Radiated Noise Measurements of Rhode Island Wind Turbines

FINAL REPORT

July 11, 2014

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Executive Summary

This document summarizes radiated noise measurements made at various locations throughout Rhode Island that have wind turbines installed and operating. The study was sponsored by the Rhode Island Office of Energy Resources (RI-OER) and the main goal was to obtain calibrated baseline measurements of sound levels of these existing turbines and to compare these values with representative ambient noise levels. The effort can be considered to consist of four different stages. The first stage was a laboratory calibration to quantify differences between a Sound Level Meter (SLM), and three sets of microphone recording systems. In the second stage, the SLM and microphone recording systems were utilized to record noise levels at the various wind turbine locations throughout the state. In this set of measurements, data was collected stationary relative to the wind turbine and also as a function of distance and azimuth to the wind turbine. In the third stage, both the SLM and microphone recording systems were again deployed in the field, but data was now collected along specified paths that consisted of the property lines of the wind turbine location. The fourth stage consisted of ambient noise recordings at various locations away from the wind turbine locations. This efforts was performed for the Rhode Island Office of Energy Resources. The primary author of this report is Dr. Harold T. Vincent, Research Associate Professor of Ocean Engineering, at the University of Rhode Island. For corrections, clarifications or additional information, he can be reached by phone at (401) 874-6814 or by e-mail at `bud@oce.uri.edu`.

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1. Background

1.1 Original Scope of Work

The original scope of the radiated noise measurement effort was to make radiated noise measurements at wind turbine locations listed in Table 1.1 and shown in Figure (1.1). At each site, measurements were to be made at fixed locations relative to the wind turbine. These measurements were to include recordings using the following equipment:

- Sound Level Meter
- Condenser microphone and Audio Band recording system (20 Hz - 20 kHz)
- Infrasonic condenser microphone and recording system (1 Hz - 200 Hz)

The overview of the original scope can be seen in the slide presentation given in a public "stakeholders" meeting January 2013. The stakeholders are citizens of the state representing developers, homeowners, policy officials, town planning and zoning officials, etc. Measurements were planned to collect data at all locations except Portsmouth High School and Tiverton (non-operational locations). However, measurements were also not made at the North Kingstown and Middletown locations due to refusal of the owners to allow access to their property for data collection.

Table 1.1: Wind Turbine Locations.

	Name	**System Size**	**Height**	**Longitude**	**Latitude**
1	Sandywoods Farm - Tiverton	275 kW	231 ft	-71.15188	41.62307
2	North Kingstown Green	1.5 MW	402 ft	-71.48685	41.58166
3	Portsmouth - Hodges Badge	250 kW	197 ft	-71.25495	41.56644
4	Portsmouth - High School	1.5 MW	336 ft	-71.25139	41.61434
5	Portsmouth - Abbey	660 kW	240 ft	-71.26866	41.59906
6	Middletown Aquidneck Corporate Park	100 kW	157 ft	-71.28673	41.50218
7	Narragansett - Fishermen's Memorial	100 kW	157 ft	-71.49060	41.38080
8	Warwick - New England Tech	100 kW	157 ft	-71.45146	41.73277
9	Warwick - Shalom Housing	100 kW	157 ft	-71.46646	41.72367
10	Narragansett Bay Commission 1	1.5 MW	360 ft	-71.38991	41.79270
11	Narragansett Bay Commission 2	1.5 MW	360 ft	-71.38683	41.79448
12	Narragansett Bay Commission 3	1.5 MW	360 ft	-71.38971	41.79524

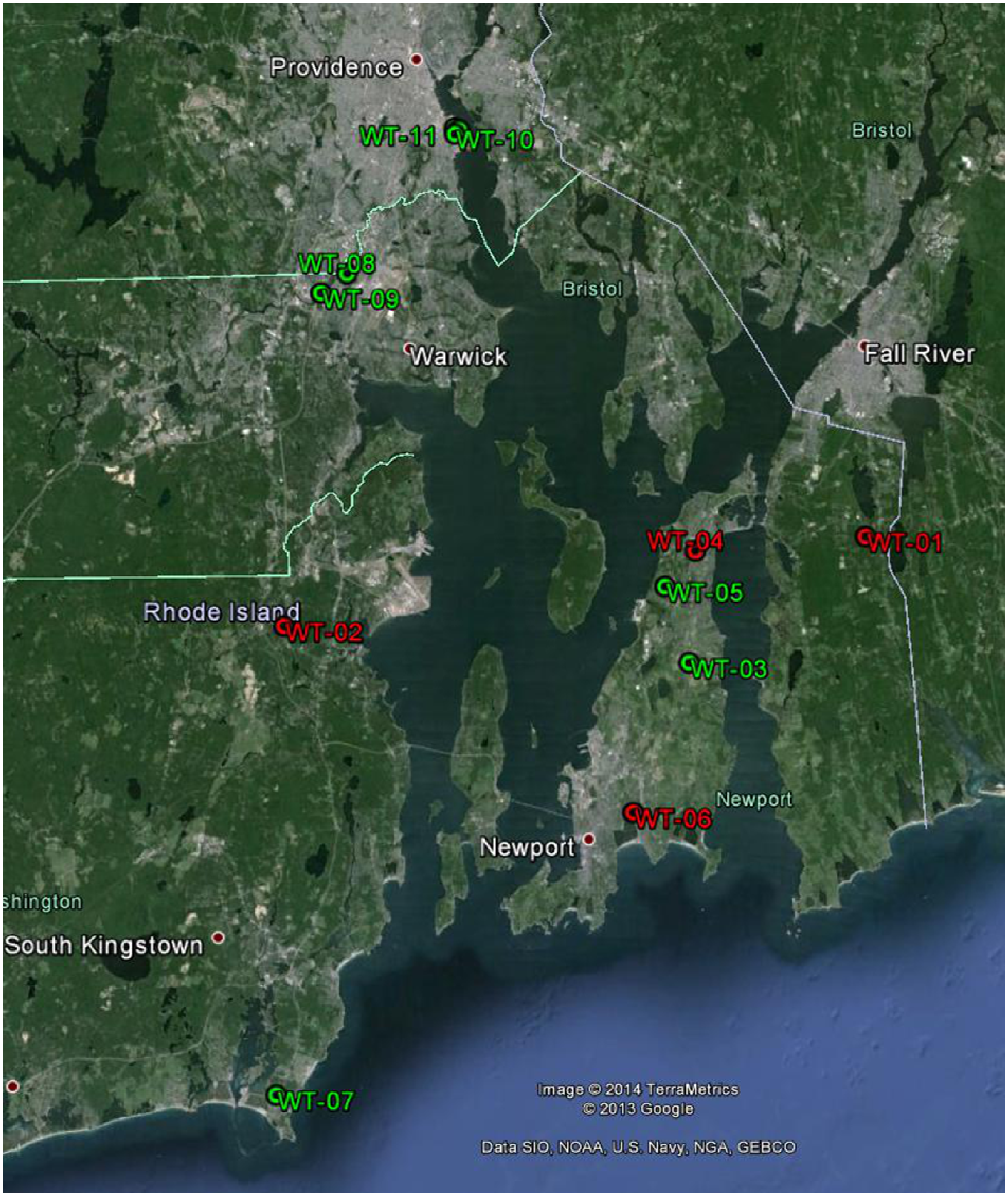

Figure 1.1: Locations of Wind Turbines in Rhode Island. Green dots represent turbine locations at which measurements were obtained. Red dots represent locations where measurements were not obtained due to owner refusal or non-operational turbines.

1.2 Scope of Work Modification 1

Based on comments and discussion at the stakeholders meeting, it was decided to modify the original scope to not only make radiated noise measurements at each wind turbine location, but also to make measurements as a function of range (distance) and azimuth relative to the wind turbine. In other words, to map the radiated noise field. The intent was to identify the affect of distance and azimuth on the radiated noise. Such range dependent effects can be modeled with various levels of fidelity, and this data could potentially provide a means to compare noise field data with model predictions. It is important to note that this change in scope represented a significant increase in the data processing workload. Instead of just recording data at a fixed location, geo-spatial data (e.g. from a GPS receiver) had to be synchronously recorded and merged with the acoustic data. It is estimated that this change represented a four to five fold increase in data reduction and data processing. [1]

1.3 Scope of Work Modification 2

During an internal review session in July 2013, RI-OER requested to modify the scope of work again to collect data along the property lines surrounding the operating wind turbines. The desire was to collect data to try and determine if the radiated noise levels measured at these specific locations could be used to verify if presently installed turbines comply with the draft guidelines published in the Statewide Planning Program Technical Paper entitled *Renewable Energy Siting Guidelines Part 1: Interim Siting Factors for Terrestrial Wind Energy Systems.*

2. Calibration

2.1 Objective

To measure the radiated noise from the various wind turbine locations, three independent acoustic measurement systems were utilized as follows:

- Low Frequency (Infrasound) Microphones and Recording System
- Audio Frequency Microphones and Recording System
- Sound Level Meter (SLM)

The infrasonic microphone system was utilized to record and analyze low frequency (20 Hz – 200 Hz) and infrasonic (1 Hz – 20 Hz) signals. The audio recorder system was utilized to record and analyze audio band signals (20 Hz – 20 kHz). The SLM was used to measure levels from 31.5 Hz to 8 kHz. For both microphone systems, the values recorded are voltage time series which can be converted to pressure time series using the corresponding microphone sensitivity.[2] The reason for using audio recording system in addition to the SLM is to allow an independent measurement of sound levels and also to allow more complex analysis (e.g., narrowband and time-frequency).

Theses systems were all simultaneously used to have actual data collected in the lab and on-site to clearly demonstrate that only using a Sound Level Meter may not "tell the whole story" Two sounds that will be perceived differently in terms of loudness and irritation can have exactly the same Sound Pressure Level (SPL) as measured by the SLM. Only by looking at the Pressure Spectrum Level (PSL), or even the Time-Frequency nature of the signal, can one explain and show why there is such a difference. This can be seen by comparing two different PSL that have the same SPL and would produce the same sound level reading from a SLM, and again, these would be perceived very differently. This is best shown "live" to someone by playing two such signals through a stereo system, letting them listen and look at the SLM - it really drives home the point when they get to listen and look at the SLM to see two very different sounding noises producing the same SPL output from the SLM.

2.1.1 Infrasound Recording System

The low frequency (Infrasound) microphones and recording system consists of the microphone, signal conditioning electronics, Analog to Digital Converter (ADC) and laptop computer. The microphone is a G.R.A.S. Model 40AZ. The signal conditioning electronics consist of a 1/4" microphone pre-polarized preamplifier for low frequency and low noise measurements with a 3 meter cable. The data acquisition system is a Data

Translation Model DT9837C-BNC USB Data acquisition module operating in a current source mode. The infrasonic microphone and recording system are calibrated to ASTM ANSI.

2.1.2 Audio Recording System

The audio frequency microphone is a Behringer ECM-8000 condenser microphone that has a flat frequency response from 15 Hz to 20 kHz and omnidirectional polar receive pattern. It operates connected to a TASCAM DR-40 4-Track Handheld Digital Audio Recorder. The audio recorder can sample up to 96 kHz but was operated at a 44.1 kHz sample rate for this calibration and subsequent field study.

2.1.3 Sound Level Meter

The Sound Level Meter (SLM) is a General Class 2 Model DSM402SD that contains an integrated microphone and data acquisition system. It employs embedded signal processing to convert the microphone output to a Sound Intensity Level (IL) or a Sound Pressure Level (SPL). The IL and SPL are equivalent if the acoustic wave is propagating and driving the same acoustic impedance. The SLM operating frequency range is 31.5 Hz to 8 kHz. It can measure ranges from 30 to 130 dB in auto ranging mode, and has selectable fixed ranges from 30 to 80 dB, 50 to 100 dB, or 80 to 130 dB. It has frequency weighting using either the A or C standard. It also has fast or slow time weighting (200 ms or 500 ms response time respectively). The measurement accuracy (with A frequency weighting) is:

- 3.5 dB @ 31.5 Hz
- 2.5 dB @ 63 Hz
- 2.0 dB @ 125 Hz
- 1.9 dB @ 250 Hz
- 1.9 dB @ 500 Hz
- 1.4 dB @ 1 kHz
- 2.6 dB @ 2 kHz
- 3.6 dB @ 4 kHz
- 5.6 dB @ 8 kHz

The SLM can log a data measurement every second.

2.2 Calibration Procedure

The G.R.A.S. condenser microphones were factory calibrated and have nominal sensitivities of 50 mV/Pa. The Behringer microphone has a stated sensitivity value of -60 dB. [2] For the normal microphone reference sensitivity of 1V/Pa, this yields an absolute sensitivity of 1 mV/Pa. To verify the system outputs, a so-called "Comparison Calibration" was undertaken. The calibration consists of simultaneously recording all of the sensors listed in a common sound field and comparing the sound levels obtained from each system. This procedure was repeated twice and consistent results were observed between the two tests.

2.2.1 Acoustic Source

The acoustic source was a low frequency, sub-woofer loudspeaker system driven by a function generator and power amplifier. All three of the acoustic recording systems were then co-located and simultaneously exposed to the sound source. See Figures 2.1 through 2.3.

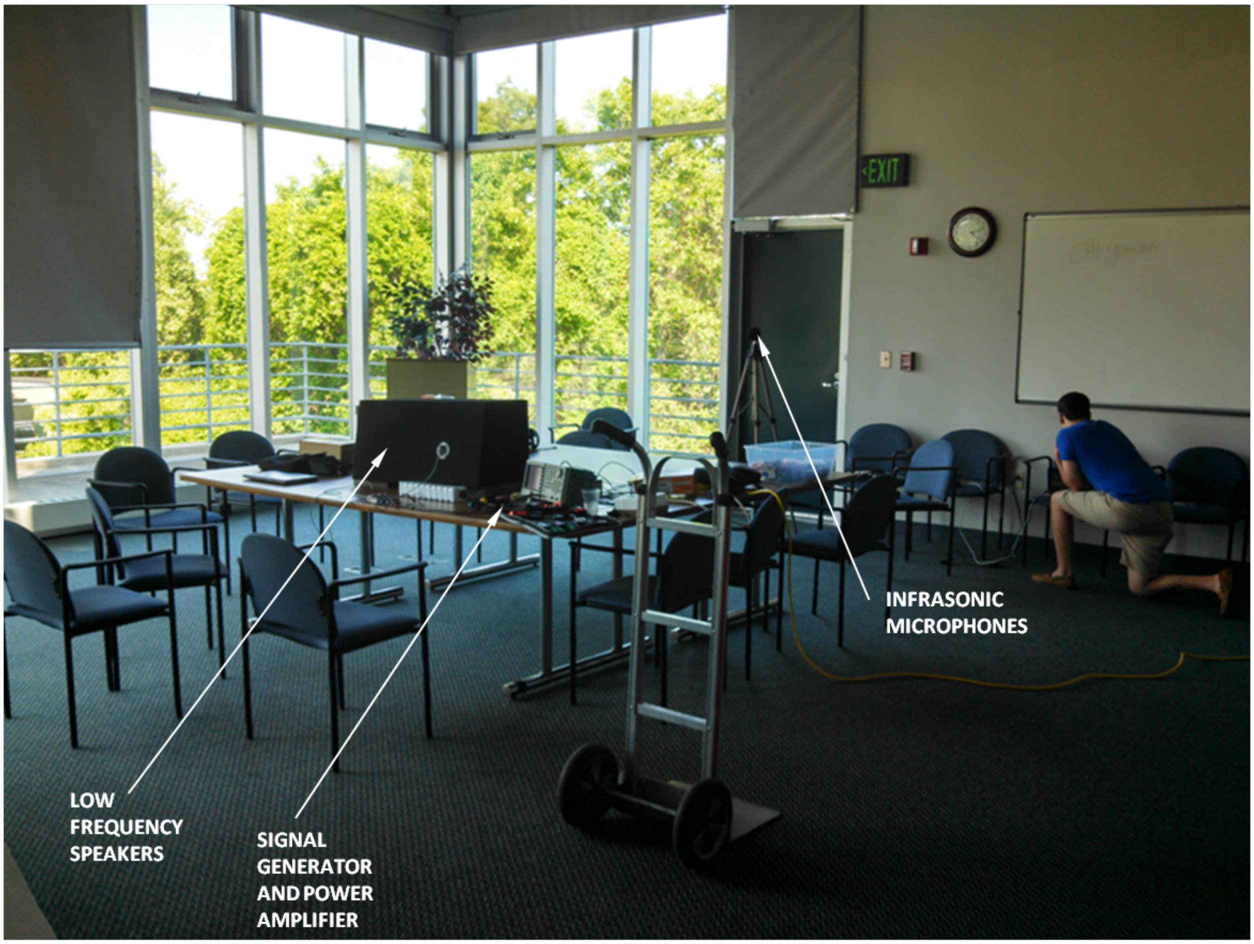

Figure 2.1: Calibration Setup 1.

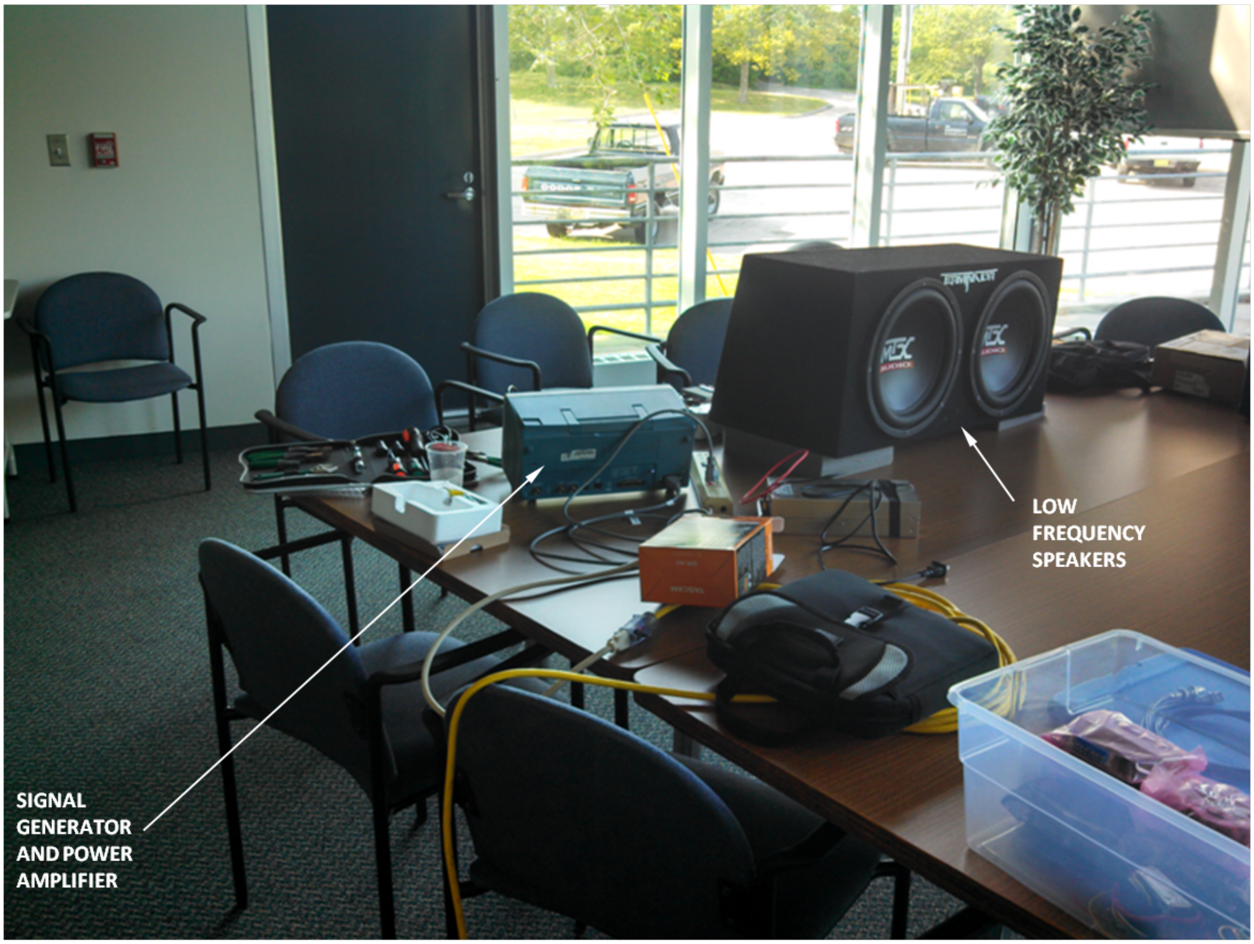

Figure 2.2: Calibration Setup 2.

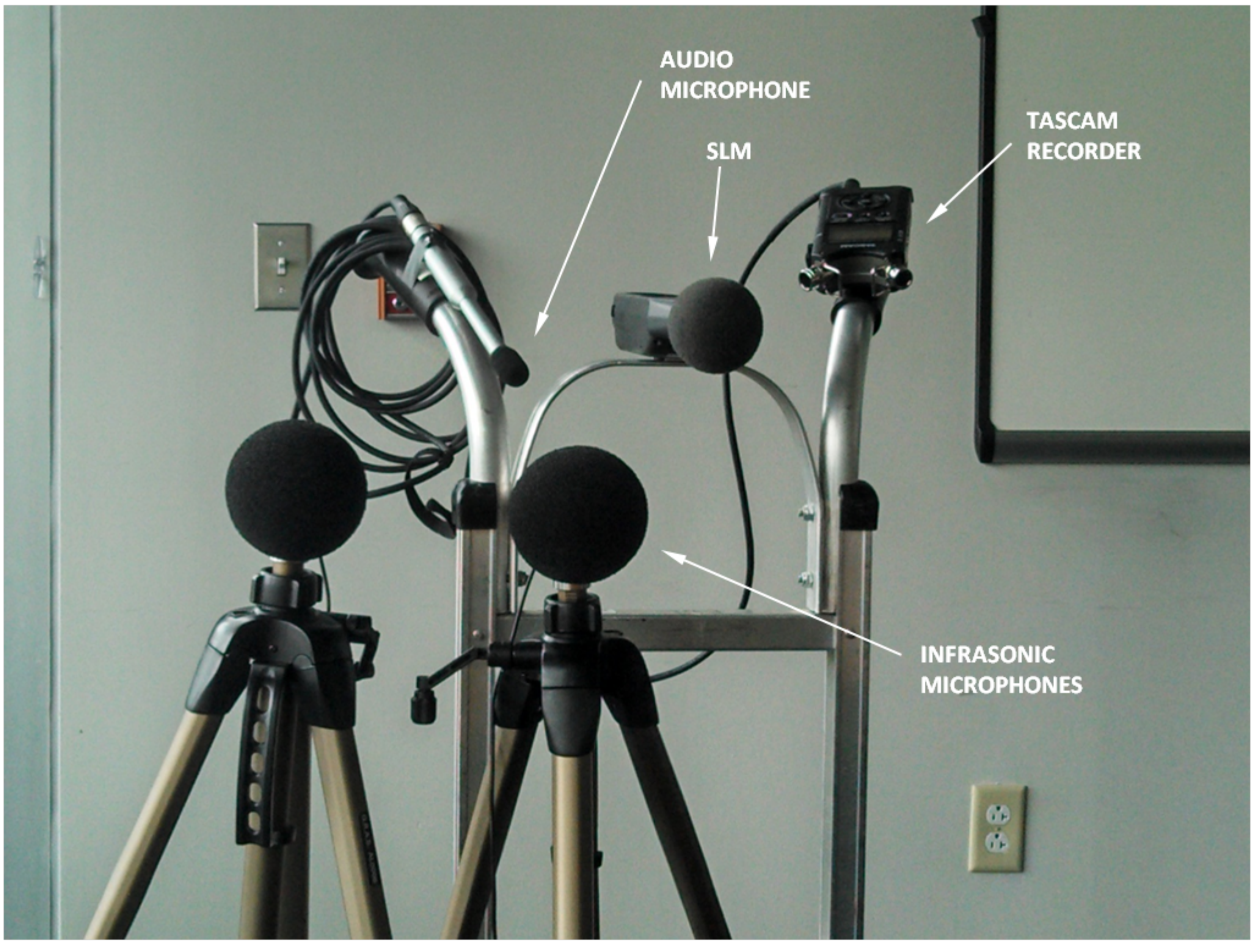

Figure 2.3: Calibration Setup 3.

2.3 Calibration Results

Figures 2.4 and 2.5 shows a comparison of the Behringer-TASCAM system with the SLM. In Figure 2.4 the voltage time series and associated spectrogram are shown. From this, it is clear that the transmitted signal consisted of a Linear Frequency Modulated (LFM) or chirp signal. Figure 2.5 shows this data converted to a Sound Pressure Level for direct comparison to the SLM. From this TASCAM to SLM comparison, it is clear that the SLM appears to have some limitations. First, the SL values recorded by the SLM are not consistent. They consistently estimate values too low but occasionally log a value too high. The fact that the SLM underestimates the SL value is not un-expected due to the weighting that is applied. However, it is troubling that the SLM values are not consistent from LFM chirp to the next. In contrast, both the TASCAM and Infrasound system are consistent and repeatable. The TASCAM and Infrasound System have different sensitivities (how much voltage is output for the same sound pressure). Because of the this the blue signal and red signal have different amplitudes. But the ratio between them is in agreement based on these different sensitivities.

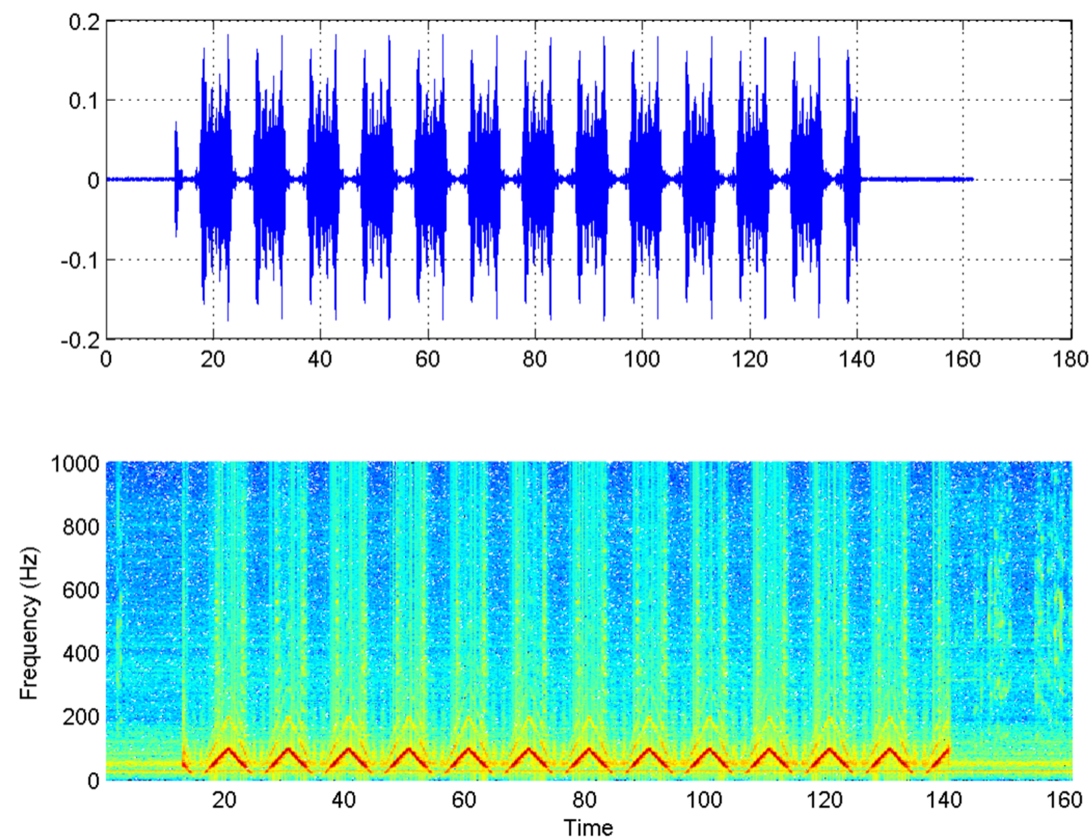

Figure 2.4: Voltage Time Series and Spectrogram for TASCAM recording system for LFM calibration signals.

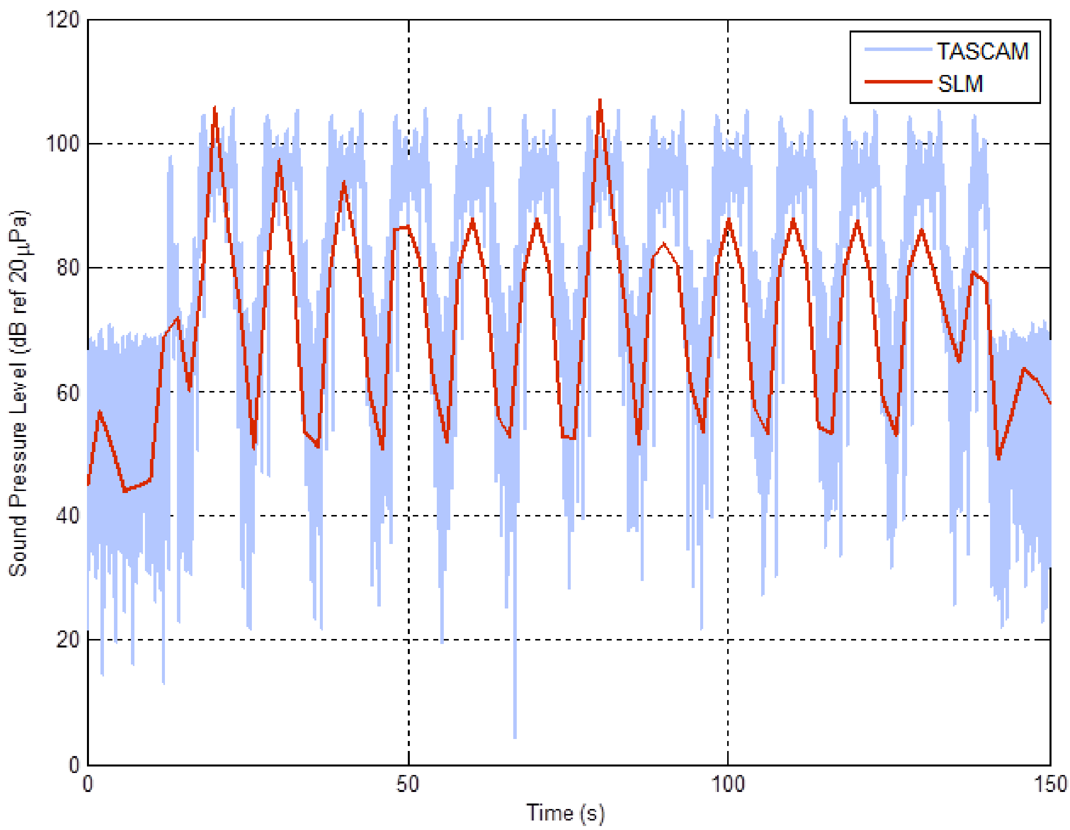

Figure 2.5: Comparison of SPL measurements computed from TASCAM with SPL measurements logged by SLM.

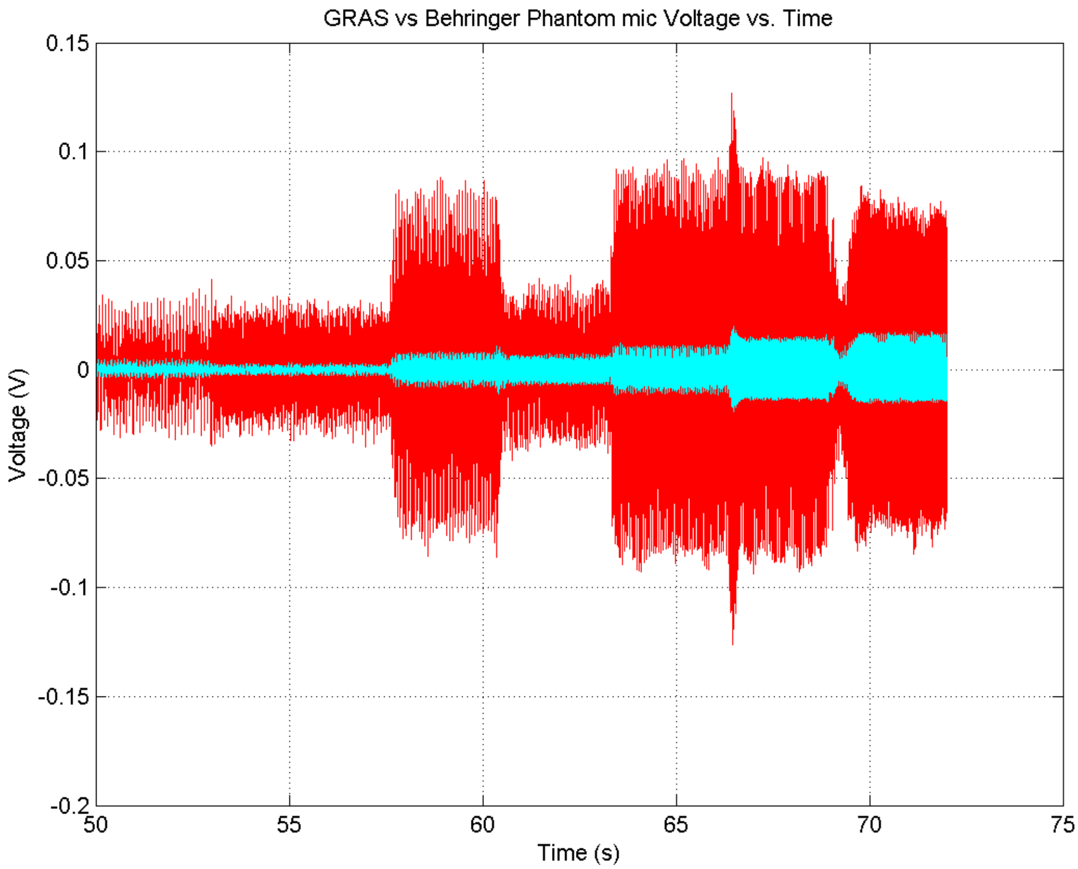

Figure 2.6: Comparison of Voltage Time series between Infrasound system and TASCAM system. The TASCAM and Infrasound System have different sensitivities (how much voltage is output for the same sound pressure). Because of the this the blue signal and red signal have different amplitudes. But the ratio between them is in agreement based on these different sensitivities.

2.4 Calibration Conclusions

The calibration data collection and analysis indicates the following:

- The SLM data displays some inconsistencies (lack of repeatability). This is particularly important when moving the SLM to obtain geo-referenced sound field mappings.
- The SLM consistently reads too low. This is not unexpected due to the weighting applied to the signals that attenuates, or de-empasizes the lower frequency components.
- The infrasonic and audio systems are repeatable and consistent. Both can be used to construct SPL data in a manner similar to the SLM. However, it offers the additional benefit of obtaining un-weighted SL measurements, narrowband analysis, and time-frequency analysis.
- It is recommended that acoustic measurements for wind turbine installation studies (pre and post construction) use full bandwidth audio recordings instead of (or in addition to) a Sound Level Meter.

3. Mapping Radiated Sound Field

3.1 Objective

The objective of mapping the radiated noise field was to obtain measurements that showed how the SPL changes as a function of distance or azimuth from the wind turbine. This is in contrast to noise measurements made at a fixed location. At each wind turbine site, both fixed and mobile recordings were made. Fixed recordings were made using the infrasound system. Mobile recordings were made with the TASCAM and SLM systems.

3.2 Methods

To accomplish creation of a geo-referenced sound field mapping, the TASCAM and SLM were activated and then transported around each site. Concurrent with these systems recording acoustic data, GPS receivers were recording time and location. At the conclusion of walking around the premises, both the acoustic and GPS systems were stopped. Afterwards, the SLM, TASCAM, and GPS data files were time synchronized and merged.

3.2.1 GPS

Time and position data was recorded from the output of a Global Positioning System receiver. During the first field tests, a Garmin was used to collect this data. However, due to software issues it was not possible to transfer the data from the hand held device to a computer for integration with the acoustic data and the subsequent data processing. For the following tests, a smartphone with an embedded GPS receiver was employed. This could allow the data to be saved to a memory device and transferred to a PC for merge with the acoustic data. An example of the GPS data is shown in Table 3.1.

3.2.2 Sound Level Meter

Time and Sound Level data (A-weighted or dBA) was recorded from the output of Sound Level Meter. Due to firmware issue in the meter recording system, the times are logged as all the same value. This created some difficulties to allow time synchronization with the data collected from the GPS. This was overcome by data processing algorithms that would time align the SL data using manually recorded start and stop recording times. An example of the SLM data is shown in Table 3.2.

Table 3.1: GPS Data Example.

T	2013-06-21	18:25:00	41.7942540	-71.3895300	24.3
T	2013-06-21	18:25:05	41.7942470	-71.3895950	24.7
T	2013-06-21	18:25:09	41.7942300	-71.3896560	26.3
T	2013-06-21	18:25:14	41.7942120	-71.3897200	26.7
T	2013-06-21	18:25:20	41.7942000	-71.3897860	27.4
T	2013-06-21	18:25:26	41.7941970	-71.3898500	27.5
T	2013-06-21	18:25:32	41.7941550	-71.3898850	27.8
T	2013-06-21	18:25:38	41.7941000	-71.3898850	28.0
T	2013-06-21	18:25:44	41.7940520	-71.3899000	28.2
T	2013-06-21	18:25:49	41.7940100	-71.3899200	28.7
T	2013-06-21	18:25:54	41.7939600	-71.3899400	28.5
T	2013-06-21	18:25:59	41.7939150	-71.3899460	29.0
T	2013-06-21	18:26:04	41.7938600	-71.3899600	29.4
T	2013-06-21	18:26:09	41.7938160	-71.3899700	29.1
T	2013-06-21	18:26:14	41.7937700	-71.3899700	29.0
T	2013-06-21	18:26:20	41.7937130	-71.3899900	29.1
T	2013-06-21	18:26:25	41.7936600	-71.3899900	29.8
T	2013-06-21	18:26:30	41.7936060	-71.3900100	29.5

3.2.3 Audio Recorder

To utilize the TASCAM recording to generate SPL data, one must first convert the voltage time series to a corresponding (un-weighted) SPL value using the calibration values discussed in the previous section. An example of the TASCAM Voltage Time Series and corresponding SPL values is shown in Figure 3.1.

Table 3.2: Sound Level Meter Data Example.

Place	Date	Time	Value	Unit
04357	2013/06/21	11:45:10	00056.6	dB
04358	2013/06/21	11:45:10	00055.6	dB
04359	2013/06/21	11:45:10	00060.6	dB
04360	2013/06/21	11:45:10	00064.2	dB
04361	2013/06/21	11:45:10	00078.8	dB
04362	2013/06/21	11:45:10	00068.1	dB
04363	2013/06/21	11:45:10	00065.6	dB
04364	2013/06/21	11:45:10	00061.2	dB
04365	2013/06/21	11:45:10	00058.8	dB
04366	2013/06/21	11:45:10	00057.4	dB
04367	2013/06/21	11:45:10	00054.9	dB
04368	2013/06/21	11:45:10	00055.9	dB
04369	2013/06/21	11:45:10	00058.5	dB
04370	2013/06/21	11:45:10	00062.3	dB
04371	2013/06/21	11:45:10	00056.6	dB
04372	2013/06/21	11:45:10	00061.4	dB
04373	2013/06/21	11:45:10	00058.5	dB
04374	2013/06/21	11:45:10	00055.6	dB
04375	2013/06/21	11:45:10	00059.6	dB

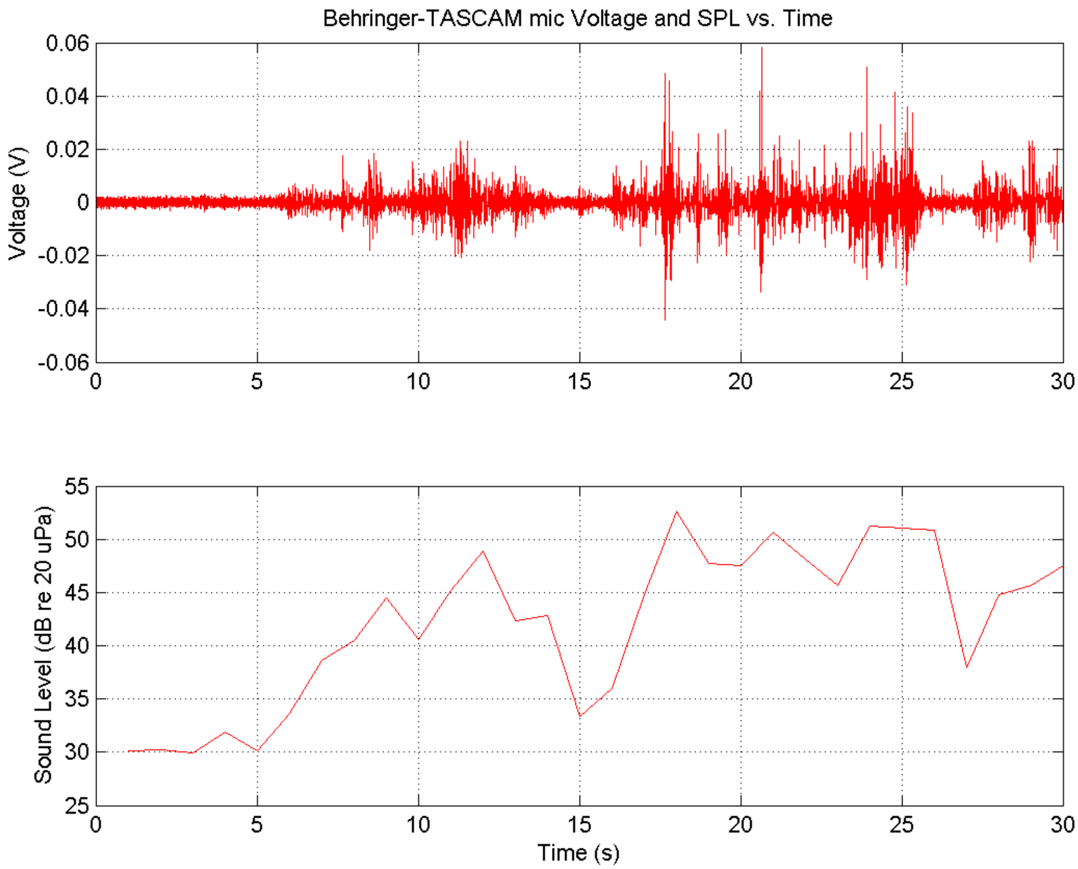

Figure 3.1: Example of TASCAM voltage time series and corresponding SPL.

3.3 Results

3.3.1 Fisherman's Memorial State Park

Figure 3.2: Data collection at Fisherman's Memorial Campground (RI-DEM). Left is the condenser microphone and audio recorder. Right is the SLM and GPS. Both must be time synchronized and merged post-test to generate geo-referenced measurements.

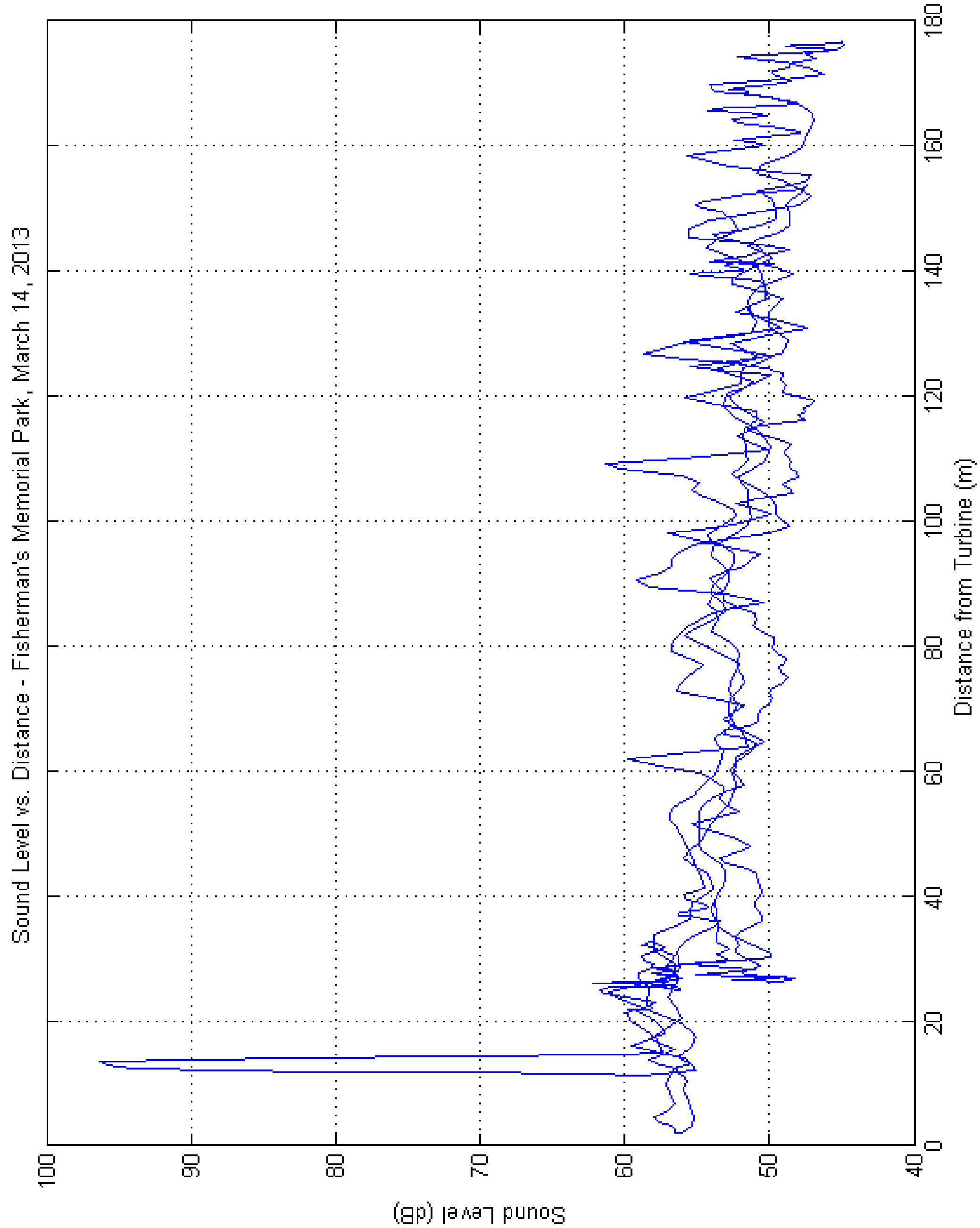

Figure 3.3: Sound Level vs. Distance at Fishermans Memorial Campground, Narragansett, RI on 14 MAR 2013.

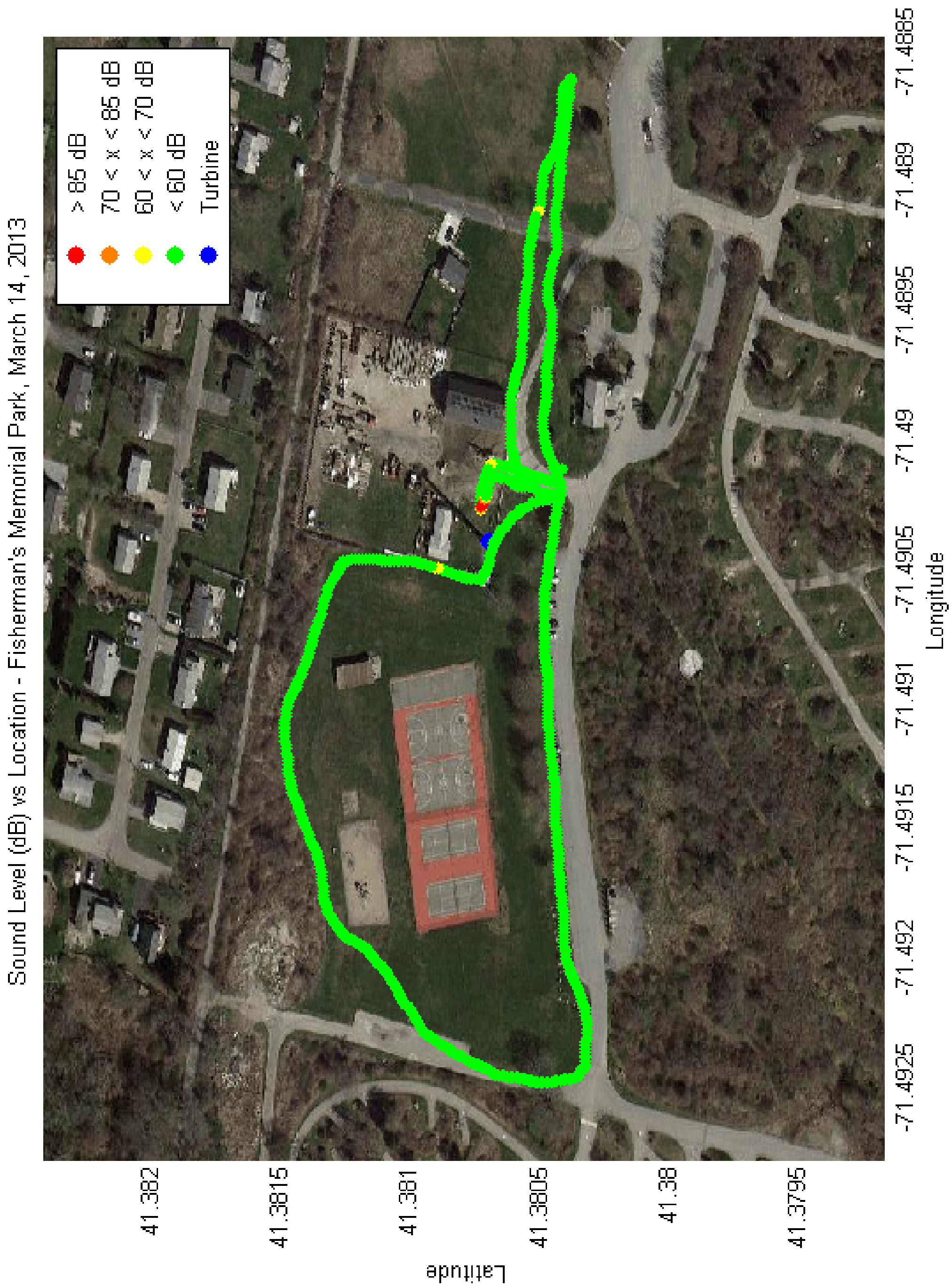

Figure 3.4: Sound Level Mapping at Fishermans Memorial Campground, Narragansett, RI on 14 MAR 2013.

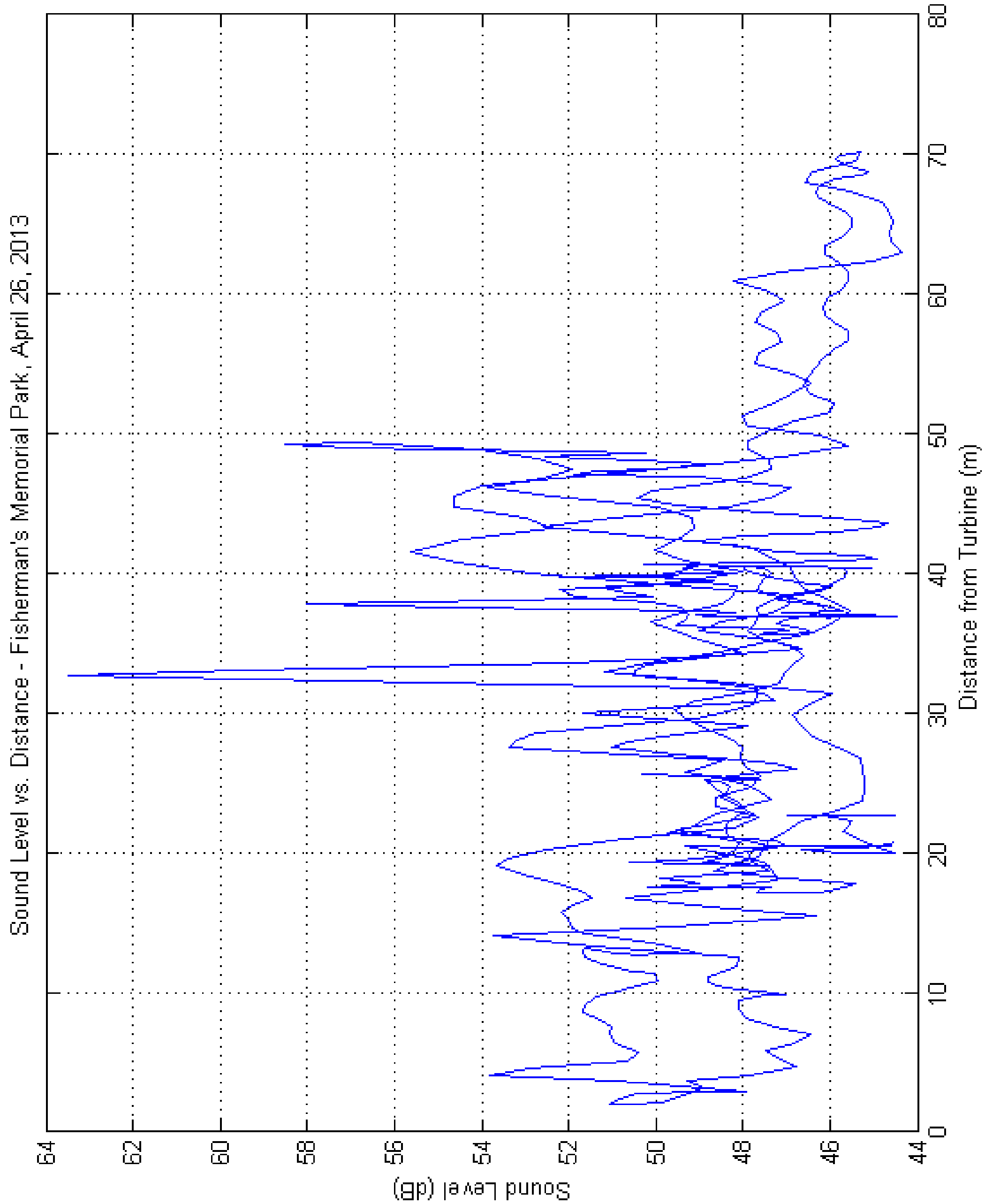

Figure 3.5: Sound Level vs. Distance at Fishermans Memorial Campground, Narragansett, RI on 26 APR 2013.

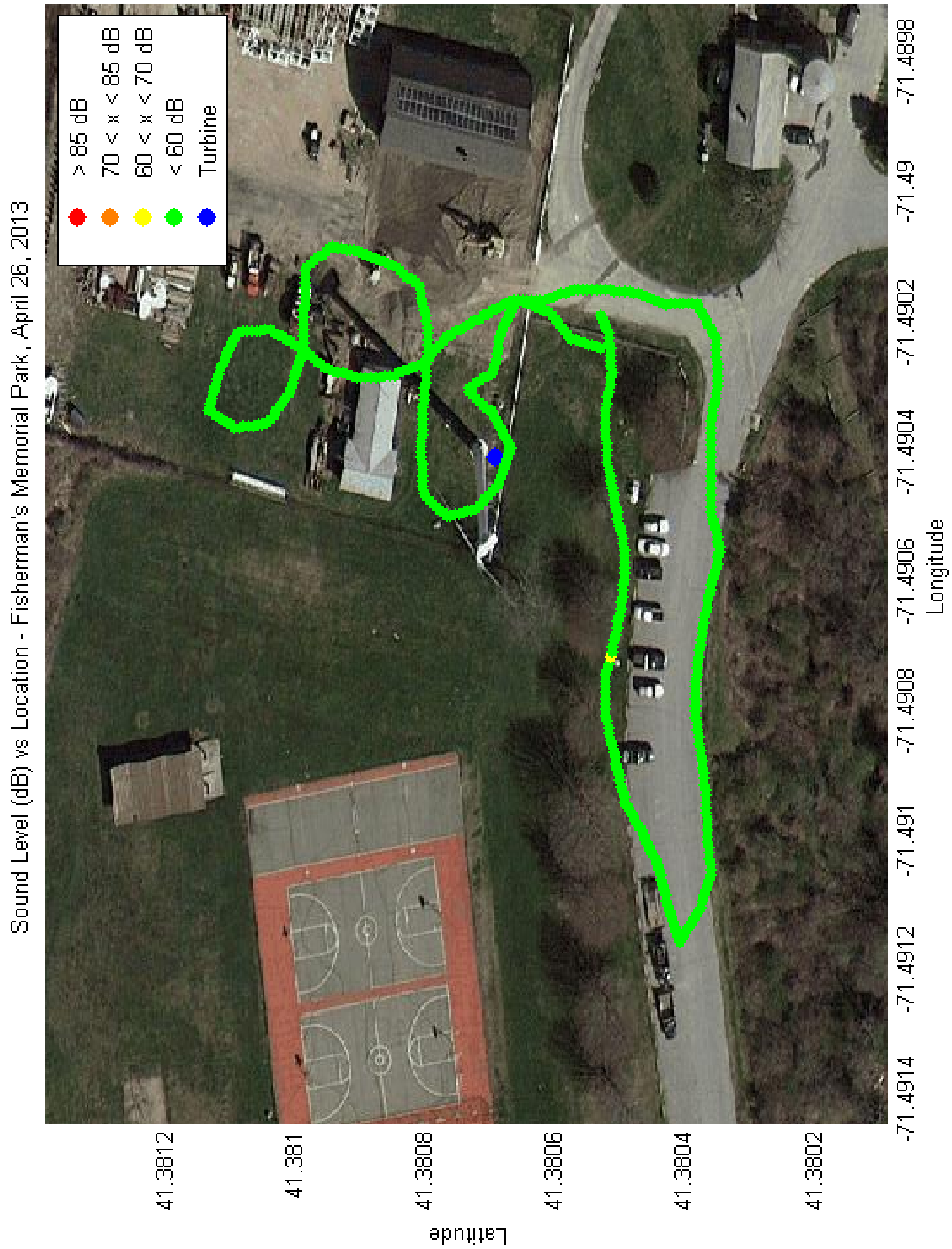

Figure 3.6: Sound Level Mapping at Fishermans Memorial Campground, Narragansett, RI on 26 APR 2013.

3.3.2 Narragansett Bay Commission

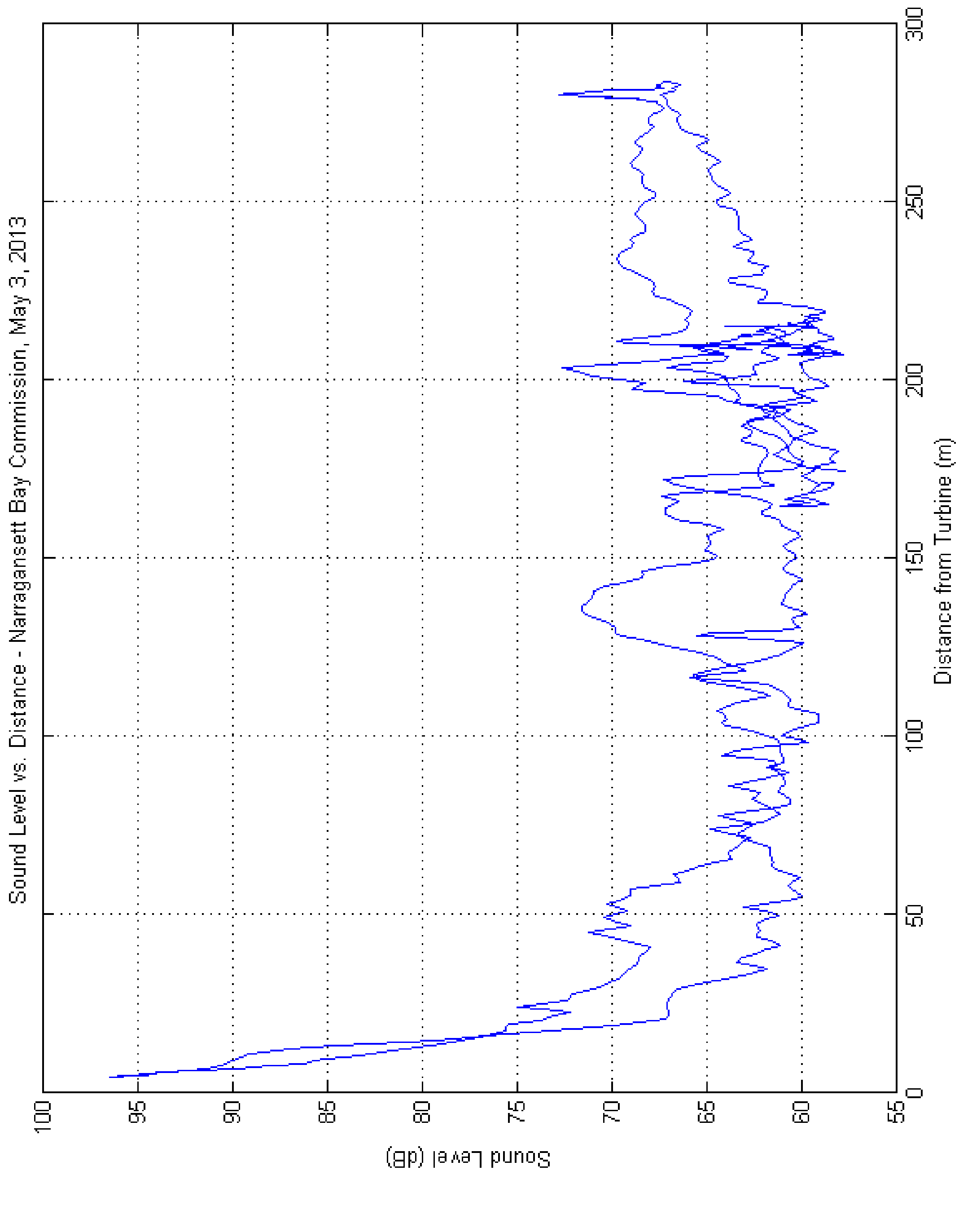

Figure 3.7: Sound Level vs. Distance at Narragansett Bay Commission, Providence, RI on 3 MAY 2013.

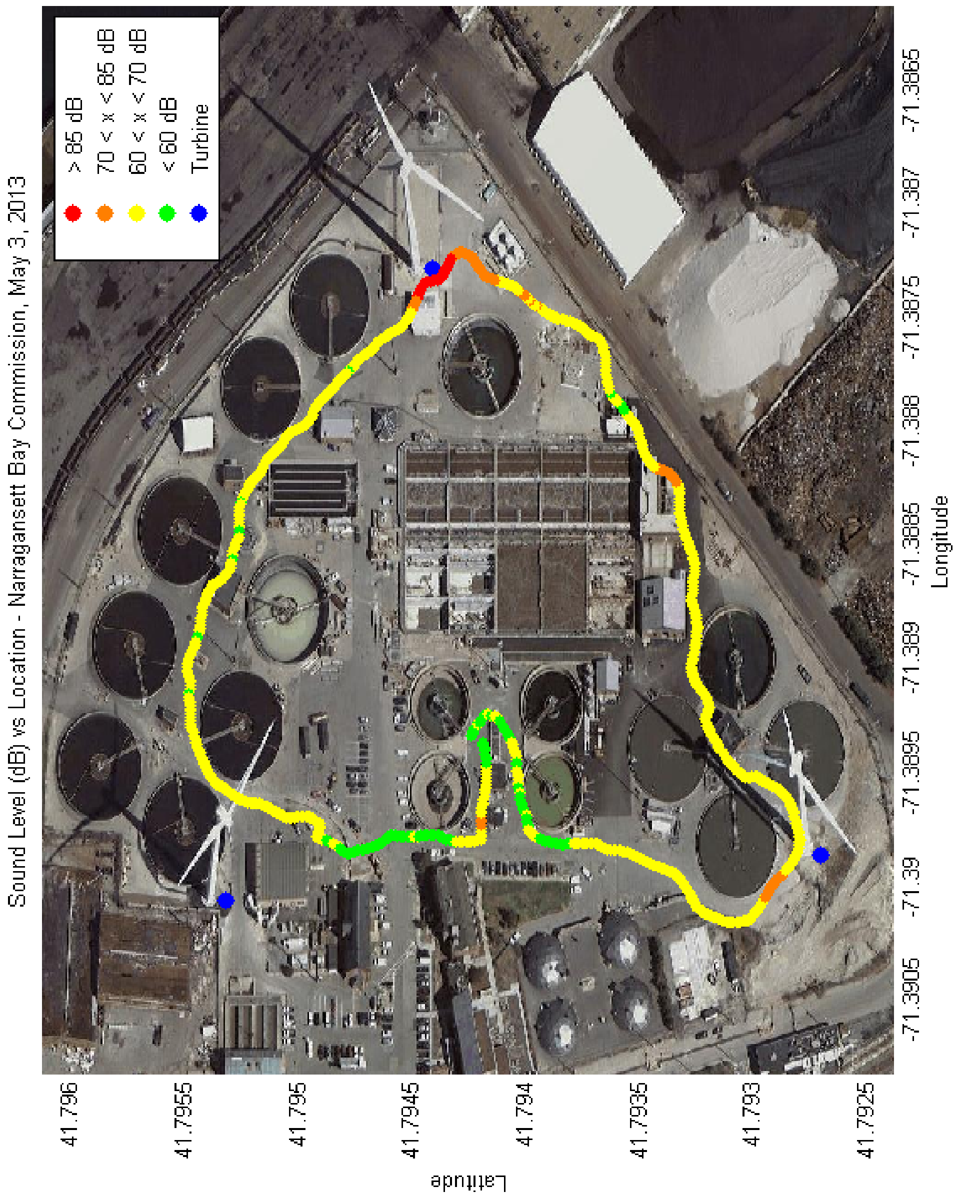

Figure 3.8: Sound Level Mapping at Narragansett Bay Commission, Providence, RI on 3 MAY 2013.

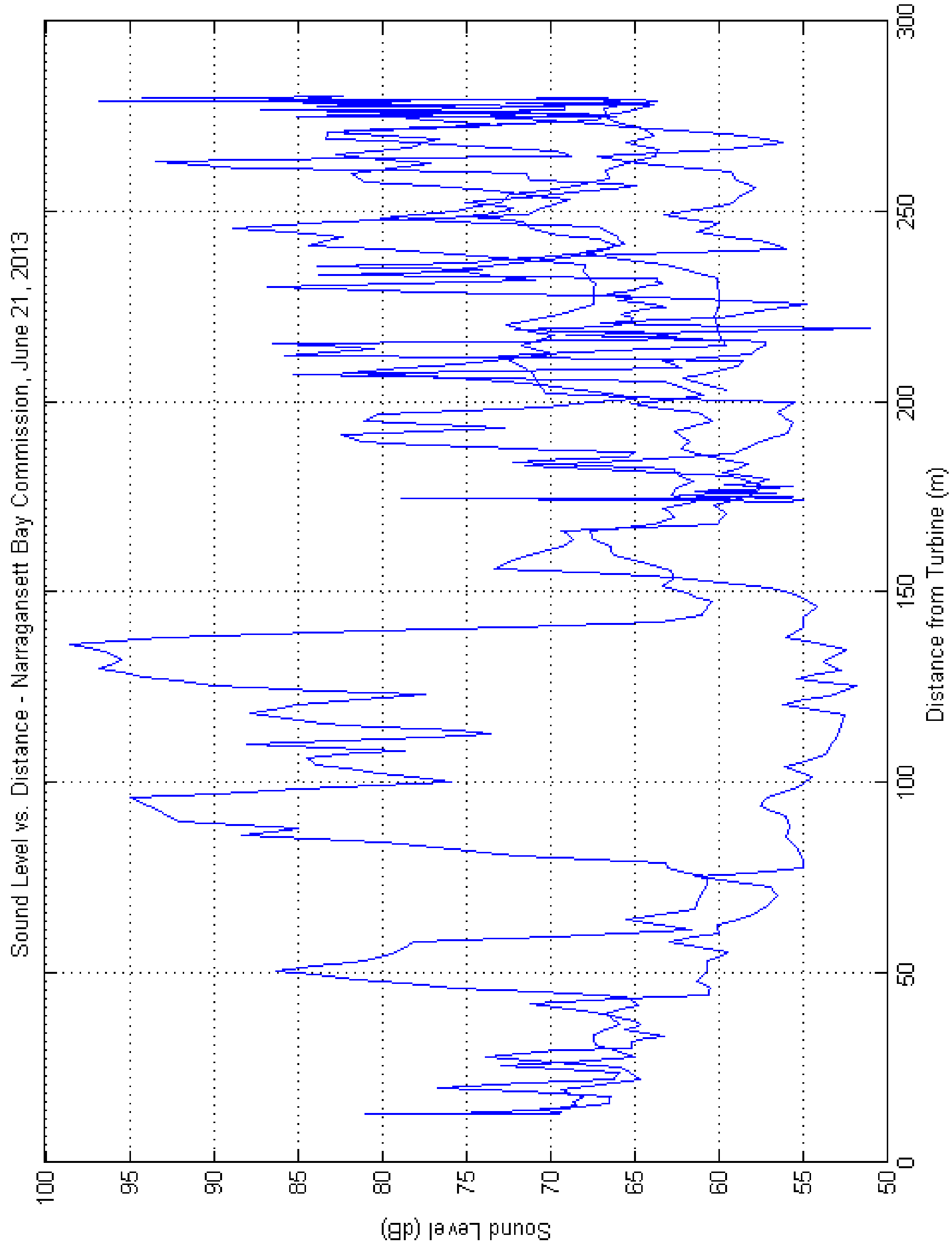

Figure 3.9: Sound Level vs. Distance at Narragansett Bay Commission, Providence, RI on 21 JUN 2013.

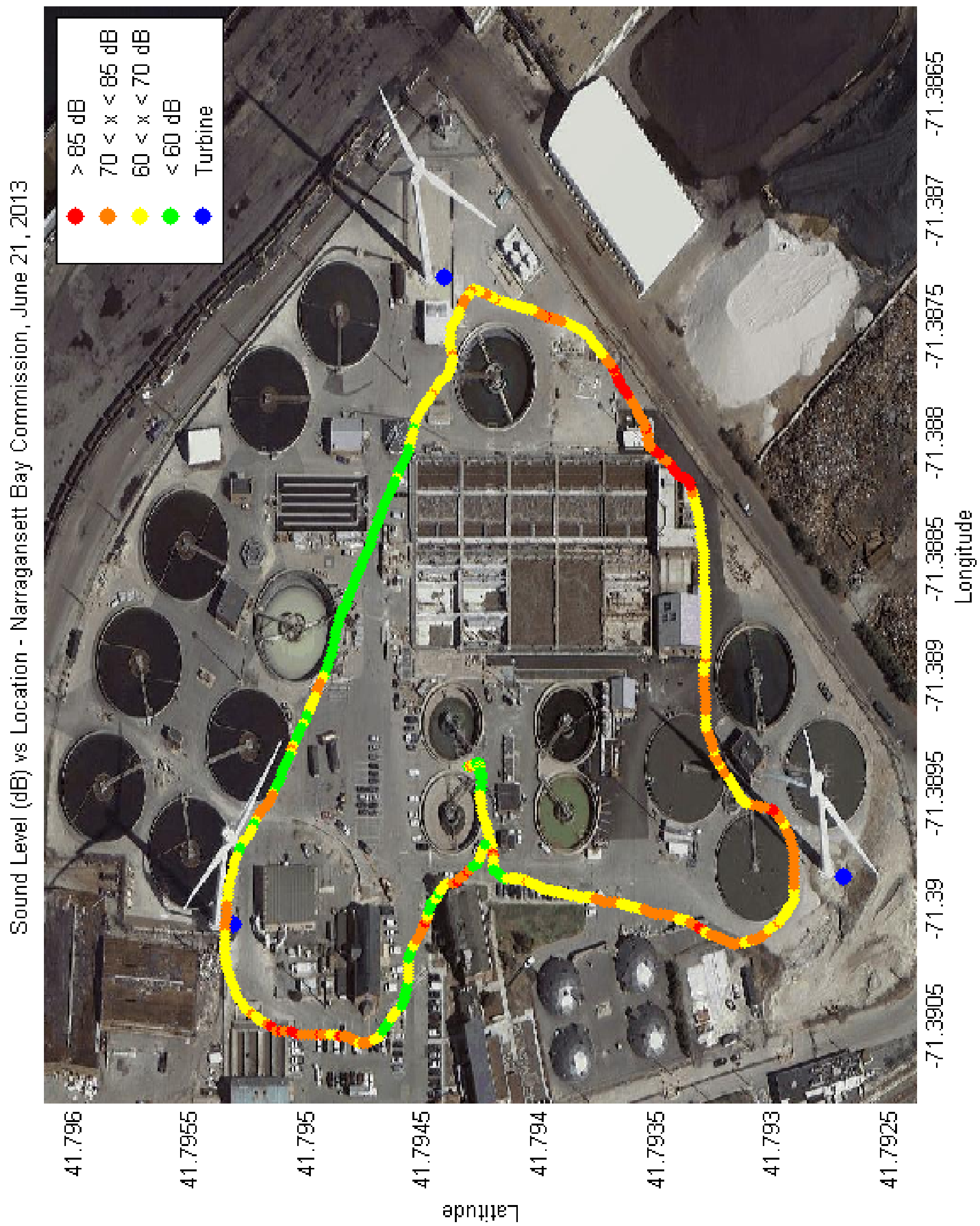

Figure 3.10: Sound Level Mapping at Narragansett Bay Commission, Providence, RI on 21 JUN 2013.

3.3.3 Hodge's Badge Company

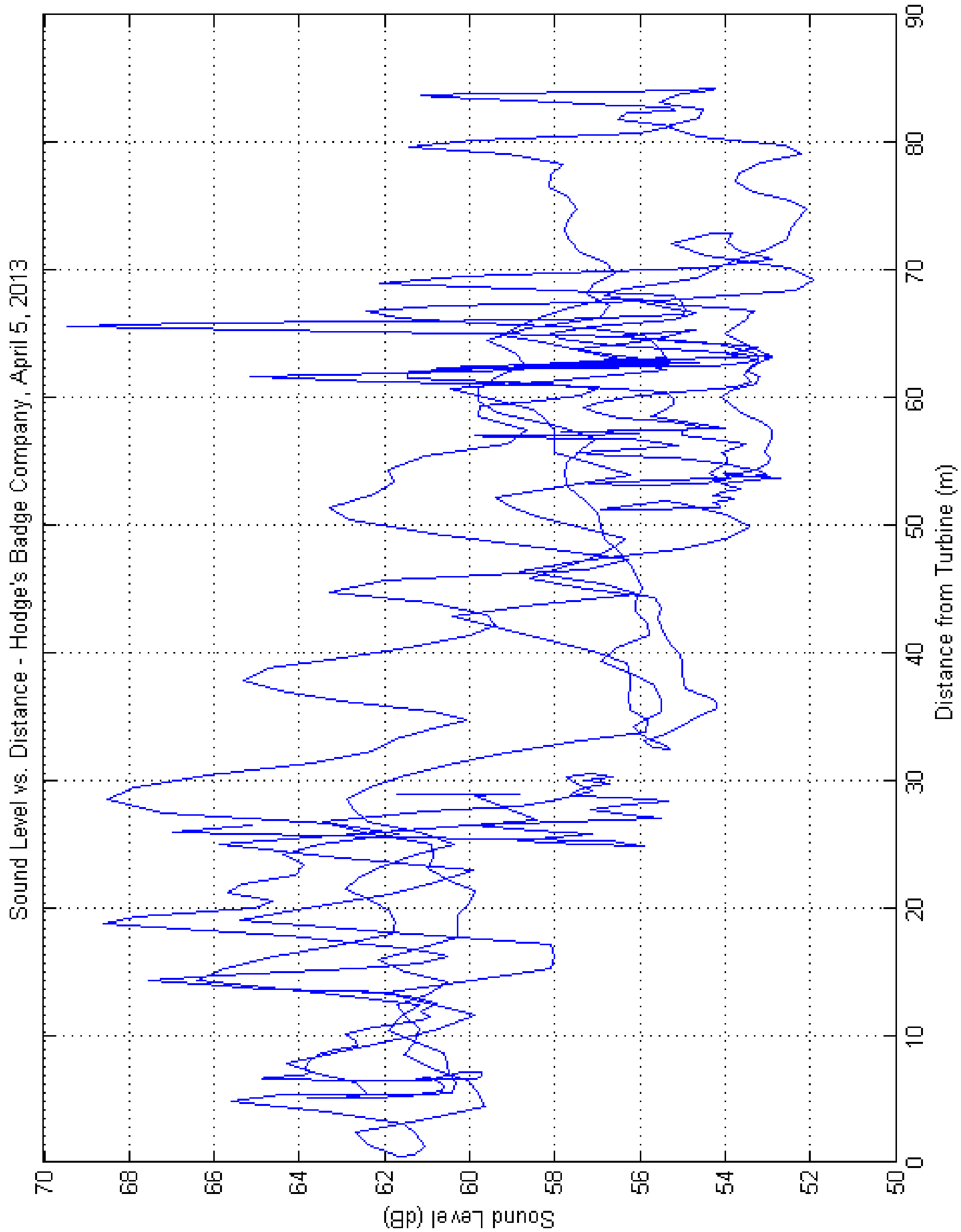

Figure 3.11: Sound Level vs. Distance at Hodge's Badge Company, Portsmouth, RI on 04 MAY 2013

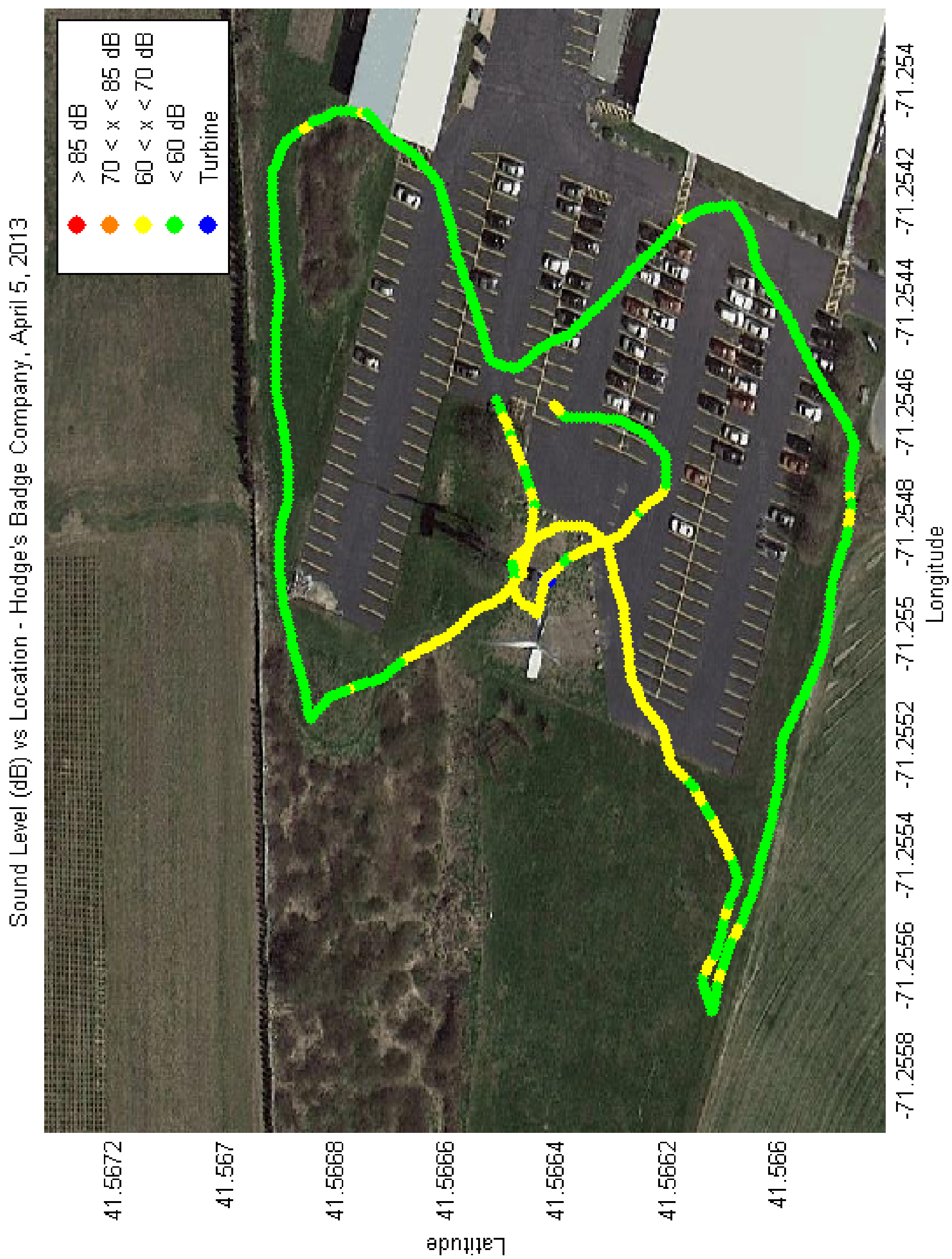

Figure 3.12: Sound Level Mapping at Hodge's Badge Company, Portsmouth, RI on 04 MAY 2013

3.3.4 New England Tech

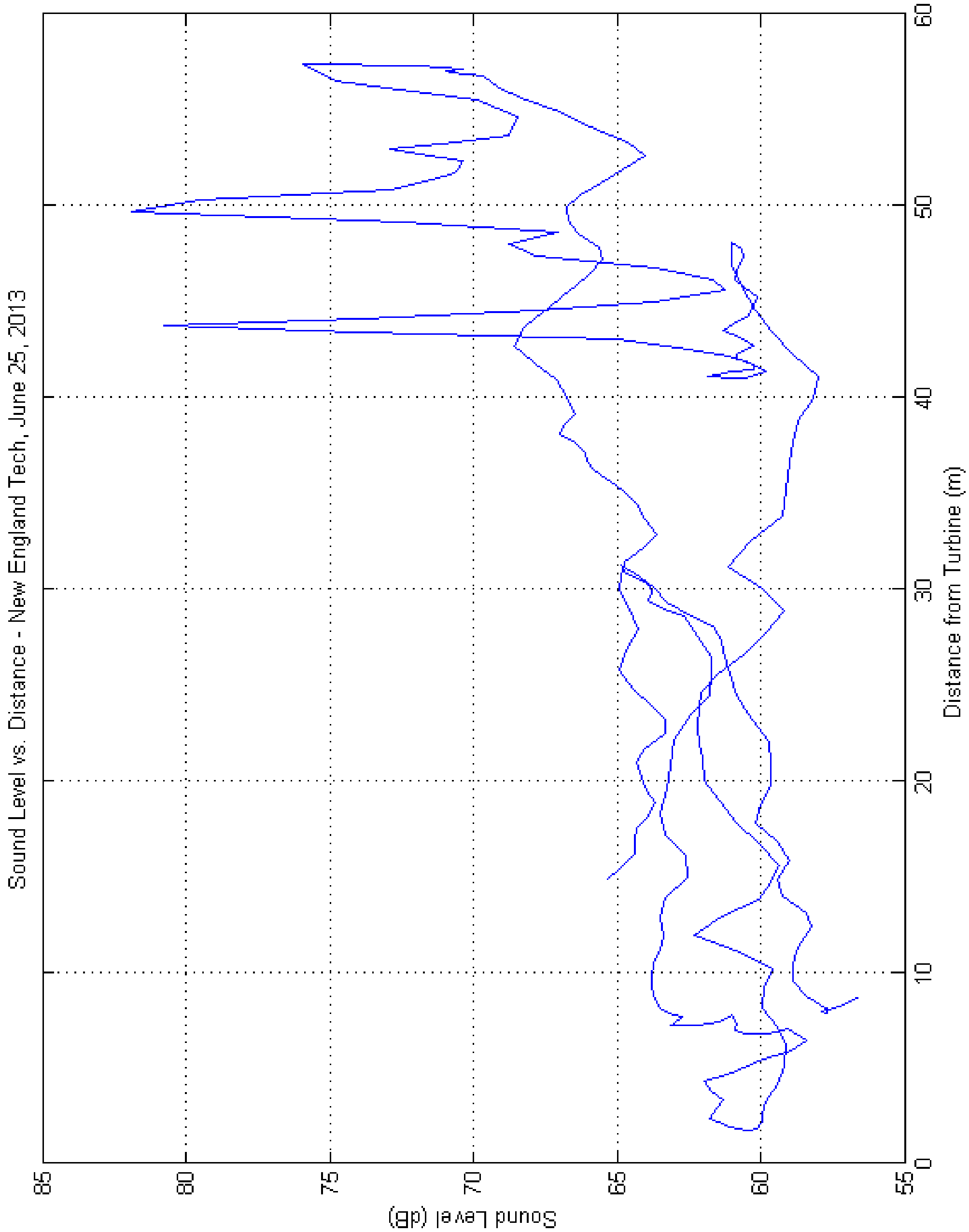

Figure 3.13: Sound Level vs. Distance at New England Tech, Warwick, RI on 25 JUN 2013.

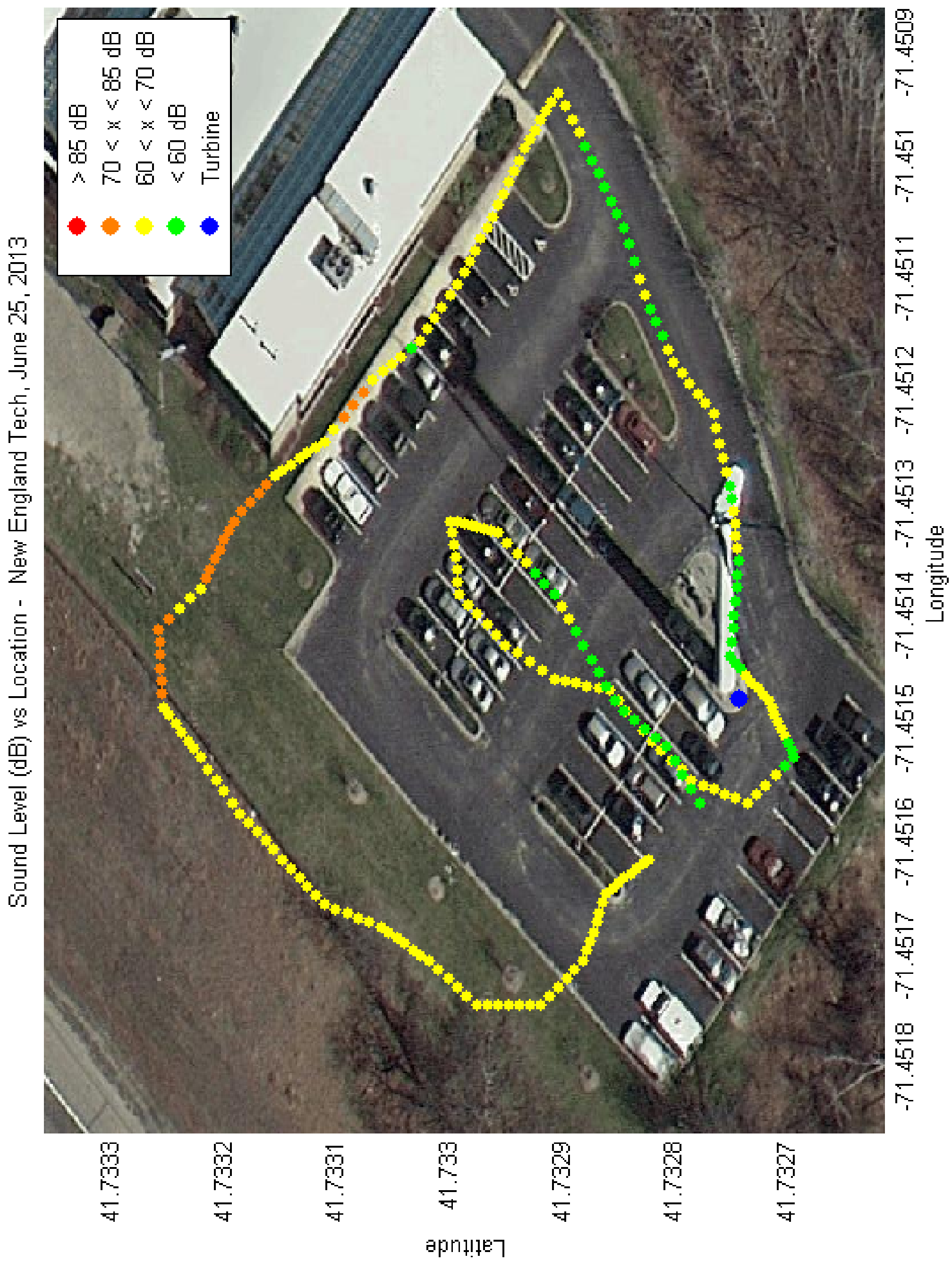

Figure 3.14: Sound Level Mapping at New England Tech, Warwick, RI on 25 JUN 2013.

3.4 Conclusions

The analysis of the sound level data collected at various sites throughout RI shows that the SL is not consistent as a function of range. Specifically there is significant variability (on the order of 15 dB) at the same range (distance) but at a different azimuth. Additionally, sometimes the SL does not decrease as the distance from the wind turbine increases as predicted by various acoustic models. This can be easily explained in some circumstances by the fact that there are louder noise sources present that mask the wind turbine noise. A prime example is NE Tech site at which the noise increase as you move away from the turbine and towards the RT-95 interstate highway. In this case the vehicle traffic noise is louder than the turbine noise.

4. Infrasound Measurements

4.1 Objective

Due to increased concerns about the infrasound levels produced by wind turbines[3, 4, 5], recordings were made using low frequency infrasonic microphones and associated recording equipment as shown in Figure 4.1. For this data, the microphones and recording electronics were stationary at a fixed point relative to the wind turbine. Infrasound data was collected at all of the sites visited, however only the analysis for the Narragansett Bay Commission location is shown here. The results from the other sites are similar.

Figure 4.1: Infrasonic microphones for recording low frequency and infrasound for conversion to un-weighted SPL and PSL values. This photograph was taken at the New England Tech turbine location. The same instrument configuration was used at all sites.

4.2 Results

An example of the data collection, signal processing steps, and final results for Infrasound Levels (below 20 Hz) are shown for the Narragansett Bay Commission site.

Figure 4.2: Satellite image showing relative location of the two co-located infrasonic microphones relative to the three wind turbines installed at the Narragansett Bay Commission site at Fields Point, Providence.

The relationship between the Sound Pressure Level (SPL) and the Pressure Spectrum Level (PSL) is given

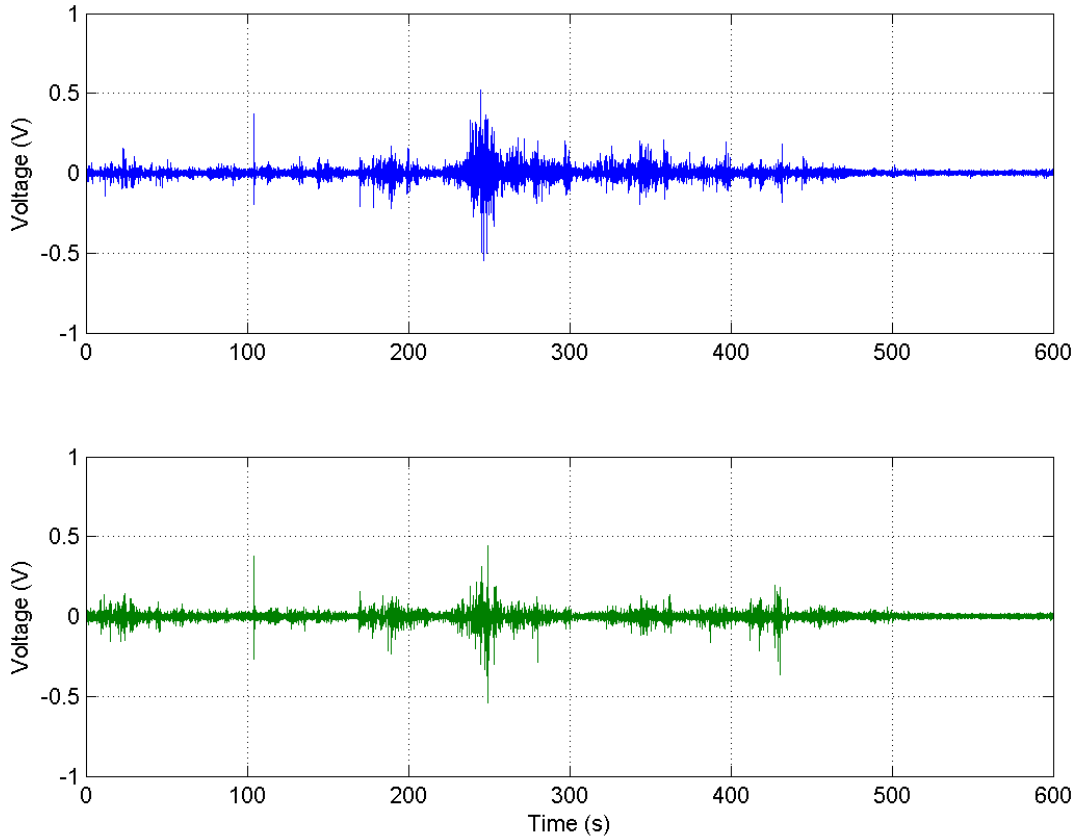

Figure 4.3: Voltage time series recorded by the two co-located infrasonic microphones. The two recordings are correlated in time and the voltage time series will be converted to a pressure time series using the receive sensitivity for each microphone.

by:

$$SPL = PSL + 10\log_{10}(w) \tag{4.1}$$

in which w is the bandwidth. Referring to Figure 4.8, if one considers the 100 Hz to 200 Hz band then the SPL would be given according to:

$$40 + 10\log_{10}(100) = 60 \text{ dB} \tag{4.2}$$

with 40 dB used as the average PSL in that band. If one instead considers the 100 Hz to 1 kHz band, the result is similar because although the bandwidth is increased, the average value in the middle of the band is now lower at approximately 30 dB. Because the PSL is changing as a function of frequency, the actual

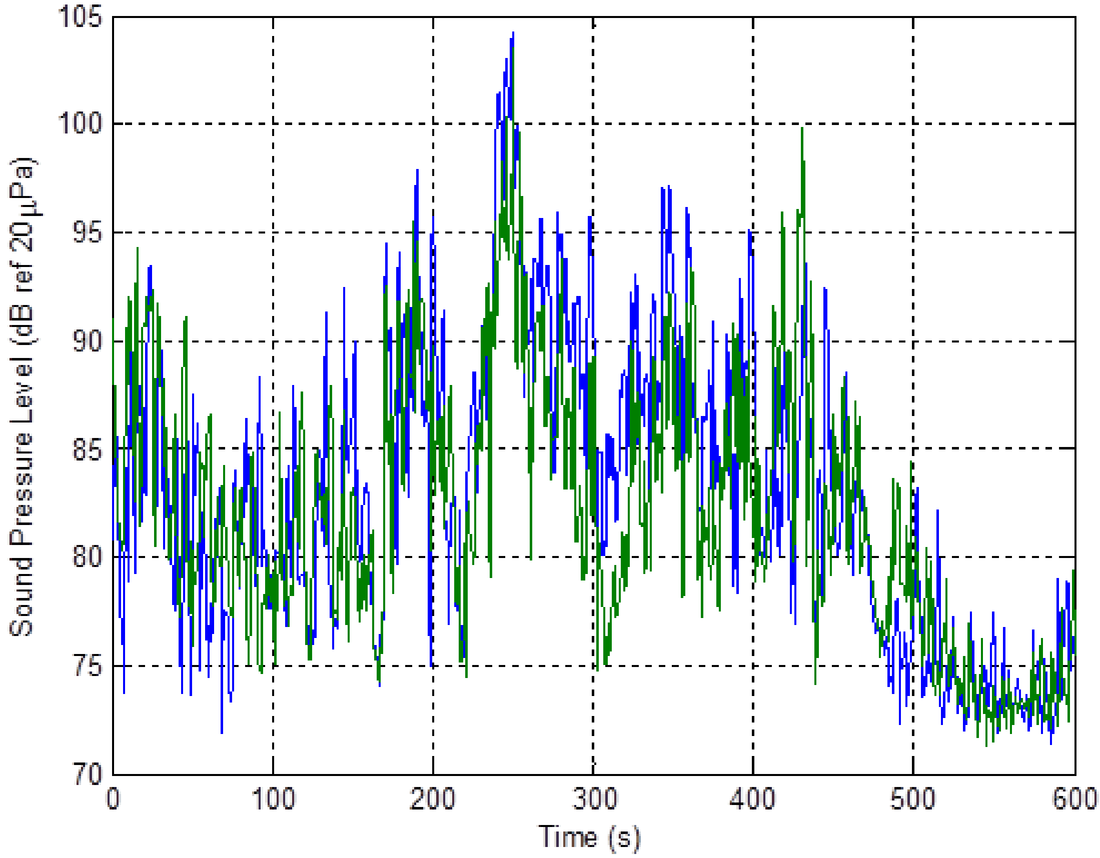

Figure 4.4: Sound Pressure Level values (un-weighted) computed from infrasonic microphone recordings. The levels are calculated from the RMS pressure over a one second window. As with the audio band recordings, these levels are consistently higher by approximately 18-20 dB, than the levels measured using the Sound Level Meter with A weighting.

conversion requires one to integrate the PSL over the *entire* frequency band of interest as shown in [2], yielding and SPL of 80 dB.

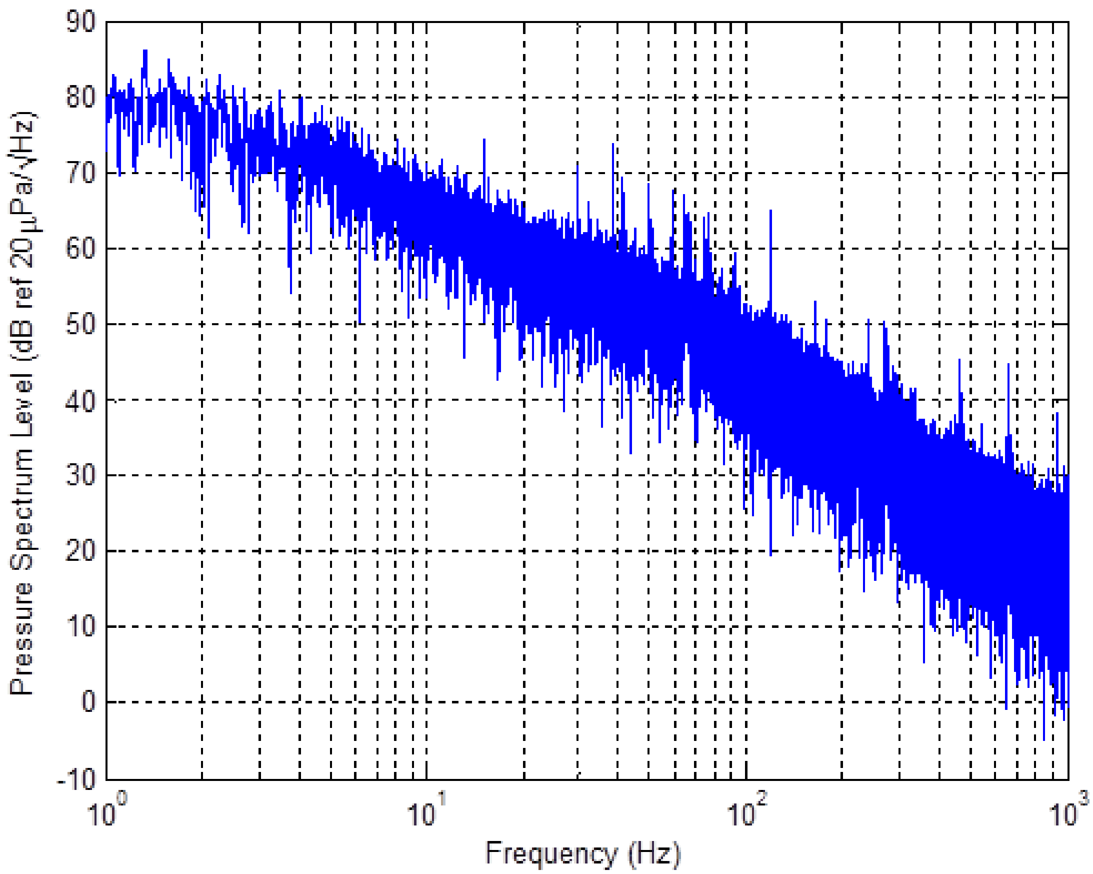

Figure 4.5: The voltage time series (converted to pressure time series using each microphone sensitivity) yields the un-weighted Pressure Spectrum Level. This representation shows the distribution of acoustic power as a function of frequency. Most of the acoustic power is concentrated in the low frequency (20 -200 Hz) and infrasonic frequency (1-20 Hz) bands.

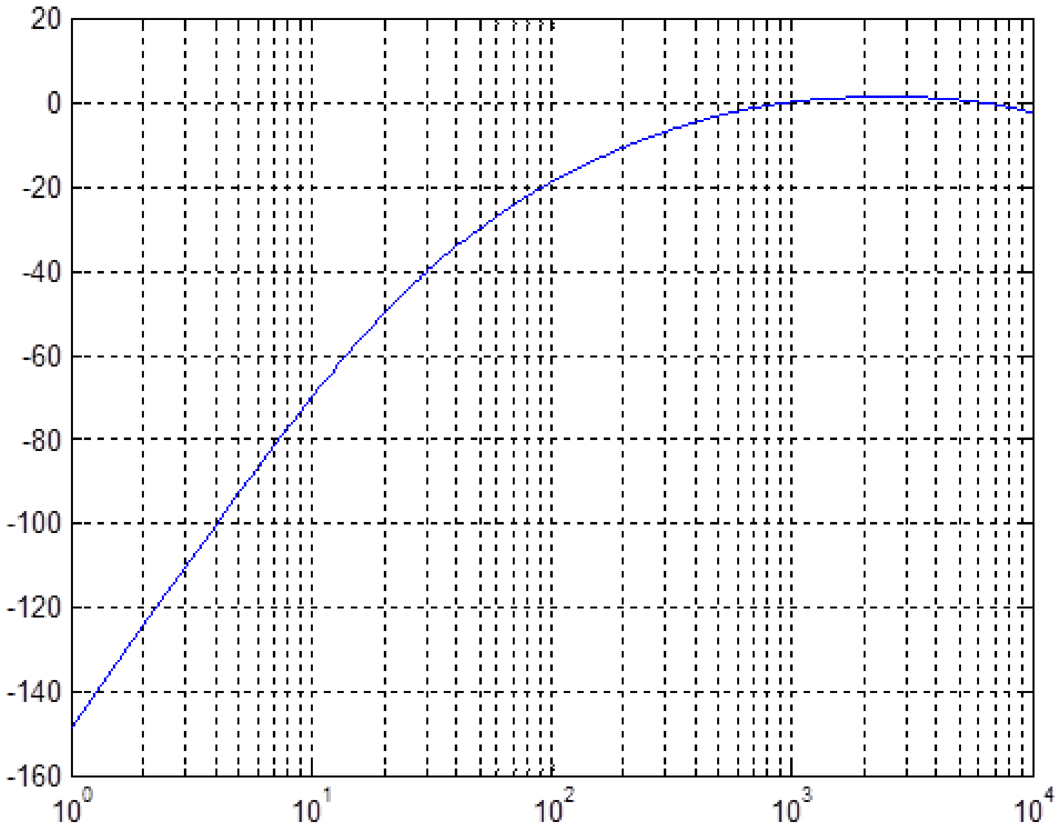

Figure 4.6: A-weighting values for Audio and Infrasonic Bands. Applying these weights will reduce the PSL at frequencies below 1 kHz. For example the measured PSL at 100 Hz will be reduced by 20 dB.

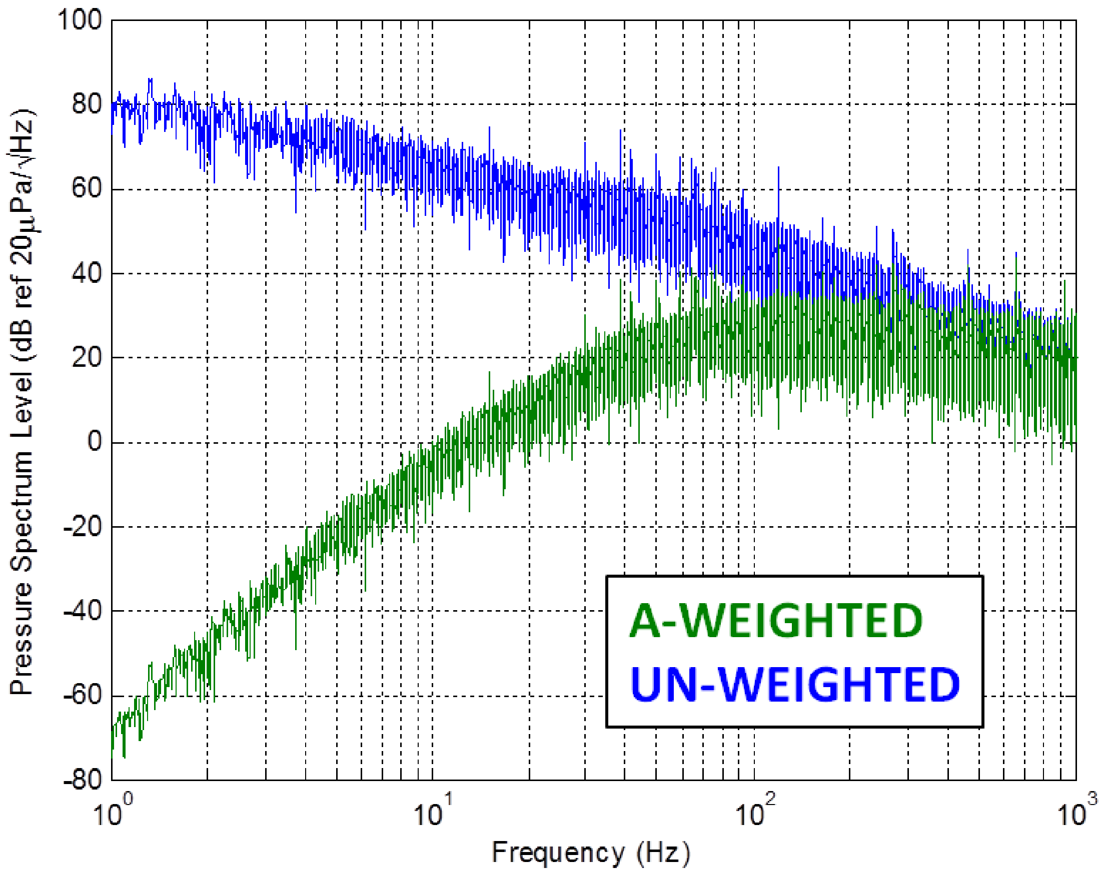

Figure 4.7: Comparison of Un-weighted and A-weighted PSL obtained from Infrasonic microphone. Because most of the acoustic power is concentrated at lower frequencies, a SLM that employs weighting will compute a lower SPL relative to an un-weighted measurement.

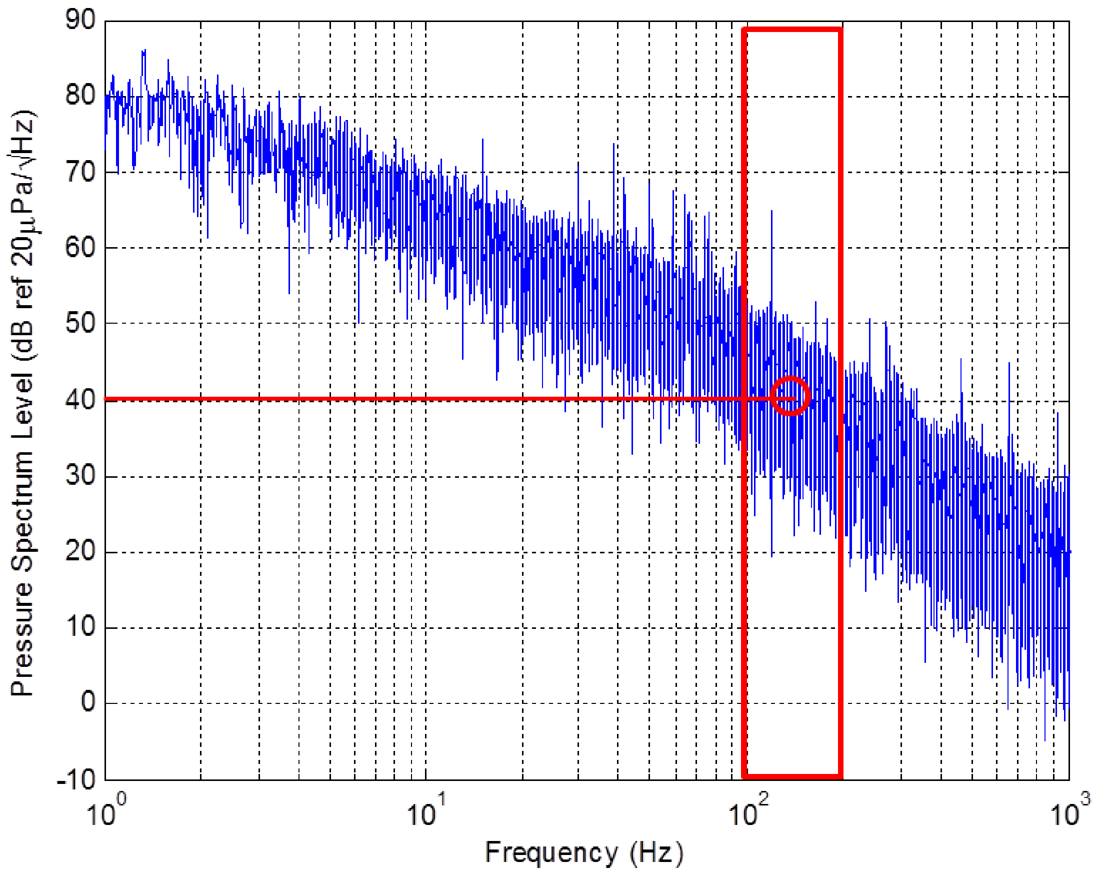

Figure 4.8: Example conversion of PSL to SPL. The example shown highlights the 100-200 Hz band. For this band the average PSL is approximately 40 dB and the corresponding SPL is 60 dB. If the entire un-weighted band were used, the SPL would be 80 dB.

4.3 Conclusions

The infrasound recordings measure PSL and corresponding SPL values higher than those measured by the SLM. This is not un-expected due to the limited low frequency response of the SLM coupled with the weighting that de-emphasizes the low frequency components. The un-weighted, infrasonic SPL values are on the order of 80 dB at the various test locations. Because the infrasonic microphones and recording systems remained stationary throughout the test, mapping of the infrasonic sound field was not possible.

It is recommended that all field measurements of ambient background data and all turbine noise measurements employ full bandwidth recordings and present un-weighted data. The use of Sound Level Meters for this purpose is not recommended even if they have an un-weighted option because the spectral content associated with the turbine noise cannot be captured and analyzed.

5. Property Line Measurements

5.1 Objective

The objective of this effort was to collect SPL data along the property lines at the wind turbine sites (as opposed to just as a function of distance and azimuth). This added a new level of complexity to the data collection task. First, all of the property lines had to be identified. Second, a means of identifying them in the field and navigating using the GPS system to allow traversing the property lines had to be realized. This data would then be compared to "ambient" noise data collected elsewhere to try and make some kind of assessment about possible increases in ambient noise along the property boundaries due to wind turbines.

The impetus for this revised scope was to try and assess the efficacy of draft guidelines for siting wind turbines.[6] Those guidelines (for large WES) state:

> Acoustic study required maximum of 5 dB(A) above ambient, calculated for both daytime and night time. If absolute standard used, must vary based on existing land use and noise ordinances i.e., higher standard in industrial areas, lower in residential or rural areas. state ambient .

5.2 Methods

The methods to collect the SPL data along the property lines are the same as those employed for the sound field mapping described previously. It is just that now prescribed paths will be traversed and those will be unique to each site.

5.3 Results

5.3.1 Portsmouth Abbey

Figure 5.1: Sound Level along property lines for Portsmouth Abbey wind turbine site, Portsmouth, RI.

5.3.2 Ambient Noise

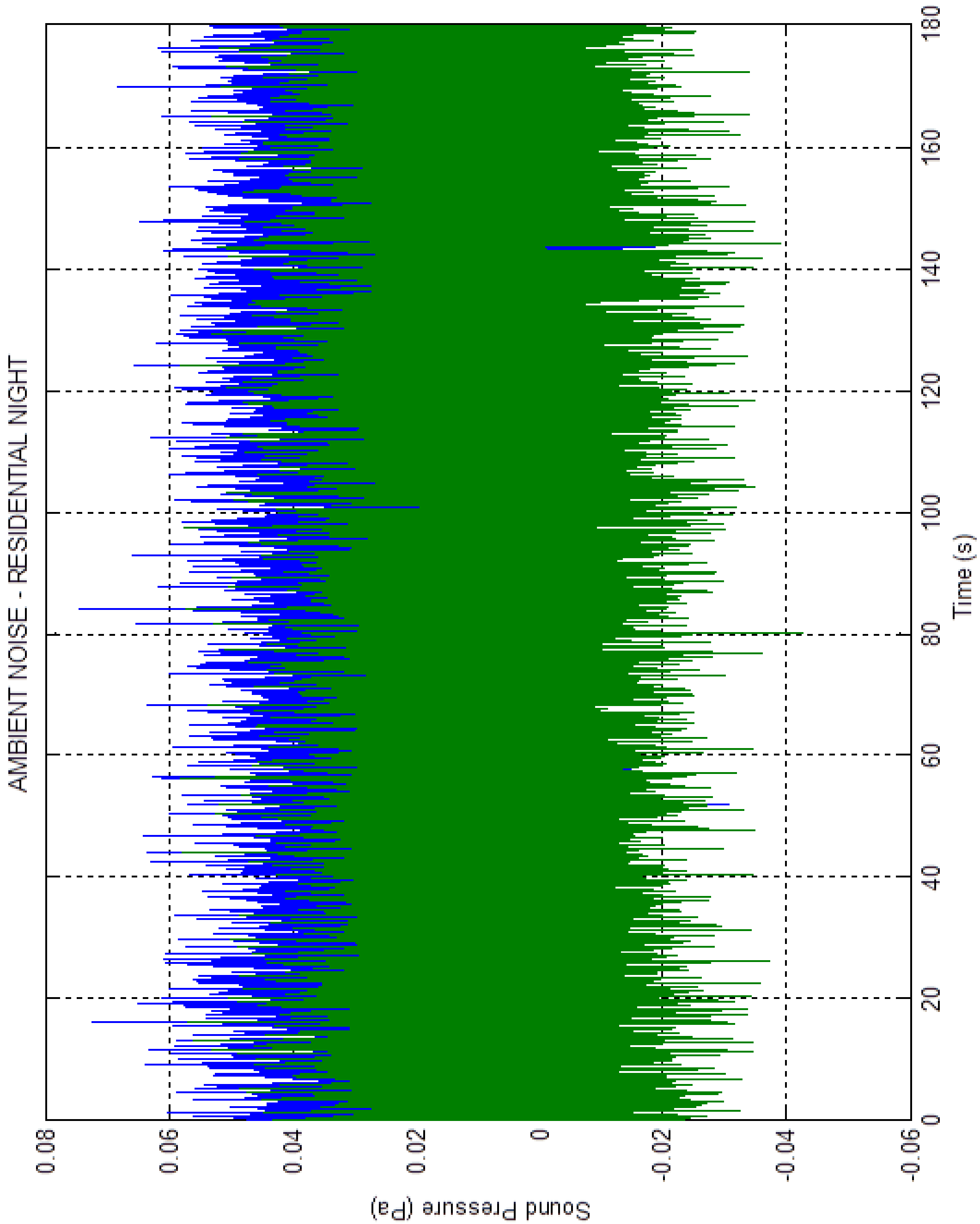

Figure 5.2: Time series of residential, nighttime ambient noise levels.

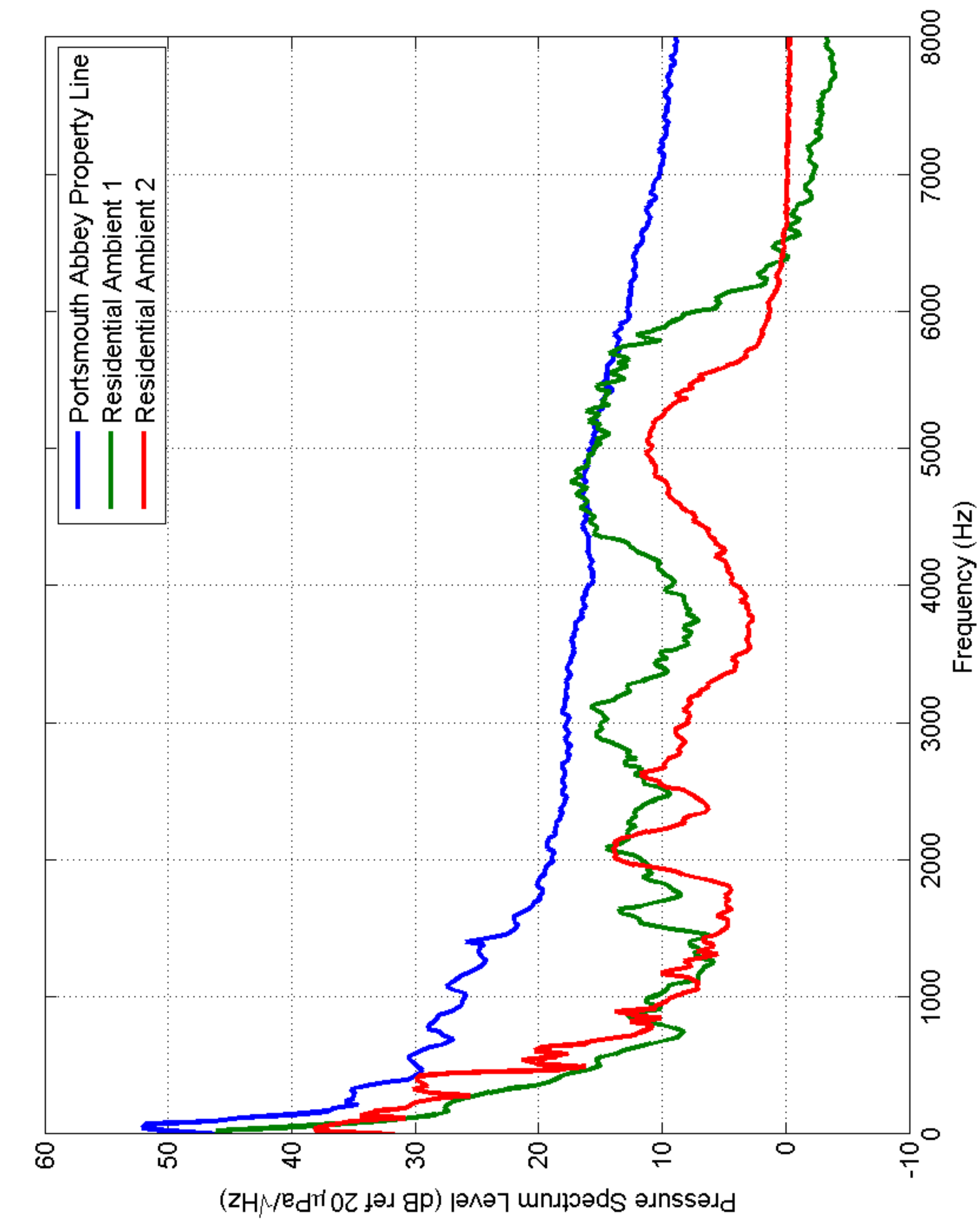

Figure 5.3: Comparison of Pressure Spectrum Levels. The PSL measured at the property line of Portsmouth Abbey (quietest location) is plotted overlaid with two separate residential, nighttime ambient noise levels.

5.4 Discussion and Conclusions

A question has been raised regarding possible conclusions that can be made regarding wind turbine noise level measurements obtained at the turbine property lines with respect to the interim draft guidelines issued by the RI Dept of Administration. The guidelines summary states: *"Acoustic study required - maximum of 5 dB(A) above ambient, calculated for both daytime and night time. If absolute standard used, must vary based on existing land use and noise ordinances - i.e., higher standard in industrial areas, lower in residential or rural areas. State ambient."*. More details are given in the *Noise* section of the guidelines. Specifically this section recommends that municipalities establish Standards for WES and outlines both General Guidelines and also suggests components that should be included in a Standard. The guidelines in this section are as follows:

Standards - Noise standards should:

- *State the level at which noise must be limited and the limiting criteria in bB(A) above ambient:*
  - *Example: daytime and nighttime. "X" dB (A) above ambient.*
  - *dB(G) should also be considered*
- *State the period of time for noise averaging:*
  - *Examples: 24 hours, 8 hours, or 1 hour*
- *State at which point noise shall be measured:*
  - *Example: at the property line*
- *State the standards that noise must be measured and modeled according to (ANSI,IEC, etc.)*
- *State the procedures to address noise complaints from neighbors along with procedures for curtailment or shutdown of the turbine if standards are exceeded.*
- *Consider and implement penalties for low-frequency noise, amplitude modulation.*

The specific question at hand then appears to be the following "based on the measured noise levels, do existing RI wind turbines meet these guidelines?" No definitive conclusions can be made at this point due to the uncertainty in the guidelines coupled with the uncertainty of the measurements. The noise levels obtained are valid measurements, checked by careful calibration of the microphones and recording system electronics. The noise level measurements were made along the property lines utilizing the property line data base information and GPS receivers to ensure we were in the correct locations. Therefore, it is not the quality of the measurements that prevents us from drawing a conclusion and providing a definitive answer, instead it is the applicability of these measurements to answering the question just posed. First, for all of the data collected at the various sites, none have noise standards that have been established in conformance with the published guidelines. As a result, there is no clear definition of what ambient noise level is, how it should be defined, or how it is measured (other than the night and day). As suggested by the guidelines, how long must ambient noise levels be measured - over weeks and months, in all weather conditions, etc. Should these be time averaged in some fashion? If so, how? Should data be collected along the entire property boundary, or just at a few select points? Should be averaged over the boundary lines to produce a single number? Is the spectral content of the ambient noise levels important? How is should it be quantified? Because a Standard is not available, only the general guideline can be used (i.e. the 5 dB above ambient at the property line). A separate issue from the definition and specification of ambient noise is the fact that the wind turbines are already installed and operating, therefore ambient noise data must be collected at other "representative" locations. Are the ambient noise levels acquired at these other locations, equivalent to, and acceptable as, surrogates for the ambient noise levels at the property lines of the existing wind turbines prior to the turbine installation? Although it seems reasonable to answer in the affirmative, we have no definitive way to prove this and the conclusion could easily be challenged by a skeptical reader.

It appears that the only way to properly answer the question would be to collect a set of measurements with the turbine operating, and then shut down the turbine and repeat the measurement. As long as no other interfering noise sources appear in the interim, the differences in noise levels can reasonably be attributed to the wind turbine, and any measurable differences along the property lines would give factual evidence to answer the question and draw the necessary conclusions.

6. Conclusions

Overall the acoustic study met its objectives by recording and analyzing the radiated noise from wind turbine presently installed in RI. There were operational sites that were not recorded due to the property owner denying access to the site to make measurements. This occurred at only two sites, North Kingstown and Middletown. At the locations where measurements were recorded, simultaneous GPS, Sound Level Meter and audio band recorders were able to map the spatial extent of the
The following list summarizes the major conclusions obtained from the results of processing noise measurements (acoustic and GPS data) at various wind turbine sites throughout Rhode Island.

- Wind turbines produce measurable infrasonic and low frequency noise in the 1 Hz to 100 kHz band. These levels were measured at an average of 84 dB SPL over this band with variation in time of up to 16 dB.
- A-weighting masks these levels (de-emphasizes infrasound levels by -20 to -150 dB from 100 Hz down to 1 Hz).
- The Sound Level Meter was not capable of measuring infrasound levels, and is not accurate for measuring audio band noise levels. The SLM measurements should be adjusted by adding 18 dB when using A-weighting and 9 dB when using C weighting.
- The Sound Level Meter is not capable of measuring transients, narrowband tonals or complex noise characteristics.
- The use of raw audio and infrasound recordings with appropriate processing allows computation of un-weighted levels and can reveal complex time-frequency behavior of the wind turbine noise.
- The description of either wind turbine or ambient noise is not adequately characterized by a single SPL number.
- It is feasible to map the spatial extent of the sound field surrounding turbines utilizing Geo-referenced and time synchronized audio recordings. However, the data indicate that it is not feasible to generalize the noise level behavior as a function of distance due to the variability and directionality of the wind turbine noise.
- It is not possible to make any conclusions regarding turbine noise levels relative to ambient noise levels at the property lines of the wind turbine locations (see previous section for the detailed discussion on this point).

A. Infrasound Measurements

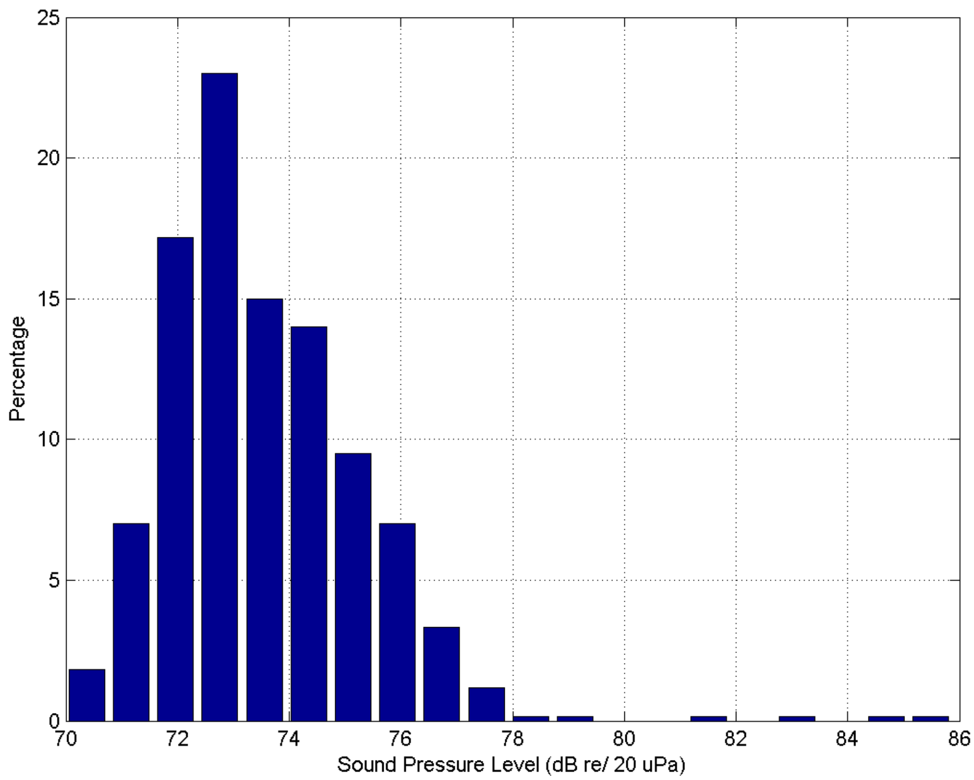

Figure A.1: Infrasound Data Recordings at Portsmouth Abbey 11 OCT 2013 (Channel 1 Histogram).

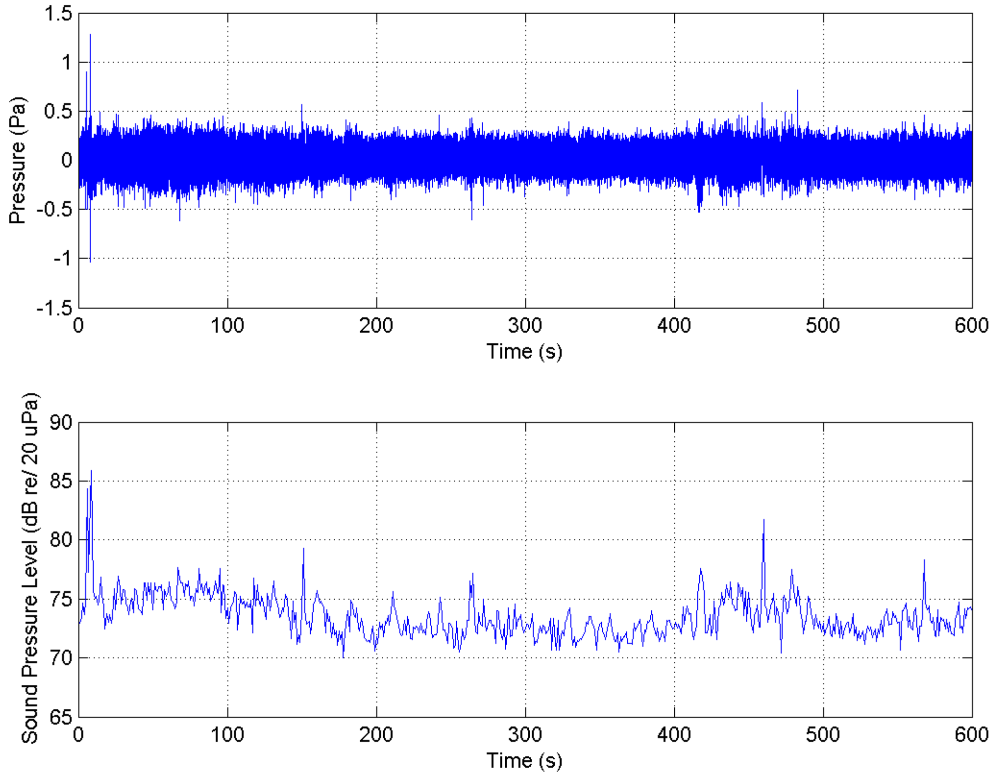

Figure A.2: Infrasound Data Recordings at Portsmouth Abbey 11 OCT 2013 (Channel 1 Time Series).

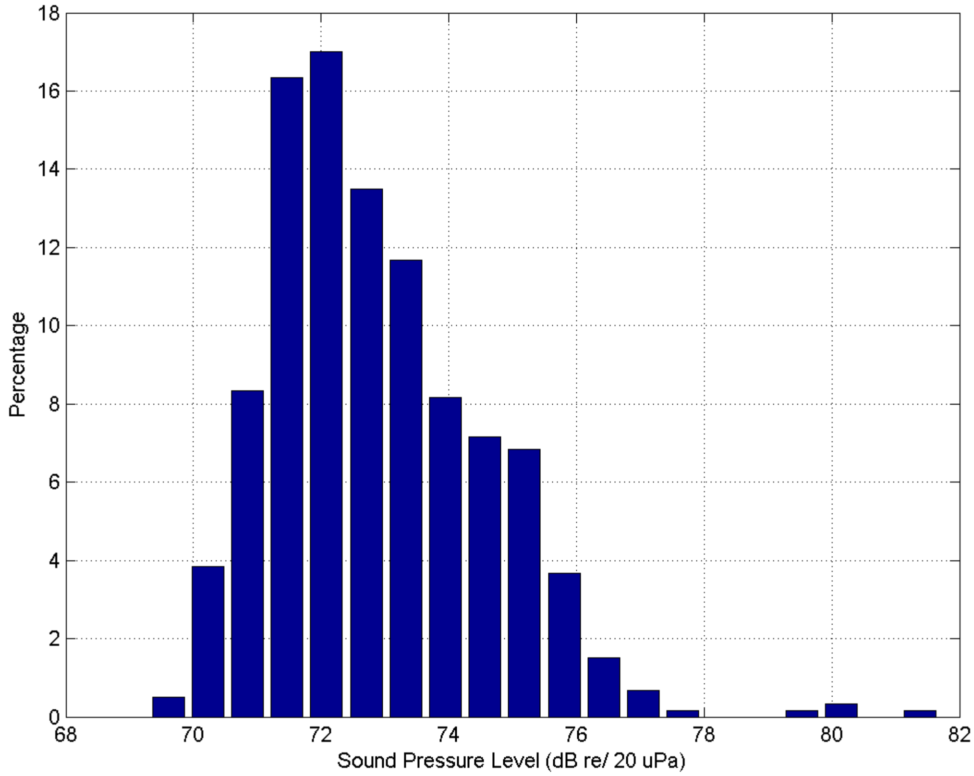

Figure A.3: Infrasound Data Recordings at Portsmouth Abbey 11 OCT 2013 (Channel 2 Histogram).

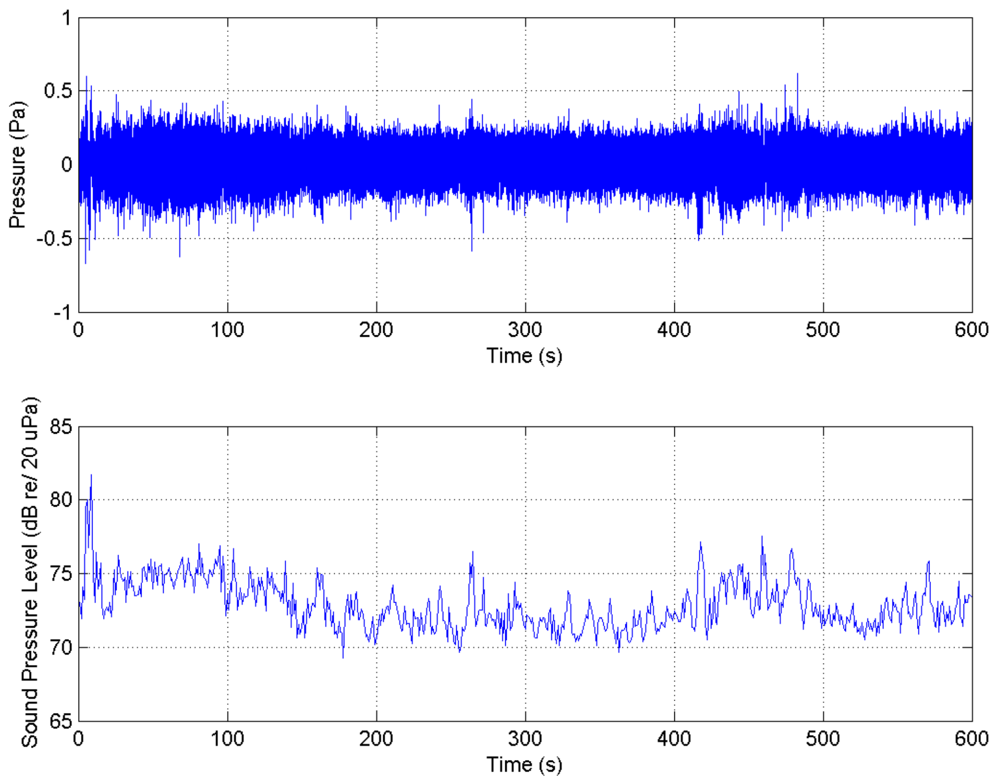

Figure A.4: Infrasound Data Recordings at Portsmouth Abbey 11 OCT 2013 (Channel 2 Time Series).

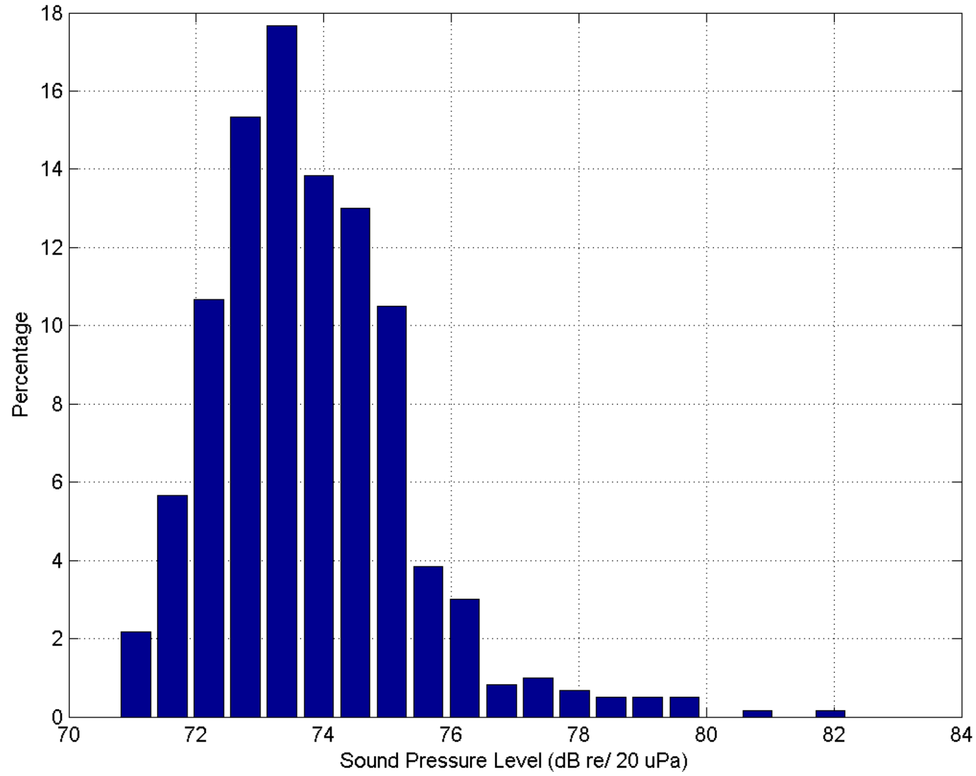

Figure A.5: Infrasound Data Recordings at Portsmouth Abbey 11 OCT 2013 (Channel 1 Histogram).

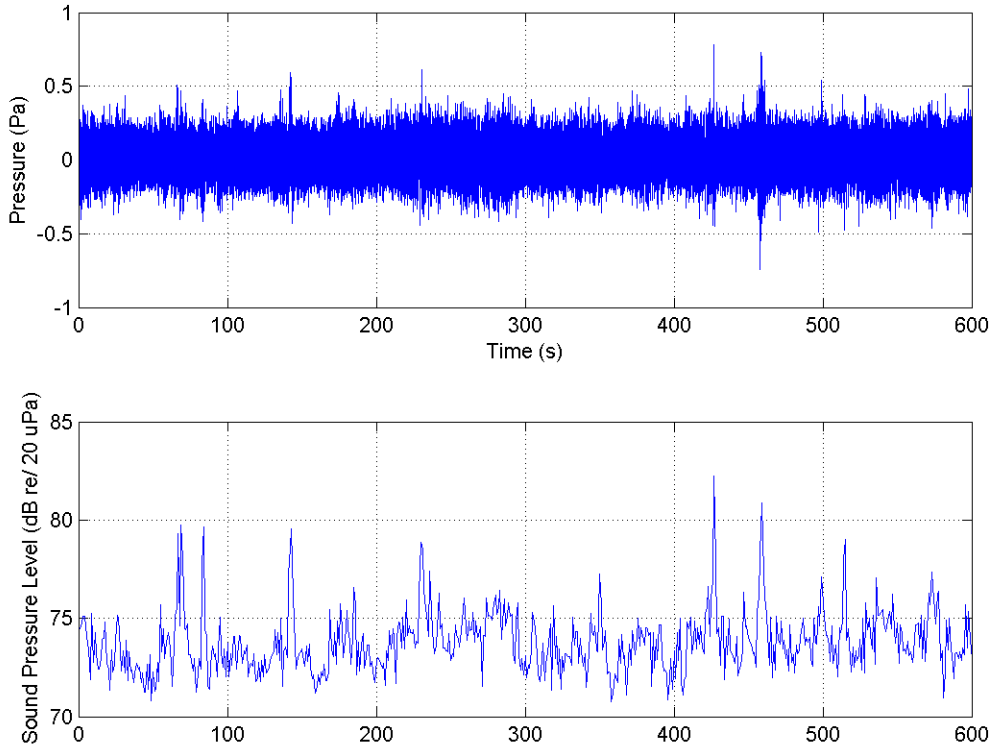

Figure A.6: Infrasound Data Recordings at Portsmouth Abbey 11 OCT 2013 (Channel 1 Time Series).

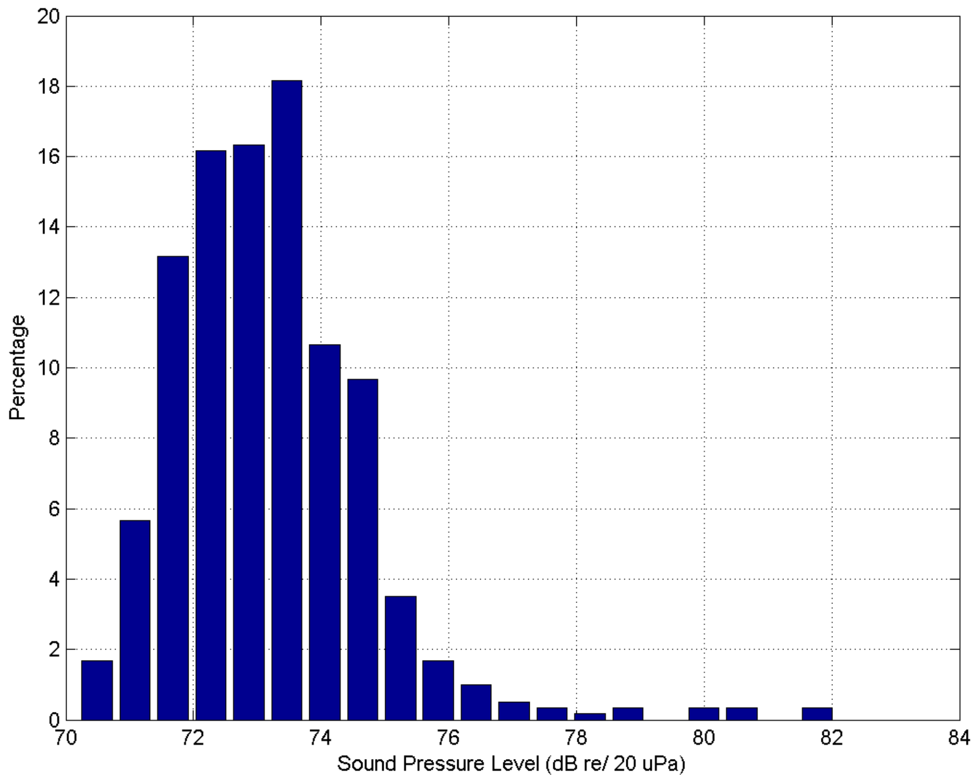

Figure A.7: Infrasound Data Recordings at Portsmouth Abbey 11 OCT 2013 (Channel 2 Histogram).

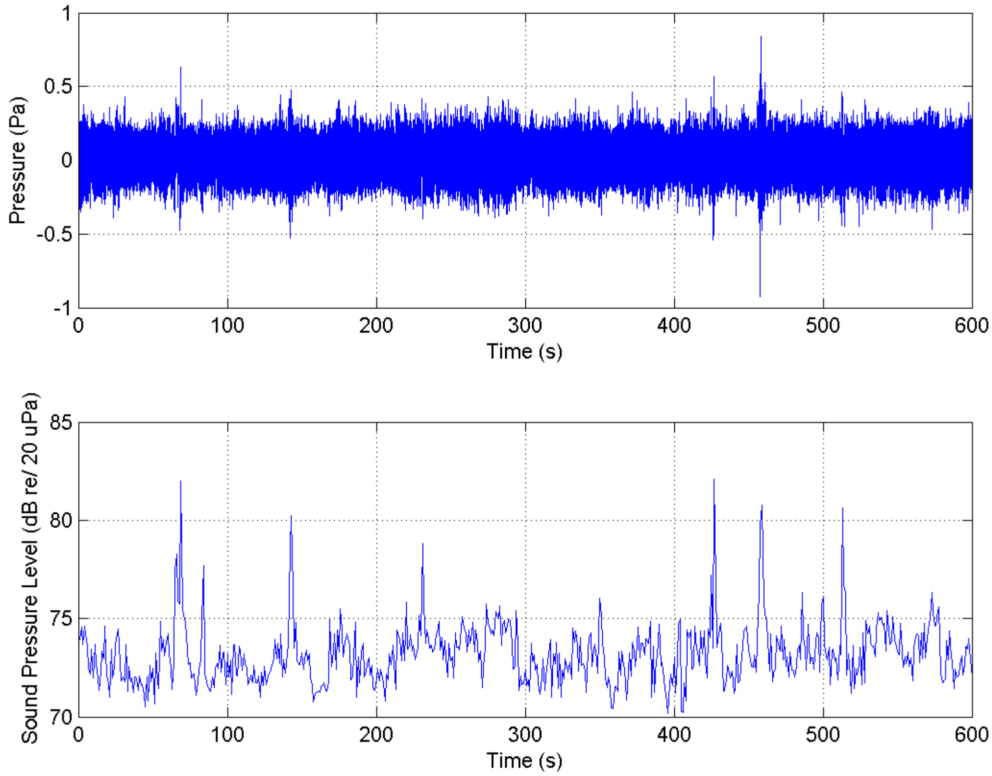

Figure A.8: Infrasound Data Recordings at Portsmouth Abbey 11 OCT 2013 (Channel 2 Time Series).

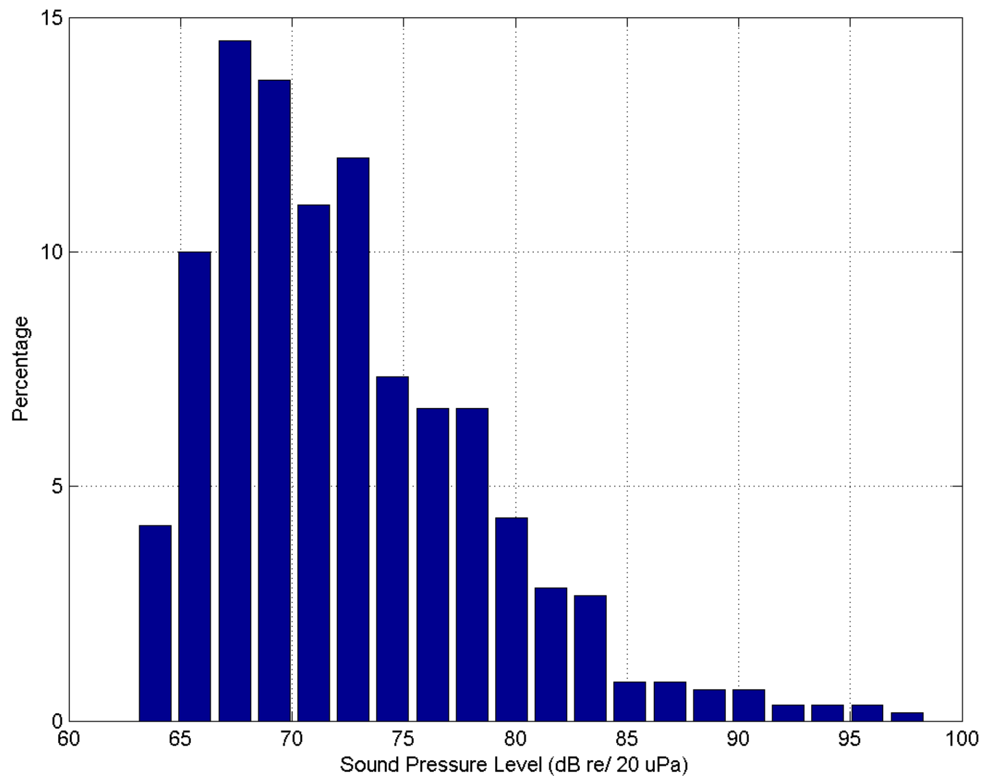

Figure A.9: Infrasound Data Recordings at Portsmouth Abbey 18 OCT 2013 near ice rink. (Channel 1 Histogram).

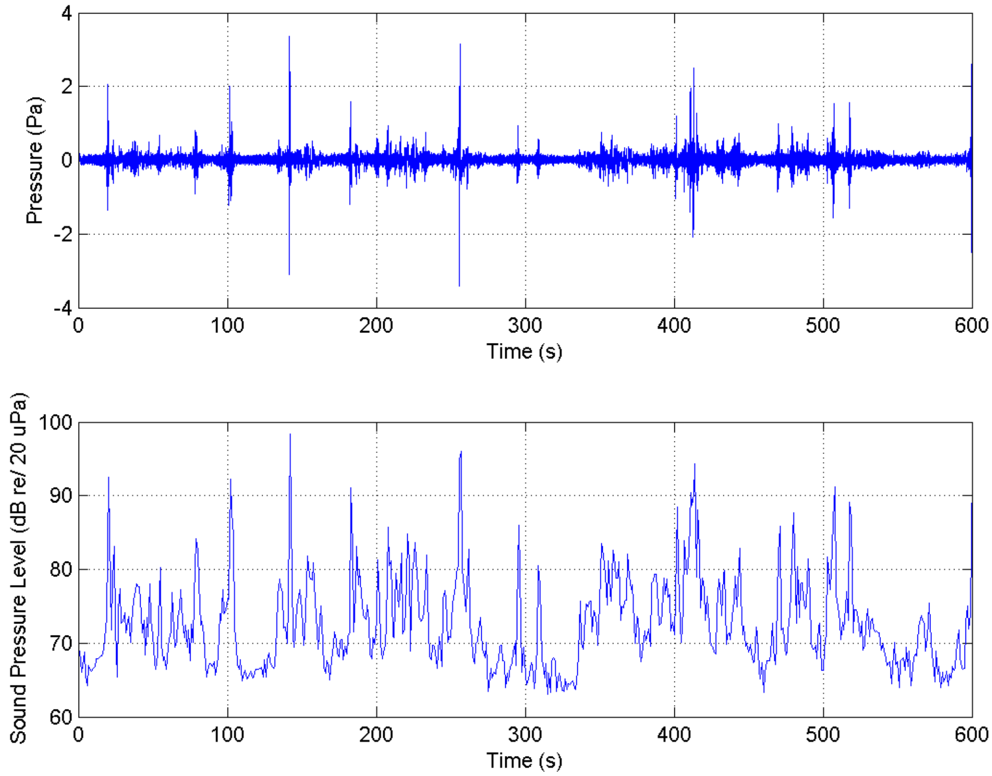

Figure A.10: Infrasound Data Recordings at Portsmouth Abbey 18 OCT 2013 near ice rink. (Channel 1 Time Series).

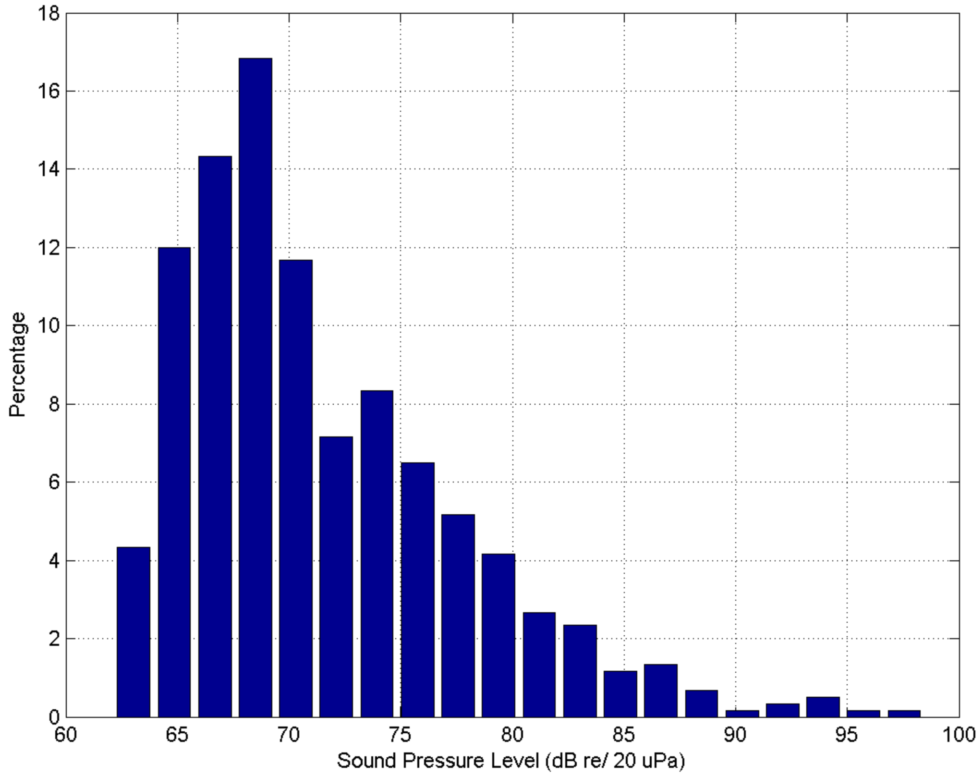

Figure A.11: Infrasound Data Recordings at Portsmouth Abbey 18 OCT 2013 near ice rink. (Channel 2 Histogram).

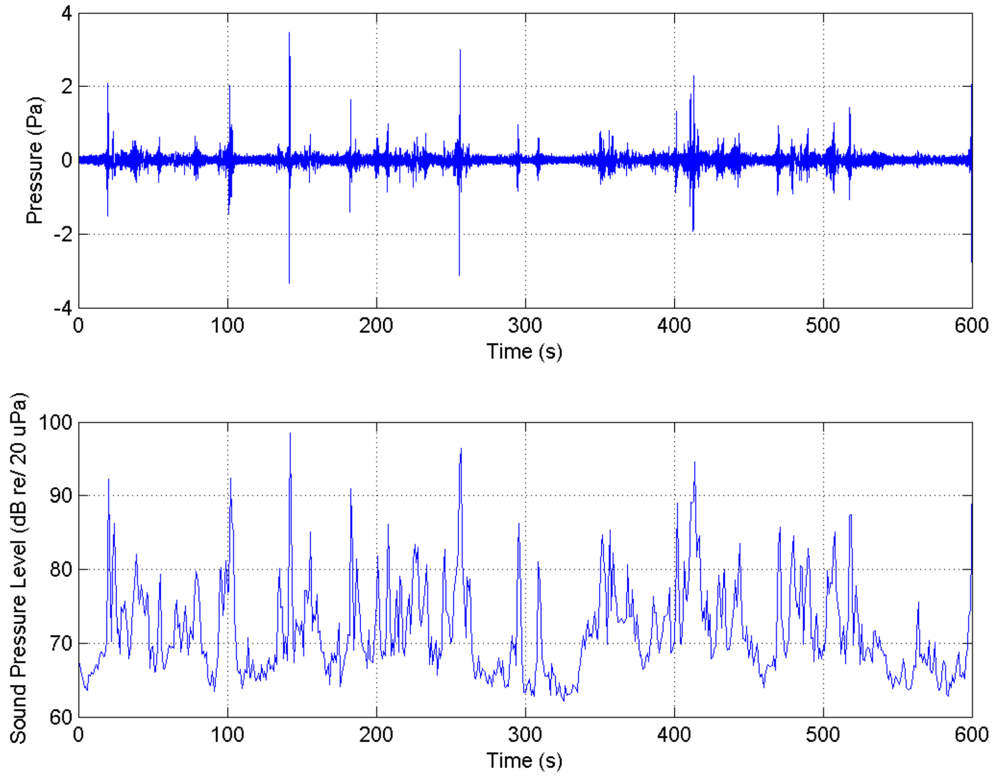

Figure A.12: Infrasound Data Recordings at Portsmouth Abbey 18 OCT 2013 near ice rink. (Channel 2 Time Series).

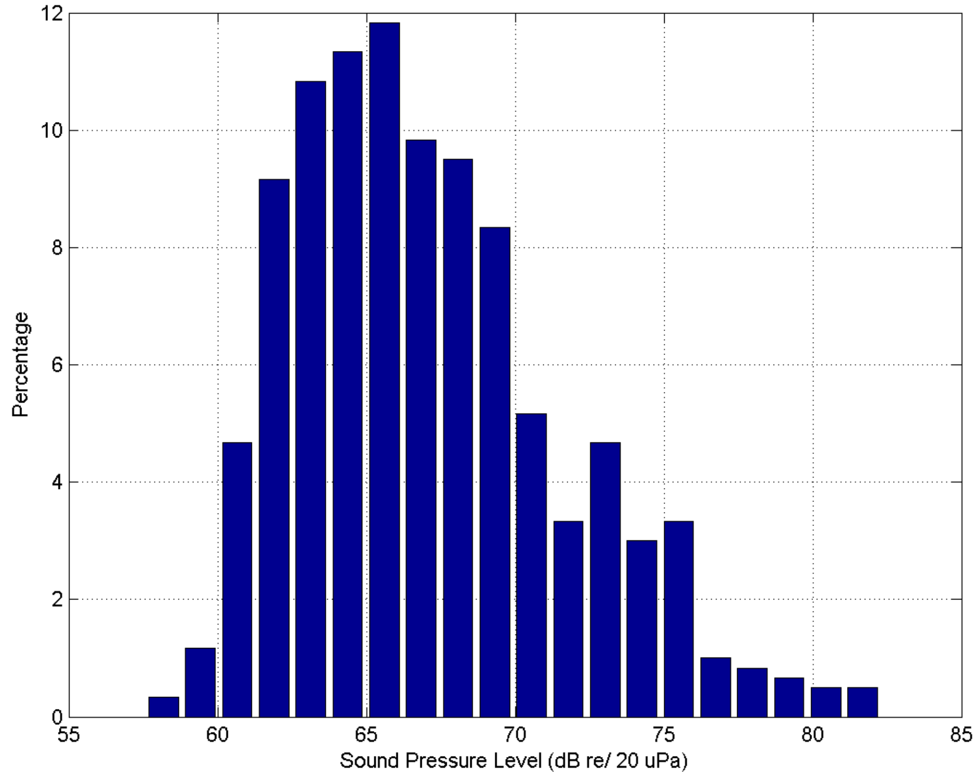

Figure A.13: Infrasound Data Recordings at Portsmouth Abbey 18 OCT 2013 near bay. (Channel 1 Histogram).

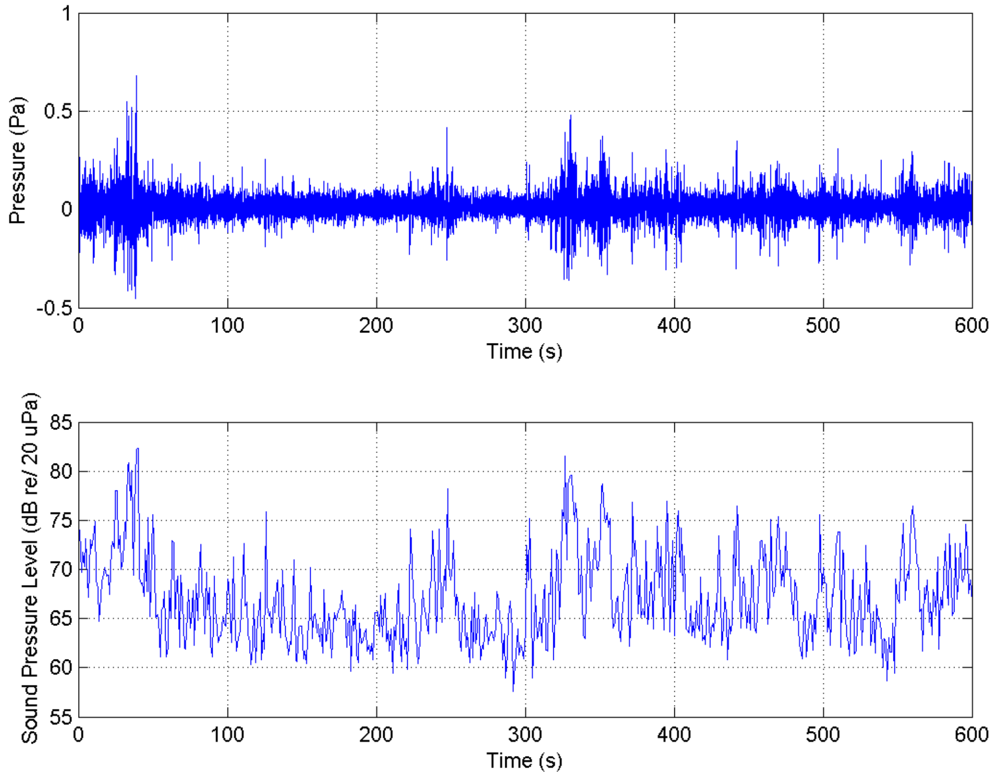

Figure A.14: Infrasound Data Recordings at Portsmouth Abbey 18 OCT 2013 near bay. (Channel 1 Time Series).

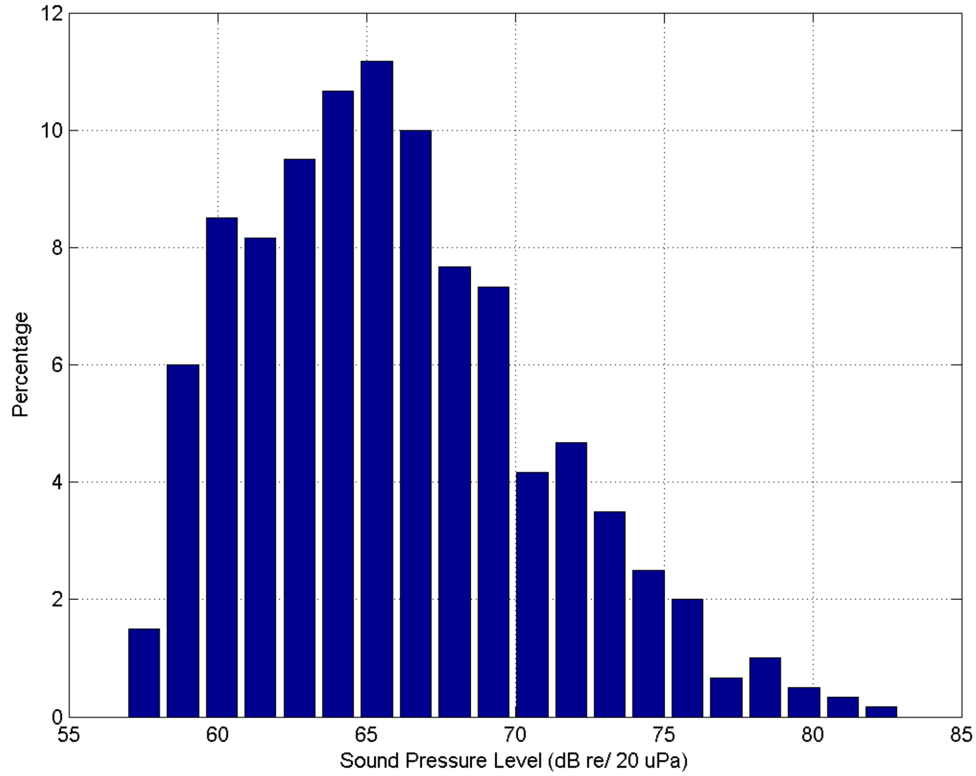

Figure A.15: Infrasound Data Recordings at Portsmouth Abbey 18 OCT 2013 near bay. (Channel 2 Histogram).

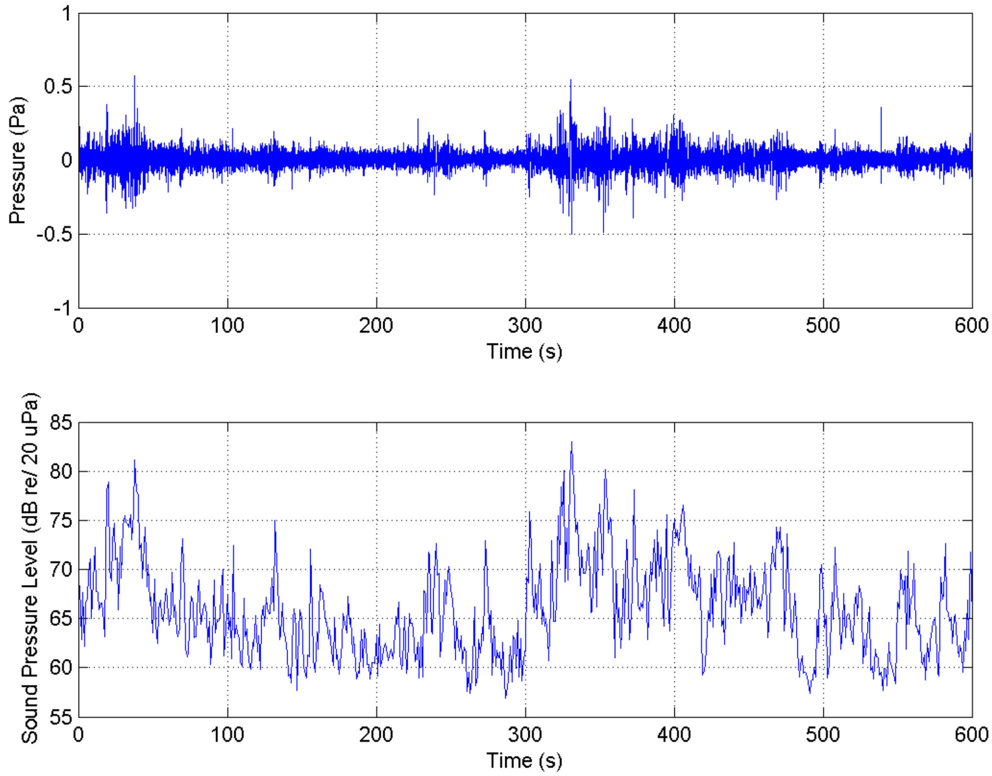

Figure A.16: Infrasound Data Recordings at Portsmouth Abbey 18 OCT 2013 near bay. (Channel 2 Time Series).

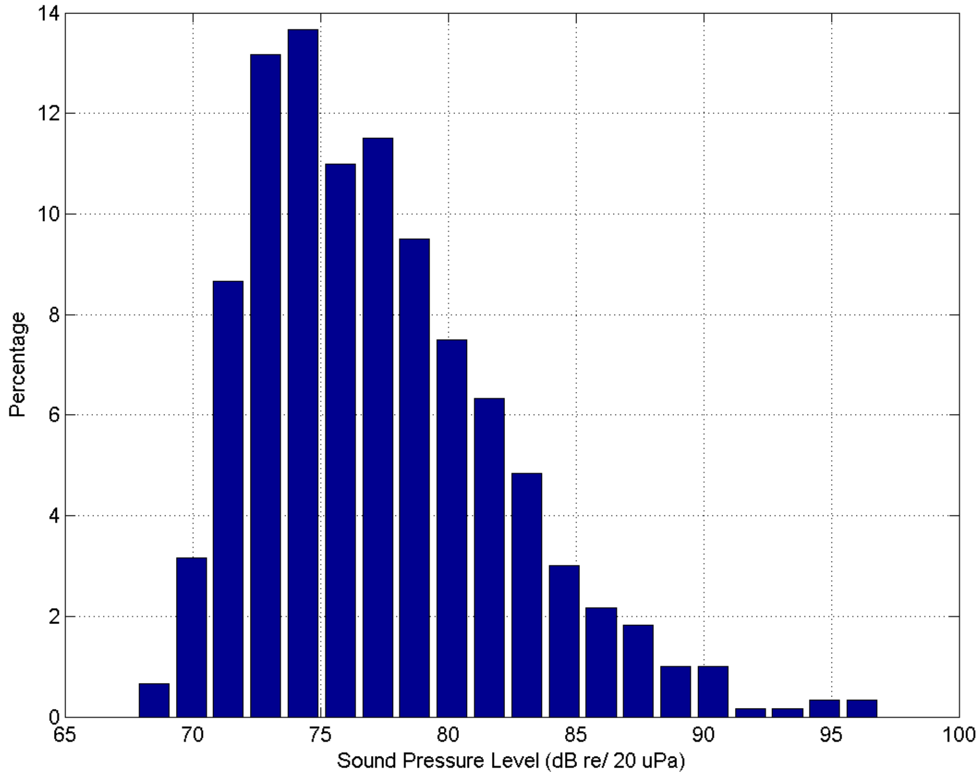

Figure A.17: Infrasound Data Recordings at Portsmouth Abbey 18 OCT 2013 near West Main Rd. (Channel 1 Histogram).

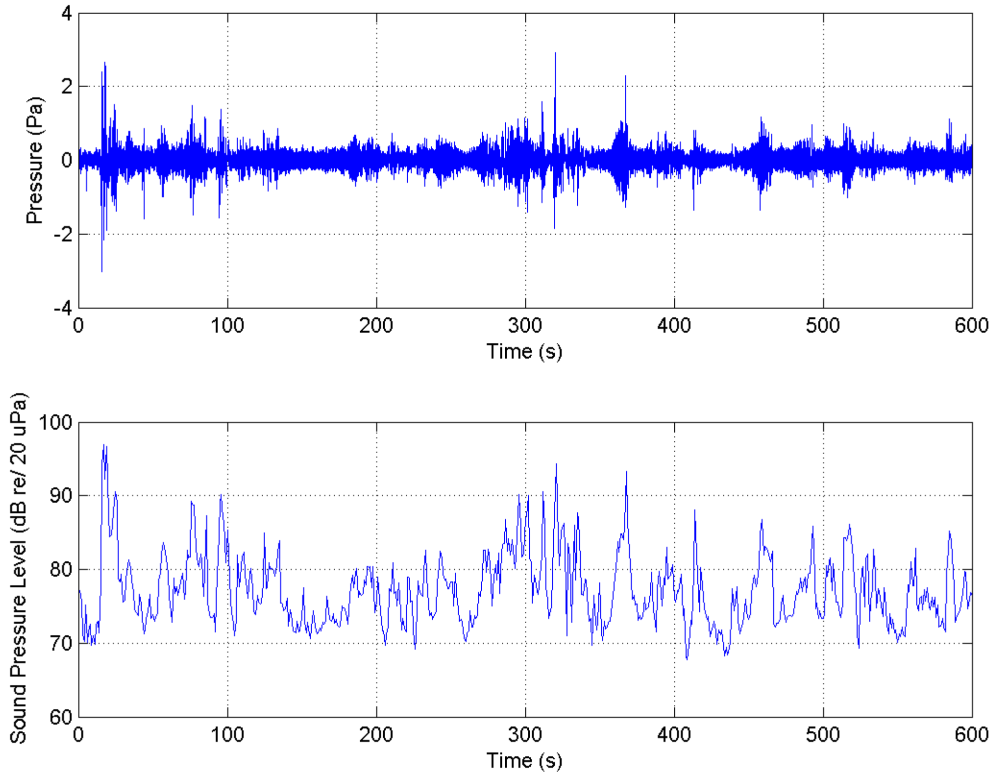

Figure A.18: Infrasound Data Recordings at Portsmouth Abbey 18 OCT 2013 near West Main Rd. (Channel 1 Time Series).

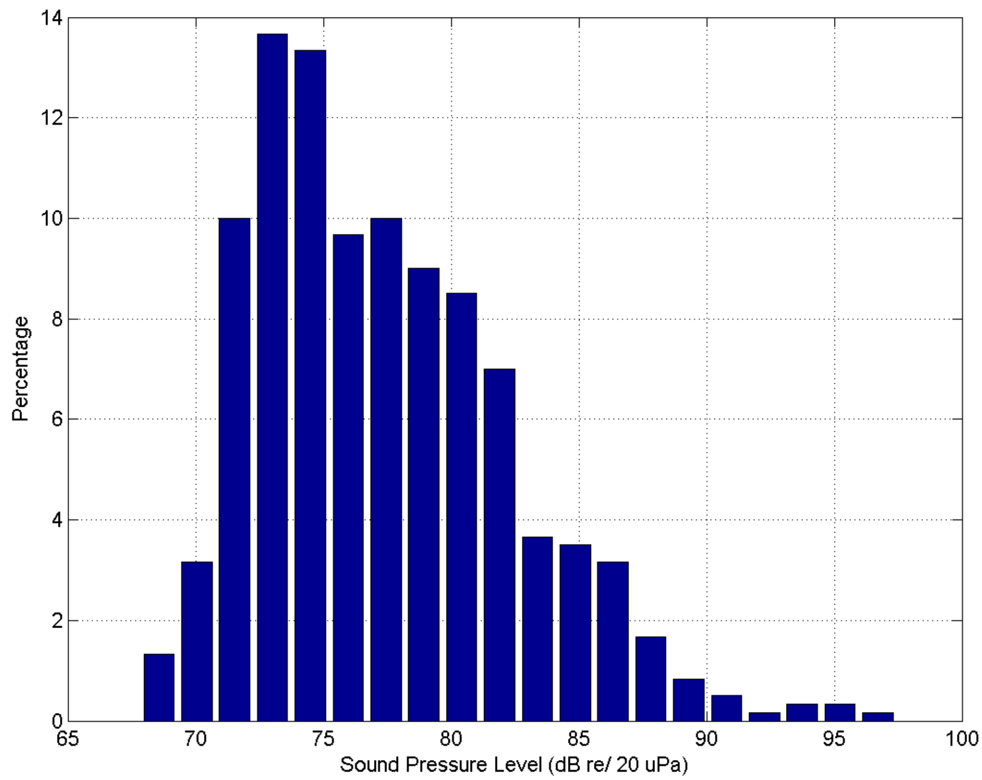

Figure A.19: Infrasound Data Recordings at Portsmouth Abbey 18 OCT 2013 near West Main Rd. (Channel 2 Histogram).

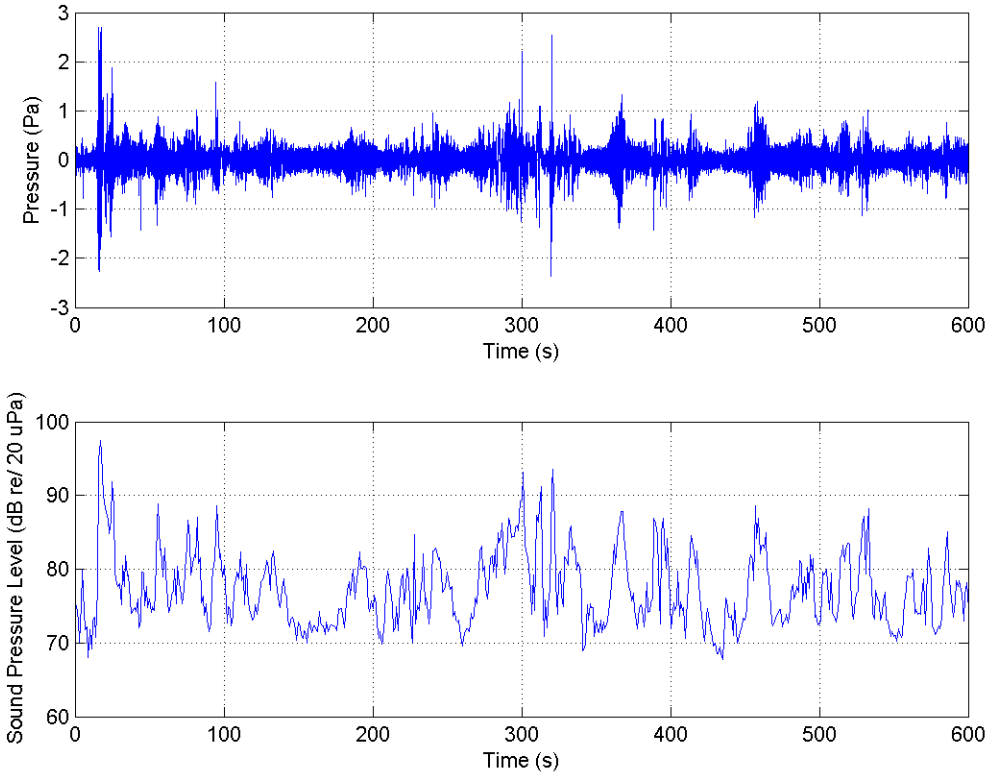

Figure A.20: Infrasound Data Recordings at Portsmouth Abbey 18 OCT 2013 near West Main Rd. (Channel 2 Time Series).

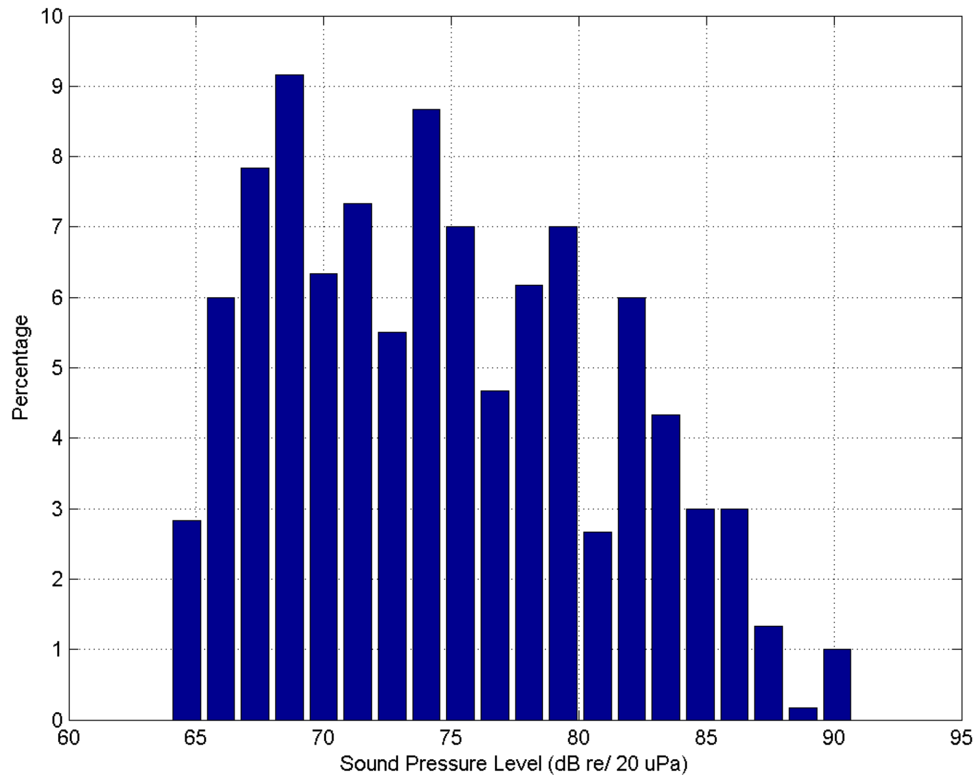

Figure A.21: Infrasound Data Recordings at Hodges Badge Co. 15 OCT 2013 at location 41 33 57.33 N, 071 15 17.18 W. (Channel 1 Histogram).

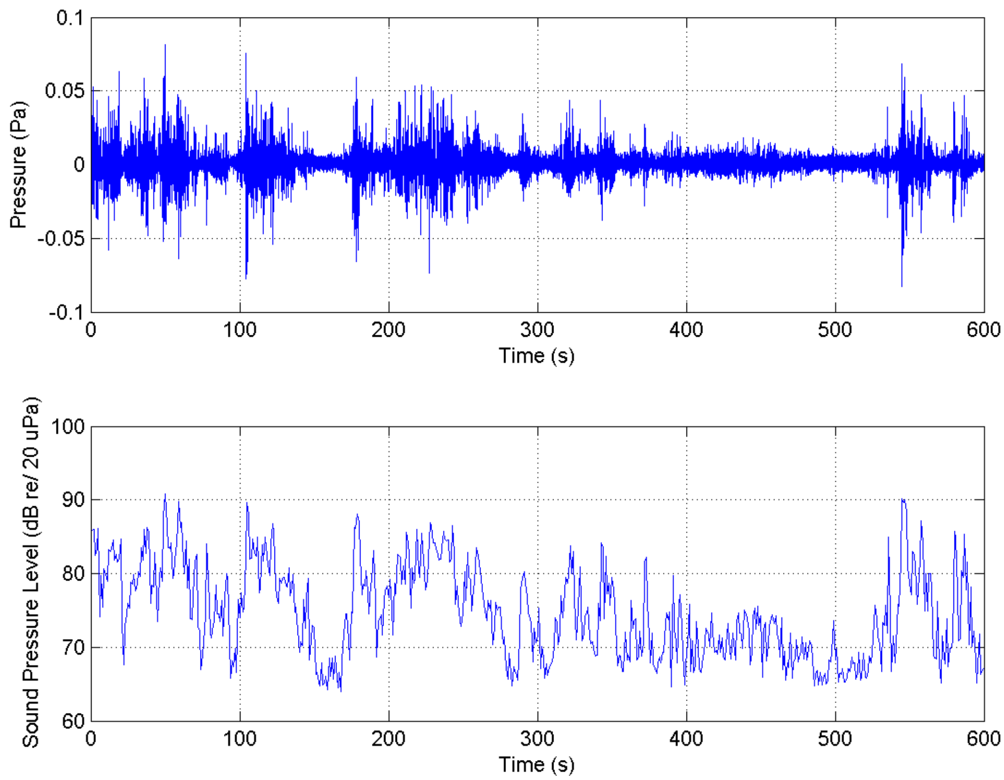

Figure A.22: Infrasound Data Recordings at Hodges Badge Co. 15 OCT 2013 at location 41 33 57.33 N, 71 15 17.18 W. (Channel 1 Time Series).

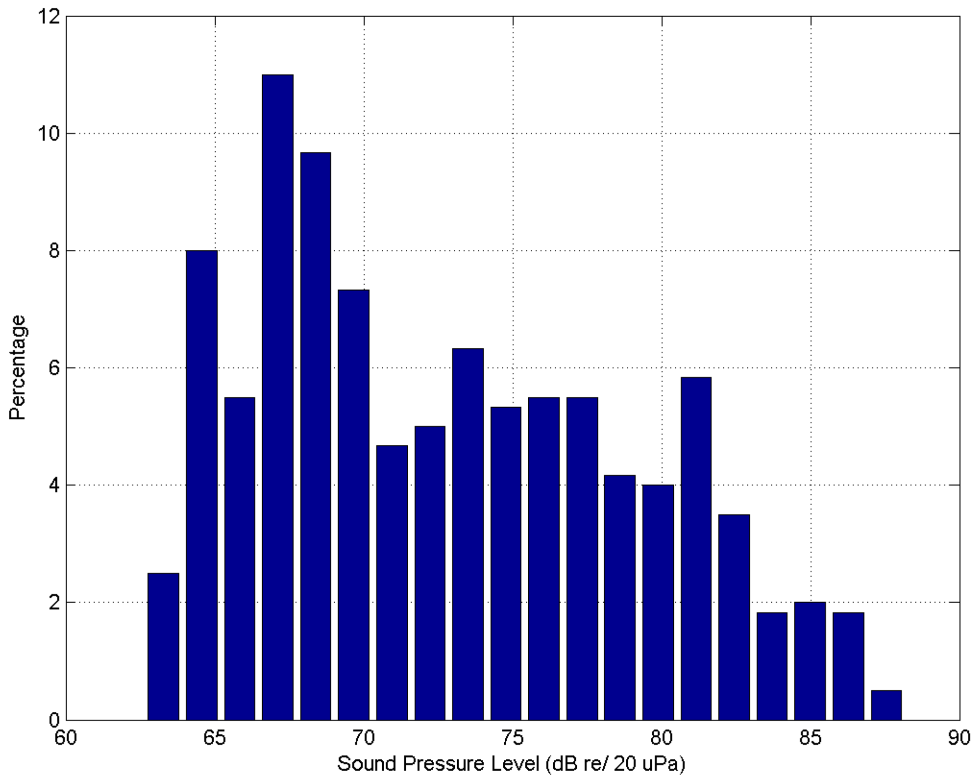

Figure A.23: Infrasound Data Recordings at Hodges Badge Co. 15 OCT 2013 at location 41 33 57.33 N, 71 15 17.18 W. (Channel 2 Histogram).

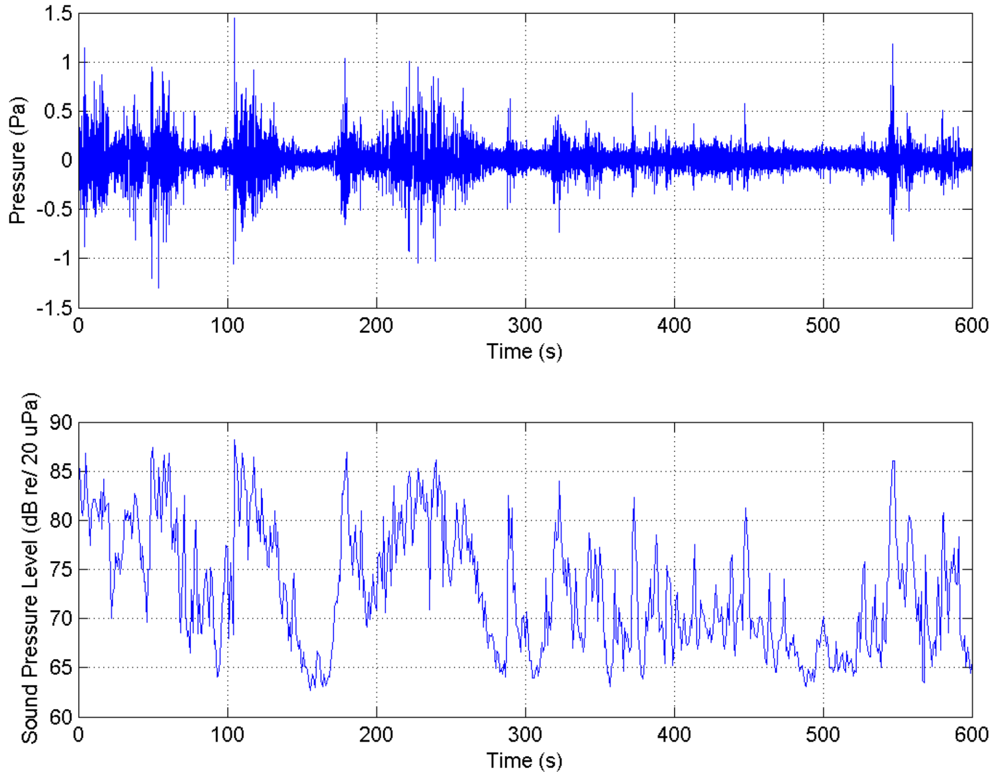

Figure A.24: Infrasound Data Recordings at Hodges Badge Co. 15 OCT 2013 at location 41 33 57.33 N, 71 15 17.18 W. (Channel 2 Time Series).

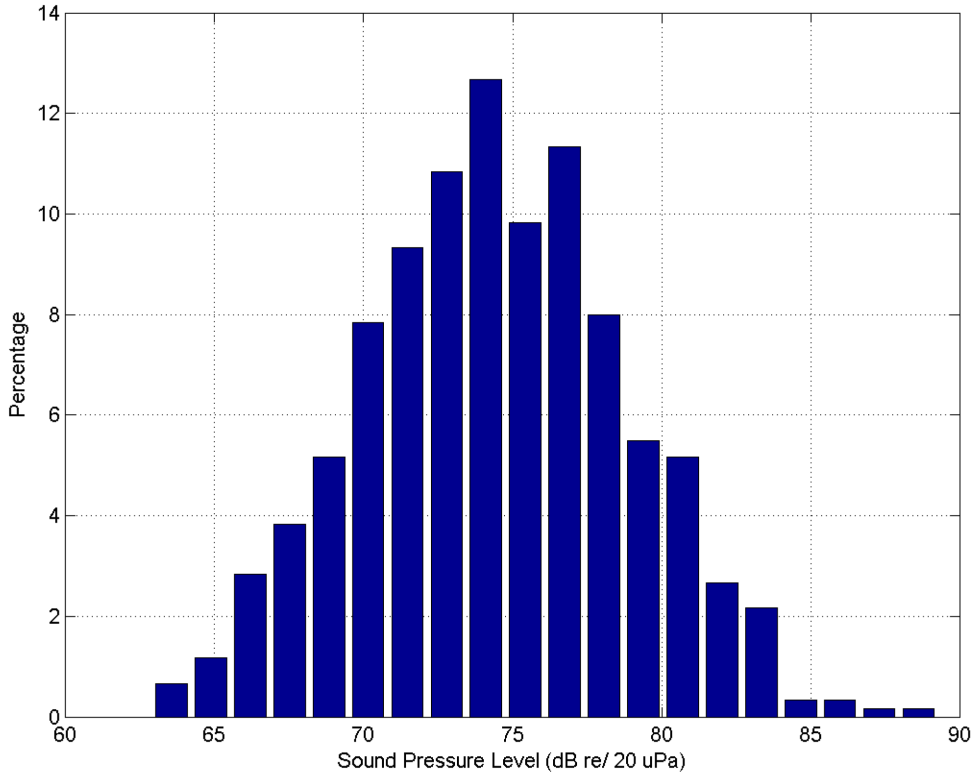

Figure A.25: Infrasound Data Recordings at Hodges Badge Co. 15 OCT 2013 at location 41 33 58.7 N, 071 15 22.5 W. (Channel 1 Histogram).

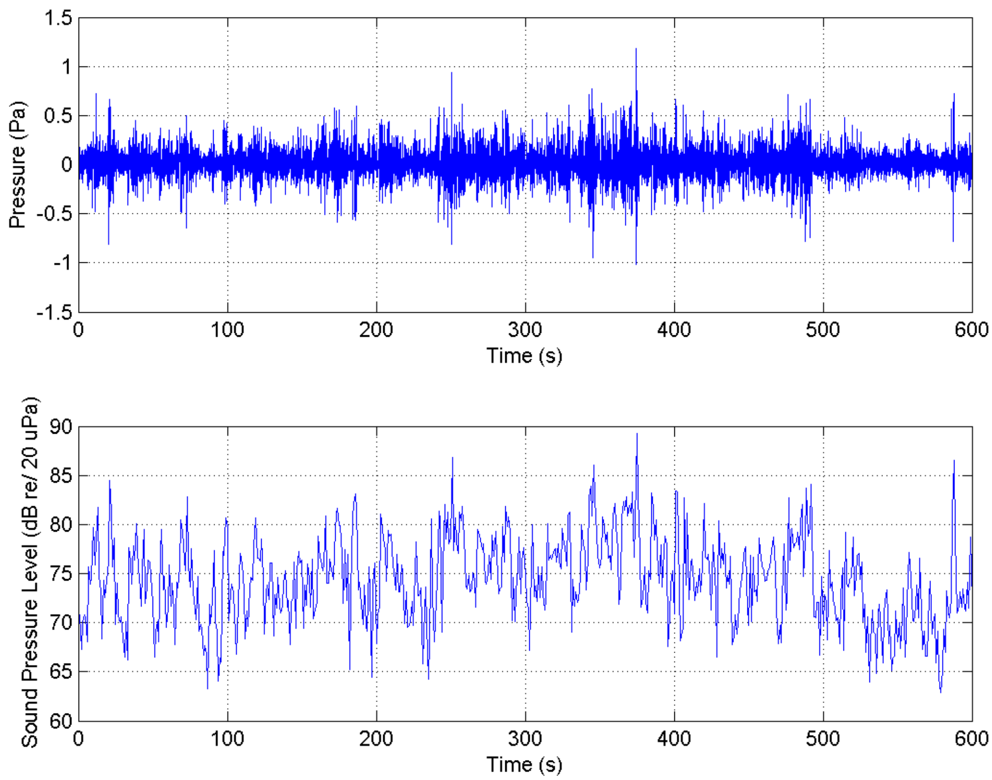

Figure A.26: Infrasound Data Recordings at Hodges Badge Co. 15 OCT 2013 at location 41 33 58.7 N, 071 15 22.5 W. (Channel 1 Time Series).

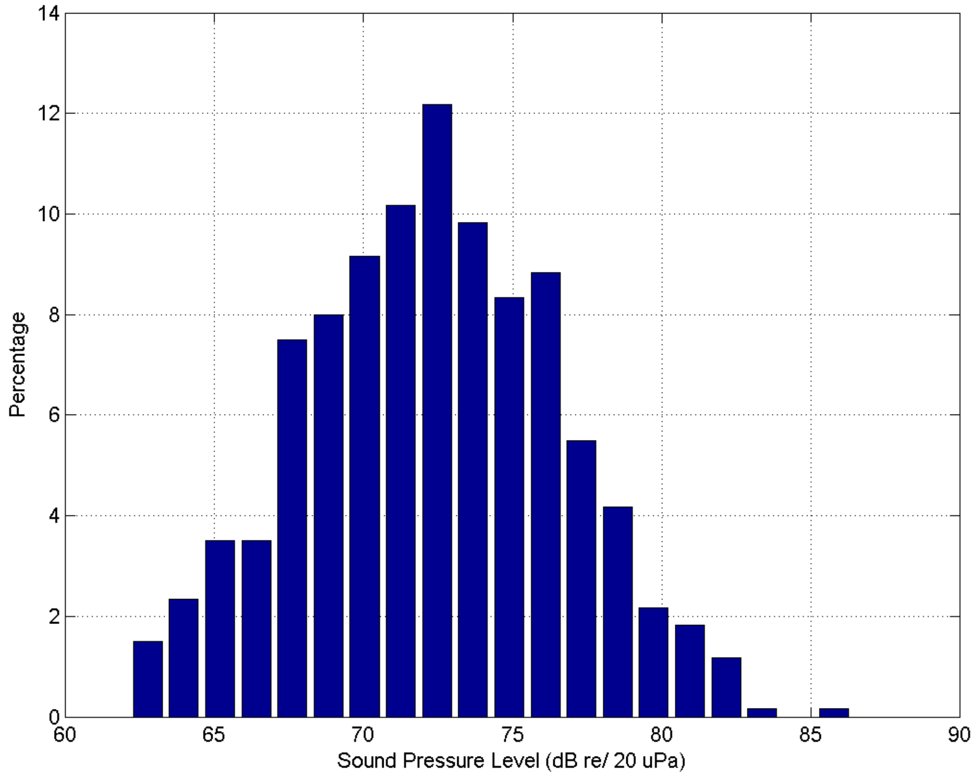

Figure A.27: Infrasound Data Recordings at Hodges Badge Co. 15 OCT 2013 at location 41 33 58.7 N, 071 15 22.5 W. (Channel 2 Histogram).

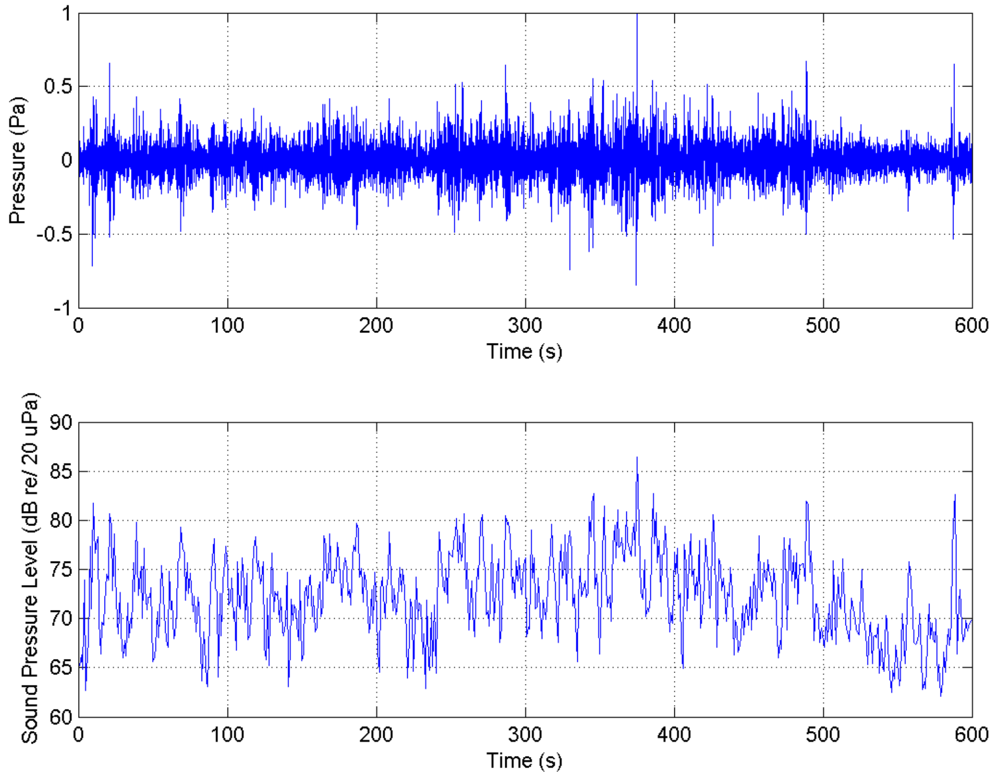

Figure A.28: Infrasound Data Recordings at Hodges Badge Co. 15 OCT 2013 at location 41 33 58.7 N, 071 15 22.5 W. (Channel 2 Time Series).

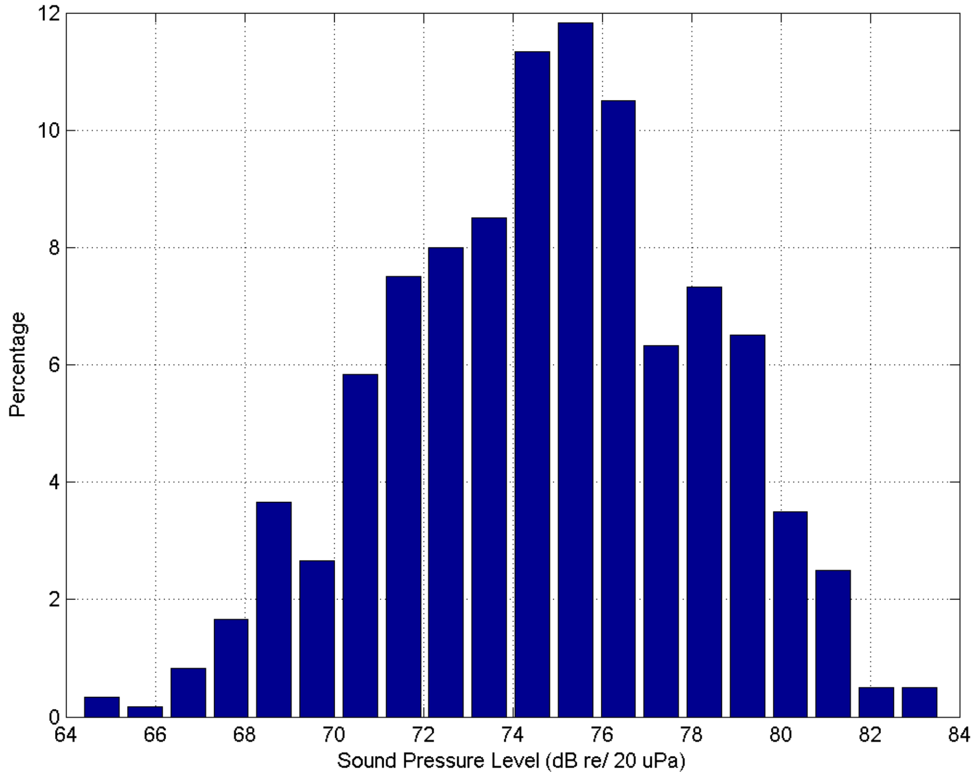

Figure A.29: Infrasound Data Recordings at Hodges Badge Co. 15 OCT 2013 at location 41 34 0.88 N, 71 15 17.24 W. (Channel 1 Histogram).

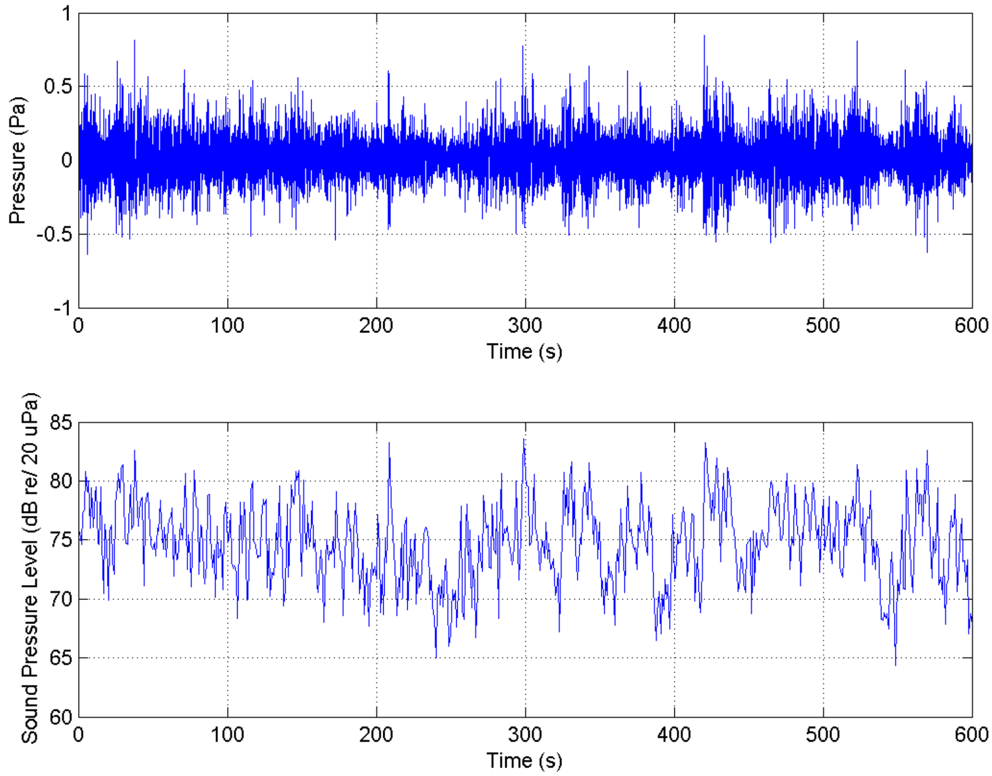

Figure A.30: Infrasound Data Recordings at Hodges Badge Co. 15 OCT 2013 at location 41 34 0.88 N, 71 15 17.24 W. (Channel 1 Time Series).

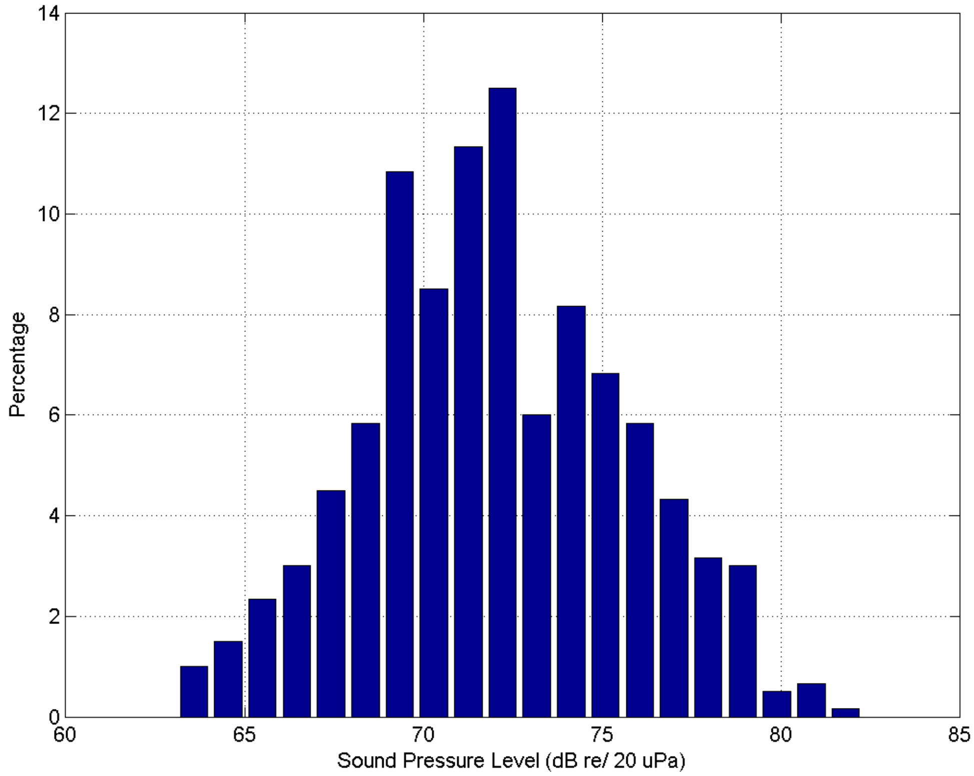

Figure A.31: Infrasound Data Recordings at Hodges Badge Co. 15 OCT 2013 at location 41 34 0.88 N, 71 15 17.24 W. (Channel 2 Histogram).

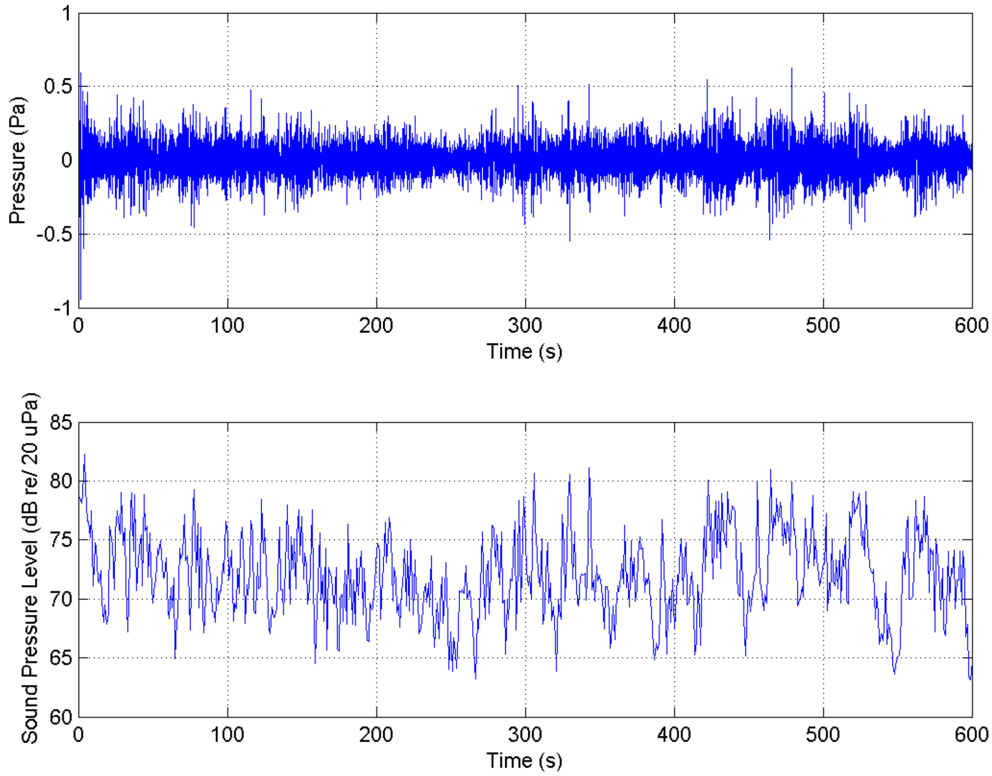

Figure A.32: Infrasound Data Recordings at Hodges Badge Co. 15 OCT 2013 at location 41 34 0.88 N, 71 15 17.24 W. (Channel 2 Time Series).

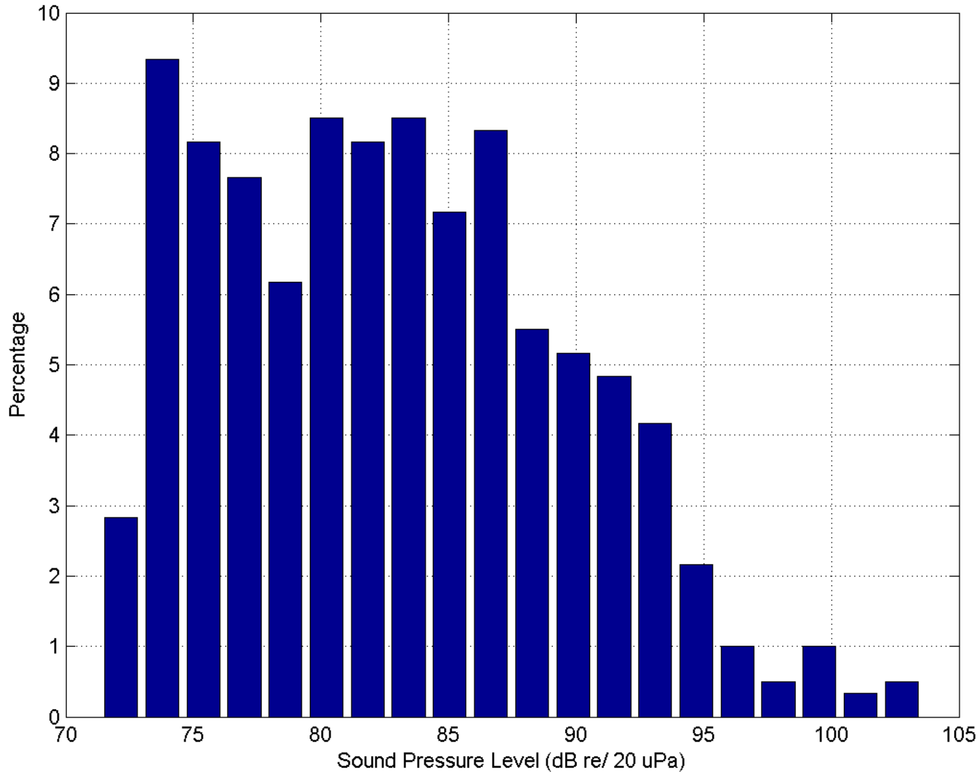

Figure A.33: Infrasound Data Recordings at Narragansett Bay Commission 21 JUN 2013. (Channel 1 Histogram).

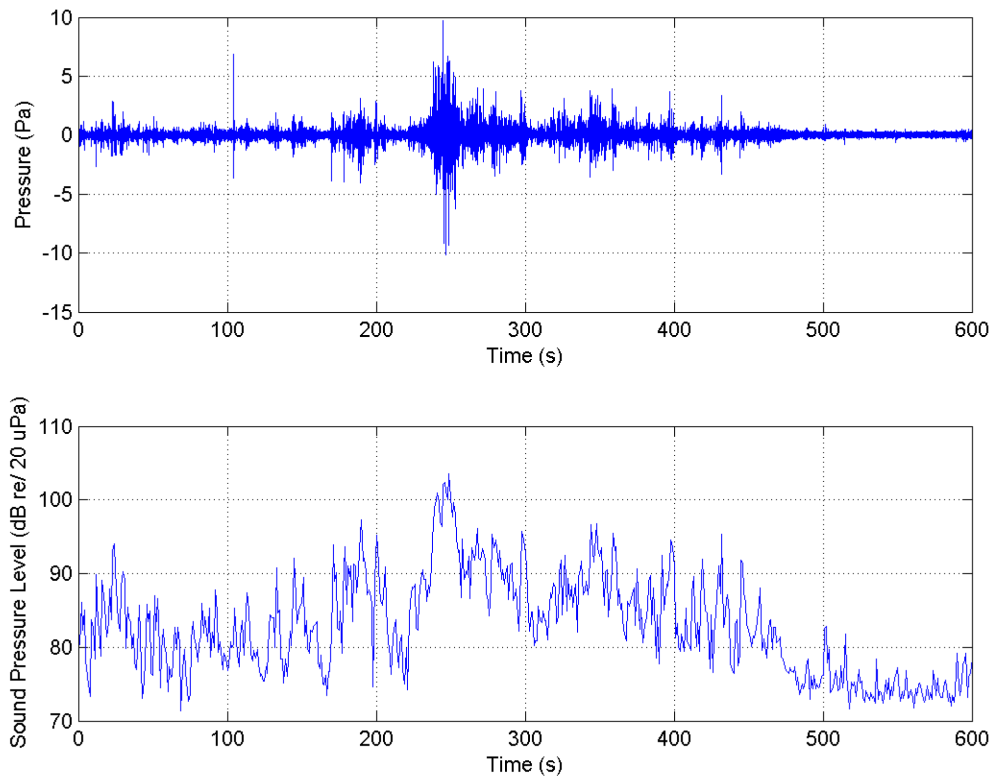

Figure A.34: Infrasound Data Recordings at Narragansett Bay Commission 21 JUN 2013. (Channel 1 Time Series).

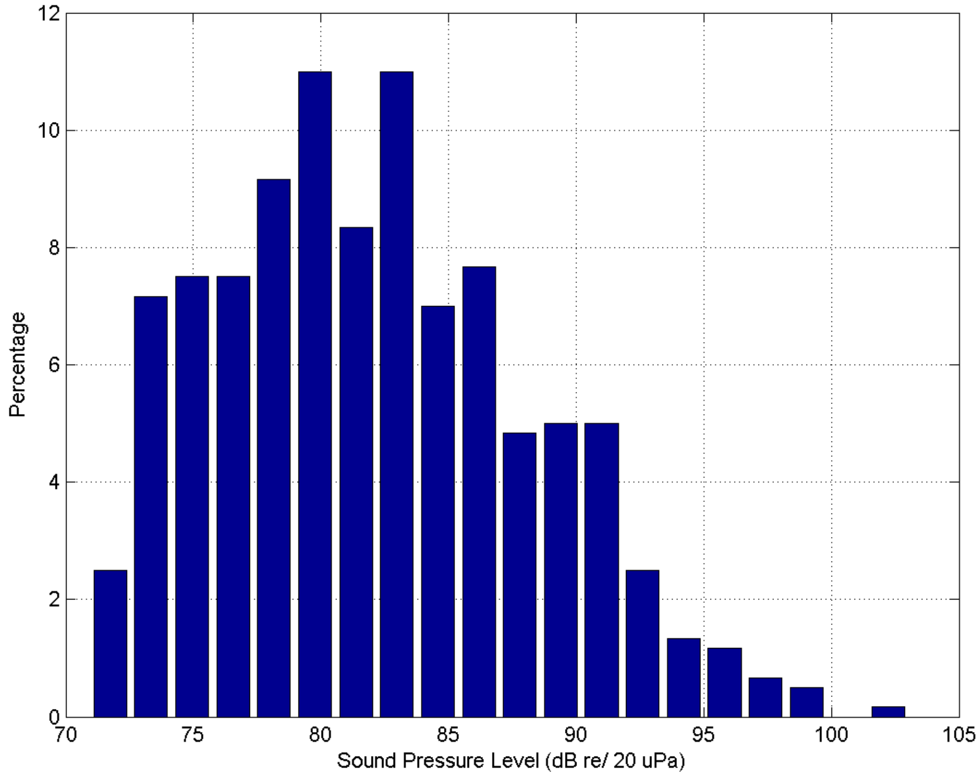

Figure A.35: Infrasound Data Recordings at Narragansett Bay Commission 21 JUN 2013. (Channel 2 Histogram).

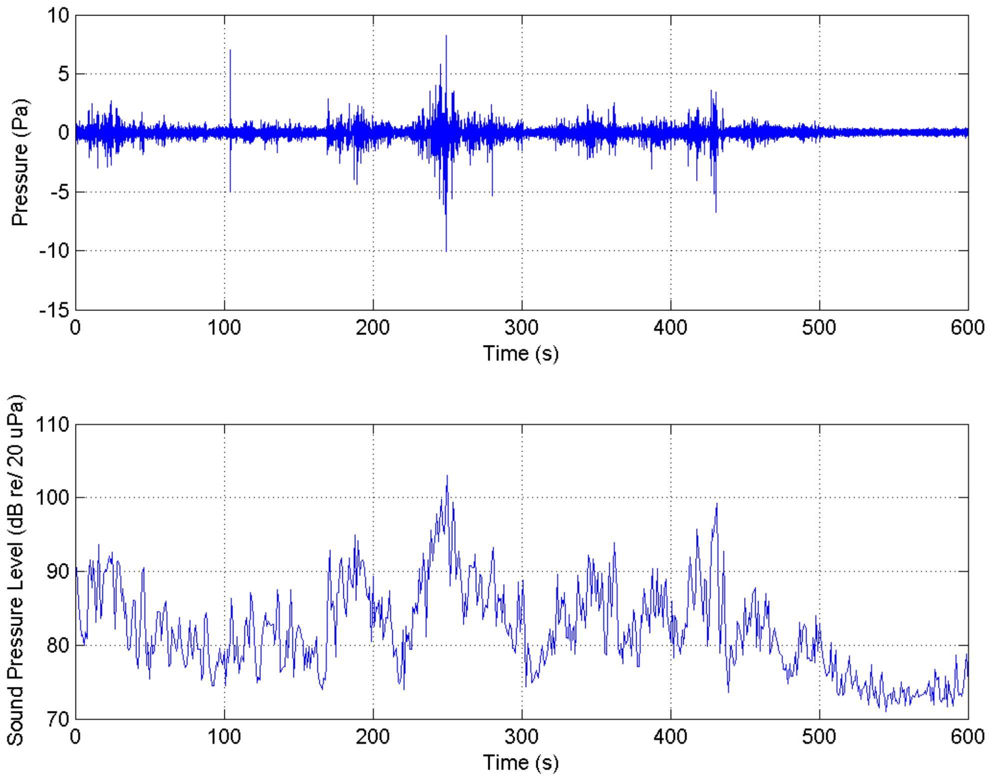

Figure A.36: Infrasound Data Recordings at Narragansett Bay Commission 21 JUN 2013. (Channel 2 Time Series).

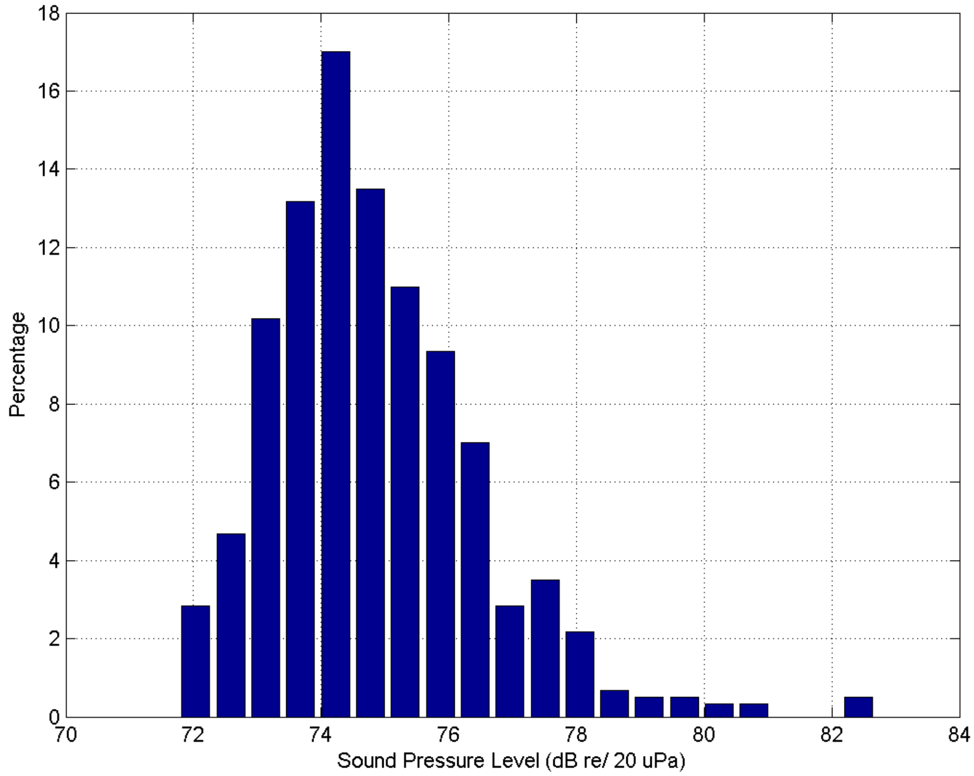

Figure A.37: Infrasound Data Recordings at New England Inst. of Technology 27 OCT 2013 at location 41 43 58.48 N, 71 27 06.38 W. (Channel 1 Histogram).

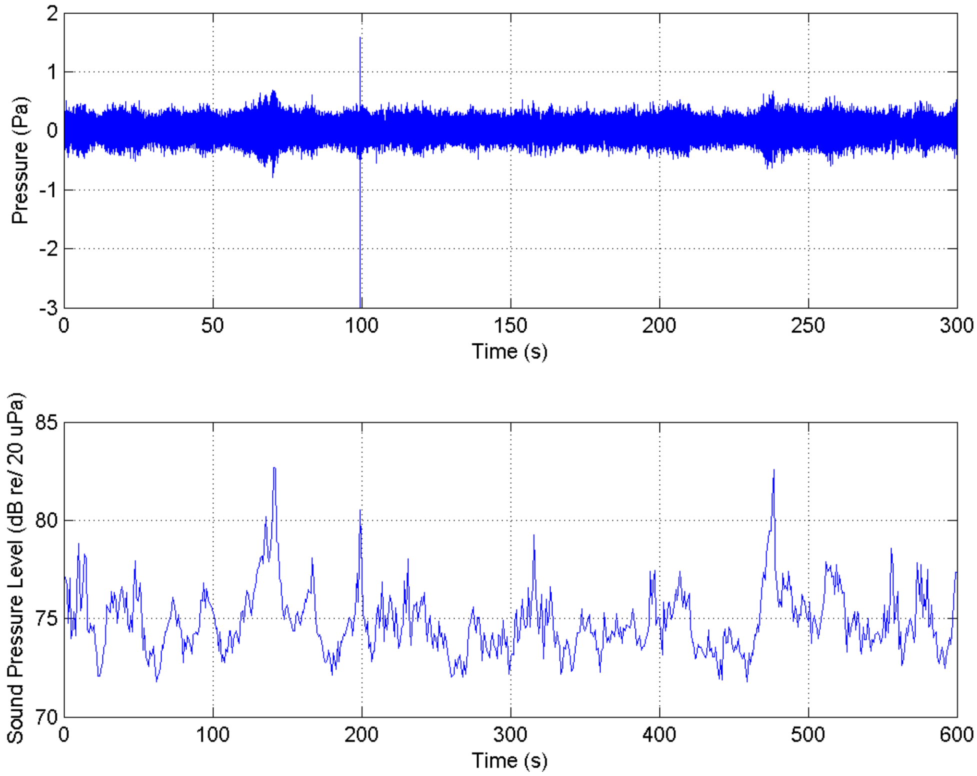

Figure A.38: Infrasound Data Recordings at New England Inst. of Technology 27 OCT 2013 at location 41 43 58.48 N, 71 27 06.38 W. (Channel 1 Time Series).

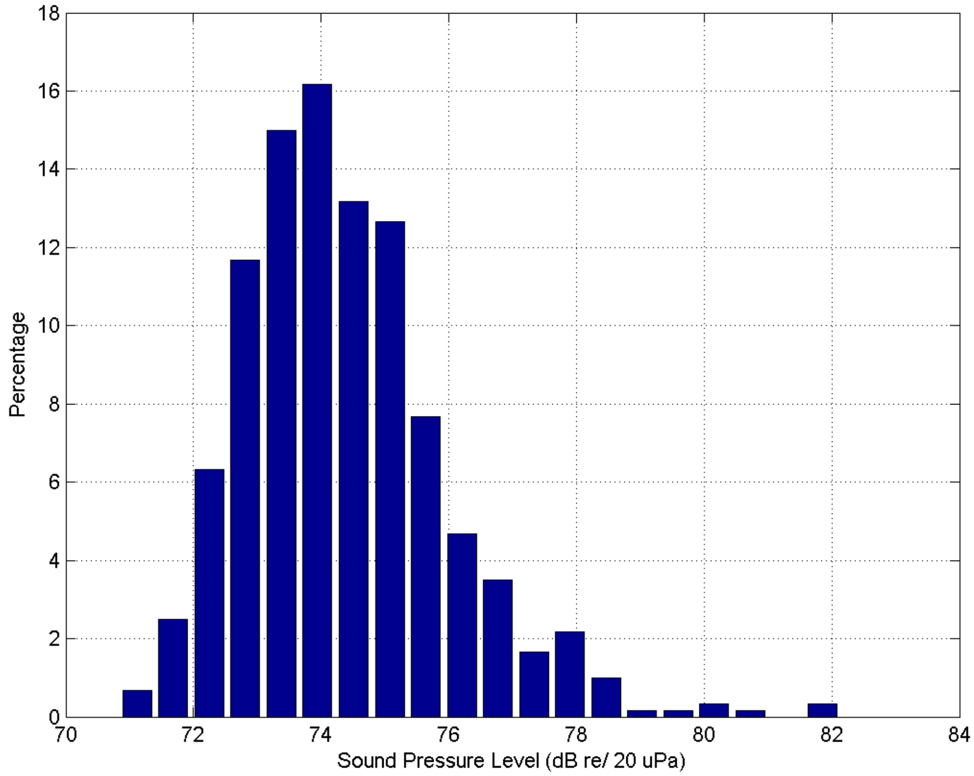

Figure A.39: Infrasound Data Recordings at New England Inst. of Technology 27 OCT 2013 at location 41 43 58.48 N, 71 27 06.38 W. (Channel 2 Histogram).

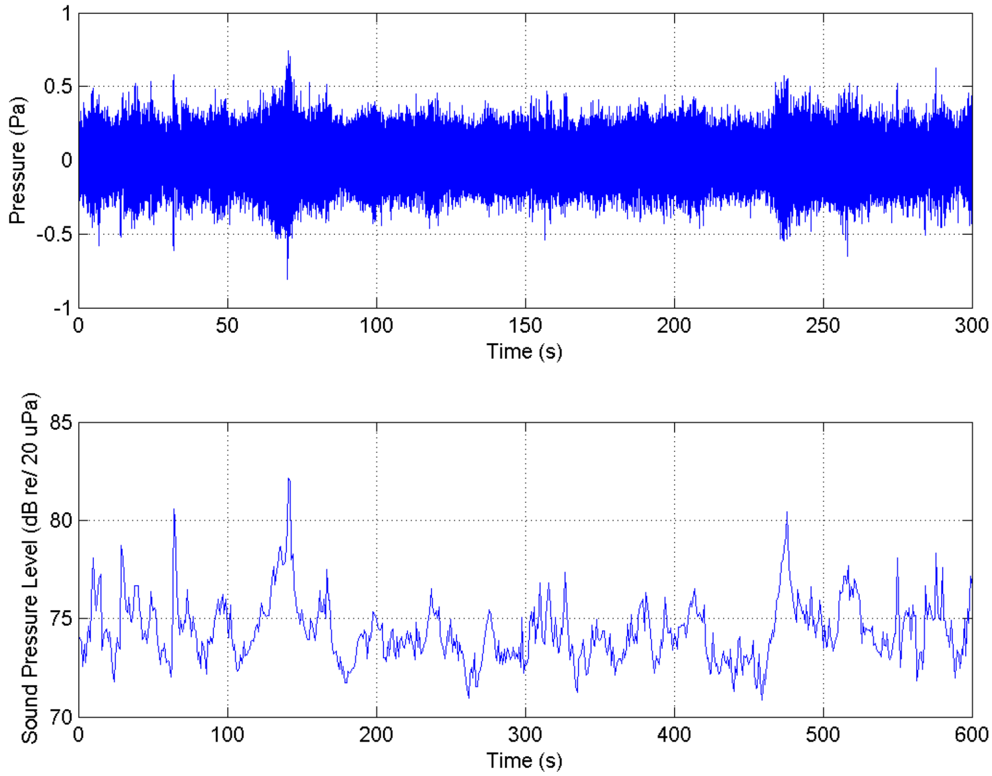

Figure A.40: Infrasound Data Recordings at New England Inst. of Technology 27 OCT 2013 at location 41 43 58.48 N, 71 27 06.38 W. (Channel 2 Time Series).

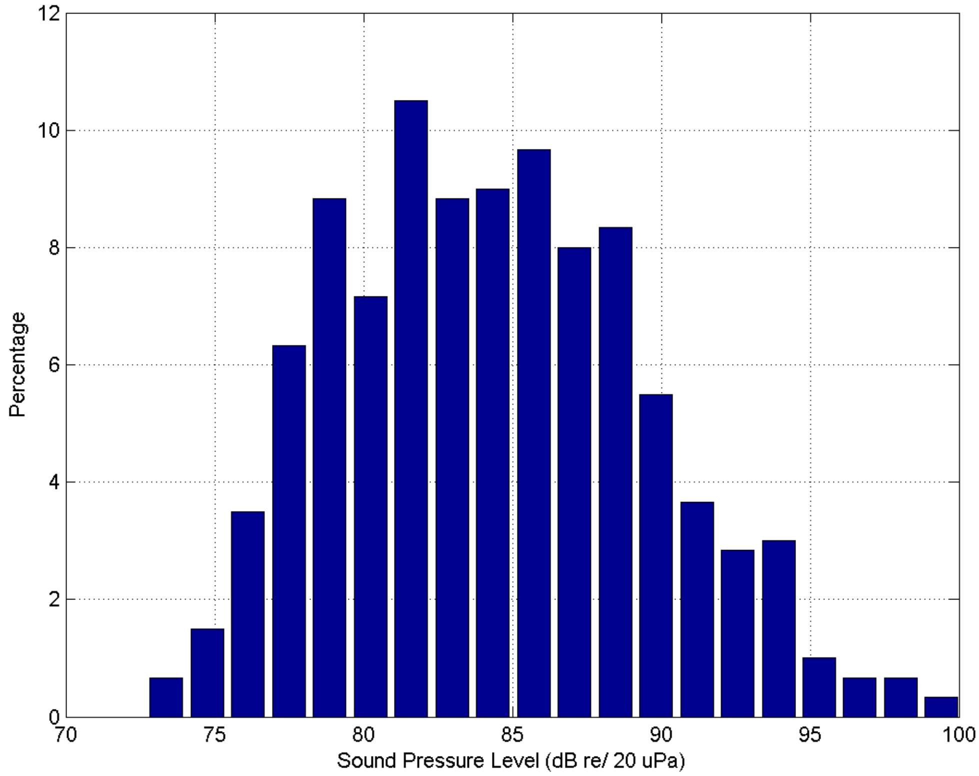

Figure A.41: Infrasound Data Recordings at New England Inst. of Technology 27 OCT 2013 at location 41 44 04.01 N, 71 27 00.33 W. (Channel 1 Histogram).

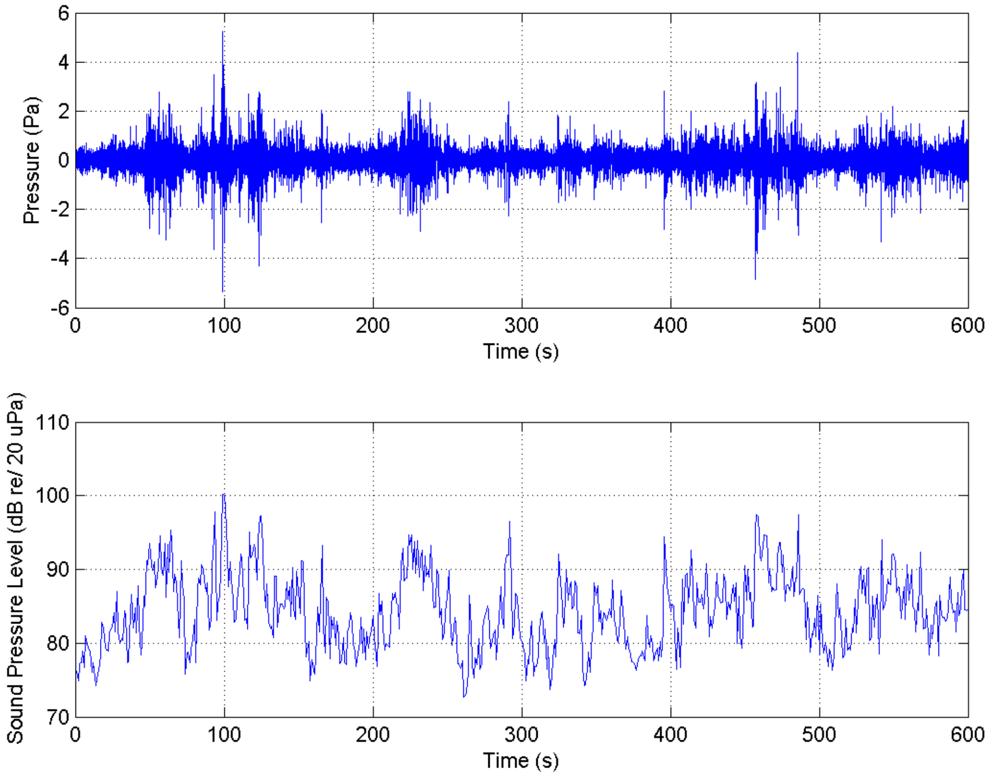

Figure A.42: Infrasound Data Recordings at New England Inst. of Technology 27 OCT 2013 at location 41 44 04.01 N, 71 27 00.33 W. (Channel 1 Time Series).

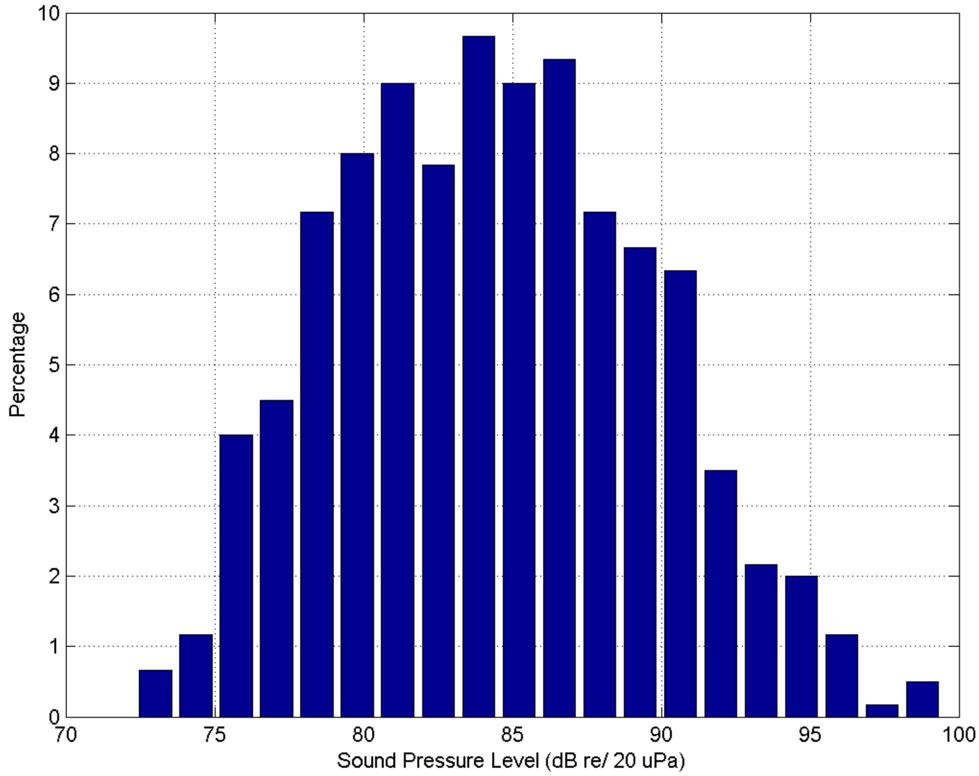

Figure A.43: Infrasound Data Recordings at New England Inst. of Technology 27 OCT 2013 at location 41 44 04.01 N, 71 27 00.33 W. (Channel 2 Histogram).

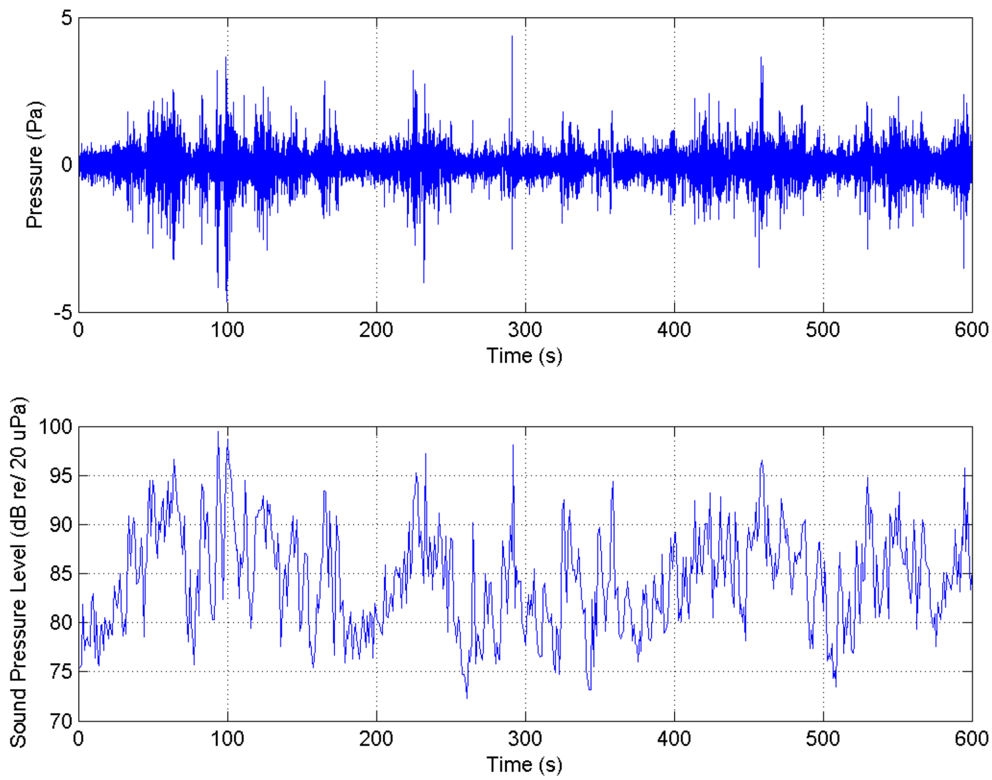

Figure A.44: Infrasound Data Recordings at New England Inst. of Technology 27 OCT 2013 at location 41 44 04.01 N, 71 27 00.33 W. (Channel 2 Time Series).

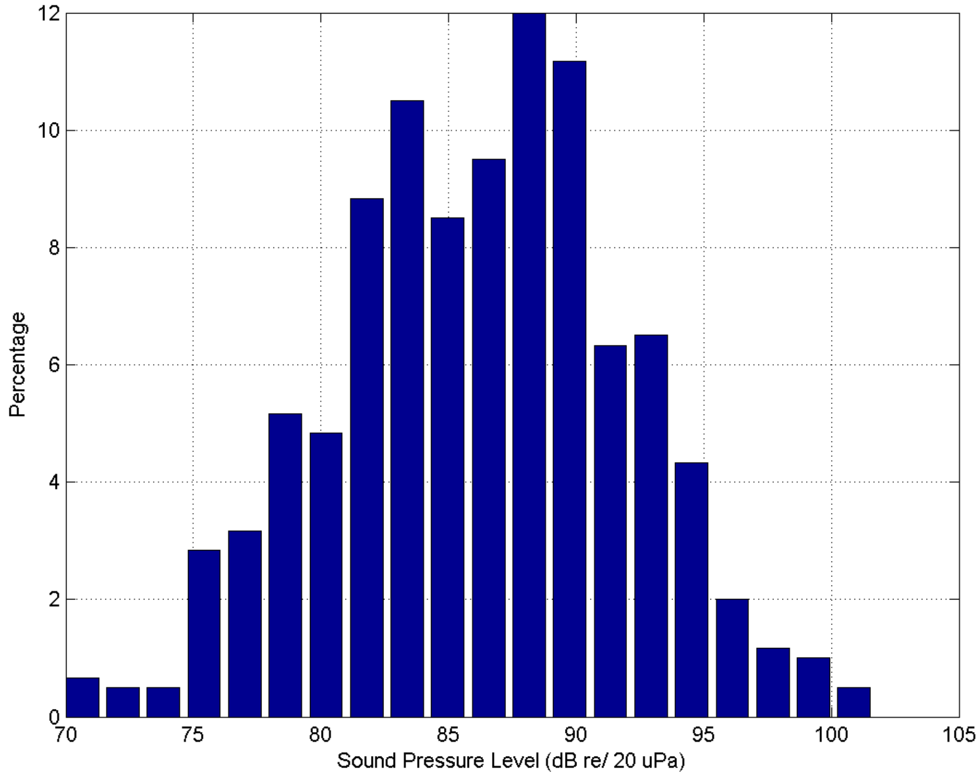

Figure A.45: Infrasound Data Recordings at New England Inst. of Technology 27 OCT 2013 at location 41 44 0.91 N, 71 26 53.92 W. (Channel 1 Histogram).

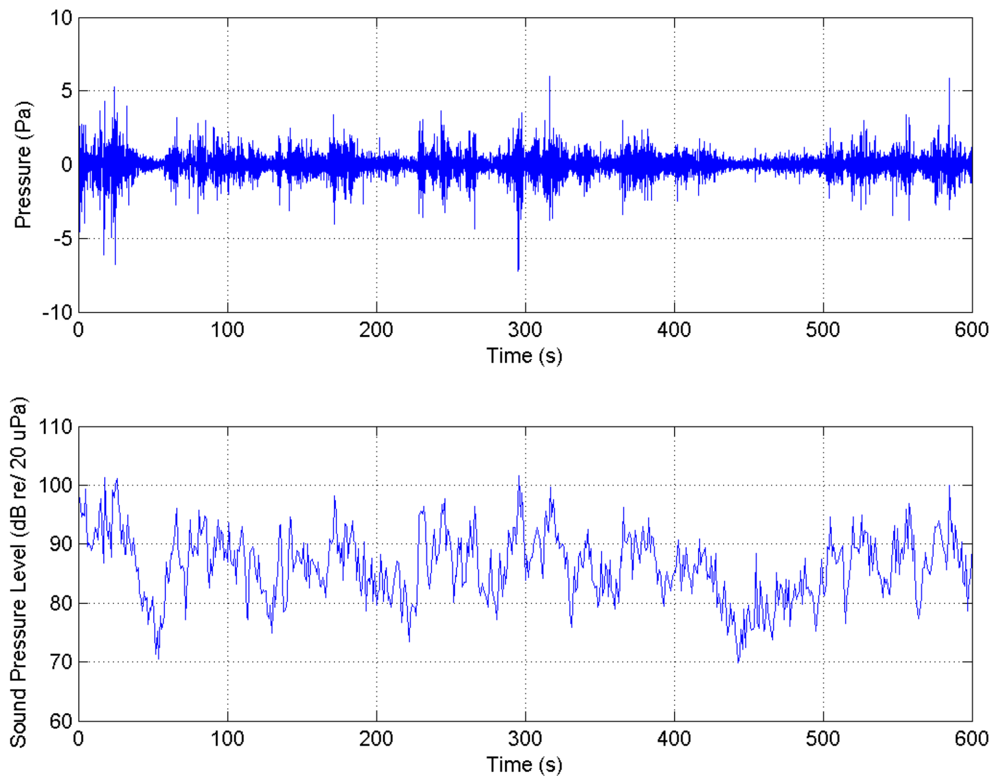

Figure A.46: Infrasound Data Recordings at New England Inst. of Technology 27 OCT 2013 at location 41 44 0.91 N, 71 26 53.92 W. (Channel 1 Time Series).

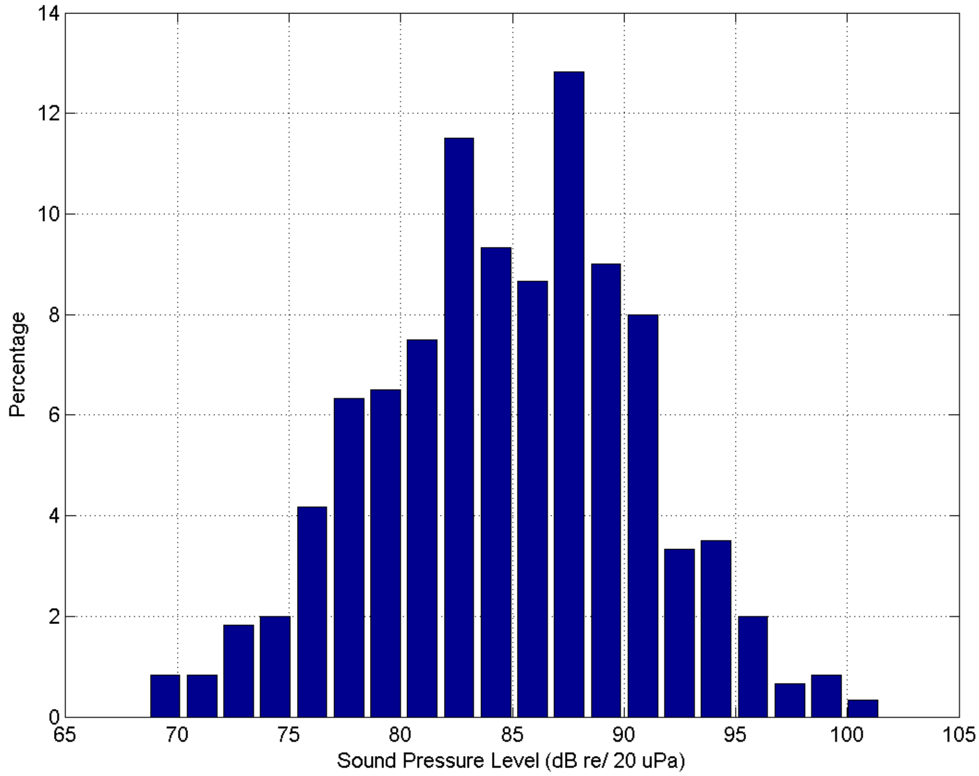

Figure A.47: Infrasound Data Recordings at New England Inst. of Technology 27 OCT 2013 at location 41 44 0.91 N, 71 26 53.92 W. (Channel 2 Histogram).

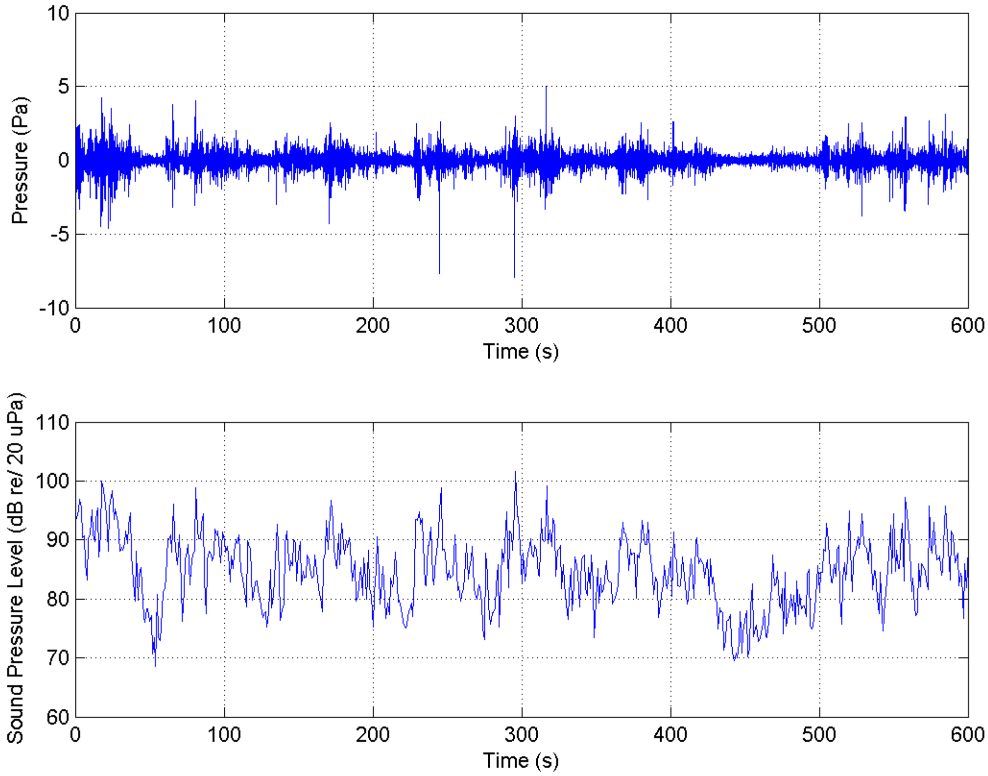

Figure A.48: Infrasound Data Recordings at New England Inst. of Technology 27 OCT 2013 at location 41 44 0.91 N, 71 26 53.92 W. (Channel 2 Time Series).

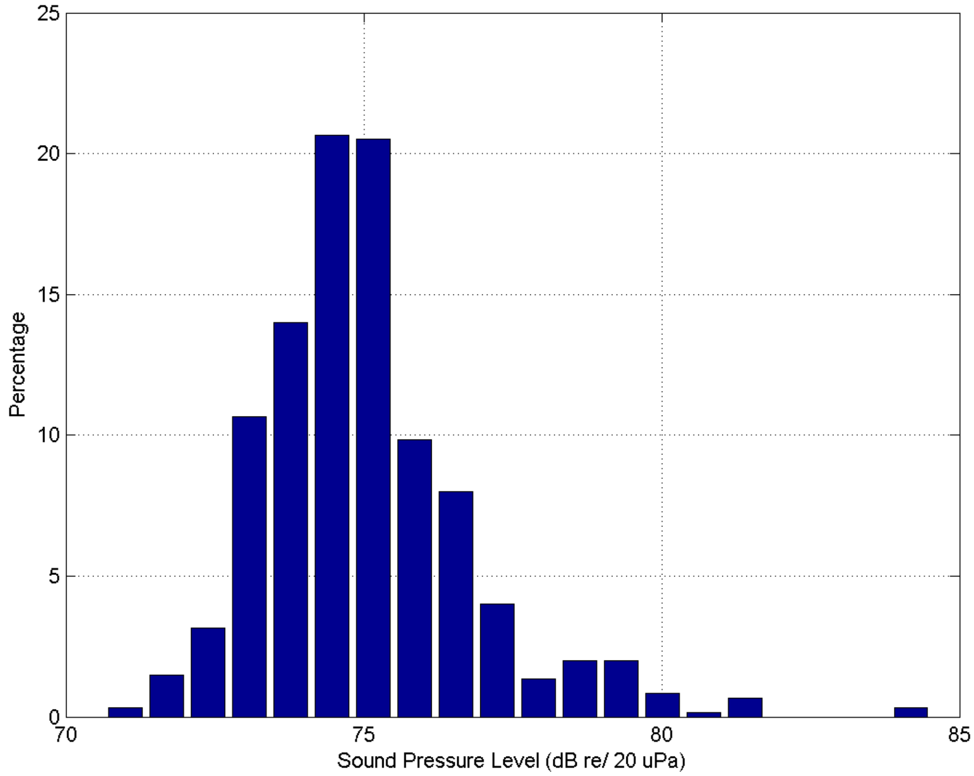

Figure A.49: Infrasound Data Recordings at New England Inst. of Technology 25 JUN 2013. (Channel 1 Histogram).

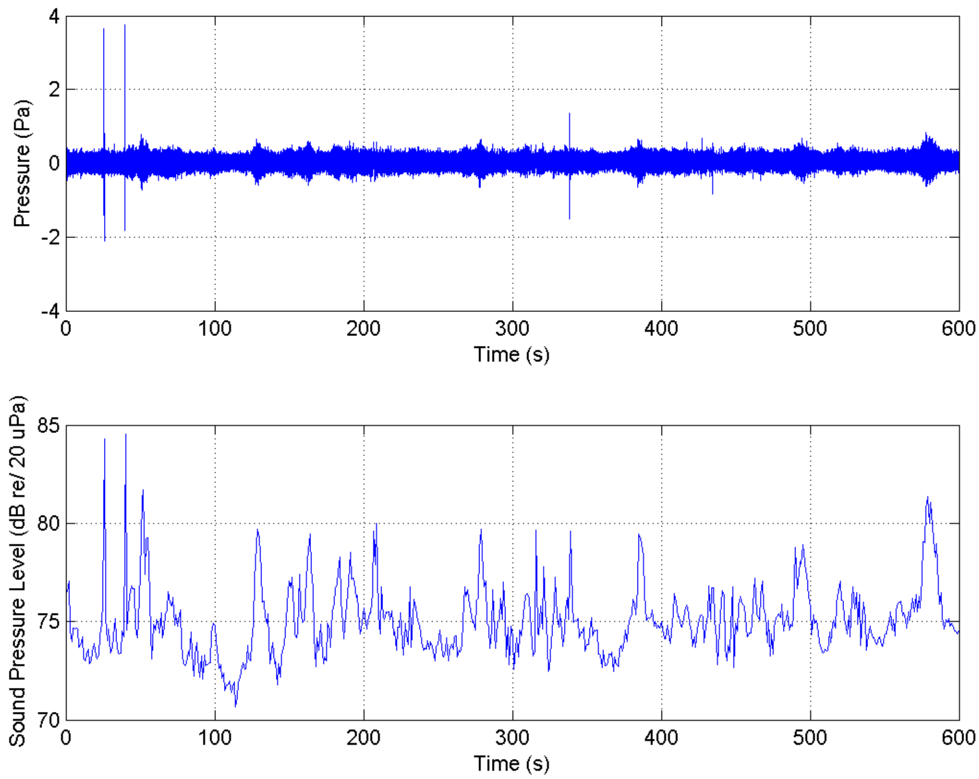

Figure A.50: Infrasound Data Recordings at New England Inst. of Technology 25 JUN 2013. (Channel 1 Time Series).

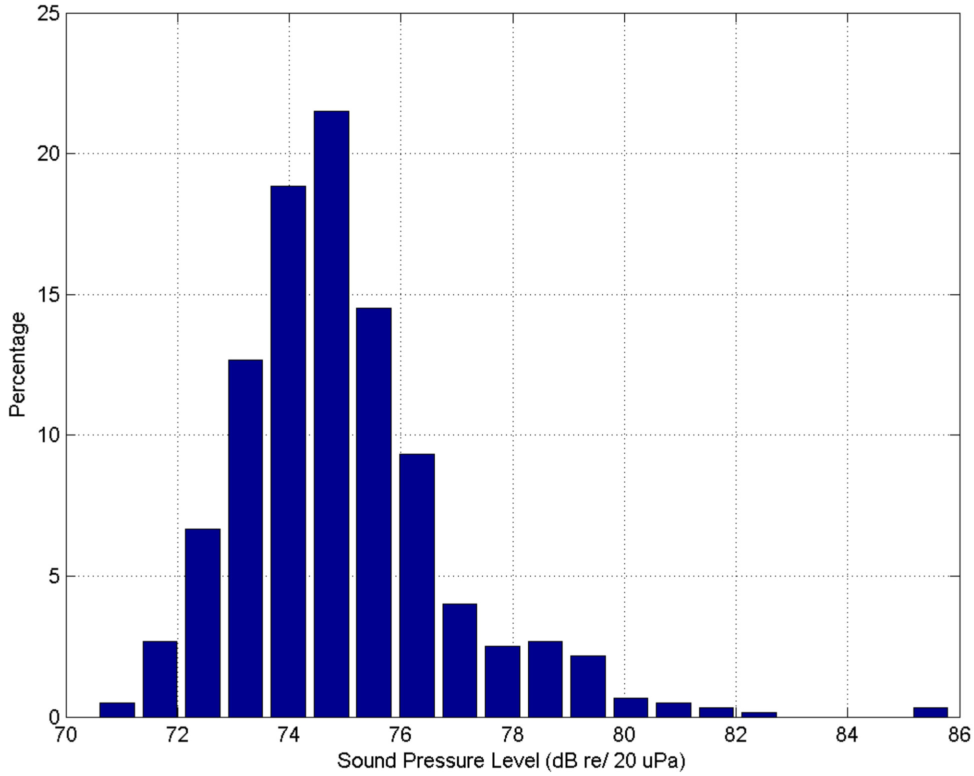

Figure A.51: Infrasound Data Recordings at New England Inst. of Technology 25 JUN 2013. (Channel 2 Histogram).

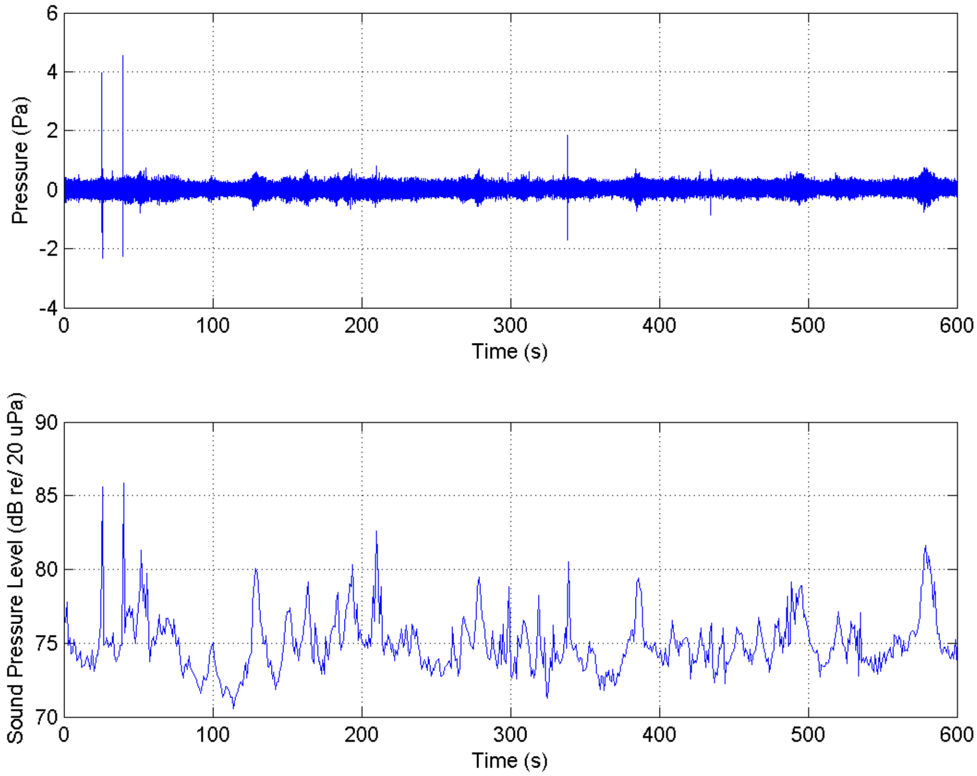

Figure A.52: Infrasound Data Recordings at New England Inst. of Technology 25 JUN 2013. (Channel 2 Time Series).

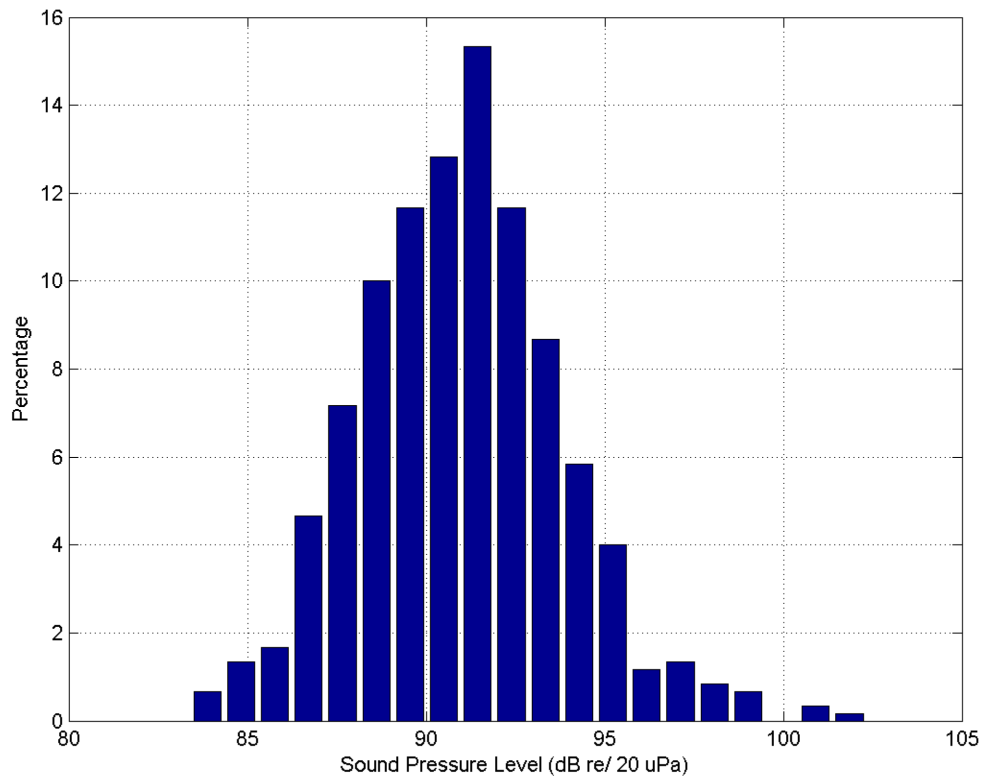

Figure A.53: Infrasound Data Recordings at Second Beach 07 OCT 2013. (Channel 1 Histogram).

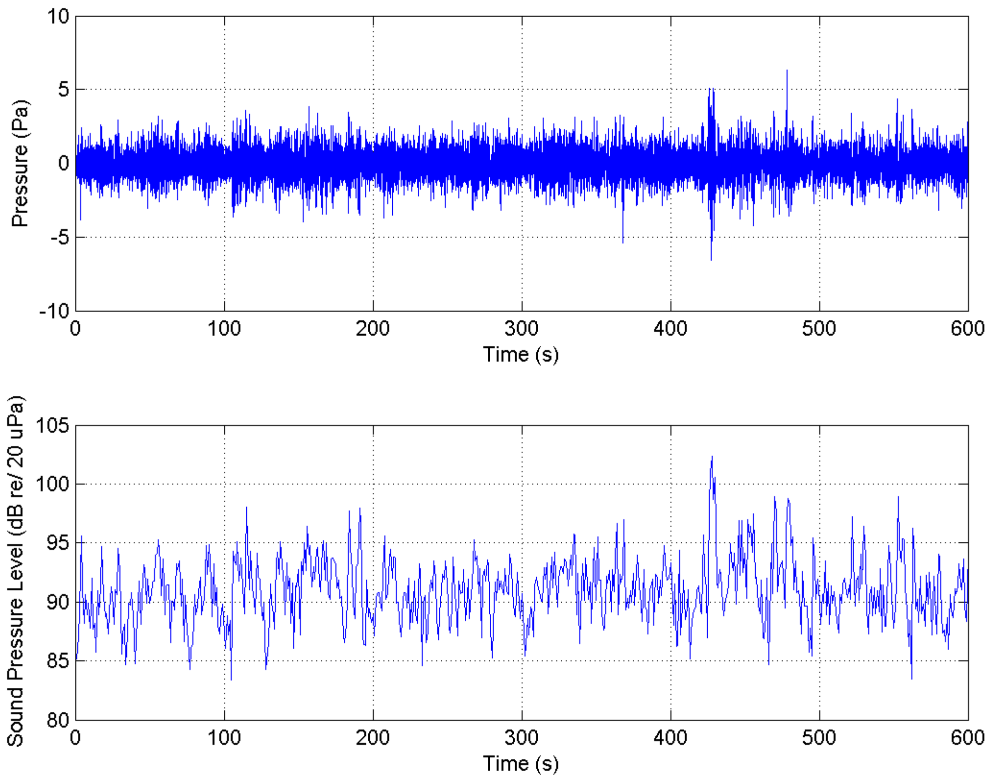

Figure A.54: Infrasound Data Recordings at Second Beach 07 OCT 2013. (Channel 1 Time Series).

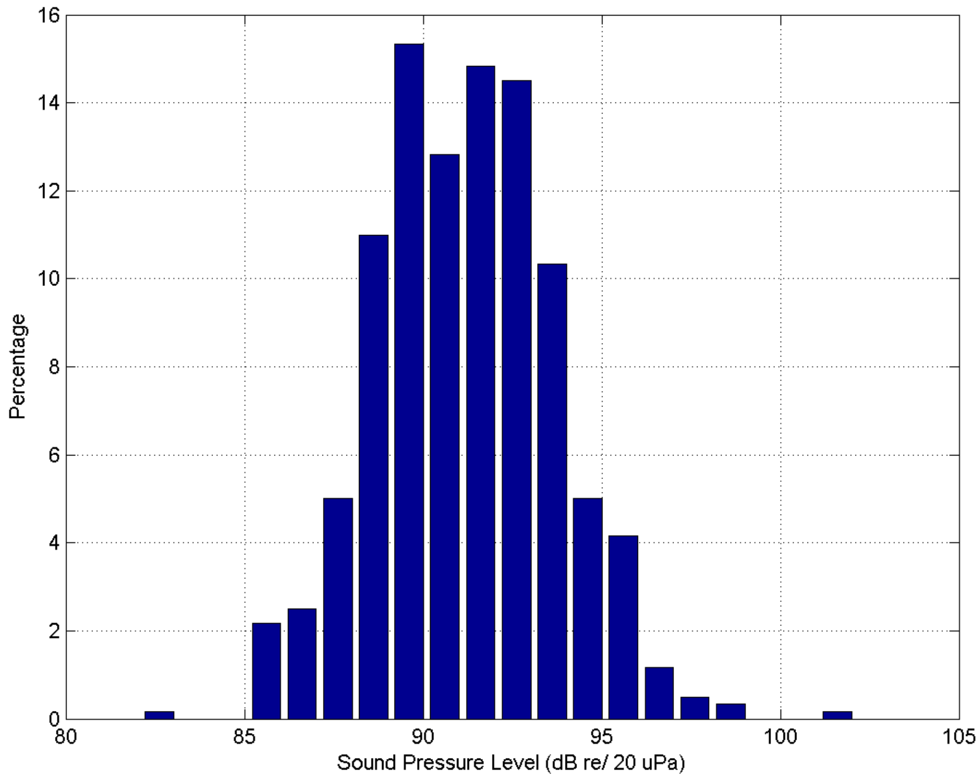

Figure A.55: Infrasound Data Recordings at Second Beach 07 OCT 2013. (Channel 2 Histogram).

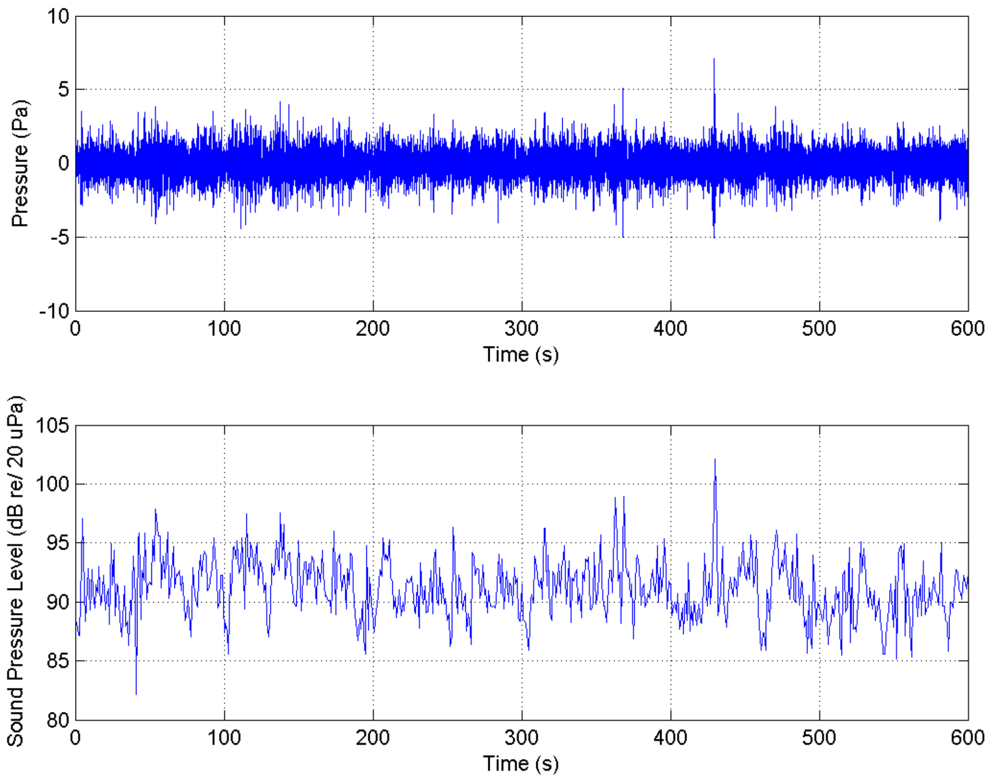

Figure A.56: Infrasound Data Recordings at Second Beach 07 OCT 2013. (Channel 2 Time Series).

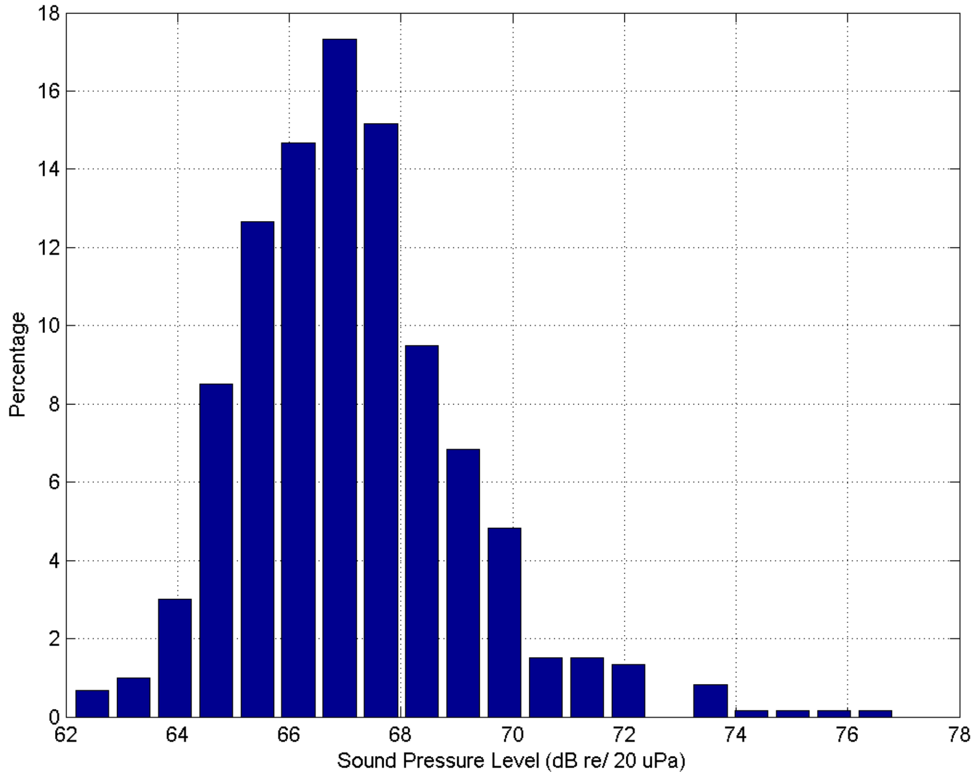

Figure A.57: Infrasound Data Recordings at Second Beach 08 OCT 2013. (Channel 1 Histogram).

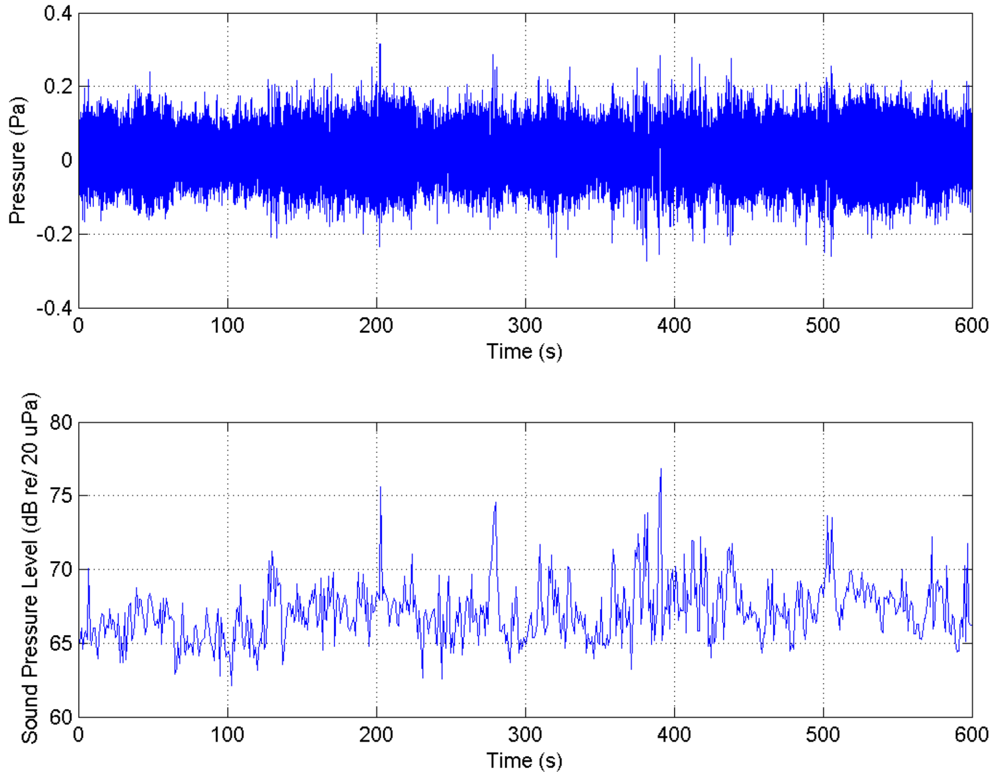

Figure A.58: Infrasound Data Recordings at Second Beach 08 OCT 2013. (Channel 1 Time Series).

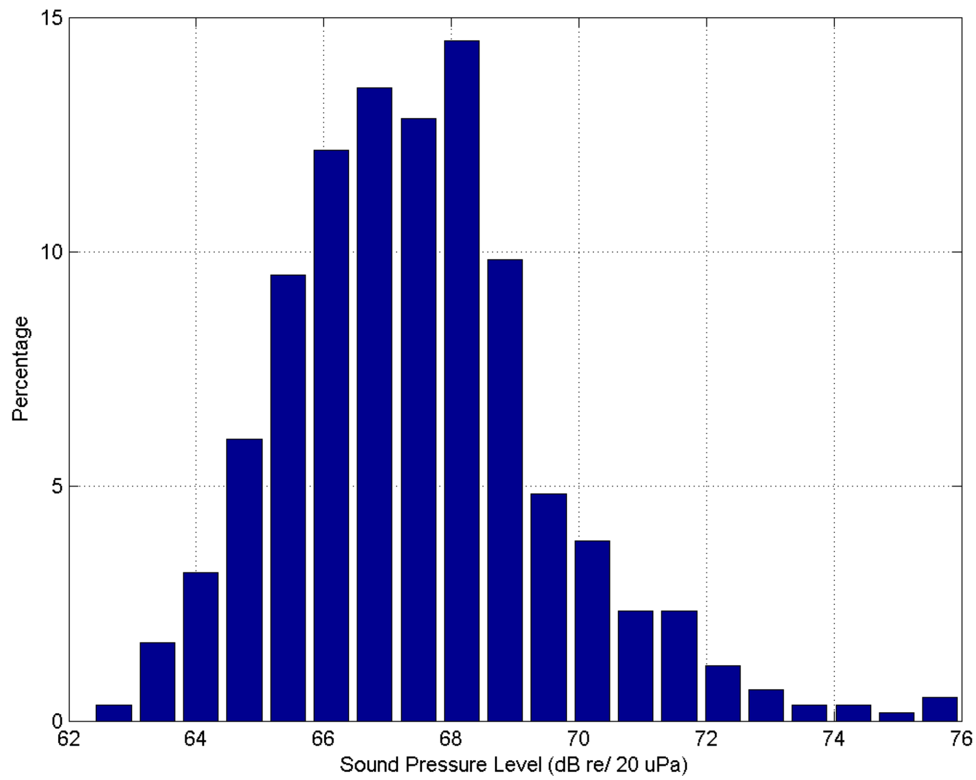

Figure A.59: Infrasound Data Recordings at Second Beach 08 OCT 2013. (Channel 2 Histogram).

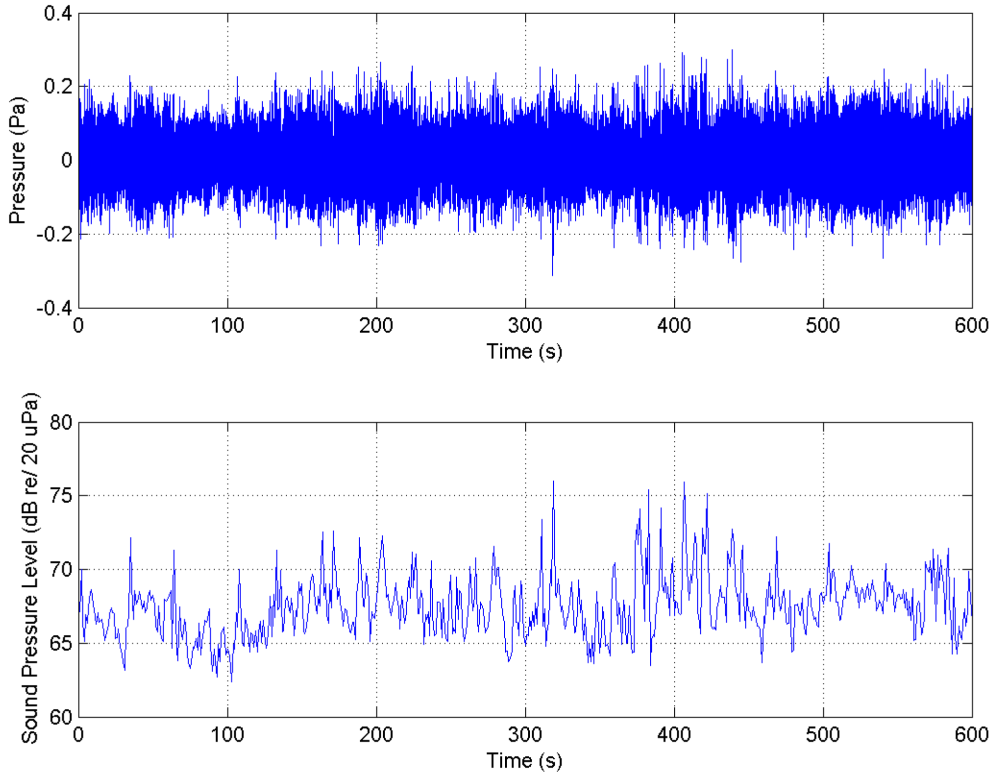

Figure A.60: Infrasound Data Recordings at Second Beach 08 OCT 2013. (Channel 2 Time Series).

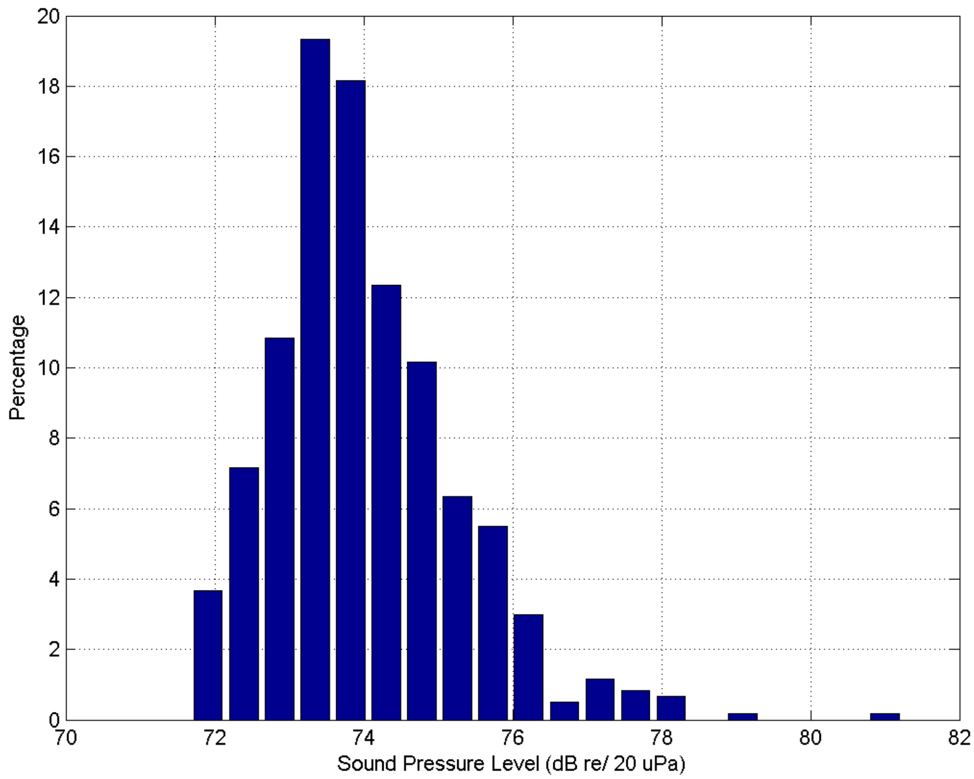

Figure A.61: Infrasound Data Recordings at Shalom Housing 05 NOV 2013 at location 41 43 27.12 N, 71 27 59.82 W. (Channel 1 Histogram).

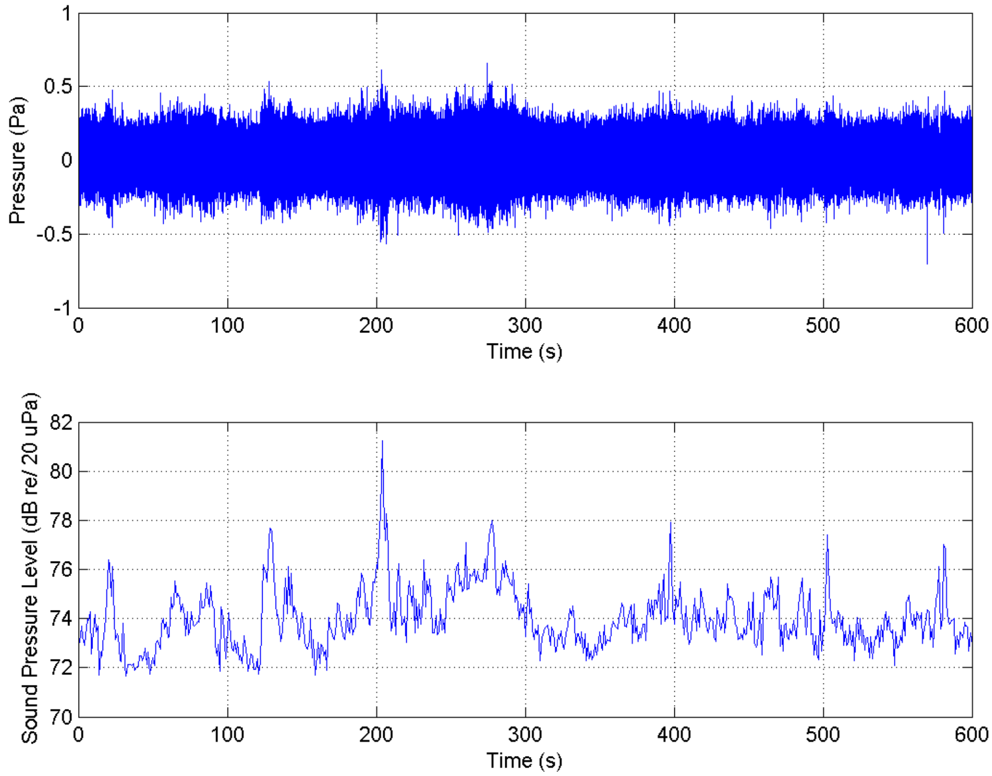

Figure A.62: Infrasound Data Recordings at Shalom Housing 05 NOV 2013 at location 41 43 27.12 N, 71 27 59.82 W. (Channel 1 Time Series).

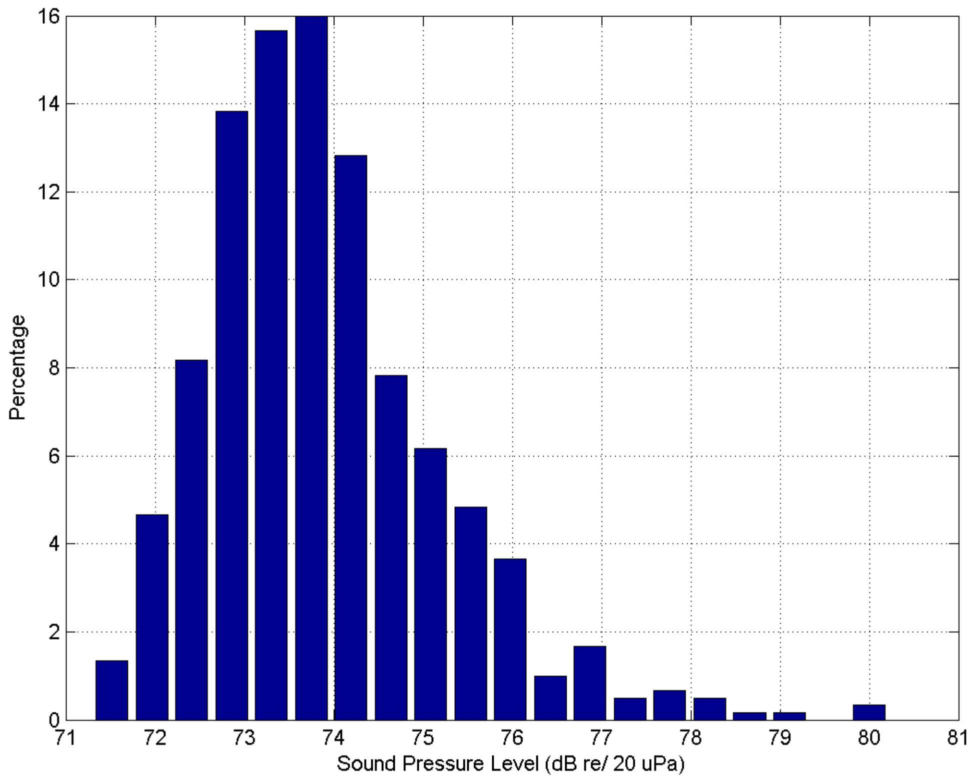

Figure A.63: Infrasound Data Recordings at Shalom Housing 05 NOV 2013 at location 41 43 27.12 N, 71 27 59.82 W. (Channel 2 Histogram).

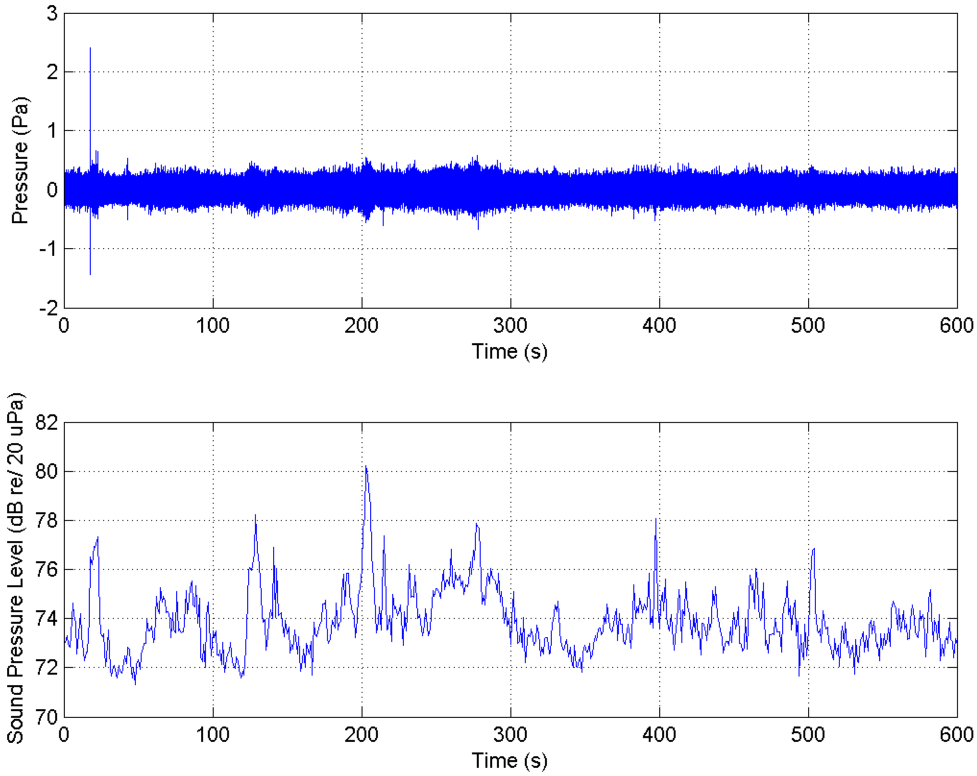

Figure A.64: Infrasound Data Recordings at Shalom Housing 05 NOV 2013 at location 41 43 27.12 N, 71 27 59.82 W. (Channel 2 Time Series).

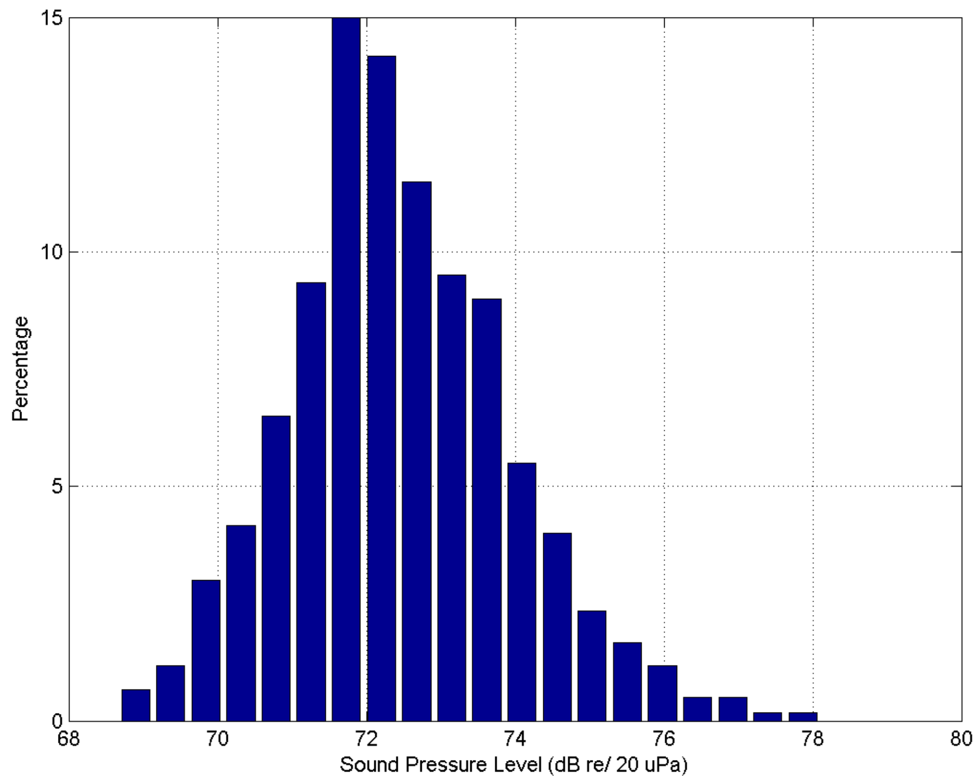

Figure A.65: Infrasound Data Recordings at Shalom Housing 05 NOV 2013 at location 41 43 25.86 N, 71 28 01.02 W. (Channel 1 Histogram).

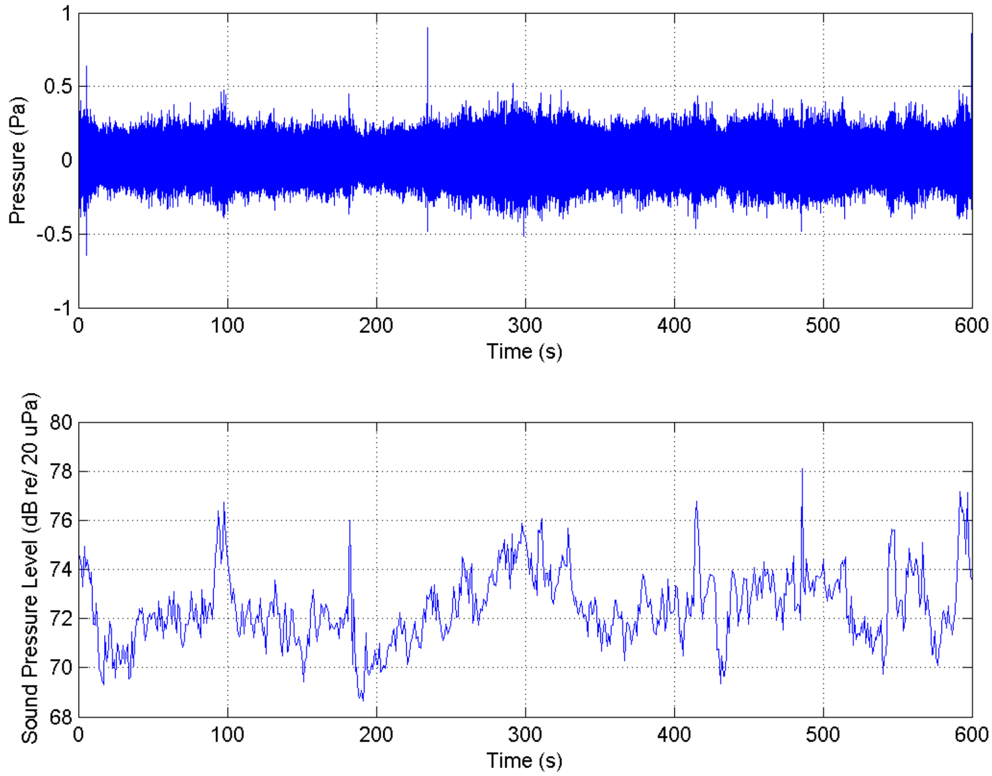

Figure A.66: Infrasound Data Recordings at Shalom Housing 05 NOV 2013 at location 41 43 25.86 N, 71 28 01.02 W. (Channel 1 Time Series).

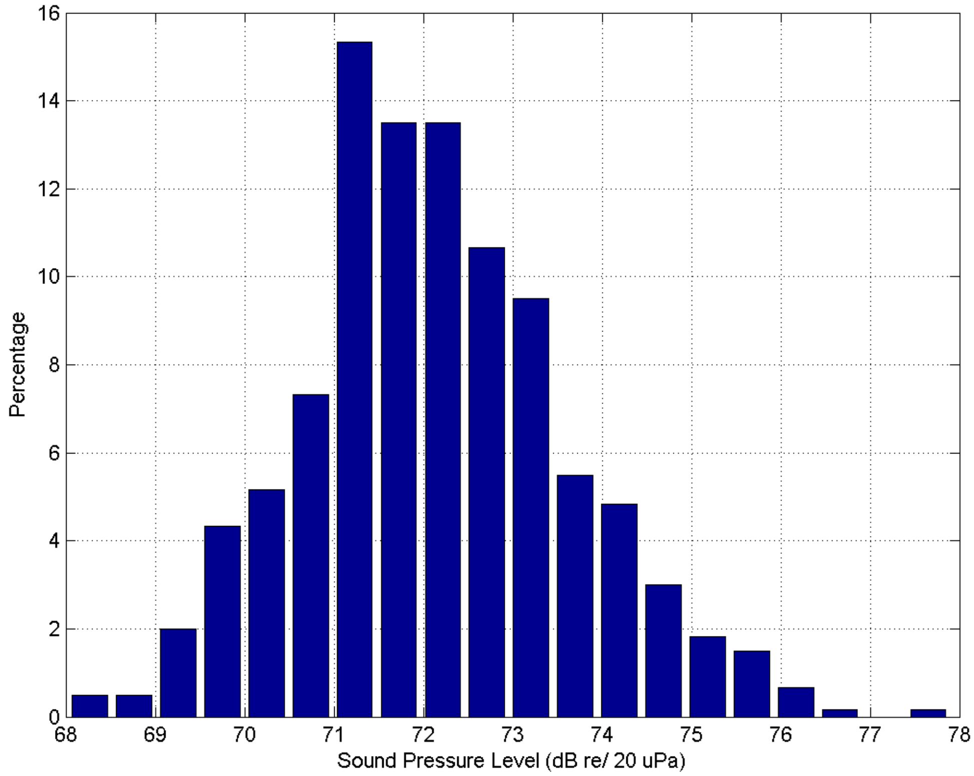

Figure A.67: Infrasound Data Recordings at Shalom Housing 05 NOV 2013 at location 41 43 25.86 N, 71 28 01.02 W. (Channel 2 Histogram).

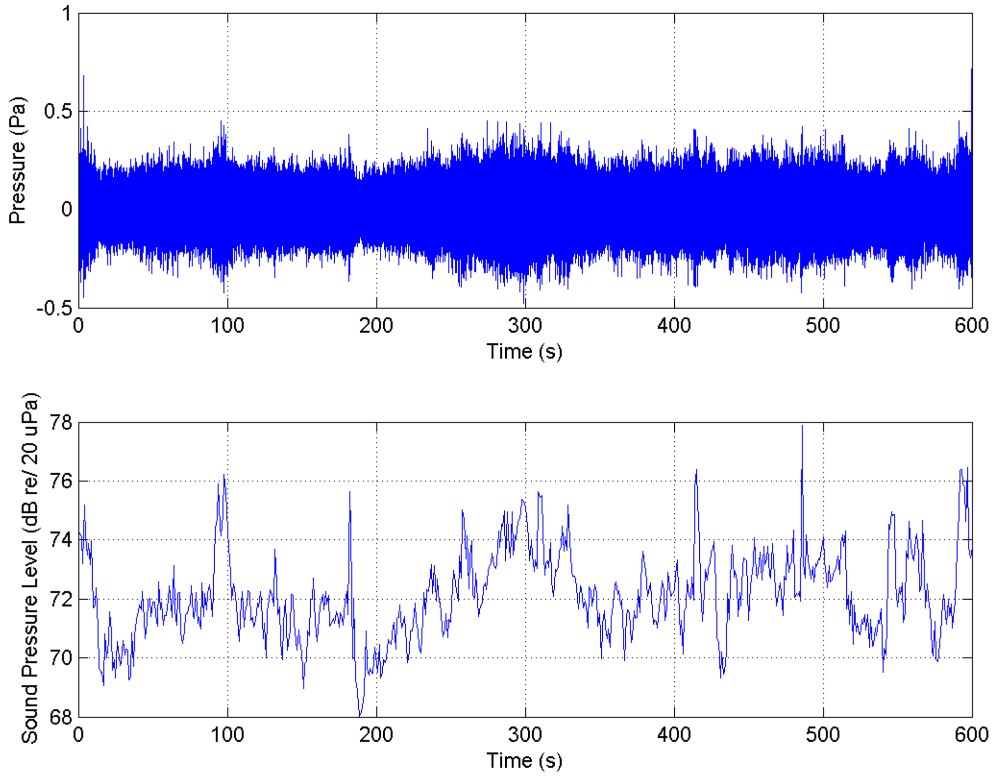

Figure A.68: Infrasound Data Recordings at Shalom Housing 05 NOV 2013 at location 41 43 25.86 N, 71 28 01.02 W. (Channel 2 Time Series).

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