The Characterization of Underwater Infrasound Generated by Vibratory Pile Driving Within the Context of the Characteristics of Sound Known to Result in Avoidance Response by Juvenile Salmonids

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Introduction

Marine construction, including pile driving, is regulated to reduce potential impacts to migrating salmon and steelhead. The reason frequently given for limiting the time and place where pile driving can be conducted is that the generation of underwater sound may affect the behavior of migrating fish. However, until recently there was very little data to document the nature of sound generated by pile driving or the response of fish, particularly salmon and steelhead, to sound.

The construction of a new pier by Oregon State University at the Hatfield Marine Sciences Center offered the opportunity to measure the sound field generated by vibratory pile driving. Vibratory pile driving is one of the two most commonly used methods to drive piles in the Pacific Northwest, the other being impact pile driving. A vibratory pile driver consists of a heavy weight and a pneumatically driven mechanism that vibrates the pile in the plane perpendicular to the long axis of the pile. The combination of the weight on the pile and the vibratory motion forces the pile into the substrate. The maximum range of the vibratory hammer's oscillatory motion is approximately 2 inches where the vibrator attaches to the top of the pile. The sound field generated by vibratory pile driving is a result of the oscillatory movement of the pile in the water as it is being driven.

Methods

Sound field measurements were made at the new pier on 8/29-30/96. On 8/29, sound measurements were made from two different locations along the pier as fender piles were being driven along the perimeter of the pier. The fender piles being placed at this site were steel pipe approximately 9 inches in diameter and 60 feet long. Logistics and safety considerations prevented underwater sound measurements from being made at ranges less than 75 feet on the 29th.

On 8/30 a boat and operator were made available by OSU, which permitted underwater sound measurements to be made in the immediate vicinity of piles being driven. The location of the hydrophone used to acquire the sound signals relative to the location of the piles was optimal for a

series of six piles being driven along the outer perimeter of the pier. The range from the hydrophone to the piles was less than 50 feet for all six piles.

The equipment used to acquire and process the sound signals is given in the table below. The hydrophone, charge amplifier, and DAT recorder were used to acquire and store raw sound signals. The signal processing hardware and software was used to process and analyze the acquired signals.

Instrument	Manufacturer	Model No.
Hydrophone	Bruel & Kjaer	8104
Charge Amplifier	Bruel & Kjaer	2635
Digital Audio Tape Recorder	Sony	PC204Ax
Signal Processing Digital Acquisiton Board and Software	National Instruments	DSP-2200, Joint Time- Frequency Analysis Toolkit

The frequency response of the B&K 8104 hydrophone is flat from DC to 10 kHz. Over this range its receiving sensitivity is 53.7 μV/Pa. The B&K 2635 charge amplifier is designed so that the calibration constant for the hydrophone can be input to the amplifier thereby permitting the amplifier output to be read directly in terms of sound pressure level in Pa. The charge amplifier also permitted control of the gain of the output signal so that the dynamic range of the DAT recorder could be optimized. The frequency range of the Sony instrumentation digital audio tape recorder is DC to 20 kHz. The frequency response of the recorder over this range is essentially flat.

The hydrophone cable was attached to a line marked in foot increments so that the hydrophone could be easily deployed at any depth to 30 feet, the length of the hydrophone cable, while keeping the hydrophone cable free of any load. This cable length was sufficient since the maximum depth of water near the pier during the time measurements were made was 29 feet. The hydrophone was held in position by a weight attached to the bottom of the line supporting the hydrophone cable and a buoy attached to the line at the surface. The hydrophone was mechanically decoupled from the boat. The buoy was attached to the line by a snap so that its position could be changed to permit positioning the hydrophone at different depths.

The table below shows the identification number of the pile being driven, the range from the hydrophone buoy to the pile, the depth of the hydrophone, the start and stop times for each pile, and the time required to drive each pile.

Pile ID Number	Pile to Hydrophone Range in Feet	Hydrophone Depth in Feet	Pile Driving Start Time in HHMMSS	Pile Driving End Time in HHMMSS	Time Required to Drive Pile in HHMMSS
ID01	50	25	110008	110033	000026
ID02	48	25	110152	110229	000037
ID03	46	20	110401	110451	000050
ID04	46	5	111007	111027	000020
ID05	46	10	110803	110902	000059
ID06	48	15	110619	110710	000051

With the exception of the first two piles, all of the underwater sound measurements were made at different depths. This sampling strategy was selected to obtain sound measurements near the surface and bottom boundaries in addition to midwater. Although the distance between the piles and the hydrophone was short, it was unclear what effect, if any, the surface and bottom might have on the sound field. While the sampling method implemented does not permit evaluation of the effects of the boundaries, it did permit observation of the sound field generated by vibratory pile driving over the vertical range available to fish. While the use of a single hydrophone to sample a complex three dimensional sound field is limiting, the observations obtained are felt to be representative of the sound field generated by vibratory pile driving.

The recorded sound measurements were processed using a National Instruments Joint Time-Frequency Analysis (JTFA) software toolkit and DSP-2200 digital data acquisition board. The signals were digitized by taking 1,024 measurements at a sampling rate of 1 kHz. The toolkit and digital acquisition board filtered the data prior to digitization to remove frequencies higher than the Nyquist frequency at the 1 kHz sampling rate. Initial analysis of background samples showed significant energy at frequencies below 2 Hz resulting from hydrostatic (not sound) pressure variation due to low amplitude wave action. The analysis also showed that background energy

levels were down over 30 dB at 2 Hz with no significant energy above 2 Hz within the frequency range analyzed. The energy at these low frequencies was removed using features available for that purpose in the JTFA toolkit as an initial step in power spectrum analysis of the sound generated by pile driving.

The output of the JFTA toolkit included a one-sided power spectrum and time domain waveform in a spreadsheet format. The sound signal tape recording for each of the piles was sampled five times at locations approximately equally spaced throughout the time required to drive each pile. Five one-sided power spectra and time domain waveforms were obtained for each pile. All of the power spectra and waveforms were placed in a Microsoft Excel workbook which was organized by pile. Using Excel functions, the spectra and waveforms were adjusted to compensate for DAT recorder gain, differences in charge amplifier settings between piles, and to compute the mean, standard deviation, and 90% confidence interval for each set of power spectra. The individual one-sided spectra were multiplied by two to obtain the total power spectra prior to statistical analysis.

Results

The results of the six pile measurement series are summarized in Figures 1 through 18. There are three figures for each pile. The first figure for each pile is a plot of the average power spectrum for the set of five measurements made for each pile. The second figure is a plot of the individual power spectrums for each of the five measurements for each pile. The last figure for each pile is a plot of a representative time domain waveform for each pile.

The average power spectrums for each pile are very similar. Each spectrum shows spikes at low frequencies that correlate with features distinguishable in the time domain waveforms. The correlation between the time domain waveforms and the power spectra are particularly clear for piles 1, 2, 3, and 6. For all piles, most of the energy in the sound field is located at frequencies below 50 Hz with approximately half at infrasound frequencies. While the location of spectral maxima remains quite consistent from one sample to another for any pile, there is significant variation in the total power at any particular frequency from sample to sample for each pile.

The data presented also includes a set of two figures obtained from a study that characterized the sound field generated by a volume displacement infrasound source (Carlson, 1996). Figures 19 and 20 show the sound spectrum and time domain waveform for measurements of the sound field generated by a volume displacement infrasound source. These figures show that the volume displacement infrasound source generates sound with energy concentrated in a relatively narrow band around 11 Hz, which is within the range of maximum sound energy production of vibratory pile driving. Comparison of the time domain waveform of the infrasound source with that of vibratory pile driving also show similarities. Both sources show easily detectable low frequency features with the major difference being the relative "cleanliness" of the volume displacement source, a result of its design to generate sound within a relatively narrow band.

Discussion

After several decades of research, it has been learned that salmonids respond to the flow component within the near field of volume displacement infrasound sources (Carlson, 1994, Knudsen, 1992, 1994). Recently completed studies have shown that wild and hatchery Pacific salmon and steelhead from swimup fry to smolt exhibit an innate avoidance response to infrasound within the frequency range of 8 to 12 Hz at water particle acceleration greater than 0.01 ms^{-2}. (Knudsen, 1996; Neitzel, et. al., 1996). There is no ambiguity, salmonids respond to infrasound. In addition, the characteristics of sound to which they exhibit a definite avoidance response is specific and is located within the near field of the sound source, not the propagating portion of a sound field. While there is still some uncertainty about the frequency range below 100 Hz within which salmonids will respond, there is no uncertainty that salmonids respond primarily to water particle motion and not pressure.

The fact that salmonids respond primarily to water particle motion and not pressure presents sound field assessment challenges since the relationship between sound pressure and particle motion is complex within the near field of sound sources. The complication arises because it is considerably easier and cheaper to measure sound pressure than water particle motion. Given this complication, and a limitation to measure sound pressure only, the data acquisition and analysis strategy selected for this study has two parts. The first part is the use of sound pressure measurements to characterize the spectral composition and the time domain waveform (variation in

sound pressure with time) of the sound field generated by vibratory pile driving. The second part is to compare the characteristics of the sound field generated by vibratory pile driving with similar measures of the sound field generated by a volume displacement infrasound source. The volume displacement infrasound source measurements provide the characteristics of infrasound known to cause an avoidance response by juvenile salmonids. These characteristics are used as a template for interpretation of the vibratory pile driving sound data within the context of probable impact on juvenile salmonid behavior.

The first step in evaluation of the sound field generated by vibratory pile driving is to compare the frequency content of the vibratory pile driving average power spectra for individual piles with the power spectra for the volume displacement infrasound source. Comparison of the spectra show that the vibratory pile driving generates a sound field with considerable energy in the infrasound frequency range at frequencies where salmonid avoidance behavior has been observed.

In general, the power levels are similar for the volume displacement infrasound source and vibratory pile driving, particularly if the power in the individual vibratory pile driving average power spectra are integrated over frequencies in the infrasound region (≤ 20 Hz). The range between the hydrophone and the source for the volume displacement source was approximately 8 feet while that for the piles was approximately 50 feet. Under free field conditions for a propagating sound wave, this difference in range would imply that given equivalent source strengths, sound pressure levels should be approximately six times lower at 50 feet than eight feet while particle motion would be approximately 125 times lower. The difference being the rates of decay of sound pressure and particle motion which are known to be Range^{-1} and Range^{-3} respectively (Kalmijn, 1988). Even considering the fact that the sound pressure measurements for both vibratory pile driving and the volume displacement infrasound source were made in the near field (at infrasound frequencies) it seems reasonable to conclude that, in general, the source level of the piles was higher than that for the volume displacement source. The implication here being that vibratory pile driving generates infrasound at sufficiently high levels to affect the behavior of juvenile salmonids. Quantification of exactly how much higher the source level was for the piles that the volume displacement source would require considerably more data that that available in the present data set.

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The final question is the probable response of salmonids to vibratory pile driving and the range from the piles that avoidance response is likely. Controlled experiments with volume displacement infrasound sources have determined a threshold for near field particle acceleration above which salmonids exhibit avoidance response. This threshold is water particle acceleration of 0.01 ms^{-2}. The range to this acceleration value for the volume displacement source characterized in terms of power spectrum and time domain waveform in Figures 19 and 20 has been determined to be approximately 10 feet (Carlson, 1996). If the source level of the piles (i.e. the source level of an incremental portion of the pile, discounting integration over the pile or any consideration of directivity) in terms of water particle acceleration was similar to that of the volume displacement infrasound source, the region within which fish would show avoidance would look something like a cylinder with a radius of 10 feet centered on a pile. If the source strength of the pile was 10 times that of the volume displacement infrasound source, in terms of maximum water particle acceleration at the face of the pile, the radius of the region above the avoidance threshold would only slightly more than double to approximately 22 feet because of the rapid decay in particle motion with distance assuming free field conditions.

It appears unlikely that the impact of vibratory pile driving in terms of avoidance response by juvenile salmonids, given the conditions observed at the OSU pier, extends beyond the immediate vicinity of the pile driving activity. Generation of water particle motion levels in excess of fish behavioral response thresholds appears unlikely at ranges over 20 to 30 feet from the pile being driven. This conclusion is supported by the similarity between vibratory pile driving and volume displacement infrasound source observations in power levels at infrasound frequencies, the physical parameters for decay of the local flow portion of the near field of a sound source, and the results of replicated controlled experiments documenting the response of juvenile salmonids to infrasound and the threshold for observed avoidance responses.

An additional element worth discussing is the duration of generation of infrasound during vibratory pile driving. The average time it took to drive a pile was 40.5 seconds and the total time the vibratory hammer was operating to drive all six piles was 4 minutes 3 seconds. A typical day of pile driving consists of many activities such as placement of jigs, preparation of piles, and many other related tasks that must be completed before pile placement can begin. Once all the preparations for a series of piles has been completed the actual time required to drive the piles can

be very short, as this series demonstrates. This data makes it clear that vibratory pile driving construction activities do not result in continuous generation of infrasound. In fact, the amount of time infrasound is generated is most likely, for most projects, a relatively small portion of the total work time. The relatively short time during which infrasound is generated by vibratory pile driving in association with the likely relatively short range of the component of the total sound field to which salmonids show avoidance response, leads to the conclusion that it is quite unlikely that this type of construction activity has a significant impact on migrating salmonid behavior.

References

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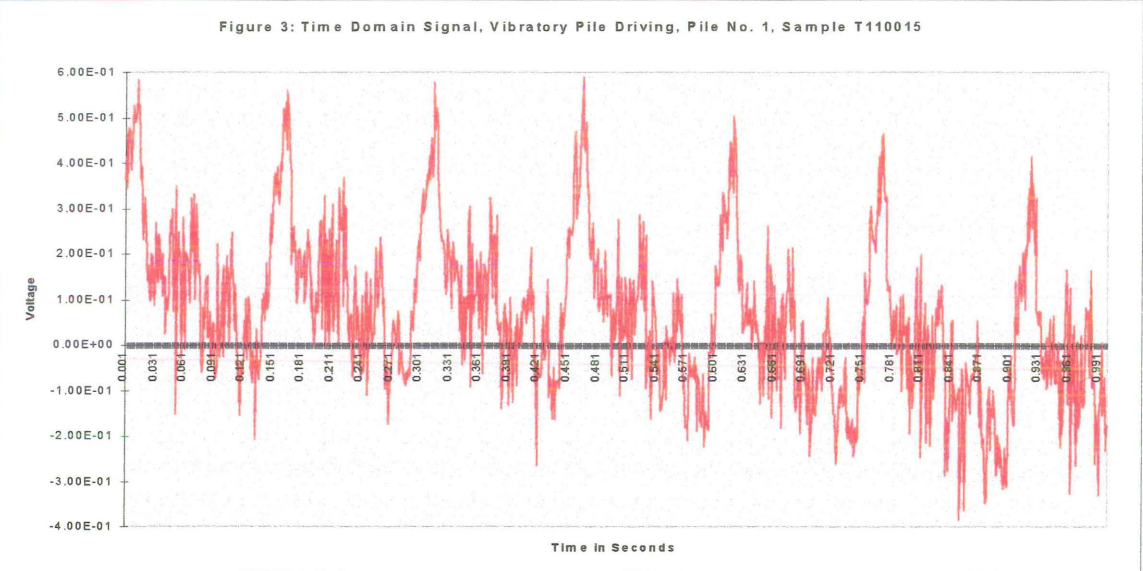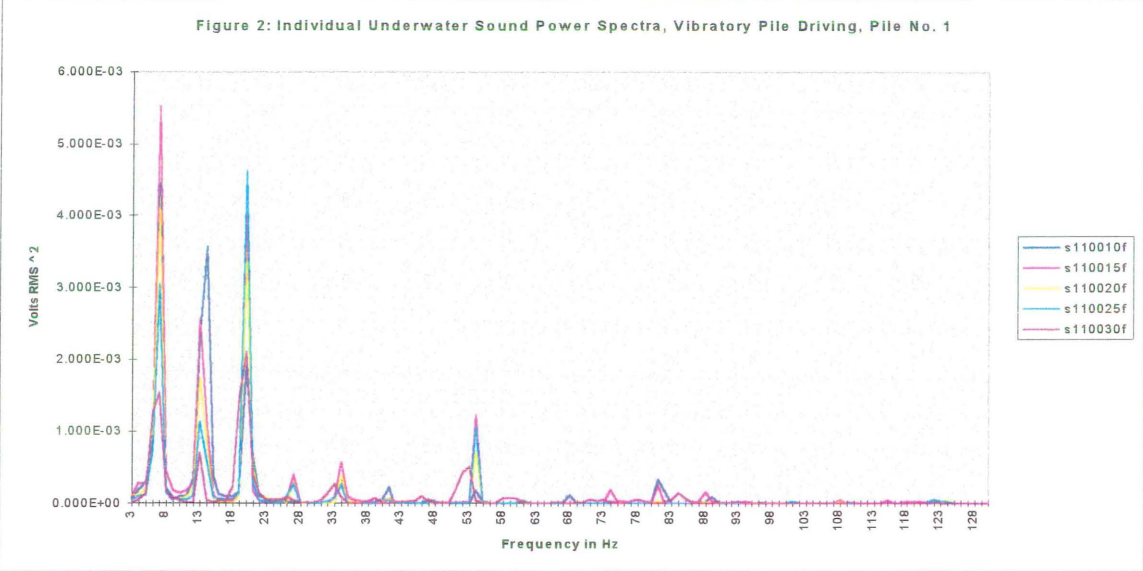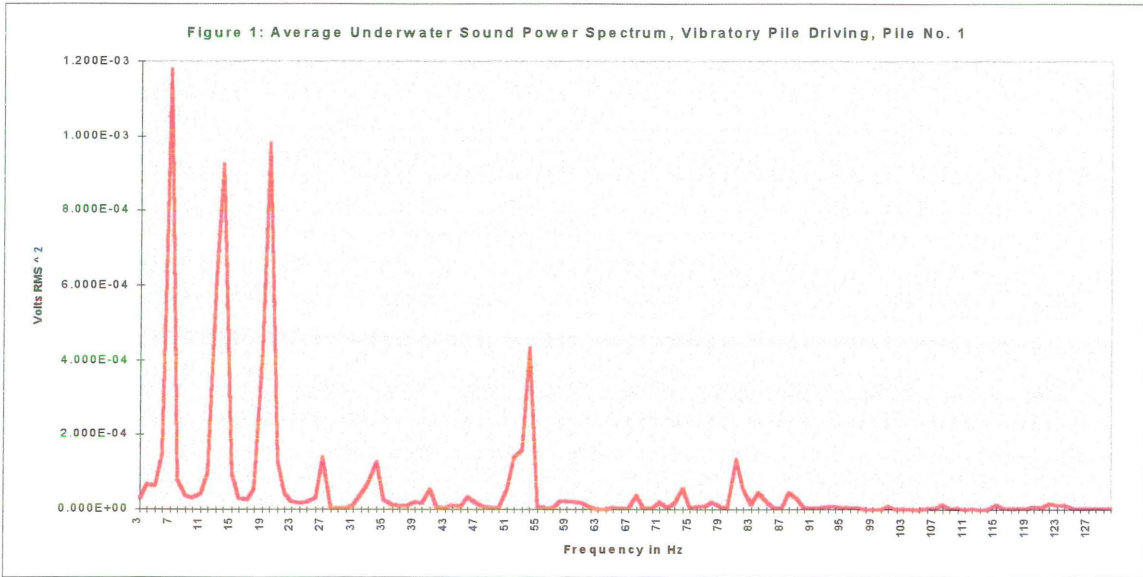
Figure 1: Average Underwater Sound Power Spectrum, Vibratory Pile Driving, Pile No. 1
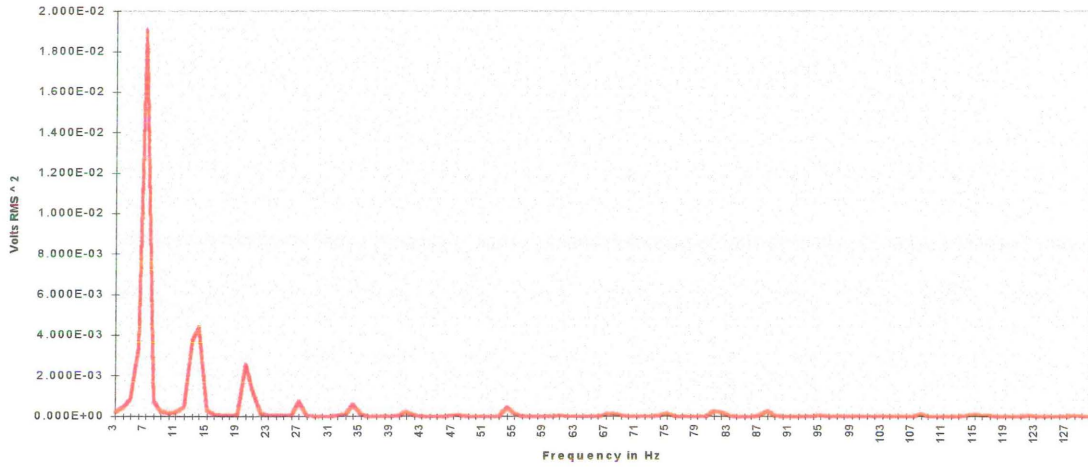

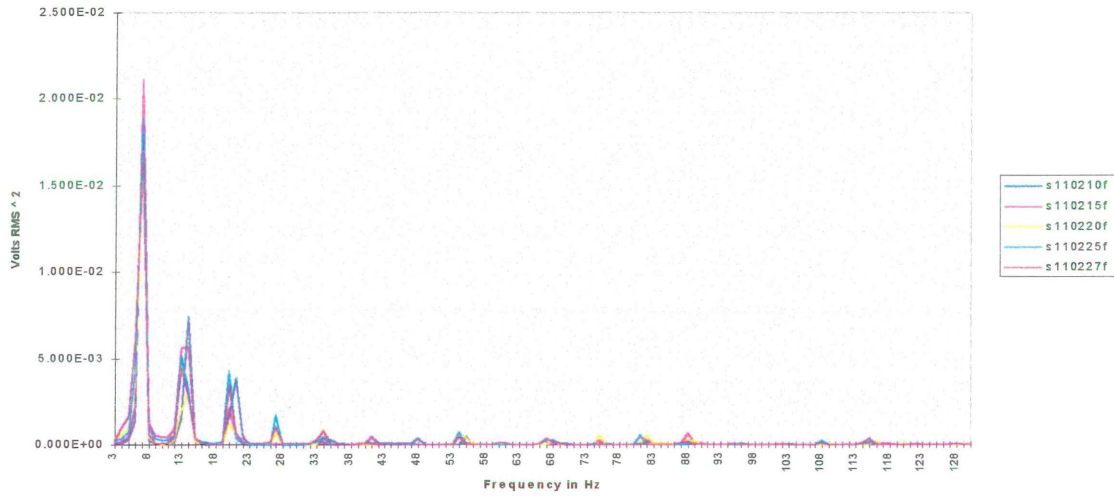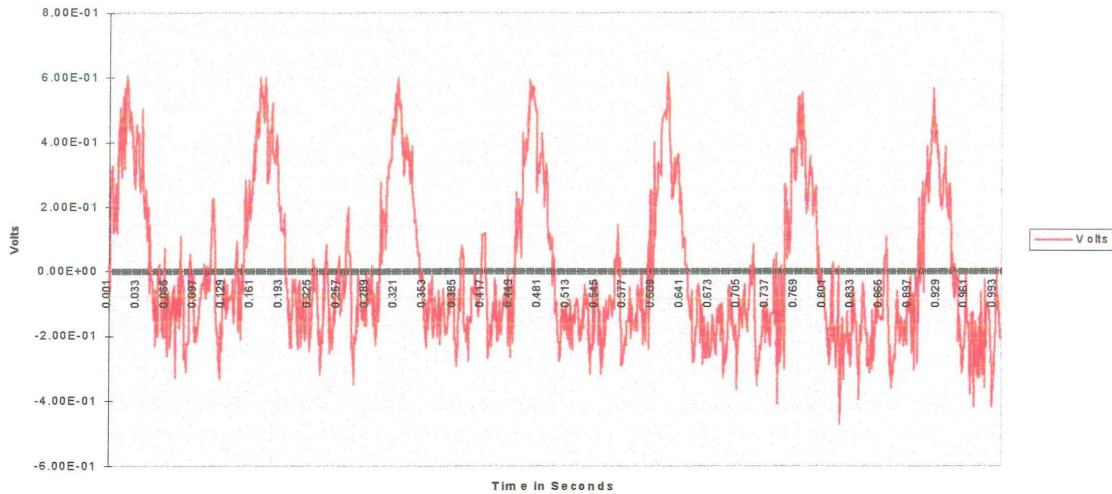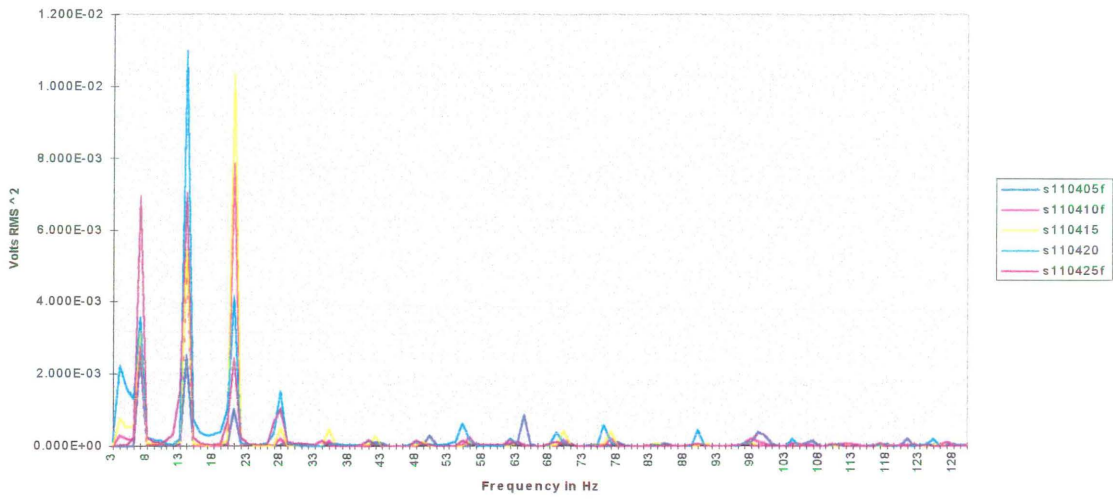Figure 2: Individual Underwater Sound Power Spectra, Vibratory Pile Driving, Pile No. 1

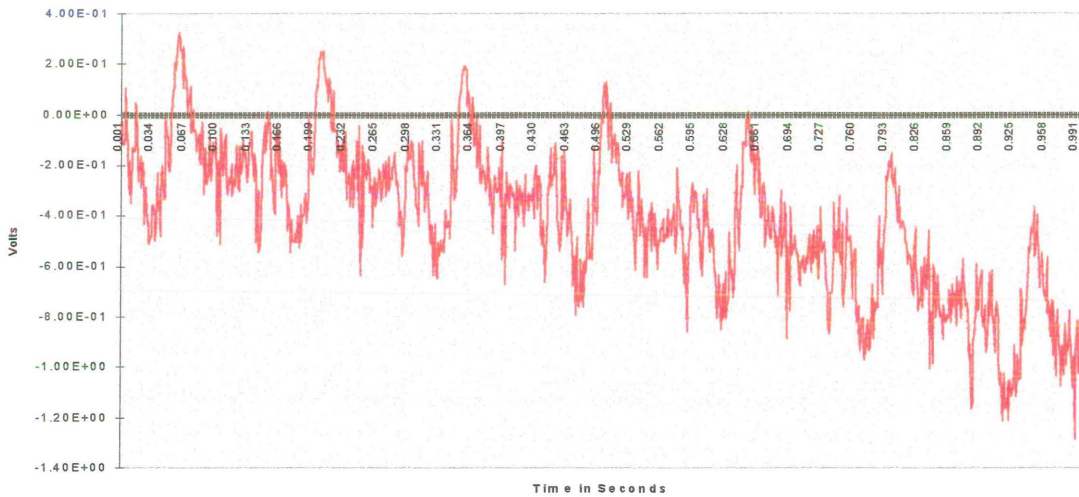Figure 3: Time Domain Signal, Vibratory Pile Driving, Pile No. 1, Sample T110015

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Figure 4: Average Underwater Sound Power Spectrum, Vibratory Pile Driving, Pile No. 2
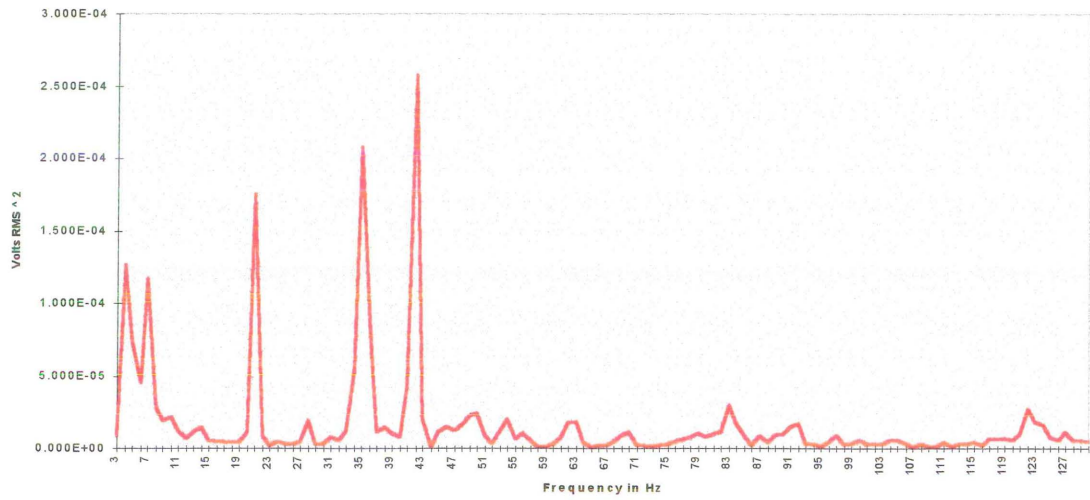
Figure 5: Individual Underwater Sound Power Spectra, Vibratory Pile Driving, Pile No. 2
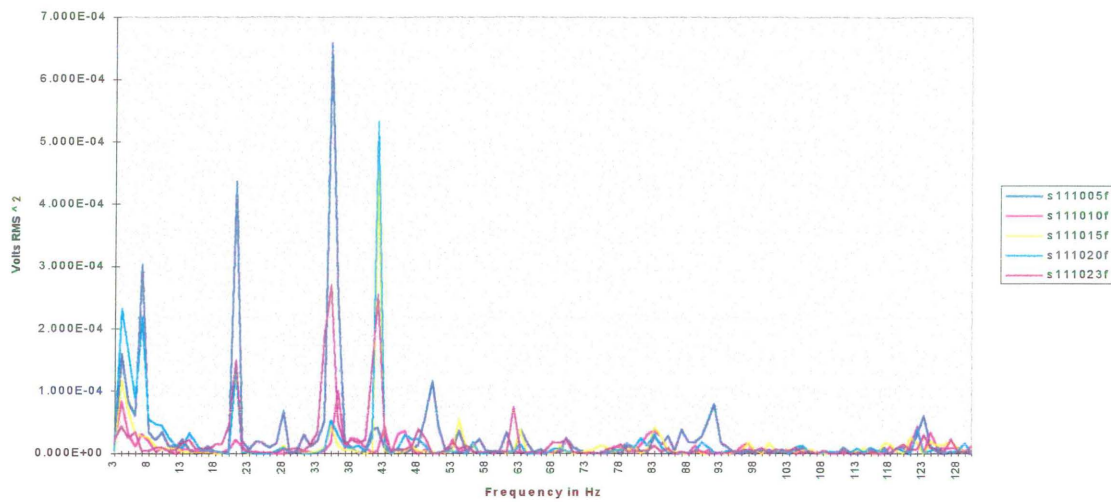
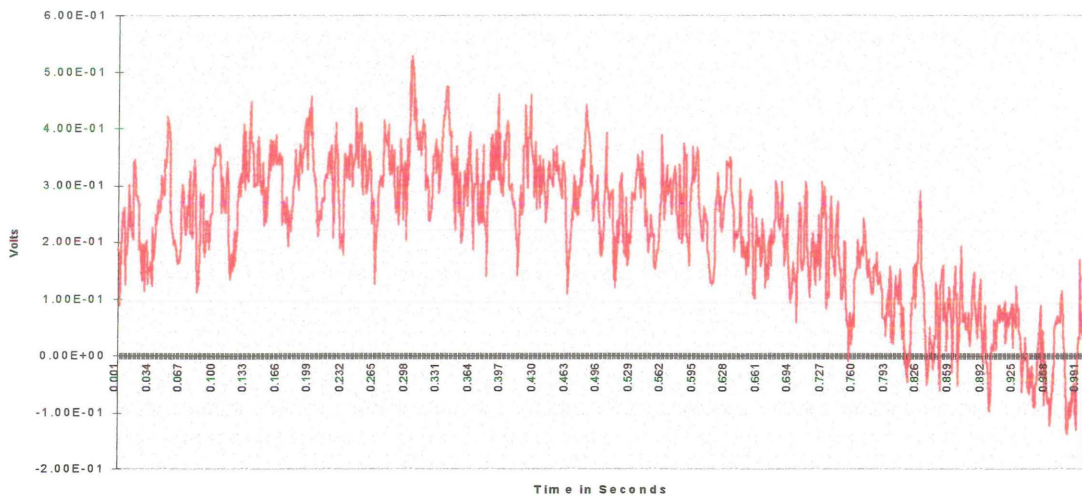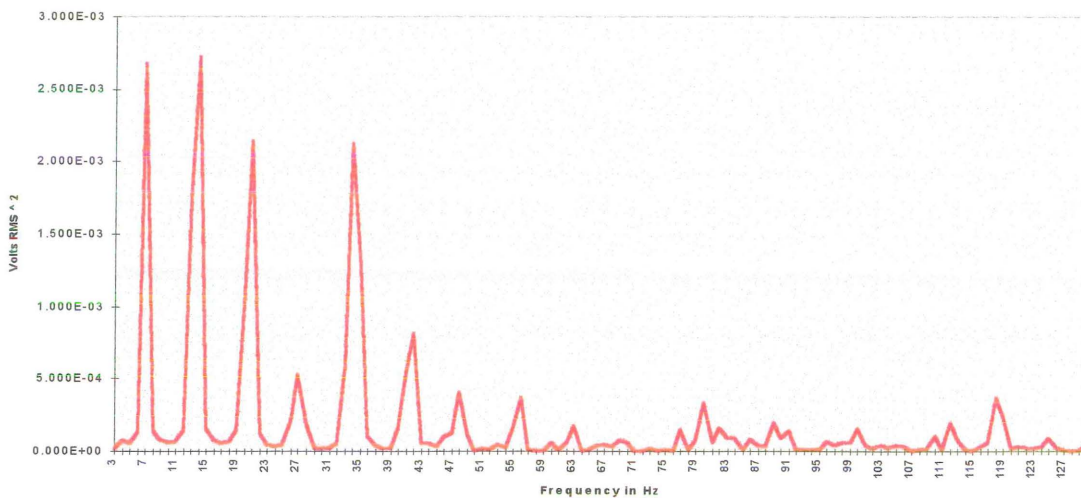**Figure 6: Time Domain Signal, Vibratory Pile Driving, Pile No. 2, Sample T110215**

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Figure 7: Average Underwater Sound Power Spectrum, Vibratory Pile Driving, Pile No. 3

Volts RMS ^ 2 vs Frequency in Hz
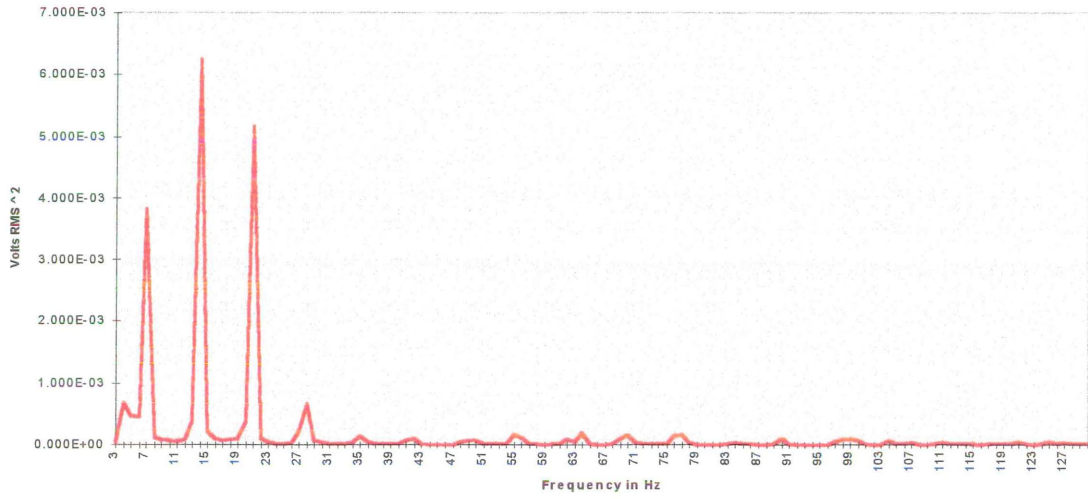
Figure 8: Individual Underwater Sound Spectra, Vibratory Pile Driving, Pile No. 3

Volts RMS ^ 2 vs Frequency in Hz

Legend:
- s110405f
- s110410f
- s110415
- s110420
- s110425f

Figure 9: Time Domain Signal, Vibratory Pile Driving, Pile No. 3, Sample T110420

Volts vs Time in Seconds

Figure 10: Average Underwater Sound Spectrum, Vibratory Pile Driving, Pile No. 4

Volts RMS ^ 2

Frequency in Hz

Figure 11: Individual Underwater Sound Spectra, Vibratory Pile Driving, Pile No. 4

Volts RMS ^ 2

- s111005f
- s111010f
- s111015f
- s111020f
- s111023f

Frequency in Hz

Figure 12: Time Domain Signal, Vibratory Pile Driving, Pile No. 4, Sample T111005

Volts

Time in Seconds

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Figure 13: Average Underwater Sound Spectrum, Vibratory Pile Driving, Pile No. 5

Y-axis: Volts RMS ^ 2
X-axis: Frequency in Hz

Figure 14: Individual Underwater Sound Spectra, Vibratory Pile Driving, Pile No. 5

Y-axis: Volts RMS ^ 2
X-axis: Frequency in Hz
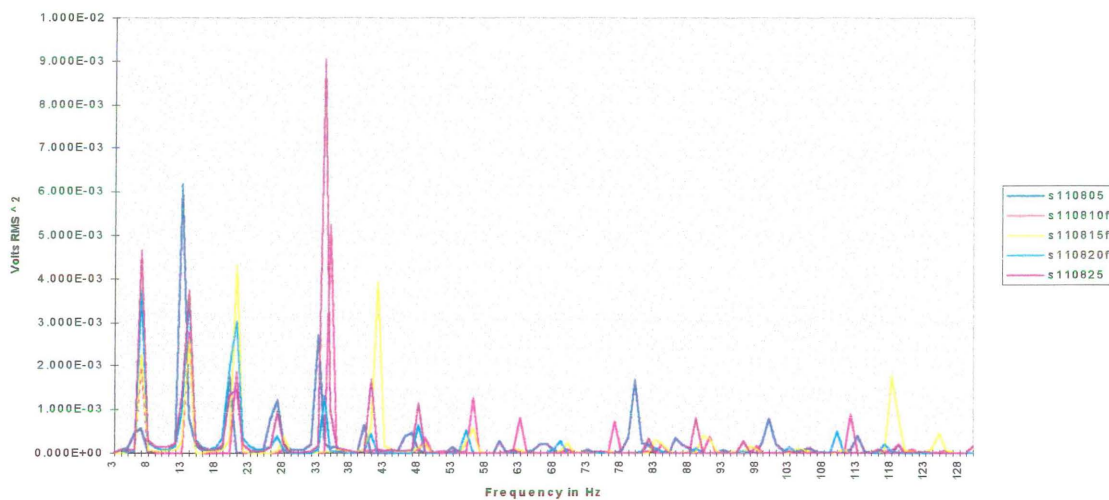
Legend:
- s110805
- s110810f
- s110815f
- s110820f
- s110825

Figure 15: Time Domain Signal, Vibratory Pile Driving, Pile No. 5, Sample T110810
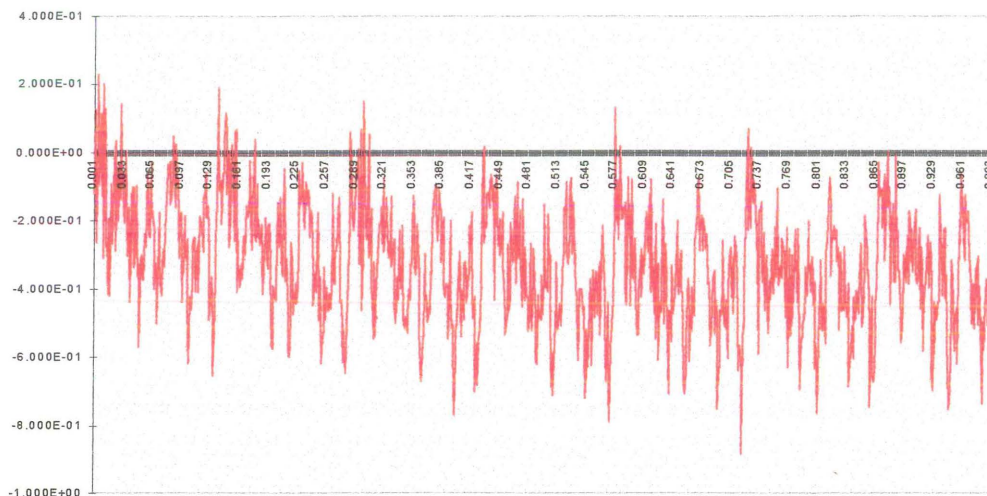
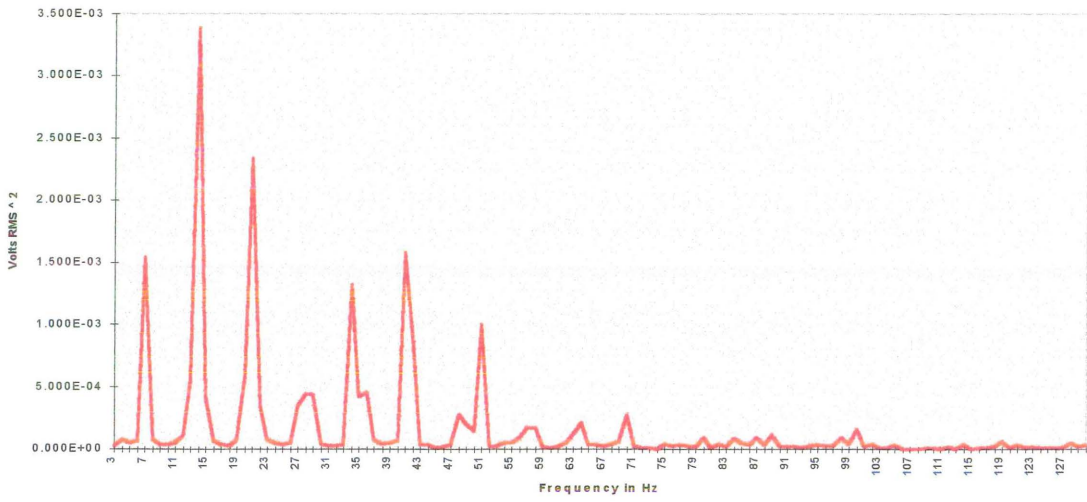**Figure 16: Average Underwater Sound Spectrum, Vibratory Pile Driving, Pile No. 6**

Volts RMS ^ 2 vs. Frequency in Hz

Figure 17: Individual Underwater Sound Spectra, Vibratory Pile Driving, Pile No. 6

Legend:
- s110625f
- s110630f
- s110635f
- s110640f
- s110645

Volts RMS ^ 2 vs. Frequency in Hz
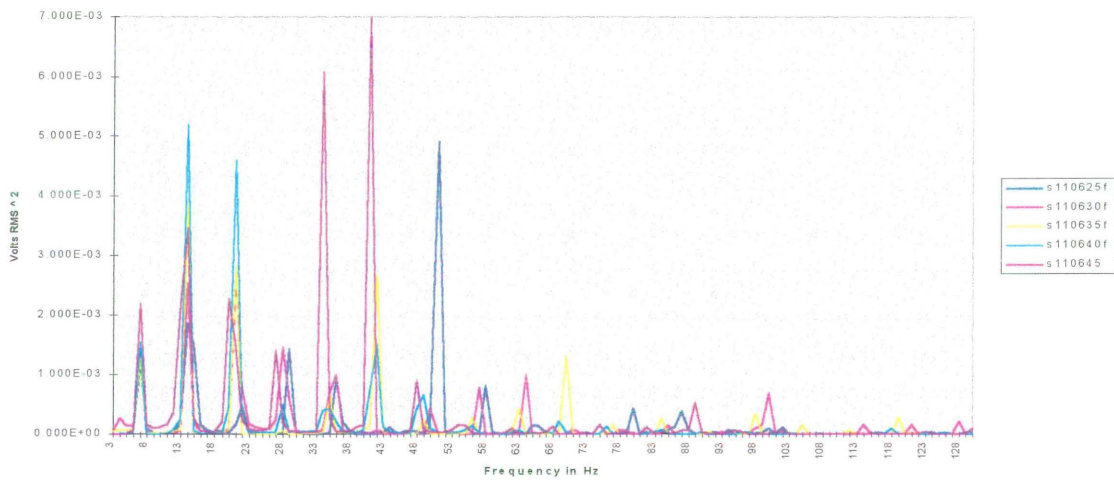
Figure 18: Time Domain Signal, Vibratory Pile Driving, Pile No. 6, Sample T110630

Volts vs. Time in Seconds
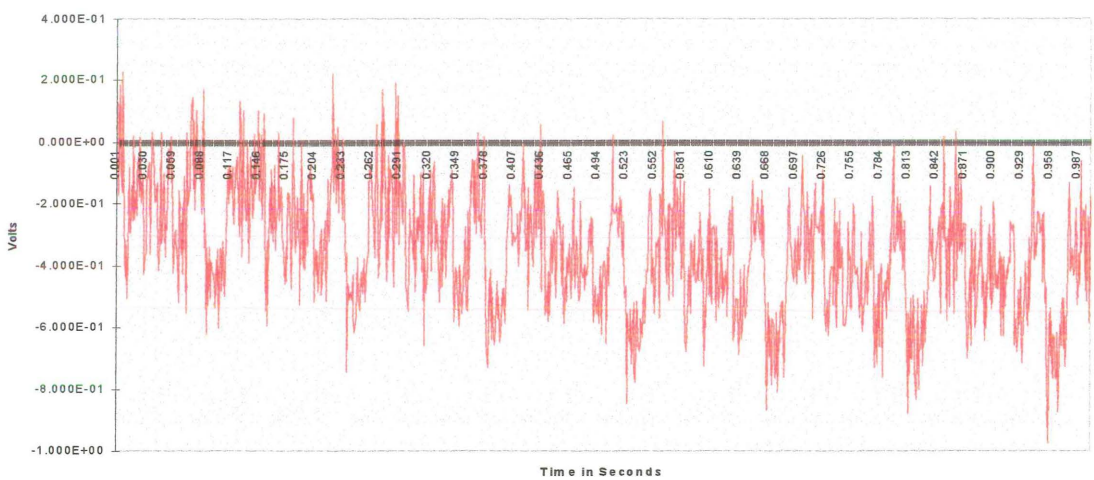
Figure 19: Underwater Sound Power Spectrum, Volume Displacement Infrasound Source

Y-axis: Volts RMS ^ 2 (0.00E+00 to 9.00E-01)
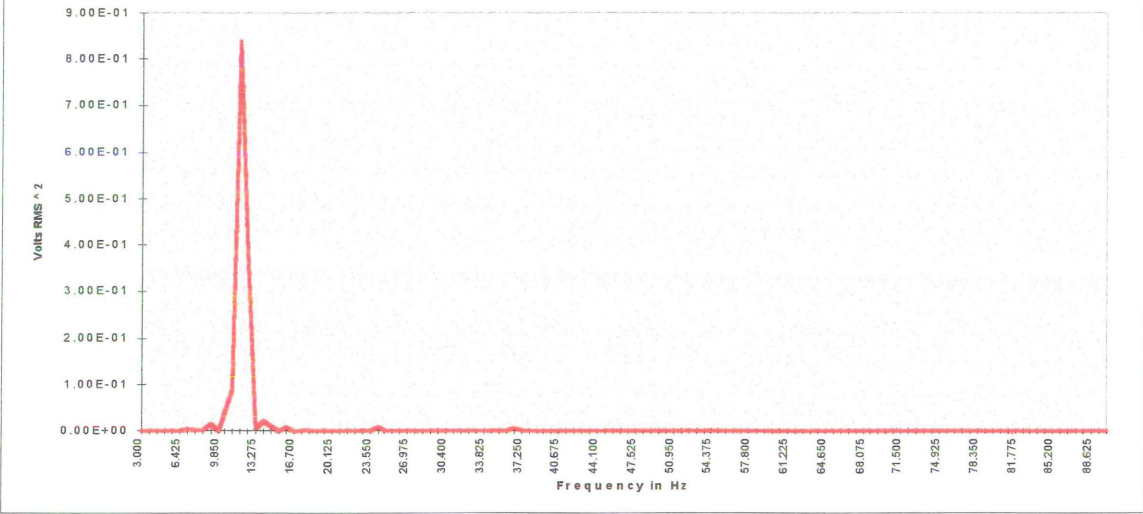
X-axis: Frequency in Hz (3.000 to 88.625)

Figure 20: Time Domain Signal, Volume Displacement Infrasound Source

Y-axis: Volts (-4.00E-01 to 4.00E-01)

X-axis: Time in Seconds (0.0002 to 0.7484)

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