Hydroacoustics of a Submarine Eruption in the Northeast Lau Basin Using an Acoustic Glider

H. Matsumoto[1], S. E. Stalin[2], R. W. Embley[3], J. H. Haxel[1], D. R. Bohnenstiehl[4], R. P. Dziak[1], C. Meinig[3], J. A. Resing[3], and N. M. Delich[3]

[1]Oregon State University, 2115 SE OSU Dr. Newport, OR 97365

[2]Pacific Marine Environmental Lab (PMEL), National Oceanic and Atmospheric Administration (NOAA), Bldg 3, 7600 Sand Point Way NE, Seattle, WA 98115

[3]PMEL, NOAA, 2115 SE OSU Dr. Newport, OR 97365

[4]North Carolina State University, 2800 Faucette Drive, Rm. 1125 Jordan Hall, Raleigh, NC 27695-8208

***Abstract-* A 1000-m Slocum glider® (Teledyne Webb Research Corporation) with CTD, turbidity, and hydrophone sensors was operated for two days in the Northeast Lau Basin. The survey was conducted near West Mata Volcano, where in November of 2008 the NOAA PMEL Vents program observed an active eruption emanating from near its summit at 1207 m—the deepest submarine activity ever to be witnessed. Our goal was to use the glider as a forensic tool to search for other nearby eruption sites with onboard sensors that detect the chemical and hydroacoustic signatures associated with the volcanic and hydrothermal plumes. The glider was launched on May 6, 2010 at 15° 8'3.60"S-174° 6'15.00"W, approximately 40 km to the west of West Mata. It flew toward West Mata and was recovered near the summit of the volcano after repeating 13 yos during a 41-hour mission. Although the recordings were affected by mechanical noise from the glider's rudder, the data demonstrate that the system can detect the wide-band noises (>1 kHz) associated with submarine volcanic and intense hydrothermal activity. The glider recorded variable acoustic amplitudes based on its distance from West Mata and temporal variations in the volcano's rate of activity, and demonstrated that these geologic processes contribute to the region's high ambient noise levels.**

I. Introduction

During the last decade, the value of hydroacoustic studies in monitoring mid-ocean ridge seismicity has been demonstrated through work using the U.S. Navy's SOund SUrveillance System (SOSUS) [1] and arrays of moored autonomous underwater hydrophones (AUHs) [e.g., Fox et al., 2001]. These studies utilize earthquake-generated Tertiary (T-) waves, which are thought to be excited by scattering from a rough seafloor in the abyssal setting. Due to the efficiency of sound propagation in the oceans, hydroacoustic data can provide significant improvements in the location and detection capability afforded by land-based seismic stations, improving the sensitivity level of detection by 1.5-2.0 orders of magnitude for remote areas of the ridge crest [2]. The analysis of hydroacoustic data has revolutionized our understanding of mid-ocean ridge eruptive processes, illuminated the impact of submarine earthquakes on the hydrothermal system and shown great promise as a tool in addressing a variety of tectonic problems.

The Lau Basin was formed by the splitting of a volcanic arc associated with the subduction of the Pacific Plate [3]. This young ocean basin is delineated by the volcanically active Tonga Ridge to the east and inactive Lau Ridge to the west. Historically the area has a high seismic-tsunami hazard potential [4]. Just recently, on September 29, 2009, a strong earthquake took place south of the Samoa Islands in the Northern Lau Basin, which triggered a local tsunami causing considerable damage and 189 fatalities on the Samoa Islands and in the northern Tonga archipelago [5]. The rapid trench rollback induced by the high convergence rate also creates one of the Earth's most volcanically active backarc regions [6].

In May, 2009, the deepest active underwater volcano, West Mata (1174m), was discovered by a joint NOAA Vents and NSF Ridge2000/Margins program. Subsequent dives with the *Jason* remotely operated vehicle (ROV) documented spectacular explosive magmatic degassing and seafloor eruptions of tephra and lava [7]. This deep site was an enticing target for hydroacoustic studies, especially following on the recording of a wide-band acoustic signal (in excess of 50 dB above the sea-state 0 ambient noise level) recorded at the shallower (~530 m) NW Rota-1 submarine volcano in the Mariana arc [8].

In January 2009, an AUH array consisting of 13 fixed hydrophones encompassing an area of 126,000 km^2 was deployed in the Lau Basin. It continuously recorded acoustic signals at 250-Hz sampling rate for 1.3 years. In December 2009, in response to the discovery of the deepwater eruption, a smaller array consisting of four high-sampling rate (1 kHz) AUH moorings was deployed in the West Mata region. The short baseline of this array, only ~20 km between moorings, was designed to provide a more detailed study of the volcanic and hydrothermal activity in the vicinity of the volcano (Fig.1). Both arrays were recovered in April of 2010, just prior to the glider mission.

The four fixed hydrophones (WM-W, WM-N, WM-E, and WM-S) recorded sounds from the West Mata volcano which indicated that it was continuously erupting for the entire monitoring period (December 13, 2009-April 22, 2010) with wideband acoustic bursts very similar to the records observed at the NW Rota-1 volcano [9].

Moored hydrophone technology has arguably emerged as the most robust and cost effective method for basin-scale acoustic monitoring. Since the program began in 1994, NOAA PMEL's AUHs have collected multi-year acoustic records

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from many of the world's oceans [10, 11 and 12]. Although autonomous monitoring provides a colossal amount of data, (~1 Terabytes per a year in the case of the Lau study), it is not a real time measurement and the equipment needs to be serviced periodically. New technologies are emerging as alternative platforms, including ocean gliders [13] and profiler floats [14] which can provide shot-term range-depth-dependent synoptic environmental data for an erupting underwater volcano by sound and chemical sensors for urgent assessments.

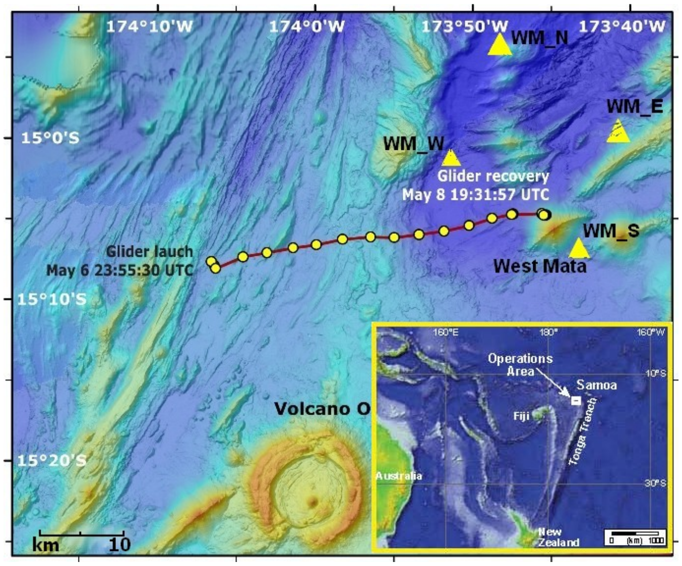

Figure 1. Four AUH moorings (yellow triangles) in the Northeastern Lau near the West Mata volcano and glider navigation. Inset shows the area of operation near Western Samoa and Fiji.

An underwater glider such as the Seaglider® or Slocum glider® controls its buoyancy, pitch and converts vertical motion to horizontal using wings, and thereby propels itself forward with very low power consumption. The lack of noisy electric motor-driven propellers makes them relatively quiet platforms and useful for acoustic studies. It can navigate around the obstacles and resurfaces every few hours to transmit the data in near real time. Moore et al. [15] successfully used the Seaglider with hydrophone to monitor the blue whale's acoustic activities and Bogue et al. [16] have been able to detect the high frequency vocalizations from marine mammals (e. g., beaked whale) at sampling rates in excess of 196 kHz with storage capacity of 1.5 terabytes [16].

This paper describes a deployment of the PMEL acoustic Slocum glider® which was launched on May 7, 2010 in the northern Lau Basin and flew toward the active West Mata underwater volcano. The glider's range-depth-dependent acoustic spectrograms are compared with those from fixed AUH's, and the frequency-dependent interference pattern as a result of multipath propagation is discussed.

II. GLIDER MISSION RESULTS

A. Description of the PMEL glider

PMEL's Slocum gliders are 1000-m rated and equipped with a standard Seabird CTD, Chlorophyll (sensitivity 0.01µg/l) and Turbidity sensor (0.01NTU sensitivity). The acoustic system was developed by PMEL and tested for three days off Kona in March, 2010 prior to the Lau operation. The hydrophone is HTI92B from High Tech with a sensitivity of -175dB (re 1V/1µPa). With a pre-amp (f_{max}= 12 kHz) and CF1® based data logger, it records 16-bit data continuously on 32-GB Compact Flash Card (CFC) with a maximum sampling rate of 32 kHz. Since most seismo-volcanic acoustic signals are low frequency, we set the sampling rate to 2-kHz for the Lau glider operation.

Because the data rate of Iridium is limited (2400bps), no acoustic data were sent from the glider to shore in real time. The acoustic data were stored on the CFC for data analysis after the expedition. Only the CTD data were sent in real time when the glider surfaced at approximately 3.5-hour intervals.

A new type of rudder, called "Digifin", was installed on the Slocum glider®. Because there was no known issue with this particular rudder at the time, the hydrophone was installed under the rudder in the aft cowling section (Fig. 2) where the least flow noise was expected. During the trial off Kona, Hawaii in March, 2010, however, we discovered that the rudder was programmed to move every 4 to 8 seconds and generated a short (~250 ms) wideband mechanical noise and affected the acoustic data. Because the shipment date for the cruise was close, it was shipped as was and the rudder noise was removed by a signal post-processing after the cruise.

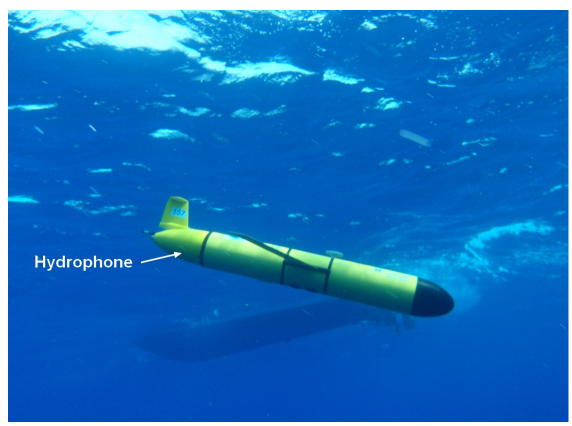

Figure 2. Underwater picture of the PMEL Slocum glider® at the initial descent stage. Hydrophone was installed in the aft cowling section of the glider (courtesy of Teledyne Webb Research).

B. Glider mission overview

The glider deployment was originally scheduled for the hydrophone recovery cruise on *R/V Kilo Moana* in April 2010 but weather and ship problems precluded this. Instead, the glider was deployed off the *R/V Kilo Moana* on May 6 during a hydrothermal exploration cruise in the northeast Lau. The glider mission files were set up remotely and the glider was flown from PMEL, Seattle, WA, which was 5,000 miles away. It was launched from the A-frame with a quick release at 15°08'3.60"S-174°06'15.00"W approximately 40 km west of the West Mata volcano. The ship kept at least 10 nm of distance during the flight to avoid ship-noise influence to the glider data. The glider then followed a nearly straight line from west to east toward the volcano at an average horizontal speed of 27cm/sec while conducting 950-m dives and surfacing every 3.5 hours.

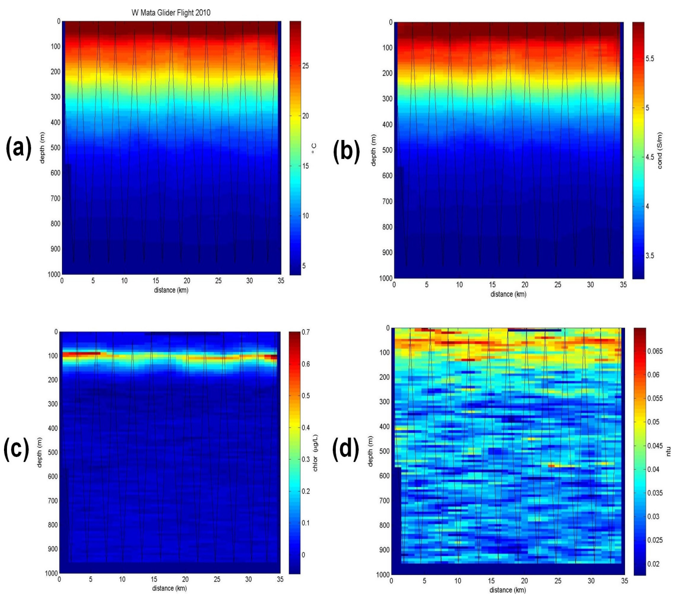

Figure 3. Temperature (a), conductivity (b), chlorophyll (c) and turbidity (d) data of the glider. The glider moved from the left to right and distance '0' km corresponds to the deployment location. The sawtooth-shaped black lines show the yos.

On May 8, after 41 hours, travelling approximately 40 km and making 13 yos, it was recovered near the northern flank of the West Mata at 15°04'49"S-173°45'30"W. The glider status, navigation and CTD data were continuously monitored from the lab in Seattle, WA. All sensors recorded continuously throughout the period. Although no obvious hydrothermal anomaly was observed from the CTD data near West Mata, this is not surprising given that the glider's maximum depth was ~250 m above the summit of the volcano. In addition, the distance of the glider from the volcano, would require a more sensitive turbidity sensor (0.003 NTU resolution versus its 0.01 NTU) to detect the particles from the eruptive activity.

III. Glider Acoustic Data

A. Acoustic noise

The 56 files containing approximately 460 MB of acoustic data were collected and stored on a 32 GB CFC. The acoustic data were sampled at 2 kHz (8-pole 860-Hz low pass) and each file was approximately 8.193 MB and 35-min long. The data logging started at the surface when the buoyancy motor was turned on which typically lasted 150 sec and low-frequency self-noise masked incoming ambient signals (Fig. 4a). The line noise associated with the R/V Kilo Moana was observed for the first 50 min but disappeared completely as the ship moved away from the glider's operating area.

When it reached the yo depth (950 m for the Lau operation), the pitch motor was turned on and for ~120 sec and dominated the acoustic record (not shown). Not known at the time of installation, the rudder was on at every 4-8 second intervals and generated short duration mechanical vibrations (Fig. 4b). Because the hydrophone was mounted inside the aft cowling near the rudder, the noise contaminated the entire length of the acoustic records. The rudder noise appeared as spikes in the time series and line noises on the spectrogram making the spectral estimate difficult.

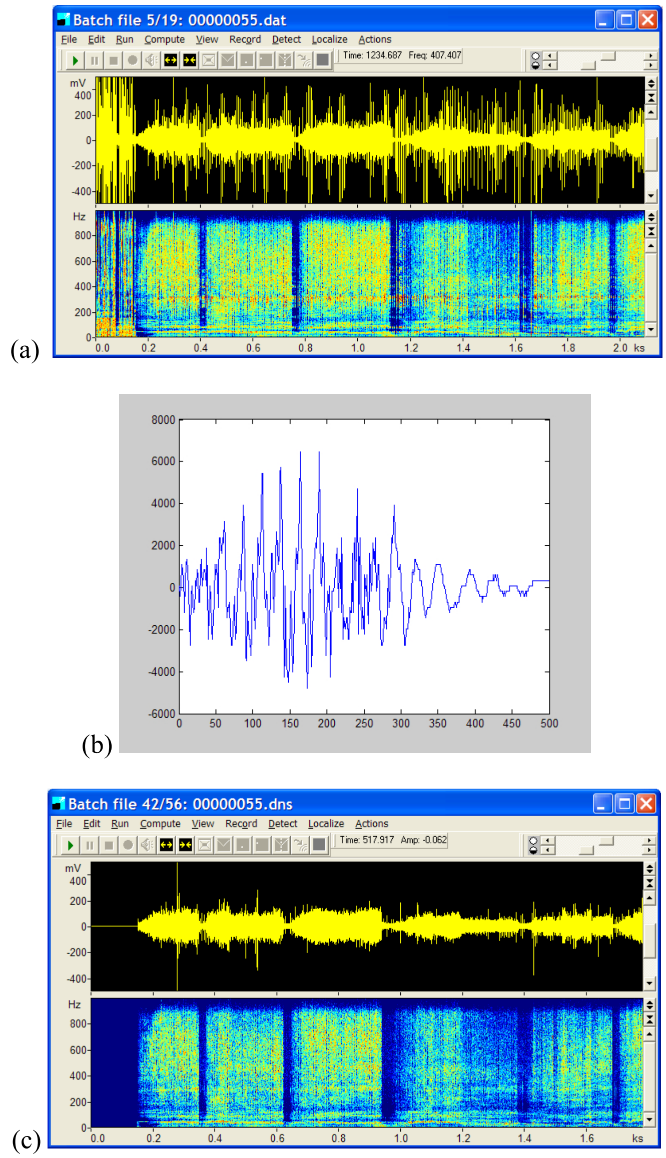

Figure 4. (a) Unprocessed glider acoustic data. First 150 second contains the buoyancy engine noise. Short duration rudder noises appear as spikes at 4 to 8-second intervals. (b) Rudder noise signal used as a kernel (250msec long). (c) De-noised record. Rudder noise affected durations were removed from the record without data filling. As a result the record was much cleaner but the length became shorter.

To estimate the sound intensity accurately, the motor and rudder noises had to be removed from the records. To remove the rudder-noise affected sections, a simple filter was developed. It is based on cross-correlation technique, eq. (1). The kernel k used to remove the rudder noise was from a typical rudder noise section of 250-msec long.

$$y_i = \sum f_i \ k_{i+j} \qquad (1)$$

where k_{i+j} is a kernel from a typical rudder noise. If y_i exceeded a threshold value, which was determined by visual inspection of the result, the corresponding section was removed from the data without filling the data. As a result, the record length became 10 to 20% shorter depending on the noise level (Fig. 4c). When the volcano was active and generated wide-band signal, de-noising process took out more data than the quieter period.

B. Comparison to the fixed hydrophone data

Fig. 5a is the time series (top) and spectrogram (bottom) of one of the acoustic records from the WM-W AUH mooring (Fig. 1) located ~8 km north of the glider path and ~15 km from the summit of West Mata volcano. The sampling rate of the AUH was 1 kHz with 440Hz cut-off and the file length was approximately 2048 sec or 35 min. The AUH is a moored hydrophone system suspended at 1000 m below the surface with a subsurface float on top and acoustic release and anchor on the bottom. Almost all the records during the monitoring exhibited a similar repeated pattern in time, i.e., intermittent wide-band acoustic bursts lasting few to several minutes followed by quiet periods. The spectrograms reveal an interference pattern which repeats the nulls and peaks in the frequency domain at a constant interval of ~30 Hz. Although the phenomena resembles harmonic tremor [17], the frequency peaks are too broad and too steady for harmonic tremors.

Fig. 5b is the acoustic record from a B-Probe® hydrophone (Greeneridge Sciences) which was placed near the summit of West Mata by the Jason ROV approximately ~20 m from the volcanic vent for a few days during the May 2009 expedition in May for a few days. It also shows the wide-band bursts but the frequency interference pattern is not evident. The signal was clipped often because of the proximity to the source although the sensitivity (-190 dB constant from 10 to 7 kHz) was much lower as compared to the AUHs (~-130dB @400Hz). These wide-band bursts were generated by explosive magmatic bubble bursts observed directly by the video from the ROV during the same time period [7].

Fig. 5c is one of the acoustic records of the glider when it was approximately 35 km from the West Mata diving from 400 to 800 m. The overall sensitivity was set 12dB lower than the other AUHs to reduce the risk of saturation when the glider came near the volcano. It too exhibited the acoustic bursts similar to the other four fixed hydrophone records but with a more complex frequency interference pattern. Null-to-null (or peak-to-peak) bandwidth changed slowly from ~100 Hz to ~25 Hz as the glider moved through the water column and the depth changing from 400 to 800 m, and moving horizontally ~550 m during the 35 minute file length toward the wide-band volcanic sound source on the West Mata volcano.

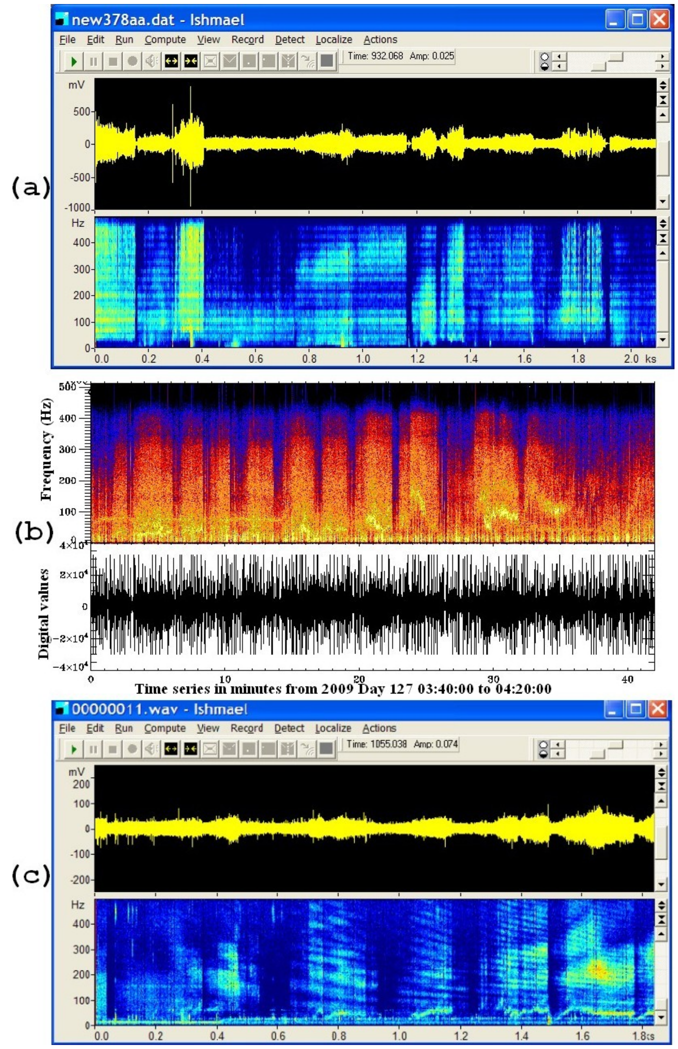

Figure 5. (a) Fixed hydrophone data from the WM-W about 15 km to the northwest of the West Mata summit. (b) 2009 data from the B-Probe hydrophone deployed on seafloor. The probe was about 20 m from the volcanic vent. (c) Glider acoustic data at 35 km from the volcano at depth of 400-800 m.

Because these frequency interferences are depth-range dependent, the phenomena is interpreted to be due to multipath interference associated with time delays on the order of 10 ms to 40 ms. This is similar to the Lloyd mirror effect that is usually observed in relatively short distances, i.e., a few hundred yards for shallow water by wide-band ship noise under moderately calm seas [18].

Fig. 6 shows the Eigen rays which correspond to Fig. 5 where the source depth was 1200 m, the receiver (glider) was at a depth of 600 m and 35 km in horizontal range from the source (volcano). There are seven Eigen rays and five of which are refracted paths with no reflection losses. Arrival time differences among the five rays are between 3 to 30 ms.

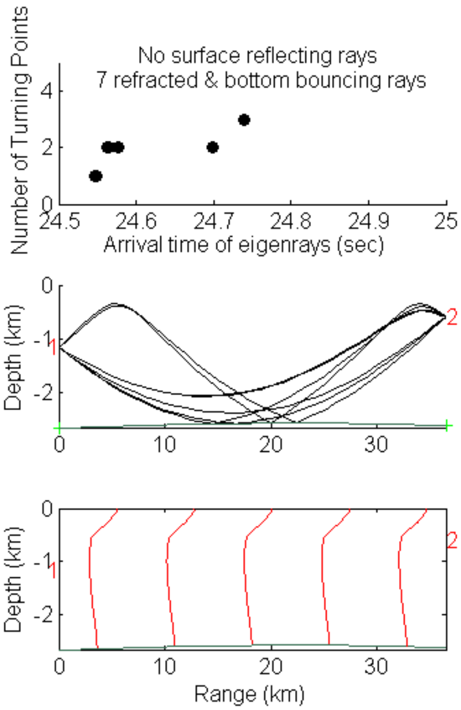

Figure 6. Top: Time of arrivals of Eigen rays (top). Middle: Eigen rays between the volcanic sound source at 1 and glider at 2 (middle). The glider was at 35 km range and 600 m deep. There were 7 Eigen rays including 2 bottom-bounced and 5 refracted paths. No surface reflected ray made it to the receiver. Bottom: Velocity profiles from the model.

The ray tracing method is probably not the best tool and the bathymetry may not be accurate enough to duplicate the exact interference pattern we observed by the gilder but it demonstrates that the spectral interferences are indeed due to the multipath propagation of a wide-band signal originating from the volcanic activity.

Because the source levels of these volcanic sources are deemed much larger than the ship noise, despite propagating over a long distance, 35 km, i. e., >15 times the water depth, the signals of both the refracted and in some cases reflected paths are coherent enough so that constructive and deconstructive interferences occurred, and form complex interference pattern as the glider repeats dives and ascends.

C. Volcano signal level vs. range and depth

Based on the glider's hydrophone sensitivity (-175dB re µPa), frequency dependent pre-amp gain (5dB @5Hz, 26dB @400Hz, 31dB @800Hz) and A/D's spec (16-bit resolution with 0-2.5V input), the signal level in dB relative $\mu Pa^2/Hz$ was calculated for the entire flight as a function of time as well as range (Fig. 6). The lower figure is the glider's depth and GMT time at which the 1-minute-averaged spectral densities were calculated. When the glider's motor was on near the surface and the pitch angle was changed at the depth 950 m (inflection points), the signal was masked so that no spectral level was estimated and left blank.

Since the volcanic explosive events were temporal, the signal spectral level was not entirely range dependent, but overall the spectral level increased as the glider approached the summit of volcano. At approximately at 0700 (GMT) on May 8 and 28 km from where the mission has started and about 10 km from the West Mata summit, the signal level reached the maximum. At this range, between 10 and 300 Hz, the spectral level was in average 25dB higher than the sea-state 0 noise level. It also shows the spectral content of eruption sound exceeds well over 1 kHz.

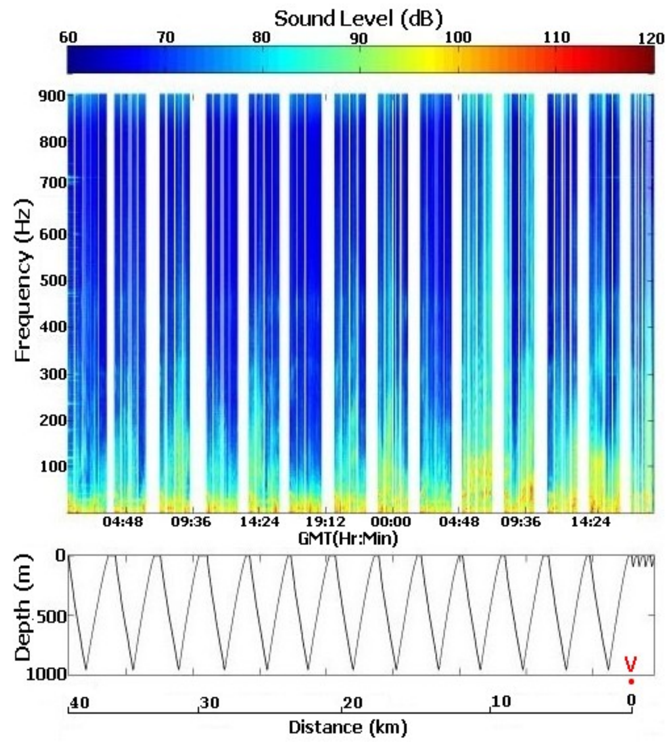

Figure 7. Top: Spectral density ($\mu Pa^2/Hz$) of the volcanic eruption sound as the glider approached the source. White spaces in the spectrogram are data gaps when the glider motor was on when it was near the surface and inflection points (950m). Middle: The dive depth of glider vs. time (GMT). Bottom: Distance along track in km. The volcano (V sign in red) is on the right side near the 0-km mark.

IV. Conclusions

An acoustic glider experiment found that an underwater volcanic eruption was influencing the regional ambient noise level of the large area in the northern Lau basin. The submarine volcanic eruption produced a wide band (at least 1 kHz) signal that was coherent enough that a complex multipath interference pattern appeared over a range exceeding 15 times the water depth The interference pattern was dependent on the glider's depth and range from the erupting volcano. The sound level gradually increased as the glider travelled toward the volcano and range dependence was observed. The recent discovery of long-term active submarine volcanoes in the western Pacific provides new opportunities to study propagation of hydroacoustic waves using combinations of gliders and fixed hydrophones. Future plans include sending spectral information back in realtime from the glider to further explore active volcanism in the area.

ACKNOWLEDGMENT

The glider project was funded by NOAA Office of Oceanic and Atmospheric Research and PMEL. Hydrophone deployments and ship time were funded by NSF grant 0825295 and Office of Ocean Exploration. The authors thank to the crew of the R/V *Kilo Moana* for expert assistance with the glider operation. We also thank Ben Allsup of the Teledyne Webb Research who supported glider operation during the cruise. Mark Koehn at NOAA supported the shipments of the gilders in/out the country. Susan Merle at NOAA Newport Lab. has provided the GIS overlay of the glider navigation.

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