Marine Physical Laboratory of the Scripps Institution of Oceanography University of California, San Diego

Project Report for Bubbleology Research International, LLC

Long-Term Acoustic Monitoring of North Sea Marine Seeps

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Introduction

Monitoring marine seeps is imperative to understanding how seafloor emissions of methane, an important greenhouse gas, may affect the atmospheric methane budget. Bubble formation sounds from marine seeps previously have been recorded with underwater hydrophones; however, there appear to be no reports of long-term acoustic recordings of these sounds. Passive acoustic monitoring (PAM), a proven method for recording marine mammal sounds and ambient noise over long periods, was used to monitor sounds from a seafloor seep area in the North Sea for three months in the summer of 2011 and for four months during the fall and early winter of 2011-2012. The analysis techniques for evaluating long-term sounds from seafloor seep systems presented are new, thus, interpretation of results from these analyses still is being developed. To date, initial data analysis has focused mostly on the first deployment data set. The second data set is still being processed into the format used for analysis, but one significant event in the late fall is presented. The recordings show high sound spectrum levels from 10 Hz to 10 kHz and above, with the low frequency contributions from ship and seismic exploration (air gun) sources, and mid-high frequency sources likely from seafloor bubble emissions or the subsurface system. Analysis of long-term spectral time series of mid-frequency sounds reveal patterns with cycles from hours to days along with high and low intensity episodic events suggesting changes in the flux of the local seep system.

Methods

Passive Acoustic Monitoring

To monitor underwater sounds over long time periods in the North Sea, a High-frequency Acoustic Recording Package (HARP) data logger, battery and hydrophone were attached to a Benthic Lander (P. Linke – GEOMAR) and deployed at 57° 55.360’N, 01° 37.862’E on the seafloor at 104 m depth (Figure 1A). The deployment was near a site of previously known high-level of seabed emissions. There were two deployments of a HARP on a Benthic Lander at this site of 3 and 4 months duration during 2011-2012. HARPs record underwater sound from 10 Hz to 100 kHz with approximately 10 months of continuous data storage onto 2.5” laptop-type computer hard disk drives. The HARP instrument is described in Wiggins and Hildebrand (2007). For the North Sea deployments, the hydrophone was mounted horizontally within the Benthic Lander frame above the syntactic flotation (Figure 1B). Each HARP is calibrated in the laboratory to provide a quantitative analysis of the received sound field. Representative data loggers and hydrophones also have been calibrated at the U.S. Navy’s TRANDEC facility in San Diego, California to verify the laboratory calibrations.

Acoustic Data

Two acoustic data sets were recorded from 13 June to 9 September 2011 and from 1 September 2011 to 8 January 2012. Upon recovery, HARP data disks were removed from the instrument and sent to Scripps Institution of Oceanography for processing, quality evaluation, archiving and initial analysis. HARP data were recorded in a compressed format sequentially to 16 individual hard disk drives. An exact copy of the data from each HARP hard disk was made as a single large (120GB or 320GB) file disk image. The data from each disk image are uncompressed and saved into many smaller

(~1 GB) XWAV files. XWAVs are an enhanced version of the standard loss-less audio format wav and include additional meta-data information such as data timing, location, and instrument and experiment identification. In addition to full band (100 kHz) data, decimated XWAVs were generated using a factor of 8 and 100 resulting in data sets with 12.5 kHz and 1 kHz bandwidth, respectively. These decimated data sets allow for less computationally intensive, and therefore more efficient data analysis for low to mid frequency sounds.

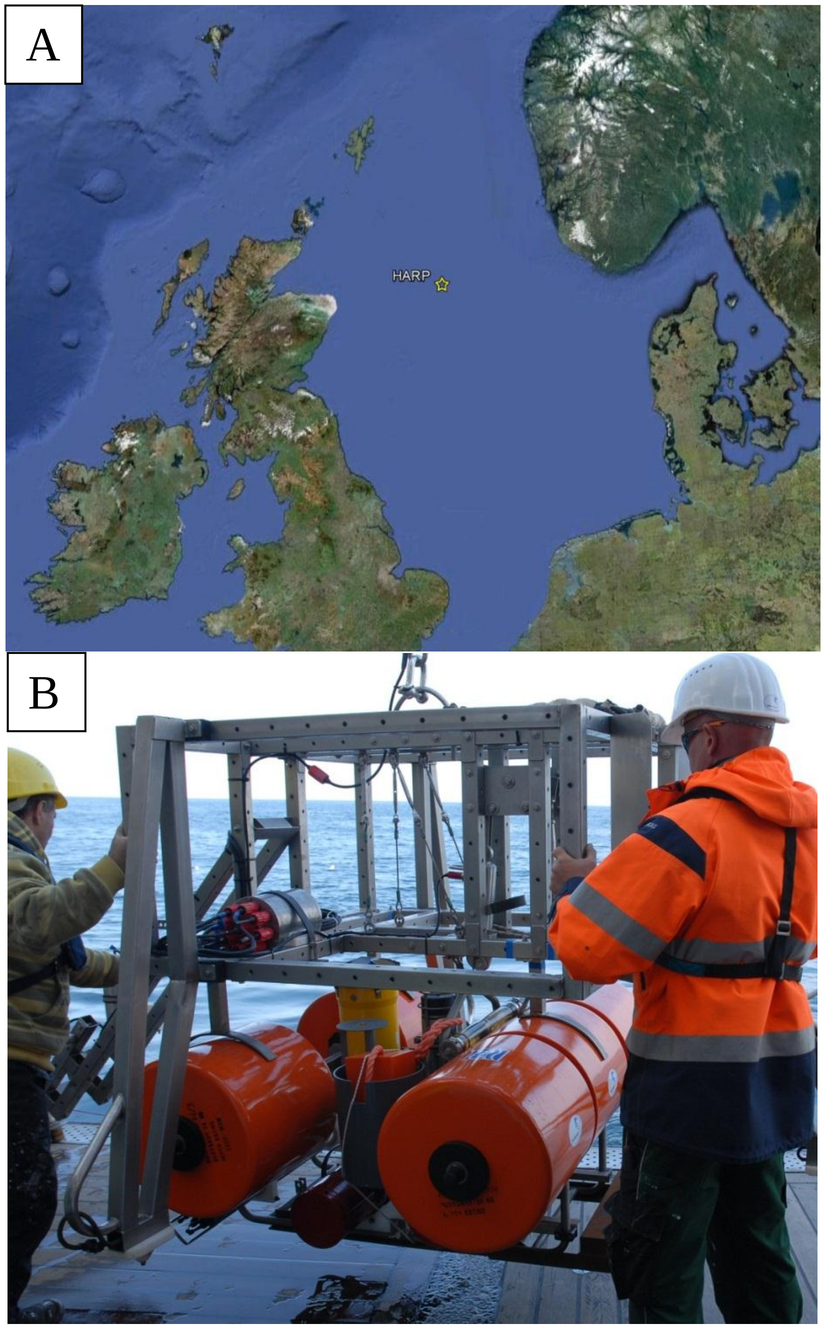

Figure 1. (A) Map of Benthic Lander with HARP deployment site indicated by yellow star in the North Sea between Scotland and Norway at 57° 55.360'N, 01° 37.862'E, 104m deep. (B) Photo of Benthic Lander with HARP prior to deployment. Hydrophone is mounted horizontally above and orange tube toward the center of the lander (photo provided by Peter Linke - GEOMAR).

Acoustic Analysis

Long-term spectral averages (LTSAs) were computed for the full band and decimated data sets to provide an efficient means of evaluating long periods of acoustic data (see Wiggins and Hildebrand, 2007). LTSAs are essentially spectrograms with each time slice covering a window of many seconds (5s for this data set) and consisting of an average of many (1000 for the full band data) non-overlapping fast Fourier transforms (FFTs) instead of just one. This spectral averaging allows hours- to days-long spectrograms to be displayed and analyzed. In addition, LTSAs provide a graphical means to easily access the original data as waveforms, spectra, and standard spectrograms for further fine-scale investigation of sounds of interest. The sets of average spectra comprising the LTSA time slices also can be used as a basis for additional analysis such as calculating and comparing average spectra over various periods from minutes to months.

Average spectrum levels were calculated for various time intervals, for example, 15-minutes, one-hour, one-day, one-month, and for the full 88 day deployment from the LTSA, but differences were small, so the full-deployment average spectrum was subtracted from the different interval-averages to provide anomalies from the mean spectrum levels. To provide a single measure of acoustic power for each interval-average, the spectrum level anomalies were averaged across a band of frequency bins. The frequency band choice depends on the spectral character of the source of interest. The acoustic anomalies for the different intervals were plotted versus time to evaluate changes in acoustic activity.

Using LTSAs, many sounds that are short duration (<1ms to >10s) and repetitive are easily identified such as biological sounds from whales and dolphins (e.g., Oleson *et al.*, 2007; Soldevilla *et al.*, 2008; Baumann-Pickering *et al.*, 2010) and anthropogenic sounds from ship echosounders. On the other hand, the acoustic signature from ship propeller cavitation is different and appears in LTSAs with much longer durations (minutes to hours) and at low frequencies, often with varying intensity interference patterns (e.g., McKenna *et al.*, 2012). Many natural, abiotic sounds have patterns that occur over even long periods (hours to days or longer) such as storms (i.e., rain, wind, breaking waves), underwater flow and seep bubble emissions. To help separate various natural abiotic sounds, additional ancillary information from other sensors can be used for correlation analysis with the acoustic recordings. For example, wind and rain data from above the seasurface can be compared to the mid-frequency band (~ 1000-20000 Hz), and subsurface pressure and current flow (ADCP) data can be associated with low frequency (<1000Hz) sound. Correlations between acoustic data and ancillary measurements were only preliminarily evaluated for this report.

Results

This report summarizes the results of the preliminary analysis of 88 days of acoustic data recorded in the North Sea from 13 June to 9 September, 2011 and one even on 8 December 2011. Discussed are recorded spectrum levels, LTSAs, spectrum level variations over time, and examples of various sound sources.

Seismic air guns

Used for seismic exploration, air gun shots were present in the recording continuously during June and July, and occurred nearly continuously during August and September, 2011. Seismic air guns are low frequency, impulsive sources, but often in shallow water wave guides, such as the North Sea, the signal can travel long distances becoming dispersed as it separates into multiple modes with different frequencies arriving at different times (Figure 2). In this data set, most of the energy from air guns arrives below 100-200 Hz, but closer sources can extend up to 500 Hz and above. Because of the constant presence of air gun sounds, most of the analysis was focused above 100 or 500 Hz.

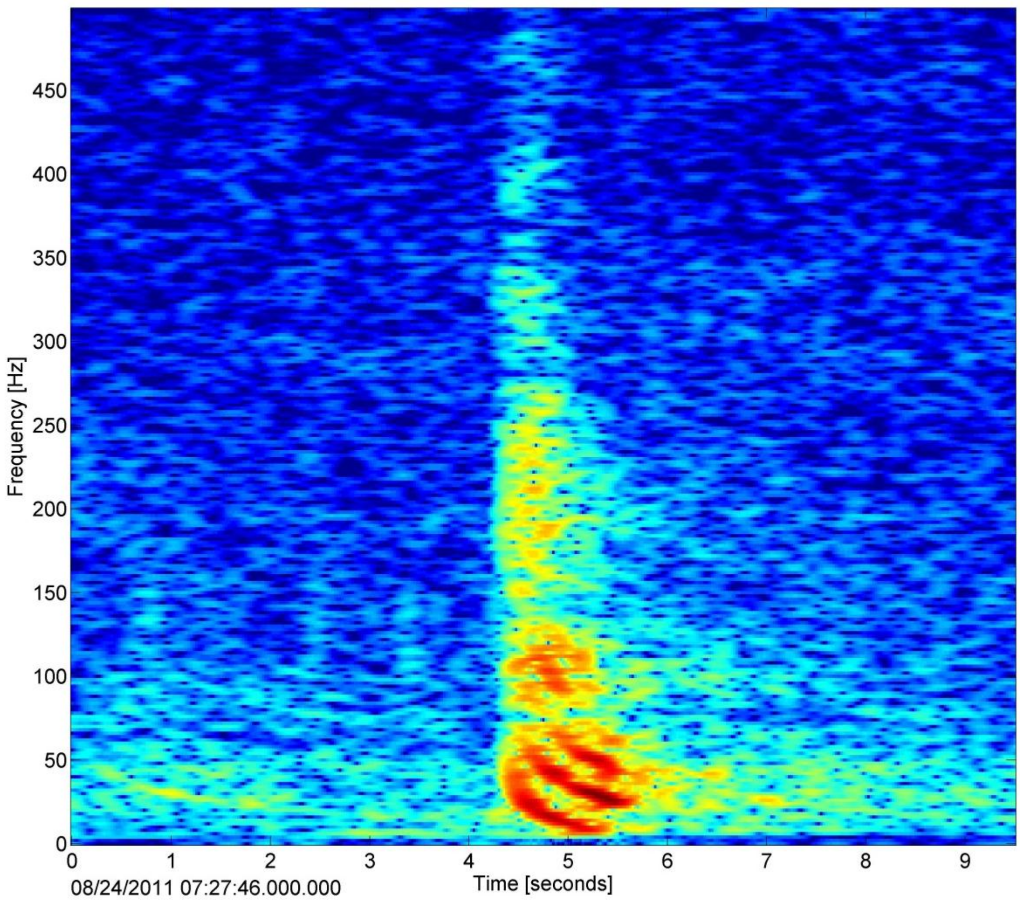

Figure 2 Example spectrogram of recorded seismic exploration air gun shot shows arrival of dispersed modes as downsweeps below ~ 125 Hz, although energy extends up to 500 Hz. Air guns were present almost continuously throughout the first data set. Spectrogram was made from full band data (200 kHz sample rate, 100,000 samples, 95% overlap, Hanning window, warm colors represent higher intensity).

Monthly Average Spectra

Spectrum levels averaged for each month were computed using the LTSAs and correcting for the calibrated hydrophone sensitivity. While June and September recordings were not full months, the average spectra levels did not vary more than 1 or 2 dB re µPa^2/Hz (Figure 3). Recorded levels are 10-20 dB higher across the 100 Hz to 10 kHz band compared to many other oceanic sites (e.g., McDonald *et al.*, 2006; McDonald *et al.*, 2008; McKenna *et al.*, 2012; Roth *et al.*, 2012). At low frequencies up to about 500 Hz, seismic exploration air guns and ships are the dominant sources.

Above about 800 Hz are spectral peaks that are likely associated with seafloor seep system based on the location of the deployment, the long-term persistent character of the spectra, and similar frequencies of acoustic energy to previous acoustic studies of natural marine hydrocarbon seafloor seeps, especially the peak near 1500-1700 Hz (Leifer and Tang, 2007).

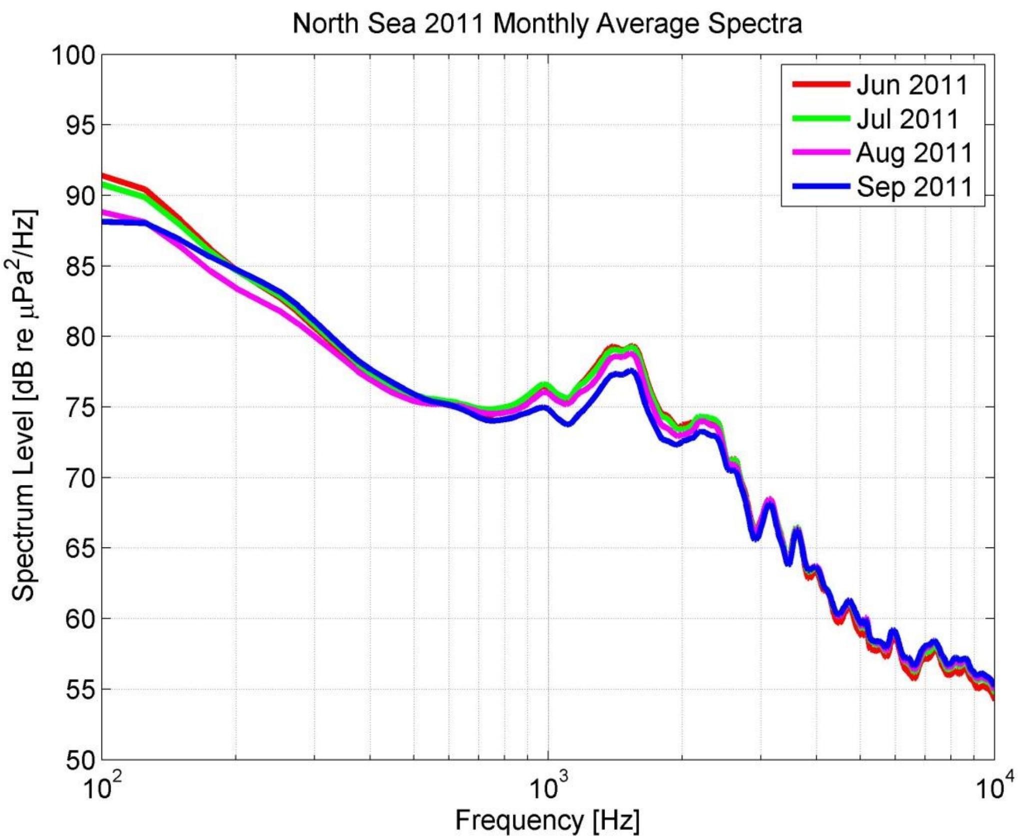

Figure 3 Monthly average spectrum levels from decimated LTSA and corrected with calibrated hydrophone sensitivity to provide values in units of pressure spectrum density.

Long-term Variations

LTSAs provide insight to spectral energy variations over long periods. An LTSA of a mid-frequency band (500 – 2500 Hz) shows periods of increased and decreased activity over the 88 day recording (Figure 4). For example, on 27 June 2011, there was a sharp decrease in acoustic energy for about one day; this event will be discussed in more detail below. Increased energy events occurred around 24 July and 28 August, both with durations lasting a few days. There was a down-step in acoustic energy around 10 August and various short-term (~ one day or less) oscillations in energy throughout the deployment, especially during the end of the recording in the beginning of September. Thirteen shorter, ~7-day LTSAs are included in the Appendix for higher resolution plots of shorter term events over the full deployment period.

Daily-mean acoustic anomalies were calculated over the 1-3 kHz band and show the same low energy event on 27 June, the high energy events on 24 July and 28 August, and the down-step event on 10 August as the LTSA (Figure 5). An overall downward trend in acoustic energy is apparent in both the LTSA and acoustic anomaly plot, but short duration oscillations are more easily observed in the LTSA plot.

Daily-mean wind speeds for Dyce Airport, Aberdeen, Scotland (57.2° N, 2.2° W) show some of the same events as the LTSA and acoustic anomalies; for example, the two high energy events around 24 July and 28 August, in addition to event around 9 August (Figure 6). Even though these wind measurements were about 240 km WSW from the HARP location, the correlation with the high energy events is strong suggesting these acoustic events are related to local weather. Conversely, the low energy event on 27 June was not observed in the wind data, supporting the possibility that this event was related a decrease in activity of the seep system acoustics.

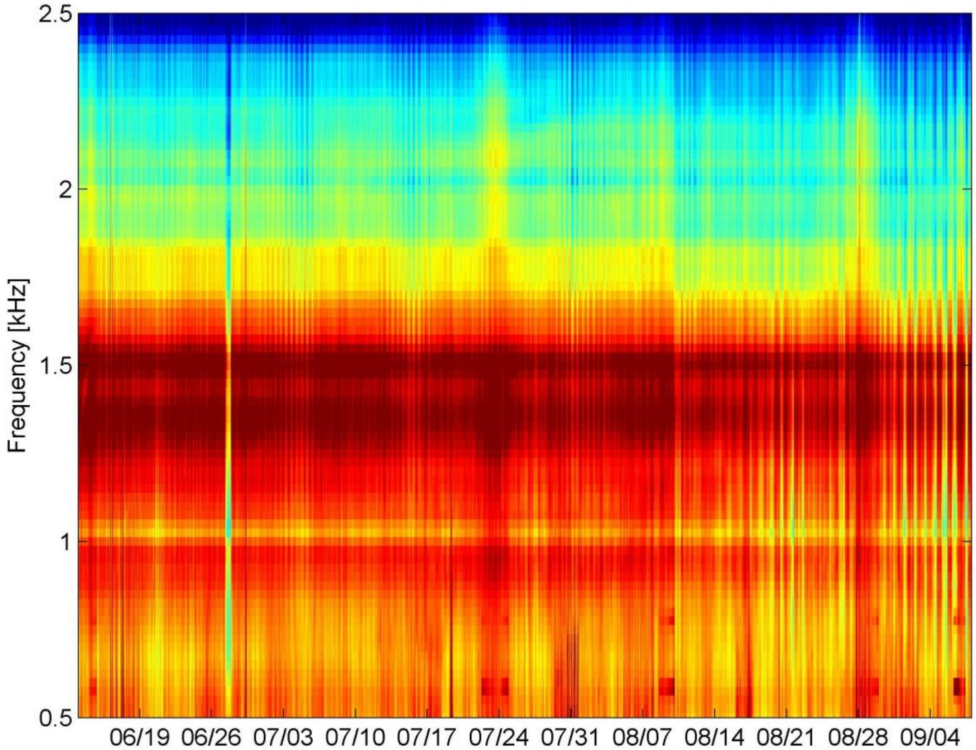

Figure 4 Long-Term Spectral Average (LTSA) of complete 88 day recording focusing on a mid-frequency band presumed to be associated with the local seafloor seep system. The beginning of the LTSA is 13 June 2011. Warm colors represent higher intensity sound than cool colors. Spectral averages are over 5s with 25Hz frequency bins.

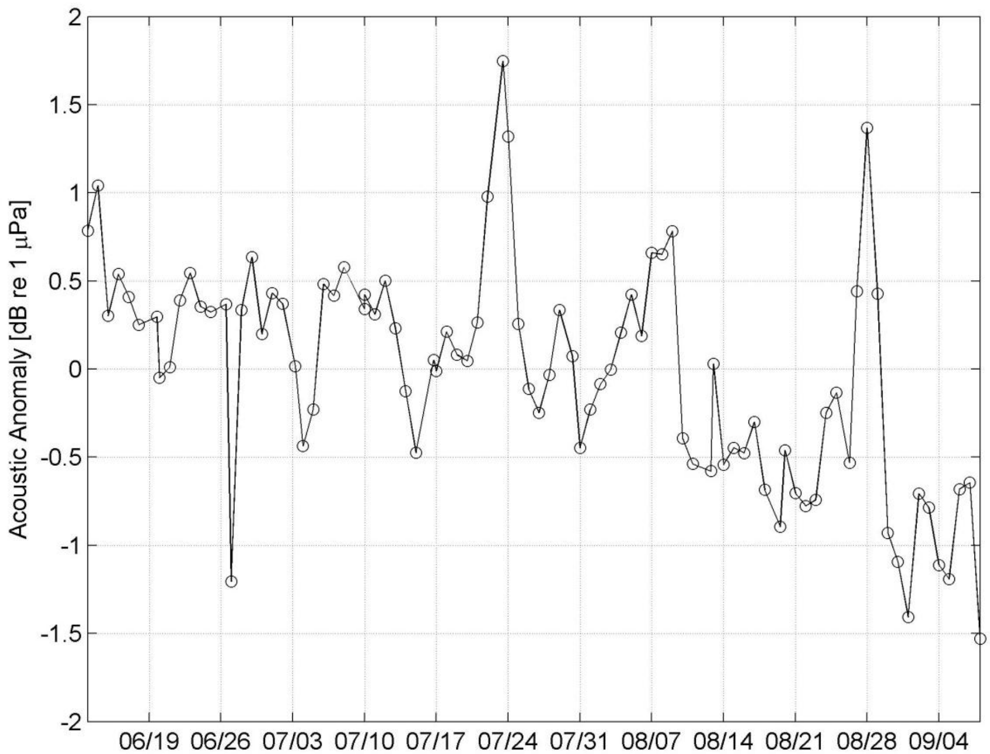

Figure 5 Daily-mean acoustic anomalies over the 1-3 kHz frequency band for the 88 day deployment. Peaks and notches, and overall downward trend match LTSA in Figure 4.

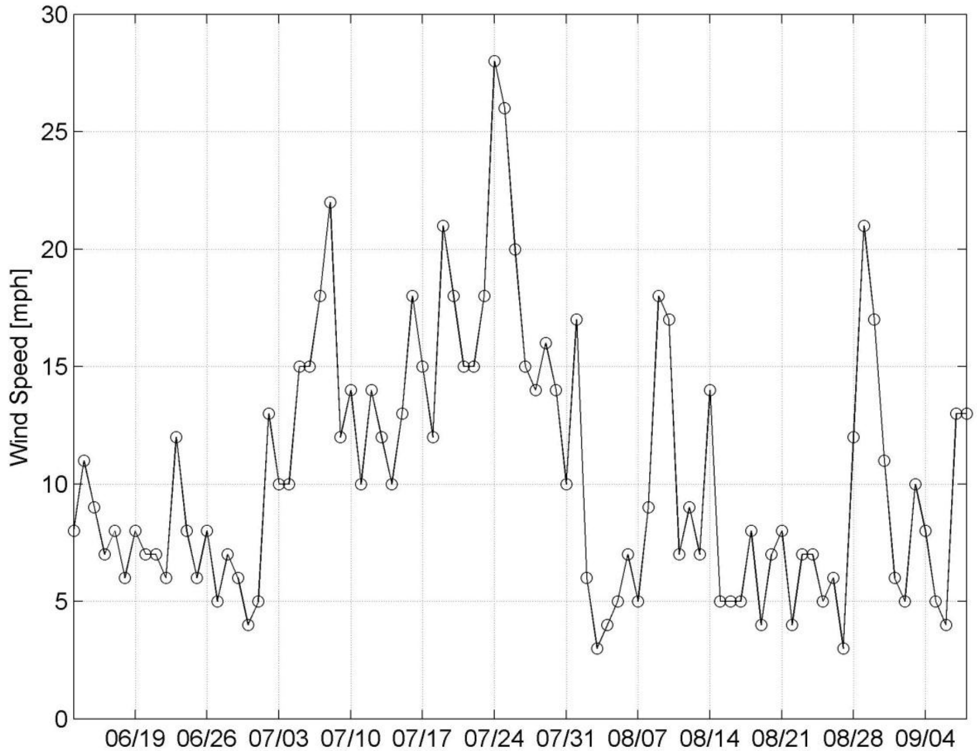

Figure 6 Daily-mean wind speeds from Dyce Airport, Aberdeen, Scotland at 57.2° N, 2.2° W ~ 8km inland from the coast and ~ 240km WSW of the HARP site. Data obtained from Aaron Howard, BRI.

Daily Fluctuations

During the last week of the first deployment, a diel pattern was observed in the LTSA and hourly-average acoustic anomaly (Figure 7). Changes from high to low and from low to high sound levels typically occurred rapidly. Even though sound levels for this week were mostly below the deployment mean (i.e., < 0 dB acoustic anomaly), the majority of the time the sound levels were above the median for the week with lower levels occurring for only a few hours each day.

Computing a spectrogram of the hourly-mean acoustic anomalies provides a measure of the periodicity of events on the daily and sub-daily time scales. An hourly-mean acoustic anomaly spectrogram for the first deployment shows likely tidal related events (two cycles per day) for about one week in duration every other week (Figure 8). The strong diel pattern from the LTSA and acoustic anomaly from Figure 7 is apparent near the end of the spectrogram. A periodicity of about 6 h (four cycles per day) also is present.

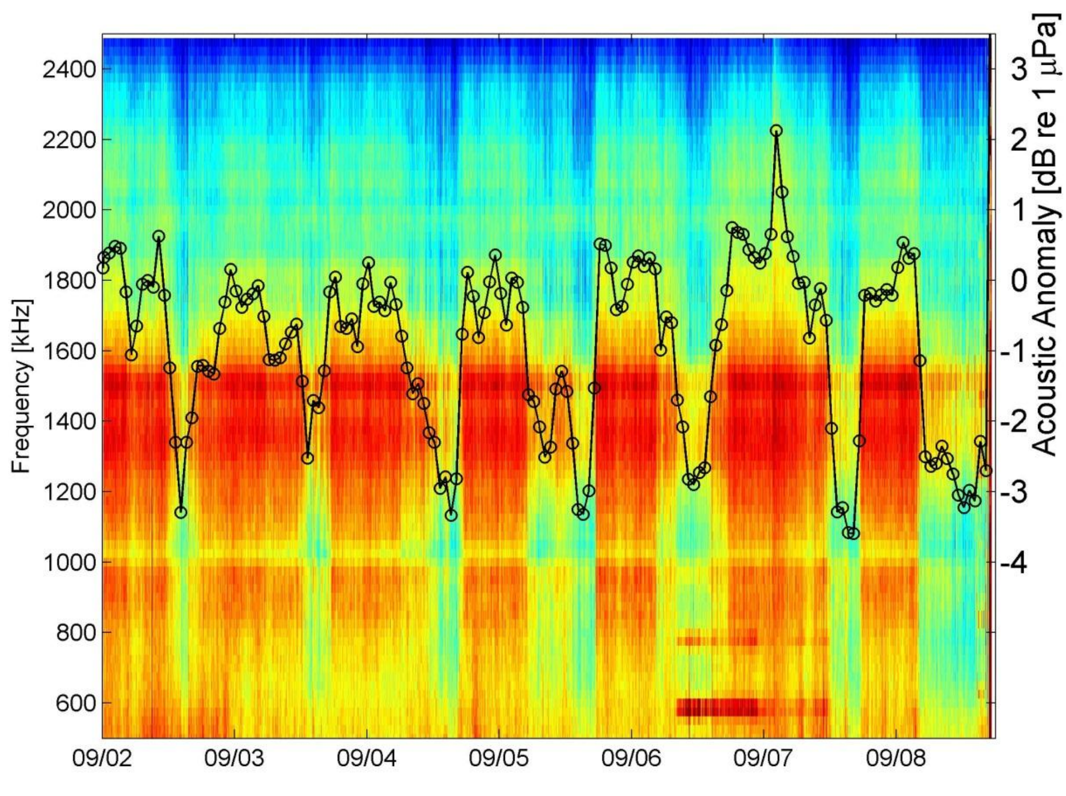

Figure 7 Starting on 2 September 2011, LTSA and hourly-averaged acoustic anomaly for the last week of the first deployment. LTSA frequency axis is on left and hourly-mean acoustic anomaly axis is on the right.

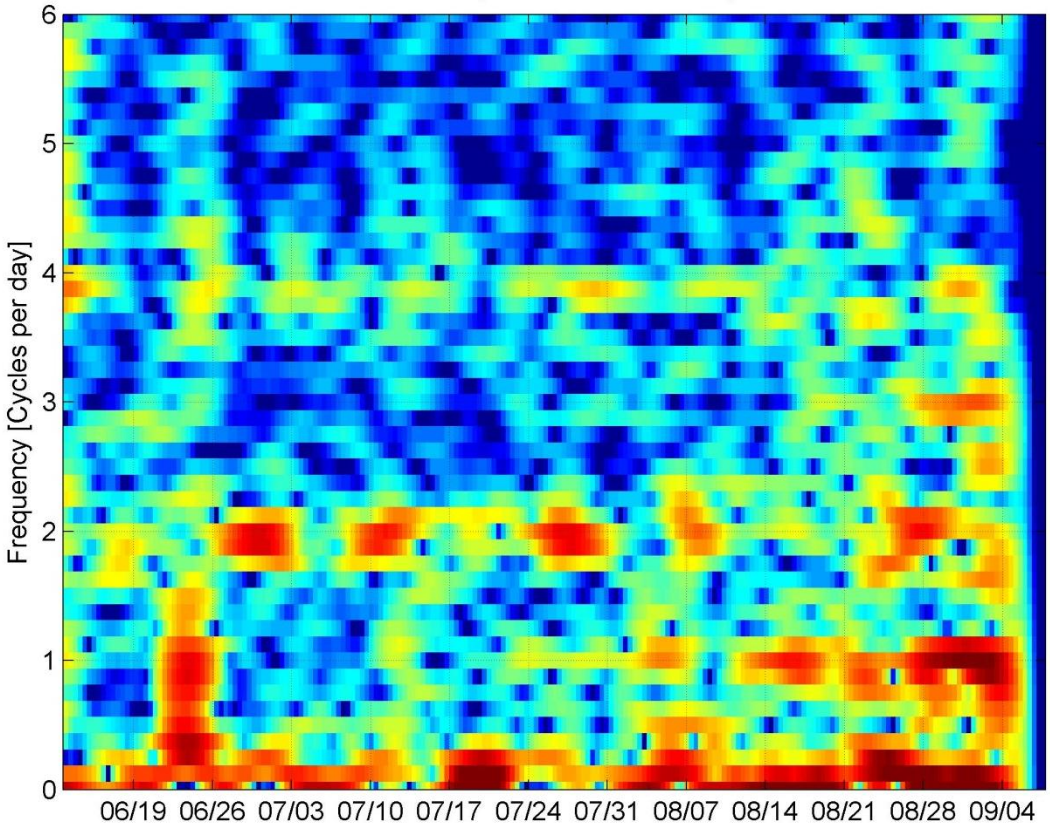

Figure 8 Spectrogram of hourly-mean acoustic anomalies for the first deployment. The events around two cycles per day are likely tidal related.

27 June 2011 Event

The decrease sound levels on 27 June 2011(Figures 4 & 5) is shown in finer detail with LTSA and 15-minute mean acoustic anomalies over a 24 h period (Figure 9). The acoustic levels are slightly raised (0.5-1.0 dB acoustic anomaly) for approximately the first 5 h and then there is a sharp decrease which rebounds a few times over the next 6 h but slowly decreases until a short duration pulse is recorded just after 11 h from the beginning of the period. Three more pulses occur during low sound levels (down to ~ -4 dB) over the next 7 h after which the spectrum returns to the slightly raised levels observed prior to this event.

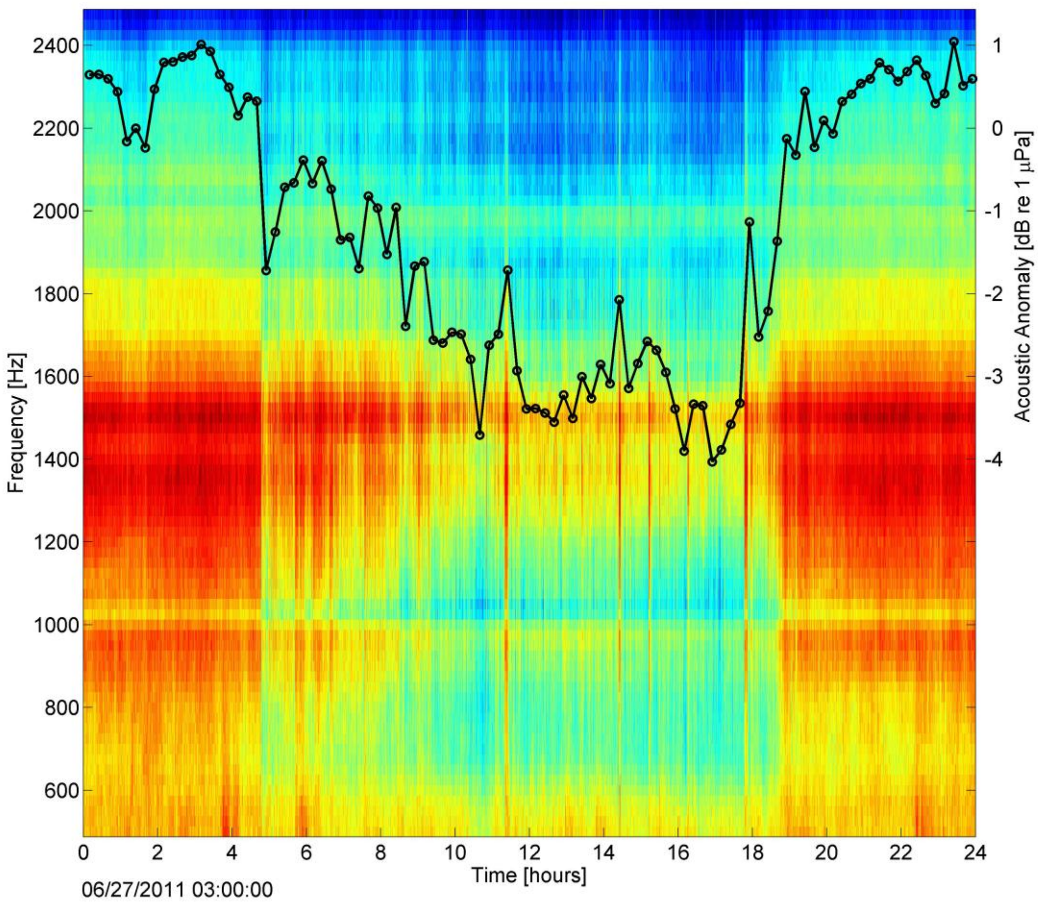

Figure 9 LTSA and 15-minute mean acoustic anomaly for 24 h starting at 03:00:00 on 27 June 2011. Left vertical axis is for the LTSA and the right vertical axis if for the acoustic anomaly.

Closer evaluation of the pulses shows that they are one to two hours apart and only a few minutes in duration (Figure 10).

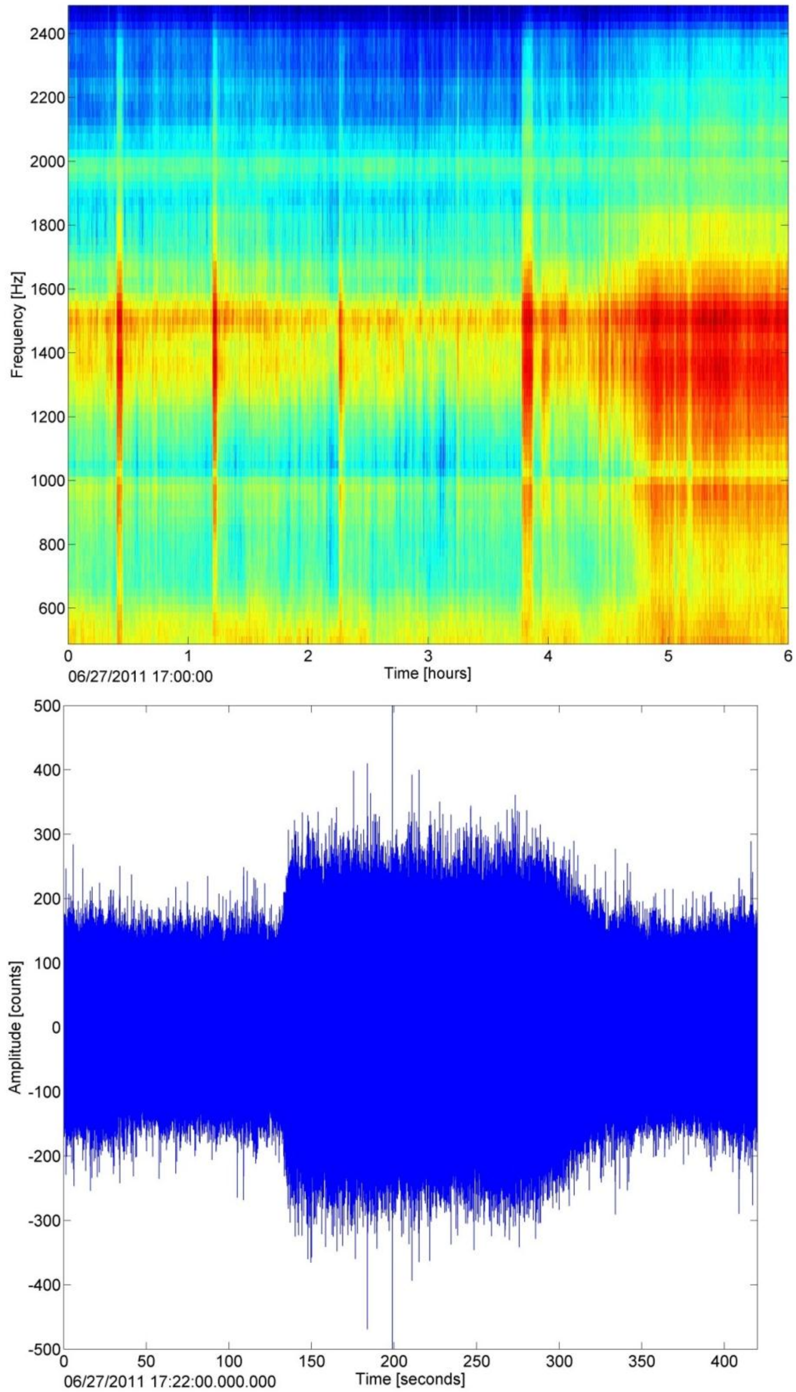

Figure 10 Increased sound level pulses during 27 June 2011 low sound level event. Top panel, 6-hr LTSA, shows interval between pulses ~1-2 h and the bottom panel, 7-minute time series, shows the pulse events are a few minutes in duration.

8 December 2011 Event – Second Deployment

As July 2012 when this report was formed, the acoustic data for the second deployment had not been completely processed, and therefore, not available for analysis. However, during preliminary data quality evaluation, an anomalous acoustic event was detected on 8 December 2011 around 20:20 GMT. The event was an abrupt increase in acoustic energy lasting many days (Figure 11). A time series of salinity measurements over the second deployment also shows a significant change just prior to 9 December (Figure 12).

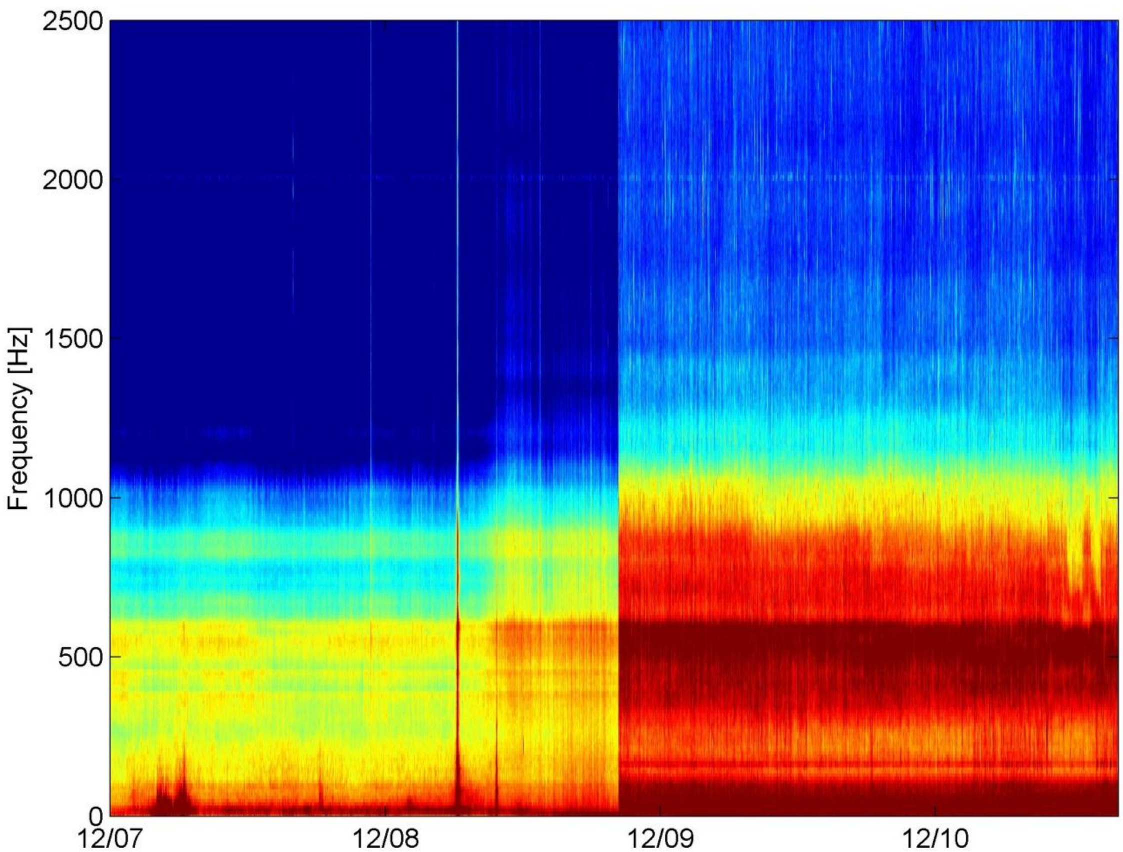

Figure 11 LTSA over less than four days starting at 7 December 2011. Near the end of 8 December at 20:20 GMT an abrupt and long-lasting increase of acoustic energy occurred across the frequency band suggesting a major change the acoustics of the seep system. The short-term event around 04:00 on 8 December was from a transiting ship.

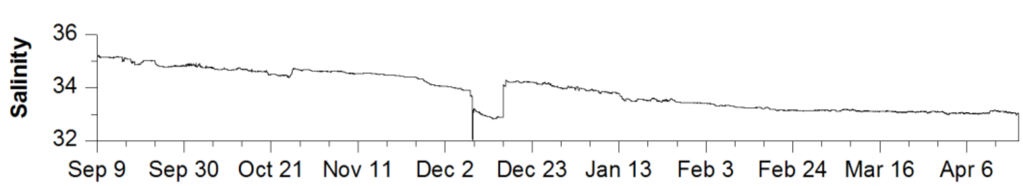

Figure 12 Salinity [$^{0}/_{00}$] measured during the second deployment on the Lander with an abrupt event just before 9 December with low values lasting about 1 week. (Plot provided by P. Linke – GEOMAR).

Spectrum levels 10 minutes prior to and 10 minutes after 20:20 on 8 December show about a 10 dB increase in sound levels across the frequency band from 100 to 10,000 Hz (Figure 13). Also, the spectral peak character changed slightly in frequency from before to after 20:20.

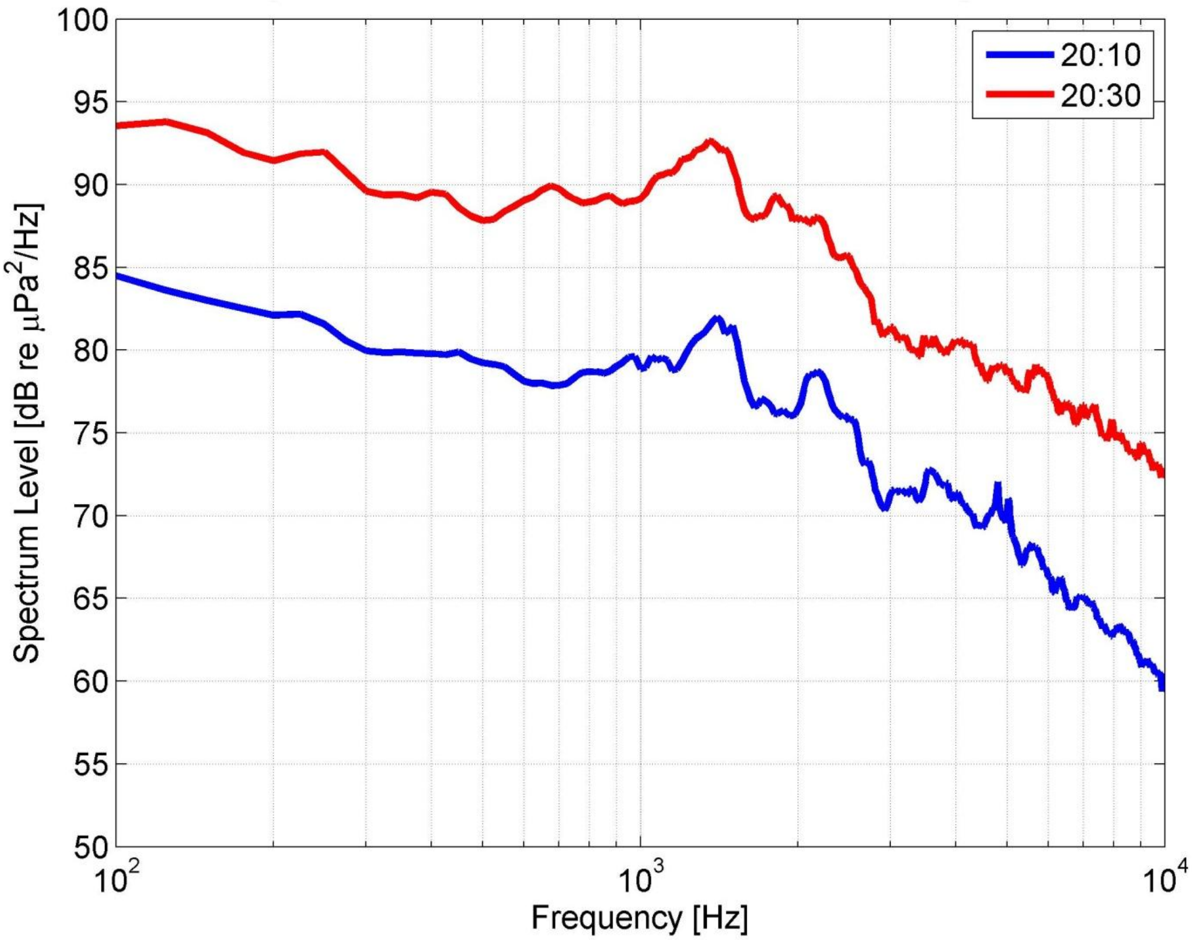

Figure 13 Spectrum levels from before and after the abrupt event at 20:20 on 8 December. An increase in about 10 dB across the frequency band from 100 Hz to 10,000 Hz occurred between the two periods with slight changes in spectral peak character.

High temporal resolution evaluation of the 8 December event shows that the onset of high acoustics levels occurred quickly over about 20 s with a few discrete high energy impulses and very low energy pulse (Figure 14).

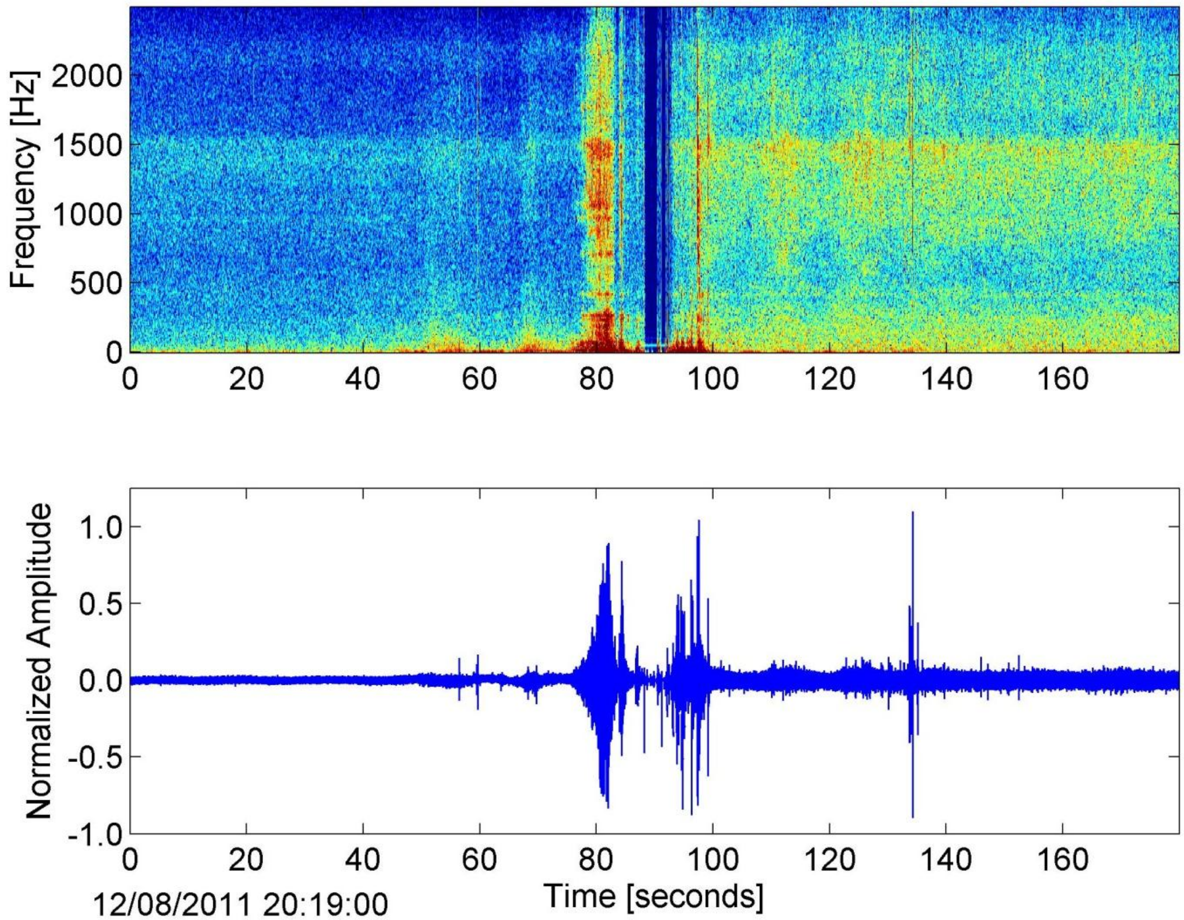

Figure 14 Spectrogram and time series from just before to just after 8 December event. While levels are increased across the frequency band after the event, the event appears to have a discrete initiation.

Marine Mammal Sounds

Marine mammals, such as whales and dolphins, make sounds that can be recorded with a HARP. While the focus of this project was not marine mammal recordings, two distinct types of sounds, likely from porpoises and dolphins, were recorded and noted while analyzing the acoustic data (Figures 15 & 16). Because the deployment site is at relatively shallow depths, sounds from sperm whales or beaked whales are not expect in the data as these are deep diving species. Baleen whales, such as fin whales, may occur near the deployment site, but the presence of persistent airguns and ship sounds in the same frequency band as these animals precluded detecting any fin whale calls in the first data set. Perhaps less anthropogenic activity in the area during the second deployment in the early winter will allow baleen whale sounds to be detected.

The dolphin encounters observed at this site last only a few minutes likely because the shallow water depth results in absorption of the high frequency energy as the clicks reflect off the seafloor. The dolphin echolocation clicks show a spectral peak structure similar to Pacific white-sided and Risso's dolphin offshore of southern California (Soldevilla *et al.*, 2008). This structure is presumed to be caused by the shape of the animal's head and reflections within the head. Dolphin's that are known to occur in the North Sea and that have head morphology similar to those two Pacific species are Atlantic white-sided and white-beaked dolphins. The spectral peaks for the North Sea dolphins are around 27.5, 35, and 42 kHz, potentially with another peak near 50 kHz (Figure 15).

The porpoise encounters are also short in duration, but consist of higher frequencies extending from 70 or 80 kHz up to the Nyquist frequency (one-half the sample rate or 100 kHz) of the HARP (Figure 16). It is likely that some or most of the energy from these clicks is from frequencies above the Nyquist frequency which have been aliased around to lower frequencies, as porpoises typically exhibit clicks with frequencies above 100 kHz (e.g., Mohl and Andersen, 1973). The amplitude time series of the clicks show ramping up and down of click received levels as is often observed with odontocetes when the direction of the narrow-beam echolocation clicks is swept by the hydrophone when the animal turns its head or body.

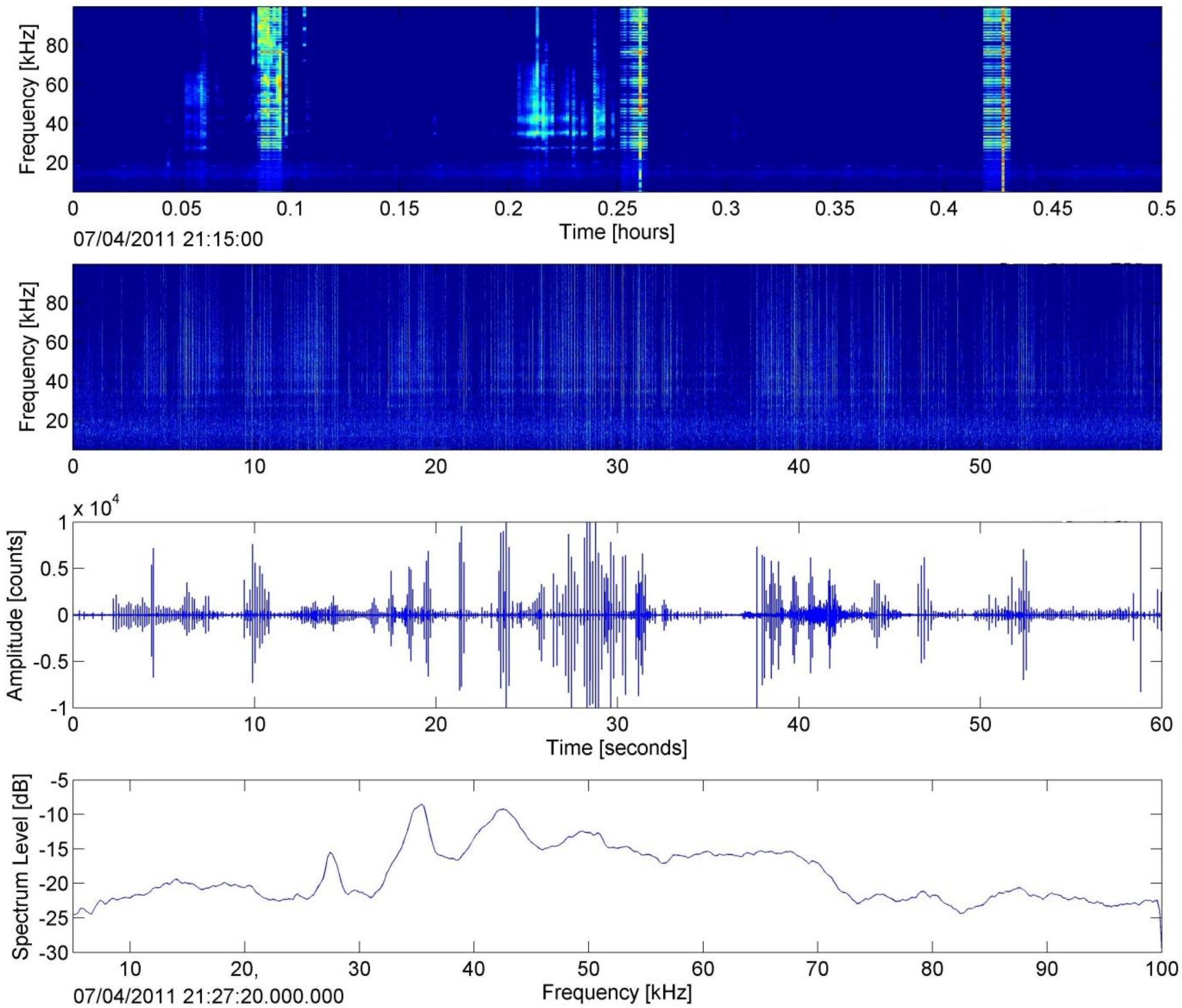

Figure 15 Dolphin echolocation clicks from the North Sea on 4 July 2011. Top panel LTSA shows two short bouts of dolphin clicking starting at 0.05 h and 0.2 h. The broadband pulses every 10 minutes (i.e., before 0.1 h, after 0.25 h and after 0.4 h) are from active sonar aboard the Benthic Lander. Middle two panels are dolphin clicks spectrogram and time series, respectively. The bottom panel is spectrum level over the 60 s window. All spectral panels clearly show a spectral peak structure associated with these echolocation clicks, potentially providing species identification.

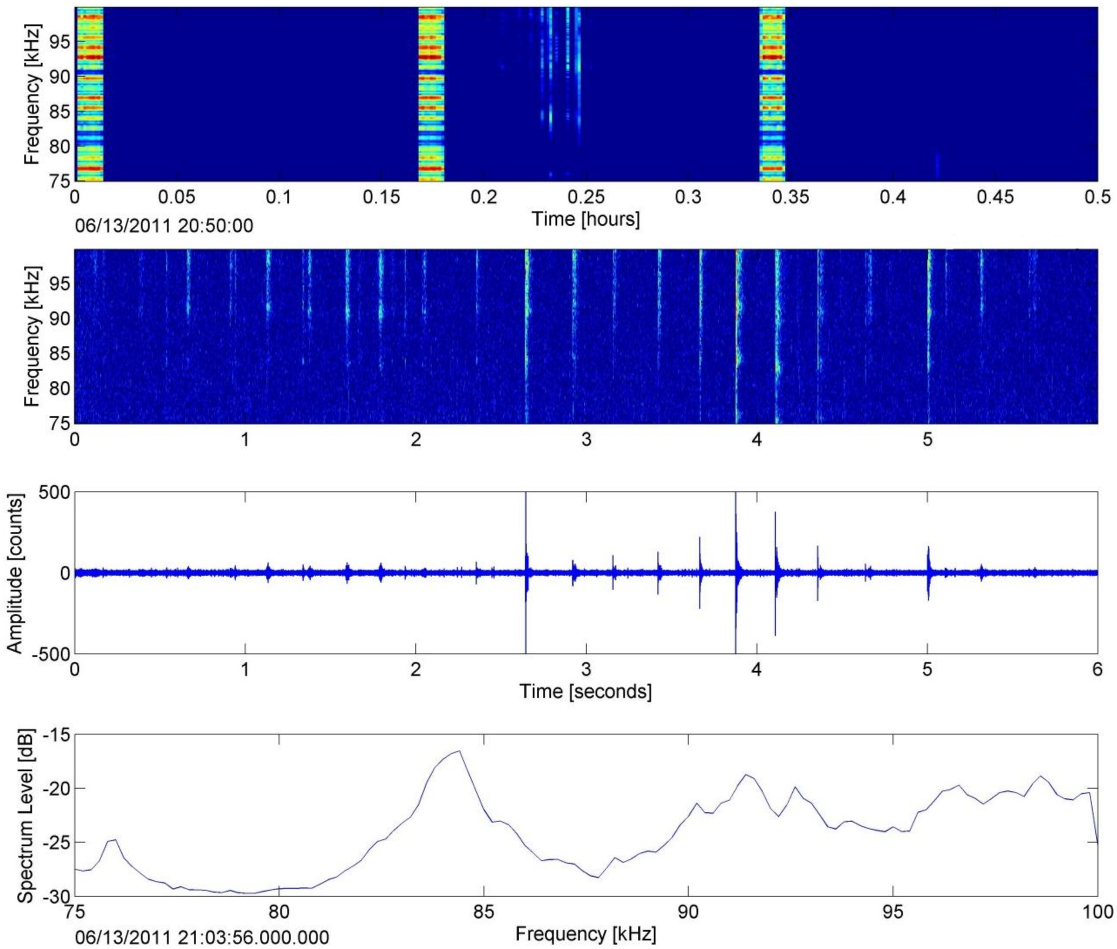

Figure 16 Porpoise echolocation clicks from the North Sea on 13 June 2011. The top panel LTSA shows porpoise clicks above 80 kHz starting around 0.22 h. Broadband pulses every 10 minutes are from sonar aboard Benthic Lander. Middle two panels are porpoise clicks spectrogram and time series, respectively. The bottom panel is spectrum levels over the 6 s window showing distinct peaks. These clicks are likely produced at frequency above the 100 kHz Nyquist frequency of the HARP and are aliased around to lower frequencies.

Conclusion

Long-term acoustic monitoring of seafloor seeps in the North Sea shows variability on various time scales potentially providing detailed information on seep activity including possible eruption (8 December), de-pressurized (27 June), and tidally influenced events. Additional studies are recommended to provide a better understanding of the correlation between acoustic measurements marine seep activity.

Acknowledgments

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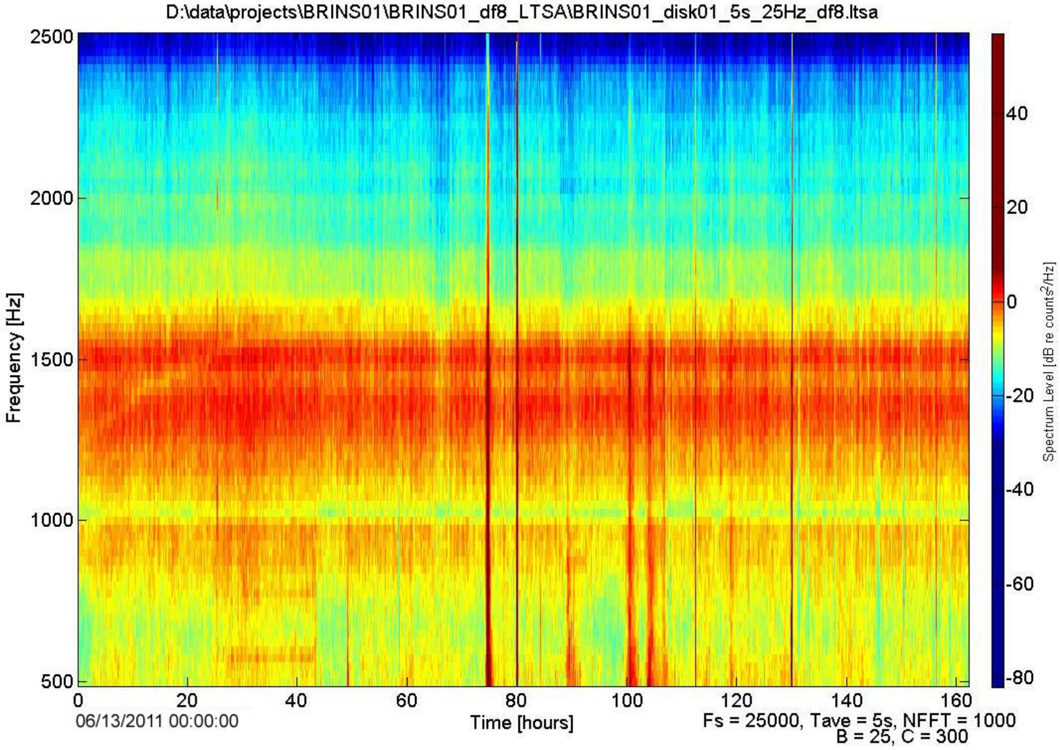
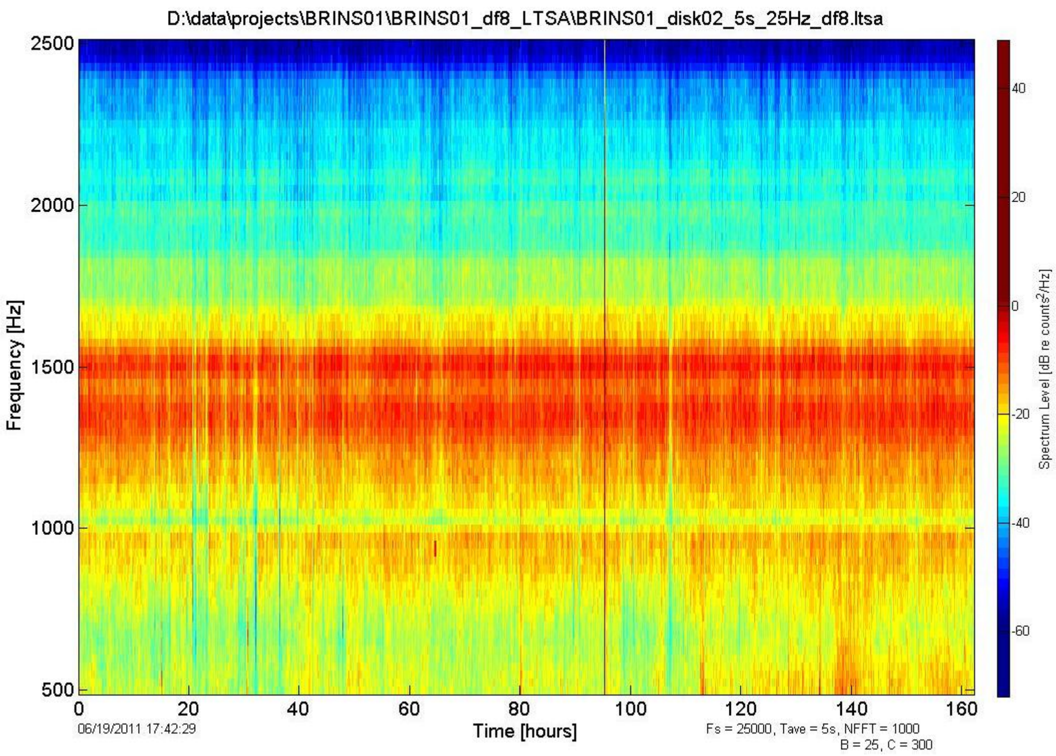
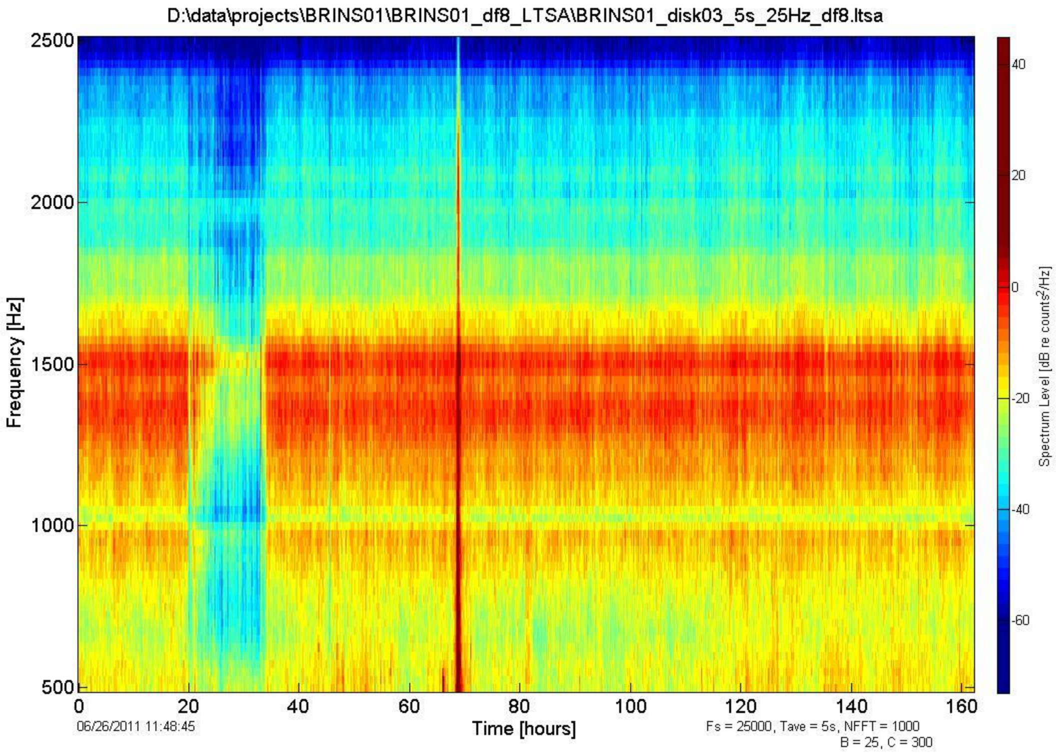
Appendix - Long-Term Spectral Averages (LTSAs) for approximately 1 week (6.75 d) from decimated x8 (i.e., 25000 Hz sample rate) data for 500 – 2500 Hz from the first deployment. Spectral time average is 5 s, and frequency bin size is 25 Hz.



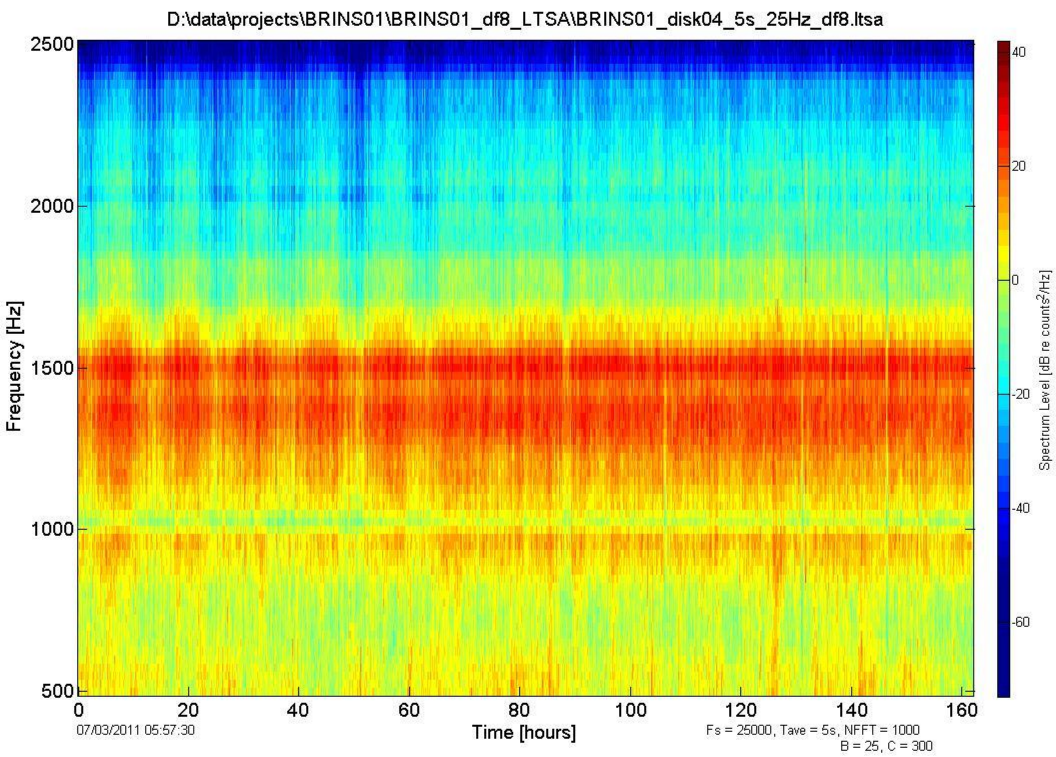
A.1 LTSA for first week.



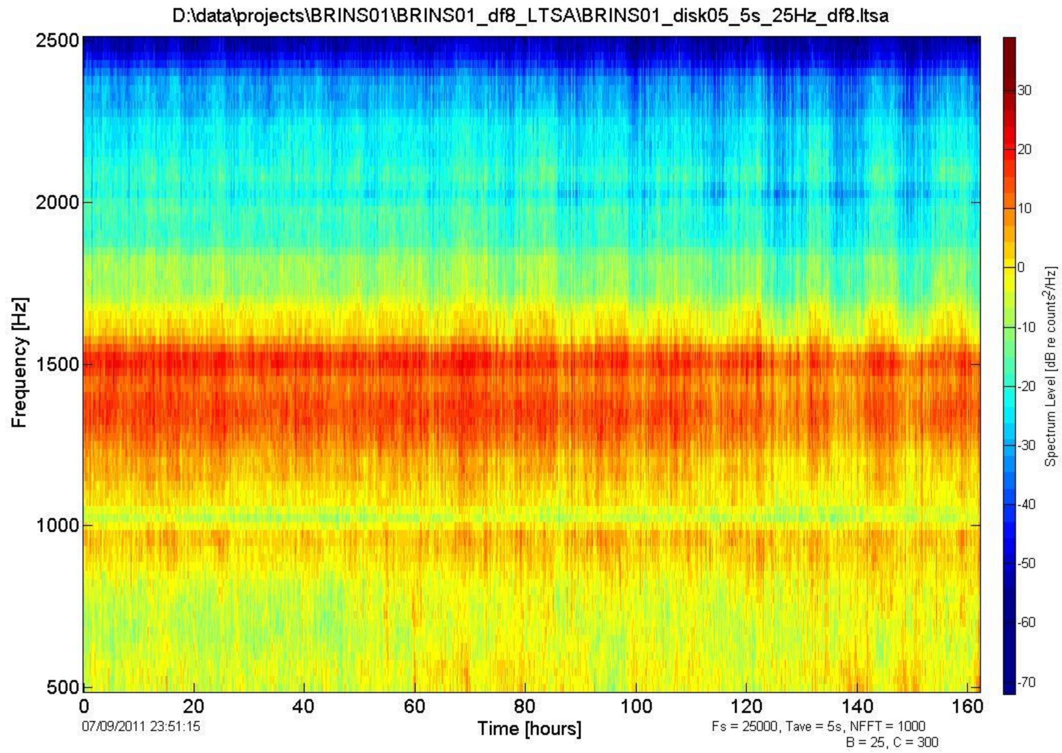
A.2 LTSA for second week.



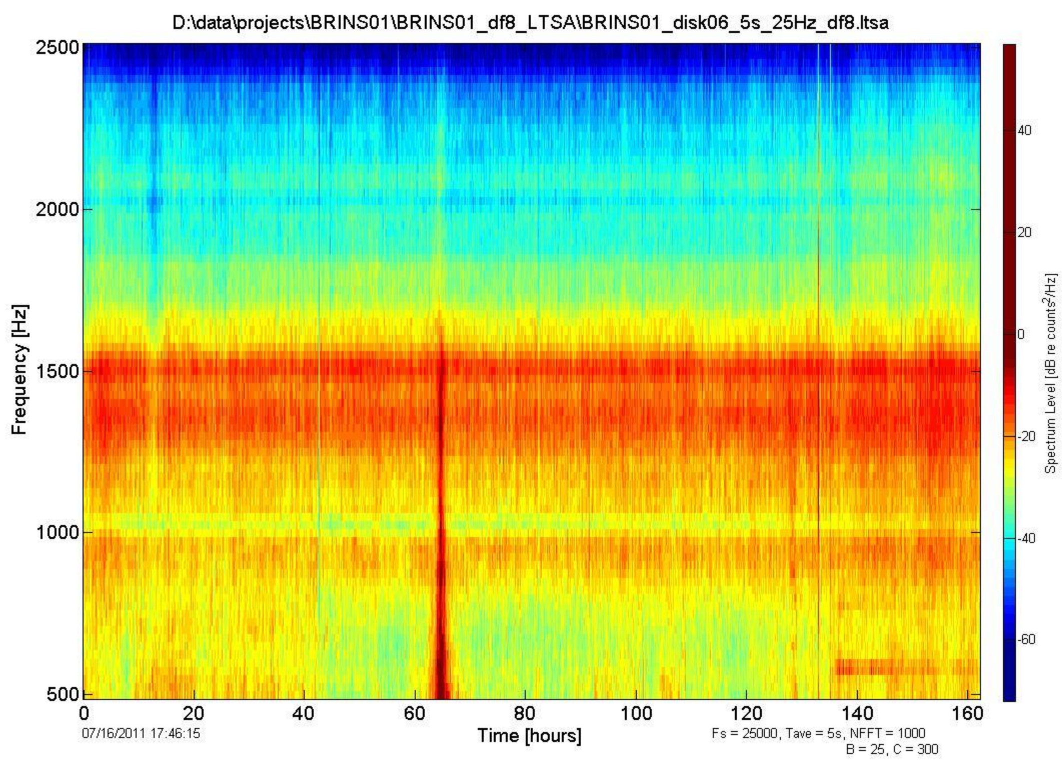
A.3 LTSA for third week.



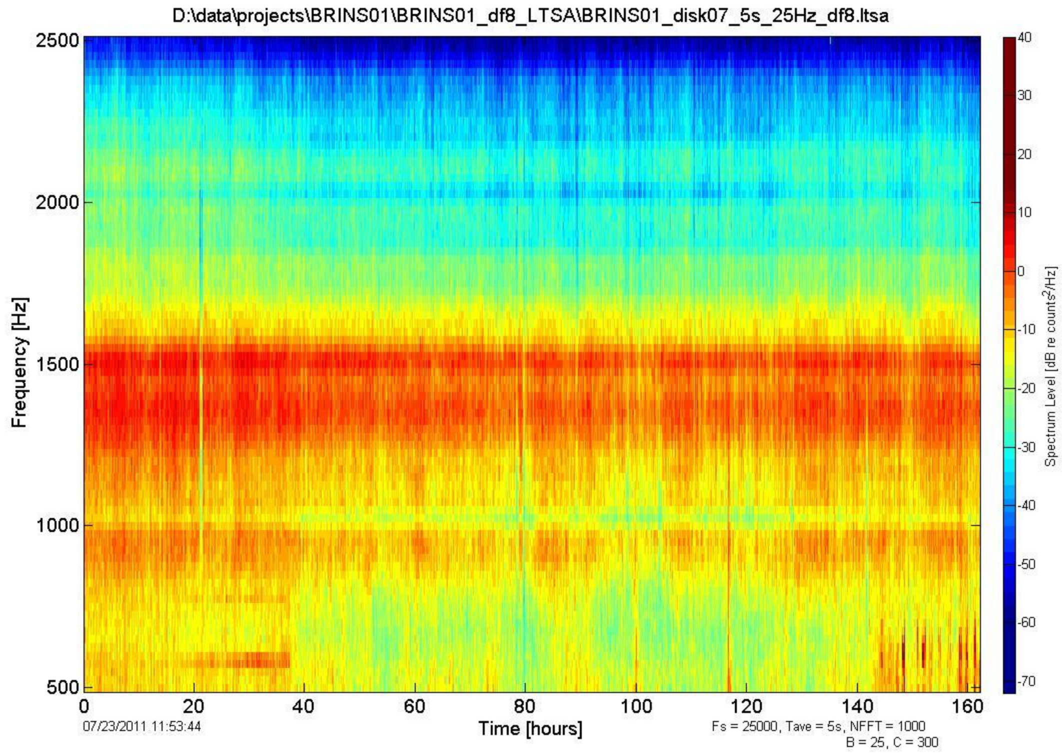
A.4 LTSA for fourth week.



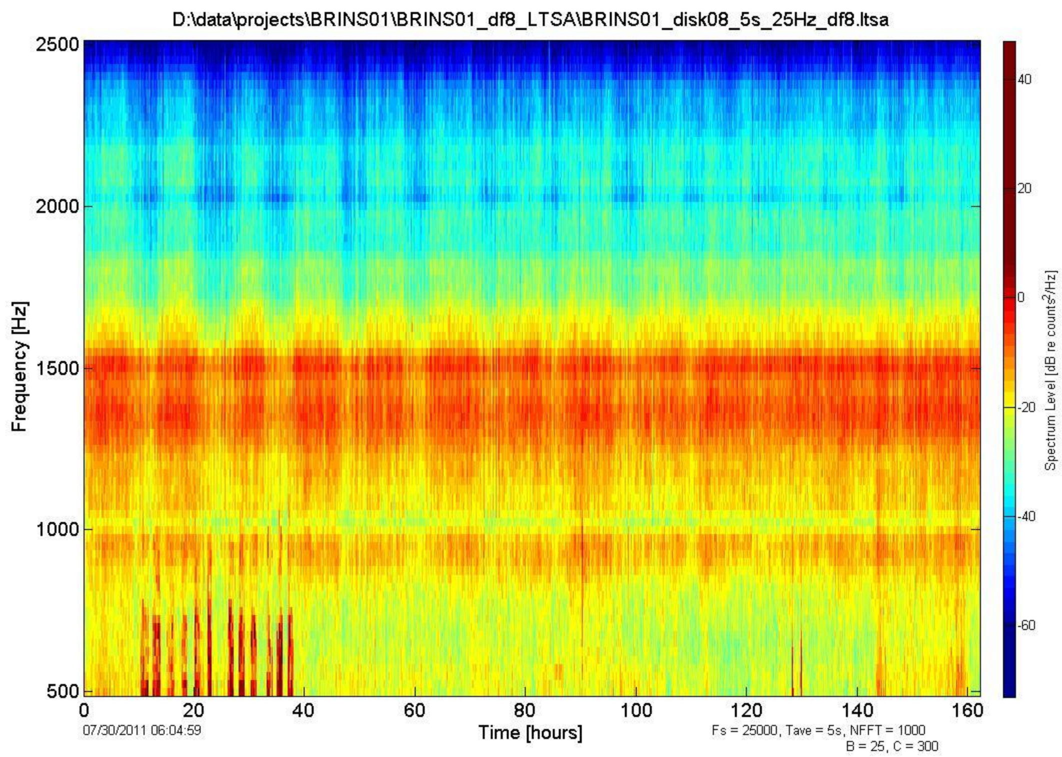
A.5 LTSA for fifth week.



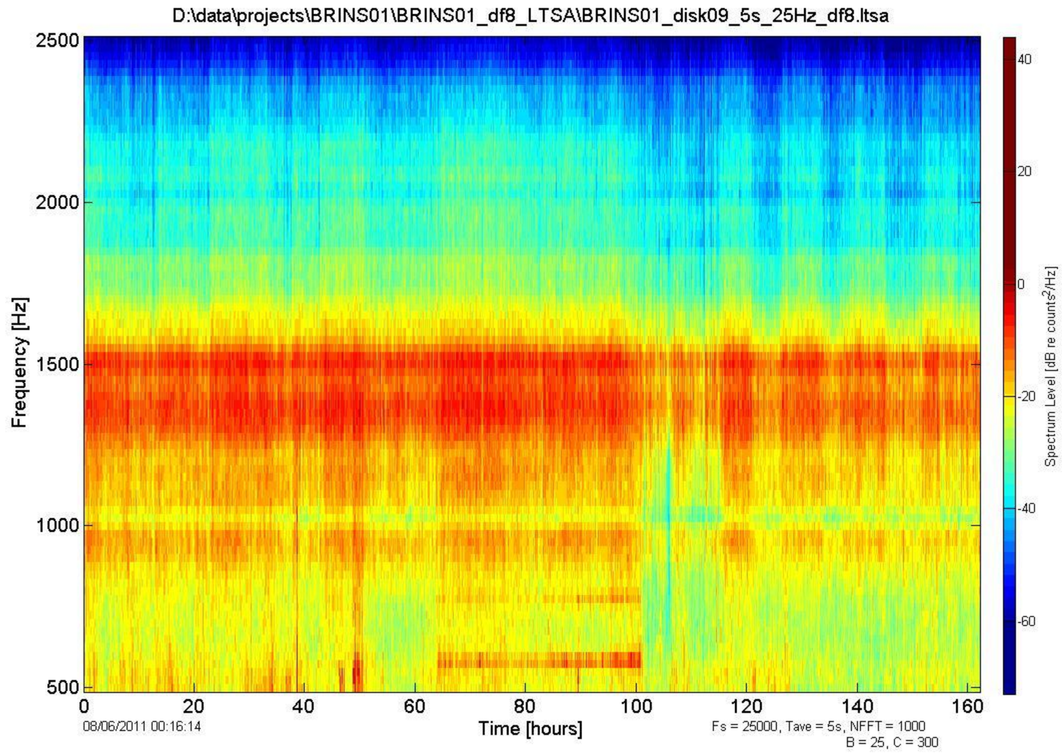
A.6 LTSA for sixth week.



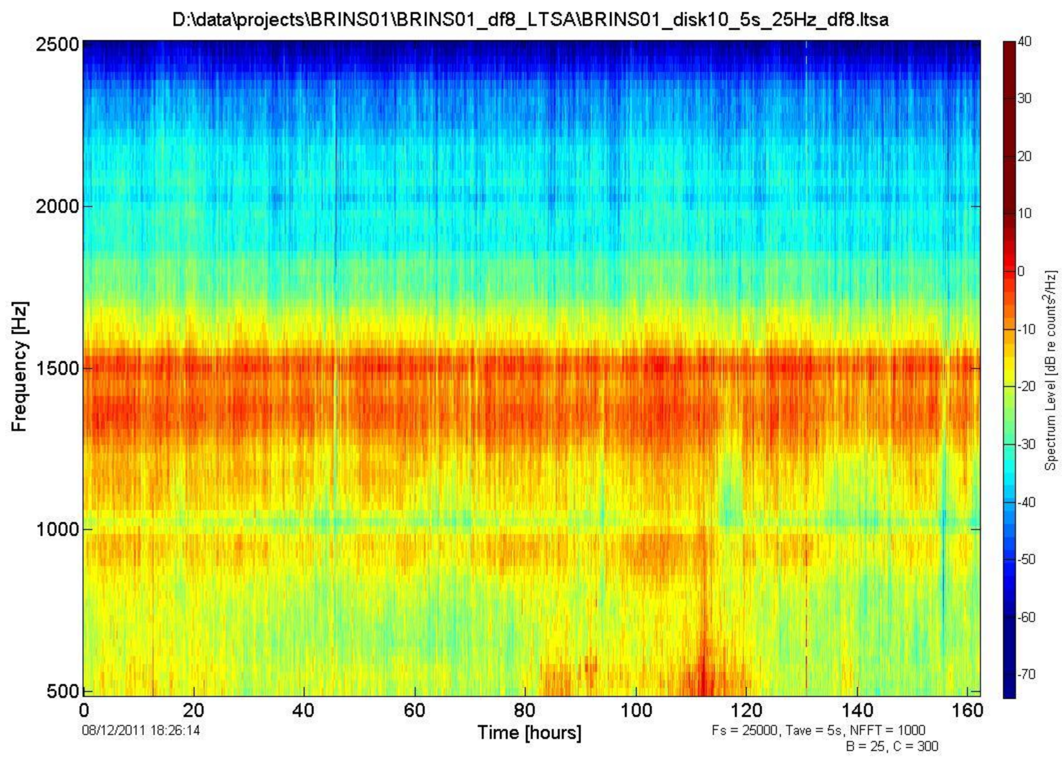
A.7 LTSA for seventh week.



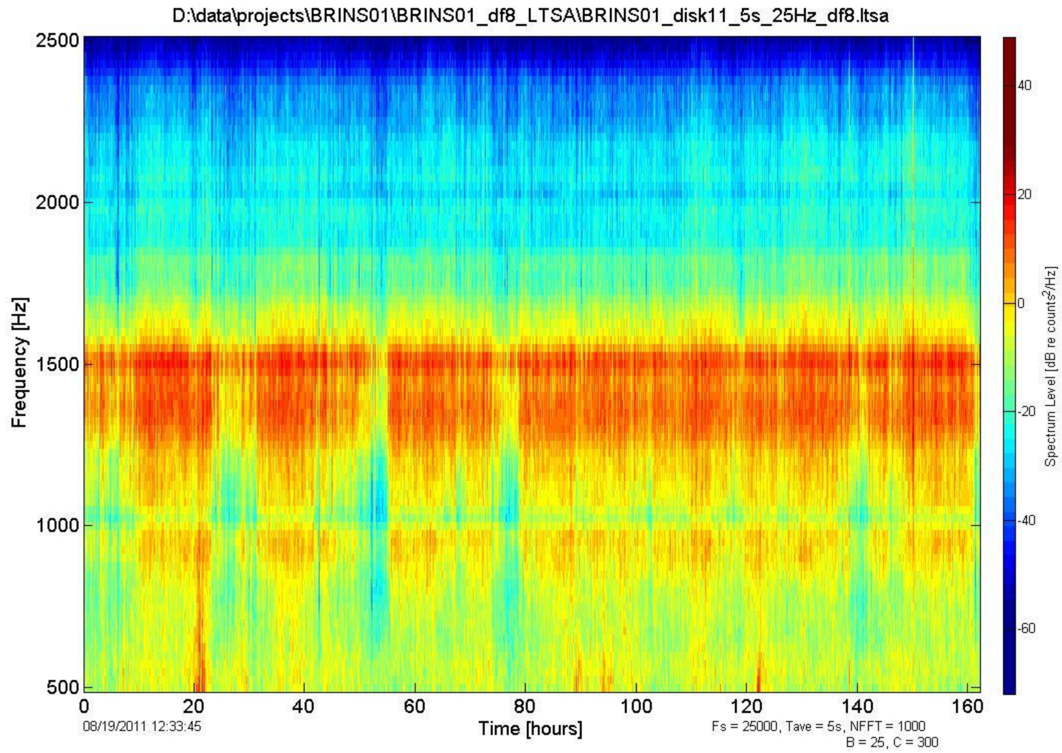
A.8 LTSA for eighth week.



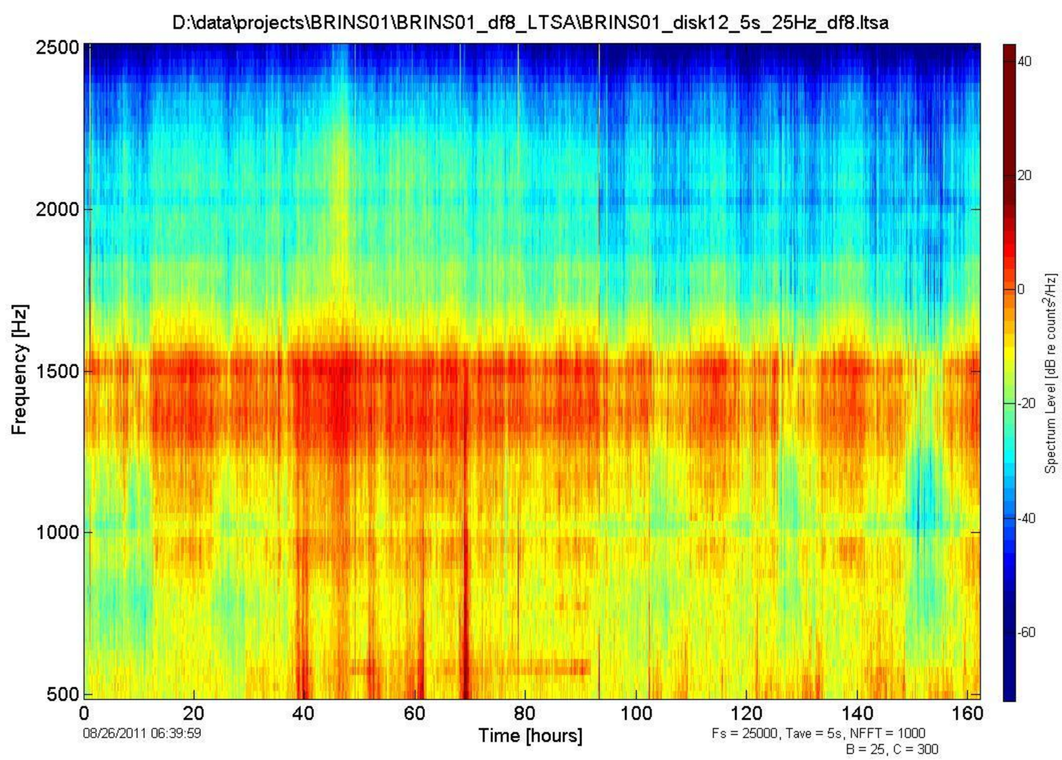
A.9 LTSA for ninth week.



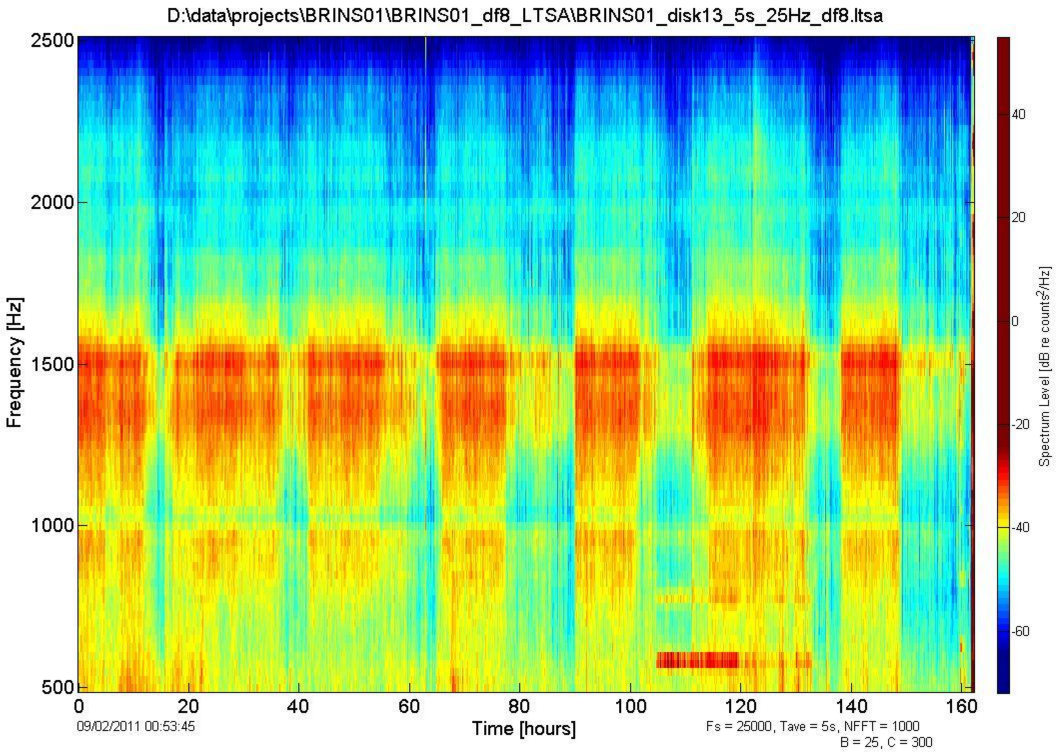
A.10 LTSA for tenth week.



A.11 LTSA for eleventh week.



A.12 LTSA for twelfth week.



A.13 LTSA for thirteenth week.