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By Michael Beale

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New Approaches to Analyze Sound Barrier Effectiveness

For the degree of Master of Science in Electrical and Computer Engineering

Is approved by the final examining committee:

Eliza Du Chair	
Yaobin Chen	
Jason Saleem	

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NEW APPROACHES TO ANALYZE SOUND BARRIER EFFECTIVENESS

A Thesis

Submitted to the Faculty

of

Purdue University

by

Michael P. Beale

In Partial Fulfillment of the

Requirements for the Degree

of

Master of Science in Electrical and Computer Engineering

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Indianapolis, Indiana

This thesis is dedicated to my family, especially my Fiance, Mom, Dad, Brother and Sister.

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ABSTRACT

Beale, Michael P. M.S.E.C.E., Purdue University, August 2012. New Approaches to Analyze Sound Barrier Effectiveness. Major Professor: Eliza Du.

Highway noise can cause annoyance, affect sleep patterns, and reduce the property value for people in the proximity. Current methods for analyzing the effectiveness of sound barriers only take loudness into consideration. This paper introduces new methods that can be used to analyze the effectiveness of the sound barriers. Our approach uses psychoacoustic measures including sharpness, roughness, fluctuation strength and annoyance. Highway noise is non-stationary, therefore each of these metrics are calculated over a short time. Finally analysis is performed the distribution and change over time. We used nth nearest neighbor algorithm to remove sounds that are not a part of the experiment. In the future this data can be combined with human surveys to see if the change in sound quality do to the presents of a sound barriers have a meaningful impact people's lives.

1. INTRODUCTION

Highway noise can cause annoyance, affect sleep patterns, and reduce the property value for people in the proximity [1–8].

Soundwalls are built to reduce highway noise and by doing so improve the quality of life for people living near the soundwalls. However, soundwall are very expensive. Soundwall cost about 2.5 million dollars per mile in construction cost alone. Some have proposed alternatives to soundwalls, such as the line of the side (LOS) walls. However it is unclear how effective LOS walls are at stopping sound. To better understand the effectiveness of the sound barrier for highway noise, it is important to develop evaluation methods that can provide an objective measurement of the impact soundwalls have. Current methods for analysis use just the loudness calculated using A-weighted equivalent sound pressure level to analyz traffic noise. This method is widely used for several different models [9–12] and is widely accepted because it is easy to compute, and it provides policy makers a definitive threshold. This method is used in most current models and policies that relate traffic noise. However it provides a minimum amount of information about a sound and it could not provide information about of how people perceive the sound.

Many factors account for how people feel about a sound [13]. Some of these factors like temporal variation, and frequency density are not accounted for using A-weighted sound pressure level. Highway noise, is a result of many different sound sources, and as result is a complex and dynamic signal. Many of these acoustic features greatly affect how people feel about a sound, however they are not accounted for when sound is measured using only loudness. In this thesis, we propose using parameters that provide additional information about the acoustic properties of the highway noise to evaluate the effectiveness of the soundwall. Similar psychoacoustic tests have been used for commercial products [14–17]. These methods have proven effective for predicting how people feel about sounds, and helping engineering improve the sound quality of various products, however no extensive environmental noise evaluation has performed analysis using psychoacoustic parameters.

2. BACKGROUND

2.1 Acoustic Signal Processing

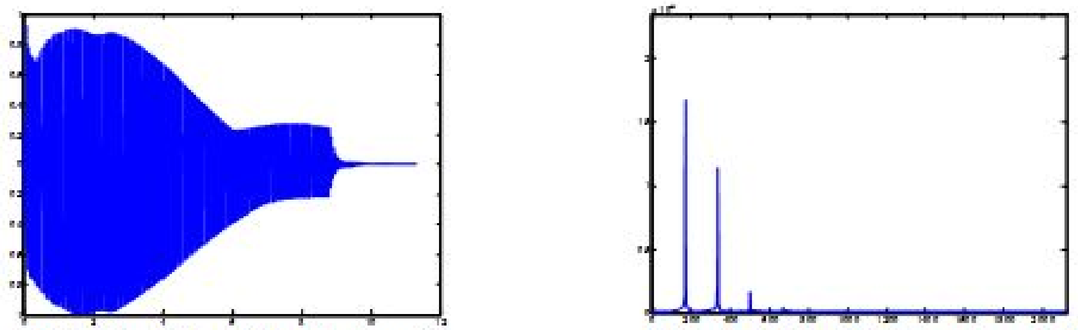
In this section is a review of acoustic signal processing. We will also formalize the some of the terminology that is used throughout the thesis.

2.1.1 Signal vs. Noise

Time domain representation of sound signals is a one dimensional signal where the magnitude references to the pressure of the air at a given time. In this research the sound from the highway (traffic noise) is considered to be the signal.

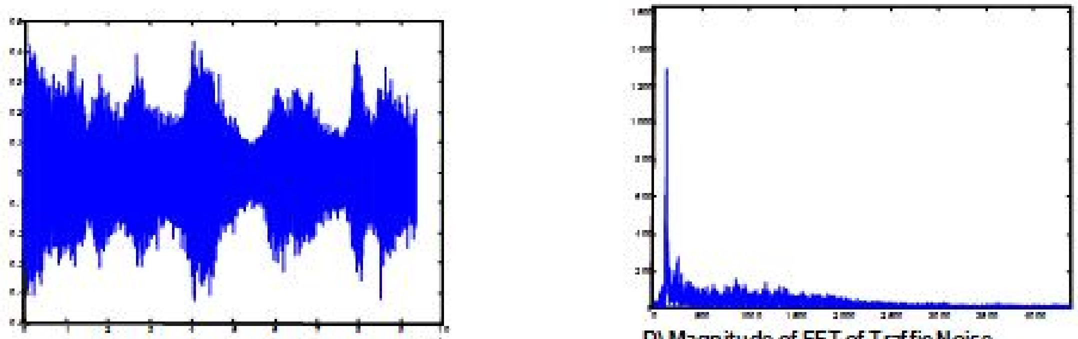
2.1.2 Acoustic Signal Characteristics

Fig. 2.1 plots two different sound signals in time and frequency domains. For keyboard sound, we can see that there is a fundamental frequency just below 200Hz and some energy at multiples of the fundamentals or harmonics. However, for the traffic sounds, the sound frequency is more distributed and no regular pattern is observed. There is a peak at 135 Hz in the traffic noise example.



A) Time Domain Sound from a Keyboard

B) Magnitude of the FFT of Sound from a Keyboard



C) Time Domain Sound of Traffic Noise

D) Magnitude of FFT of Traffic Noise

Fig. 2.1. Examples of sound signals

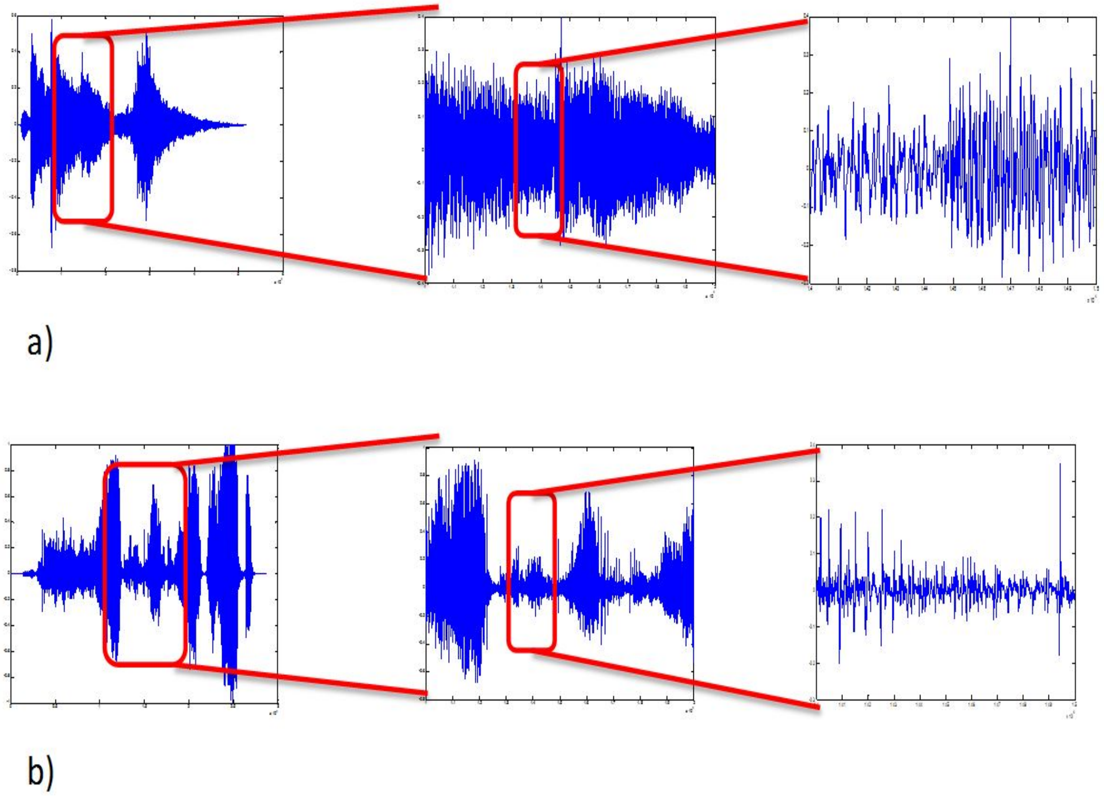


Fig. 2.2. Two time domain sound signals magnified a) tranquil piano sound b) chalk board sound

In Fig. 2.2 two sounds with contrasting properties in terms of annoyances are compared. These images show very little difference in time. In Fig. 2.2 a) the natural decay of the sound observed, and in Fig. 2.2 b) this change is more drastic. Other than this characteristic there is no obvious difference between these sounds. The visual similarity highlights the need to process the signal inorder to understand how the properties of these signals.

2.1.3 Human Perception of Sound

Sound is a change in pressure of the air over time. Pressure is measured in Pascals (Pa). The human ear is capable detecting changes in pressure; this is what is causes the sensation of hearing. The quietest sound detectable is about 0.0001 Pa and the threshold of pain is 100 Pa. Because the range of sound pressure is so wide sound is described in terms of sound pressure level (L) [18, 19].

$$L = 10log\frac{p^2}{p_0^2} \tag{2.1}$$

Here, p0 is a standard reference pressure of p0 = 20Pa, and p is the sound pressure in Pascals. In the real world sound signal vary over time so it is necessary to find how loud an equivalent steady sound is. This value is called equivalent sound pressure level.

$$L_{eq} = 10log\frac{1}{t_2 - t_1}[\int_{t_1}^{t_2} \frac{P_A^2}{P_{02}} dt] \tag{2.2}$$

Leq is the equivalent continuous sound pressure level [dB], p0 is the reference pressure level = 20Pa, pA is the acquired sound pressure in Pa, t1is the start time for measurement, t2 is the end time for measurement.

2.2 Review of Environmental Noise Evaluation

Since the 1960 researchers have been studying environmental noise and its effect on people [6]. Most of these early studies use A-weighted equivalent sound pressure level and correlate perceived loudness and/or annoyance.

In [20]Crocker compared perceived annoyance with dBA sound pressure level percentiles of environmental noise. This data did not have many data points, but it showed a nonlinear relation between dBA and perceived annoyance. Berglund et al. uses different environmental sounds at a set loudness to see how well Zwickers loudness and sharpness correlated to perceived loudness and annoyance[33]. Berglund concluded that for all sounds, besides the powerline noise, Zwickers loudness was a good judge of loudness and annoyance, but the variance of annoyance was far greater. They also suggested sharpness would be helpful in predicting perceived annoyance.

In [21] researchers created several new methods for analyzing traffic and train noise. They created two new metric, the spectral variance and temporal variance. They then used 6 participates to rate the annoyance of the data they recorder. At the end they showed that the method they came up with fit was a considerably better method for predicting annoyance than Zwicker loudness calculated over 10 minutes and LAeq calculated over ten minutes. However this is limited group of subjects to evaluate the sound. In [22] Zwickers loudness was able to predict perceived loudness and annoyance in short sound samples of urban environmental noise. They used twenty 15 second sound samples of environmental noise. In this research perceived annoyance was predicted less accurately than perceived loudness. They concluded that sounds such as children, birds, moped and buses created different levels of annoyance in different people.

Another interesting study of evaluating experimental sounds was performed in [23]. In this paper data was gather at a location with a soundwall and a location without a soundwall. This paper compares perceived annoyance and loudness to A-weighted SPL. They found at close distances 10-50m that at a given SPL, the sounds recorder at locations with a sound wall were perceived as more annoying. The researcher suggested this is because of the underestimation of low frequency sounds.

2.3 Previous Work in Soundwall Effectiveness Evaluations

This is a review of the methods to evaluate soundwalls. A classical approach is insertion loss [8, 18, 19, 24, 25]. In this method a before and after measurement is taken at the same location and reference measurement are used before and after. This method is very effective because the reference can be used to mitigate changes in traffic patterns. This allows for a equal comparison regardless of the traffic patterns. Also, because the data is taken in the same location, no other geographical changes effect the measurement. The equation below shows how insertion loss would be performed using LAeq data:

$$ILi = (LAref + Ledge - LArec) - (LBref - LBrec) \tag{2.3}$$

ILi is insertion Loss for location I; LAref is reference SPL after wall; Ledge is edge diffraction correction factor; LArecis rceiver SPL after wall; LBref is receiver SPL before wall; LBrec is reference SPL before wall. The insertion loss method has some limitations. First although this method is not limited to a certain metric, it most commonly performed with simply A-weighted sound pressure level. Also, before and after measurements are required in order to analyze the wall. An in-situ method for analyzing sound walls are outlined in [26]. This is for calculating insertion loss of a barrier if the barrier is already built. This method works by finding a site with similar geographic and acoustic properties, but without a wall and using data collected from that site as the before results. This method is necessary if there is no way to remove the soundwall, however it is difficult to find a location with the same properties, so this method could only provide an estimate of the noise reduction. In [27] researchers used an indirect predicted method given in [23] to evaluate different kinds of walls. The model these researchers used was based on the FHWA 1978 standard. The accuracy of this method is a concern as they reported insertion losses in the range of 6-21 dBA. This is unusually high for any material; it is criticized to be inaccurate [28]. Another method for analysis of a soundwalls effectiveness is the Andrienne method [29–35]. In this method the reflection loss measurement and the transmission loss measurement can be calculated. Like insertion loss, when calculating transmission loss there is a before and after data. However, for both cases a maximum length sequence (M.L.S.) is generated and using a loudspeaker, transmitted to a microphone on the other side of the wall or future site of the wall. Then the M.L.S. signal is extracted from the noise and an accurate measure for how much the M.L.S. signal decayed is calculated. Comparing the before and after signal gives a measure of the soundwalls effectiveness. Because this method using a sound source is considered an active method.

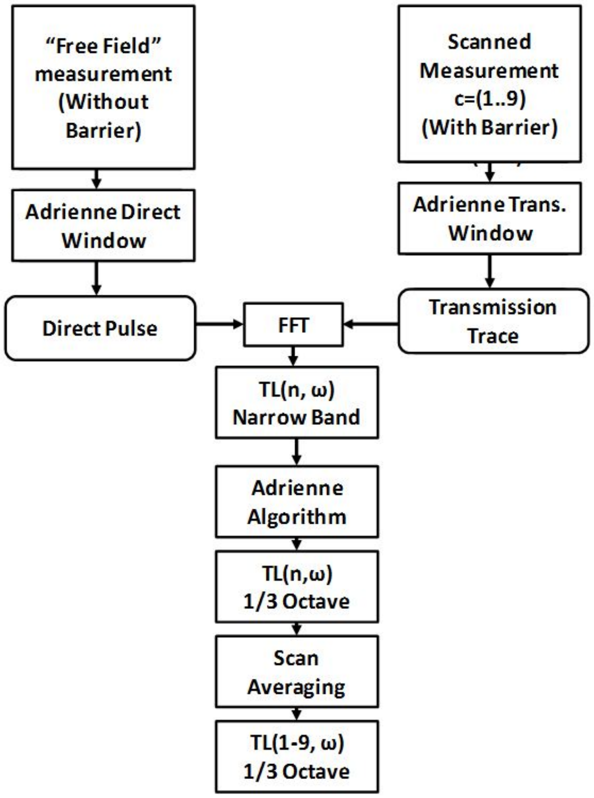


Fig. 2.3. Adrienne method

The Adrienne method has several advantages, it can analyze how a sound barrier would attenuate sounds of various frequencies. However this method does not take into account the sound that is being stopped or relate the information about the reduction of the sound to the how people perceive the sound. Also, the Andrienne method requires additional equipment to generate sound in that aspect it is more complicated. This sound has to be at least 10dB higher than the background noise, so near a highway where the noise can be near dangerous level around 80dB at times, the signal that would need to be generated would be very loud to overcome the background noise. Or the traffic would have to be stopped so the background noise is low enough to perform this method.

2.4 Problems with Existing Methods

The existing methods for analysis are useful, however all of them only focus on loudness. A-weighted sound pressure level does not account for the effect that time varying sound has on people. The Adrienne method is good for measure how much sound is stopped by a sound barrier. But the effect this will have on people really depends on what the characteristics of the sound are at the location of the barrier.

3. OUR APPROACHES

Fig. 3.1 illustrates the model highway noise transmission. Highway noise, it is a non-stationary signal. As the highway noise propagates from the highway to the observers, the highway noise can be reflected, absorbed, and/or attenuated depending on the frequency of the sound and propagation routs. *Hbi* is the filter for observer *i* before the construction of the wall and *Hai* is the filter for observer*i* after the construction of the wall. By observing the difference of the filters *Hi* and *Hi* it is possible to ascertain to what extent the soundwall changed the sound for each location. The local noise is represented by *n1* to *nN* for this experiment. This factor varies from time to time and location to location. In order to maintain consistence in the experiment, this factor will be mitigated. Local noise is created by wildlife, local traffic, and instrument noise. To select locations to setup the data collect equipment, we used the standard method that is adopted by environmental engineers and government organizations at the Indiana Department of Transportation. Of the appropriate locations to set the equipment, selections were made to minimize local noise, and to compare different conditions.

3.1 Method for Evaluation

To more accurately evaluate the soundwall effect, we need to mitigate the impact of environmental variances. In this research, we propose to use reference data to measure the sound in such a way that the presences of a soundwall will not affect the reference measurement. In order to evaluate the soundwall, several factors need to be adjusted to get a reasonable comparison of the before and after conditions. In this way the only factor that affects the observed noise is the affect of the soundwall. The traffic noise and environmental factors vary from time to time because of changes in

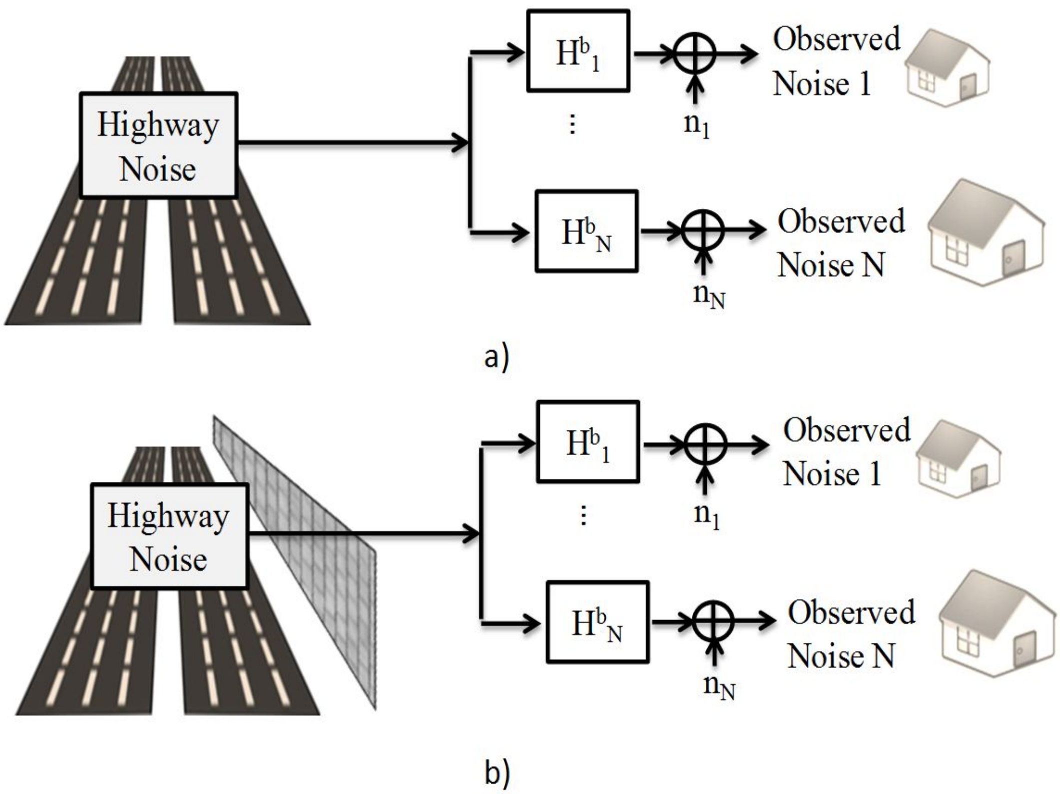


Fig. 3.1. a) The model of highway noise transmission before construction of the wall b)The model of highway noise transmission after construction of the wall

traffic patterns therefore, this must be taken into. The location of the observer must remain constant from experiment to experiment to insure that only the sound wall is the only factor that changes in the filter. Local noise must be mitigated to reduce the error it causes.

3.1.1 Reference Data

Reference data is used to account for the variation of different traffic patterns and different environmental factors. The traffic noise is not a stationary sound, it varies as vehicles enter and exit the soundscape. Even for similar vehicles there is a large range of different sounds that are observed. The condition and speed of the vehicle greatly influence the sound. Rather than trying to model and predict this, we have devised a method that will allow a reasonable comparison regardless of variations of the highway noise. This method involves using a reference data to gather data that is not affected by the wall. The idea of using reference is well know it is used when calculating insertion loss (section 2.4). In this equation if the reference data is brought out front, the following factor is added to the difference in of the before and after receiver, we will call this reference correction RefC.

$$RefC = LAref - LBref \tag{3.1}$$

In this equation the reference correction is calculated using subtraction, this is because dB is used (dB is a log value). If the values are not logarithmic then this value can be calculated as a ratio of the after value over the before value. In this way the RefC can be created for any metric used to quantify a sound.

3.2 Location

There are many factors that affect how sound propagates over an area. Atmospheric adsorption is how much of the sound is absorbed by the air. Ground effect is how much of the sound is absorbed or reflected off the ground, this is determined by the reflective index of the ground, frequency and location of the receiver. Barrier including houses and foliage can reflect and/or absorb sounds [19]. The elevation will also makes huge impact on how sounds travel through an area. Because of this complex interdependence of variables each different location has a unique acoustic distance from the highway noise. Therefore, it is important to measure several different locations and repeat the same location of the before and after condition. In the data acquisition section the procedure for locating the same position was outlined.

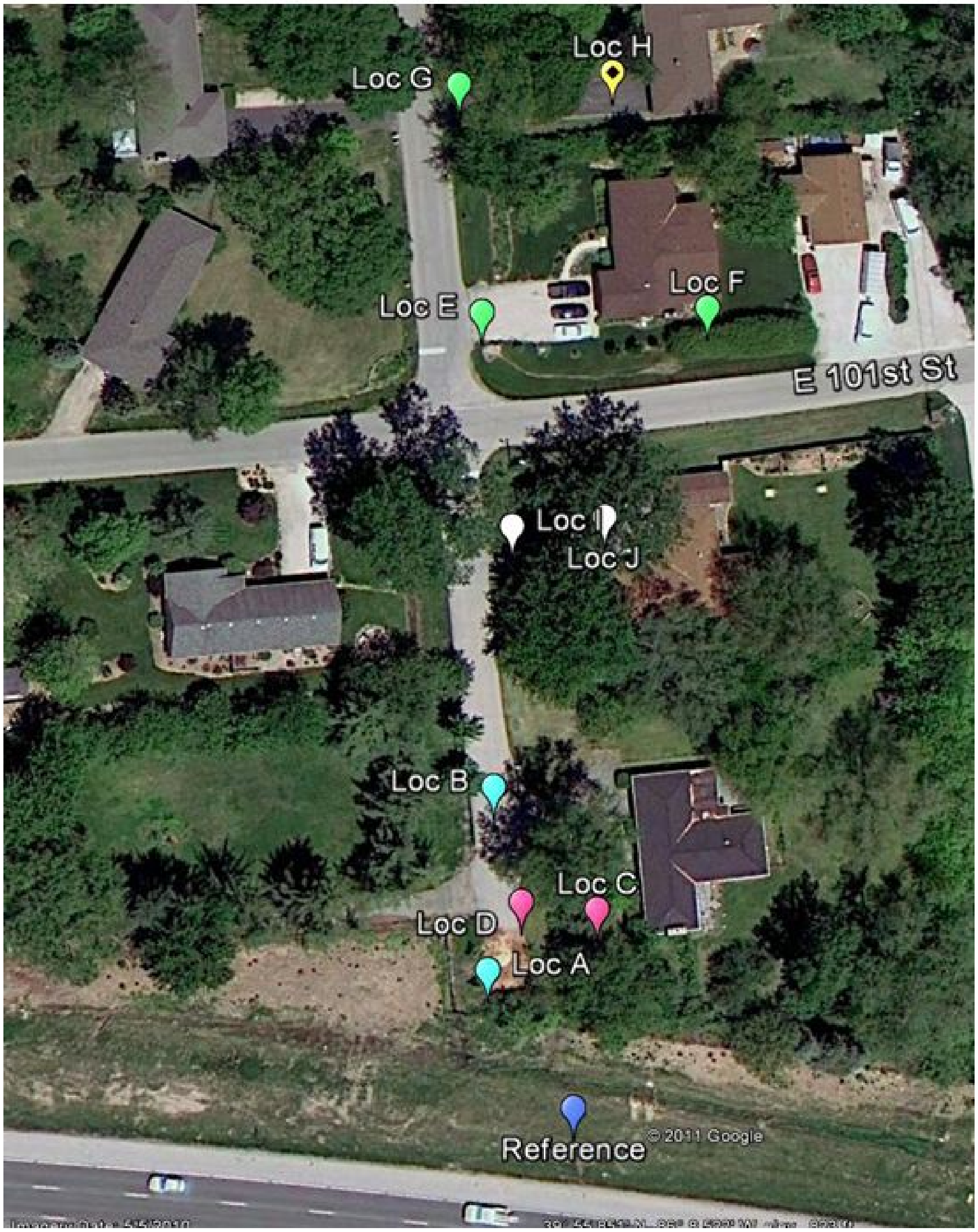


Fig. 3.2. Map of measurement locations from Google Earth

3.2.1 Data Acquisition

A non-trivial aspect of this experiment was designing and executing a data acquisition method that was highly accurate and very robust. This involved selection, and

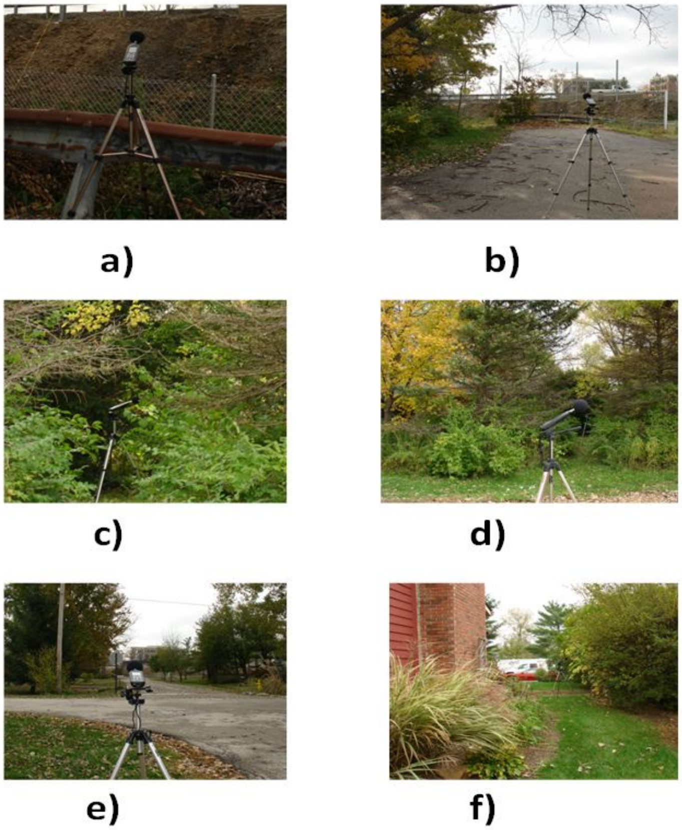


Fig. 3.3. Pictures of equipment at different locations

maintaining of proper equipment. Executing the data collection was also a challenge as only certain days worked with the weather and schedule constraints.

Equipment

A description of the equipment is provided in this section. To acquire the data, ANCI type 1 sound level meters (SLMs) were used to record the traffic noise. For this experiment Larson Davis 831 with a inch microphone was the equipment used. The SLMs were calibrated with ANCI type 1 calibrator before and after an experiment to verify the accuracy of the instruments. The sample rate used was 48kHz, as this allowed for analysis up to the highest frequency that humans can hear.

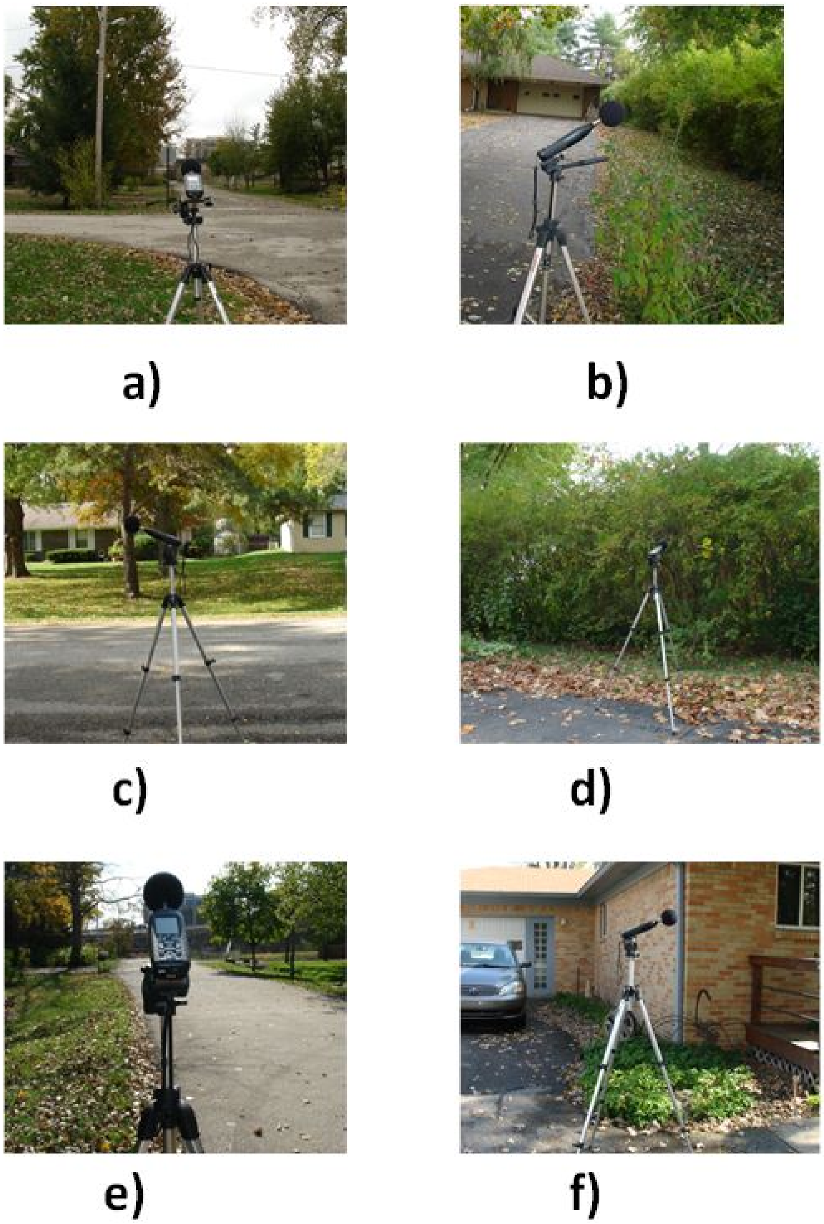


Fig. 3.4. Pictures of equipment at different locations

Setup

For the measurement behind the wall, camera style tripods were used to hold the SLMs. For the reference SLM a system was devised to hold the SLM higher than the wall. A handheld gps unit was used to record the location of the each SLM. Digital images of all the locations were taken as well to insure that exact locations can be repeated on future visits. To synchronize the SLMs the internal clocks were used.

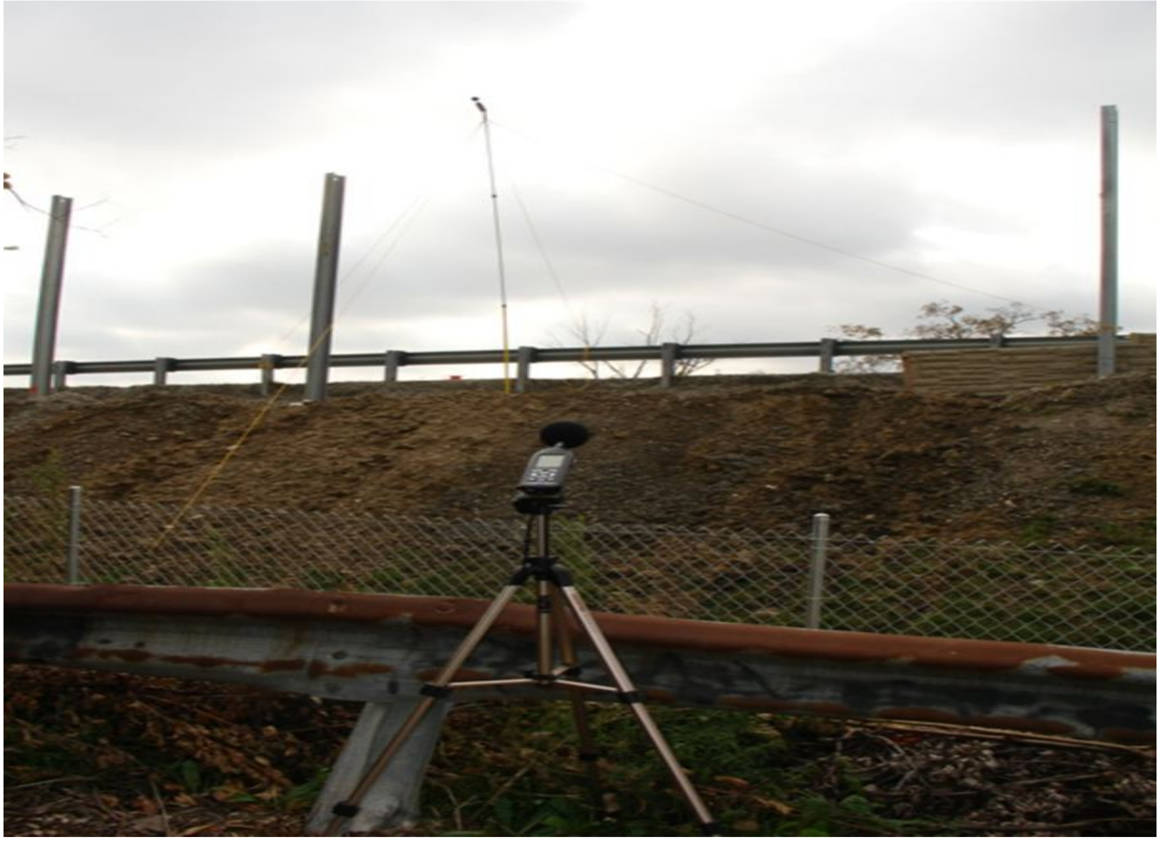


Fig. 3.5. Picture of SLM setup. Notice the reference and the local SLM

3.2.2 Local Noise Reduction

When measuring highway the goal is gather data from the highway only, and minimize noise called by other sources. In gather data for INDOT Ive noticed bird sounds that affect the measurements greatly. The first is bird noise, in some locations when birds are chirping the data recorded is twice as loud as when there are no birds. The wel used in the next section that will be covered. This includes how the training

Fig. 3.6. A close-up look at the reference SLM

data was obtained. The pattern recognition algorithm and parameters that will be used are also covered in this section.

Training Data

To gauge how well our system performed we manually listened to two 15 minutes and classified each 100ms segment based whether it had a bird chirping or not. We used a binary classifier and our best judgment; this is what we have used as ground truth in this experiment. However, this process is not 100 percent perfect as some of the sounds contained some degree of bird noise. There is also a degree of human error that is impossible to escape in a process as tedious as this.

Algorithms Selected and Parameter Selection

To remove bird sounds, specific loudness was selected as it was the parameter most affected by the birds chirping. The algorithm that is used is the nearest neighbor[50, 51] (NN), to select an appropriate number of neighbors a test was performed using up to 25 neighbors.

Fig. 3.7 contains the results of this preliminary experiment. Because this only had a small amount of data from the loc2C, the second location substantially out performed loc1C. This test showed that about 3 neighbors are optimal for reducing error. More tests were performed but omitted from this report for the sake of brevity. This also showed I needed training data from both categories. It also shows that with more than 17 neighbors, all the data gets classified as no noise. In Fig. 3.8 an experiment is conducted only using data from from loc2c.

This shows that using NN is less accurate than leaving the data alone when the training came from a different location. In our case the loud sounds were generally misclassified as bird sounds in loc1c resulting in lower loudness calculation when bird sounds were removed. This method does provide better results when the training data came from the same location. With the lower number of neighbors, the average from the obtained result is almost exactly the same as the ideal case. Using the knowledge we gained in the preliminary experiments we set up the following experiment. We ran tests with randomly selected training sets; 900 points (10 percent), 300 points (3.33 percent) 100 points (1.11 percent) from each data set (9000 data point each). We then used 3-nearest neighbor to classify the data. In each experiment we used 20 different random samples for each experiment. The results are in Figs. 3.9,3.10 and 3.11.

These results show that the even when training data is selected from both datasets, loc2c performs better than loc1c. This data shows that the number of misses is far less than the false alarms for most cases. This data also shows that accuracy is greatly dependent on the training set. In test 2 both loc2c and loc1c have a higher

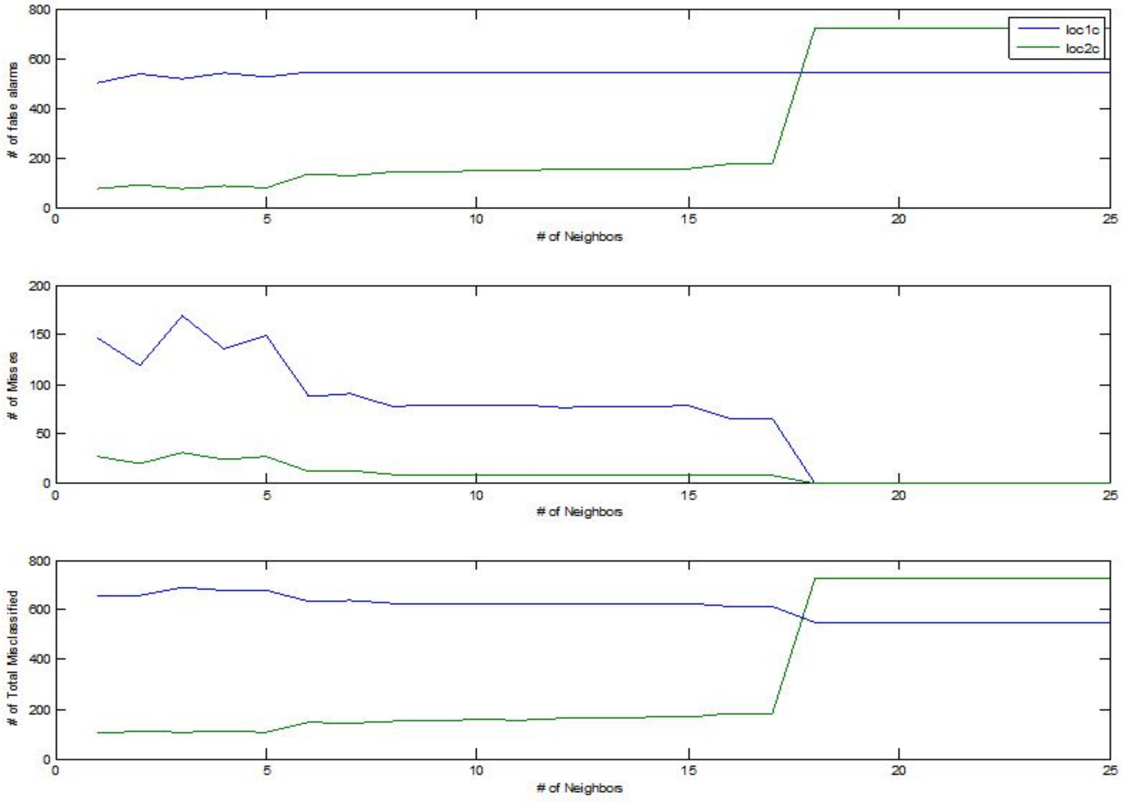


Fig. 3.7. Results from a training set consisting of 10 seconds of data (100 points) from the loc2c, the specific loudness to classify the data

than usual number of misses. The data also shows that as more data is used the greater the accuracy. Rather than explain the results using false rejection rate (FRR) and false acceptance rate (FAR) we plan to evaluate the effectiveness of this method based on how much improvement is observed in the final result of the experiment. The goal of this experiment is to measure the loudness so, if removing the bird sounds makes the output close to the ideal case, then it is successful. Figs. 3.12,3.13, and 3.14, are most important output of the experiment; it shows that using this method can improve the accuracy of the test. The red line shows the ideal result using the loudness of the training data. The blue line is the loudness that was actually

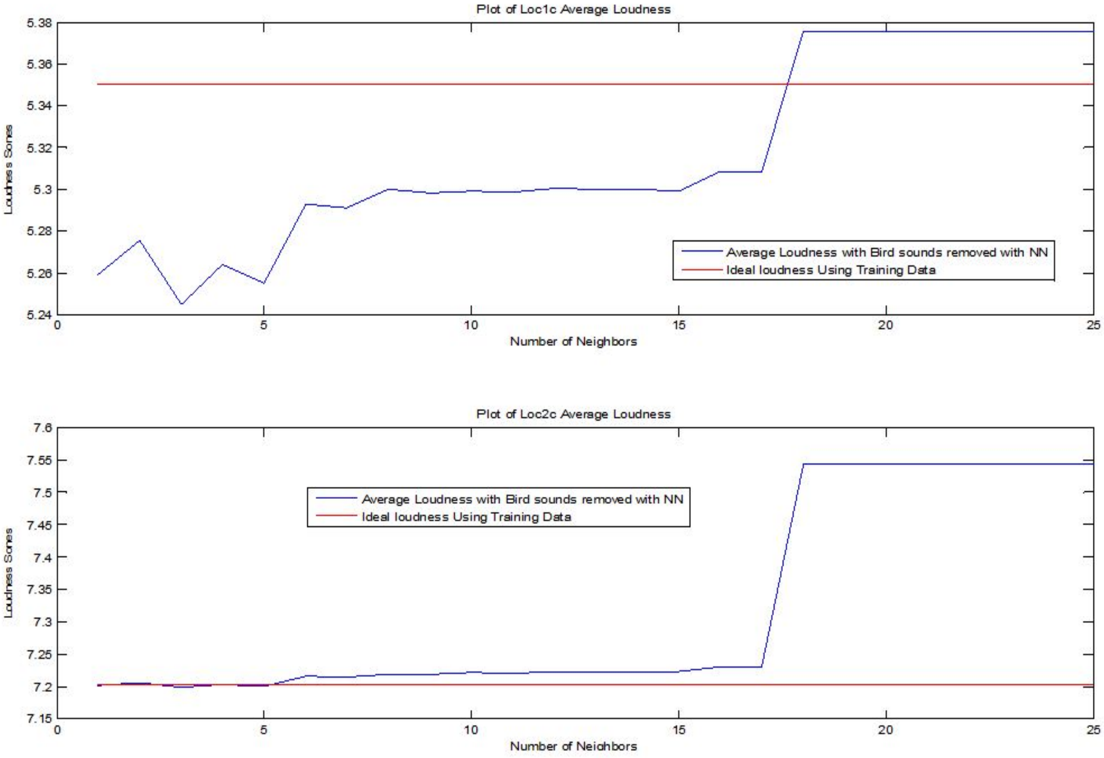


Fig. 3.8. Using training data from only loc2c and the specific loudness method, the following average loudness was obtained only from sounds not classified as bird noise.

obtained. The difference between the red and blue lines for any of these cases signifies an inconsequential change in loudness.

Figs. 3.15, 3.16 and 3.17 show the loudness of the bird sounds that were removed in comparison to the ideal case obtained using the result obtained manually. This data is less important to experiment but it provides some insight and underlines the need for this procedure. As it is plainly seen the loudness of the bird sound are greater than that of the non-bird sounds. This difference is greater in the loc2c, and this explains the reason that loc2c performed better than loc1c. This follows the background knowledge of the experiment; loc2c was closer to the birds.

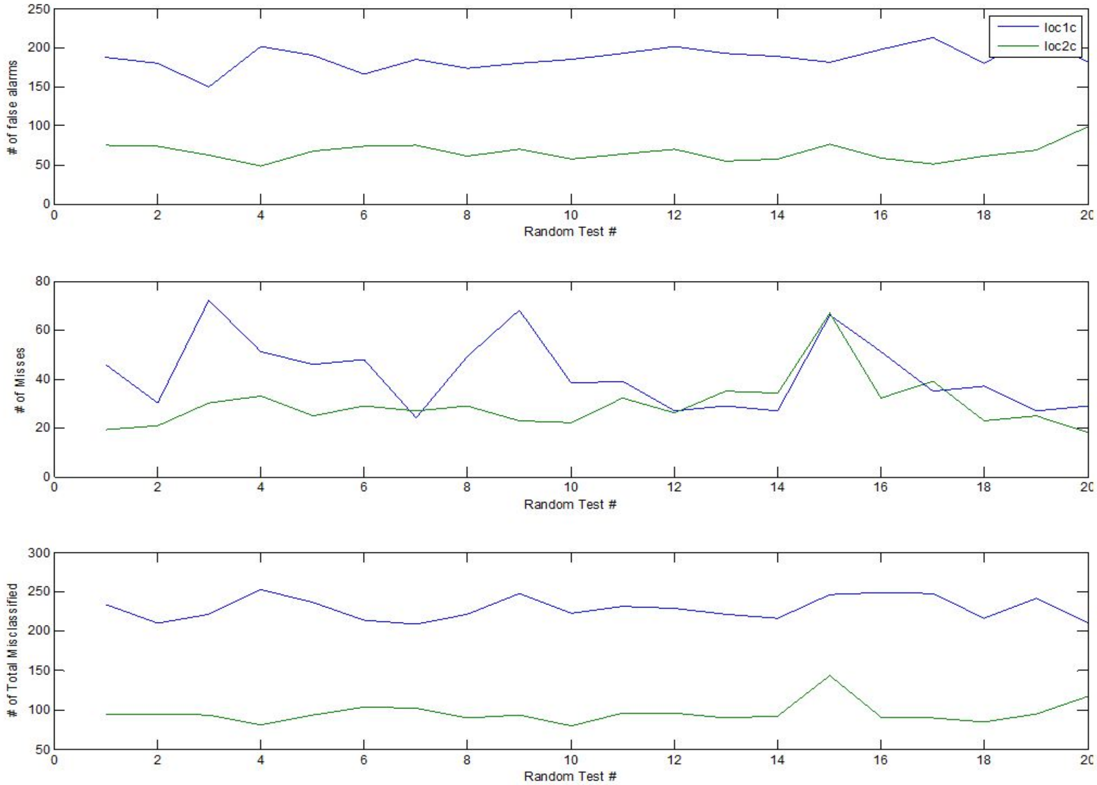


Fig. 3.9. The accuracies of 20 randomly selected training sets. This included 900 points from both loc1c and loc2c.

3.3 Sound Quality Metrics

Sounds have many different characteristics explained in section 3.3.2.1 to 3.3.2.5. This section shows why and how they will be used in experiment.

3.3.1 Rational for Use of Sound Quality Metrics

For metrics to evaluate the soundwall we used several in order to be as compressive as possible. There are limitations of LAeq; it is in a sense averages the sound over the length of the data acquisition. The signal is not exactly averaged but rather squared, integrated and divided by time, before the log of the value is taken. Because

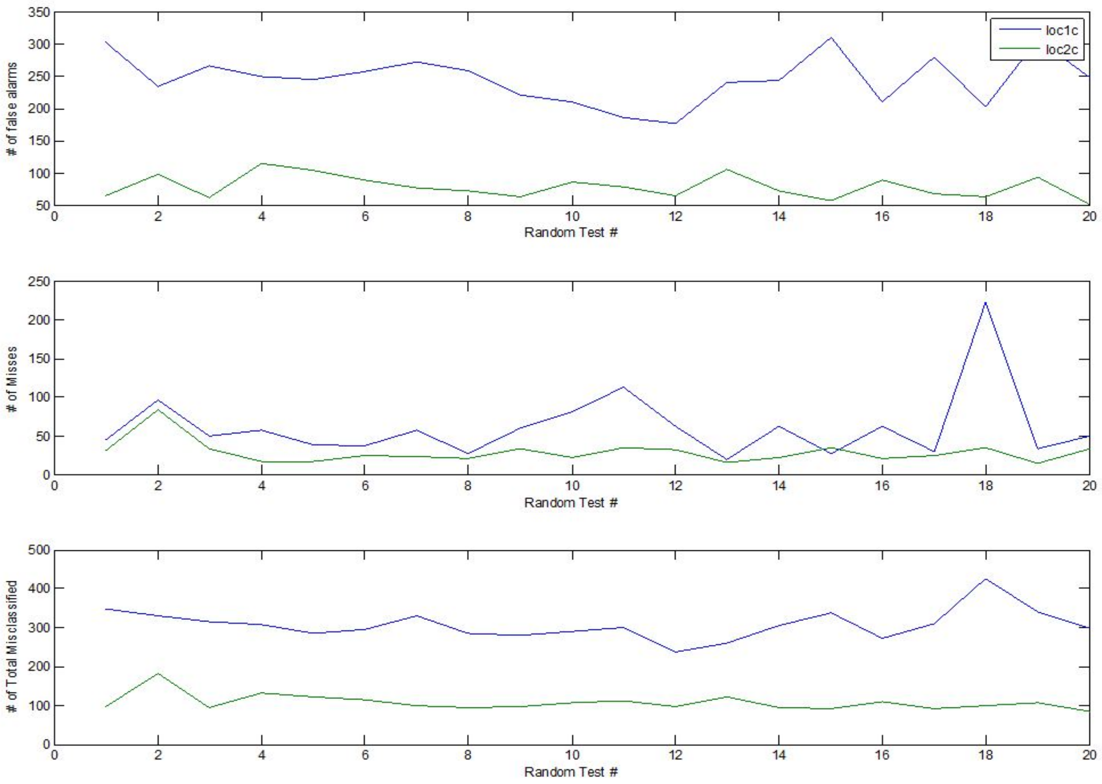


Fig. 3.10. The accuracies of 20 randomly selected training sets. This included 300 points from both loc1c and loc2c.

of this the distribution of different sound levels is not taken into account, besides their contribution to the total value. Although the A-weighting process accounts for the frequency response of the ear, this method is not as compressive as other methods for doing so. As show in Fig. 3.18 the human ear senses low frequencies better at higher SPL. Because of this the A-weighting curve can underestimate the contribution of the low frequency sounds. Also, masking might be a factor in this experiment as the sound source, traffic noise, consists of complex sounds coming from tires, engines and exhausts of many different vehicles. Many researchers believe that the distribution of sound, particularly N5 has an important effect on the perception of annoyance and loudness[28]. Observing how much a soundwall stops sound of a certain distribu-

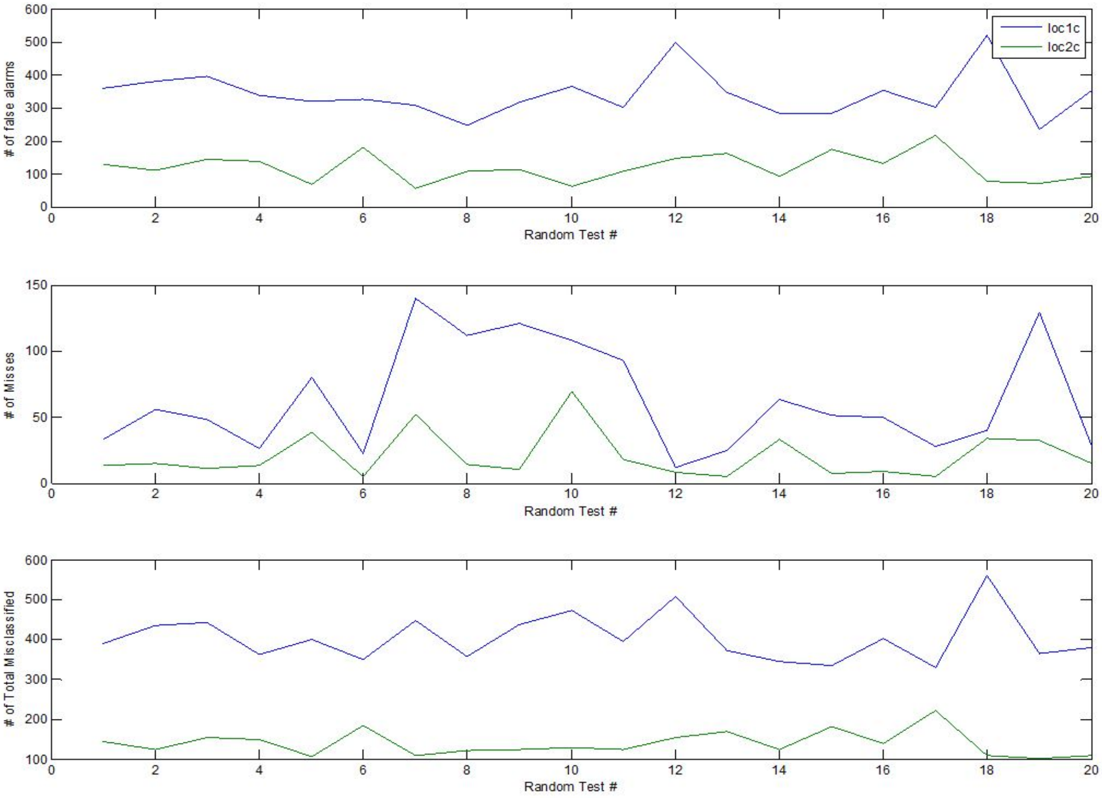


Fig. 3.11. The accuracies of 20 randomly selected training sets. This included 300 points from both loc1c and loc2c.

tions of loudness could be key in quantifying how much the soundwall improved the soundscape. For example, if a soundwall was only effective at stopping the quietest sounds, a high insertion loss could be calculated with LAeq. However, this would not provide much improvement to the soundscape. The averaging that happens when LAeq is calculated also hides various temporal patterns. These temporal patterns are perceived by humans as fluctuation strength and roughness. It has been shown that these sound quality properties contribute to annoyance when they come from noise. The balance of high frequency components to other frequency components has an effect on annoyance. This property is not accounted for in LAeq.

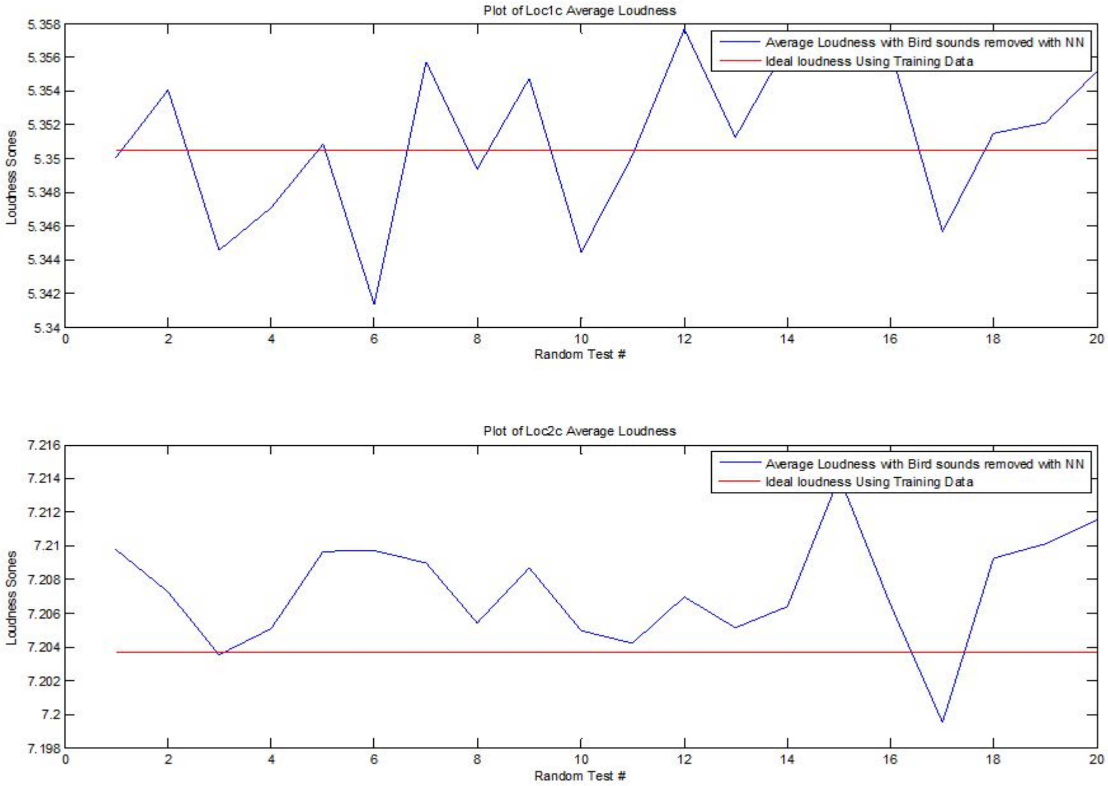


Fig. 3.12. The accuracies of 20 randomly selected training sets. This included 100 points from both loc1c and loc2c.

3.4 Models for Sound Quality

Sound quality characteristics (aside from loudness) are not standardized and there many different way that they can be calculated. Below we have given an explanation and justification for the model to be used.

3.4.1 Review of Loudness

Loudness is an important sound quality metric, it is the perceived magnitude of a sound.

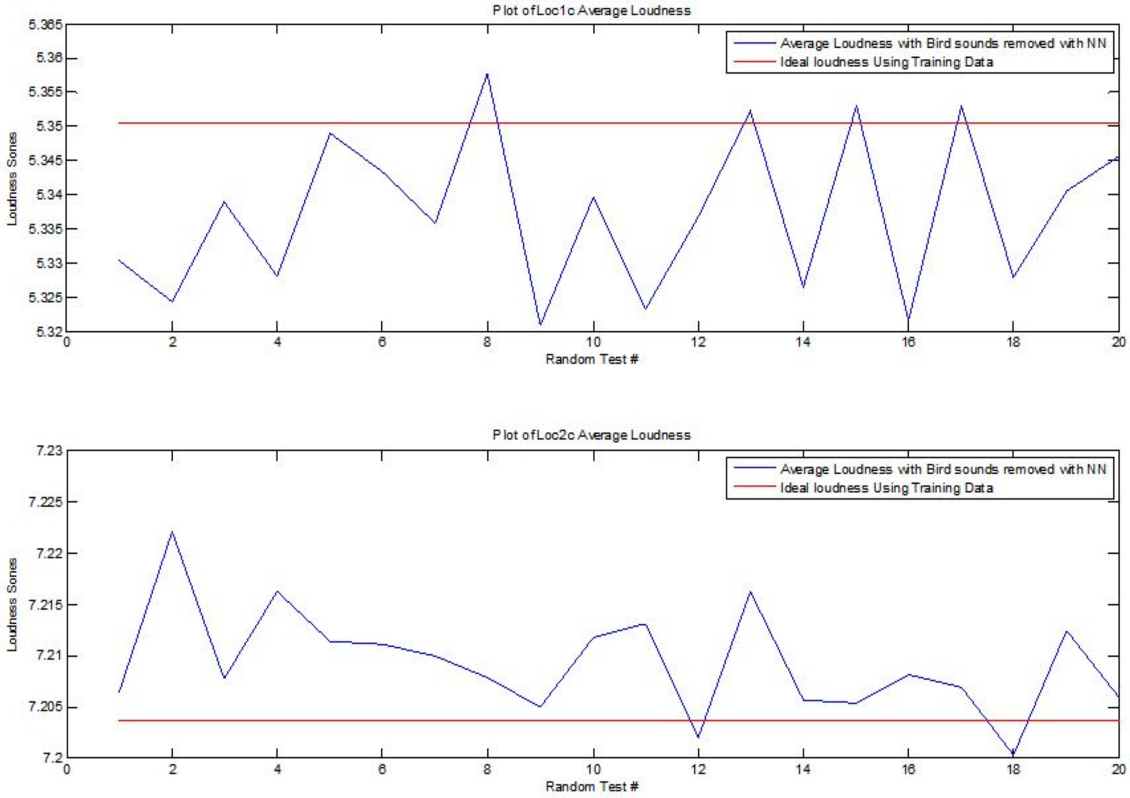


Fig. 3.13. The result of removing the bird sounds on the test with 900 training points from each dataset.

Phons and Equal Loudness

The earliest important method for evaluating the loudness of a sound was presented by Barkhausen [13]. This method involved comparing different sounds to a reference sound. The most common reference sound is a 1kHz sin wave. To test a sound the decibel level of the reference sound was changed so that it was as loud as the sound being tested. Using the technique described it is possible to compare the loudness of two sounds, one being a reference with known values, the other with different properties. The unit associated with the equivalent loudness of a 1kHz sin wave is Phons. Using this technique equal loudness curves can be constructed for

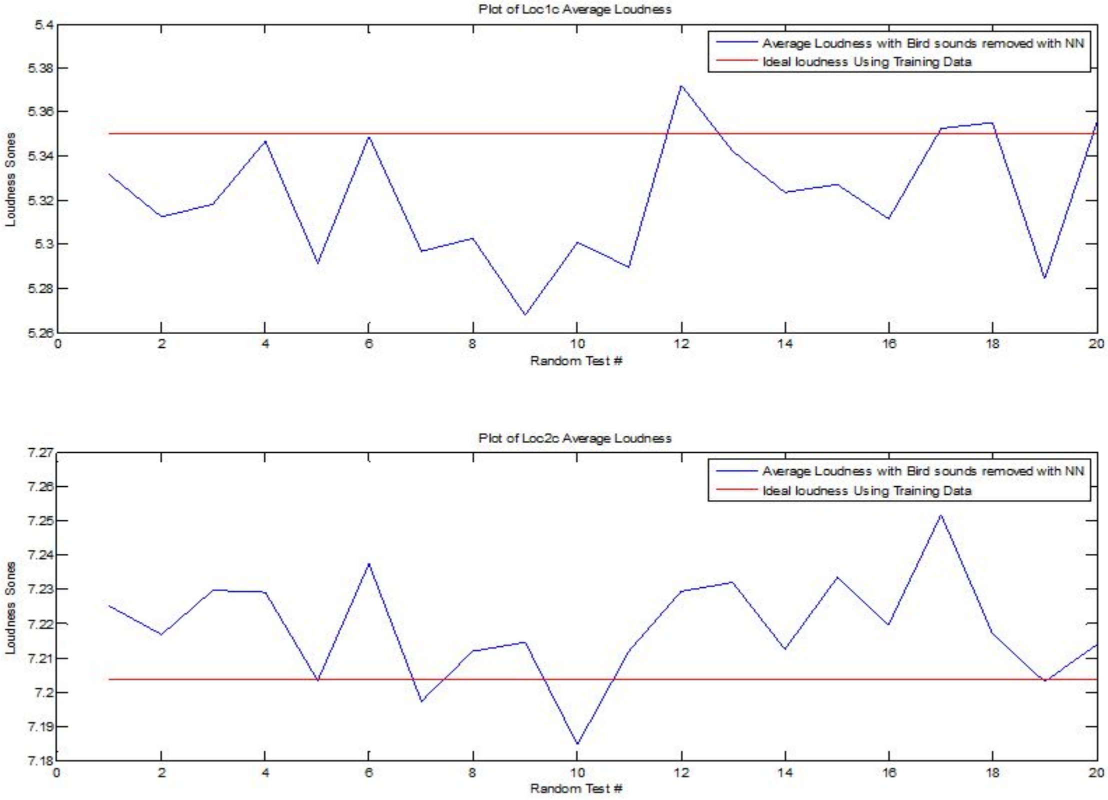


Fig. 3.14. The result of removing the bird sounds on the test with 300 training points from each dataset.

given loudness using pure tones of various frequencies Fig. 3.18. This figure shows how sensitive humans are to pure tones over the frequency spectrum. It is important to note that the functions are not just shifted copies of each other. The low frequency tones are not as comparatively loud at lower levels. This is evident in the steep slope of the low frequencies part of the functions. This method for analyzing loudness is important for a first step in understanding how the human ear responds to different frequencies. However this method insufficient by its self as to loudness depends on several other factors besides frequency and level. The bandwidth, spectral density, and temporal variations all effect loudness in a meaningful way therefore it is to get a true evaluation of loudness a single filter is not adequate.

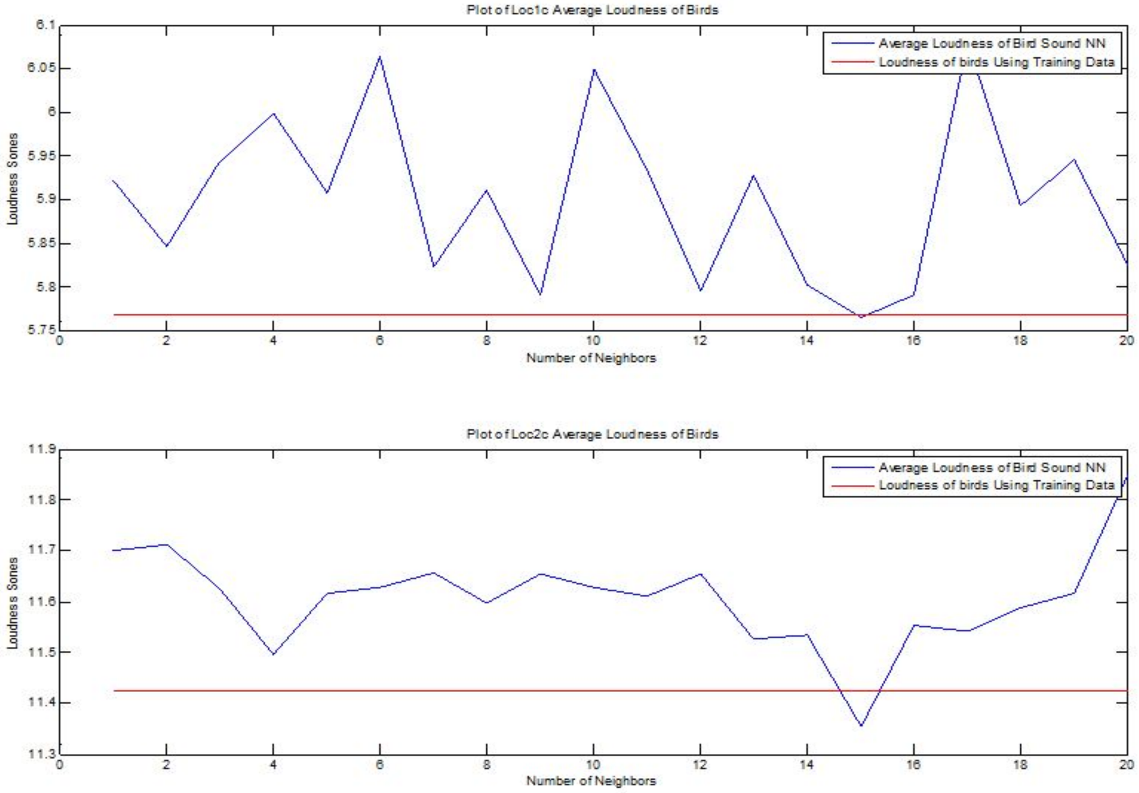


Fig. 3.15. The loudness of the removed sounds using 900 training points from each dataset.

Weighted Sound Pressure Level

From knowledge obtained from equal loudness studies it is possible to make a filter that compensates for the different responses of frequencies. This is called weighted filters. The most common filters are the A, C filters, Fig. 3.19, [19,36]. A weight filter, is based on the 40 Phon equal loudness curves, this is the filter that is most common for analyzing traffic noise. C weight is for louder sounds. By filtering an acoustic signal then calculating the equivalent sound pressure level the weighted equivalent sound pressure can be calculated LAeq or LCeq depending on the filter. This is the method currently used to evaluate sound wall [8].

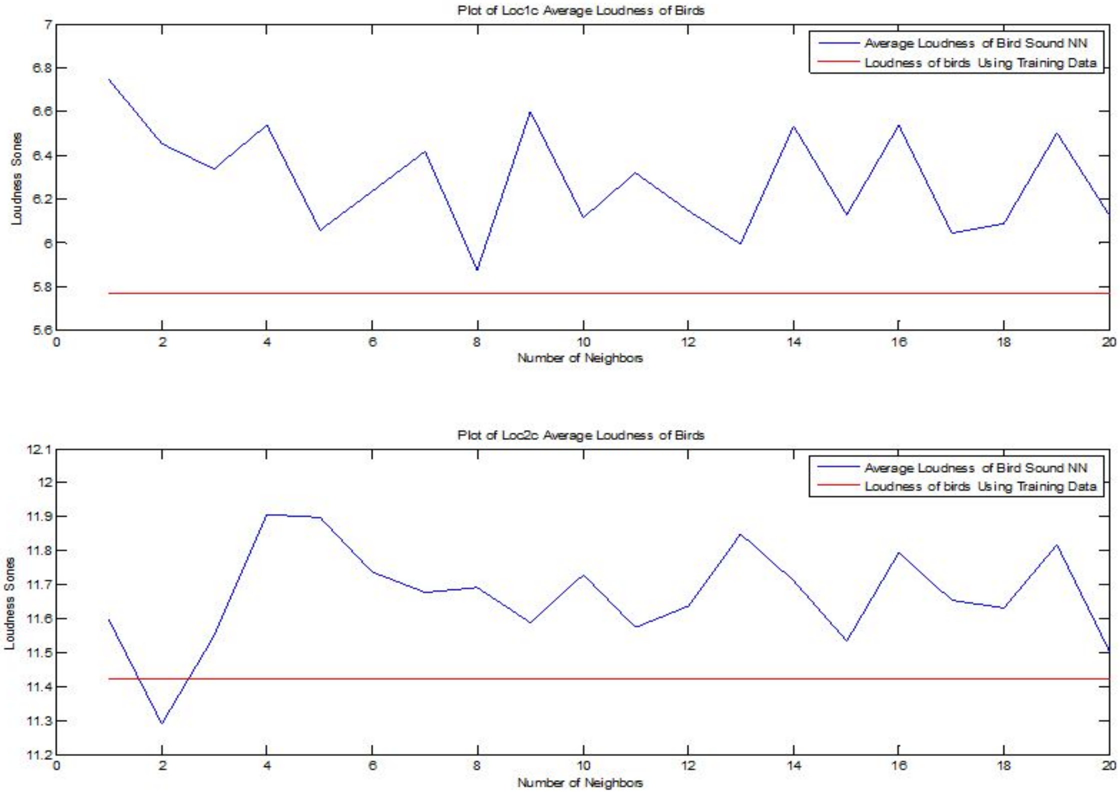


Fig. 3.16. The loudness of the removed sounds using 300 training points from each dataset

Phons and Sones

To get a sound that is twice as loud the sound needs to increase by 10dB. In this sense it is not as easy to directly compare two loudness values in Phon or any other dB value. The unit that was defined to be directly related to loudness is Sone. One Sone is defined as a sound equivalent to a 40 dB 1kHz sound. To get a sound that is two Sones the sound would twice as loud as 40 dB1kHz sound. Using the ISO523B and ANSI S34 2007 interpretations the following mapping can be defined [38, 39].

$$Phon = 40 * Sone0.35 if Soneislessthan1other \tag{3.2}$$

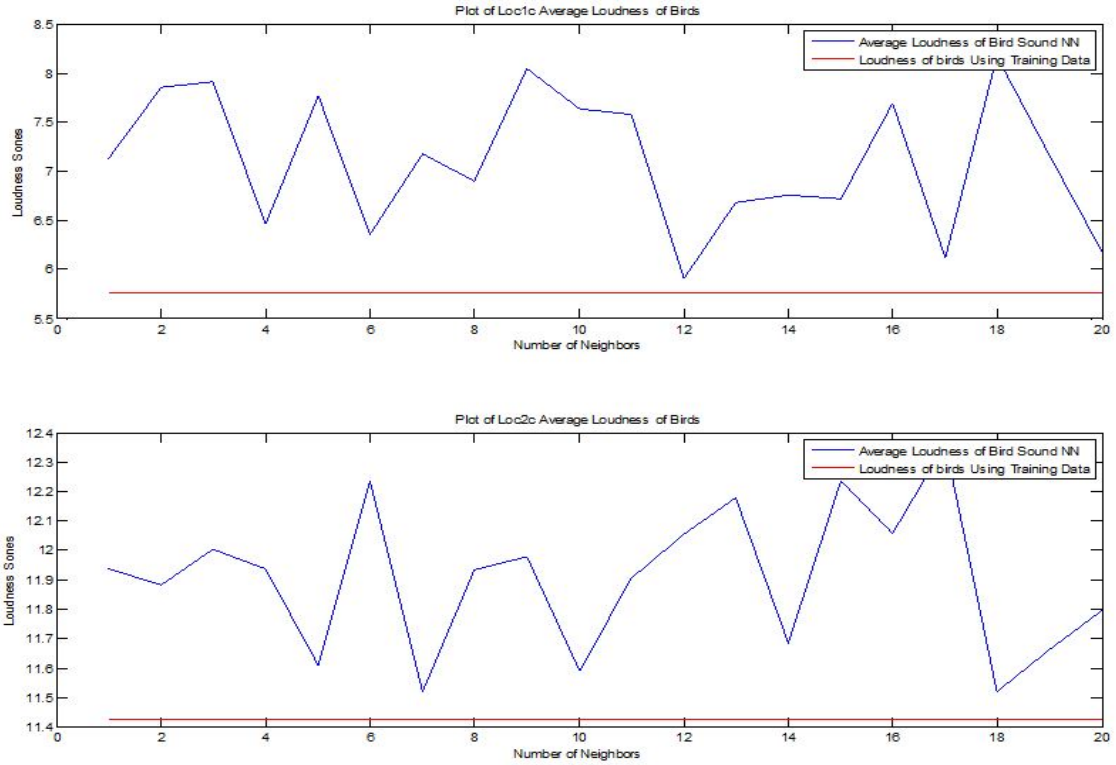


Fig. 3.17. The loudness of the removed sounds using 100 training points from each dataset

$$Phon = 40 + 10 * log2(Sone) ifSoneisgreaterthanorequalto1 \tag{3.3}$$

For the ANSI S34 2007 standard a table of values is given and values in between the given values are calculated using linear interpolated. These functions are important and allow a loudness level to be mapped to direct measure of loudness. However there still other areas that need to be addressed, if we hope to calculate loudness analytically without using a human to test the sounds.

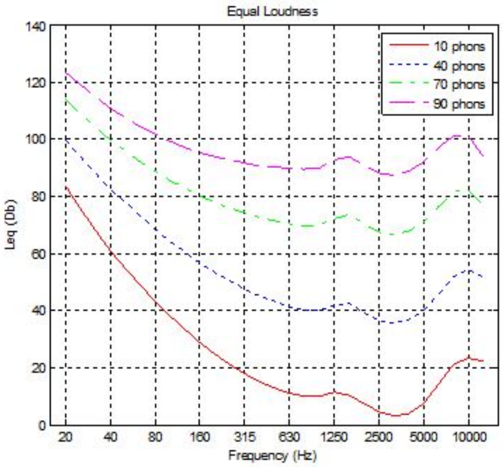


Fig. 3.18. Equal Loudness Contours

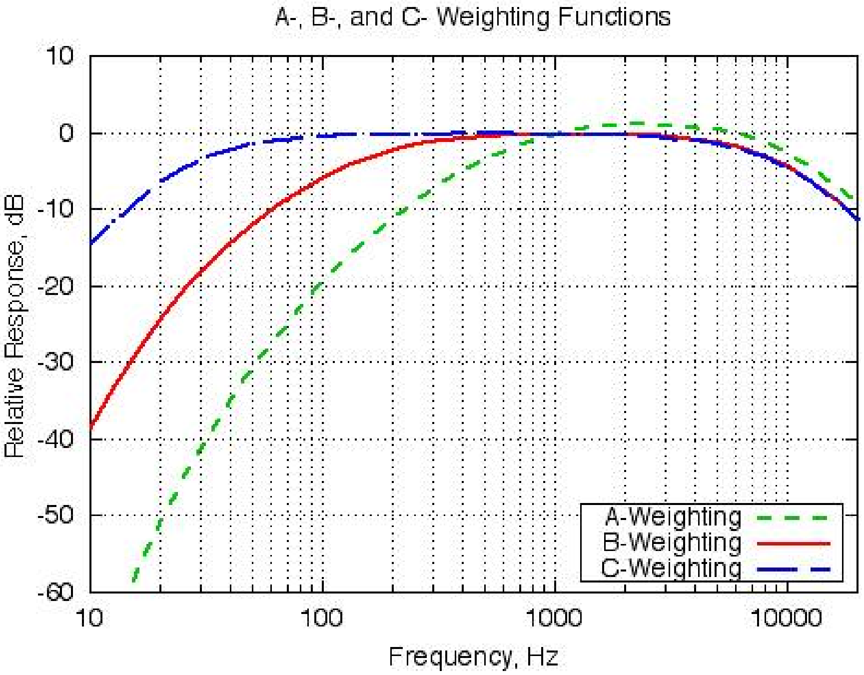


Fig. 3.19. A and C weight Functions [37]

Critical Band Analysis

The frequency distribution has a great effect on how the loudness is perceived. A sound is heard because different areas of the basilar membrane vibrate. Each of

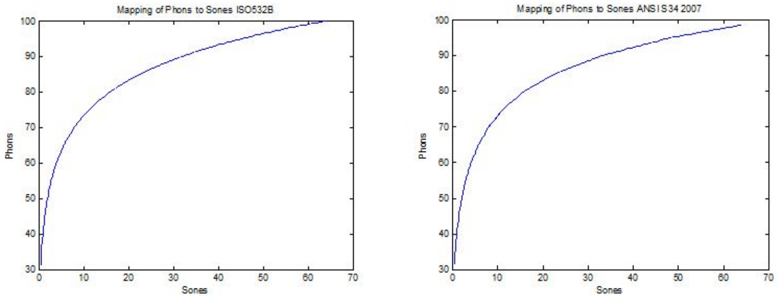


Fig. 3.20. Loudness mapping Sones to Phons both of these methods are very similar, especially in the range of traffic noise. For ISO523B the mapping is performed

these separate regions responds to a certain frequency range. In this way the ear interprets sound like a filterbank, breaking down a sound by frequency regions [36]. The loudness associated with a specific critical band is called specific loudness. There are two common critical band filterbanks Equivalent Rectangular Bands (ERB) and Critical Bands (Barks).

Models for Steady State Loudness Calculation

One common method for calculating loudness is published in ISO523B, Fig. 3.21. This standard compensates for a change in frequency response as a function of level and the filterbank characteristic of the human hearing system. An implementation of this standard uses 1/3 octave band data to calculate specific and total loudness [38]. The programs maps the 1/3 octave bands to critical bands or Barks. When the program is mapping the 1/3 octave band to Barks it also compensates for 1/3 octave bands that are in the same critical band. The program also accounts for spectral masking. Moore et al. have a method for calculating loudness similar to that of Zwicker with a few differences [40]. The first difference with these is that Zwicker and Moore use different filters to simulate the transfer of sound through the outer and middle ear. Another difference between the two models is that Moore uses equivalent rectangular bands (ERB) rather than critical bands (Barks). Finally Zwicker and Moore have a different method for calculating the excitation pattern. Zwicker makes uses a masking for each tone. Moore on the other hand has modeled excitation pattern by calculating the output of the auditory filters centered on the frequencies composing the sound.

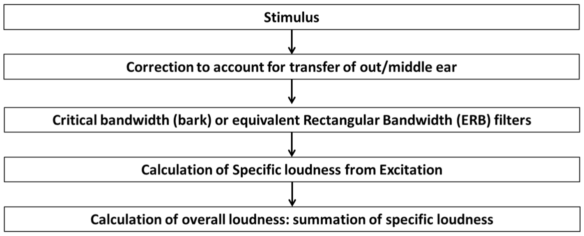


Fig. 3.21. Model for loudness

Dynamic Loudness Calculation

The Zwicker Dynamic Model is a method to calculate the loudness for sounds that are continuously varying. This model is similar to the equal loudness but it accounts for the temporal characteristics of loudness. See Fig. 3.21. It does this with both a postmasking filter and a upward spread masking filter

3.4.2 Sharpness

Sharpness is a sensation sound quality characteristic that is caused by high frequency sound [13]. Sharpness is a sensation independent from total sound pressure level. The spectral envelope has little effect on sharpness, however the spectral content does greatly influence this calculation because this metric quantifies how much of a sound is made up of high frequency components. It is used to calculate annoyance and pleasantness models create by Zwicker.

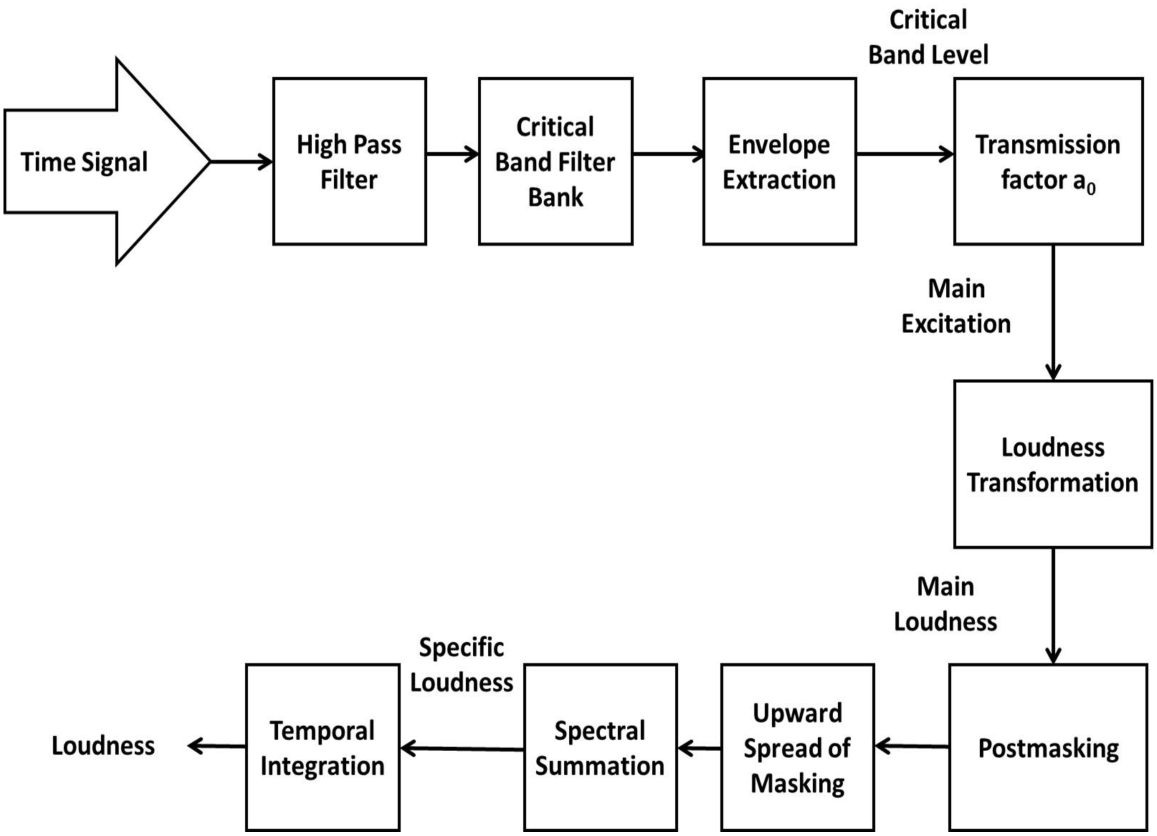


Fig. 3.22. Dynamic Loudness Model (DLM)

3.4.3 Roughness

Roughness is a sensation caused by the fluctuation of sound in the 15Hz to 300Hz range. Roughness for a single tone amplitude modulated is maximized when a 1kHz tone is modulated at 70Hz. The unit to describe roughness is asper. In order to standardize roughness, 1 asper is defined by a 1kHz tone 100 percent modulated by a 70Hz tone with a sound intensity of 60dB. In order to characterize this sensation Zwicker used juries to see how changing parameters of synthetic sounds affected the perception of roughness [13].

The degree of modulation obviously affects the perception. When Zwicker plotted the subject data vs. the degree of modulation he found that it was related by the

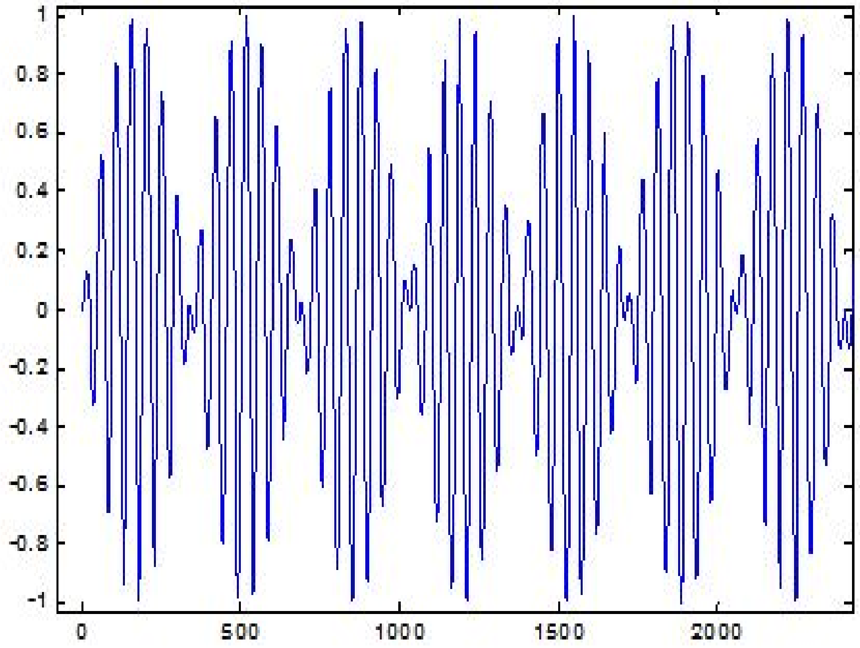


Fig. 3.23. Amplitude modulated signal

power law with an exponential of 1.6. If a 1kHz tone is modulated 25 percent then it produces a roughness of 0.1, or a sensation that many subjects described as no longer rough. In another graph Zwicker describes the affect of modulation frequency and carrier on roughness. The 1kHz carrier is maximized at a modulation frequency of 70Hz and decreases steadily at higher and lower modulation frequencies. Higher carrier frequencies have the same pattern but are less rough throughout. Lower frequencies follow a similar pattern too but as the frequency of the carrier frequency gets lower the modulation frequency at which the roughness is maximized also gets lower. To get a model for roughness Zwicker concludes that roughness is proportion to the modulation frequency times the depth of modulation. To be more precise

Zwicker noted that the modulation depth L is dependent on the critical band so a more comprehensive form.

$$R = 0.3\frac{fmod}{khz}\int_0^{24}\frac{\Delta L_E}{dB/Bark} \tag{3.4}$$

Fmod is the modulation frequency and LE is the modulation depth for each critical band excitation level. The factor of 0.3 is to make the data conform to the standard scale. This model is important because it clearly calculates roughness for amplitude modulated sounds. However this model does not provide methods for calculating frequency modulated tones because no L value is present for such signals. This method is implemented in [15]. In this thesis sewing machines are being analyzed so the signals are stationary, therefore it is possible to make to find fmod manually for each test. LE was calculated by dividing the max specific loudness by the min specific loudness for each critical band. Another method proposed by Aures [41]. Aures method was implemented in matlab by [42]. In Aures method takes an excitation pattern, in the case of [42] ERB was used. Then an overlapping filterbank with offset of half a critical band and bandwidth of a critical band are used. Then each specific excitation is filtered with a bandpass filter equivalent to how much each frequency contributes to roughness. These filters are designed based on the graphs made by Zwicker and vary based on how modulation frequencies contribute to roughness in each critical band. In this way the separate contribution of each critical can be added together.

The cross correlation of the filtered signal are then taken. This is done because roughness in adjacent bands causes an overestimation of the total roughness, especially for broadband sound. Next the modulation depth is estimated. To estimate the modulation depth, the magnitude of the filtered signal is divided by the average excitation pattern. Finally the modulation depth is multiplied by the correlation factor and g(zi) which is a function that adjust the specific roughness of each critical band. Other methods for extracting roughness have been proposed, these are generally used for analysis of music. In [43] Pressnitzer performs a roughness calculation similar to Aures, without processing the each critical band channel separately. Another method

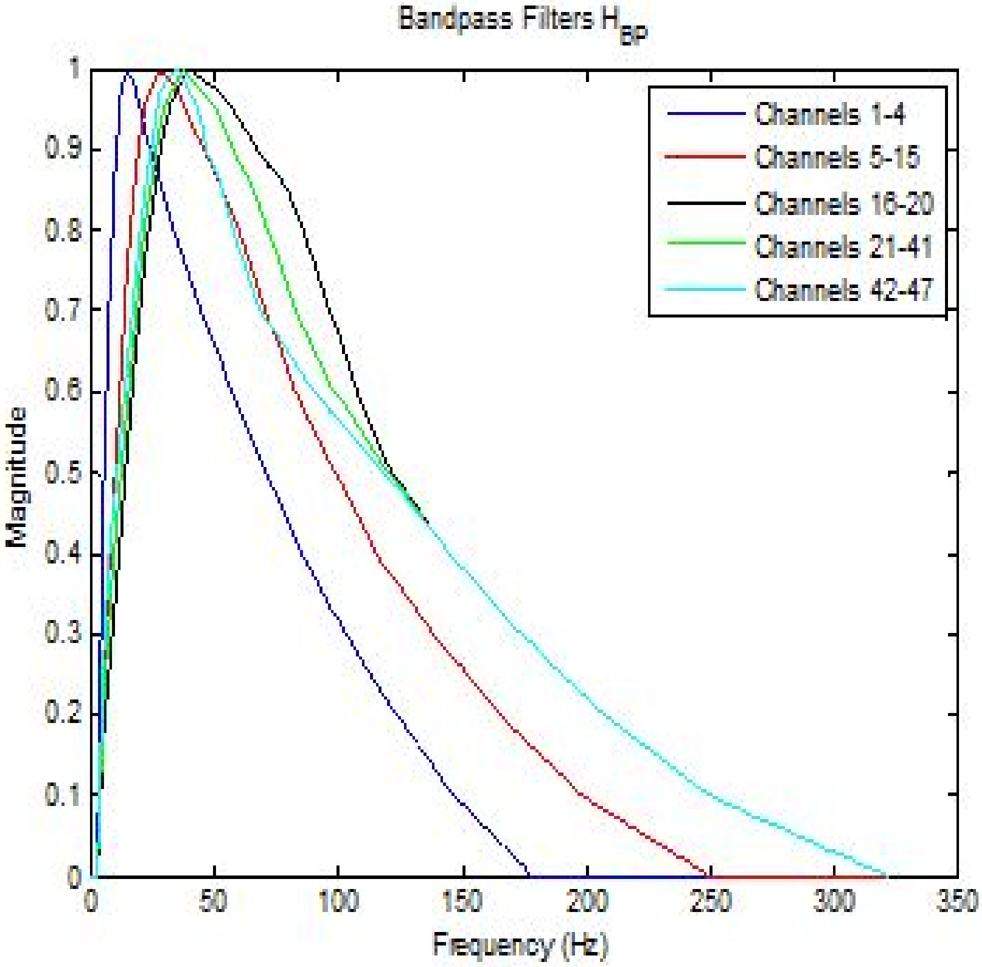


Fig. 3.24. Filters used for each critical band filter

for roughness calculation is called Spectral and Roughness Analysis of Sound Signals (SRA) [44–46].

$$R = (A_{min} * A_{max})^{0.1} * 0.5(Y^{3.11}) * Z \tag{3.5}$$

Where Amin and Amax are the minimum and maximum amplitudes of frequency components respectively.

$$Y = 2A_{min}/(A_{min} + A_{max}) \tag{3.6}$$

Where fmax and fmin are the maximum and minimum frequency respectively. Spectral analysis in SRA uses an improved Short-Time Fourier Transform (STFT) algorithm that is optimized for this application.

3.4.4 Review of Fluctuation Strength

Fluctuation strength is a sensation similar to roughness as in it is caused by a variation of sound, but the range of variation for fluctuation strength is 2 to 30Hz. Fluctuation strength and roughness having a similar description and overlapping range. The transition from roughness and fluctuation strength is not a black and white one; a sound can stimulate both of these sensations. The equation for fluctuation strength is described in [13]:

$$F = \frac{0.008 \int_0^{24} (\Delta L/dBBark) dz}{(fmod/4Hz) + (4Hz/fmod)} \tag{3.7}$$

Here, is the modulation depth of each critical band and fmod is the modulation frequency. The units for this measure is vacil and the 0.008 is in this equation to normalize the measurement. This method is good for describing synthetic sounds, but when L is not supplied, in the case fm modulated sound, this model will be inadequate for calculating. This method would also be very difficult to implement for sounds that are varying. Fastl said that methods using specific loudness can be used similar to Aures roughness [41, 47].

3.4.5 Review of Psychoacoustic Annoyance

Psychoacoustic Annoyance is a method to combine several different sound quality metrics to get a single value that describes a sound. In [13] Zwicker based this formula off quantitative experiments evaluating many different sounds. This method was also show to work very well in predicting the annoyance of car sounds in a survey.

$$PA = N_5(1 + \sqrt{w_S^2 + w_{FR}^2}) \tag{3.8}$$

Where N5 is the 5th percentile loudness and

$$ws = (\frac{S}{acum} - 1.75) * 0.25lg(\frac{N_5}{sone}) + 10 \tag{3.9}$$

$$w_{FR} = \frac{2.18}{(N_5/sone)^2}(0.4 * F + 0.6 * R) \tag{3.10}$$

where S is sharpness S greater than 1.75 acum where F is fluctuation strength and R is roughness

3.5 Models Used

3.5.1 Sharpness

To calculate sharpness the specific loudness is used. The unit of sharpness is acum, 1 acum is a narrow-band noise one critical-band wide centered at 1kHz with a level of 60dB.

$$S = 0.11\frac{\int_0^{24} N'g(z)zdz}{\int_0^{24} N'dz} \tag{3.11}$$

Where N is the specific loudness.

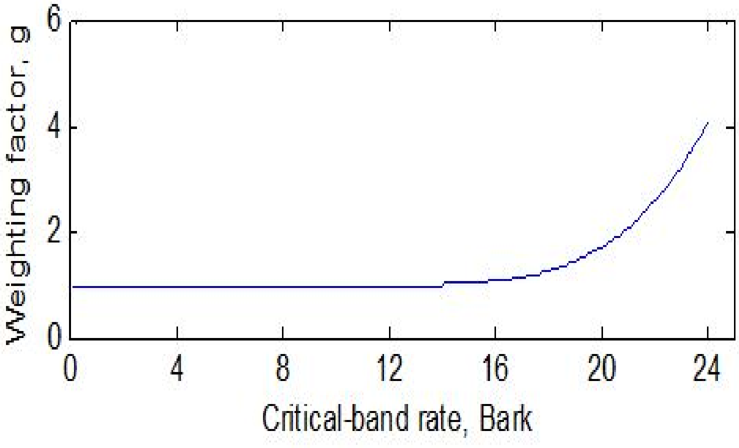


Fig. 3.25. G(Z) used in calculation of sharpness

For sharpness the method above was used. The results were calculated every 100ms with the specific loudness obtained from the loudness calculation. To normalize sharpness the following method is performed. First a reference correction value was calculated. This value is a ratio that corrects for the difference of the highway noise in the before and after tests.

$$SRefC = SAref/SBref \tag{3.12}$$

SRefC is sharpness reference correction, SAref is sharpness of a location after the wall is built, and SBref is sharpness at the reference before the wall. Next, the sharpness wall reduction is calculated. This is done by taking the ratio of the sharpness of the before construction of the soundwall measurement and dividing by the after construction of the soundwall measurement. This value is then multiplied by the sharpness reference correction.

$$SWR = SRefC * SBloc/SAloc \tag{3.13}$$

SWR is sharpness wall reduction, SAloc is the observed sharpness after the wall, SBloc is the observed sharpness before the wall.

3.5.2 Loudness

Methods for calculated loudness were discussed in a previous section. ISO523B is one technique that generally applied to stationary sound[28]. However, if ISO523B loudness is calculated numerous time this method can offer insight into the varying nature of traffic noise without the overly computational heavy requirements of the dynamic loudness models. This assumption is valid because even though highway noise varies, the nature of these variations is generally not rapid or extremely drastic. By heuristically evaluating the wav files it was noticed that a single vehicle influenced the loudness of the recording for about one to ten seconds. We calculated loudness every 100ms to make sure the influence of multiple cars entering or leaving the soundscape is accounted for in an accurate fashion. To use loudness the data needs to be normalized to account for random variations in the traffic noise. Because loudness is a direct comparison of how a sound is perceived, a ratio is used to describe the division between the reference and the location data. In this way, this model is similar to that of insertion loss. NRefC= NAref/NBref NRefC is loudness reference correction, NAref is loudness of a location after the wall is built, and NBref is loudness at the reference before the wall. NWR=NRefC*NBloc/NAloc NWR is Loudness wall reduction, NAloc is the observed loudness after the wall, NBloc is the observed loudness before the wall.

3.5.3 Roughness

The model of roughness we will use is Daniels optimized Aures method [47]. This model was implemented in the PsySound3 software package. Like Aures method Daniels method uses the bark scale. Rather than directly filtering the excitation to get specific excitation a different method is used. Daniels uses an adaptive filter that compensates for the location and magnitude of each frequency component. Similar to the method used by Moore to calculate loudness. The only other difference in Daniels method is a squared cross correlation factor.

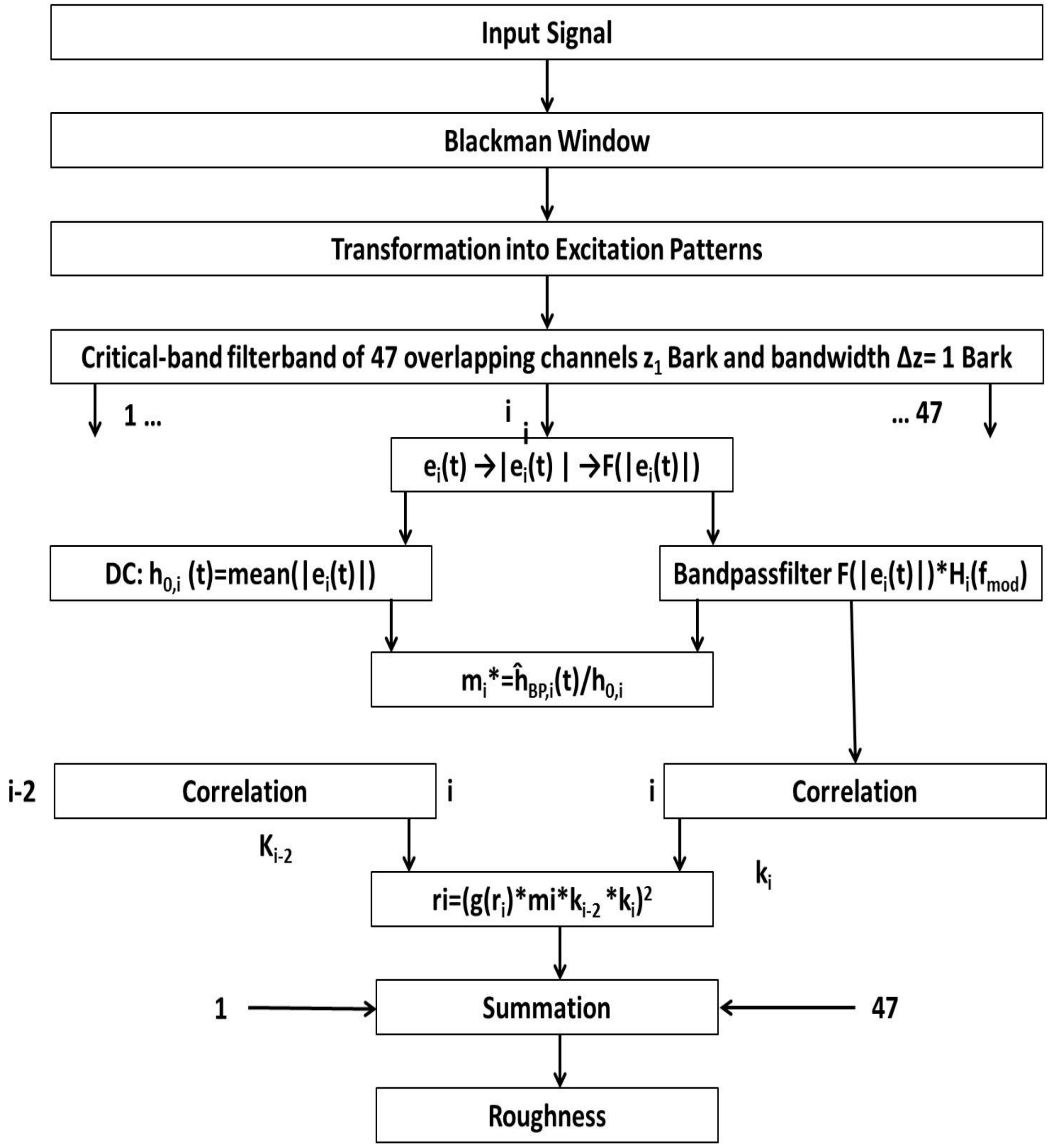


Fig. 3.26. Diagram of roughness model

To normalize roughness the following method is performed:

$$RRefC = RAref/RBref \tag{3.14}$$

RRefC is roughness reference correction, RAref is roughness of a location after the wall is built, and RBref is roughness at the reference before the wall.

$$RWR = RRefC * RBloc/RAloc \tag{3.15}$$

RWR is roughness wall reduction, RAloc is the observed roughness after the wall, RBloc is the observed roughness before the wall.

3.5.4 Fluctuation Strength

Fluctuation strength is sensation like roughness [47]; the difference between roughness and fluctuation strength is the modulation frequency. Do to the fact that roughness and fluctuation strength are similar, an adaptation of the roughness model was used to find the fluctuation strength. In roughness the different modulation frequencies are extracted by using different HBPi that are tuned for each critical band channel. By changing these filters to accommodate the range of fluctuation strength this model will provide fluctuation strength. To design these filter the figures in Fastl's book will be used. The graph in Fastl's book of modulation frequency vs. relative fluctuation strength is the one that will be used. This graph shows how different frequencies of modulation effect how people perceive the fluctuation strength of a sound. Fastl provided three different graphs in this section, one for am broad band noise, one for am tone and one for fm tone. Since traffic noise is broad band, the am broad band noise plot will be used. In the roughness model there were several different ıHBPi for different ranges of critical bands, but Fastl says that fluctuation strength is less dependent on carrier frequency in terms of am modulation. Therefore our model will only have one ıHBPi which will be used for all critical bands.

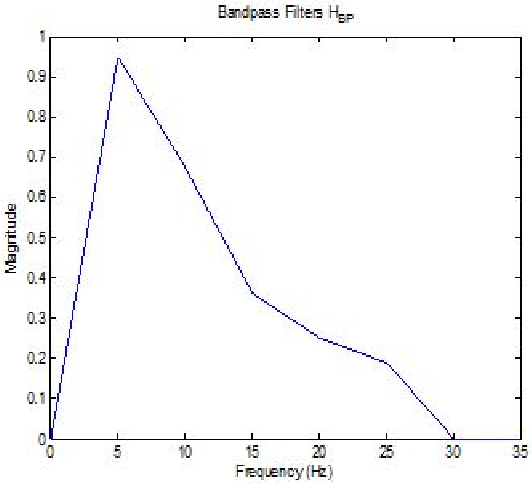


Fig. 3.27. Bandpassfilter used for fluctuation strength

This is the resulting HBP that will be used, that data had to be interpolated so that it lines up with the frequency domain samples. To normalize fluctuation strength method is performed as following

$$FSRefC = FSAref/FSBref \tag{3.16}$$

FSRefC is fluctuation strength reference correction, FSAref is fluctuation strength of a location after the wall is built, and FSBref is fluctuation strength at the reference before the wall.

$$FSWR = FSRefC * FSBloc/FSAloc \tag{3.17}$$

FSWR is fluctuation strength wall reduction FSAloc is the observed fluctuation strength after the wall, FSBloc is the observed fluctuation strength before the wall.

3.5.5 Annoyance

To calculate annoyance Zwicker's method will be used [47]. The average roughness, fluctuation strength, and sharpness is used, the N5 is also calculated from loudness(it is the fifth percentile loudness). For the after condition the normal values will be used. But to get a fair comparison the normalized before values will be used. Each of the respective metrics will be normalized in the following method:

$$PA = N_5(1 + \sqrt{w_S^2 + w_{FR}^2}) \tag{3.18}$$

Where N5 is the 5th percentile loudness and

$$ws = (\frac{S}{acum} - 1.75) * 0.25lg(\frac{N_5}{sone}) + 10 \tag{3.19}$$

$$w_{FR} = \frac{2.18}{(N_5/sone)^2}(0.4 * F + 0.6 * R) \tag{3.20}$$

where S is sharpness S greater than 1.75 acum where F is fluctuation strength and R is roughness

4. DATA AND ANALYSIS

This section has the data and analysis of the data that was collected. Data was collected at residential locations that are near a highway. These locations were chosen because at these locations a sound is going to be constructed. The data is a sound recording collected using a sound level meter. The length of the recording is 15 minutes.

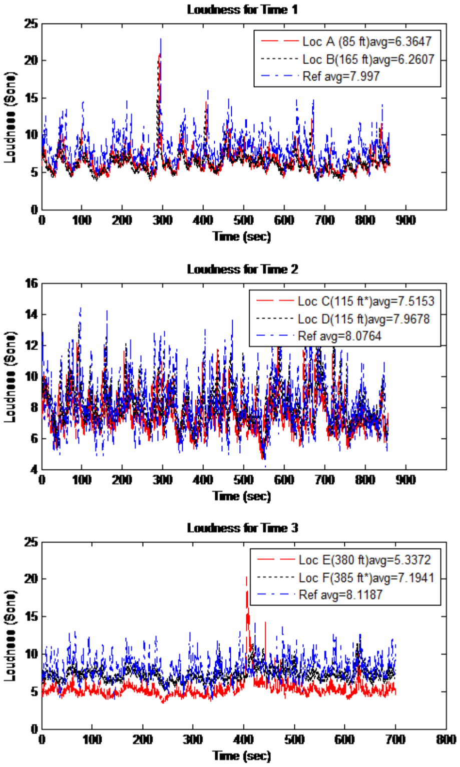


Fig. 4.1. Loudness data from times 1, 2, and 3

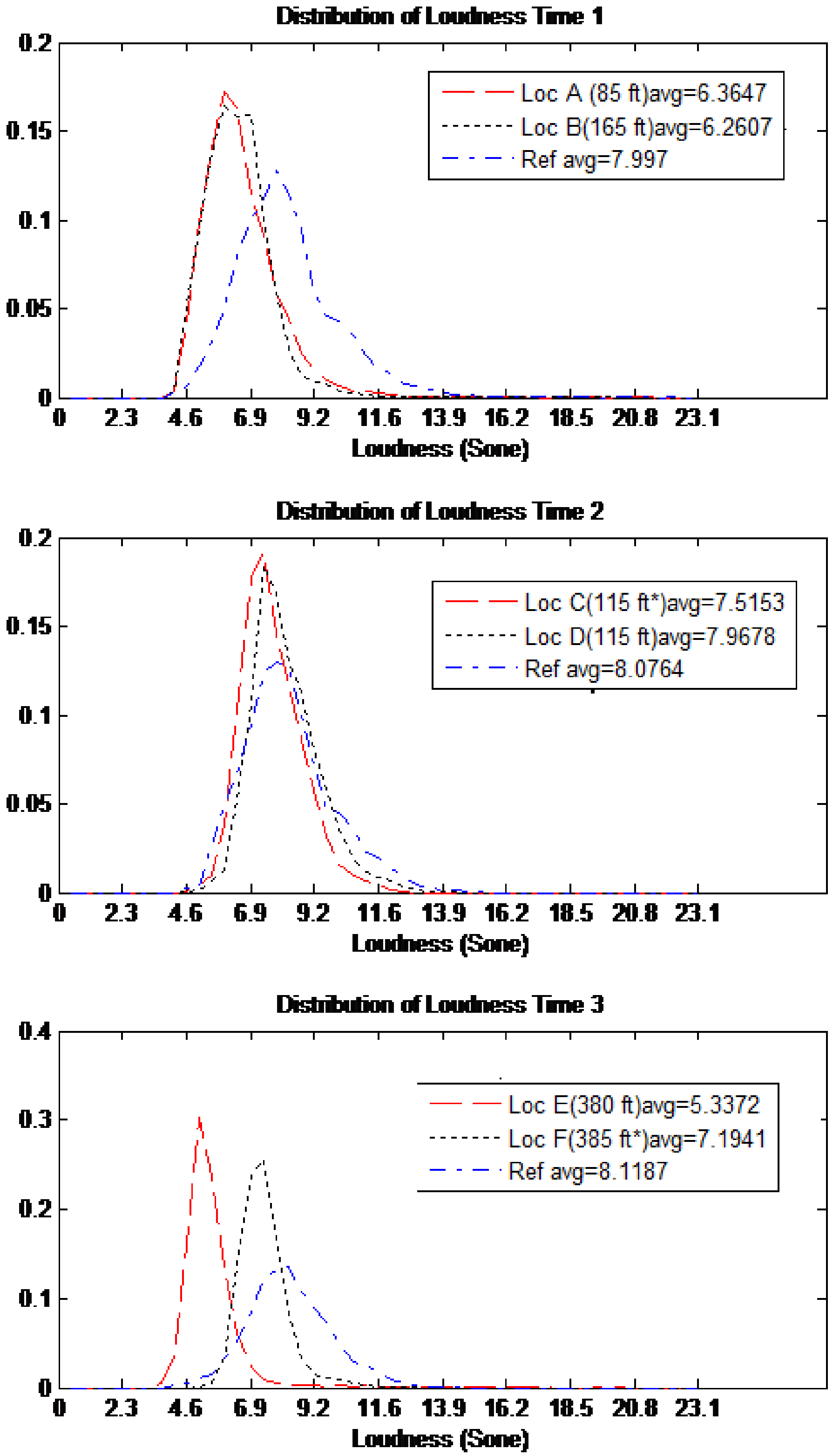


Fig. 4.2. Loudness distribution data from times 1, 2, and 3

Fig. 4.1 A) shows that at a close distance, there is only a slight difference in loudness in the two measurements, the closer measure experienced a slightly louder sound. The distributions show that the majority of the energy is in the same range, however the closer measurement point has more data in higher loudness. For the second time, the loudness between data had line of sight and a location where the view was obscured by bushes was compared. The data in Fig. 4.1 B) shows that the measure from behind the bush attenuated the loudness slightly. The distributions of the two locations have similar but slightly offset distributions. In the third time measuring the data, another comparison was made between data at the same distance from the road, but a different location along the road. This time the data shown in Fig. 4.1 C). This time the location with the line of sight obscured experienced more loudness. The distribution of this sound seen in Fig. 4.1 C) shows that location E has a more data than most of the distributions located in the range of 4.6 Sones.

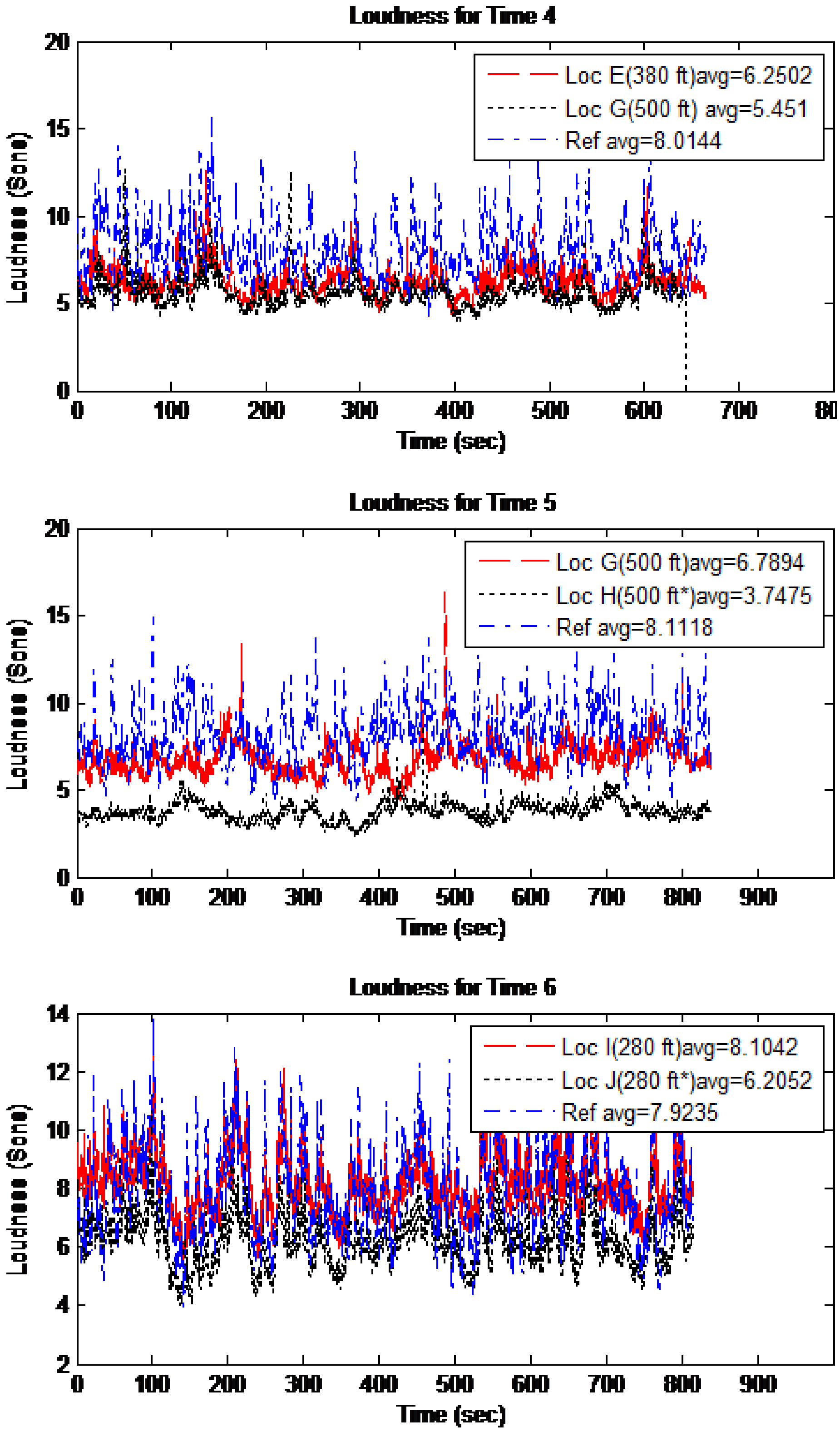


Fig. 4.3. Loudness data from times 4, 5, and 6

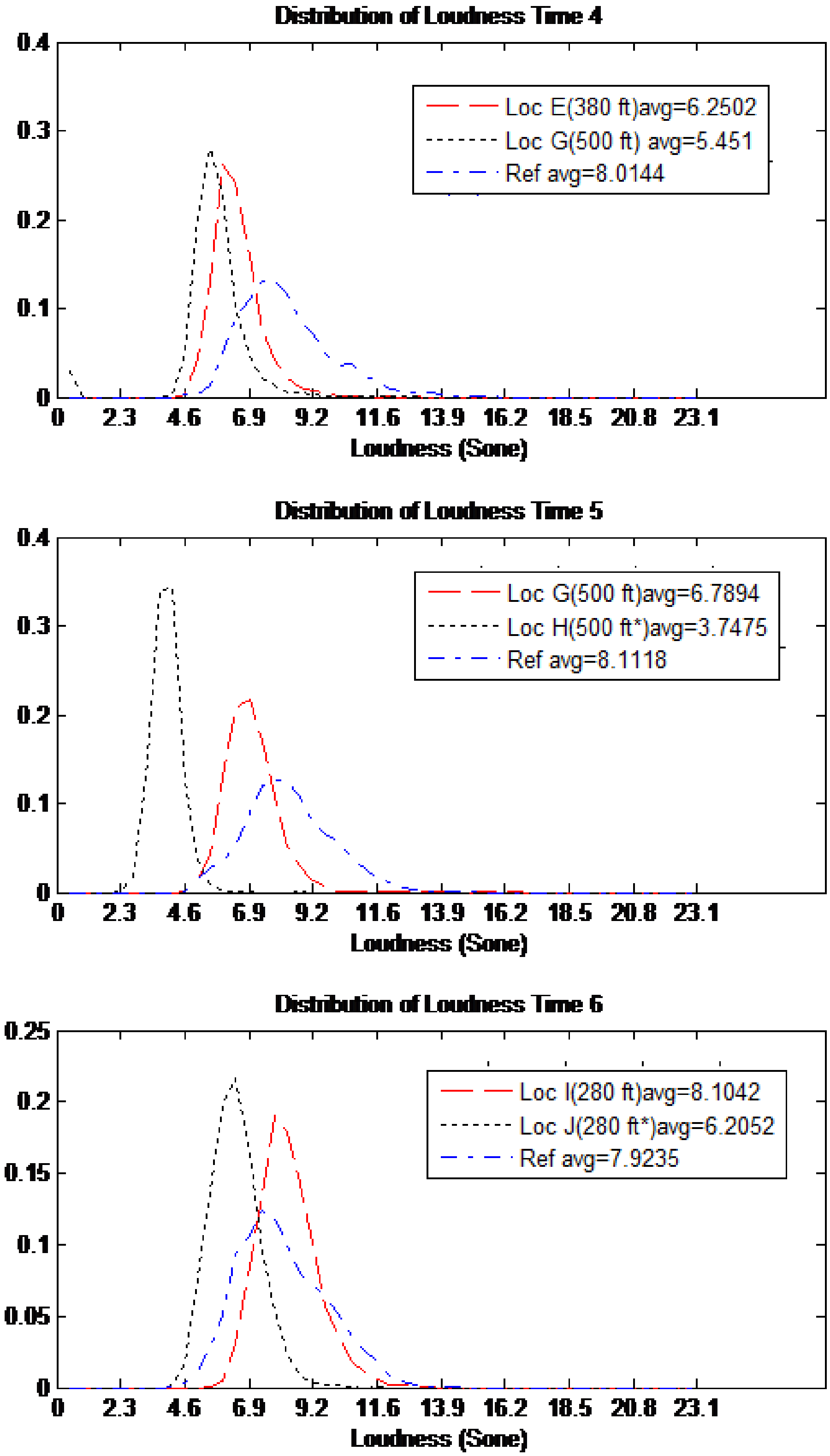


Fig. 4.4. Loudness distribution data from times 4, 5, and 6

The forth time of data collect was collected at two locations at different locations from the road, Fig. 4.3 A). This data was taken further away than previous comparisons made at time 1. The attenuation experienced at this distance was far greater than the first time. The distributions of this time show similarly distributed, but shifted centers, Fig. 4.3 A).

The data collected at the fifth time compares data taken at the same distance from the road, but at different locations Fig. 4.3 B). One of these locations was close to a house and it did not have a line of sight due to a houses and vegetation. In this experiment the location that did not have line sight to the road was almost half as loud.

At the sixth time the data collected was two locations similar distances from the road Fig. 4.1. Once again the location were the there was no line of sight less loudness was experienced. The reference data for all locations roughly followed a similar distribution Fig. 4.2 and Fig. 4.4. The data is has a mean around 8 Sones and that is where most of the energy in the distribution is located. All the loudness of the reference data then roughly fits into a bell like shape, except for extra energy around 10 Sones.

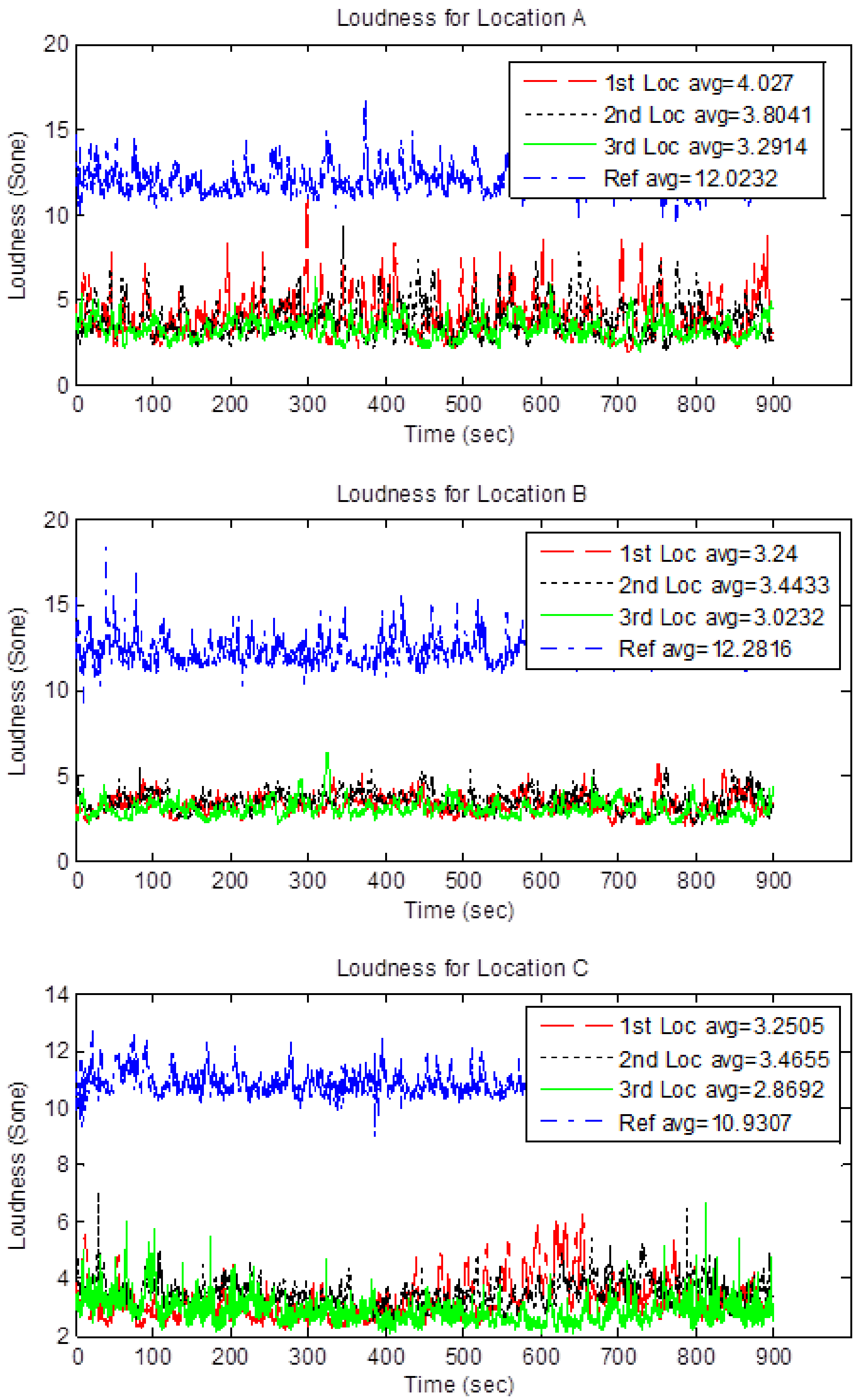


Fig. 4.5. Loudness data from test locations

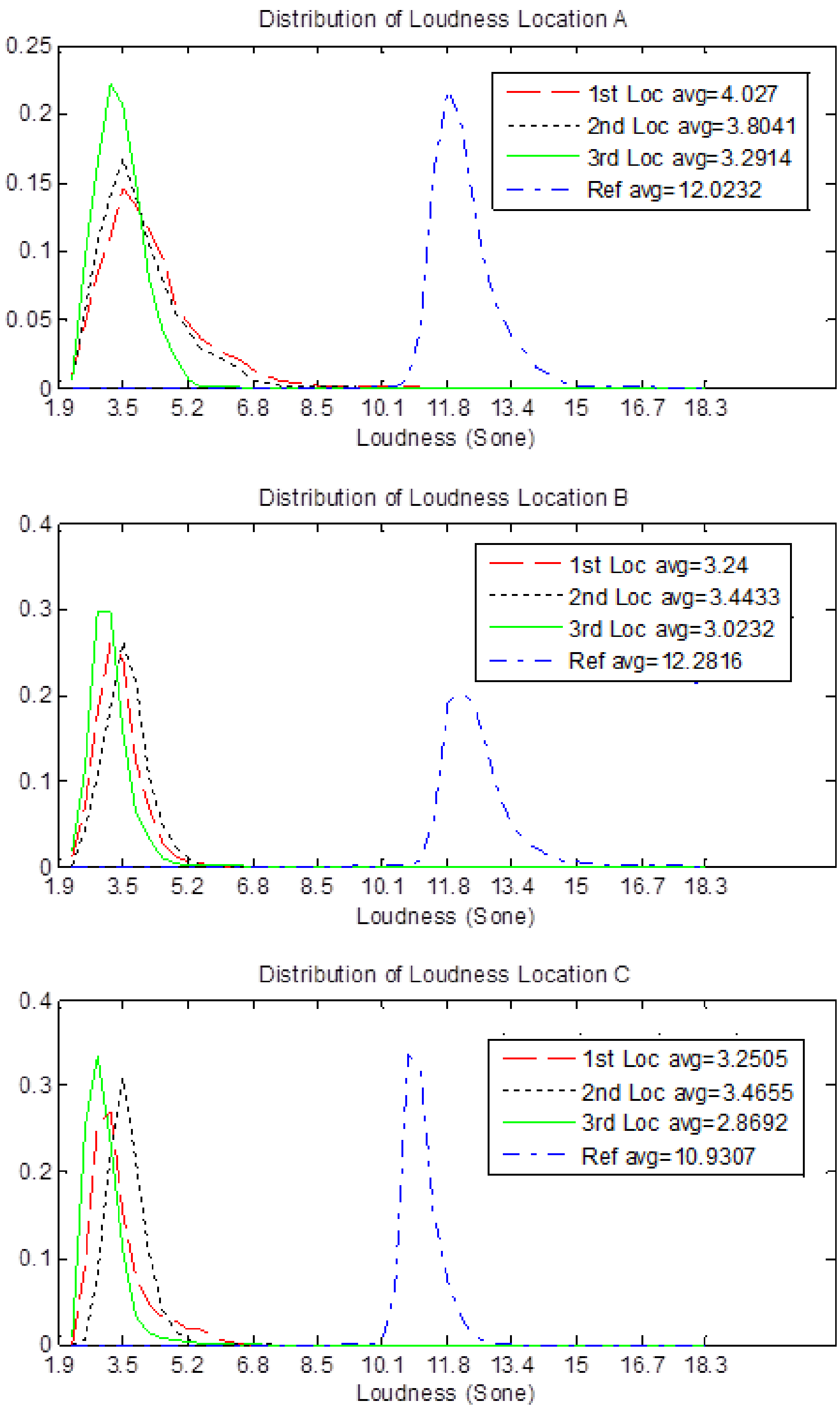


Fig. 4.6. Loudness distribution data test locations

The loudness at the test sites Location A Fig. 4.5 and Fig. 4.6 show a decrease in loudness at the locations further away from the highway. The distribution show that the furthest distance is particularly skewed to the less loud end. This is because there is no wall at this location and therefore distance is the only factor that effects the loudness experienced.

The second location Location B the first location is particularly less loud than the section location while the third location is the least loud of any of the three test locations. This is caused because the first location is very close to the wall and attenualted the sound greatly, while the second location benefited less from the soundwall. The third location was far enough aways that the loudness was attenuated by the distance.

For location C a similar pattern was observed. The first location experienced less loudness than the second but the third location was least loud. This again is because the soundwall's effectiveness is reduced as the distance from the wall is increased, but moving away from the wall causes attenuation.

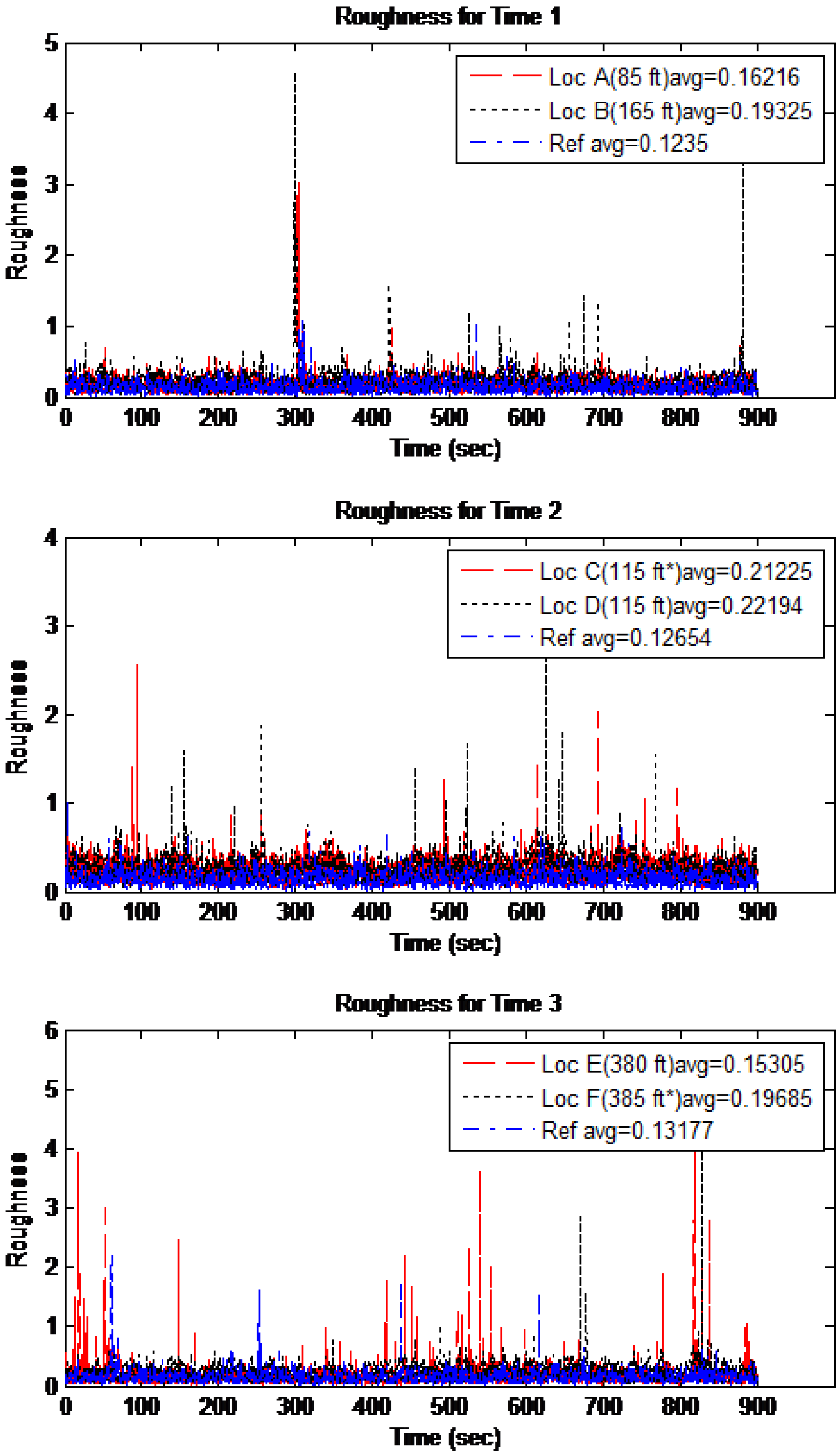


Fig. 4.7. Roughness data from times 1, 2, and 3

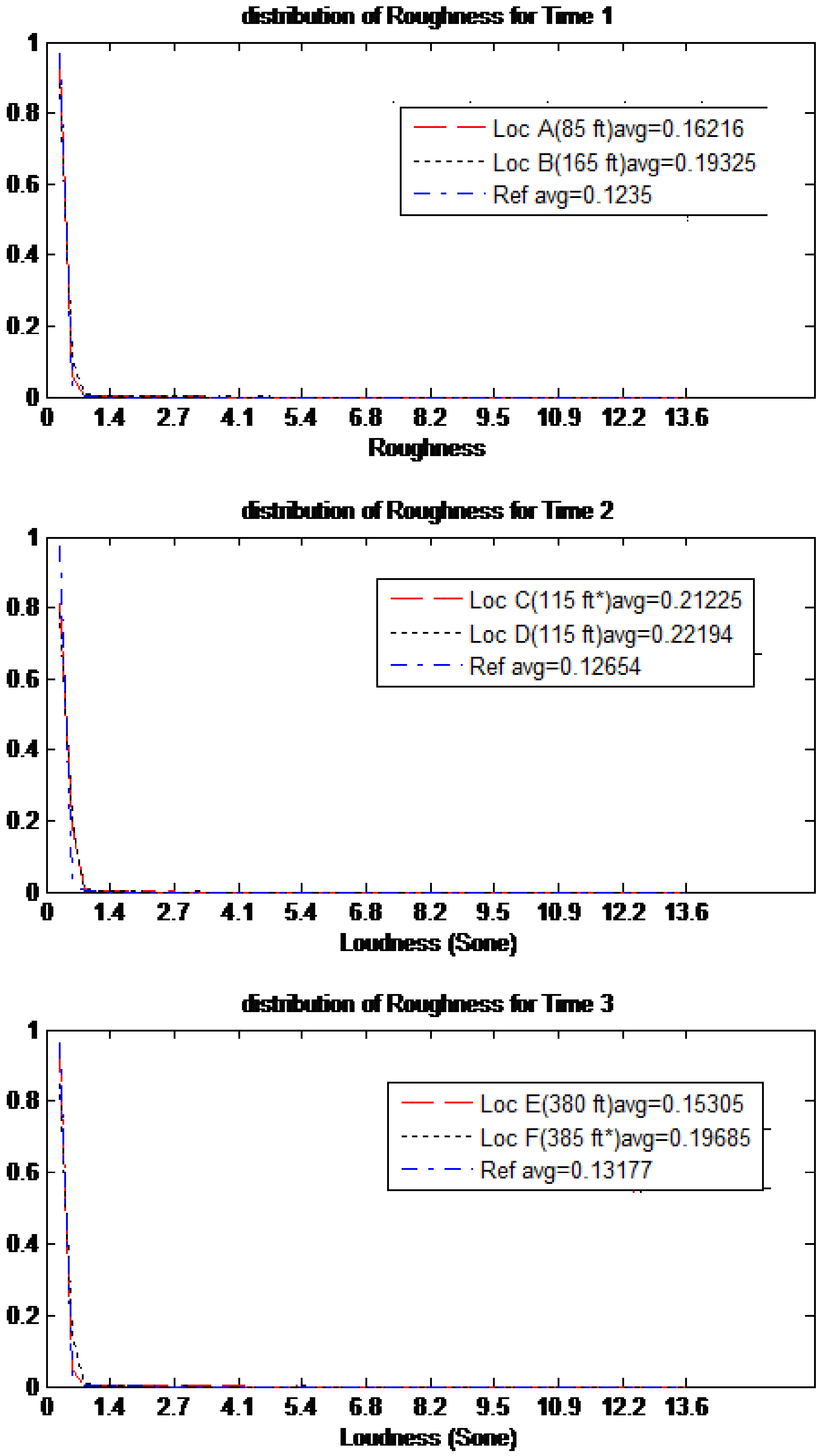


Fig. 4.8. Roughness distribution data from times 1, 2, and 3

For the first time of data collection an interesting pattern emerged Fig. 4.7 and Fig. 4.8. The reference experienced less roughness than either location and the closer distance experienced less roughness than the further distance. This suggests that fluctuation that causes roughness is less prevalent very close to the road.

The second time compares two different levels of obstruction. Location C (the site with the line of sight obstruction) experiences less roughness than location D. This suggest that obstructing the light of sight at this distance will no cause the roughness of the sound to be more prevalent, even though moving further away from the location can cause an increase in roughness.

The third time represents another location where one of the data collection locations has an obstructed line of sight. In this collection time the location with the obstructed view has a greater roughness. This time the obstructed location experienced more roughness. This is in line with the other metrics that also saw an increase in this location.

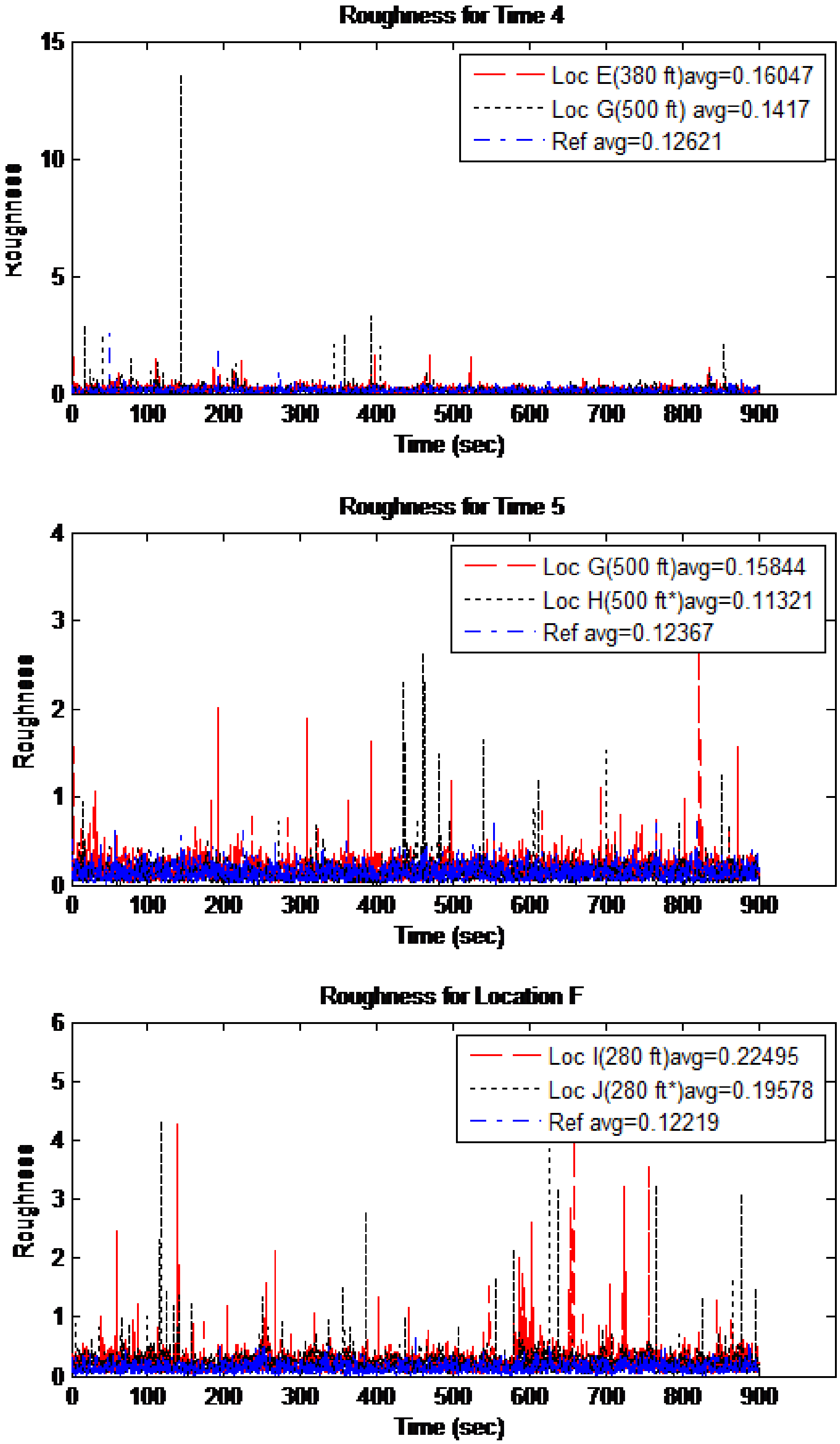


Fig. 4.9. Roughness data from times 4, 5, and 6

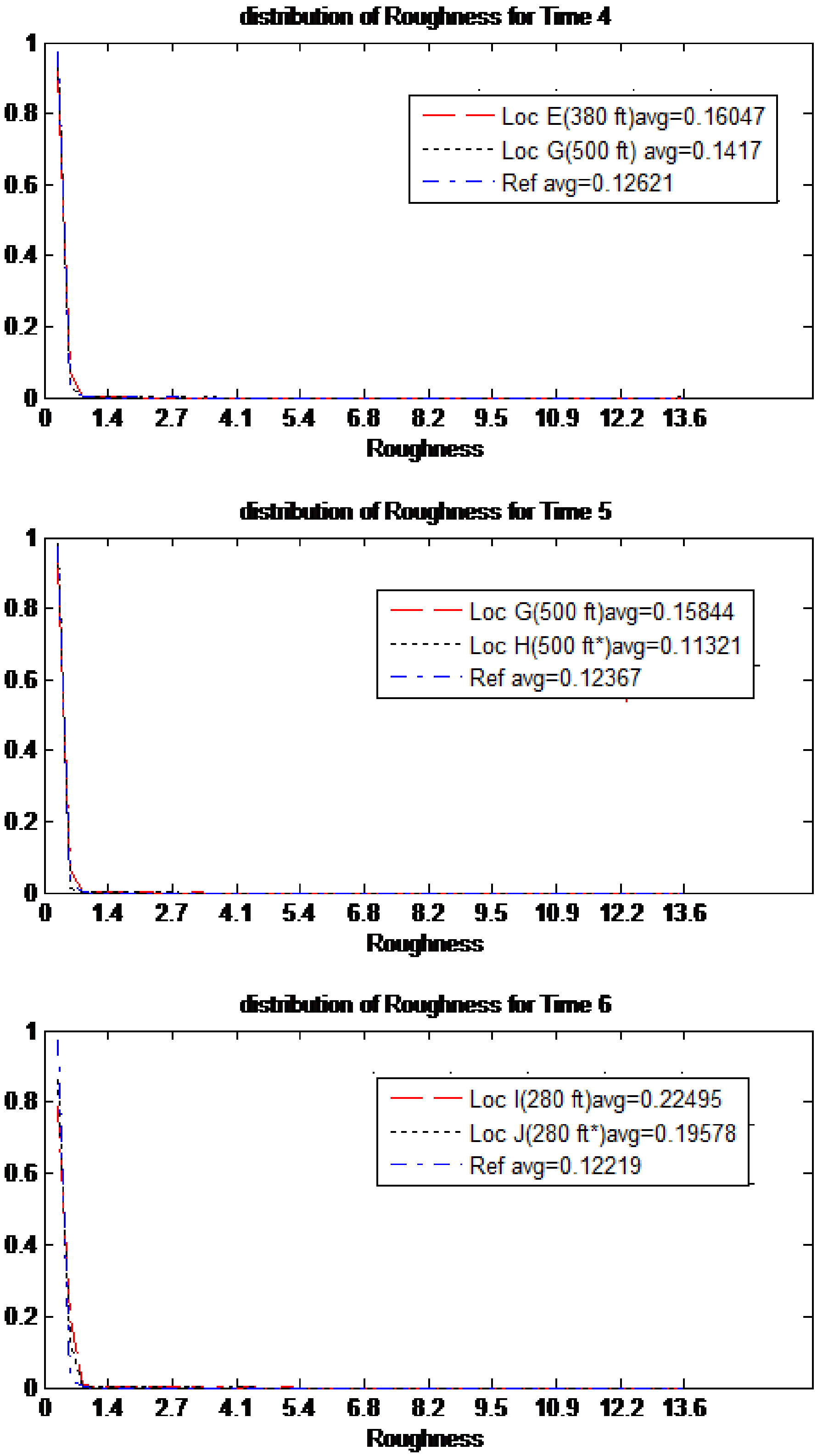


Fig. 4.10. Roughness distribution data from times 4, 5, and 6

The fourth time show a location where the two different distance are compared in Fig. 4.9, and Fig. 4.10. In this experiment the distance from the road is greater. At this distance the increase in distance from the road caused the roughness to decrease.

The fifth time of data collection showed that even at 500 feet from the road, roughness decrease when line of sight is obstructed.

The sixth time compares another distance where the line of sight is obstructed. At this distance the location with the line of sight obstruction experienced less roughness. This experiment showed that at a close location there is less roughness, this is because the sound is more constant. At slightly further distances more roughness is observed.

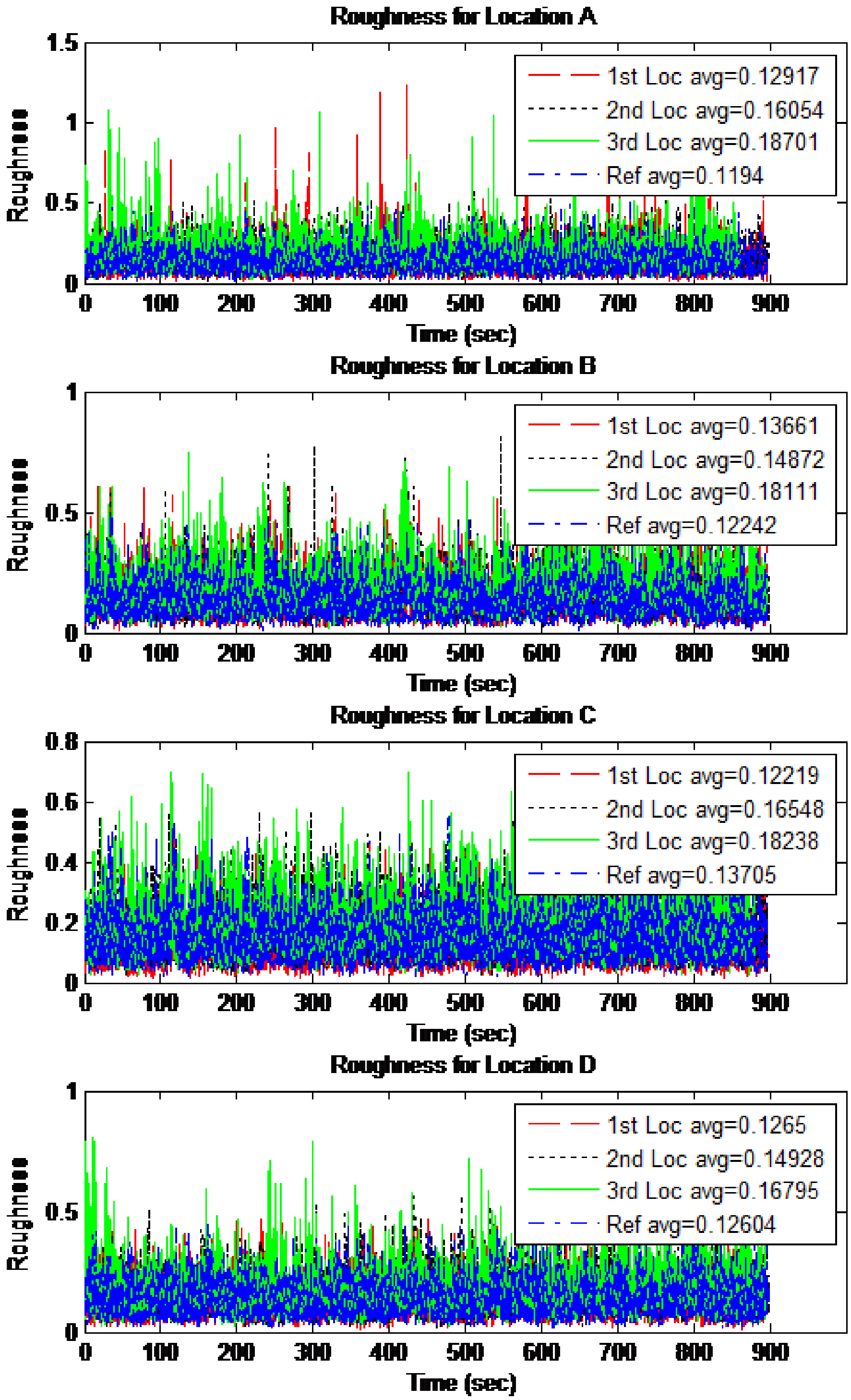


Fig. 4.11. Roughness data from test location

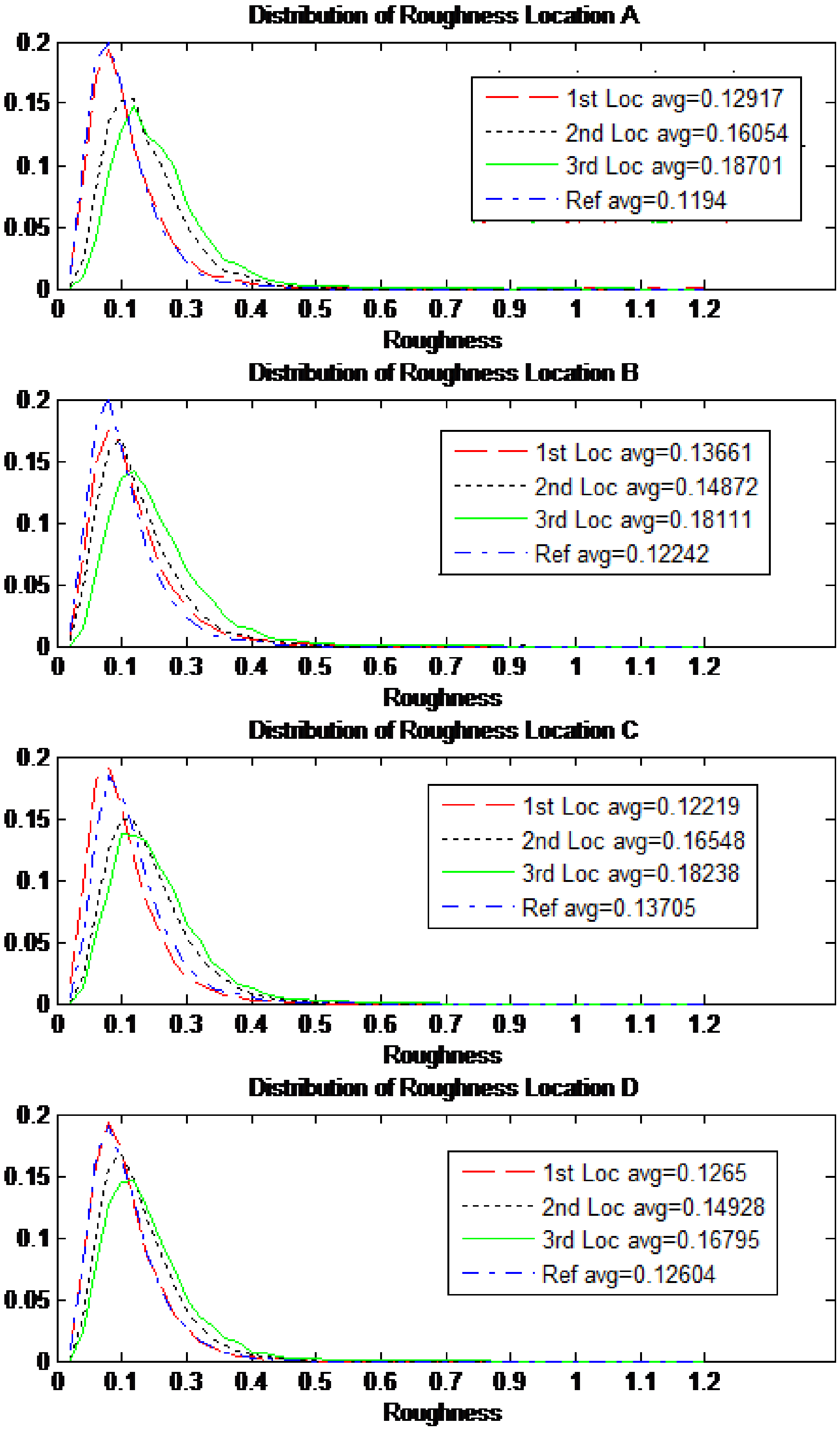


Fig. 4.12. Roughness distribution data from test location

The roughness data and distribution are shown in Fig. 4.11 and Fig. 4.12. The data from Location A shows that the roughness increasing as the distance from the road is increasing. This same pattern is experienced in the other experiments.

The roughness in Location B and Location C follow the same pattern as well, this is because at the close location the sound is dominated by a single source, but at further distance the combination of sound sources increases the roughness. The soundwall in Location B or Location C did not effect the roughness observed in a significant way.

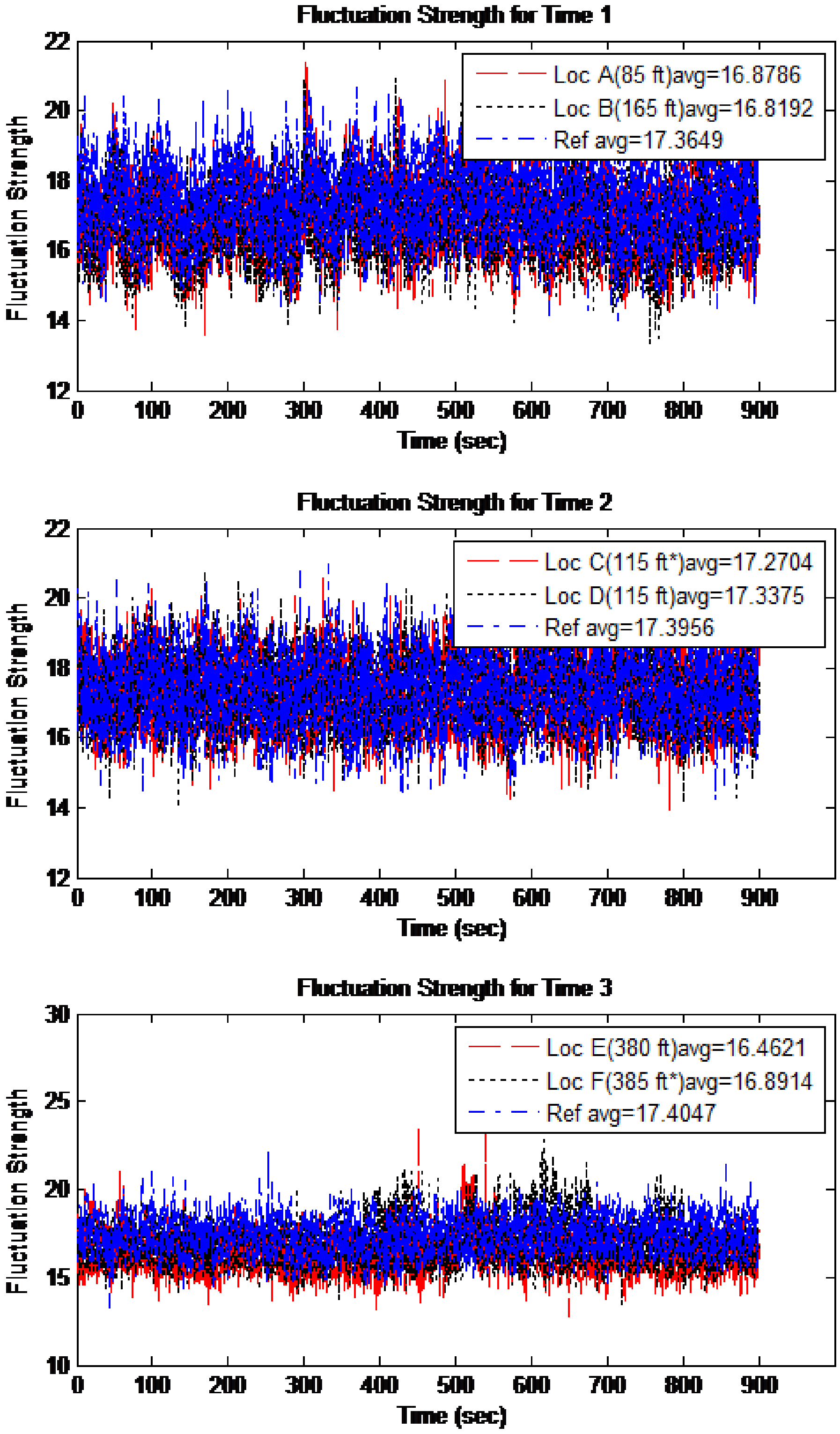


Fig. 4.13. Fluctuation strength data from times 1, 2, and 3

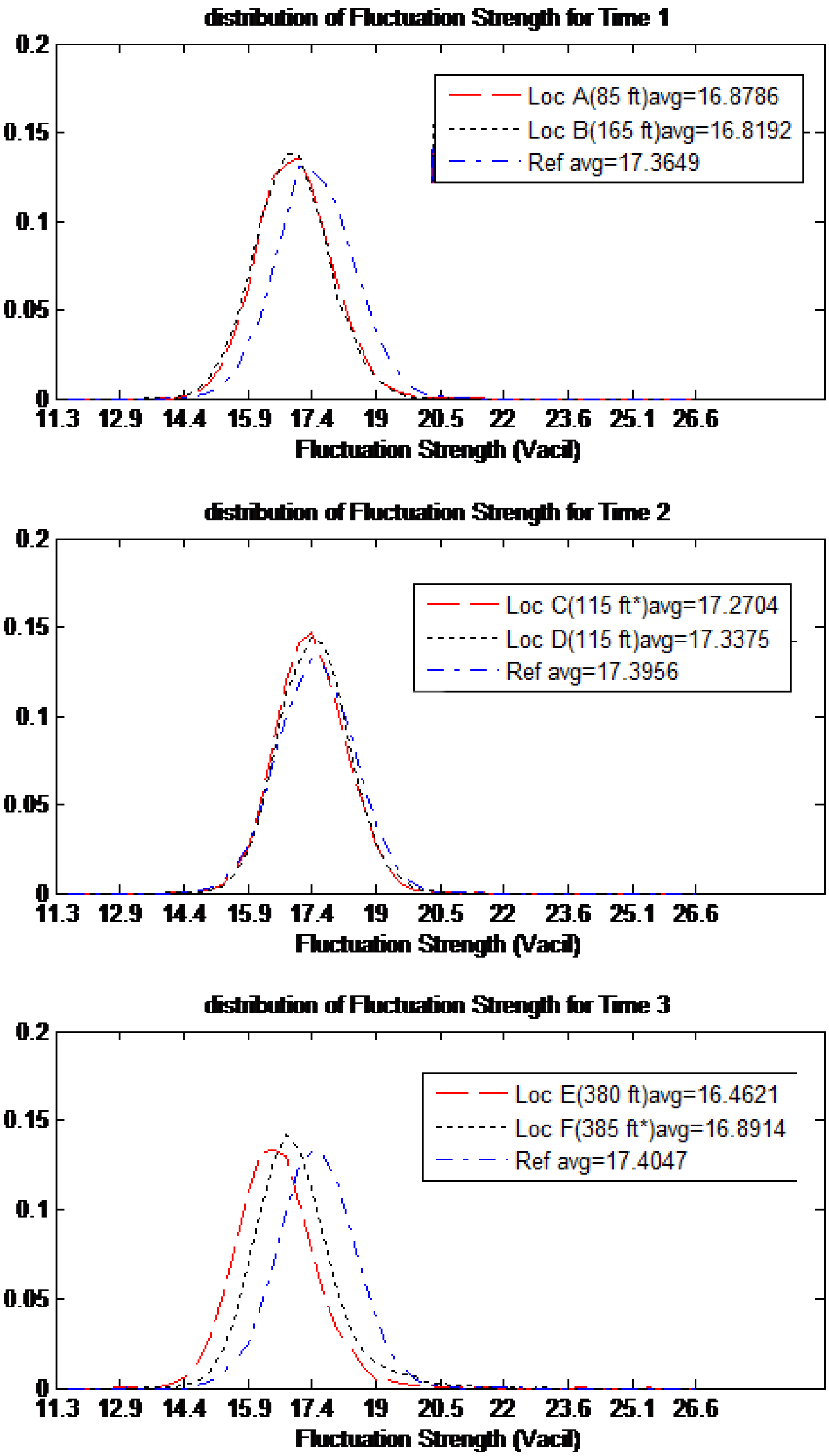


Fig. 4.14. Fluctuation strength distribution Data from times 1, 2, and 3

For the first time of data collection there is only a slight difference between the data collected at different distances from the road. As seen in Fig. 4.13, the data collected further from the road observed slightly less fluctuations strength during this test. The distributions in Fig. 4.14 are similar in shape, but the reference data is shifted to the right. Because the difference in fluctuation strength is so small between these two locations despite the fact that location A is almost twice as close to the road as location B; at close distances the change in distance has a nominal effect on the attenuation of the sounds that contribute to fluctuation strength. The second location shows that location C observed less fluctuation strength than location D. The obstruction caused by bushes and shrubs attenuated the Fluctuation strength. Although this change is still rather small, it is greater than the difference between location A and B. This suggests that although the line of sight obstruction of the foliage provides better attenuation than the changing the distance. The third time is another comparison of the effect of foliage on the attenuation of foliage on the sounds that contribute to fluctuation strength. This test, however, seems to contradict the test of time 2. In time 3 location E experiences less fluctuation strength than location F even though location F is behind the foliage and a house. A similar inconsistency is observed in the other phycoacoustic metrics. This is caused by noise from the adjacent house.

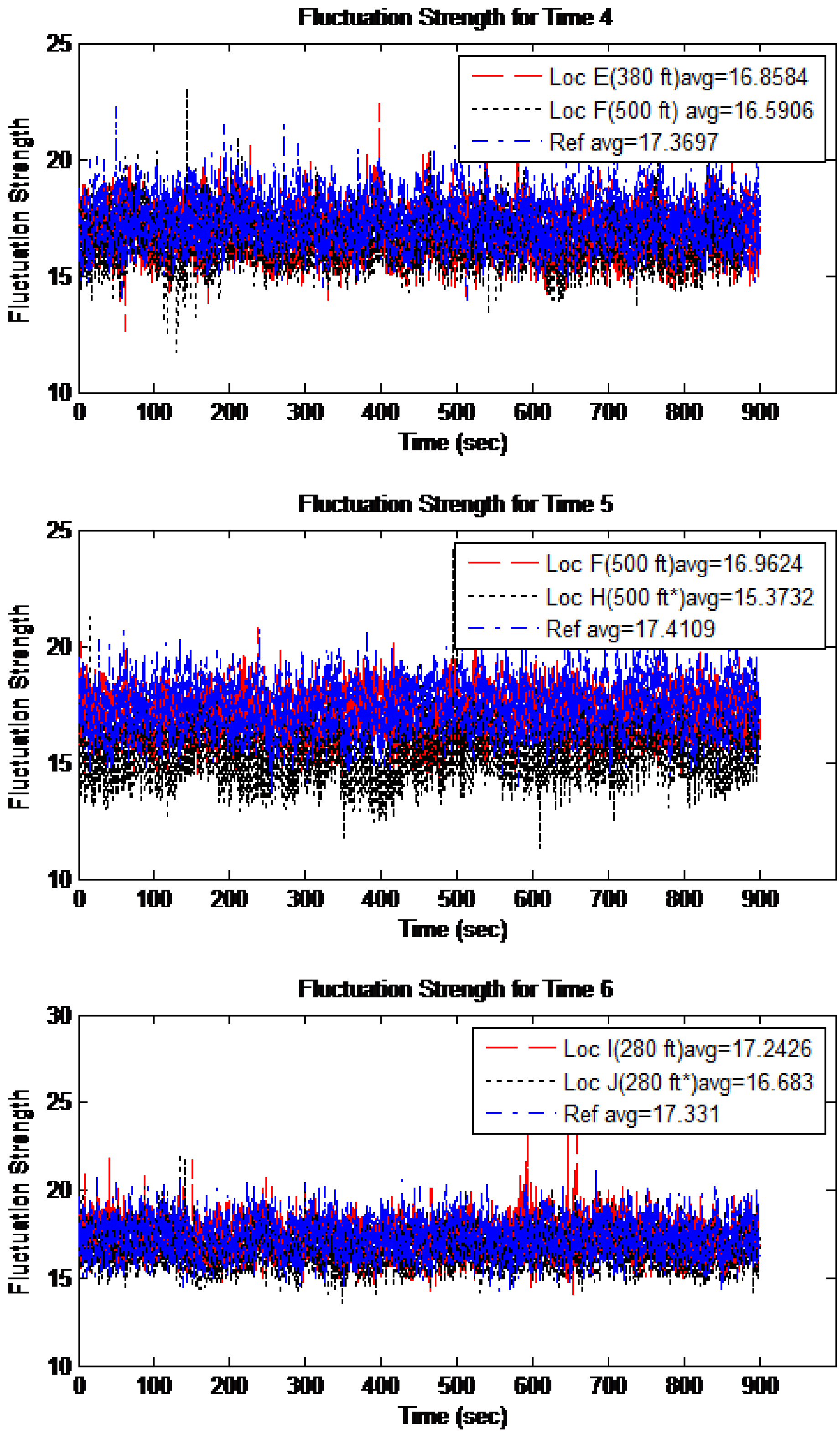


Fig. 4.15. Fluctuation strength from times 4, 5, and 6

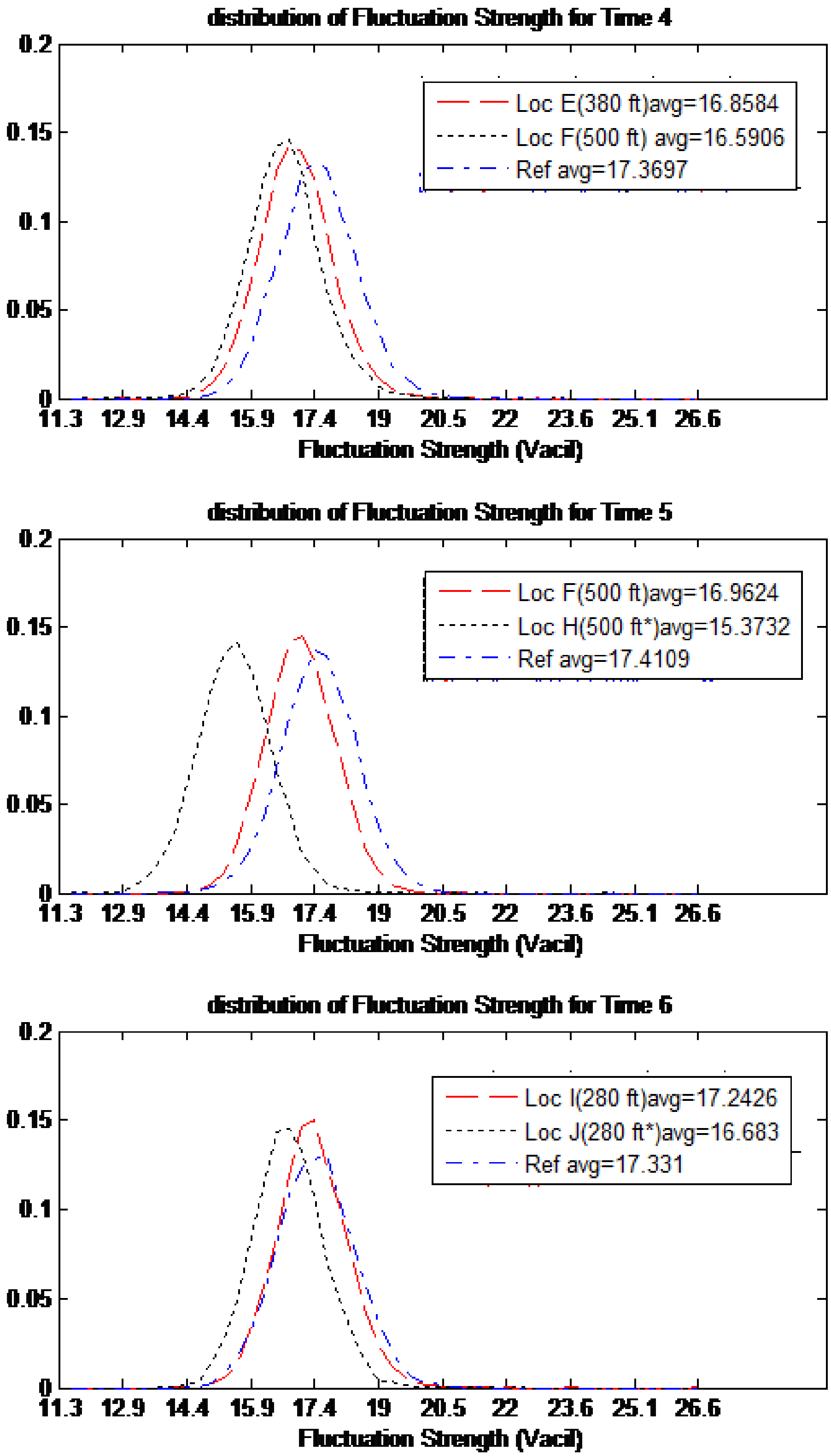


Fig. 4.16. Fluctuation strength sata from times 4, 5, and 6

At time four two different distances are compared Fig. 4.15 and Fig. 4.16. At this further distance the attenuation of the fluctuation strength is far greater than that at time one. The distributions of these results show that the they have a similar shape but an offset center. At time five a comparison of another line of sight location and a non-line of sight location is made. This result show that the fluctuation strength is significantly attenuated when the observation were made behind foliage and structures. The distribution of these plots have a similar bell like distribution, however location H is center far left location F. For the sixth time another comparison of line sight is made. In this measurement location I is compared to location J it is observed that location J has been significantly attenuated. This data shows that even slight foliage coverage can result in some reduction of fluctuations strength.

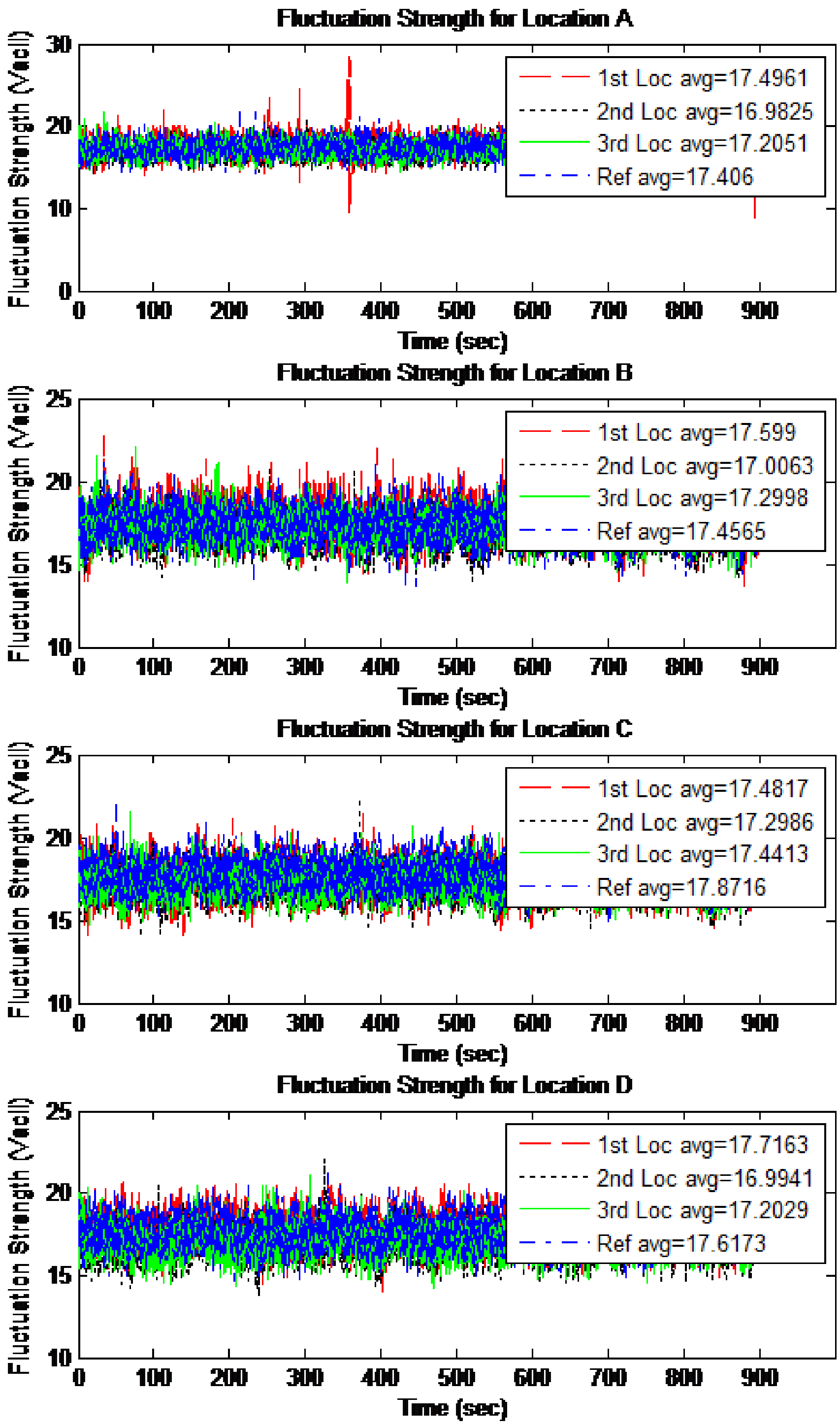


Fig. 4.17. Fluctuation strength from test location

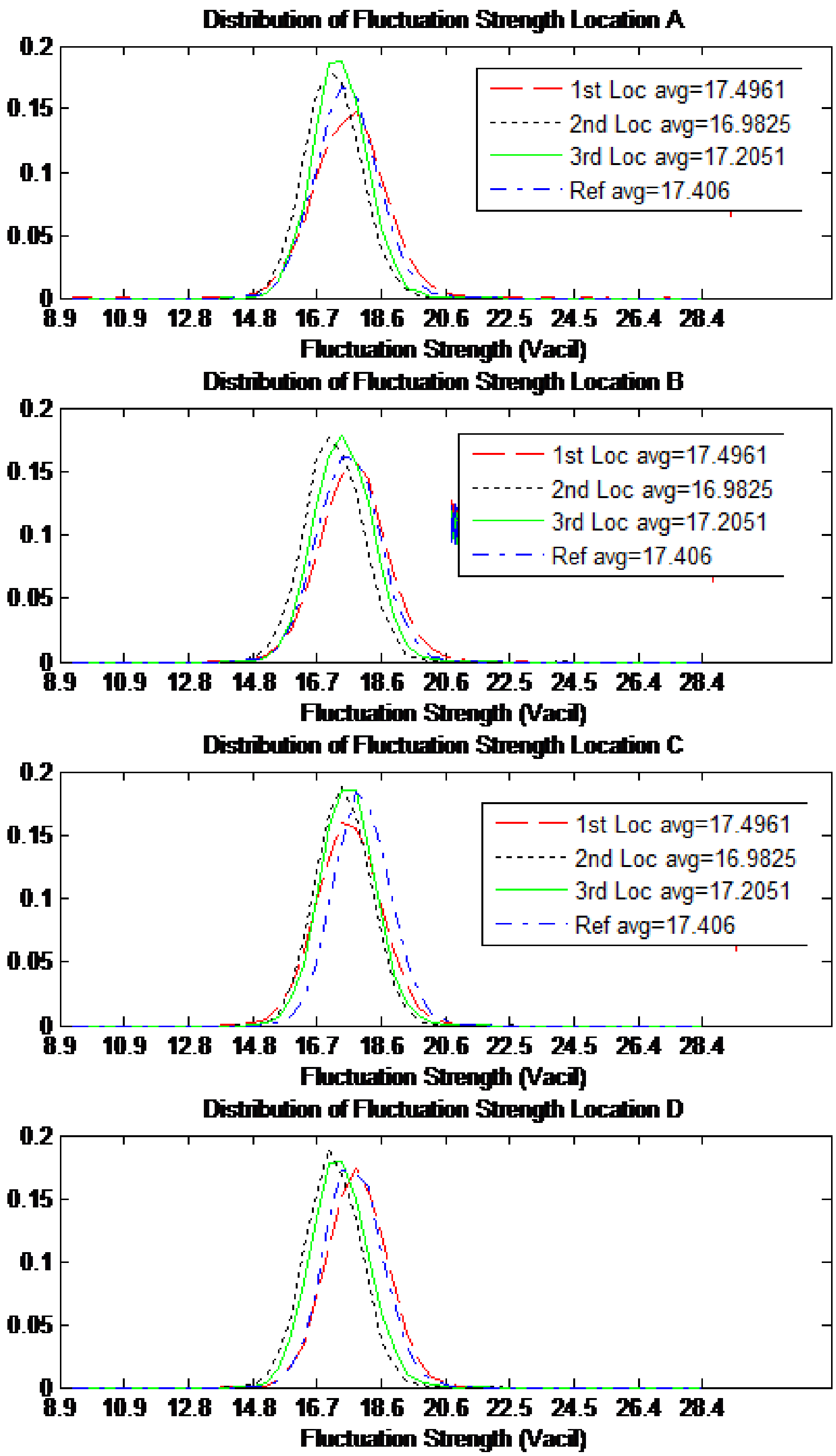


Fig. 4.18. Fluctuation strength data from test location

The fluctuation strength for the test location is shown in Fig. 4.17 and Fig. 4.18. For Location A the fluctuation strength was high at the close and further distances than at the medium range test. Close to the sound barrier the fluctuation strength was reduced greatly, however further from the wall this change was less noticable. However, once the data was taken significantly further from the sound source the attenuation do to distance is has a great effect on the reduction of fluctuation strength than the wall. This same pattern followed for Location B and Location C.

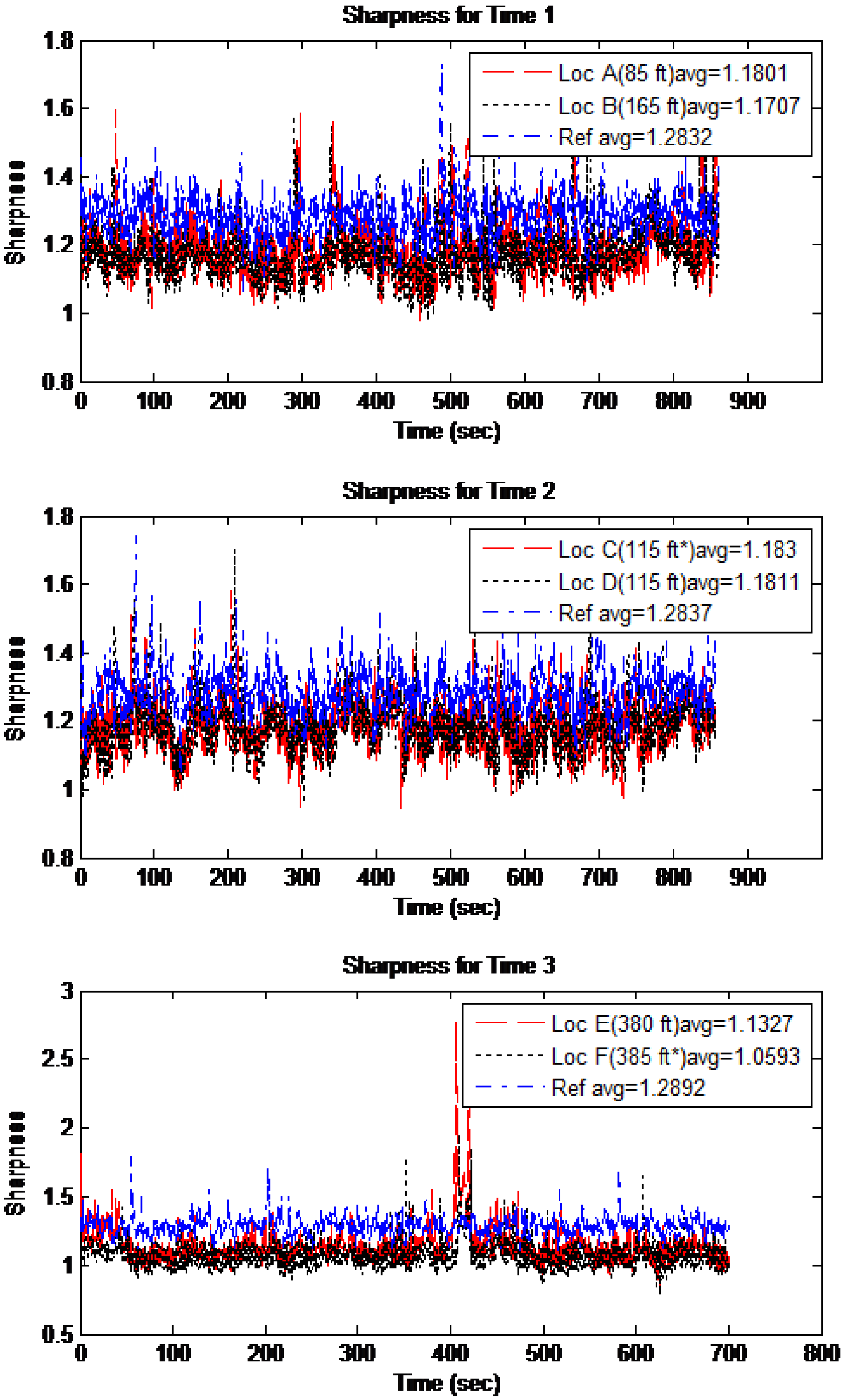
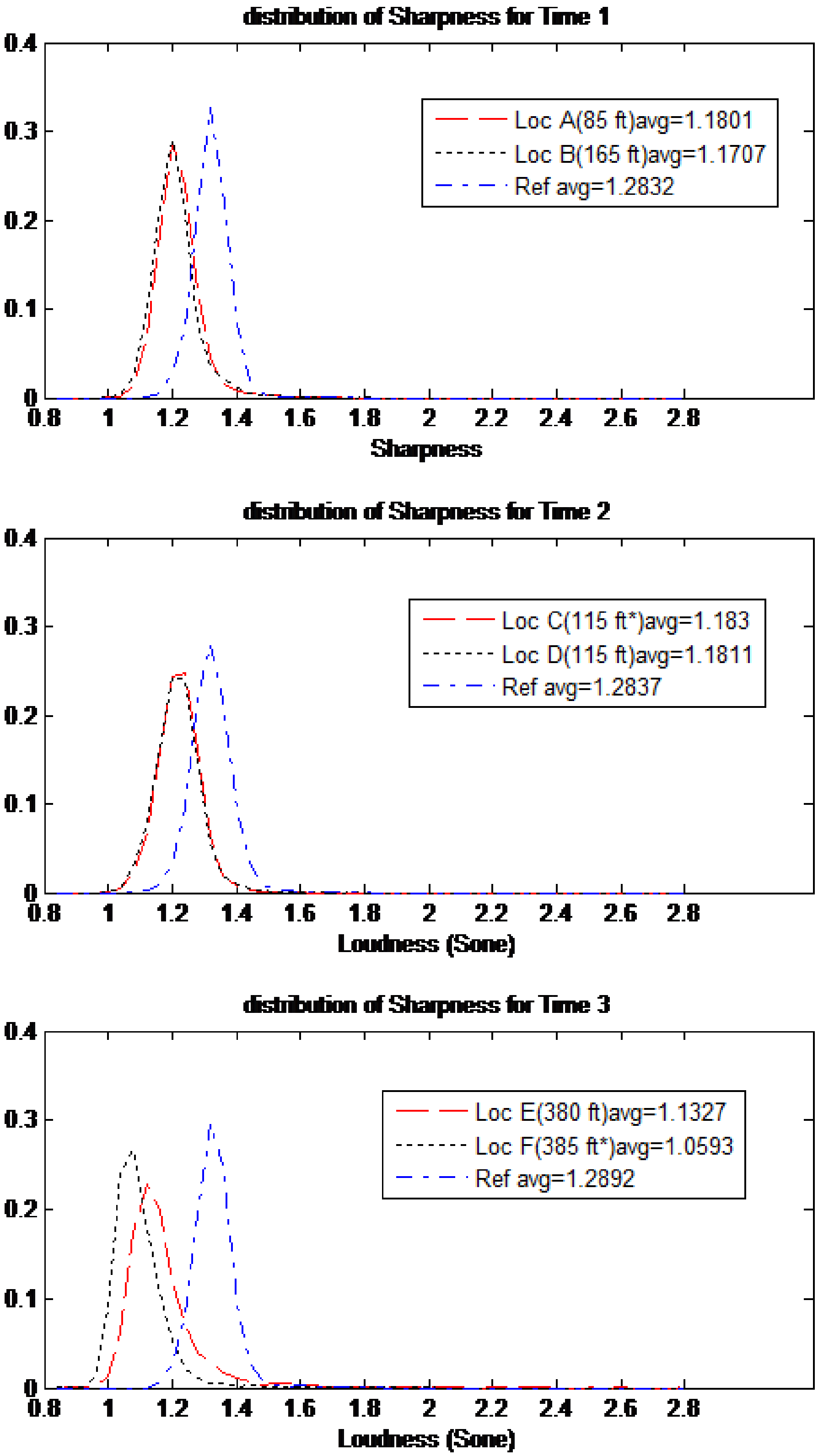


Fig. 4.19. Sharpness data from times 1, 2, and 3



distribution of Sharpness for Time 1

distribution of Sharpness for Time 2

distribution of Sharpness for Time 3

Fig. 4.20. Sharpness distribution data from times 1, 2, and 3

For the first time of data collection both of the location data samples look almost identical. Even their distributions have a similar shape. From this data collection experiment moving the collection location 80 feet back makes no difference on the sharpness.

The second time also shows two locations with the same distance from the road, but the second location out of the line of sight of the road. The difference between these locations is minimal. This suggests that sharpness is not attenuated because of folliage.

At the third time two more locations at the same distance from the road are compared, the line of sight of one these locations is obstructed. In this location the location where there was not obstruction experienced more sharpness. This location also experienced more loudness.

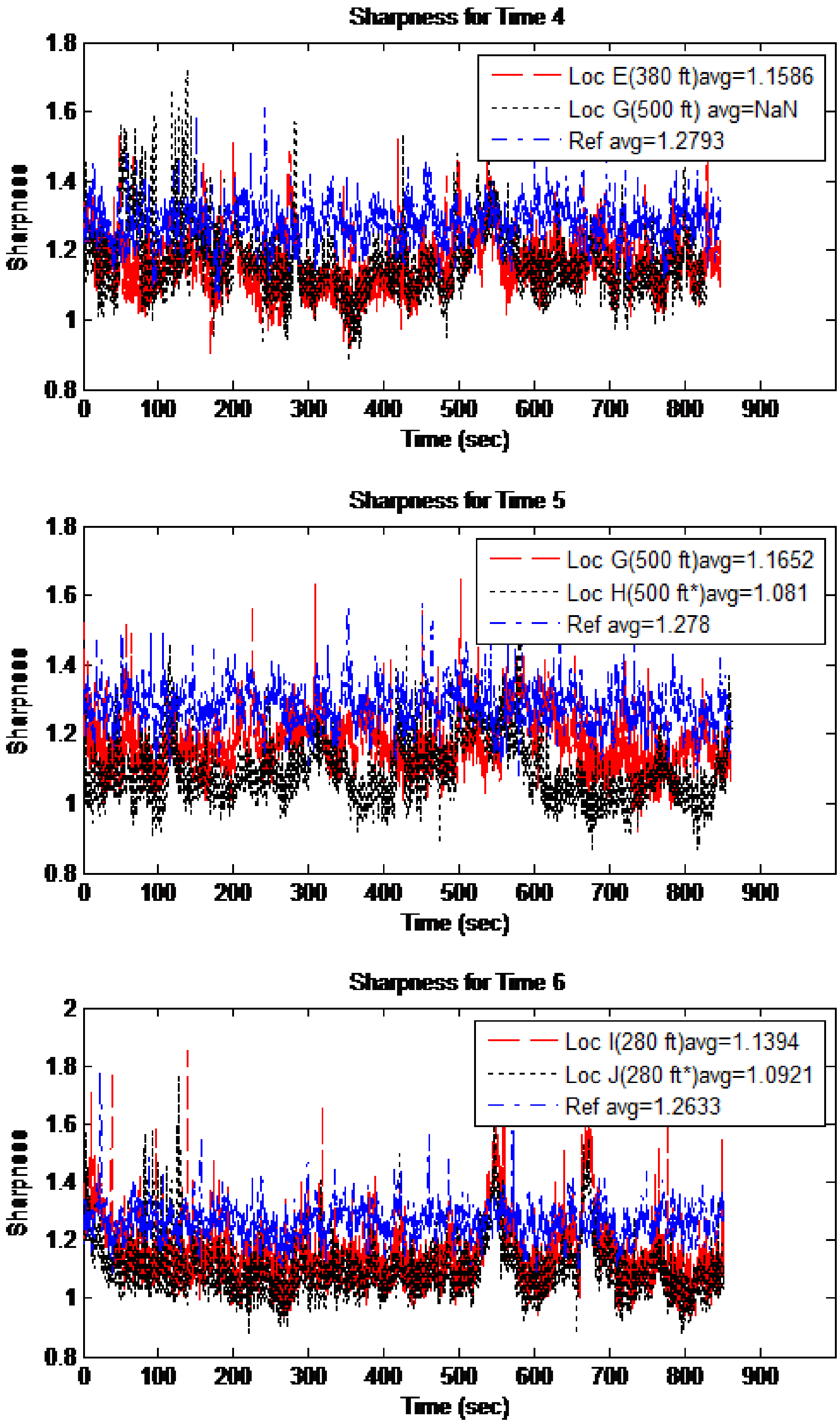


Fig. 4.21. Sharpness from times 4, 5, and 6

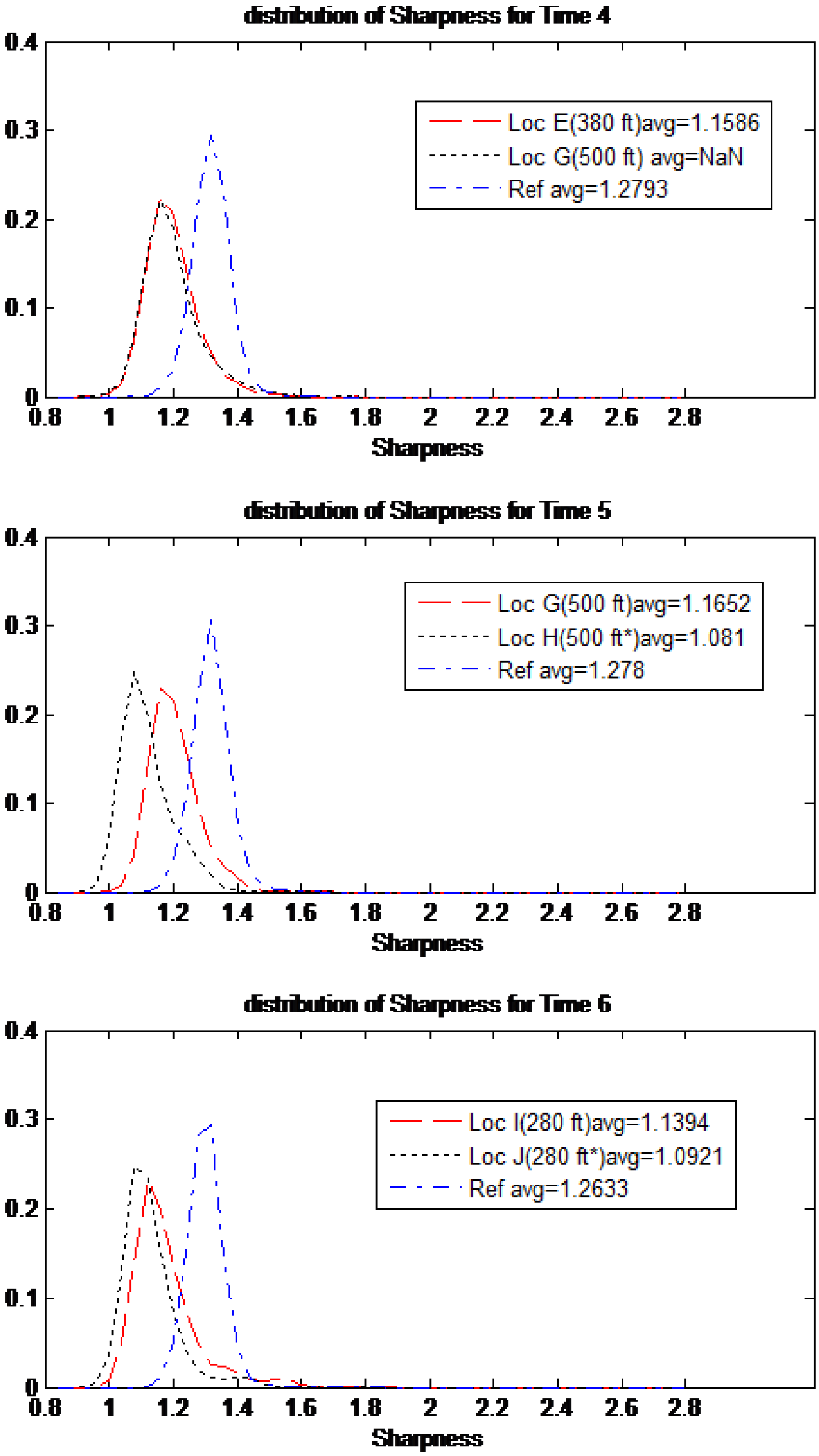


Fig. 4.22. Sharpness data from times 4, 5, and 6

The Sharpness for time is shown in Fig. 4.21 and the distribution is shown in Fig. 4.22. For time 4 the sharpness of both locations were very similar. This shows that moving the collection from 380 feet to 500 feet made a nominal difference in the sharpness. This is in contrast to some of the other parameters that analyzed, such as loudness. For time 5 the obstruction of the houses cause a significant reduction in the sharpness, this is similar to the other parameters that were analyzed. The distributions for time 5 show a shifted of about 0.1 Acum. For time 6 there was a slight reduction in sharpness for the data collected behind the foliage.

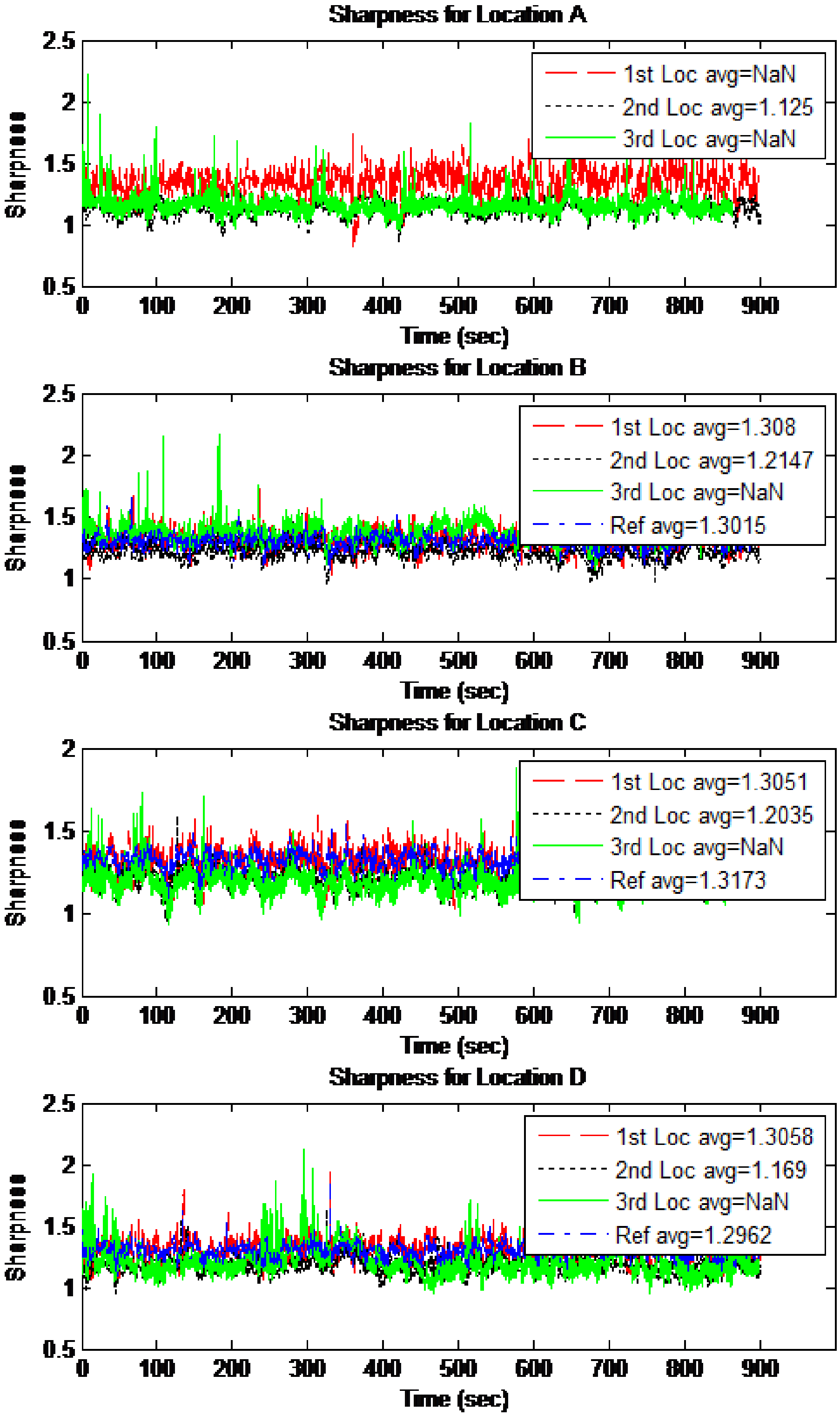


Fig. 4.23. Sharpness from test location

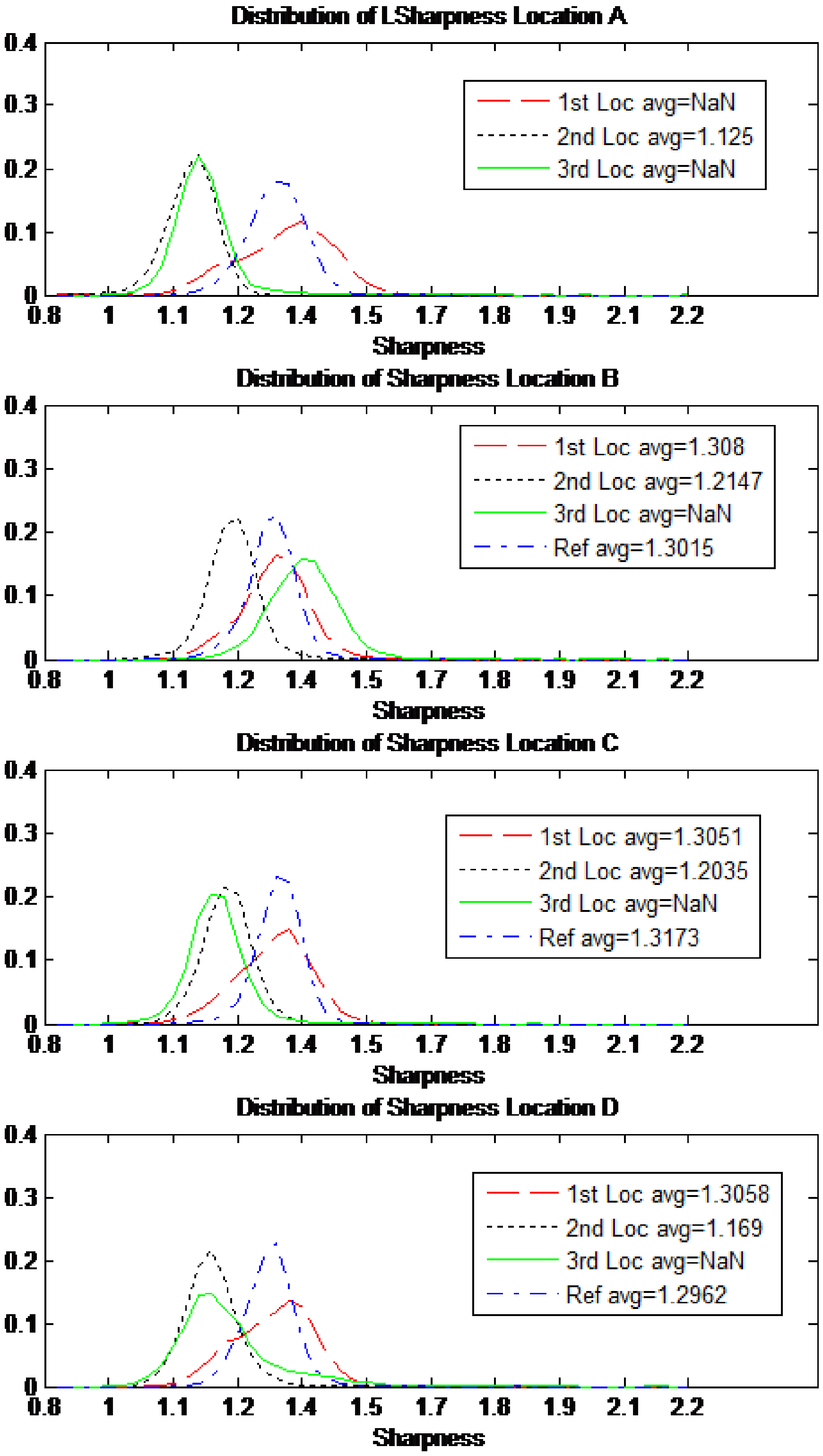


Fig. 4.24. Sharpness data from test location

The sharpness from the test location exhibited different behavior Fig. 4.23 and Fig. 4.24. In location A the data collected at the first had more sharpness than the reference. This is because the first location was located much lower in elevation than the other data points. The data from the other two collection points at Location A acted as expected and decreased sharpness was the distance increased. For location B the second location experienced more sharpness than the reference data. In this experiment the other two locations had progressively less sharpness. Each location in the second location B has more sharpness than the location B. This means that there the wall can contribute to sharpness. Location C the sharpness decreased as the distance from the wall increased. The first location once again experienced more sharpness than the reference location. The other two distances then experienced progressively less sharpness. Location D is another location with a wall. This data collection location experienced similar patterns as Location B and Location C.

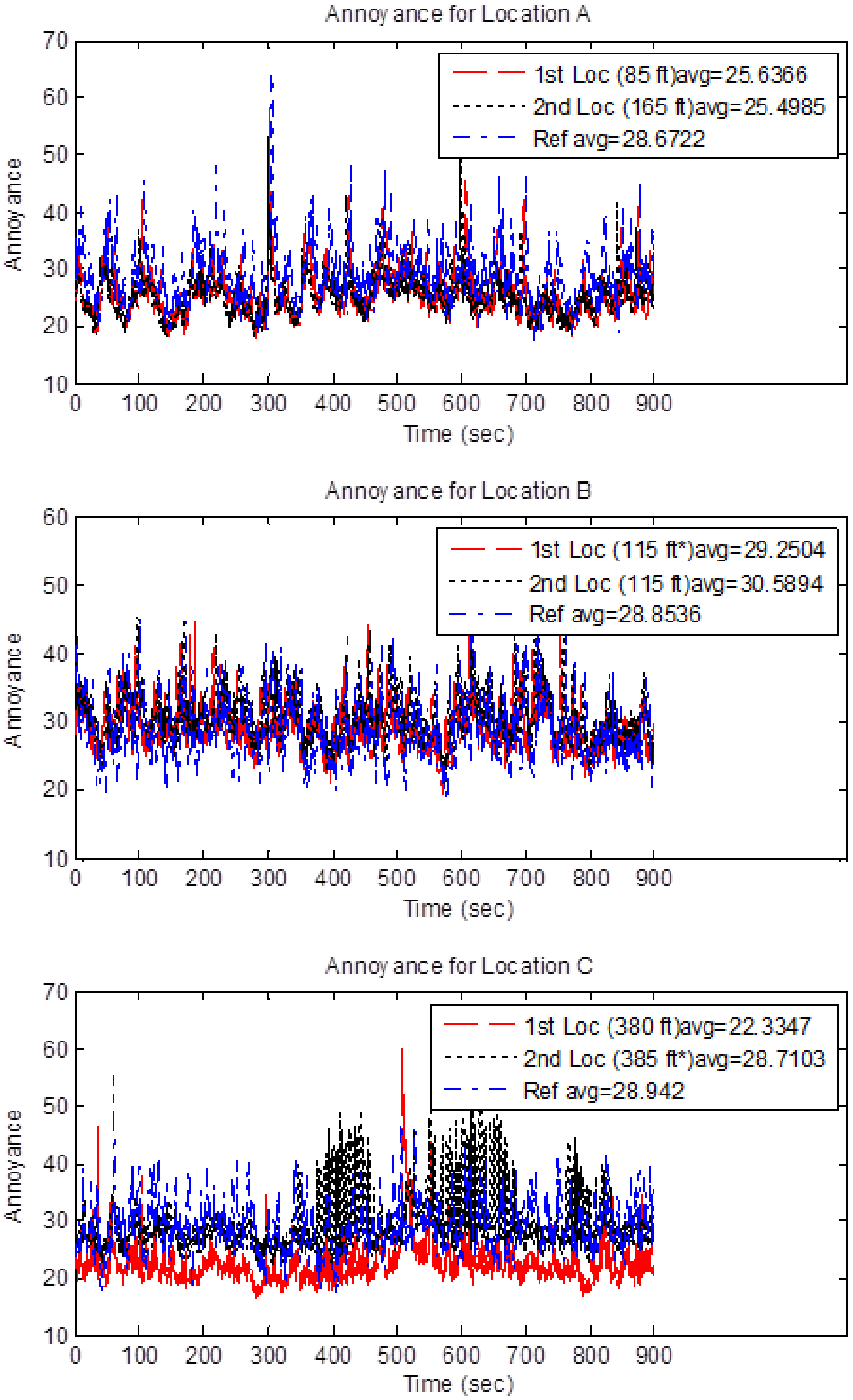


Fig. 4.25. Annoyance data from times 1, 2, and 3

For the first time of data collection a similar annoyance was obtained from both data collection point Fig. 4.25 and Fig. 4.26. This shows that moving 80 feet aways from the sound source makes a nominal change in the annoyance. The second time of data collection slightly less annoyance was observed at the location with the location with the line of sight obstruction. It is also interesting that the relative to the reference data, this annoyance is higher than the first time. This has to do with the increase in roughness at this time. For the third time the location near the house, but behind the obstructions experienced more annoyance. This has to do with the household noise from this location that caused an increase in sharpness and loudness at this time. This is why despite being behind foliage, and line of sight obstructions there is more annoyance observed.

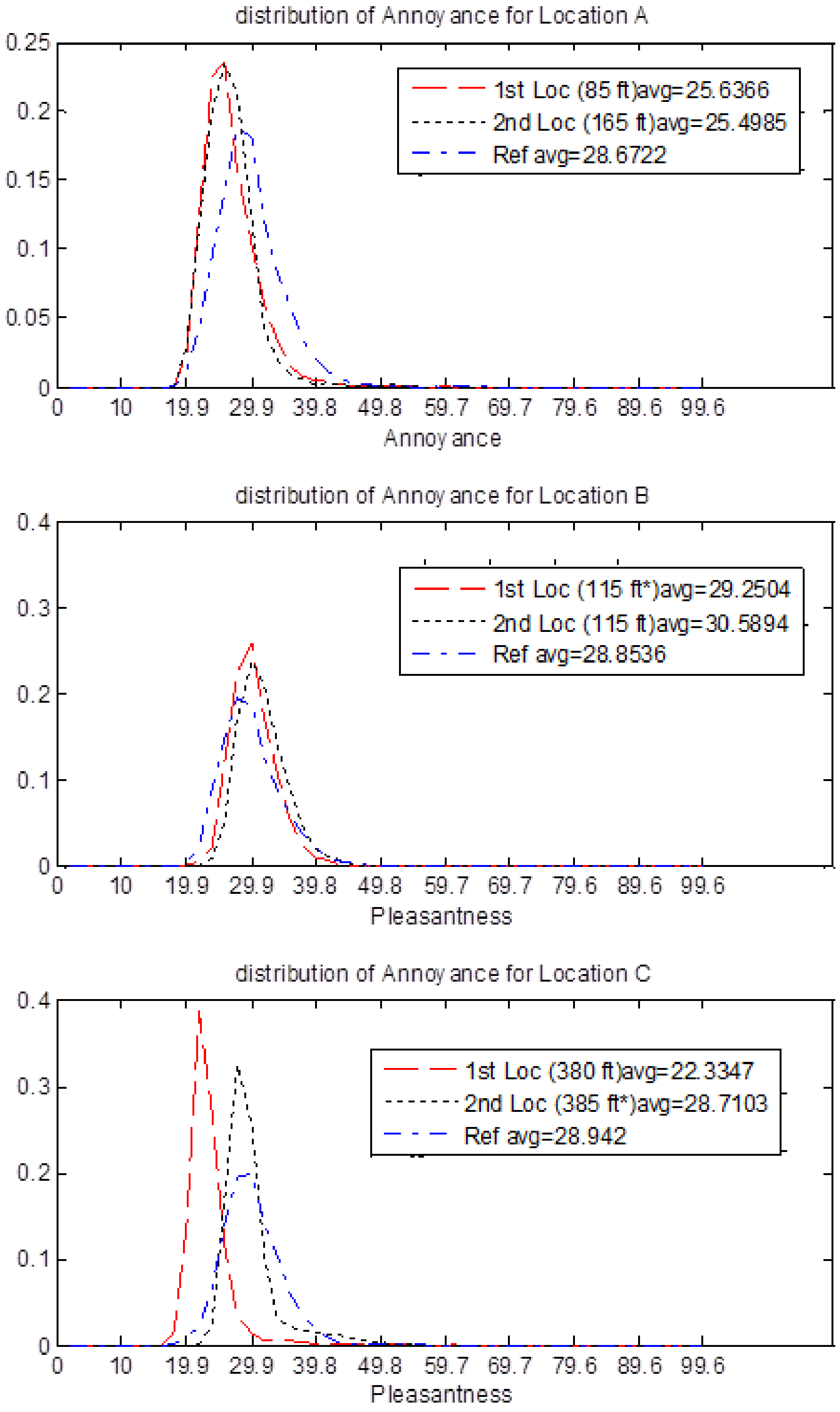


Fig. 4.26. Annoyance distribution data from times 1, 2, and 3

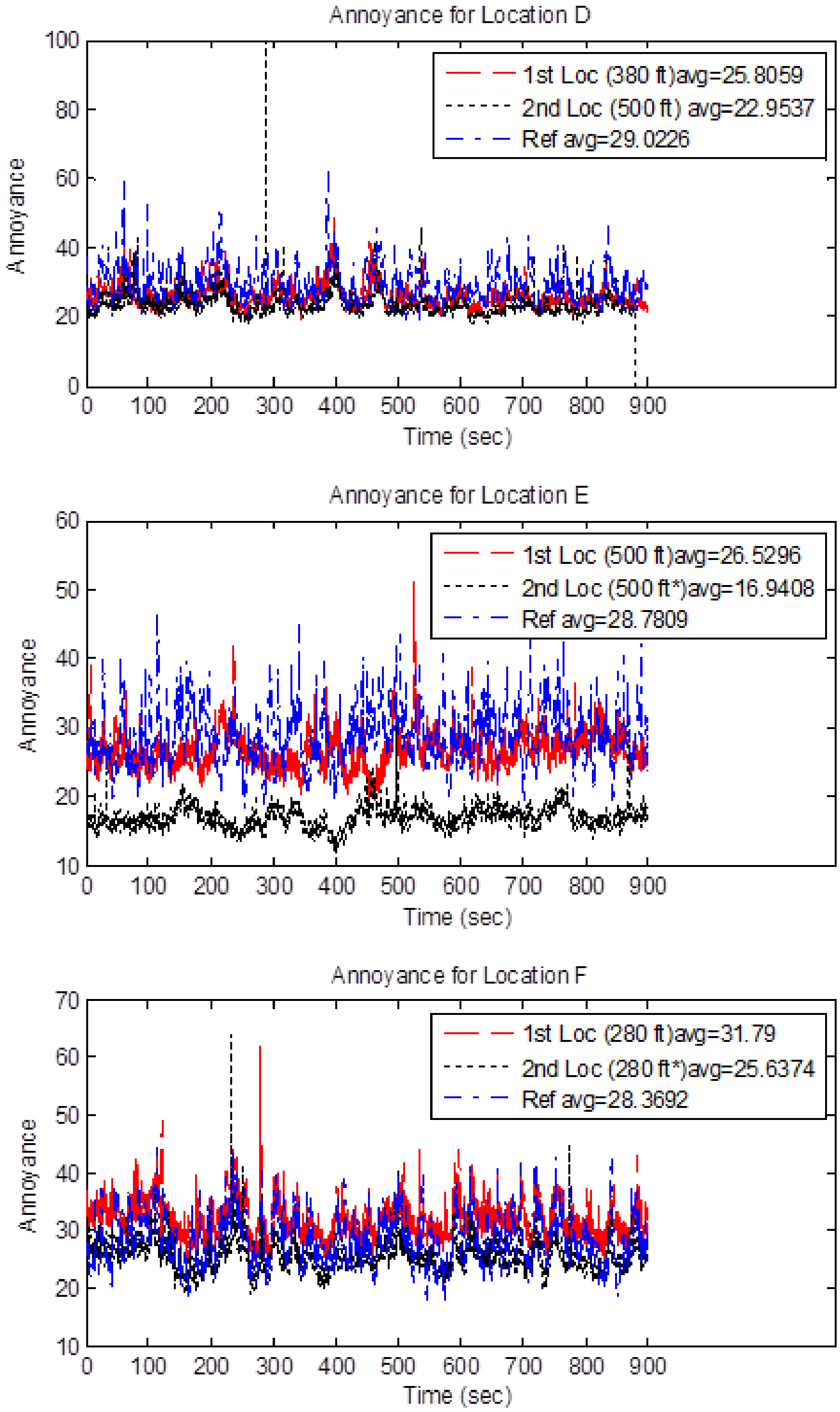


Fig. 4.27. Annoyance from times 4, 5, and 6

For time four annoyance was reduced as the distanced was increased Fig. 4.27 and Fig. 4.28. A the fourth time all of the psychoacoustic parameters were reduced so the annoyance was less at this location. For the fifth time the location with line of sight obstruction observed a significant reduction in annoyance. In this experiment, all of the psychoacoustic parameters were reduced significantly, so there is a very noticeable reduction in annoyance. The sixth time collecting data a significant reduction in annoyance was measured. At this location, the roughness was higher causing the annoyance to be greater at the first test location. The line of sight reduction caused significant reduction in annoyance.

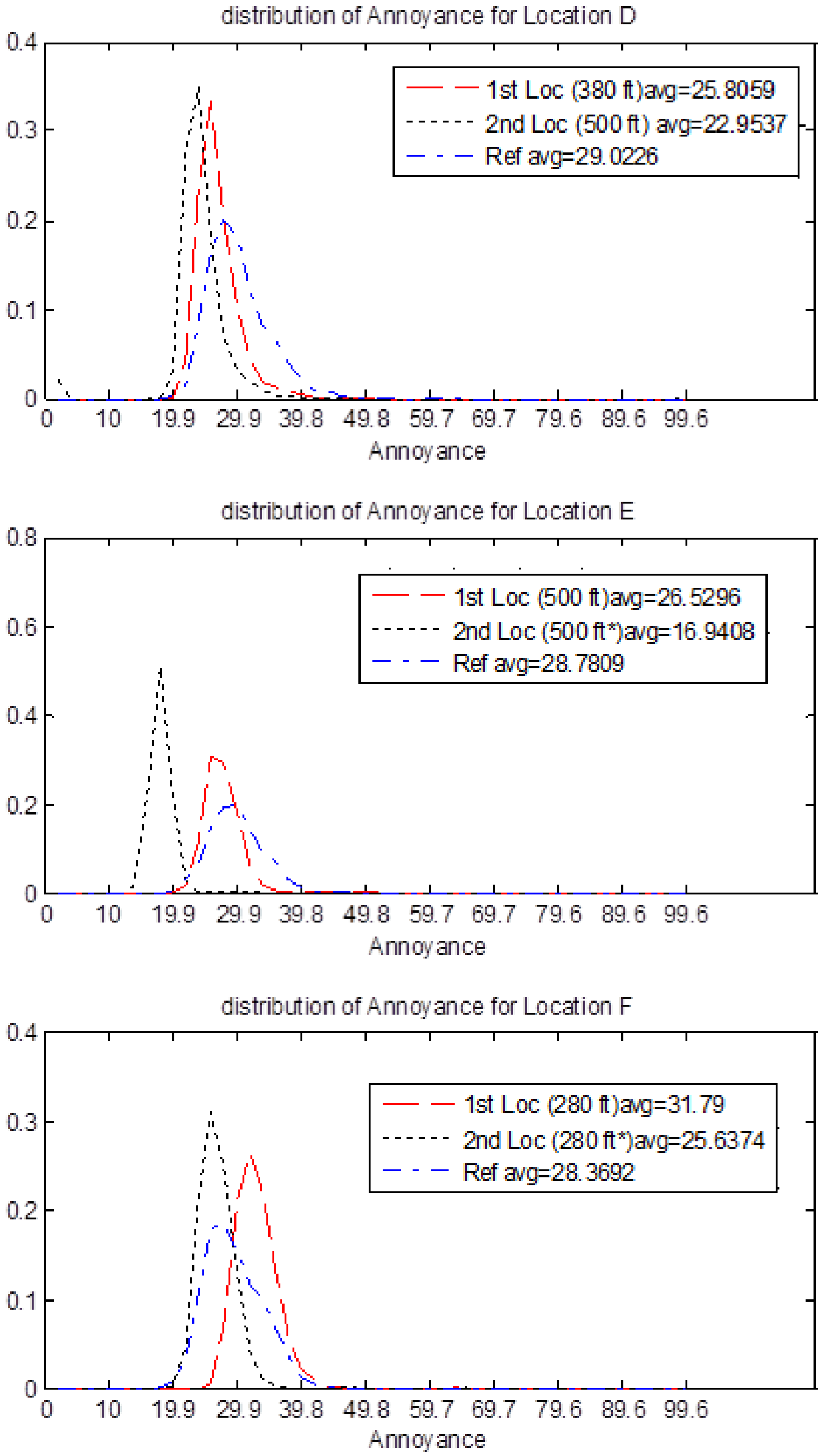


Fig. 4.28. Annoyance data from times 4, 5, and 6

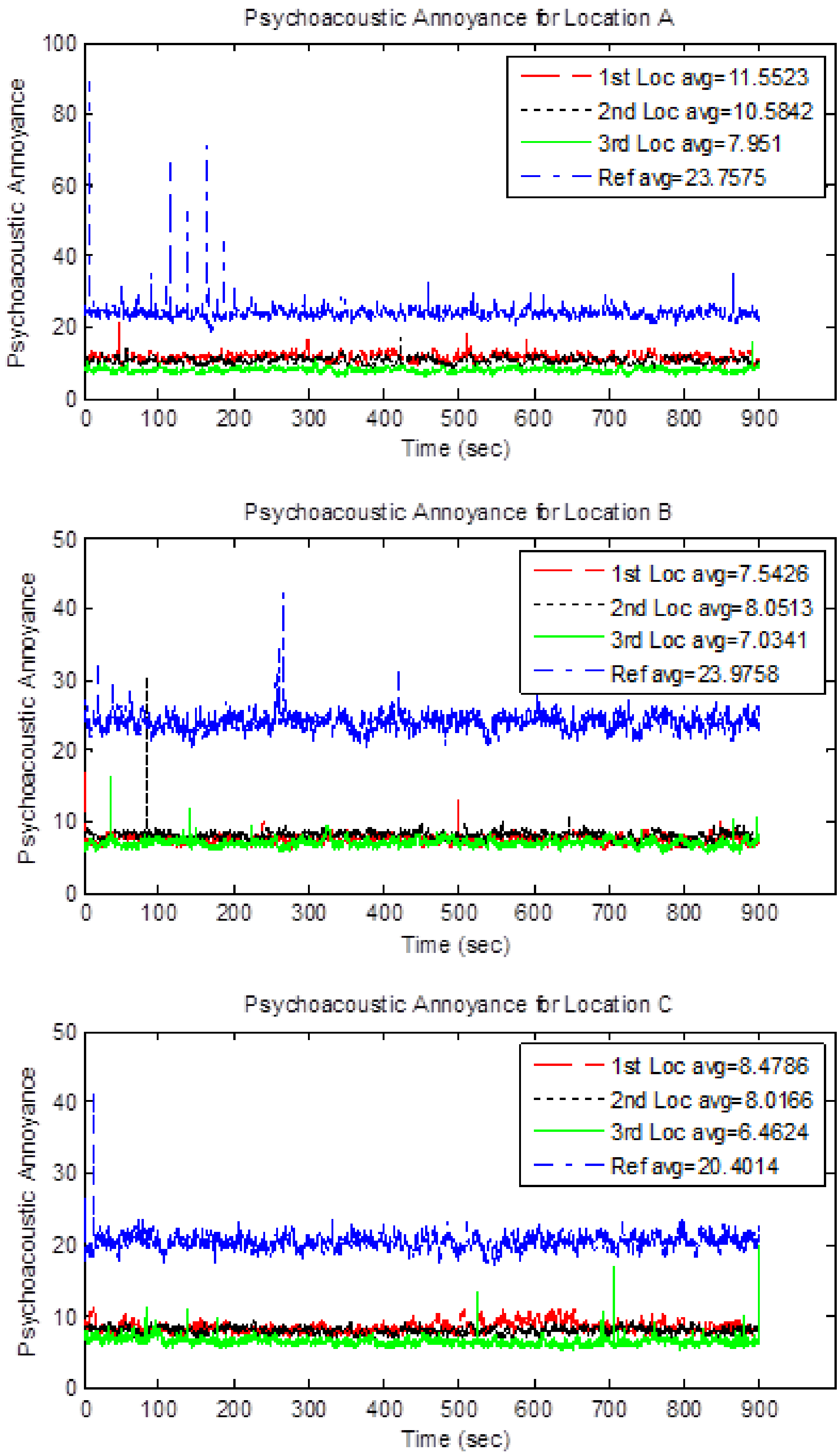


Fig. 4.29. Annoyance from test location

At the test locations the annoyance was calculated Fig. 4.29 and Fig. 4.30. For location A the annoyance was reduced as the sound got further and further from the sound source. Location B a different pattern was observed, the first location saw a significant reduction in annoyance, however, the second location, the benefit of the sound is reduced. Finally, the third location experienced even less annoyance than the first or second location. This shows that close to the barrier it is very effect but at a distance the effectiveness of the sound barrier decreases. However there is an improvement in annoyance for all three locations even relative to the reference annoyance. At the third location the measurement closest to the wall had the most annoyance while and the annoyance decreased as the locations were farther from the wall. The reference data at this location has less annoyance so there is significantly different characteristic happening at this location. However even in relation to the reference data, this location shows an improvement in annoyance to location A.

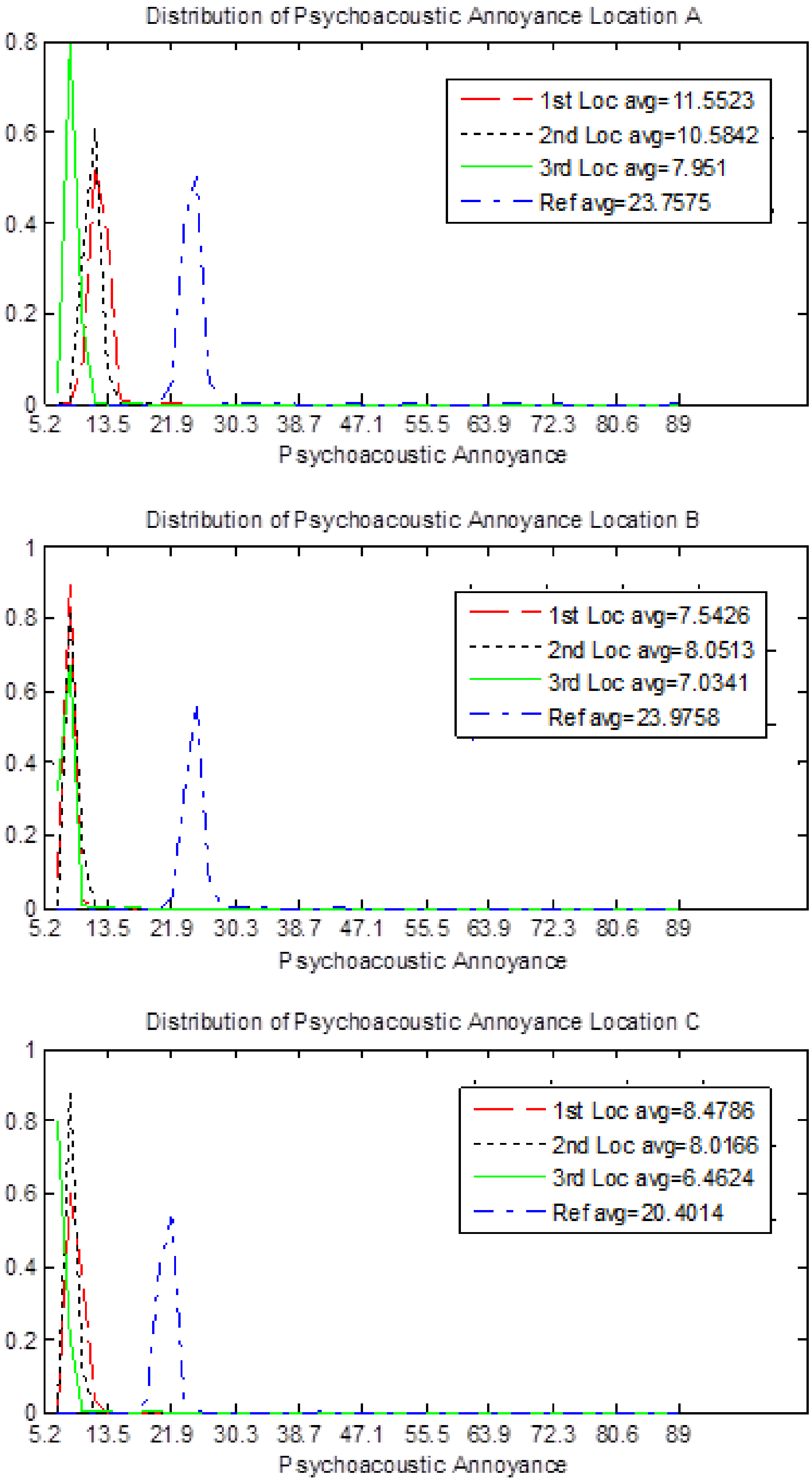


Fig. 4.30. Annoyance data from test location

5. ANALYSIS

5.1 Loudness Analysis

4.1 A) shows that at a close distance, there is only a slight difference in loudness in the two measurements, the closer measure experienced a slightly louder sound. The distributions show that the majority of the energy is in the same range, however the closer measurement point has more data in higher loudness.

For the second time, the loudness between data had line of sight and a location where the view was obscured by bushes was compared. The data in Fig. 4.1 shows that the measure from behind the bush attenuated the loudness slightly. The distributions of the two locations have similar but slightly offset distributions.

In the third time measuring the data, another comparison was made between data at the same distance from the road, but a different location along the road. This time the data shown in Fig. 4.1, this time the location with the line of sight obscured experienced more loudness. The distribution of this sound seen in Fig. 4.1 shows that location E has a more data than most of the distributions located in the range of 4.6 Sones.

The forth time of data collect was collected at two locations at different locations from the road, Fig. 4.3. This data was taken further away than previous comparisons made at time 1. The attenuation experienced at this distance was far greater than the first time. The distributions of this time show shapes, but shifted centers, Fig. 4.3.

The data collected at the fifth time compares data taken at the same distance from the road, but at different locations Fig. 4.3. One of these locations was close to a house and it did not have a line of sight due to a houses and vegetation. In this experiment the location that did not have line sight to the road was almost half as loud.

At the sixth time the data collected was two locations similar distances from the road Fig. 4.1. Once again the location where there was no line of sight, less loudness was experienced. The reference data for all locations roughly followed a similar distribution Fig. 4.2 and Fig. 4.4. The data has a mean around 8 Sones and that is where most of the energy in the distribution is located. All the loudness of the reference data then roughly fits into a bell like shape, except for extra energy around 10 Sones.

5.2 Roughness Analysis

For the first time of data collection an interesting pattern emerged Fig. 4.7 and Fig. 4.8. The reference experienced less roughness than either location and the closer distance experienced less roughness than the further distance. This suggests that fluctuation that causes roughness is less prevalent very close to the road.

The second time compares two different levels of obstruction. Location C (the site with the line of sight obstruction) experiences less roughness than location D. This suggest that obstructing the light of sight at this distance will no cause the roughness of the sound to be more prevalent, even though moving further away from the location can cause an increase in roughness.

The third time represents another location where one of the data collection locations has an obstructed line of sight. In this collection time the location with the obstructed view has a greater roughness. This time the obstructed location experienced more roughness. This is in line with the other metrics that also saw an increase in this location.

The fourth time shows a location where the two different distance are compared Fig. 4.9 and Fig. 4.10. In this experiment the distance from the road is greater. At this distance the increase in distance from the road caused the roughness to decrease.

The fifth time of data collection showed that even at 500 feet from the road, roughness decreased when the line of sight is obstructed.

The sixth time compares another distance where the line of sight is obstructed. At this distance the location with the line of sight obstruction experienced less roughness. This experiment showed that at close location there is less roughness, this is because the sound is more constant. At slightly further distances more roughness is observed.

5.3 Fluctuation Strength Analysis

For the first time of data collection there is only a slight difference between the data collected at different distances from the road. As seen in Fig. 4.13, the data collected further from the road observed slightly less fluctuation strength during this test. The distributions in Fig. 4.14 are similar in shape, but the reference data is shifted to the right. Because the difference in fluctuation strength is so small between these two locations despite the fact that location A is almost twice as close to the road as location B; at close distances the change in distance has a nominal effect on the attenuation of the sounds that contribute to fluctuation strength. The second location shows that location C observed less fluctuation strength than location D. The obstruction caused by bushes and shrubs attenuated the fluctuation strength. Although this change is still rather small, it is greater than the difference between location A and B. This suggests that although the line of sight obstruction of the foliage provides better attenuation than the changing the distance. The third time is another comparison of the effect of foliage on the attenuation of foliage on the sounds that contribute to fluctuation strength. This test however seem to contradict the test of time 2. In time 3 location E experiences less fluctuation strength than location F even though location F is behind the foliage and a house. A similar inconsistency is observed in the other phycoacoustic metrics. This is caused by noise from the adjacent house. At time four, two different distances are compared Fig. 4.15, Fig. 4.16. At this further distance the attenuation of the fluctuation strength is far greater than that at time one. The distributions of these results show that the they have a similar shape but an offset center. At time five a comparison of another line of sight location and a non-line of sight location is made. This result show that the fluctuation strength is significantly attenuated when the observation were made behind foliage and structures. The distribution of these plots have a similar bell like distribution, however location H is center far left location F. For the sixth time another comparison of line sight is made. In this measurement location I is compared to location J it is observed that location J has been significantly attenuated. This data shows that even slight foliage coverage can result in some reduction of fluctuations strength.

5.4 Sharpness Analysis

For the first time of data collection both of the location data samples look almost identical. Even their distributions have a similar shape. From this data collection experiment moving the collection location 80 feet back makes no difference on the sharpness.

The second time also shows two locations the same distance from the road, with one location out of the line of sight of the road. The difference between these locations is minimal. This suggests that sharpness in not attenuated because of foliage.

At the third time two more locations at the same distance from the road are compared, the line of sight of one these locations is obstructed. In this location the location where there was not obstruction experienced more sharpness. This location also experienced more loudness.

6. CONCLUSIONS AND FUTURE WORKS

6.1 Conclusions

In conclusion, we proposed using psychoacoustic metrics to analyze effectiveness of sound barriers, relative sharpness method, KNN approach to remove local bird noise. To evaluate these methods we propose an engineering setup for data collection and analyzed the real-life data we collected. Our contribution will allow for engineers to provide a more comprehensive evaluation of how a sound barrier changes the sound and how people persevere sound. In our experiments, we found that loudness decreases as distance increases. This result is similar to that obtained with LAeq. However, other psychoacoustic parameters do not follow this trend. Roughness is greater when closer to the sound source. The fluctuation strength decreases with distance, however, its decrease is far less than loudness. Local foliage can help mitigate, particularly at far distances. We concluded that sound barriers can help mitigate highway noise however, its effectiveness reduces with distance.

6.2 Future Works

The first area that future work should be directed is to include more data into the experiment. Test and analyze the data from after the wall is built. Conduct similar studies on different sound barriers; a survey has been performed at the future location of a line of sight wall. Future research should also be directed at human subject tests to see how people feel about various highway noise sound with different sound quality properties. Another suggestion for future work would be to use the knowledge gained from this experiment to explore new methods for sound barriers. Active noise control, using destructive sound wave interference to reduce the amplitude of a wave, is used in headphones and for specific industrial applications; however these techniques have not been used to control highway noise.

LIST OF REFERENCES

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[1] J. Eberhardt, L. Stråle, and M. Berlin, "The influence of continuous and intermittent traffic noise on sleep," *Journal of sound and vibration*, vol. 116, no. 3, pp. 445–464, 1987.

[2] B. Griefahn, "Environmental noise and sleep. reviewneed for further research," *Applied Acoustics*, vol. 32, no. 4, pp. 255–268, 1991.

[3] B. Griefahn, "Sleep disturbances related to environmental noise," *Noise and health*, vol. 4, no. 15, pp. 57–60, 2002.

[4] E. Öhrström, E. Hadzibajramovic, M. Holmes, and H. Svensson, "Effects of road traffic noise on sleep: Studies on children and adults," *Journal of environmental psychology*, vol. 26, no. 2, pp. 116–126, 2006.

[5] E. Öhrström and A. Skånberg, "Sleep disturbances from road traffic and ventilation noiselaboratory and field experiments," *Journal of sound and vibration*, vol. 271, no. 1, pp. 279–296, 2004.

[6] D. Ouis, "Annoyance from road traffic noise: a review," *Journal of Environmental Psychology*, vol. 21, no. 1, pp. 101–120, 2001.

[7] S. Stansfeld, B. Berglund, C. Clark, I. Lopez-Barrio, P. Fischer, E. Öhrström, M. Haines, J. Head, S. Hygge, I. van Kamp, *et al.*, "Aircraft and road traffic noise and children's cognition and health: a cross-national study," *The Lancet*, vol. 365, no. 9475, pp. 1942–1949, 2005.

[8] J. BOYER, "Traffic noise in montana: Community awareness and recommendations," *Montana Department of Transportation*, 2004.

[9] P. Schomer, "Criteria for assessment of noise annoyance," *Noise control engineering journal*, vol. 53, no. 4, pp. 125–137, 2005.

[10] B. Kotzen, *Environmental noise barriers: a guide to their acoustic and visual design*. Taylor & Francis, 2009.

[11] TW Enviromental, "Us highway 97 reroute-north redmond interchange and overcrossing alternatives technical noise report," *Oregon Department of Transportation*, 2006.

[12] R. Manual, "Traffic noise analysis and abatement manual," *North Carolina Department of Transportation*, 2007.

[13] H. Fastl and E. Zwicker, *Psychoacoustics: facts and models*, vol. 22. Springer-Verlag New York Inc, 2007.

[14] H. Fastl, “6 psycho-acoustics and sound quality,” *Communication acoustics*, p. 139, 2005.

[15] K. Zajdo, J. van der Stelt, and T. Wempe, “The role of principal component analysis in vowel acquisition research,” *The Journal of the Acoustical Society of America*, vol. 116, no. 4, p. 2632, 2004.

[16] L. Jiang and P. Macioce, “Sound quality for hard drive applications,” *Noise Control. Engineering Journal*, vol. 49, no. 2, 1996.

[17] P. Susini, S. McAdams, S. Winsberg, I. Perry, S. Vieillard, and X. Rodet, “Characterizing the sound quality of air-conditioning noise,” *Applied Acoustics*, vol. 65, no. 8, pp. 763–790, 2004.

[18] D. Havelock, S. Kuwano, and M. Vorländer, *Handbook of signal processing in acoustics*, vol. 1. Springer Verlag, 2008.

[19] T. Rossing, *Springer handbook of acoustics*. Springer Verlag, 2007.

[20] M. Crocker and D. Raichel, “Encyclopedia of acoustics,” *The Journal of the Acoustical Society of America*, vol. 104, no. 1, pp. 19–19, 1998.

[21] A. Torija, D. Ruiz, D. Botteldooren, and B. De Coensel, “Taking into account the temporary and spectral structure of the sound energy for the characterization of the annoyance generated by the road and railway traffic,” in *Proceedings of the 5th Iberian congress of acoustics (Acustica08), Coimbra, Portugal*, 2008.

[22] B. Defréville and C. Lavandier, “Unpleasantness of urban sound environment based on identification of sources: a perceptive and an acoustic approach,” in *Forum Acusticum, Budapest*, 2005.

[23] M. Nilsson, M. Andéhn, and P. Leśna, “Evaluating roadside noise barriers using an annoyance-reduction criterion,” *The Journal of the Acoustical Society of America*, vol. 124, no. 6, pp. 3561–3567, 2008.

[24] S. Blaeser and G. Wong, “Acoustical standards news,” *J. Acoust. Soc. Am*, vol. 115, no. 1, 2004.

[25] G. Daigle, “Technical assessment of the effectiveness of noise walls,” *I-INCE Publication*, pp. 98–1, 1999.

[26] F. Anfosso-Ledee, “Combination of low noise road surfaces with road and building equipments,” *Swedish Road and Transport Research Institute*, 1992.

[27] T. Boothby, H. Manbeck, C. Burroughs, C. Bernecker, S. Grgurevich, S. Cegelka, and M. Ritter, “Development of wood highway sound barriers,” in *Proc, 1996 Natl. Conf. Wood Transportation Structures, FPL-GTR*, vol. 94, pp. 158–167, 1996.

[28] C. Steele, “A critical review of some traffic noise prediction models,” *Applied Acoustics*, vol. 62, no. 3, pp. 271–287, 2001.

[29] M. Garai and P. Guidorzi, “European methodology for testing the airborne sound insulation characteristics of noise barriers in situ: Experimental verification and comparison with laboratory data,” *The Journal of the Acoustical Society of America*, vol. 108, p. 1054, 2000.

[30] R. Wayson and R. Peppin, “Evaluating sound absorption in situ using” adrienne”,” in *Noise-Con 04. The 2004 National Conference on Noise Control Engineering*, 2004.

[31] M. Garai and P. Guidorzi, “Experimental verification of the european methodology for testing noise barriers in situ: sound reflection,” *Proc. Inter-Noise 2000*, pp. 477–482, 2000.

[32] L. Tronchin, A. Venturi, A. Farina, and C. Varani, “In situ measurements of reflection index and sound insulation index of noise barriers,” *International Congress on Acoustics* 2010.

[33] Y. Takahashi, T. Otsuru, and R. Tomiku, “In situ measurements of surface impedance and absorption coefficients of porous materials using two microphones and ambient noise,” *Applied Acoustics*, vol. 66, no. 7, pp. 845–865, 2005.

[34] K. Jambrošić, “In-situ measurement of the absorption coefficient,” in *40^o; congreso nacional de acústicaencuentro ibérico de acústicasimposio iberoamericano y europeo de acústica ambiental y edificación acústicamente sostenible*, 2009.

[35] P. Labein, S. Tug, A. Volvo, A. Kilde, M. Beuving, and B. Hemsworth, “Improved methods for the assessment of the generic impact of noise in the environment,” 2006.

[36] J. Smith III and J. Abel, “Bark and erb bilinear transforms,” *Speech and Audio Processing, IEEE Transactions on*, vol. 7, no. 6, pp. 697–708, 1999.

[37] “Frequency weighting equations,” September 2004. *http://www.cross-spectrum.com/audio/weighting.html*. Last accessed July 2012

[38] E. Zwicker, H. Fastl, U. Widnmann, K. Kurakata, S. Kuwano, and S. Namba, “Program for calculating loudness according to din 45631 (iso 532b),” *Journal of the Acoustical Society of Japan (E)*, vol. 12, no. 1, pp. 39–42, 1991.

[39] J. Martin, “Samples homogenization for interactive soundscapes,” Master’s thesis, Universitat Pompeu Fabra, 2011.

[40] B. Moore and B. Glasberg, “A revision of zwicker’s loudness model,” *Acta Acustica united with Acustica*, vol. 82, no. 2, pp. 335–345, 1996.

[41] W. Aures, “A procedure for calculating auditory roughness, acoustica 58 (1985),” *View Record in Scopus— Cited By in Scopus (47)*, pp. 268–281.

[42] R. Duisters, “The modeling of auditory roughness for signals with temporally asymmetric envelopes,” 2005.

[43] D. Pressnitzer and S. McAdams, “Two phase effects in roughness perception,” *The Journal of the Acoustical Society of America*, vol. 105, no. 5, pp. 2773–2782, 1999.

[44] P. Vassilakis and K. Fitz, “Sra: A web-based research tool for spectral and roughness analysis of sound signals,” in *Proceedings of the 4th Sound and Music Computing (SMC) Conference*, pp. 319–325, 2007.

[45] P. Vassilakis, “Sra: An online tool for spectral and roughness analysis of sound signals,” *The Journal of the Acoustical Society of America*, vol. 120, p. 3277, 2006.

[46] P. Vassilakis and K. Fitz, “Sra: A web-based research tool for spectral and roughness analysis of sound signals (version 2.0),” 2008.

[47] P. Daniel and R. Weber, “Psychoacoustical roughness: Implementation of an optimized model,” *Acta Acustica united with Acustica*, vol. 83, no. 1, pp. 113–123, 1997.