Deployment and recovery of a full-ocean depth mooring at Challenger Deep, Mariana Trench

R.P. Dziak
NOAA/Pacific Marine Environmental Laboratory, Newport, OR 97365 USA

J.H. Haxel, H. Matsumoto
Cooperative Institute for Marine Resources Studies
Oregon State University Hatfield Marine Science Center, Newport, OR USA

C. Meinig, N. Delich, J. Osse
NOAA/Pacific Marine Environmental Laboratory, Seattle, WA 98115 USA

M. Wetzler
NOAA Ship *Okeanos Explorer*
439 West York Street, Norfolk, VA 23510 USA

***Abstract*- We present the details of a unique deep-ocean instrument package and mooring that was deployed at Challenger Deep (10,984 m) in the Marianas Trench. The mooring is 45 m in length and consists of a hydrophone, RBR™ pressure and temperature loggers, nine Vitrovex® glass spheres and a mast with a satellite beacon for recovery. The mooring was deployed in January and recovered in March 2015 using the USCG Cutter *Sequoia*. The pressure logger recorded a maximum pressure of 10,956.8 decibars, for a depth of 10,646.1 m. To our knowledge, this is only the fourth in situ measurement of depth ever made at Challenger Deep. The hydrophone recorded for ~1 hour and stopped shortly after descending to a depth of 1,785 m (temperature of 2.4°C). The record at this depth is dominated by the sound of the *Sequoia's* engines and propellers.**

I. INTRODUCTION

From January to March 2015, a specially designed deep-ocean hydrophone and pressure sensor mooring was deployed in the deepest area of the world's oceans; Challenger Deep. The goal of the project was to make a direct pressure-based measurement of ocean depth at Challenger Deep, and to record the ambient sound levels within this unique, ultra-deep (> 10 km) ocean environment. The plan is to make a baseline record of sound levels at Challenger Deep to [a] investigate the levels of anthropogenic sound, [b] gauge the contribution of natural sources, and [c] characterize any sounds generated by the unique animal life that exists at these depths. The goal is to record these deep-ocean ambient sound levels over the 10–13,000 Hz range for a time period of 3-4 weeks.

The proposed project represents true exploration and will be the first long-term (weeks to month) sound record made in Challenger Deep, significantly advancing our understanding of ambient sound levels in these deep ocean environments. Acoustic propagation models suggest anthropogenic surface noise may not penetrate to the depths of Challenger Deep. Our goal in collecting this unique data set is to establish baseline sound levels in one of the most acoustically isolated ecosystems of the world's oceans. Moreover, these recordings may provide the first audio records of sounds made by unique animals from these extreme depth habitats.

II. GEOGRAPHIC AND HISTORICAL BACKGROUND

The Challenger Deep is an ~11 km long and ~2.25 km wide east-west trending basin located in the Mariana Trench, within the territorial waters of the Federated States of Micronesia (Fig. 1). There have been several attempts throughout history to estimate the maximum depth of the ocean at Challenger Deep. In 1875, the HMS *Challenger* was the first ship to fully explore the Mariana Trench, sounding the abyss with explosives which provided a depth estimate of 8,184 m. HMS *Challenger II* returned in 1952, and with explosives, a hand-held stop watch, and a wire-line sounding machine estimated the depth at 10,862 m[2]. Other noteworthy echosounder-based measurements ensued in the following decades[3] including (1) an estimate of 11,034 m from the Soviet ship *Vityaz* in 1957, (2) 10,933 m from the R/V *Thomas Washington* in 1976, (3) 10,920 ± 10 m by the JAMSTEC R/V *Kairei* in 1984, (4) and 10,903 m by the U. of Hawaii R/V *Kilo Moana* in 2008. The latest, most thorough effort using echosounders occurred in 2011 from the USNS *Sumner,* which after comprehensive modeling, estimated the deepest point at 10,984 m ± 25 m[3].

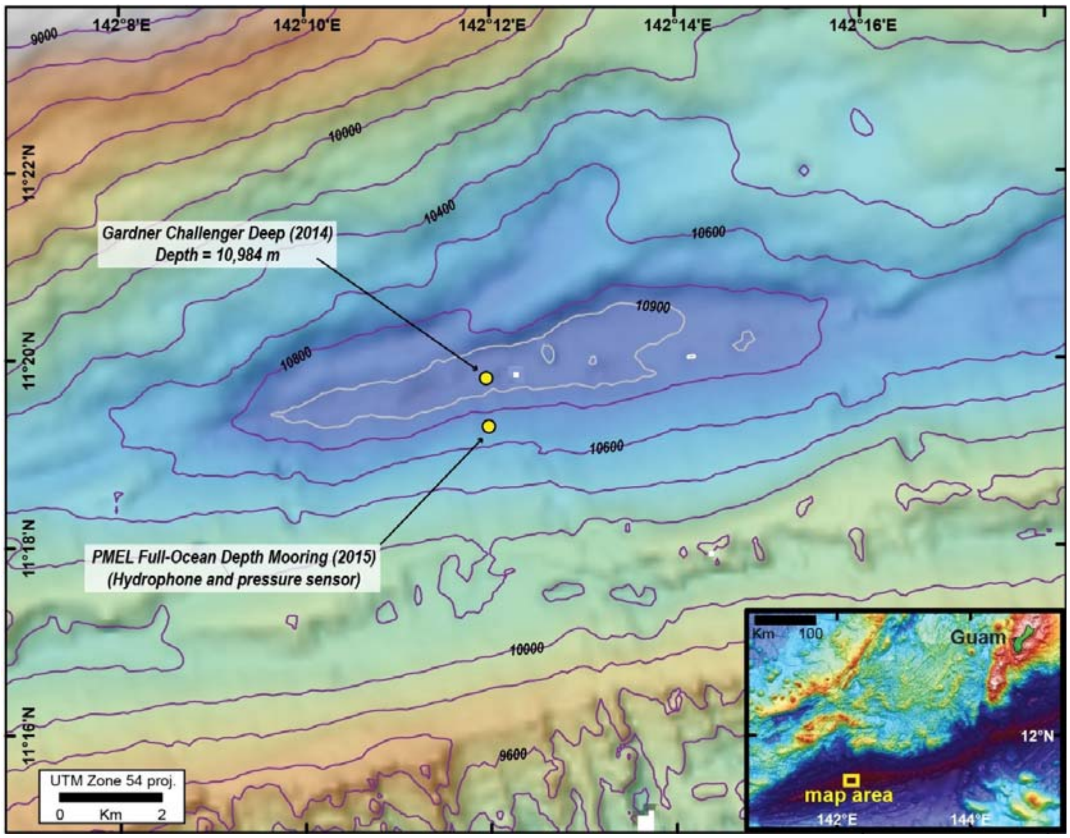

Fig 1: Bathymetric map of Challenger Deep, Mariana Trench (after Gardner et al. 2014). Inset show map location relative to Guam (~370 km distance). Yellow dots show location of deepest point estimated from bathymetry (top) and drop location of FODH mooring on 17 January 2015. Map courtesy of S. Merle (NOAA/PMEL/EOI).

In contrast there are, understandably, relatively few direct measurements of the depth at Challenger Deep using in situ pressure sensors. The first direct measurement of depth occurred during the historic dive of the manned bathyscape *Trieste* in 1960. The *Trieste* crew used an onboard pressure sensor to measure a calibrated depth of 10,911 m[1]. The next in situ measurement did not occur until 2002, when JAMSTEC deployed the remotely operated vehicle (ROV) *Kaiko*[2]. The ROV recorded a depth of 10,896 m again using an onboard pressure sensor, however no claim was made that this was the maximum depth at Challenger Deep. The last direct depth measurement, prior to this report, was performed by James Cameron in 2012[3] using his specially designed submersible *Deepsea Challenger*. Cameron[3] reported a pressure-gauge based estimate of 10,908 m deep. Again, no claim was made that this was the deepest point at Challenger Deep.

What is clear from these previous efforts is that it is very difficult to find the exact latitudinal and longitudinal coordinates of the deepest location and make a precise estimate of depth. Echosounders and multibeam measurements reliant on the accuracy of sound velocity profile estimates can only provide an averaged model of the seafloor depth, where the precise latitude and longitude position of these sonar depth estimates are derived from a rolling and pitching surface ship. In situ pressure measurements are limited by either the inexact landing of a free-falling instrument package sailing in the prevailing currents, or the drift of a robotic and/or manned submersible that tries to maintain its position relative to the sea surface.

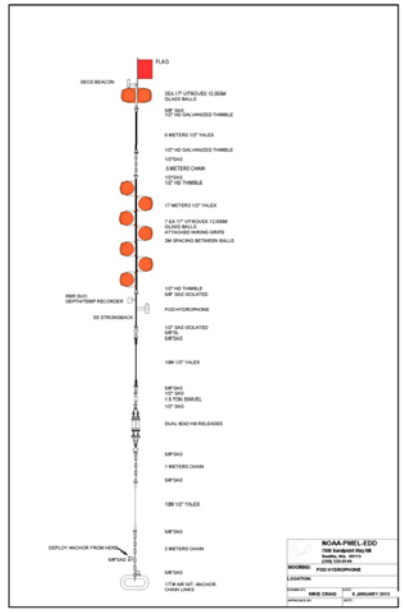

Fig. 2: PMEL deep-ocean hydrophone and pressure sensor mooring.

III. MOORING AND SENSOR DESCRIPTION

The mooring assembled for the Challenger Deep deployment (Fig. 2) is 45 m in length and consists of a hydrophone instrument package, RBR™ depth and temperature logger, and nine Vitrovex® glass spheres encased in plastic “hardhats”. The glass floats are specially designed for 12,000 m depth operations. The hydrophone and pressure sensors are attached in a double yoke frame to a 1-m long stainless steel rod shackled within the mooring for extra support. The top mooring assembly has an aluminum mast with a XEOS satellite beacon (GPS/Iridium transmitter) and flag for visibility in surface recovery operations. Housed inside one of the two top floats is a redundant XEOS satellite beacon. This in-line system is moored to an anchor using a specially modified dual acoustic release package used to increase the probability of recovery. The mooring is deployed from top to bottom using an anchor as ballast for a free-fall descent of the instrument to seafloor depth. Upon recovery, an acoustic release is triggered from the surface ship, dropping the anchor and allowing the platform to rise to the surface.

The NOAA/PMEL designed hydrophone pressure housing is capable of operational recording at full ocean depths (Fig. 3). The pressure case is made of 0.7 inch thick 6AL-4V titanium allowing it to withstand the hydrostatic pressure at 11,000 m depth (times 2 safety factor). The low-power consumption hydrophone electronics are capable of continuous recording at a 32-kHz sample rate with 16-bit resolution, resulting in a three week long record of ambient sound. The data are stored on a 128-GB Compact Flash card, enabling rapid data transfer and backup upon recovery. The hydrophone, manufactured by High Tech Inc, is oil-filled with a built-in pre-amplifier (Fig. 3). This style of hydrophone has a long, successful record of deep-water deployments (Fig. 4). One caveat is that the hydrophone is sensitive to rapid changes in

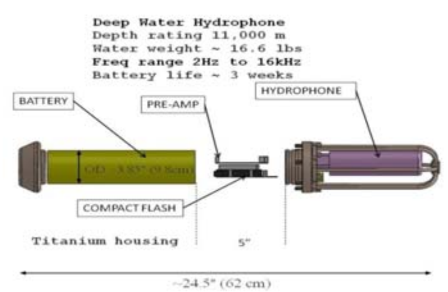

Fig. 3: Schematic of the PMEL deep-ocean hydrophone.

pressure, and its rate of descent/ascent should not exceed 5 m s^{-1} or there is a risk of damaging the ceramic element. To account for this, the mooring shown was tested to ensure proper buoyancy versus weight compensation to achieve the optimum ascent/descent rates targeted between 0.5-1.0 m s^{-1}. All pressure sensitive mooring components were successfully tested at 11,000 m of hydrostatic pressure at Deep Sea Power and Light (San Diego, CA) prior to shipment to Guam.

IV. MOORING DEPLOYMENT

The initial mooring deployment occurred during 16-18 January 2015 from the USCG Cutter *Sequoia* based in Apra Harbor, Guam. The target deployment site was the deepest point identified d by Gardener et. al[3] located in a relatively small basin within the main east-west trending trough of Challenger Deep (Fig. 1). The first attempt to deploy the mooring was made during 12-14 January, however Typhoon *Mekkhala* passed over Challenger Deep during this time preventing deployment operations.

Once on site on 17 January, we found the ocean surface current speed and direction to be 1 kt moving from due east to west. We then moved the ship to roughly 1 km east of the target deployment site and used this as the anchor drop location (Fig. 1). The anchor and mooring were in the water at 10:00 Guam time (Fig 4). Using an Edgetech 8011m deck-unit and transducer, we were able to range to the acoustic release on the mooring as it descended through the water column. The mooring buoyancy behaved as designed and descended at a rate of 60 cm s^{-1}.

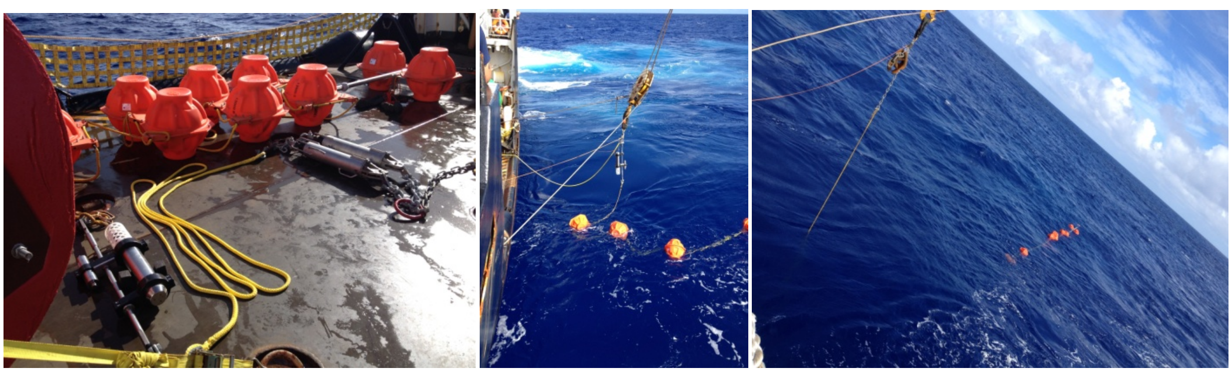

Fig 4: Left image shows mooring on deck of USCG Cutter *Sequoia*. Hydrophone pressure case (white top) and pressure sensor attached to strongback rod can be seen at left. Glass float and RF beacon mast at top, dual releases are at middle right. Middle image shows deployment of hydrophone and pressure sensor using crane from ship. Crane block at top of image, floats can be seen in water. Right image shows mooring floats and mast drifting from ship prior to anchor drop.

With a water depth in excess of 10 km, it took ~5 hours for the mooring to reach the seafloor. As the mooring descended, the acoustic slant range from the transducer to release approached true water depth. The mooring stopped descending once a depth of 10,350 m was reached, however this estimate of depth was based on assuming a sound speed of 1500 m s^{-1} over the entire water column, which is much slower than the expected sound speed profile. The ship next circled the anchor drop location while several slant ranges to the mooring were collected. These ranges and GPS ship locations were then used to derive the mooring location and depth using a simple non-linear regression algorithm and an 11 km deep sound speed profile available on the MB system website[6].

Our calculations showed the mooring was located at 11.3217°N, 142.1997°E at a depth of 10,720.2 m. Unfortunately, there was apparently a significant, unanticipated, southward current that took the mooring 1 km south of Gardner et al's[3] target location (Fig. 1). However, the calculated depth estimate is consistent with the bathymetric depth estimate at the mooring location, which indicated the mooring was at ~10,700 m.

V. MOORING RECOVERY

The mooring recovery cruise, once again onboard the *Sequoia*, took place during 18-20 March 2015. The recovery cruise was originally planned for 16-18 March, however the trip had to be delayed again because of another Tropical Storm, *Bavi*, which was tracking near the deployment site.

The *Sequoia* arrived on site on 19 March at 08:00 Guam time and we began ranging to the mooring. Acoustic communications between the mooring and transducer using an Edgetech 8011a deck unit were excellent even with the exceptional water depth. The mooring released immediately and promptly began to rise to the surface at roughly twice the rate as it had descended, reaching the surface in ~2.5 hours. Unfortunately both satellite beacons failed to transmit, and no emails were received with precise locations of the mooring at the surface as planned. However, once the ship began to steam east toward the mooring, it was spotted at a range of 1.5 nm. The mooring was found as expected, with 7 floats bobbing horizontally at the sea surface, and the mast and flag extended vertically in the air (Fig. 5).

Fig 5: Left image shows floats and mast once the mooring made it to the sea surface. Middle image shows recovery of sensors and float onto ship. Right image shows close up of hydrophone and pressure sensor immediately after recovery.

VI. INSTRUMENT RECORDINGS AND RESULTS

A. Pressure and Temperature Data Loggers

Overall, the mooring and release process worked well and all equipment was recovered and brought onboard. Once the breakdown of the mooring was complete, we removed the hydrophone and pressure sensor to inspect the data. The pressure sensor also worked as planned and showed the sensor was subjected to a maximum pressure of 10,956.8 decibars (Fig. 6). The sensor depth was then estimated from pressure using an empirical formula[7] that takes into account ocean water compressibility (density) and corrects the pressure for gravitational variation due to latitude:

$$\text{depth} = [(((-1.82\text{x}10^{-15} * p + 2.279\text{x}10^{-10}) * p - 2.2512\text{x}10^{-5}) * p + 9.72659) * p] \ g^{-1} \quad (1)$$

and

$$g = 9.780318 * [\ 1.0 + (\ 5.2788\text{x}10^{-3} + 2.36\text{x}10^{-5} * x) * x\ ] + 1.092\text{x}10^{-6} * p \quad (2)$$

where,

p= pressure (decibars), g= gravity (m s^{-2}), x = [sin (latitude / 57.29578)] ^{2}, and depth is in meters. The latitude was the acoustically ranged location of the mooring while on the seafloor of 11.3217°N.

These calculations resulted in a maximum depth estimate of 10,633.1 m. Since the sensor is 13 m above the anchor on the mooring, the actual anchor depth should be at 10,646.1 m. To our knowledge, this is only the fourth in situ measurement of depth ever made at Challenger Deep.

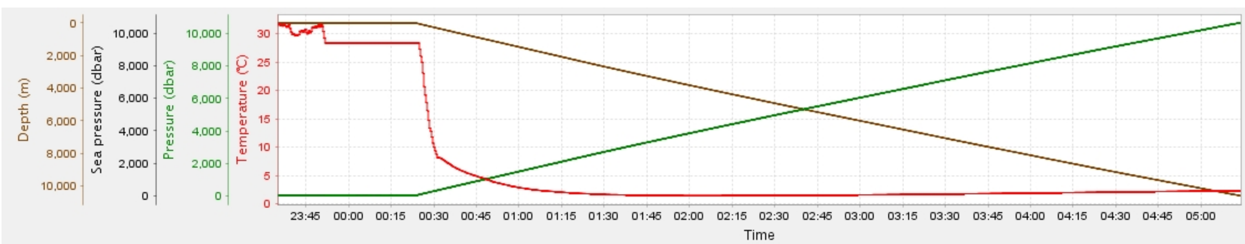

Fig 6: Graph of depth (brown, meters), pressure (green, decibars) and temperature (red, °C) recorded by the RBR™ pressure sensor during the descent of the mooring at Challenger Deep. Maximum depth attained was 10,633.1m with a recorded pressure of 10,956.8 dbars. Temperature ranged from 28.4° C near the surface to a minimum of 2.4°C at the seafloor.

Further analysis of the pressure record shows that there is a 2-3 week period during which the RBR™ gauge acclimates to the ambient pressure conditions. This acclimation period is seen in Fig. 7a as the gradual, asymptotic, decline in recorded pressure during the early part of the 2-month deployment, which with the mean removed, levels off at -0.5 decibars. Additionally, the spring-neap and semi-diurnal tidal cycles at Challenger Deep are well resolved in power spectral density estimates of the pressure time series (Fig.7b), indicating that even at these extreme ocean depths tidal processes dominate fluctuations in ambient pressure.

The temperature gauge on the RBR™ also showed that a maximum temperature of 28.4°C was recorded in the surface waters prior to deploying the anchor over the side of the ship, and a minimum 1.5°C was recorded for a short time once the mooring impacted the seafloor. However, the seafloor temperatures then stabilized at 2.4°C for the remainder of the deployment.

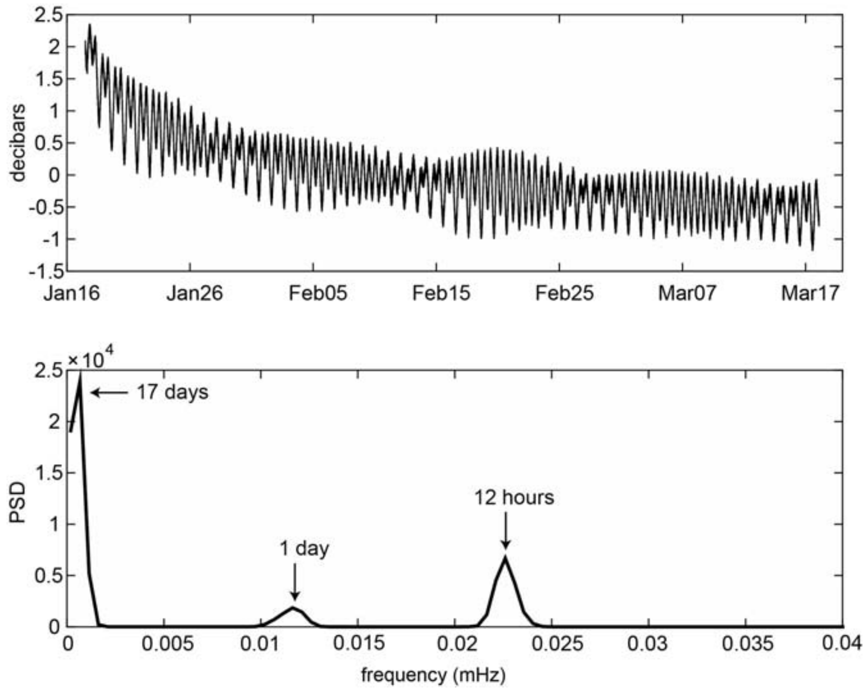

Fig 7: a) Plot of the pressure time series (mean removed) from the RBR™ instrument during the 2-month long deployment at Challenger Deep. b) Power spectral density estimate showing energy peaks associated with spring-neap (~17 days), and semi-diurnal (1 day, 12 hour) tidal fluctuations recorded at 10,646.1 m ocean depth.

B. Full-Ocean Depth Hydrophone

Unfortunately, the hydrophone stopped recording shortly after descending to a depth of 1,785 m, corresponding to a temperature of 2.4°C. The hydrophone began recording again once the mooring floats were back at the sea surface, corresponding to a sensor depth of 14.5 m and a water temperature of 28.1°C. The top diagram of Fig. 8 shows a small portion of the hydrophone data from a depth of 1,785 m shortly before it ceased to record. The record at this depth is dominated by the sound of the *Sequoia's* engines and rotating propellers, which can be seen as the short duration (~5 sec) bursts of sound (light blue to green in color) that are broadband from 1-10 kHz. The flat-topped portions of the hydrophone amplitude record are due to the ship's engine noise causing the hydrophone to "clip", even at this depth. This is likely due to the relatively high gain settings used for the hydrophone and pre-amplifier, because our goal was to record a variety of ambient sounds and levels. The banding of energy in the frequency spectrogram of the ship noise seen at 2, 4, 6, and 10 kHz are an interference pattern caused by the interaction of the sound waves from the ship's engine in the water-column and reflecting off the sea surface. No meteorological, marine animal, or geophysical sounds were observed on this 1 hour-long acoustic record.

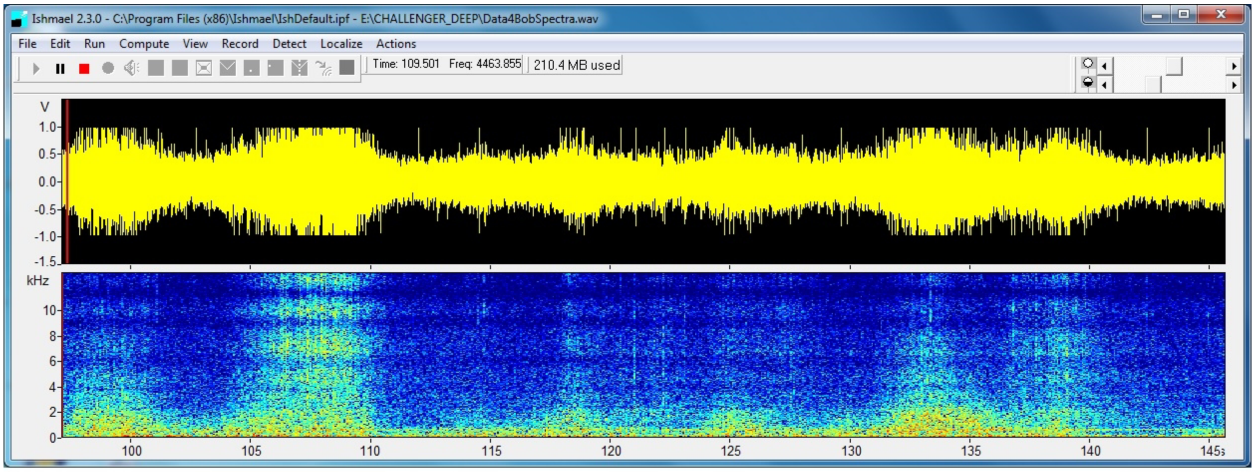

Fig 8: Top diagram shows 50 second portion of hydrophone record (amplitude in volts) at 1,785 m, shortly before hydrophone stopped recording during its descent at Challenger Deep. Bottom diagram shows the distribution of sound energy in frequency through time (spectrogram). Short duration (~5 sec) bursts of sound (1-10 kHz) are noise from the USCG R/V *Sequoia's* engines and propellers. Frequency banding seen in spectrogram at 2, 4, 6, and 10 kHz are an interference pattern caused by interaction of engine sounds reflected at sea surface with sound propagating directly to hydrophone.

We immediately engaged in testing the hydrophone to find the exact cause. It appears the ambient water temperature, and not hydrostatic pressure, caused the hydrophone to fail. Lab tests show the power supply voltage will drop below the required 5 volts necessary to power the hydrophone's microprocessor once the temperature outside of the pressure case dropped below 5°C. This is an unexpected result given the power supply was rated by the manufacturer to operate in temperatures ranging from -40° to 80°C. Also a 2-day freezer test prior to the first deployment showed no indication that the ambient ocean temperature at Challenger Deep would be a problem for proper function of the power unit.

As previously noted, both XEOS Iridium satellite-beacon units also failed to transmit throughout the mooring recovery process. Inspection of the unit mounted on the mast showed the transmitter had leaked with seawater flooding the electronics housing. Since the beacon successfully transmitted during pressure tests prior to deployment, and there were no obvious signs of damage on recovery, we speculate that failure of the unit may have been caused by a micro-crack in the ceramic top portion that occurred during mooring descent/ascent. The beacons have been sent back to the manufacturer for inspection and eventual replacement.

VII. FUTURE DEPLOYMENT PLANS

Upon return to our laboratory in April 2015 we immediately began (1) a redesign the power supply to provide higher voltage and ensure there is adequate power to keep the microprocessor functioning at all times, and (2) a week long cold temperature (freezer) test of the hydrophone electronics and pressure case confirmed full functionality at 0°C. The Captain of the *Sequoia* agreed to allow us use of the ship to re-deploy the mooring, which was successfully re-deploy on 14 July 2015, with the goal of recovering the mooring in early October 2015.

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