To analyze a typical T-wave signal with spectral content to and exceeding 25Hz [2], a relative timing accuracy of 10 ms (T/4 of the wave where T is the period) has to be maintained among the multi-instrument records throughout the monitoring period. For the ease of operation and maintenance, the master and slave VAUHs are identical and can serve either role by changing the jumper setting.

The master unit transmits the 15 consecutive *IMFlag* command with 1 second apart once a day and slaves use the timing to maintain 10 ms/day relative accuracy. The CF1 data logger independently records the all the activities, digitizes the data, time-stamps and stores the files on an 1.8” 40 GB hard disk. It also maintains the GMT time by counting the QT2001’s 1-PPS and 100-PPS pulses and updates its real time clock.

C. *Timing synchronization scheme*

Before the mooring system is deployed, QT2001 local oscillators of all the units are synchronized by the GPS NMEA time and 1-PPS signal on the bench. It requires minimum of 10 consecutive 1-PPS pulses (Fig. 5a). Once the logging program starts and becomes fully operational in the water, instead of 1-PPS square waves, IMM sends 15 consecutive *IMFlag* commands exactly 1 second apart over the modem/mooring line. The *IMFlag* is a 16-character sentence, and when received, it wakes up the slave modem which generates a pulse at the COM port of MSP430 microprocessor. These pulses are converted to a 1-PPS train of 50% duty cycle. As a result of transmission delay and time required to send/receive 16 characters of IMFlag at 1200 bps, there is ~140-msec delay (+/- 2 ms) at the leading edge of slave pulse (Fig. 5c). At the slave unit, additional 860-msec delay is added in order to make the pulse packet aligned to the master’s 1-PPS train (Fig. 5e) exactly.

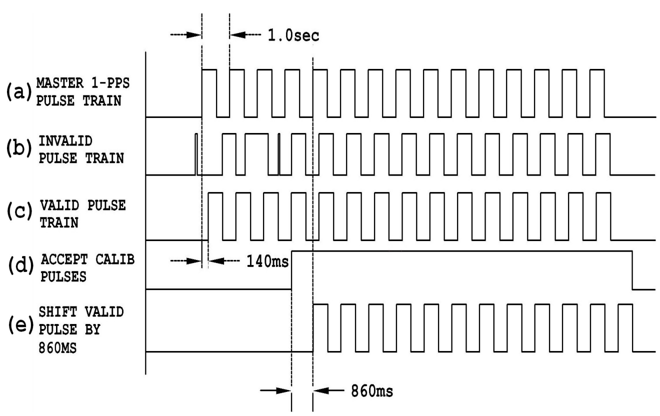

Figure 5. Master-to-slave VAUH timing synchronization scheme. Master’s 1-PPS pulses are converted to *IMFlags* and sent to the slave units. Slave discriminates the noise, shapes the pulses and adds delay to compensate the transmission delay.

Being calibrated a once-a-day, both slave units maintain a timing accuracy of 10 ms relative to the master clock during the entire monitoring period. To discriminate against the cable noise such as triboelectric noise, the slave unit looks for the first 3 valid consecutive *IMFlag* signals (Fig. 5b). If the period is off more than 0.8% (0.992 sec <ΔT<1.008 sec), the entire pulse train is considered as invalid and ignored. If all the criteria match, it accepts as a legitimate 1-PPS calibration packet and disciplines the local QT2001 OSC of the slaves.

D. *Dual clock system and A/D sampling rate fluctuation*

To keep the time current, the CF1 data logger counts 1-PPS and 100-PPS pulses of the local QT2001 OSC and converts them to 1-second and 10-msec pulse counts since Jan. 1, 1970. Using these pulse counts, the time of internal real-time clock (RTC) is updated at every 128 seconds so that the accurate time is maintained by both the RTC as well as 1-PPS and 100-PPS counters. If the CF1 data logger reboots and loses the pulse counts as a result, the 1-PPS and 100-PPS counters are refreshed based on the RTC time.

Another source of timing errors is A/D digitization. Triggering A/D occurs internally as a result of interrupt calls, which varies depending on how busy the computer is. A small amount of sampling interval fluctuation is therefore inevitable. To solve this problem, CF1 also digitize the 1-PPS wave form of QT2001 by the same A/D as acoustic channel and stores them on the same file. During the post processing, exact sampling rates are calculated at every second based on the 1-PPS records, and the A/D timing is improved significantly.

III. ACOUSTIC DATA

A. *Strumming noise*

The VAUH’s mooring line of the VAUH is of a diameter of 5/16” steel jacketed cable that also serves as modem cable. No particular anti-strumming measure, such fairing or corrugated surface, was applied in the mooring design. As a result ~20% of the VAUHs records suffered strumming noise, and the top two suffered the most (Fig. 6a).

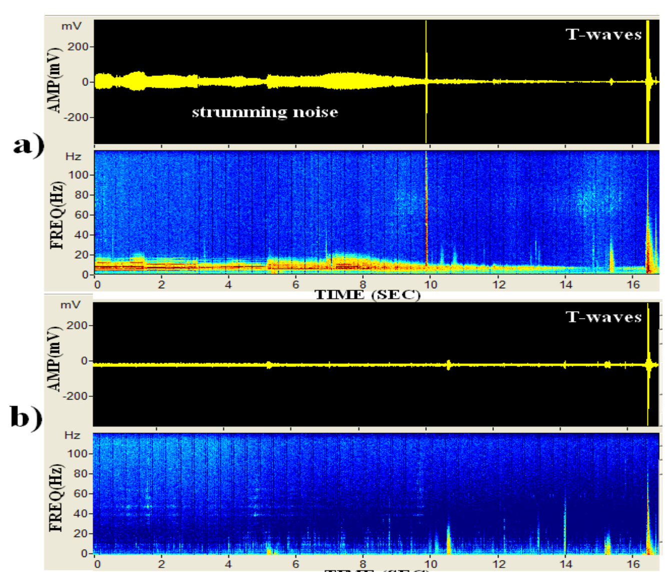

Figure 6. (a) Middle VAUH (@1000 m) record affected by the low-frequency strumming noise. The mooring line used was a 5/16” steel jacketed modem cable with smooth surface. (b) A regular AUH record (M1) during the same time period is shown here for comparison. An elastic 5/16” Polyester line was used for mooring.

Although the cable strumming noise was never strong enough to render the A/D channel to saturate (+/- 1.25V input range), it was strong enough to overwhelm the spectral content below 20 Hz. When the strumming noise affected acoustic signal, it generated a fundamental tone of few Hz and accompanied by less than ten harmonics. Typical T-waves have a frequency contents of ~25 Hz, distinguishing T-waves is not too difficult, as seen in the later half of the record in Fig. 6a.

Fig. 6b is the record of a regular single AUH mooring (M1) during the same period with ~ 6000-second offset. The line used for mooring was a 5/16" polyester line with density of 1.38, whereas the VAUH mooring cable was jacketed steel. It appeared that a rigid and heavy line (density of ~7.8) with smooth surface made the mooring more susceptible to the strumming noise by the deep water current. For the future deployments, a different mooring/modem cable must be used to reduce the vortex shedding including a mooring line with a corrugated surface.

B. Evaluation of timing accuracy

At the end of the four-month monitoring the internal software clock time was compared against the GPS time. Master unit clock shift +0.083 sec, and the top slave +3.082 sec, and the bottom slave bottom was +8.082 sec. Among all the three VAUHs, millisecond offsets were identical. There was 3-second error at the top slave and 8-second error at the bottom slave unit. The discrete second error occurred when the CF1 was too busy with other choirs and counted the same 1-PPS pulse twice. The discrete second errors were corrected using the 1-PPS pulses recorded on the second A/D channel as a reference time after the recovery.

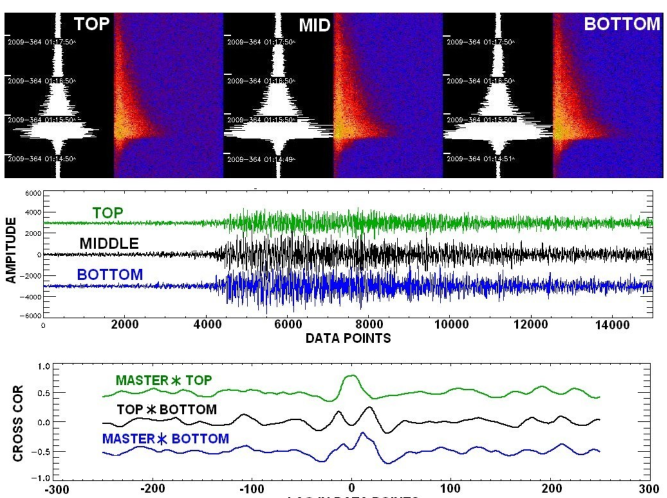

Figure 7. (a) T-wave signals (time series and spectrograms) of the top, middle and bottom VAUHs (from the left to right) on day 364, 2009 after synchronized. (b) Detailed time series. (c) Cross correlations of the three records after synchronization (sample rate 250 Hz).

The entire area was hydroacoustically active with frequent seismic events and continuous submarine volcano eruptions at the West Mata in the northern Lau Basin. Fig. 7 is a typical T-wave recorded by the three VAUHs at 01:15 :49 on day 364, 2009. T-wave energy is typically of less than 50 Hz of frequency content with a sudden onset. At all the VAUHs, the signal arrivals are almost identical and cross correlations between channels indicate that the main signal arrivals were within 10 ms of delay. The t-wave event was located by the AUH array at 18°14'24"S-176°23'24"W (a red star mark in Fig. 1) which was 340 km from the VAUH mooring.

Fig. 8 shows the eigenray arrivals from the same t-wave source to the VAUH array. All rays were bounced by seafloor at least once which can cause the signal elongation in time by scattering process. The red circles are rays that turn on the way up, but don't hit the sea surface. The blue circles are the rays bounced off the sea surface and the bottom at least once along the path. All ray tracing modeling results indicate that the signals arrived at almost the same time within 10 ms of delay, which agrees well with the actual record. The result suggests that timing synchronization scheme used for this experiment worked well.

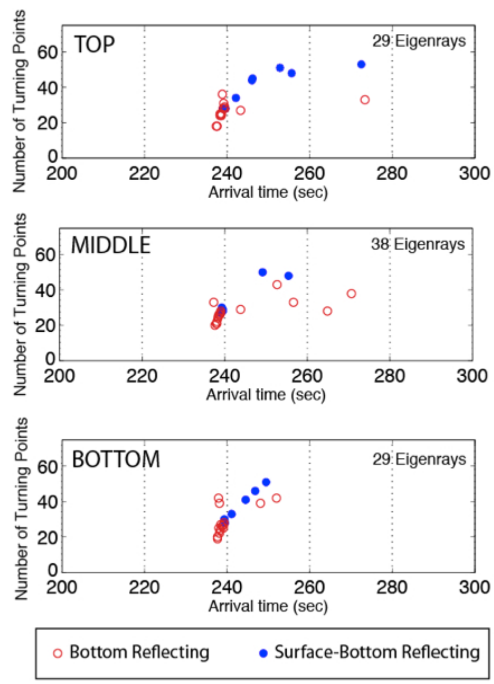

Figure 8. Eigen rays from the T-wave of Fig. 7 to the VAUHs.

Five man-made shots were made during the April, 2010 cruise by imploding a single 14" diameter glass sphere. A glass sphere was imploded by a pressure-activated piston at ~700 m and a typical acoustic record of the shot is shown in Fig. 9. It shows that most energy was concentrated between 50 Hz and several kHz. It is a relatively reliable sound source which produced a low-frequency pulse followed by small bubble pulses. By imploding the glass sphere near the sound channel axis, our goal was to calibrate the AUHs and VAUHs for timings and the system sensitivity. The typical source levels of these shots were 250-270 dB re $1\mu Pa|_{@1m}$ between 300-500 Hz [16].

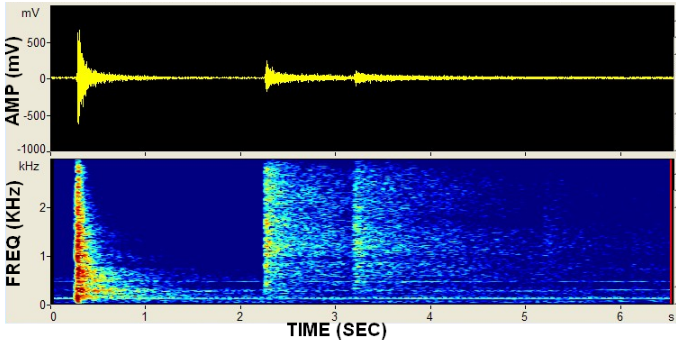

Figure 9. A 6.5-second long record of a typical glass sphere implosion recorded by the ship hydrophone on R/V *Kilo Moana* at 6-kHz sampling rate. A glass sphere of 14" diameter was imploded at 22°18'36"S-177°55'12"W at the depth of ~700 m. A direct arrival, bottom-bounded and surface multiples are seen in this picture.

Fig. 10 shows the hydrophone records of the three VAUHs at the expected time of shot arrival. The shot was fired at 00:15:09 at 22°18'36"S-177°55'12"W at the depth of ~700 m 204 km from the array and arrived when the strumming noise was high, especially with the middle VAUH. As a result, it obscured the signal arrival, but all VAUHs except for the top one clearly showed the arrivals of shot (red spikes on the spectrograms indicated by arrows). After correcting timing errors by the 1-PPS record and re-synchronizing all channels, we found that the time of arrivals between master and bottom hydrophone match with the eigenrays within a few milliseconds of relative accuracy after four months of continuous operation (Fig. 11).

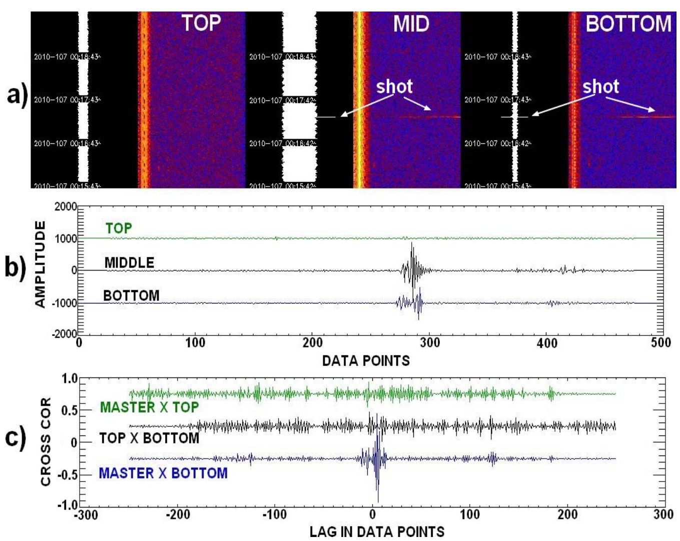

Figure 10. (a) Time series and spectrograms of the top, middle and bottom VAUHs (from the left to right) after synchronized. Glass sphere shot was observed at the bottom two VAUHs only at 00:17:25 on 4/16/2010. (b) Detailed time series after applying 30-Hz high filtering to remove the strumming noise. (c) Cross correlations of the three records after synchronization.

In this region the propagation of the sound from the source at ~700 m is bottom-limited. The ray tracing model confirms that all the rays were reflected by the seafloor at least four before they reached the seamount (~1500 m) in the middle of the path. Only a few eigenrays reached the bottom two VAUHs by refraction paths. Whereas in the case of top VAUH, all the eigenrays reached to the top unit were of bottom-reflected with no refracted rays. The signal was further dissipated by few more bottom reflections before it reached to the top unit. The calibration of the system sensitivity to improve the source level estimation is still a work in progress at the timing of this writing.

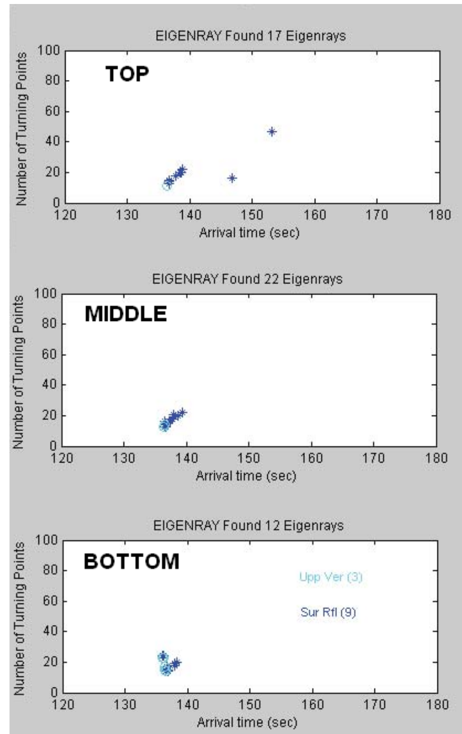

Figure 11. Engenray arrivals of the glass sphere shot to the three VAUHs. The first arrivals among the three VAUHs were within few to 10 msec of each other.

IV. Results

A new timing scheme based on inductive modem was successfully tested for synchronizing a low-frequency vertical hydrophone array. Without underwater connectors, a master instrument synchronized the two slave instruments once a day while maintaining less than 10 ms of intra-instrument timing accuracy for four months. Power consumption of the instrument is low enough so that internal battery should last at least for 1-year deployment. Although an array configuration tested consisted of only three instruments 500 m apart, it is possible to link more instruments with a narrower spacing. The technology developed is low power, robust and useful for not only the acoustic array of vertical or horizontal but also other sensor platforms such as seafloor observatory where accurate timing synchronization among the instrument is critical. A rigid steel modem/mooring cable with smooth surface is deemed as a cause of high level of strumming vibration by deep water current. A cable with corrugated surface is recommended to reduce the vortex shedding for acoustic monitoring application. Future work includes an improvement of the software controlling the 1-PPS counter to eliminate the pulse counting errors.

ACKNOWLEDGMENT

The authors thank to the crew of the R/V *Roger Revelle* and R/V *Kilo Moana*. We also thank to Darius Miller at the Sea-Bird Electronics who gave us valuable advices and supports during the early development stage. The mooring was designed by Hendrick Miller at PMEL, NOAA. Matt Fowler at the Oregon State Univ. deployed and recovered the moorings. T-K Lau at the Oregon State Univ. has processed the VAUH data.

REFERENCES

[1] H. Matsumoto, D.R. Bohnenstiehl, R.P. Dziak, M. Park and M. Fowler, "Hydroacoustic monitoring of the Scotia Sea: autonomous hydrophone experiment," *Monitoring Research Review*, pp. 605-612, 2009.

[2] C. G. Fox, H. Matsumoto, and T-K. Lau, "Monitoring Pacific Ocean Seismicity from an Autonomous Hydrophone Array," *J. of Geophy. Res.*, Vol. 106, No. B3, pp. 4183-4206, 2001.

[3] R. P. Dziak, D.K. Smith, D.R. Bohnenstiehl, C.G. Fox, D. Desbruyeres, H. Matsumoto, M. Tolstoy, D.J. Fornari, "Evidence of a recent magma dike intrusion at the slow spreading Lucky Strike segment, Mi-Atlantic Ridge," *J. Geophys. Res.* vol. 109, B12102, 2004.

[4] D. R. Bohnenstiehl, M. Tolstoy, D.K. Smith, C.G. Fox, and R.P. Dziak, "Aftershocks sequences in the mid-ocean ridge environment: an analysis using hydroacoustic data, *Techtonophysics,* 354, pp. 49-70, 2002.

[5] G. Helffrich et al., "Hydroacoustic detection of volcanic ocean-island earthquakes," *Geophys. J. Int.* 167, pp. 1529-1536, 2006.

[6] D. K. Mellinger, K.M. Stafford, S.E. Moore, R.P. Dziak, and H. Matsumoto, "An overview of fixed passive acoustic observation methods for cetaceans," Vol. 20, No. 4, 36-45 *Oceanography*, 2007.

[7] H. Matsumoto, M. Fowler, and C.G. Fox, "Evolution of Autonomous Hydrophones," *EOS Transactions, AGU*, S51B-07, 2000.

[8] H. Matsumoto, S. Nieukirk, M. Fowler, J. Haxel, S. Heimlich, D.K. Mellinger, R.P. Dziak and C.G. Fox, "Sound in the sea: hands-on experience with NOAA VENTS program," pp. 1565-1571, #918, *IEEE Oceans03*, 2003.

[9] M. A. Riedesel, J. H. Orcutt and J.A. Adams, "Seismic signals and noise recorded on a seafloor vertical hydrophone array and a colocated OBS during the LFASE experiment," *Bull. of the Seism. Soc. of Am*. V. 89, no. 2, pp. 423-432, April 1999.

[10] A. N. Gavrilov and P.N. Mikhalevsky, "Low-frequency acoustic propagation loss in the Arctic Ocean: results of the Arctic climate observations using underwater sound experiment," *J. Acoust. Soc. Am.* pp. 3694-3706, 119(6), 2006.

[11] D. B. Harris, G. D'Spain and A. Goldner, "Regional observation of a nuclear test from a vertical hydrophone array," *Bulletin of the Seismological Society of America*; v. 84; no. 4; pp. 1148-1153, 1994.

[12] D. E. Frye, and W.B. Owens, "Recent developments in ocean data telemetry at Woods Hole Oceanographic Institution," *IEEE J. Oceanic Eng.,* **16,** pp. 350–359, 1991.

[13] C. Teng, L.J. Bernard and P.A. Lessing, "Technology refresh of NOAA's Tropical Atmosphere Ocean (TAO) buoy system," *IEEE OCEANS06*, 2006.

[14] H. B. Milburn, P.D. McLain and C. Meinig, "ATLAS buoy--reengineered for the next decade," *Proc. IEEE/MTS Oceans '96*, pp. 698-702, 1996.

[15] http://www.seabird.com/products/inductivemodem.htm

[16] D. K. Blackman, C. de Groot-Hedlin, P. Harben, A. Sauter and J.A. Orcutt, "Testing low/very low frequency acoustic sources for basin-wide propagation in the Indian Ocean," *J. Acoust, Soc. Am.*, 116 (4), Pt. 1, pp.2057-2066,2004.