Project Number: DRB-0401

Multi-Channel Measurement and Analysis

of Noise Inside Automobiles

A Major Qualifying Project Report:
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of
WORCESTER POLYTECHNIC INSTITUTE
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The Degree of Bachelor of Science
in
Electrical and Computer Engineering
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Date: April 20, 2005

1. Automated
2. Recording
3. Bose

Approved:

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Letter of Transmittal:

Professor D. R. Brown **April 20th 2004**
Electrical Engineering Department
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Worcester, MA 01609

Dear Professor Brown:

Attached is one copy of the Major Qualifying report: **Multi-Channel Measurement and Analysis of Noise Inside Automobiles**, Project Number DRB 0401.

Sincerely,

Jeffrey Ford

George Roscoe

Joseph Vaughn

Abstract:

This project created a standardized system and procedure for measuring and characterizing car noise in a number of different conditions. First, a multi-channel noise acquisition system was developed for high fidelity recordings. Next, automated testing software was developed for easy, repeatable experiments in automobiles. Finally, the system was used in three distinct automobiles, data was collected and analyzed, and final reports were created utilizing the project's report generator.

Acknowledgments:

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Dr. Richard Brown III – Major Qualifying Project Advisor

Steve Laverty – Graduate Student WPI

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Everyone at Bose Inc. who has supported this project and made it possible

Executive Summary

Automobiles are being equipped with increasingly sophisticated communication, navigation, and entertainment systems. The functions of these "infotainment" systems can be complicated to control and their user interfaces can lead to unacceptable levels of driver distraction. Automotive manufacturers have begun to rely on voice control technology to allow drivers to effectively control these systems while minimizing driver distraction. The automobile cabin is, however, a difficult environment for voice control; high levels of background noise can lead to misinterpreted commands which, in turn, can lead to driver frustration and increased levels of distraction.

To improve speech recognition accuracy in automotive applications, it is important to understand the characteristics of the various noises present in the automobile cabin. One step in obtaining a better understanding of these noise characteristics is to obtain noise recordings from a variety of automobiles in a variety of driving conditions. This project developed a portable system and a repeatable procedure for obtaining multi-channel automotive noise recordings in a variety of driving scenarios.

There were three primary objectives of this project. The first objective was to design and construct a portable recording system able to simultaneously record four cannels at CD quality. The second objective was to develop automated testing and report generation software to standardize the test procedures and to provide a quick method by which detailed noise reports could be generated. The final objective was to test the system by collecting multi-channel noise recordings in three different automobiles in a variety of driving conditions.

The team achieved all three project objectives. A suitcase-based noise recording system was developed. All of the recording equipment including the laptop computer is contained in the suitcase for easy transport and the entire system can be set up in less than 15 minutes. Matlab software, including a full graphical user interface, was developed to automate the pre-test, in-test, and post-test recording phases. The Matlab software also automatically generates standardized .html reports with options for temporal, spectral, and spatial analysis results. The recording system and software was also successfully used to obtain several multi-channel noise recordings from three vehicles: a 2000 Jeep Cherokee, a 1995 Honda Civic, and a 1992 Buick Regal.

This project developed a system by which additional multi-channel automotive noise recordings can be repeatedly obtained and analyzed. It is expected that this system will be a useful tool towards the ultimate goal of perfect speech recognition in the automobile.

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1 Introduction

As automobiles are equipped with increasingly sophisticated communication, navigation, and entertainment systems, automotive manufacturers have begun to rely on voice control technology and hands-free technology to reduce driver distraction. Once available only on luxury automobiles, voice control technology and hands-free technology are now available in a wide range of 2005 model year automobiles from a variety of manufacturers. While voice control systems in different automobiles may have different levels of sophistication, they all operate on the basic principle of recognizing speech and converting the speech into a desired action. The accuracy of the speech recognition process is critical; drivers are less likely to use a voice control system if it often misinterprets commands [1].

While voice control is a fairly simple problem in a quiet environment, it is considerably more difficult in a noisy automobile cabin. Speech recognizers are much more likely to misinterpret commands when the speech is corrupted by high levels of background noise [2]. In order to improve recognition accuracy in automotive applications, it is important to understand the characteristics of the various noises present in the automobile cabin and to design recognizers to be robust to noise with these characteristics.

In order to understand the noise characteristics, it is necessary to obtain noise recordings from a variety of automobiles in a variety of driving conditions. This noise characterization effort involves recording car noises in a wide range of operating conditions in several different types of automobiles. The data can then be characterized, and solutions can be discovered that will filter out much of the external noise. This information is invaluable for designing accurate, user-friendly voice-recognition systems.

The measurement and characterization of automobile noise is not a new initiative; research on this subject has been done in the past. For example, a group from the University of Colorado completed a study to determine optimal placement of a voice recognition microphone array. More recently, in 2004, a team of Worcester Polytechnic Institute (WPI) students, working in the WPI Signal Processing and Information Networking Laboratory (spinlab), attempted to measure the noise in cars using a system of microphones and a preamp hooked up to a laptop [3]. The WPI team was successful in many aspects of the project. However, their system was cumbersome to arrange inside of an automobile, with a setup time approaching an hour and a half. In addition, the system that was not automated, which placed a large burden on the user to acquire the data. Furthermore, the system was not very robust—many parts would break if dropped. Finally, the data was overshadowed with fan noise, as well as electrical noise, both emitted from the system itself.

This particular project, also completed in the WPI spinlab, addressed the problems of the previous project, and made considerable improvements. The project goal was to create a standardized procedure for measuring and characterizing car noise under a number of different conditions using a portable system. The final system is both durable and portable, and can acquire four, high fidelity, 16-bit, 44.1 kHz, channels simultaneously. The system has a setup time of less than fifteen minutes, and includes automated testing and report generating software. These attributes combine to create a system that can facilitate repeatable, accurate testing.

2 Background

This section provides background information necessary to understand the methods and results. Similar past projects were researched and compared for valuable information. Then, the technologies of the hardware necessary for the system were researched. Finally, the section discusses noise characterization and what types will be used in this project.

2.1 Prior Work on Multi-channel Noise Collection and Characterization

A number of projects have been done in the past taking multi-channel recordings in automobiles. Projects have been completed in the UK, the University of Colorado, and at Worcester Polytechnic Institute. Studying these past projects and the methods in which they collected their data can help guide the direction of this project.

2.1.1 Colorado University In-Vehicle Speech Recognition

In the year 2000 a group of students from Colorado University did research into speech recognition in cars using noise characterization much like that which is needed in this project [1]. The focus of this project was on the collection of the noise more than the analysis. The team used five microphones connected to a multi-channel data-recording house developed by Fostex. The brand and type of microphone was not discussed in the report. The multi-channel DAT accepts the analog microphone signal, amplifies it, and converts it to digital all in one box. A Fostex D15-DAT recorder costs over $3,000 [2].

The testing was done on eight different vehicles including a compact car, minivan, cargo van, sport utility vehicle, compact and full size trucks, sports car, and a full size luxury car [3]. The team used a fixed 10-mile route including city and highway driving with mixes of stop and go traffic. At prescribed locations, driver and passenger windows, turn signals, wiper blades, and air conditioner were operated. These same variables need to be used in this project.

The group eventually used this data to create a way to sense the changing environment. The project was used to move towards sharpening the audio signal of a voice and making the voice recognition more efficient [4]. The Colorado University project is similar to this one in that this, too, will use a sedan, SUV, and a compact car. Many of the same variables, such as windows down and air conditioning will also be tested.

2.1.2 Princeton, NJ Multi-channel Voice Detection

In 2002, J. Rosca, R. Balan, and N.P. Fan at Princeton University completed a multi-channel recording project. The name of their project was *Multi-channel Voice Detection in Adverse Environments* and included voice recognition in automobiles [5]. Instead of the multi-channel recording system being the focus of the study, the focal point of this paper was on the analysis techniques.

The system used to make the recordings was not specified other than the fact that there were two or more microphones. The team completed a number of tests on the recorded signals to attempt to find what could be filtered out. The tests included power spectral densities, time vs. frequency plots, and direction of arrival. The most important finding with regards to this project was that the most appropriate analysis technique for detecting unwanted noise was direction of arrival.

2.1.3 CSLR Speech Corpora

The Center for Spoken Language Research (CSLR) department in Boulder, Colorado completed a study focused on noise collection in 2002. In this case, a multi-channel, portable recording system was developed so that people could give speeches and lectures while in a completely different environment than their listeners [6].

One of the environments used was a car. The car chosen was a Chevy Blazer. The corpus consists of speech collected from speakers from across the United States in the SUV using an unspecified 8 channel digital recorder, microphone array, reference microphone, cell-phone, and AKG/OnStar microphone. In relation to the current project, the CSLR team shows that the use of a digital recorder is a convenient, all in one option for multi-channel recordings and should be considered.

2.1.4 Worcester Polytechnic Institute

In 2003, a group of WPI students worked with Bose Inc. on a multi-channel noise collection and characterization system [7]. This system was designed for multi-channel recording inside an automobile. The basic setup was a laptop PC acting as the central processor with a USB analog to digital converter connecting the microphones to the laptop. These microphones were used to gather data from six different cars. The group designed algorithms to analyze the recordings, draw conclusions and find any recording issues.

The system the group chose to use, the microphones, external analog to digital converter, and laptop, was a portable and inexpensive way of completing multi-channel recordings. The WPI team, however, ran into difficulties when designing this project's system.

First, the system was not very robust. All of the equipment was carried separately to the car and needed to be connected before testing. Second, the team used a power inverter with a fan to power the system. In order to stop the noise from affecting the hum from the fan had to be suppressed in the back seat of the automobile. The team also had a 60 Hz interference in their recordings due to using a modified sine wave inverter rather than a pure sine wave.

2.2 Recording System Technologies

In addition to studying past projects, it is also important to discuss the current technologies in the hardware that will be needed to complete this multi-channel recording system. The section will compare and contrast different types of microphones, pre-amplifiers, sound cards, and power inverters. For this project, it is important to find products that perform well enough to make strong, useful recordings while maintaining a given budget of $2000.

2.2.1 Microphone Technology

Microphones are one of the most important parts of the recording system design. Microphone technologies are broken into two main topics: the way they record sound and the way they interface with the rest of the equipment. First, the methods of interfacing will be discussed.

2.2.1.1 Microphone Interfacing

The electrical interface of a microphone specifies its signal characteristics, impedance, and power requirements. The interface also partly determines the overall immunity of the recording system to electrical noise. The electrical interface of the microphone also must be compatible with the preamplifier. There are two common interfaces for microphones: XLR and TRS.

Exchange Line Resistor

The exchanging line resistor, or XLR, connector is commonly seen in the recording industry for microphones and instruments [8]. An XLR interface utilizes a three-pin connector, as shown in Figure 2.1.

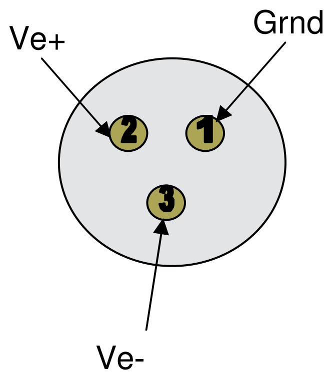

Figure 2.1: XLR connector numbering.

The specific pin designation is pin-1 common ground, pin-2 audio high and 24V DC, and pin-3 low and -24V DC (Figure 2.1). The unbalanced version is slightly different, with pin-1 being ground, pin-2 being a 30V DC input, and pin-3 being audio high. The Audio Engineering Society (AES) published the XLR standard in 1992[9]. The power to the microphone is usually provided in the form of "phantom power" from a preamplifier.

The most common XLR pin designation for microphones uses phantom power. This is a method of providing microphones with a bias voltage directly through the signal lines. Pin 1, in this case, provides the shield and negative supply while pin 3 is responsible for the negative polarity.

Most XLR microphones are larger in size than the TRS option. The microphones are usually more sensitive and more expensive than other interfacing technologies. Most XLR microphones are also relatively expensive.

Tip Ring Sleeve

Another standard electrical interface is the Tip Ring Sleeve (TRS). The tip ring sleeve connector comes in 3 different sizes: 2.5 mm, 3.5 mm, and 6.5 mm. The TRS connector, as indicated by its name, is broken into the three sections, the tip, the ring, and the sleeve (Figure 2.1). The tip is the non-inverting wire, the ring is the inverting wire, and the sleeve is the ground wire. Tip ring sleeve connections can come with mono or stereo recording capabilities [10].

The ring in a stereo connector is used for the right non-inverting signal, but in mono signals it is used, as mentioned above, for inverting the input. The ring is injected with a 5V polarizing voltage for the microphone. This supplies the bias voltage needed to record sounds. One big advantage to using TRS technology is that most soundcards use a 3.5 mm TRS input, meaning that any other connection technology would have to be converted to TRS before being input into the soundcard. Therefore a microphone without a TRS connection could create unwanted noise in the signal.

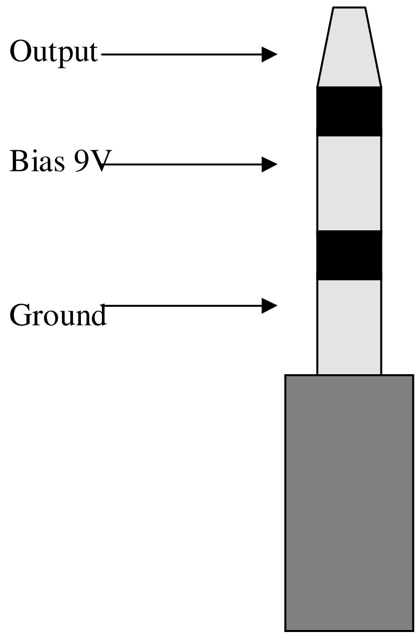

Figure 2.2: Breakdown of a TRS plug.

2.2.1.2 Microphone Transducer Technology

With the different connections, there are two types of microphone recording technologies used today, namely condenser and dynamic. Dynamic microphones convert acoustic signals to electric signals using a cone and a coil. The coil is connected to the cone diaphragm through the magnetic field, creating the electrical representation of the noise recorded [11]. The design's advantage is that it is robust and inexpensive. A large disadvantage, however, is it does not have a uniform frequency response [12].

The condenser microphone operates differently than its dynamic counterpart. The microphone has a metallic membrane connected to a back stationary plate. This forms a capacitor and a DC bias voltage is applied across the plates of this capacitor.

Speaking into the microphone causes the plates to move slightly, which causes the capacitance to vary and creates a current through the resistor. This current makes the electrical signal that simulates a diaphragm. The advantage of this method is that it generally generates a much flatter frequency response than a dynamic microphone. The disadvantage is that condenser microphones are usually more expensive than their dynamic counterparts and require a bias voltage.

2.2.2 Preamplifier Technology

Preamplifiers provide an interface between the microphones and the rest of the recording system. The main purpose of the microphone preamplifier is to amplify the signal of the microphone to a level that can be read by recording hardware and, in some cases, provide the bias voltage. Occasionally, soundcards have built in preamplifier, but these tend to be lower quality than standalone preamplifiers. Preamplifiers differ in their number of inputs and outputs, level of amplification, and their interface.

There are two main types of standalone preamplifiers, tube and solid state. A preamplifier tube (or valve) is an electronic device that amplifies the sound signal. The disadvantages to tube preamplifiers are that they are heavy, have a large power consumption, replacement tubes are expensive, and they can not be used in the cold. A solid-state preamplifier uses transistors to amplify the sound. These preamplifiers tend to be more reliable, less expensive, much smaller than tube preamplifiers, and are more applicable for portable/ automotive applications

2.2.3 Multi-channel Analog to Digital Converter Technology

The A/D converter is an important part of a sound recording system because it can limit the quality of the final signal. The quality of the converter depends on its sampling rate, bit resolution, and digital interface to a computer.

Common audio sampling rates are 44.1 kHz, 48 kHz, and 96 kHz. As expected, the higher the sampling rate, the more expensive the converter. A signal needs to be sampled at a rate at least twice that of the highest frequency recorded. This is called the Nyquist rate. Since audio equipment is made to record up to 20 kHz, there is not much need, for the specifications of this project, to have a sampling rate much over 40 kHz [13].

The main factor in the performance of an A/D converter is its resolution, often expressed in bits. An A/D converter essentially divides the analog input range into 2^N bins, where N is the number of bits. In other words, resolution is a measure of the number of levels used to represent the analog input range and determines the converter's sensitivity to a change in analog input. Because higher resolution A/D converters cost more, it is important to not buy more resolution than you need.

The two main connections from the A/D converter to a computer are Firewire and Universal Serial Bus (USB). Both technologies have sufficient throughput for multi-channel audio recording and selection is mostly a matter of convenience.

2.2.4 AC Inverter Technology

Most professional recording equipment requires 120 volt AC power. This voltage is usually not available in an automobile. An inverter solves this problem by converting the 12 volt DC voltage available in the car to 120 volt AC. To obtain the highest quality recordings, it is important to use an inverter that produces an AC power waveform that has minimal distortion.

The two primary types of DC to AC inverter outputs are "modified square wave" and "pure sine wave" [14]. The modified square wave inverters are inexpensive and work well for most applications. The output of one of these is more like a square wave than a sine wave. Figure 2.3 clearly shows the difference between a modified square wave and a pure sine wave as measured. For the test in that figure, a modified spare wave inverter and a pure sine wave inverter were plugged into a wall socket. The disadvantage to a modified spare wave is that it causes harmonics of 60 Hz that will interfere with the signals being recorded in an automobile. A pure sine wave, conversely, does not create any harmonics.

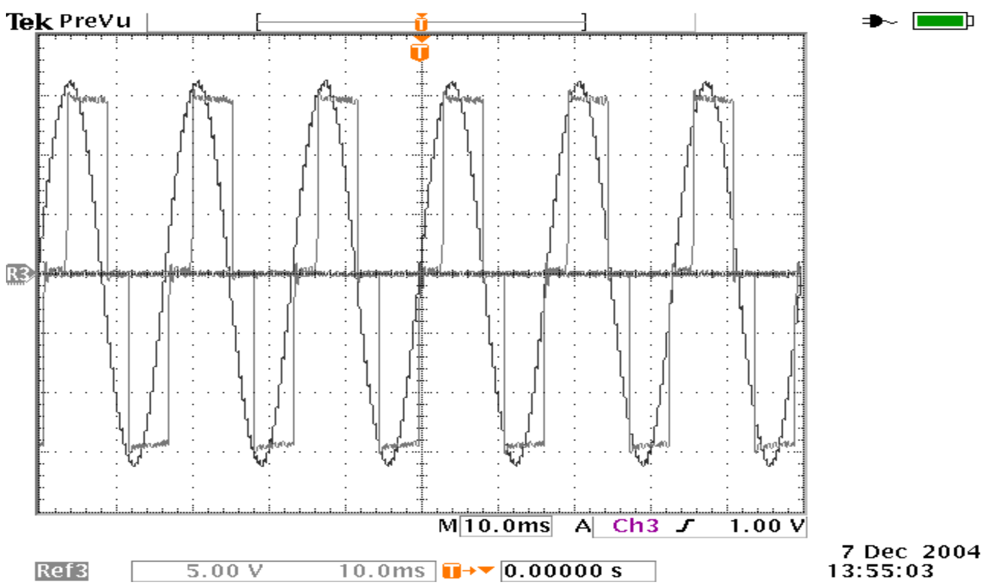

Figure 2.3: Modified sine wave vs. pure sine wave.

2.3 Noise Analysis/Characterization

In addition to collecting multi-channel vehicular noise samples, a major goal of this project is to characterize the noise in the vehicles. The major sources of noise inside of an automobile include:

- Engine: crankcase, oil sump, cylinder head, tappet covers, timing gear and its cover, engine mounts
- Exhaust system
- Intake system
- Transmission

- Fan and cooling system
- Tires
- Body panels
- Wind

The three types of characterization used in this project are temporal, spectral, and spatial. Temporal characterization relates the signal to time, spectral characterization examines the frequency content of the signal, and spatial characterization describes what direction the noise is striking the microphone array.

2.3.1 Temporal Characterization

Temporal characterization refers to characterizing signals with respect to time. A common type of temporal characterization is autocorrelation [15].

2.3.1.1 Autocorrelation

Autocorrelation is defined as the comparison of a variable with itself over successive time intervals. This means the function compares the value at a time instant of a single stochastic process with the value measured in an earlier time interval and takes the average for the whole time scale [16]. The function provides more detail about the internal properties of a signal and can show the presence of a periodic component. It also shows the similarity of a signal with time shifted versions of itself. In this project, it will be assumed that the noises in the car are stationary. The equation for autocorrelation is below.

$$R_{xx}(\tau) = E[x(t)x(t-\tau)]$$

2.3.1.2 Cross Correlation

Cross correlation is defined as the comparison of the time series x(t) and y(t), where x and y may represent the same variable measured at different locations, or a single variable measured at one location but at different times, as for the case in which y(t) represents x(t + L), where L is a specified time lag. In such cases, the two variables are usually not statistically independent and large cross correlations between x and y can result.

2.3.1.3 Time Plots

There are two useful time plots that are used for characterization. The first is the signal level vs. time. This is the standard time-domain plot of the recorded signal with time on the x-axis and amplitude on the y-axis. This plot shows clearly any times at which there is a large power spike. The other useful time plot is the smooth signal power vs. time plot. This indicates the power of the signal over time, smoothed by a windowing function. This attempts to eliminate small spikes, which are most likely just anomalies in that recording.

2.3.2 Spectral Characterization

A common method of characterizing the frequency content of stationary noise processes is the Power Spectral Density (PSD). The PSD indicates the amount of power in any frequency interval.

2.3.2.1 Power Spectral Density

The method used for PSD in Matlab for this project is Welch's method. It works by dividing the signal into equal segments and averaging the squared-magnitude of the direct

Fourier transforms of the signal blocks. The overlaps can be as large as 50-75% of the given signal. These large blocks allow for less variance and improved resolution [17].

2.3.2.2 Spectrogram

A spectrogram is a visual representation of an acoustic signal especially useful for non-stationary noise where the frequency content is changing over time. In the spectrogram itself, the vertical axis represents frequency, typically with 0 Hz at the bottom and the maximum frequency at the top. All of the spectra computed by the Fourier transform are displayed parallel to this vertical, or y-axis. The horizontal axis represents time. Either a grayscale or color pattern can be used to indicate varying levels of power along the axis.

2.3.3 Spatial Characterization

Spatial characterization is different from temporal and spectral in its behavior, as it involves signal paths. The spatial analysis can involve just the direct path of the signal, multi-path propagation, or signal bouncing off of media [18]. This project will analyze the direction of arrival. This information could be used to eliminate noise signals not arriving from the same direction as desired speech.

Direction of arrival (DOA) analysis exploits the microphone array's ability to "look" in a particular direction by combining the microphone signals in an optimal way. By forcing the microphone array to sequentially look over a range of directions, and then computing the received power in each look direction, it is possible to form a picture of the received power as a function of the angle of arrival. This information can then be used to tune the array to cancel out undesired noises while emphasizing the desired speech in the system.

The key step in all DOA analysis is the formation of the set of array weights that forces the array to look in a particular direction. There are many known techniques for the calculation of the array weights with varying levels of resolution and computational complexity. Two of the most common methods are "conventional beamforming" and "minimum variance beamforming." The minimum variance beamformer is slightly more complicated to compute but tends to provide sharper DOA estimates. [19]

Microphone array and multi-channel measurements facilitate spatial analysis of the noise in the automobile cabin. Spatial analysis can be used to determine the direction of arrival of noise sources. If the direction of arrival of noise is different than the direction of arrival of the desired speech, beamforming techniques can be used to suppress the noise without adversely affecting the speech.

There are many methods by which spatial analysis can be performed. One method with reasonable complexity and good overall performance is called "Minimum-Variance Beamforming."[20] The minimum variance beamformer computes the power received by the antenna array in frequency bin f at "look angle" a, assuming plane wave propagation. The look angle is defined as shown in Figure 3.4 where we use the convention that $\pi/2$ corresponds to the direction perpendicular to the linear array.

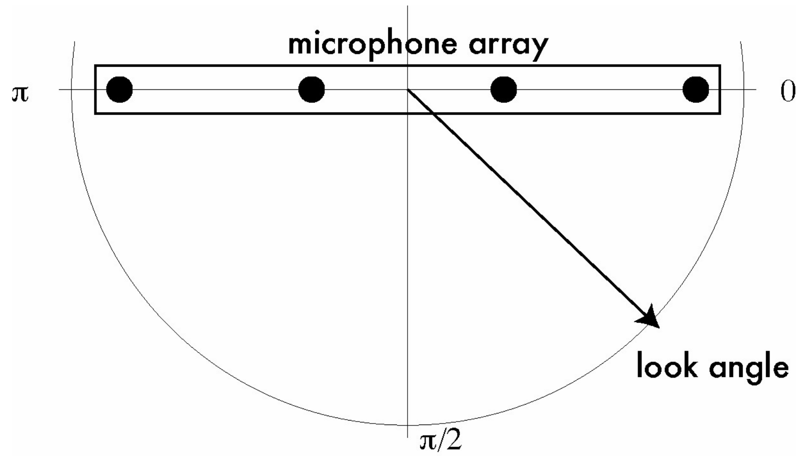

Figure 2.4: Microphone array.

The first step in the minimum variance beamforming method is to compute the "spatial autocorrelation matrix" at the desired frequency *f*. This is accomplished by taking windowed short-time Fourier transforms of each channel, picking out the term in the FFT corresponding to the desired frequency *f*, and then computing the correlation between each channel at this frequency. The resulting spatial autocorrelation matrix is denoted as ***R*** and is Hermetian symmetric with four columns and four rows.

Once the spatial autocorrelation matrix has been computed at the desired frequency *f*, the steered response of the array can be determined at the look angle a. A four-element steering vector, denoted as ***e***, is generated for the desired look angle and frequency. This steering vector represents the ideal response of the array to a complex exponential at frequency *f* arriving from angle a. The resulting power in the beamformer is just a function of the steering vector and the spatial autocorrelation matrix and can be written as

$$P(f,a) = \frac{1}{\mathbf{e}\mathbf{R}^{-1}\mathbf{e}}.$$

By sweeping the look angle from –0 to π, a profile of the power received by the array at each look angle (for frequency *f*) can be formed using this technique.

3 Methodology

This section of the report examines the processes and tests that were used to develop, build, and validate the final noise recording system. This will encompass both the hardware and software of the system. This section also describes the exact testing method undertaken in the automobiles. Specifically, the following sections will be addressed: system development, system construction, system automation, procedure, and system validation testing.

3.1 Multi-channel Noise Acquisition Hardware Development

When developing a noise analysis system to be used inside of an automobile, there are many considerations to be made. This section will explain the specific system requirements, a comparison of basic system approaches that could be used, and then explain how the chosen system is to be used inside of the automobile to take recordings.

3.1.1 Requirements

The goal of this project is to create a portable system to obtain multi-channel noise within a vehicle. Therefore, there are certain requirements that must be met. The following goals were developed for the system:

- *Durable*—the system should withstand all of the elements during transport to the vehicle, and remain intact during vehicle testing.
- *Portable*—the system should be easily carried to and from the test vehicle by one person of average strength. The system should fit easily into any vehicle and sit comfortably on the user's lap.
- *Short set-up time*—less than 15 minutes.
- *Intuitive and ease of use*—the user should be able to fully understand the system and test procedure after reading the user's manual.
- *Self powered or automobile powered*—the system has to be powered inside of a moving vehicle.

- *Daytime visible display*—all visual displays must be seen clearly, even when in direct sunlight.
- *Low cost*—less than $2,000 US.
- *Quality audio measurements*—16 bit, 44.1 kHz recordings.
- *Multi-channel recording*—minimum of four simultaneous recordings.
- *Completely automated testing*—the user must have control over the tests, but the software will prompt the user during testing.
- *Report generation*—a report of the test must be generated to the user's specifications after the completion of the tests.
- *Facilitate repeatable testing*—the tests should run smoothly, so that multiple tests can be completed quickly and accurately.

All of these specifications were taken into account when the system was designed. Every requirement was met, with the exception of the daylight visible display. This was due to budget constraints, and will be discussed in Section 2.1.2.4.

3.1.2 System Approaches

When examining the best method for implementing an easy-to-use system to test automobile acoustics, it is necessary to inspect several different approaches before making a final decision. Cost-benefit analysis was used to determine which system would meet the requirements and could be built within the scope of the project. There are several different types of portable audio field recorders currently on the market. This section will examine which method will be best suited for current needs. Table 3.1 shows an overview of each approach that will be discussed in the following sections.

Table 3.1: System approach pros and cons.

System	Pros	Cons
Dedicated multi-channel recorder (analog) For example: Fostex D15-DAT	Small, very portable Single unit, pre-assembled Battery powered Daytime visible display Durable	Require additional hardware and software Need multiple units Poor quality (low sampling rate) High cost Synchronization
Dedicated multi-channel recorder (digital) For example: Portadrive	High number of channels Single unit, pre-assembled Battery powered Daytime visible display Durable	Very high cost
Computer based system No example available	High degree of specification	Very high cost Fragile computer parts Heat
Laptop based system For example: 2003 WPI/spinlab Team	High degree of specification	Laptop cost Not daytime visible Less durable

3.1.2.1 Dedicated Analog System

One option for multi-channel noise recording is analog recorders. The recorder would do the field recording and then be interfaced with a computer to analyze the results. One such analog recorder is the Professional Portable Cassette Recorder (PMD222) with XLR microphone input by Marantz [1]. The specifications for the PMD222 include a ¼'' headphone output jack, and an unbalanced microphone and RCA. The frequency response includes a range of 40Hz-12000Hz. The device lasts 5.5 hours with one set of alkaline batteries or approximately 4 hours with rechargeable cells. This device also has 2-speed recording and a built-in condenser microphone.

The main issue with analog or cassette recorders is that they require additional software and hardware, as well as time, to convert the analog recordings to digital files for post processing and analysis. The purchasing of more equipment is expensive and the cost of the recorders alone is approximately $400.00 for each unit. This design would require four recorders to accomplish the task, putting the project well over budget. Furthermore, synchronization of the recordings, for the purposes of analysis, would be difficult. Due to these drawbacks, a dedicated analog system approach was not utilized.

3.1.2.2 Dedicated Digital System

In addition to analog recorders, there are also digital recorders. An example of an all-in-one recorder is the HHB Portadrive. The Portadrive is an 8-channel multi-recorder that can sample up to 96 kHz. The audio is recorded in either *.bwf or *.sdii formatted files. The advantages of this device are that it has six high gain XLR-3 microphones and has USB/Firewire that allows the hard drive to be interfaced with a PC. The downside is a price of approximately $1500.00, which exceeds the budget allotted for this project [2].

Another slightly different version of a digital recorder is the HHB MDP500 MiniDisc recorder, which uses a 44.1KHZ-sampling rate. It uses XLR connectors for the microphones. This device also has a USB interface, but costs around $1600.00. Again, the cost is too much for the scope of this project, as it would limit the rest of the equipment that could be used.

Overall, there are many problematic issues that arise when using the analog or digital recorders that prevent them from being a viable option. Most of the issues involve pricing and portability. Each of these recording systems costs over $1,000.00 and requires additional hardware to analyze the data produced. The price and feasibility alone makes this option less appealing than the solution proposed by the 2003 WPI team. The other major issue is the portability. For example, the PMD222 is not standalone and therefore must constantly be moved around to computers to analyze the data. The system would also have to be in four non-synchronized locations, making time sensitive analysis difficult. Again, due to these drawbacks, a dedicated digital system approach was not utilized.

3.1.2.3 Custom Personal Computer Based System

Since there are no current systems available on the market that can directly analyze noise and meet the portability requirements of the project, the possibility of a custom system was researched. A portable stand-alone recording system can be broken into six specific areas: preamp/audio input, microphones, display, power supply, motherboard, and storage space. All of these components can be made to be fan-less, creating a completely noiseless system. The system could be made to be durable and able to fit into a car. There is also flexibility in choosing the hard disk size, processor speed, and fan-less components.

Unfortunately, even though the computer parts could be mounted inside of a portable case, many of them are still fragile, and there is the issue of the system overheating. Furthermore, the system construction would be very complex, and the overall system would be very large. This would make troubleshooting the system inside the vehicle very difficult.

Finally, there is concern for the display. The display would have to have a high enough resolution to see any applications running, and the screen would have to be daytime visible. Daytime visible displays that would be compatible for computer use are very expensive; the entire system cost would well over the budget.\

Although this system approach would be the best suited for the project, it is not feasible. Budget constraints, as well as time restraints for building the system make this approach unfeasible.

3.1.2.4 Custom Laptop Based System

Finally, a laptop recording device was researched. The 2003 WPI team used a laptop as the recorder along with a USB interface device to convert the microphone's input into a format the computer could read. In their report, the team stated, "Equipped with a high-quality sound card and multi-track recording software, the laptop can be an economical solution, especially if you already own the laptop. Popular pro-level laptop sounds cards include those made by Digigram and Echo."

The system envisioned for this project is a suitcase that houses all necessary equipment for the testing. This ensures that the system will be both portable, durable, and have a short set-up time. The system would be powered from the car's power supply, and a laptop would be used as the primary user interface. While using a laptop makes the system very portable, versatile, and accurate, it does not meet the daytime visible requirement. However, after evaluating all of the options, it was determined to be the best method within the budget requirements of the project.

3.1.3 System Construction

After the approach for the system had been selected, the system was designed and constructed. This section outlines those steps in the following manner: the components used in the final system, the layout of the system, the power and signal flow of the system, the system validation testing, and how the system is used in the automobile.

3.1.3.1 System Design

The final system was designed using the laptop based system approach. As illustrated in Figure 3.1, the system is housed within a suitcase, and the laptop rests on top. Outside, the system's data collection starts at the microphones. There is also a power supply, which is placed outside the system. Inside of the suitcase is a DC bias and pre-amp for the microphones before the signal enters the sound card. Finally, the analog to digital converter sends the final signal to the laptop for recording.

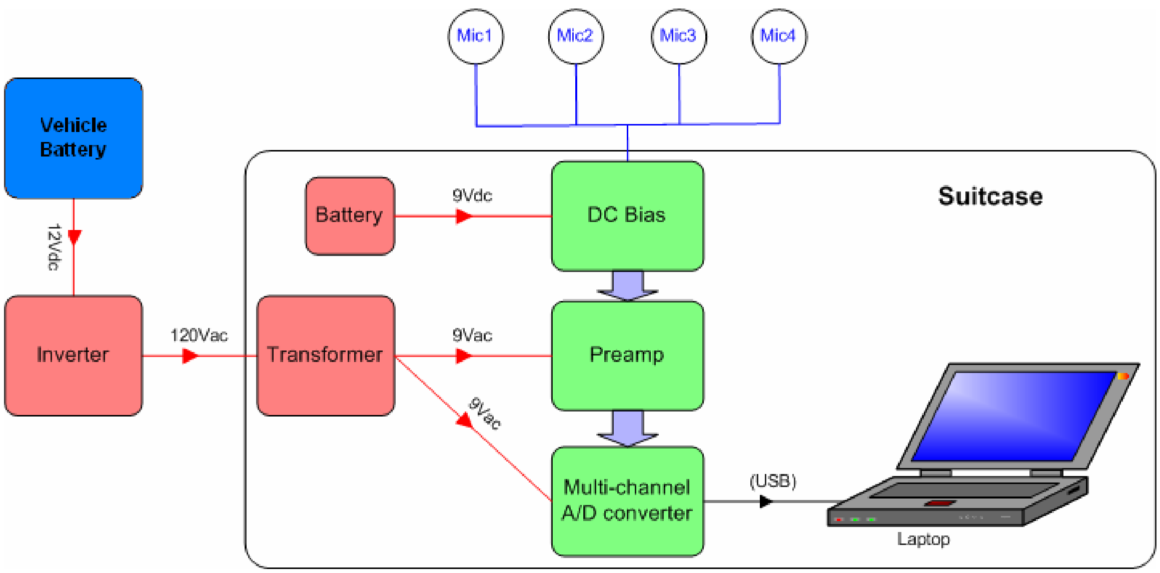

Figure 3.1: Hardware block diagram.

Now that the basic system has been defined, the parts can be specified. Table 3.2 is the part list used for this project.

Table 3.2: Part list

Part Name	Manufacturer	Part Number	Weight (lbs)	Quantity
Inverter	Samlex America	PST-15S-12A	2.5	1
Microphones	Shure	AU1000	N/A	4
DC Bias	Custom MM Series	CBM-1	0.2	4
Pre-amplifier	M-Audio	Audio Buddy	0.5	2
Multi-channel A/D converter	M-Audio	Quattro 44	1.7	1
Suitcase	Mezzi	Traveler Edition Roller Aluminum Laptop Case	9.5	1
Laptop	Dell	Inspiron 5156	5	1

The microphones are Shure AU1000, chosen because of their small size and portability. Furthermore, the microphones boast an excellent dynamic range of 20 Hz to 20 kHz, well beyond the necessary frequency range for voice recognition. The microphones require a 9 Volt DC bias and amplification to allow the multi-channel A/D converter to record the data.

The microphone signals are amplified with two M-Audio Audio Buddy microphone pre-amplifiers. The Audio Buddy pre-amplifiers have two microphone inputs with gain control. They also contain phantom power, which supports the bias for the microphones. The Audio Buddy is the most cost effective of the pre-amplifiers, and has very few gain knobs, preventing accidental setting changes. The pre-amplifiers also have ¼'' outputs that require a soundcard for computer interfacing.

The chosen analog to digital converter is the M-Audio Quattro 44, which is a USB A/D converter. While most PCI A/D converters require a breakout box for inputs, the M-Audio Quattro 44 is a one box solution. The A/D converter is connected via USB to the laptop, which will run the automation software, store the recordings, and generate the report.

The Samlex Inverter is used to convert the 12-V DC automobile power supply into a 120-V AC pure sine wave. It is also rated at 150 Watts, which is enough to power the entire system. The details of this are explained in Section 3.1.3.2 of the report.

3.1.3.2 Power & Signal Flow Considerations

In designing the system, it is important to consider the power requirements of each of the components in order to ensure that the power supply is not overloaded. The power consumption of the components of this system is shown in Table 3.3.

Table 3.3: Component wattage.

Component	**Maximum Wattage (W)**
Dell Inspiron 5156	60
M-Audio Quattro USB Sound Card	10
M-Audio Audio Buddy Preamp	10
DC Bias Boxes	1
TOTAL	*81*

The total power necessary for the system is at most 81 Watts. The Samlex Inverter is rated for 150 Watts, which is more than sufficient for this system. This will ensure that the system will never be underpowered.

The overall suitcase layout was designed so that the signal wires are routed separately from power wires. Although the power supply is stored inside the suitcase, during recordings it can be removed from the suitcase. These conditions, along with the isolated power strip within the suitcase, will help insure that noise will not be introduced into the system. A power and signal flow diagram can be seen in Figure 3.2.

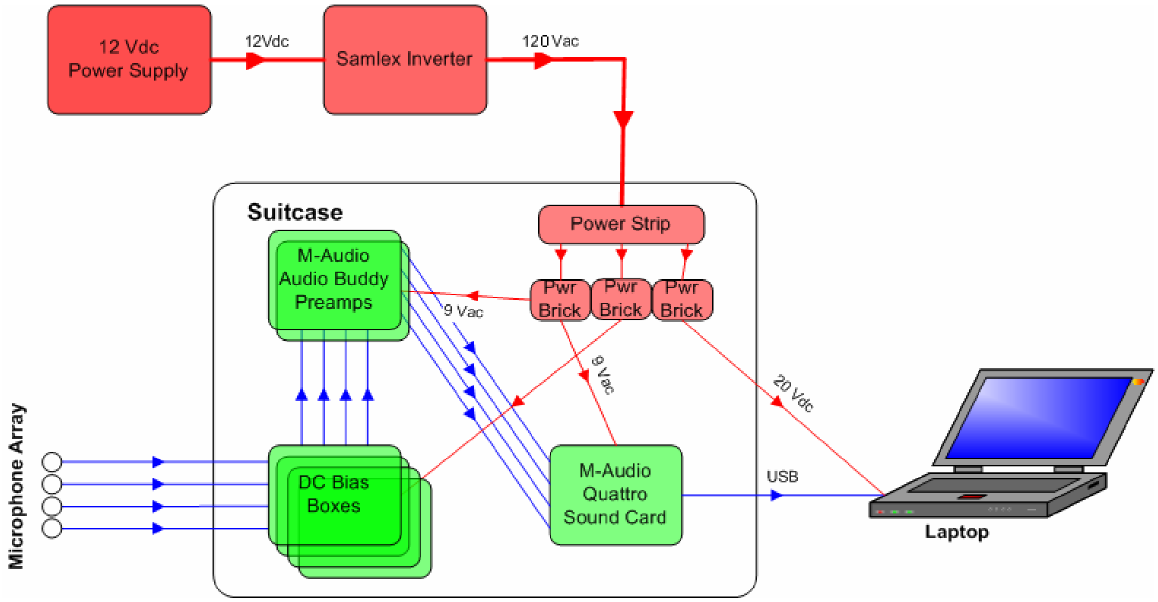

Figure 3.2: Signal and power flow diagram.

Using the Figure 3.2, the final layout of the system was designed. The finalized layout can be seen in the Figure 3.3.

3.1.4 System Layout Specifications

It was decided that the system's user would be sitting in the passenger seat during testing with the system in his or her lap. Therefore, because the microphones are connected directly to the microphone DC bias, it would be easier for the user if the microphone DC bias was located on the left side of the suitcase. This would ensure that the microphone plug would be located near the center console, allowing the microphone array could be placed nearly anywhere within the car, with little wire crossing.

With this aspect in mind, different layouts were examined, keeping in mind the power and signal flow considerations from Section 3.1.3.2. Figure 3.3 is a picture of the finalized mechanical layout.

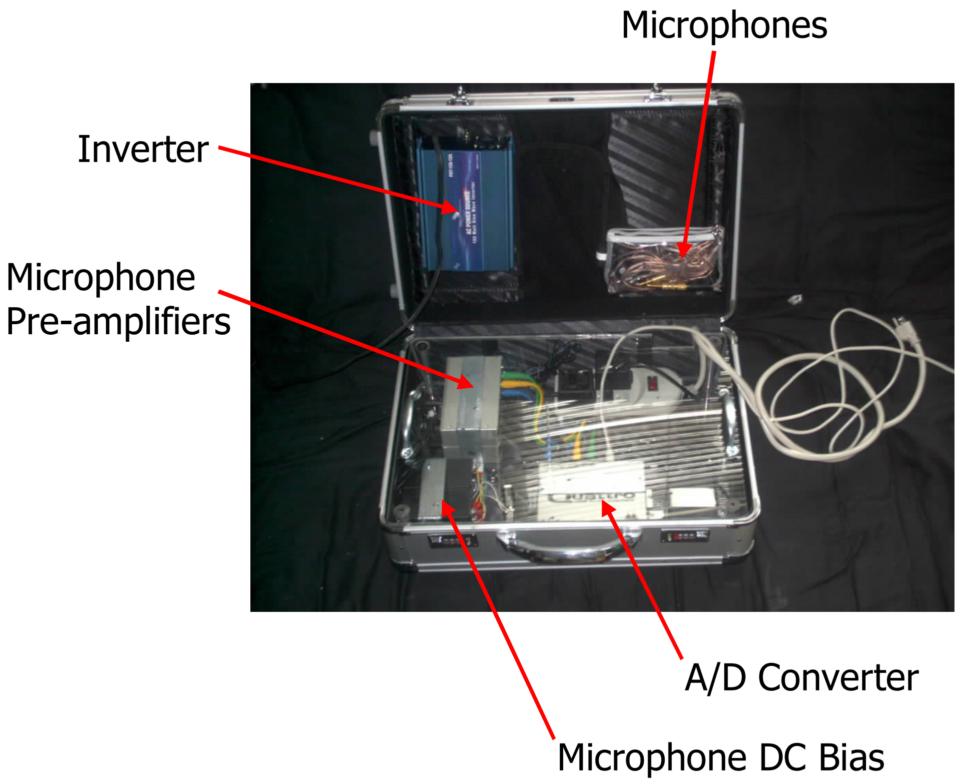

Figure 3.3: Mechanical layout of the suitcase.

The A/D converter, microphone DC bias, and microphone pre-amplifiers are mounted with aluminum straps to a sheet of 3/8" thick Plexiglas. Standoffs are attached at the four corners of the Plexiglas, and another sheet of Plexiglas is mounted to the top. This allows the user to monitor the system, and easily dismantle it if there is a malfunction. Two handles are attached to the top sheet, to allow the user to remove the bulk of the system from the suitcase.

The inverter and microphones displayed in Figure 3.3 are attached to the suitcase via Velcro. During testing, both are removed from the suitcase. The laptop, not pictured, rests on the top sheet of Plexiglas.

3.2 Multi-channel Noise Acquisition Software Development

Once the physical system was built, software was designed to acquire the data and analyze it. To do this, Cakewalk Sonar 3 Studio Edition was used as a multi-channel recording device, and a Matlab program was designed. This Matlab program has a graphical user interface (GUI) that gives the user control over the general information before the test, automobile tests to be performed, and what mathematical graphs are generated. This will be referred to as the pre-test, in-test, and post-test. All the data and graphs are then combined together in a single HTML report as will be explained in Section 3.2.3.

3.2.1 Pre-test

The first section of the GUI requires the user to input general information and vehicle information. This information is optional and can be filled out prior to testing. All data is input into text boxes except for weather, wind, and transmission, which are drop boxes. This can be seen in Figure 3.5.

To further organize this data it is categorized into two sections: general information and car information. General information consists of road conditions, the date, the name of the testers, the location of the test, and the weather. The second section consists of the car information such as car make, engine, tires, and type of transmission. Also included in the car section is a place for comments, allowing for any other information the user wishes to have in the final report that may not have fit into the other information boxes. Figure 3.4 shows the pretest controls in detail.

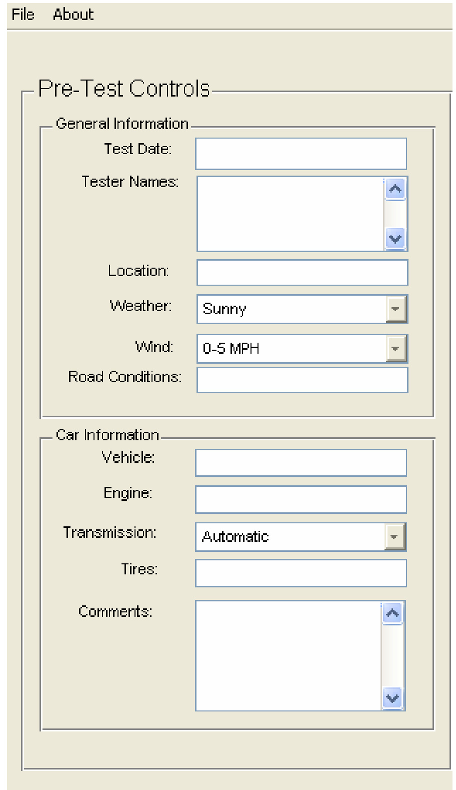

Figure 3.4: Pre-test GUI.

The reason for this design of text boxes is to allow user flexibility in the data. The inclusion of text and drop boxes also allows for reading of the data and storage as variables as MAT files. These MAT files can then be saved and loaded. A save and load feature is used that reads the text and drop boxes and then assigns each box to a global variable. These variables are then saved in the MAT file with a name chosen by the user. These saved files can then be loaded at a later time, or at the start of a test. The reason for this feature is to allow the user to complete the pretest data in the office and save time on the road.

3.2.2 In-test

Upon the completion of all the pre-test information, the next phase was to implement the in-test feature. The in-test portion of the project involved two sections:

the test selections and the prompting tool. This section of the report GUI was more difficult to implement due to the organization of the test structure. Each test is a drop box with eight options.

For the test selection section the user can select as few as one test or as many as eight. Once the tests are determined, the user then selects play to start the prompting software. Once play is pushed, the program reads through each of the test drop boxes to see if there is a test and, if so, what the test is. During this section of the program, the appropriate test prompt string is assigned to each test value. For example, if the first test is car idle, the relevant prompting string is displayed in the prompter. This is shown in Figure 3.5.

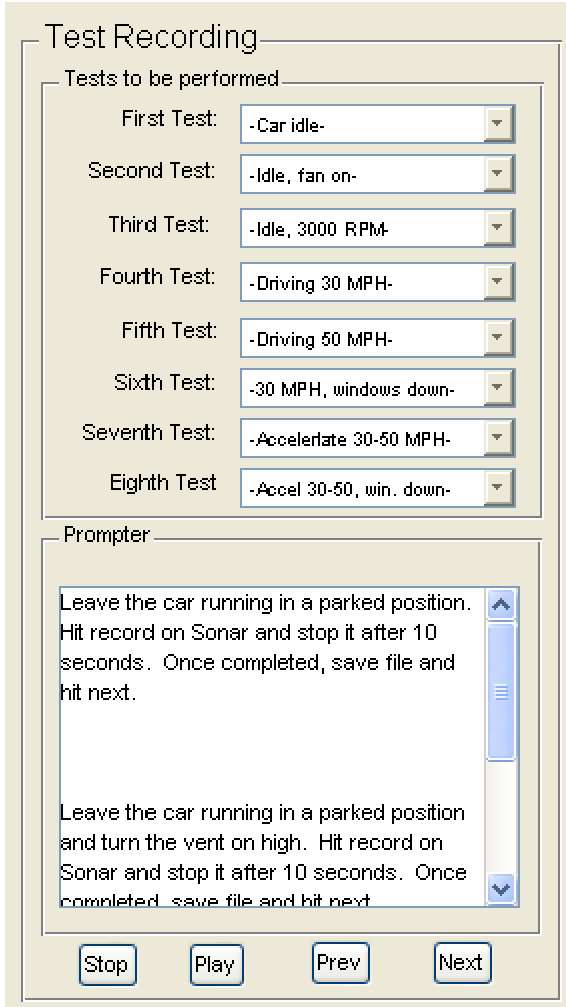

Figure 3.5: In-test GUI.

Since Matlab cannot simultaneously record four audio signals, additional software is needed to perform the actual recordings. This project uses Cakewalk Sonar 3 Studio Edition. The program is simple to use and is able to record four or more channels at a time. Since the user needs to move between Matlab and Sonar, a previous and next button is utilized in the prompter, allowing the user to make and check their recordings before moving on. The code for the play, next, and previous buttons can be found in the appendix for GUI code. Once the tests have been completed and all the recordings are done, the user moves onto the final section.

3.2.3 Post-test

The post-test section allows the user to analyze the recorded data. All of the mathematical analysis takes place in this section. The only user control needed for the post test section is choosing which graphs are desired in the final generated report. The choices are power spectral density graphs (PSD) at 1 kHz and 20 kHz, a time plot, correlation plots (both auto and cross), spectrograms at 1 kHz and 20 kHz, a power versus time graph, and finally, 3 options for direction-of-arrival (DOA). Each plot has an assigned checkbox. This is shown in Figure 3.6.

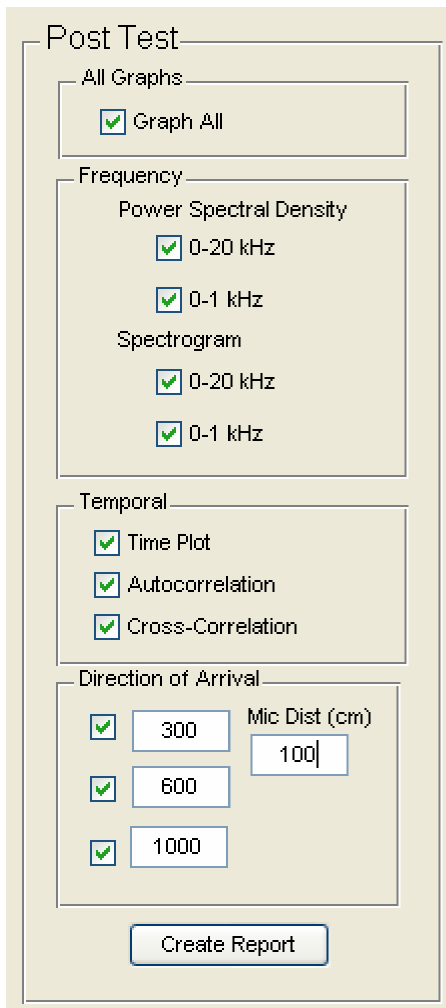

Figure 3.6: Post-test GUI.

Once the user has chosen the desired plots and completed testing, the create graph button is clicked. The user is then prompted to find each of the audio tracks recorded for every test, starting with the first and continuing until the user selects the final test. This process moves the audio data from its current location into an analysis folder. This folder is named according to the type of car and the time and date the "create graph" button was pressed. The audio files are also renamed upon their moving with the standard of test name and microphone number. Figure 3.7 illustrates the folder architecture.

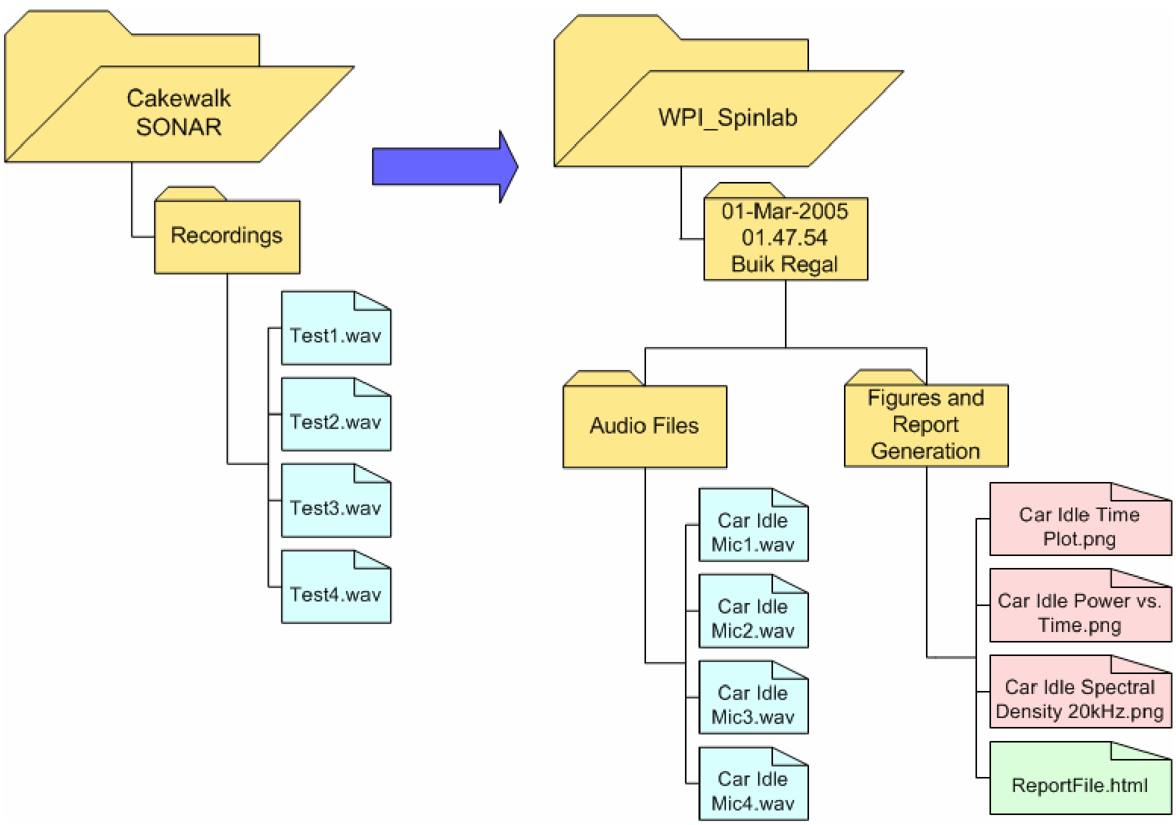

Figure 3.7: File architecture.

After the renaming is completed, each of the four audio files associated with each test are assigned to a variable. After file renaming the next phase is to use call to noise analysis m-file. The noise analysis file uses a for-loop to generate all the plots selected in the post-test GUI. The plots are saved as PNG files and sized to fit the HTML report page. The plots have a naming standard similar to the naming standard on the audio data files, using the test name and graph type. An example is “Fan On, Time Plot.png”.

Some of the plots were created using special functions. Several of the function had parameters that our group had to decide on values. The functions “pwelch”, “xcor”, and “specgram” all have parameter declarations at the top of the m-file that can be changed as the user sees fit.

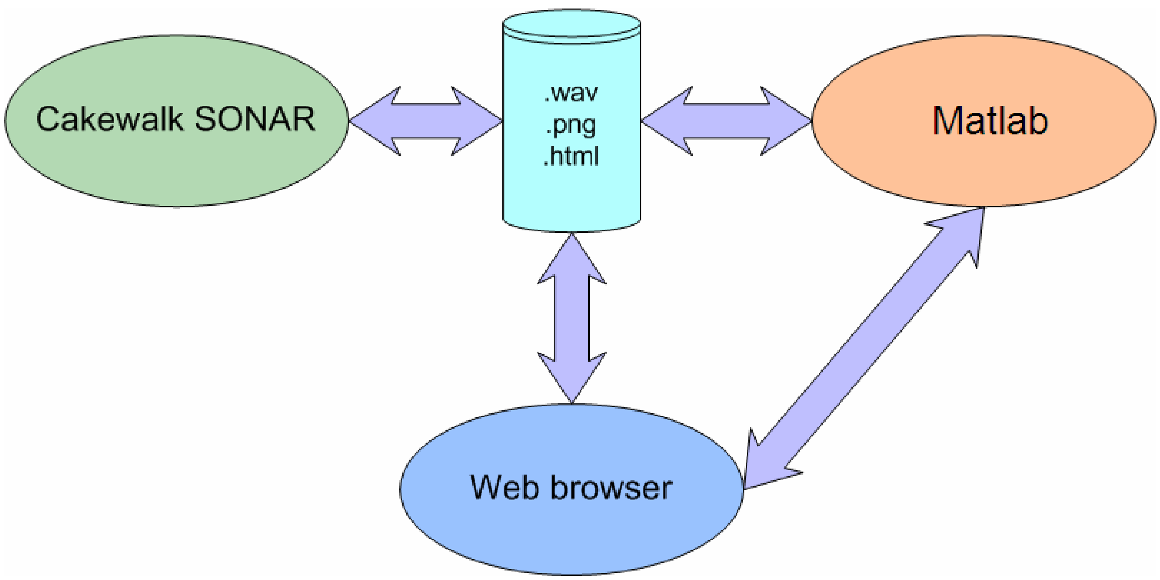

Figure 3.8: Software structure.

Figure 3.8 illustrates how Cakewalk Sonar, Matlab, and the default web browser function together. Sonar is responsible for making the recordings. Matlab utilizes those recordings and creates the file architecture, which was noted in Figure 3.7. Matlab then saves the PNG files, and creates a HTML file. The default web browser then opens the HTML file, which links to the WAV and PNG files.

3.2.4 Matlab Report Generator

The final stage of the program takes place directly after the final graph is created. The report generator is a new function in Matlab, appearing in version 7.0, which allows the user to input graphs, Matlab code, and any other data the user sees fit. The first step to successfully implement this report was to globally declare all the variables that needed to be transferred. The report generator (copies can be found in the appendix) contains the Bose/WPI information at the beginning. The second section includes all of the pretest data. The final section takes all of the created graphs and places them in the final report along with titles and labels. The report can contain a maximum of 104 graphs.

3.3 System Testing

Testing the system was done in two ways. First, the system underwent validation testing to ensure that the equipment, software, and analysis all worked as expected. The validation testing was completed to test our system in controlled environments. These tests were to ensure our system would perform as expected in the field tests. The second types of tests run were in automobiles. All the in-vehicle tests were completed following the same procedure and using the same test roads.

3.3.1 Electronic Validation Testing

The first type of validation testing performed involved testing the electronic portion of the system. The motivation for this test was to prove that the system had the frequency response expected when subjected to various signals. This would assure that the system did not have any filtering characteristics, meaning certain frequencies are not amplified by the preamp more than others.

The setup for this test required using a simple four input mixer connected to a computer. Two signals were generated using Matlab. These signals were white noise and a frequency sweep from 20 Hz to 20020 kHz. These signals were injected directly into the instrument-in lines on the Audio Buddies from the mixer. The results were recorded in Sonar exactly like a normal microphone recording is.

3.3.2 Recording System Validation Testing

The validation testing was done using the system, described in Section 3.1, and then comparing the results with a reference system. The control system used in our testing was an XLR microphone and an M-Audio Firewire 4.0 recording interface. The specifications can be found in the appendices for the components. Two types of tests were performed: test tones and white noise. For the test tones, three different frequencies were selected: 200 Hz, 700 Hz, and 1500 Hz. The tone test showed how the system responded to just a single tone. The DOA code was also tested in this section.

The test set-up was in the Mechanics Hall listening room. The microphones were positioned in a linear array, with the first and last microphone one meter apart. This can be seen in Figure 3.9.

Figure 3.9: Microphone array.

The image in Figure 3.10 shows the state-of-the art speaker and amplifier that were used. The speaker is a B&W Matrix 801 Series 2, which has crossover frequencies at 380 Hz and 3 kHz, a frequency response of 20 Hz to 20 kHz ±2dB free-field. The amplifier is the Threshold Model S/1000 Class A/AB STASIS power amplifier with optimal bias, which operates at 500 Watts.

Figure 3.10: Speaker and amplifier setup at Mechanics Hall.

The second validation test was done in the WPI listening booth. The listening booth measures 6 feet by 6 feet. The purpose was to test the system's frequency response to a frequency sweep and white noise against an M-Audio Firewire soundcard with the Audio Techniqua XLR microphone.

3.4 Test Vehicle Selection

Once the validation testing was completed and the system was confirmed to be working as expected, actual car tests were undertaken. The tests were to be performed on three distinct cars. The cars tested were a compact car, a family sedan, and a sport utility vehicle. The vehicles specifically chosen were a 1995 Honda Civic, a 1992 Buick Regal, and a 2000 Jeep Cherokee.

The same microphone array from the validation testing was again used in the vehicles. The array is about 1.1 m long, which was about the maximum size we could fit in the car without it hitting the windows on either side of the car. Velcro strapping allows the array to be strapped to the visors in the car. Also, windscreens are placed over the microphones to prevent mechanical error in recordings. Each microphone is equipped with Velcro that allows it to be easily mounted to the array board via Velcro.

The microphones can then be plugged into the box through the holes on the side. These holes are lined with rubber grommets to prevent from metal on metal contact damage to the connectors. The microphones connect to the bias box via a ¼'' to $^{1}/_{8}$" adaptors.

The use of the custom box system's efficiency is evident in the setup time. The system needs only to have the 12V inverter plugged in to start. Two different formats for box placement are possible. The first is having the box rest on thee lap with the laptop inside the box. The other option can be used if there are three people in the car. This allows for less clutter, as the box is in the front seat with the user and the laptop in the backseat.

The laptop is connected to the rest of the system through a USB cable. The wire is long enough to allow for either the first or second set-up. After the computer is plugged in, the user can perform a quick system check by making sure the preamp gains are adjusted to a proper setting as well as check to make sure all the lights are on in the system indicating power.

The 1995 Honda Civic was chosen based upon size, engine type, and availability. The car was able to be borrowed from one of the friends of the project group. The Honda Civic is one of the most popular compact vehicles on the market. The engine type is a 4 cylinder. The Regal belongs to George Roscoe. The car is considered a family sedan model in its user manual. The Buick has a V-6 engine and is a common family car. The 2000 Jeep Cherokee, chosen for its availability and also for it being a common SUV. The Jeep has an inline 6 engine.

Figure 3.11: Test automobiles.

3.5 In Vehicle Test Procedures

This section provides a detailed explanation of the test procedures, as well as results that are expected from each test. In all of the tests, the system setup, described in Section 3.5.1 is used.

3.5.1 System Setup

There is a driver present, and the user is sitting in the passenger seat. The microphone array fastened to the visors of the car, and the system in the users lap. The power inverter is removed from the suitcase, and inserted into the vehicle's cigarette lighter adapter, and the system power supply is inserted into the power inverter. The user will then verify whether or not all system components are powered. The user will turn on the laptop and open both the Matlab GUI and Cakewalk Sonar 3 Studio Edition. In Cakewalk Sonar, the user will create a new "4 Track Audio" project, and specify a microphone for each track. The microphones are specified in order along the array, starting on the driver side and ending on the passenger side. It is import to note that all cell phones and other electronic devices should be turned off at this point. Some electronic devices can interfere with the system, and have unpleasant results in the recordings.

3.5.2 Pre-Test GUI Procedure

The user will either enter the general and vehicle information for the pre-test GUI, or load the information from a saved DAT file. This is described in greater detail in Section 3.2.1.

3.5.3 In-Test GUI Procedure

The user will select the tests to be performed using in-test GUI drop-down menus. This is described in greater detail in Section 3.2.2. The tests can be done in any order, and the user can choose any of the following tests: car idle, car idle at 3000 RPM, car idle with the fan on, driving at 30 mph, driving at 30 mph with the windows down, accelerating 30 to 50 mph, accelerating 30 to 50 mph with the windows down, and driving at 50 mph. The following subsections describe in detail the procedures for each specific test.

3.5.3.1 Car Idle

Using Cakewalk Sonar Studio edition, the user will save a 4 Track Audio project; the user will choose a name that will distinguish the audio files for the car idle test. The driver will leave the vehicle running in a parked position. The user will press the record button in Sonar, and say "[tester name] [car make and model] car idle test." The user will stop recording after approximately ten seconds. Once completed, the user will save the project. The initial voice recording can be trimmed using the post-test GUI.

3.5.3.2 Car Idle, 3000 RPM

Using Cakewalk Sonar Studio edition, the user will save a 4 Track Audio project; the user will choose a name that will distinguish the audio files for the car idle 3000 RPM test. The driver will leave the vehicle running in a parked position and will step on the gas pedal until the RPM gauge reads approximately 3000; the driver will have to apply constant pressure until the user signals that the test is complete. The user will press the record button in Sonar, and say "[tester name] [car make and model] 3000 RPM test." The user will stop recording after approximately ten seconds. Once completed, the user will save the project. The initial voice recording can be trimmed using the post-test GUI.

3.5.3.3 Car Idle, Fan On

Using Cakewalk Sonar Studio edition, the user will save a 4 Track Audio project; the user will choose a name that will distinguish the audio files for the car idle, fan on test. The driver will leave the vehicle running in a parked position with the air vent on high. The user will press the record button in Sonar, and say "[tester name] [car make and model] fan on test." The user will stop recording after approximately ten seconds.

Once completed, the user will save the project. The initial voice recording can be trimmed using the post-test GUI.

3.5.3.4 Driving, 30 mph

Using Cakewalk Sonar Studio edition, the user will save a 4 Track Audio project; the user will choose a name that will distinguish the audio files for the driving 30 mph test. The driver will drive at a constant 30 mph. Once at this speed, the driver will signal the user to hit record in Sonar and say “[tester name] [car make and model] 30 mph test.” The user will stop recording after approximately ten seconds. Once completed, the user will save the project. The initial voice recording can be trimmed using the post-test GUI.

3.5.3.5 Driving, 30mph, windows down

Using Cakewalk Sonar Studio edition, the user will save a 4 Track Audio project; the user will choose a name that will distinguish the audio files for the driving 30 mph, windows down test. The driver will drive at a constant 30 mph with both the driver and passenger side windows down. Once at this speed, the driver will signal the user to hit record in Sonar and say “[tester name] [car make and model] 30 mph windows down test.” The user will stop recording after approximately ten seconds. Once completed, the user will save the project. The initial voice recording can be trimmed using the post-test GUI.

3.5.3.6 Accelerating, 30 to 50 mph

Using Cakewalk Sonar Studio edition, the user will save a 4 Track Audio project; the user will choose a name that will distinguish the audio files for the accelerating 30 to 50 mph test. The driver will drive at a constant 30 mph. Once at this speed, the driver will signal the user to hit record in Sonar and say "[tester name] [car make and model] 30 to 50 mph test." After the user finishes speaking, the driver will accelerate to 50 mph. Once at 50 mph, the driver will signal to the user, who will stop recording. Once completed, the user will save the project. The initial voice recording can be trimmed using the post-test GUI.

3.5.3.7 Accelerating, 30 to 50 mph, windows down

Using Cakewalk Sonar Studio edition, the user will save a 4 Track Audio project; the user will choose a name that will distinguish the audio files for the accelerating 30 to 50 mph windows down test. The driver will drive at a constant 30 mph with both the driver and passenger side windows down. Once at this speed, the driver will signal the user to hit record in Sonar and say "[tester name] [car make and model] 30 to 50 mph windows down test." After the user finishes speaking, the driver will accelerate to 50 mph. Once at 50 mph, the driver will signal to the user, who will stop recording. Once completed, the user will save the project. The initial voice recording can be trimmed using the post-test GUI.

3.5.3.8 Driving, 50 mph

Using Cakewalk Sonar Studio edition, the user will save a 4 Track Audio project; the user will choose a name that will distinguish the audio files for the driving 50 mph test. The driver will drive at a constant 30 mph. Once at this speed, the driver will signal the user to hit record in Sonar and say "[tester name] [car make and model] 50 mph test." The user will stop recording after approximately ten seconds. Once completed, the user will save the project. The initial voice recording can be trimmed using the post-test GUI.

3.5.4 Post-Test GUI Procedure

After the tests have been completed, the user listens to the audio files for each test. The user should pay careful attention to any "pops" or "clicks" present, which could indicate a loose connection in the system. In tests when the windows of the car are down, a "whipping" sound can indicate that the changing air pressure can indicate that the microphones are being mechanically saturated. If this is the case, denser wind screens may need to be used. Furthermore, after each test is performed, it is important to check and see if any of the red colored clipping bars are activated. If this happens, the test will have to be redone with the gains adjusted accordingly. Finally, the user is also verifying that the recordings are audible, and there are no other problems.

If all of the audio files appear to be satisfactory, then the user will select which graphs are to be generated for the final report. Once this is done, the user will select the "Create Report" button on the user interface, and will be prompted to select the appropriate audio files for each test. At this point, the user can choose to have the Matlab figures remain open, or close after generation. Next, the user can choose to trim data off of the beginning and end of the audio files. The report will automatically open in the default HMTL browser. Additional information regarding the Post-Test GUI can be found in Section 3.2.3.

4 Results and Analysis

This chapter examines the data collected as described in the methodology section. There were two main sections to the data acquisition and analysis in this project. The first section consists of the system validation testing. The second section is the three in-vehicle tests of which one will be discussed in detail.

4.1 *System Validation Testing*

The validation testing results were used to verify that the entire system was functional and would perform at the declared specifications when used in an automobile. The two phases were electronic validation, which was used to test the Audio Buddies and the Quattro, and the system/microphone validation tests done in listening rooms both on campus and at Mechanics Hall. The two types of validation done were frequency response and direction of arrival.

4.1.1 Frequency Response Validation

The frequency response of the system was tested using a 20-20 kHz frequency sweep and a white noise. The frequency response was tested both acoustically and electrically to ensure that all hardware was working properly and there was no unwanted noise in the system.

4.1.1.1 Electrical Tests

The techniques used for the electronic system frequency response validation are described in the methods section of this report. The next few plots show the system's electrical response to a frequency sweep.

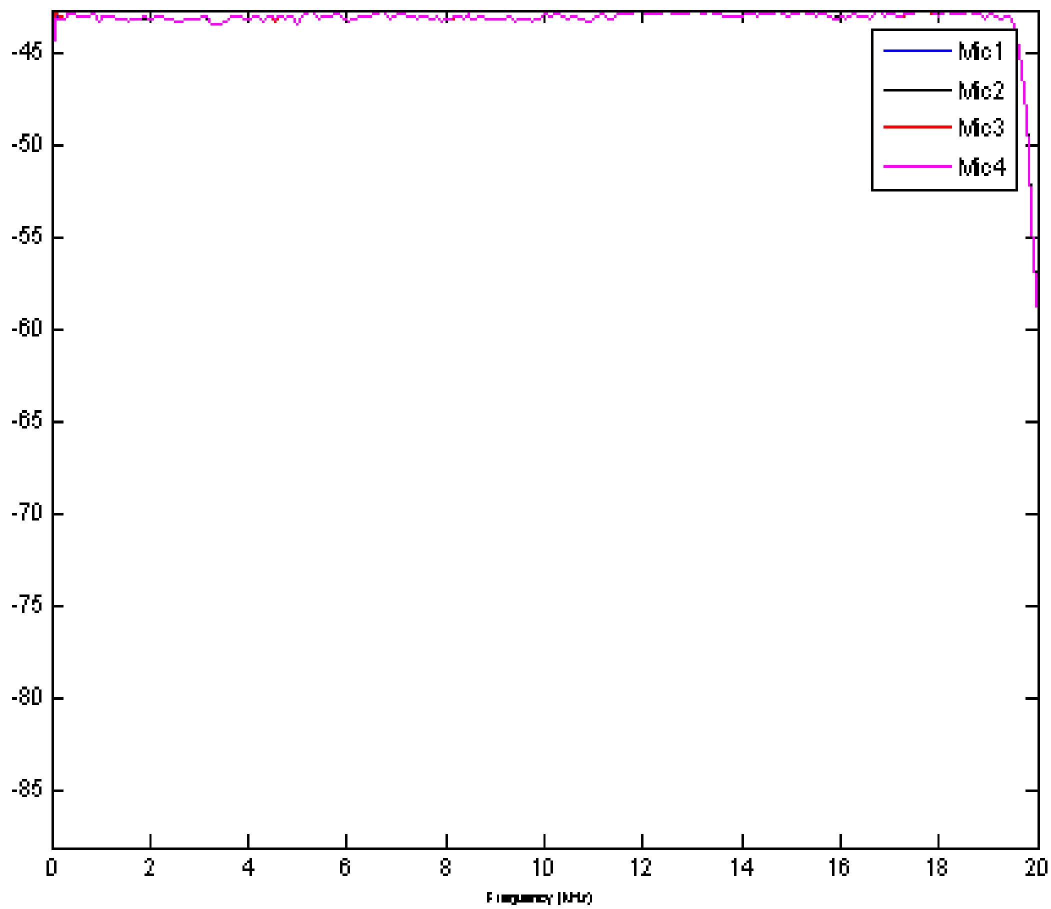

Figure 4.1: Normalized 0-20 kHz PSD.

The above plot shows the electrical response to a frequency sweep. Notice that the response is almost perfectly flat. Below shows the same plot from 0-1 kHz:

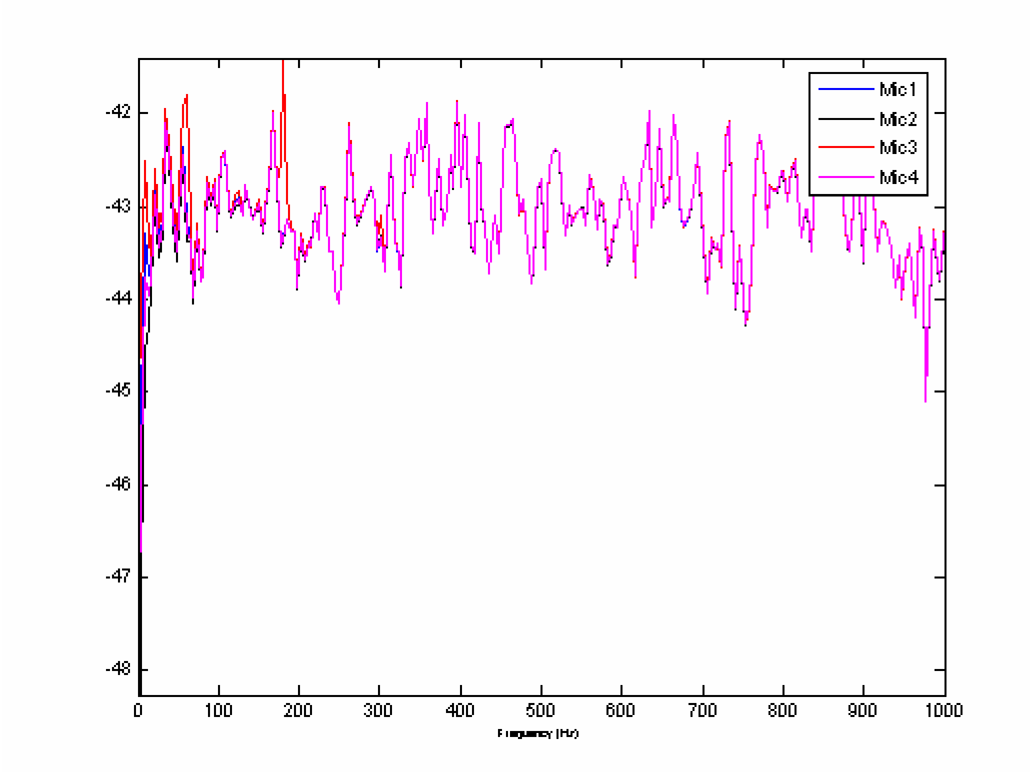

Figure 4.2: Normalized 0-1 kHz PSD.

4.1.1.2 Acoustical Tests

The acoustical tests for the frequency response were completed in the same way as the electrical tests with the only difference being that the signals are sent through a speaker, the air, the microphone, and the bias circuits before getting to the Audio Buddies. Again, the analysis will be shown through the power spectral density plots of the frequency sweep.

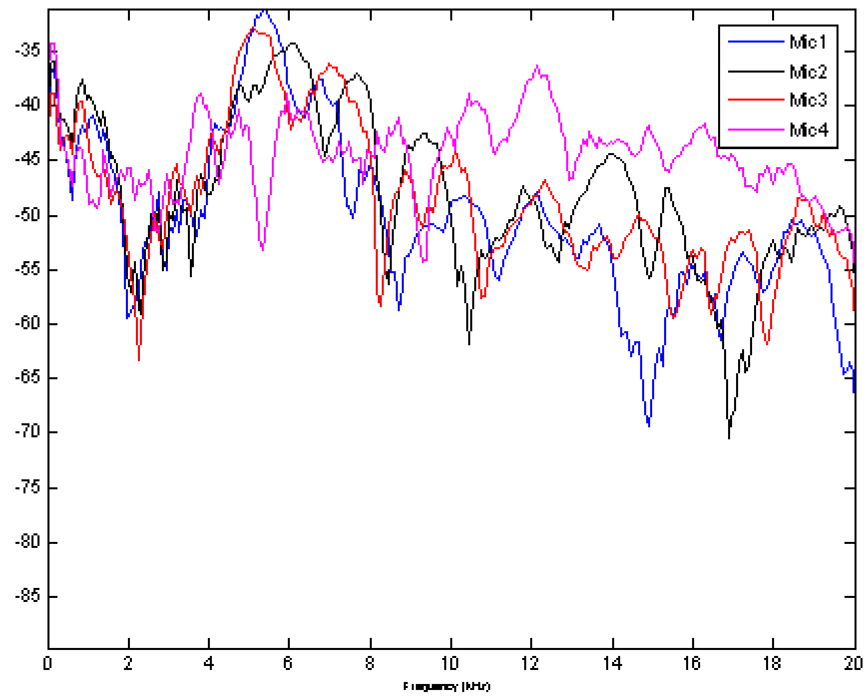

Figure 4.3: Normalized 0-20 kHz PSD.

The above plot shows the normalized PSD of the acoustical response of the suitcase system vs. an outside system (M-Audio Firewire and Audio Techniqua XLR omni-directional microphone). Between the two graphs in figure 4.3 and 4.4, both systems perform similarly in the listening booth environment. The fourth microphone is the outside test system, and from the two graphs the response of the Bose microphones and the Audio Techniqua is very similar. These results justify that the test system has a similar recording quality to an XLR microphone that costs at least US$800.00.

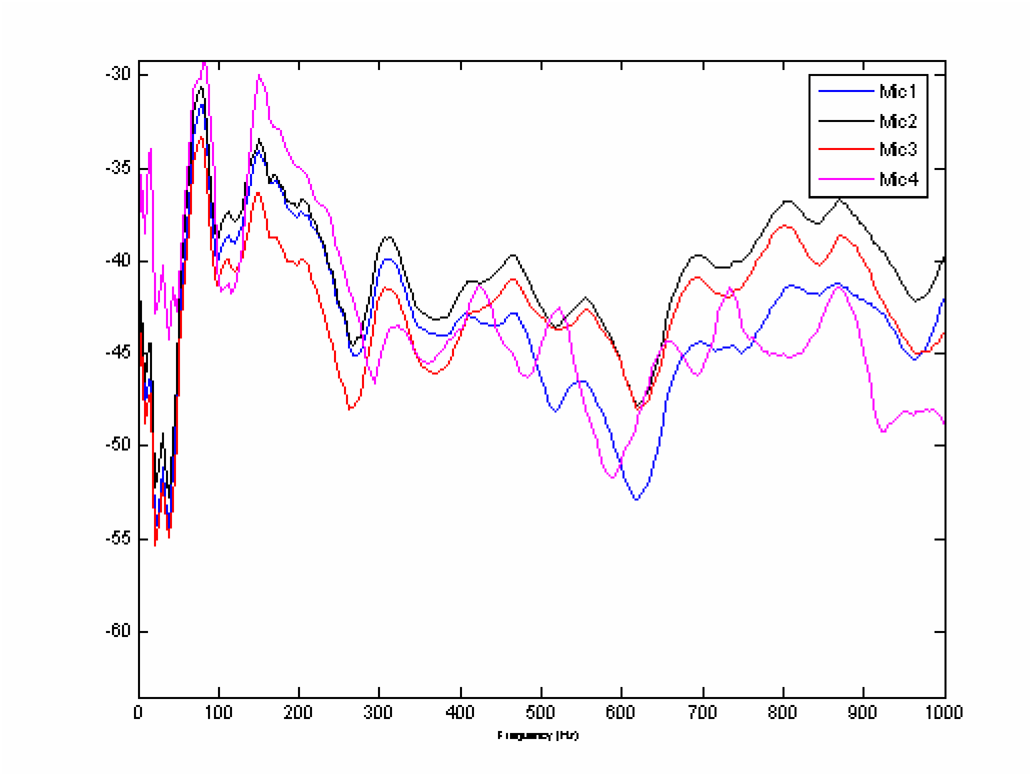

Figure 4.4: Normalized 0-1 kHz PSD.

4.1.2 Direction of Arrival Validation

The direction of arrival of the system was tested using a 200 Hz tone. The frequency of 200 Hz was chosen due to the length of the microphone array (1 meter) used. The process of the tests is described in the methods section of this report.

From the results, it was found that the direction of arrival analysis gave the expected results under certain conditions. The validation tests proved best when the microphone array is perpendicular to the source of the noise. The DOA also works best at lower frequencies, as can be seen from the graphs below.

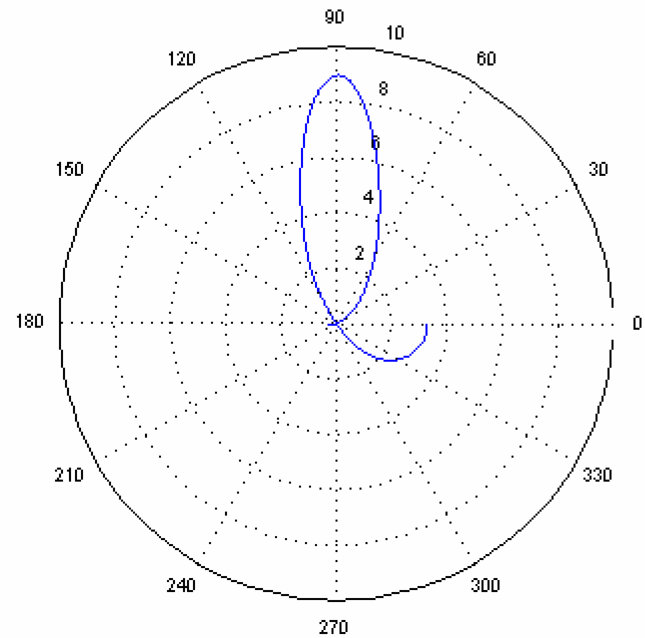

Figure 4.5: Perpendicular 200 Hz DOA.

From this graph, a clearly defined 90 angle to the wave propagation for the 200Hz tone can be seen.

Another test involved the rotation of the array from a perpendicular direction to a parallel direction of the propagating wave. Figure 4.6 does not show a clear direction to the propagating wave. Figure 4.5 and 4.6 show that the direction of the array can affect frequency detection.

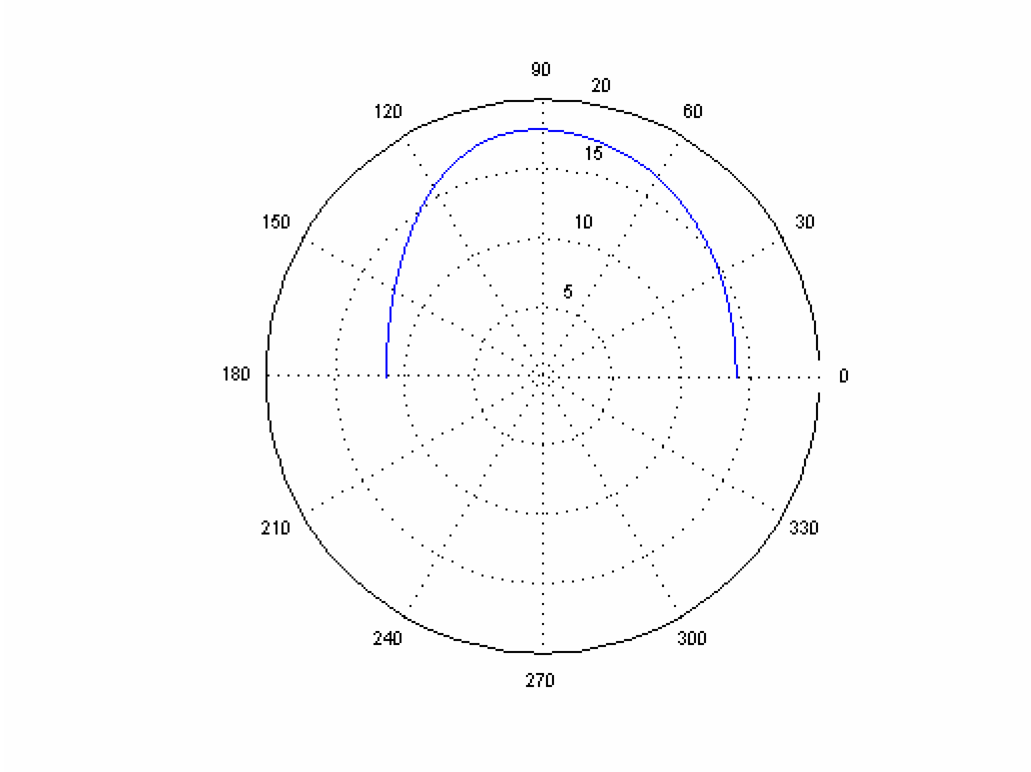

Figure 4.6: Parallel 200 Hz DOA.

The figure does not display the direction as strongly as it did in the perpendicular test.

4.1.3 Summary and Interpretation of Validation Testing Results

The validation testing and analysis proved that our system works up to the specifications declared in the methodology. The frequency response testing showed that the system has a fairly flat response from 20-20 kHz both electrically and acoustically. There are no large spikes or dips, meaning all sound that can be heard by the human ear in a car will be equally recorded.

The direction of arrival analysis proved that the array can show what direction noise in the frequency range 170-1400 Hz is coming from. The test with the array positioned perpendicular to the sound source worked in detecting the frequency, but in the parallel arrangement of the array did no show the results clearly.

4.2 In-Vehicle Testing

Once the system was validated, the team was able to make recordings in automobiles. For the procedure of how the tests were completed, where they were completed, and what cars were used, please refer to the methods section of this report. The following pages discuss the results of the in-vehicle tests. The full reports can be found in the appendix.

4.2.1 Test Conditions

This section will discuss the results of the in-vehicle test of a 2000 Jeep Cherokee. The engine is a 4.0L, 12 valves with inline 6 cylinder. The Jeep has 120 horsepower. The test was completed in early April, 2005 with dry road conditions. The temperature ranged from 50-60 degrees during the testing period. The roadway chosen was RT. 56 South at the intersection of 122 North and 56 North. The below map shows testing area RT. 56 is labeled, and RT 122 is labeled Pleasant Street.

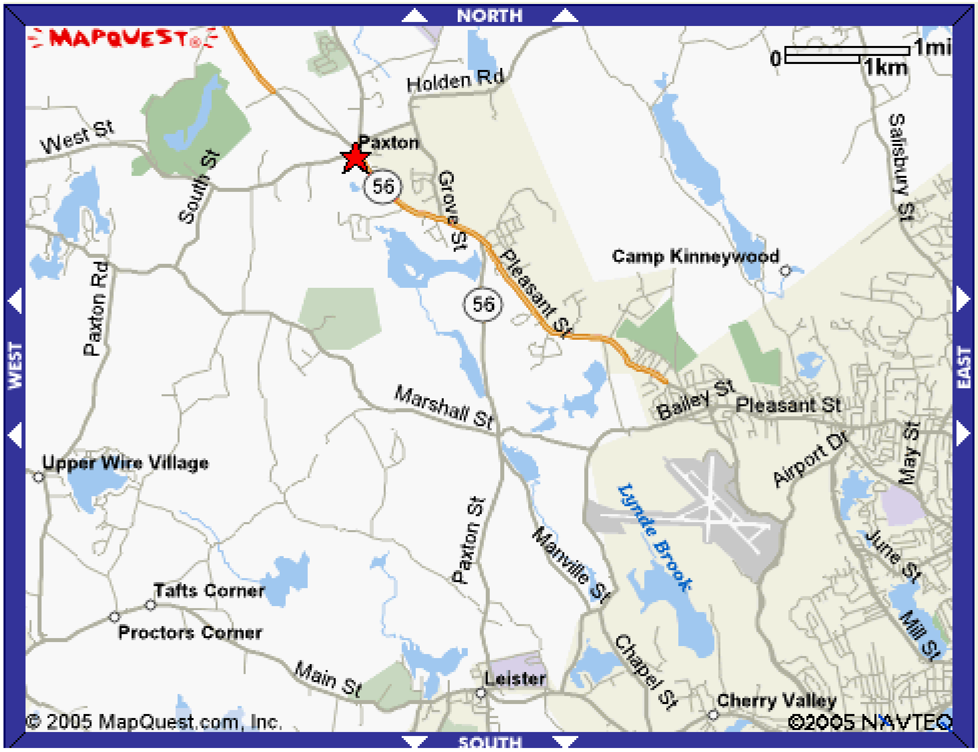

Figure 4.7: Automotive test map.

4.2.2 Engine Idle Test

Each engine has slightly different specifications. The chart below displays each of the engines specifications. These specifications are important to the calculations for what frequencies the engine is expected to produce.

Make	Model	Year	Engine	Cylinders	HP
Jeep	Cherokee	2000	4.0L, 12 Valve	Inline 6	125
Buick	Regal	1992	3.8L, 12 Valve	V6	140
Honda	Civic	1995	1.5L	4	85

4.2.1.1 Temporal Analysis

The time domain plots purpose is to show the raw data captured by the system. The data below is an example of how the graphs allow the user to see if the gains are slightly different and how the overall data pattern may vary microphone to microphone. It should be noted that the car idle test is what the car idles at without any pressure on the accelerator. The Jeep idles around 750 RPM.

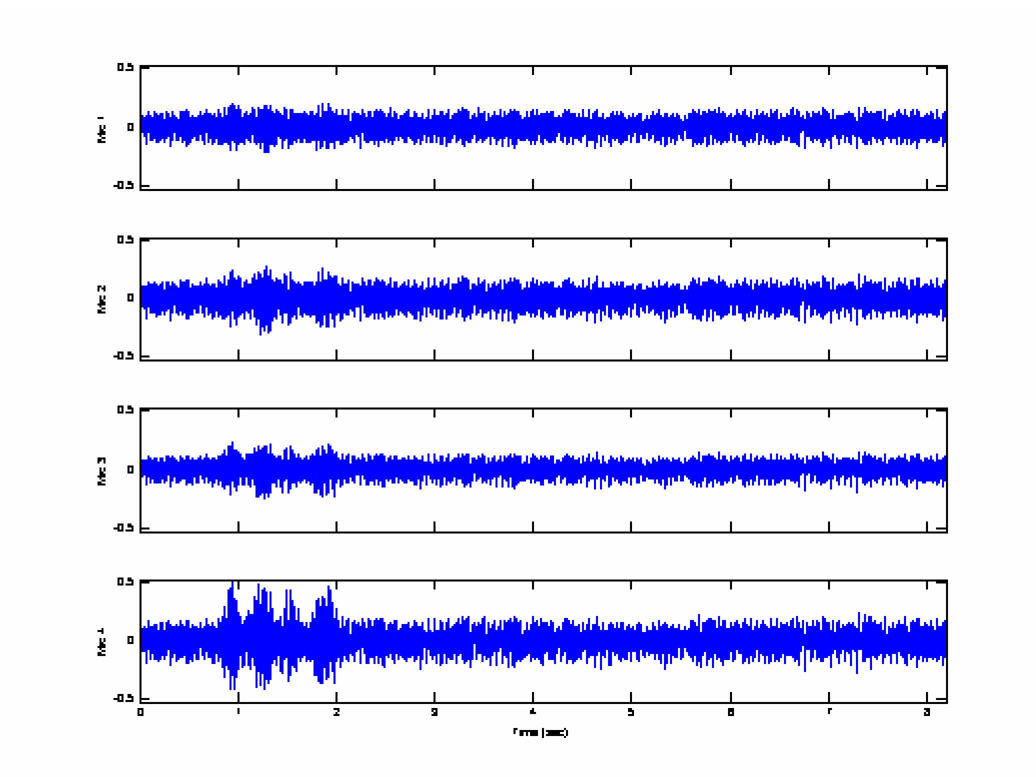

Figure 4.8: Car idle time plot.

Two types of correlation analysis were done in this project, cross correlation and autocorrelation. The format for the autocorrelation is that each microphone is given its own subplot. The cross-correlation graph, like the normalized PSD graphs, is a six-signal graph superimposed on one plot.

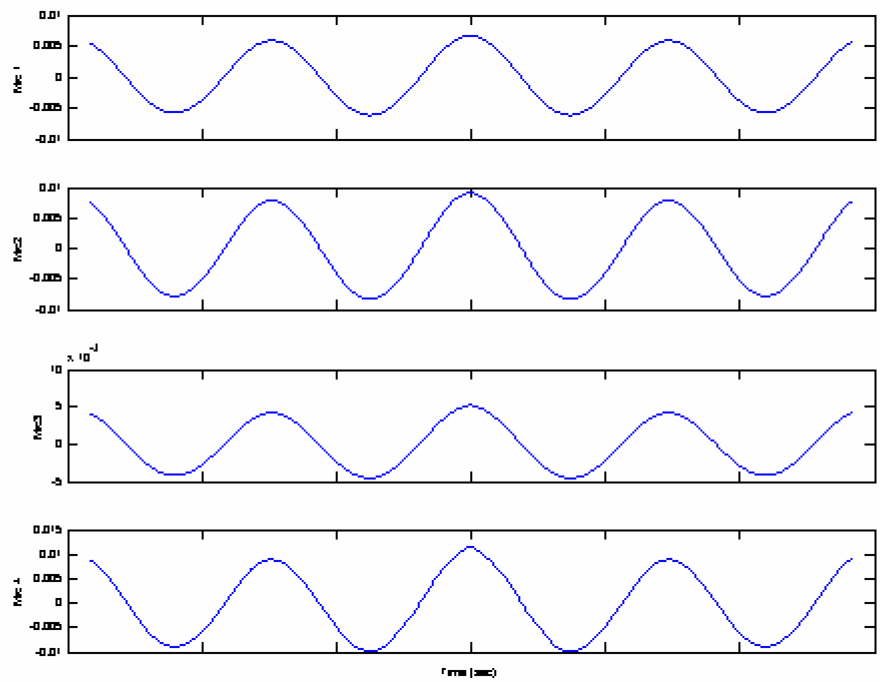

Figure 4.9: Car idle autocorrelation.

It can be seen from the following graph that each signal has a certain periodicity to it, repeating every 30 milliseconds. This is also seen in the cross correlation.

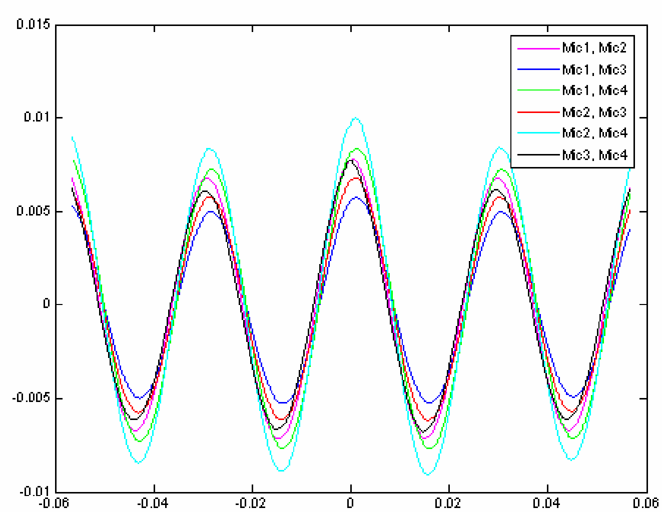

Figure 4.10: Car idle cross correlation.

The 30 milliseconds would indicate the time between ignitions looking at the Equation 4.1, we can see the relationship between RPM and the fundamental engine frequency.

$$\left({}^{RPM} / {}_{120}\right) \text{ x number of cylinders} = \text{fundamental frequency}$$

Equation 4.1: Engine fundamental frequency.

The given equation gives us a fundamental frequency of 37.5 Hz for a 750 RPM idle. The inverse of this frequency will give us the time between ignitions. This number works out to be approximately 26.67 ms. The correlation graphs agree with this value in their spacing.

4.2.1.2 Spectral Analysis

The frequency plots are done using a semi-log scale on the y axis, allowing for a large range of power levels. There are also four plots associated with the power spectral density analysis. The first plots are non-normalized 20 kHz and 1 kHz charts. They are done similar to the time plots, with each microphone being represented in one of the rows, this allows for easy comparison of each signal. The second form of plots is the same two frequencies, but the signals are normalized and superimposed on the same graph.

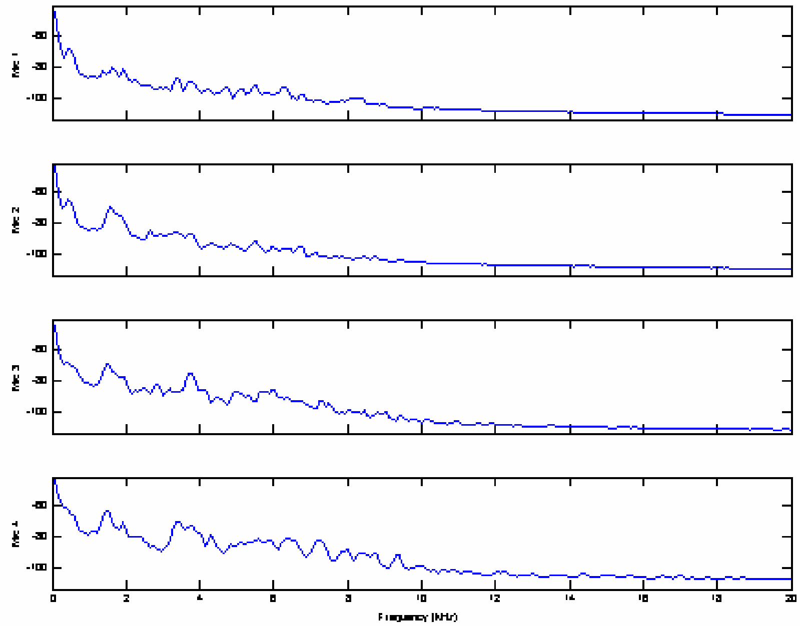

Figure 4.11: Jeep car idle non-normalized 0-20 kHz PSD.

The 0-1 kHz allows for a closer examination at the frequencies containing most of the vehicular noise

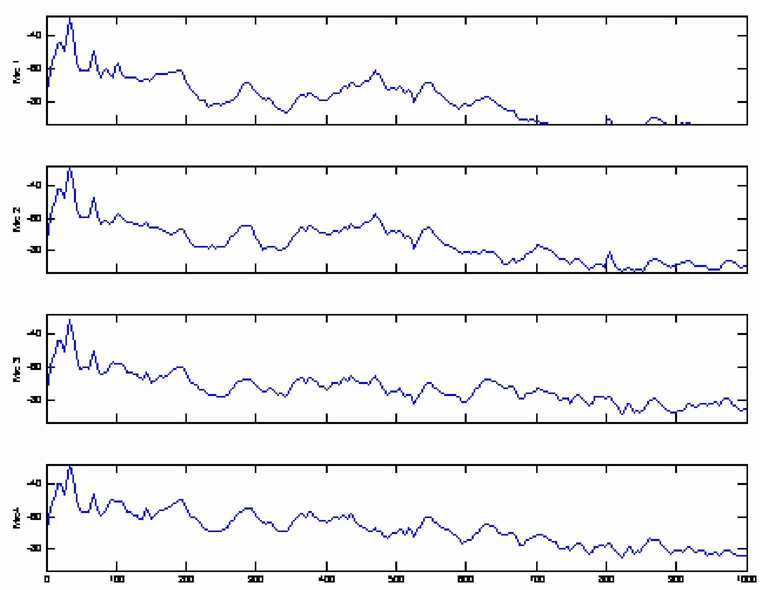

Figure 4.12: Car idle normalized 0-1 kHz PSD.

The other two plots yield similar results, but by normalizing them, the effect of having the gains slightly different is eliminated. On the following two plots, the power in dB is on the y-axis while the frequency in Hz is on the x-axis.

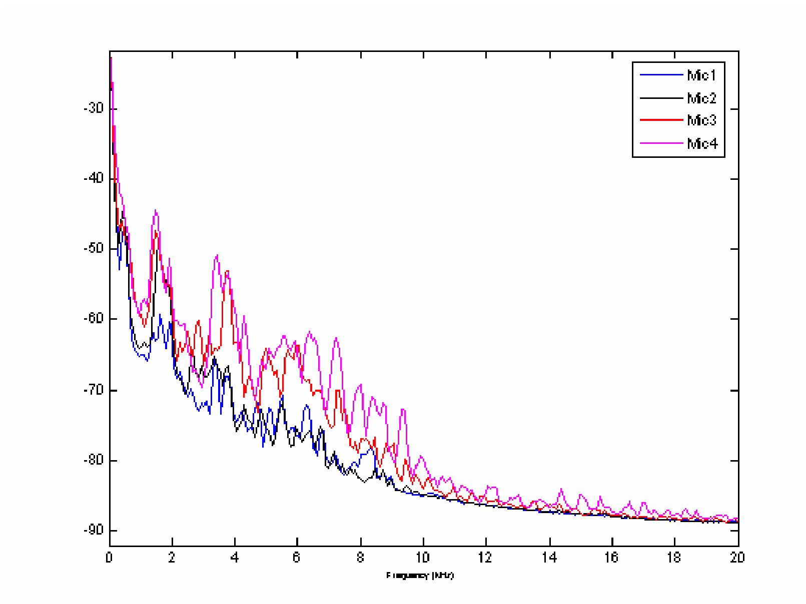

Figure 4.13: Car idle normalized 0-20 kHz PSD.

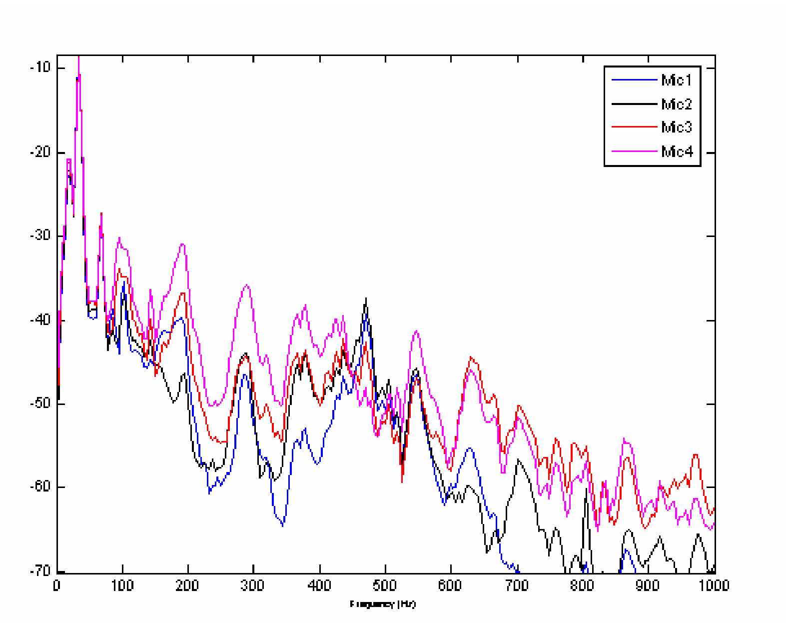

Figure 4.14: Car idle normalized 0-1 kHz PSD.

From the figures 4.11-15 we can see there is a fundamental frequency around 40Hz which is consistent with the equation 4.1 which found the frequency to be 37.5 Hz for the 6 cylinder Jeep, which is accurate given that the Jeep idles around 750 RPM. Given that the logarithmic scale for power is 10dB/decade, the engine noise is the loudest noise in the vehicle by a factor of 10, indicating this is the loudest noise in the vehicle.

Another tool to analyze the frequency data is the spectrogram, which uses color to determine the amount of frequency over a given time as discussed in the methods. For our analysis we used two frequency ranges, the range from 0 to 1 kHz and 0 to 20 kHz.

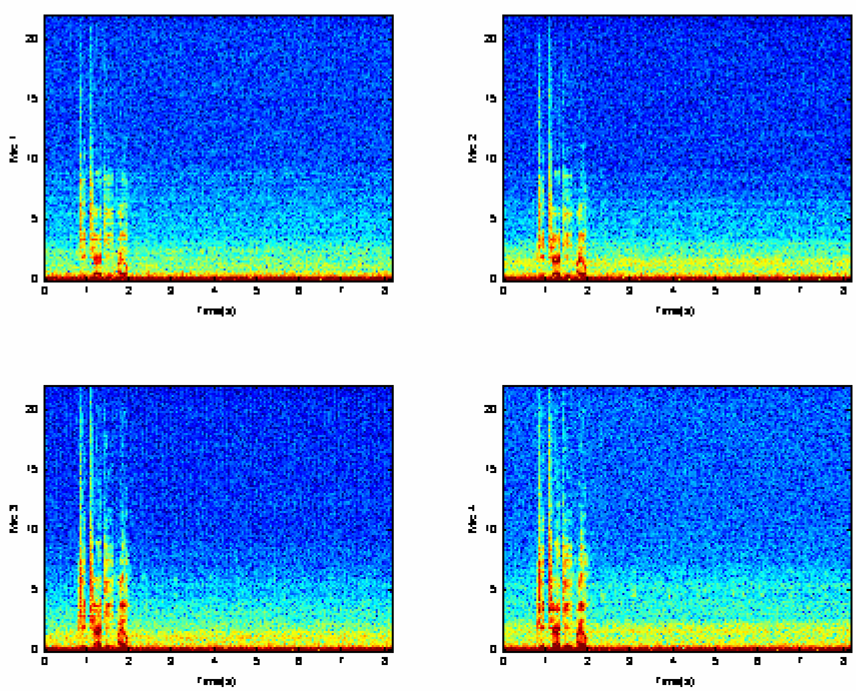

Figure 4.15: Car idle 0-20 kHz spectrogram.

Again, 0-1kHz version of the plot is seen next.

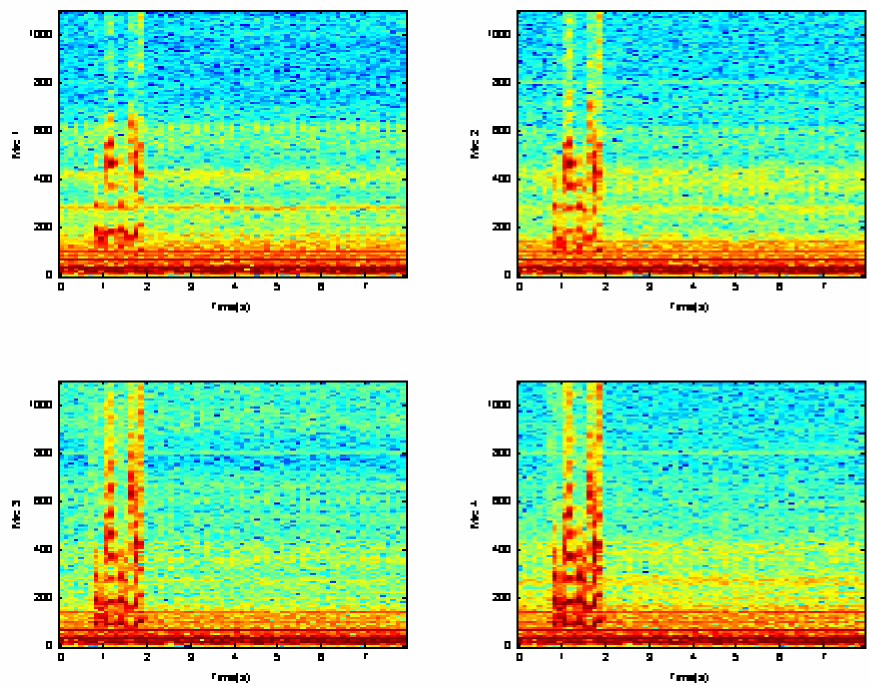

Figure 4.16: Car idle 0-1 kHz spectrogram.

The main use of the spectrogram in this project is to show which frequency ranges have the largest amount of recorded noise. Close examination of the above graph shows some high frequency noise early in the recordings. This represents human speech from the passenger seat, indicated by the strength of the signal in microphone four. Also, there are some periodic signals in the lower frequencies and a dark red line around 40 Hz indicating the engine noise.

4.2.1.3 Spatial Analysis

The final analysis performed in the automobile was DOA. The following plot is the direction of arrival at 300 Hz.

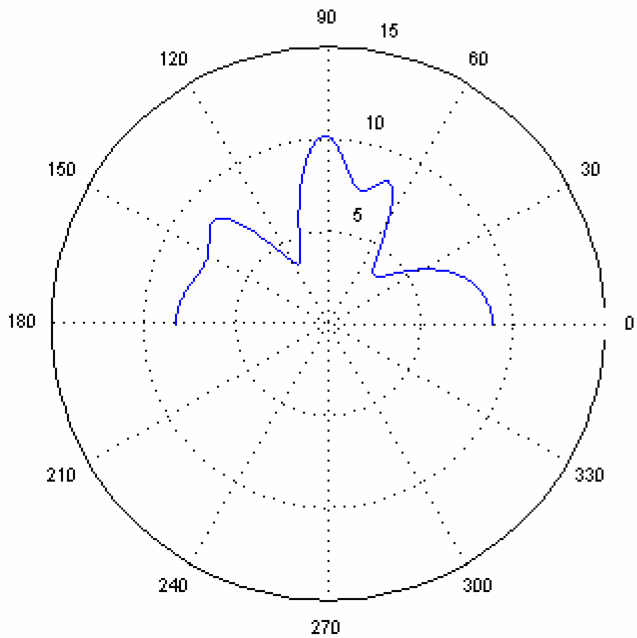

Figure 4.17: Car idle 300 Hz DOA.

As can be seen, the main noise is arriving from 90 degrees to the array. This indicates that the frequency is strongest coming directly perpendicular to the array. The frequency appears in all directions from the microphone array at some level. Figure 4.17 effects could be caused by reflection within the car or by several different noises that have some power at the given frequency.

4.2.3 Engine Idle With Fan Noise Tests

The climate control system is frequently used in automobiles and this feature changes the dynamics of the frequencies in the automobile versus the car idling. In this case, the fan used in heating and cooling system adds significant noise to the car, especially at lower frequencies. This analysis section will show some of the issues that arrive when using the system.

4.2.1.4 Spectral Analysis

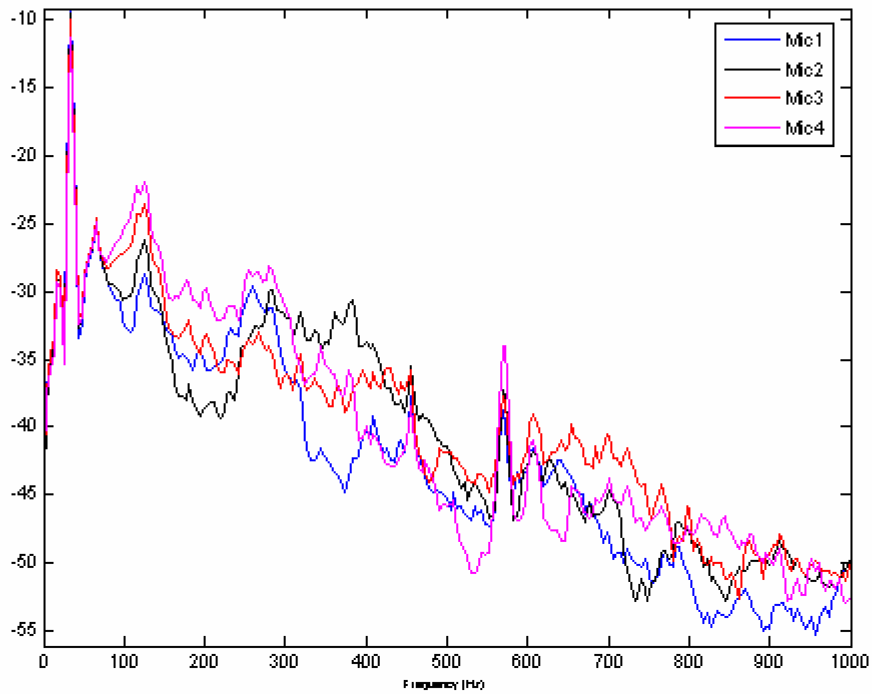

Figure 4.18: Climate control system normalized 0-1 kHz PSD.

The above graph shows that the power shifts up nearly 5dB at each frequency. The engine is still by far the most detectable frequency in the car at the 40 Hz spike. The issue with these higher power frequencies is that voice is less detectable from the noise.

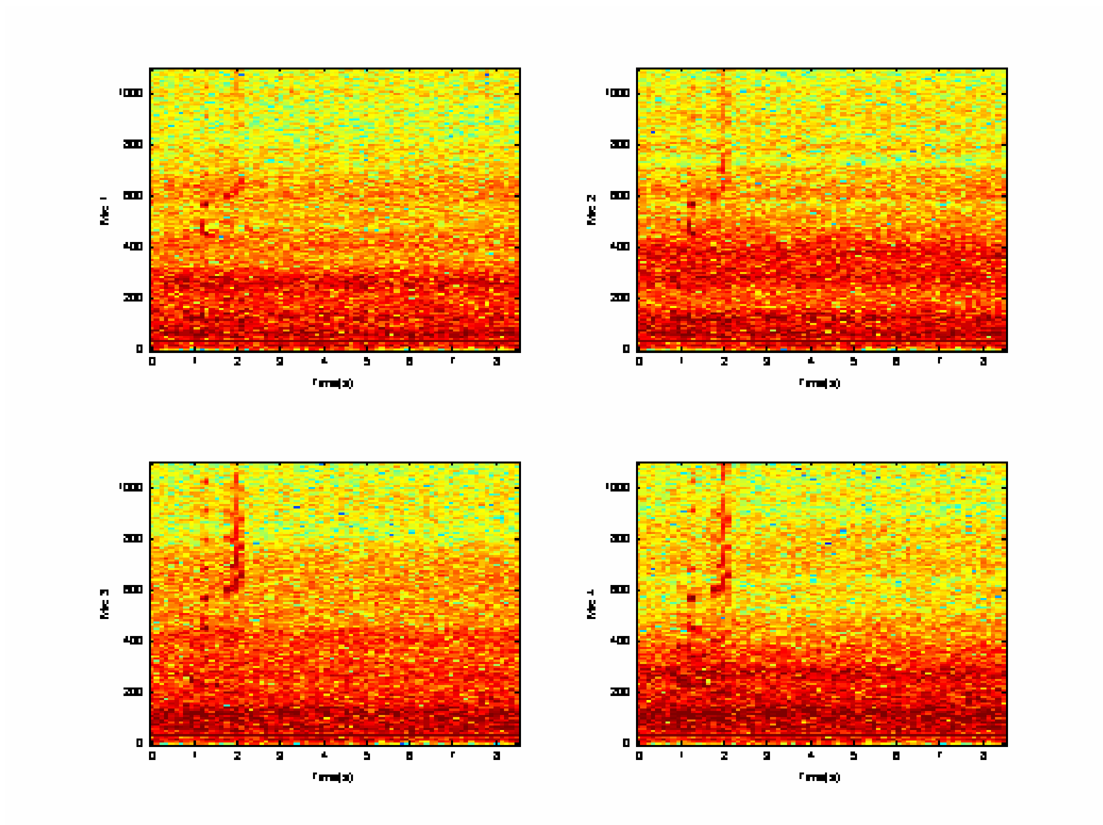

Figure 4.19: Climate control system 0-1 kHz spectrogram.

Unlike the car idle spectrogram (Figure 4.16), the speech at the beginning of this recording is not easily distinguishable.

4.2.4 Engine 3000 RPM Tests

The second test performed involved the same conditions and same tests. This section will outline the main data and information collected from this test. Refer to Appendix D for complete results.

4.2.1.5 Spectral Analysis

The power spectral density plots in this section show a change from the first idle plots, there is more than one fundamental frequency as seen in the two plots below.

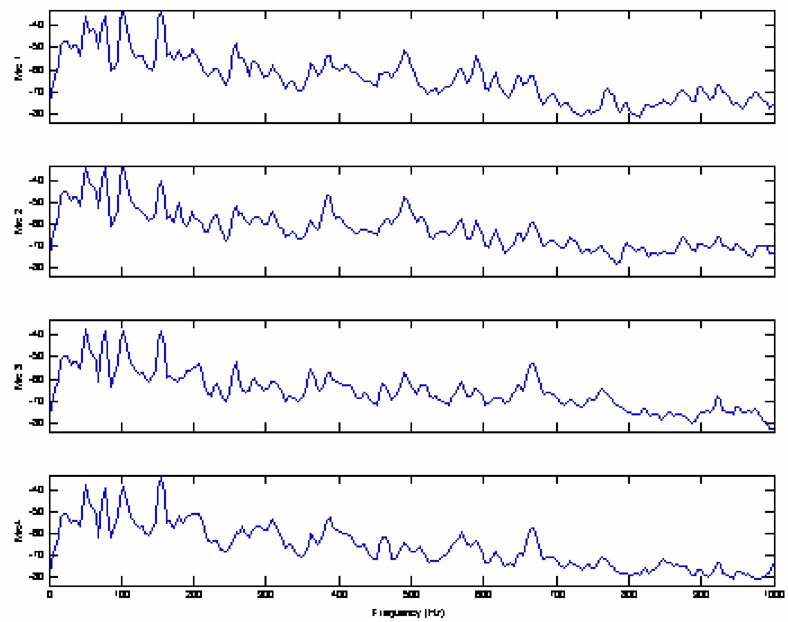

Figure 4.20: 3000RPM non-normalized 0-1 kHz PSD.

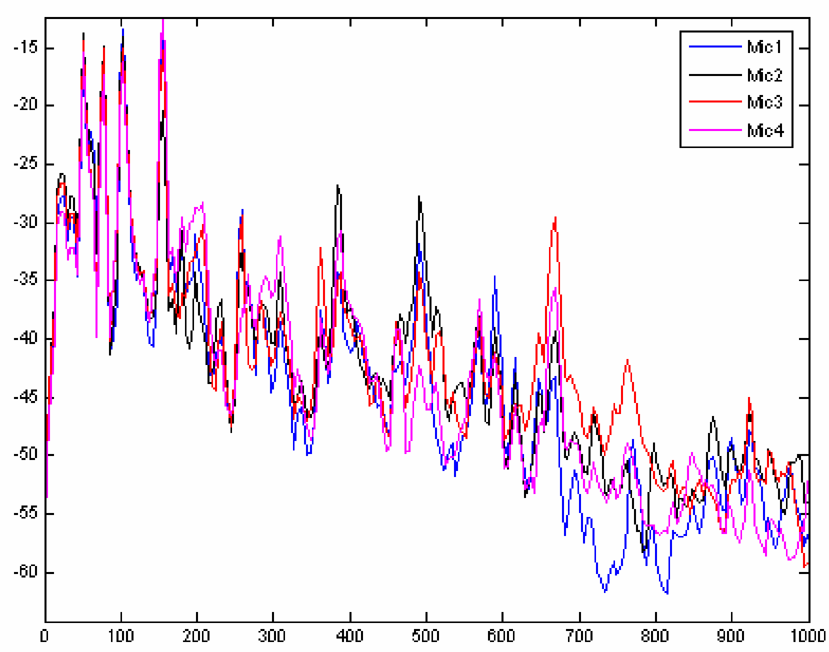

Figure 4.21: 3000 RPM normalized 0-1 kHz PSD.

Using the mathematical equation given in equation 4.1, the fundamental frequency was determined to be approximately 150 Hz. From the above graphs there are also sub harmonics at 100 Hz, 75 Hz, and 50 Hz. This is possibly the lower frequencies of each cylinder firing.

4.2.5 30MPH Constant Speed Driving Test

Driving changes the acoustics in the car from the idle state. The additional factors relate to increased engine noise, tire rotation, and the effect of wind on the car. Other factors have to be considered such as road conditions, weather, acceleration of the car, and the general shape of the car. The age of the car will also affect the data. For example an older car may not be sealed as well as a new car or there may be some loose parts. Some of these conditions cannot be controlled. For testing purposes, the roads chosen had little effect from weather and all testing was done under clear conditions.

4.2.1.6 Temporal Analysis

Another difference in driving versus idling is that the correlation graphs change from a strongly periodic signal to a single correlation.

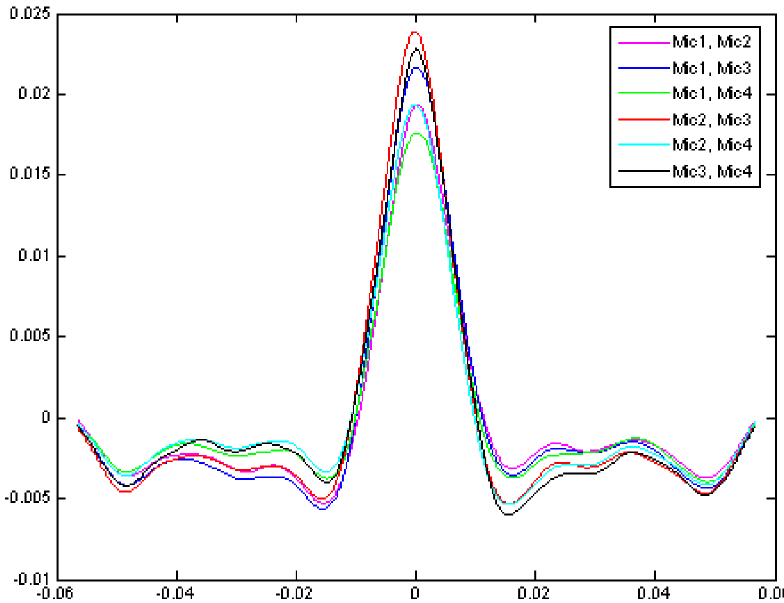

Figure 4.23: Driving 30 MPH cross correlation.

This indicates that audio data is not periodic as it was with the engine idle.

4.2.1.7 Spectral Analysis

Figure 4.22 shows the normalized PSD plots of driving 30 MPH with the windows up.

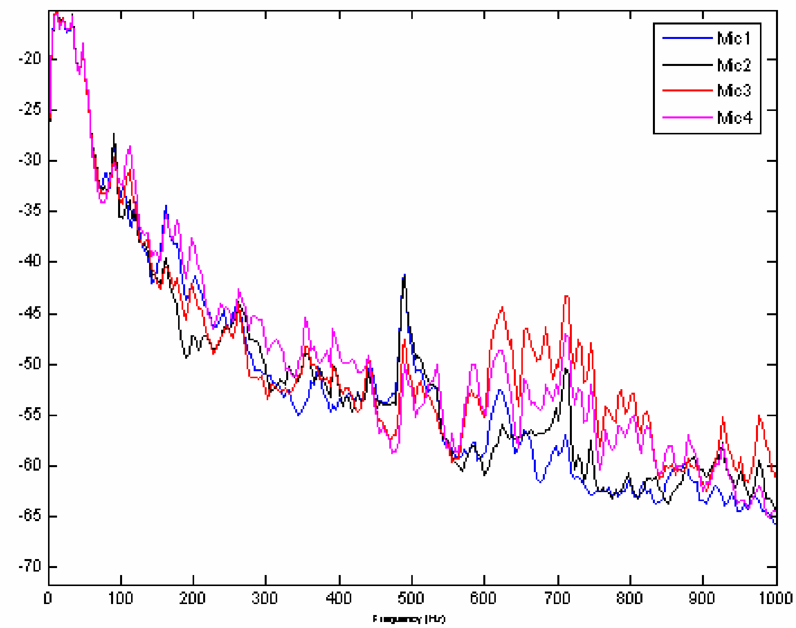

Figure 4.23: Driving 30 MPH normalized 0-1 kHz PSD.

Although it is difficult to pinpoint all frequency noises, it would seem likely that the 80 Hz spike is the engine at approximately 1600 RPM. Most of the power contained in this signal is from the lower frequency noise. This noise is likely caused by the automobile aerodynamics and by the tires. Tires cause a very low frequency noise, given by the rotation per second of the tire. Beyond this it is difficult to surmise where the other noises may come from, however below 250 Hz there is a steady drop-off in noise intensity.

4.2.6 50MPH Constant Speed Driving Test

Driving 50 MPH will present the same issues as the 30 MPH test. The differences are that with a faster velocity, many of the resistant forces will be greater.

4.2.1.8 Spectral Analysis

The below power spectral density graph shows the car driving at 50 MPH.

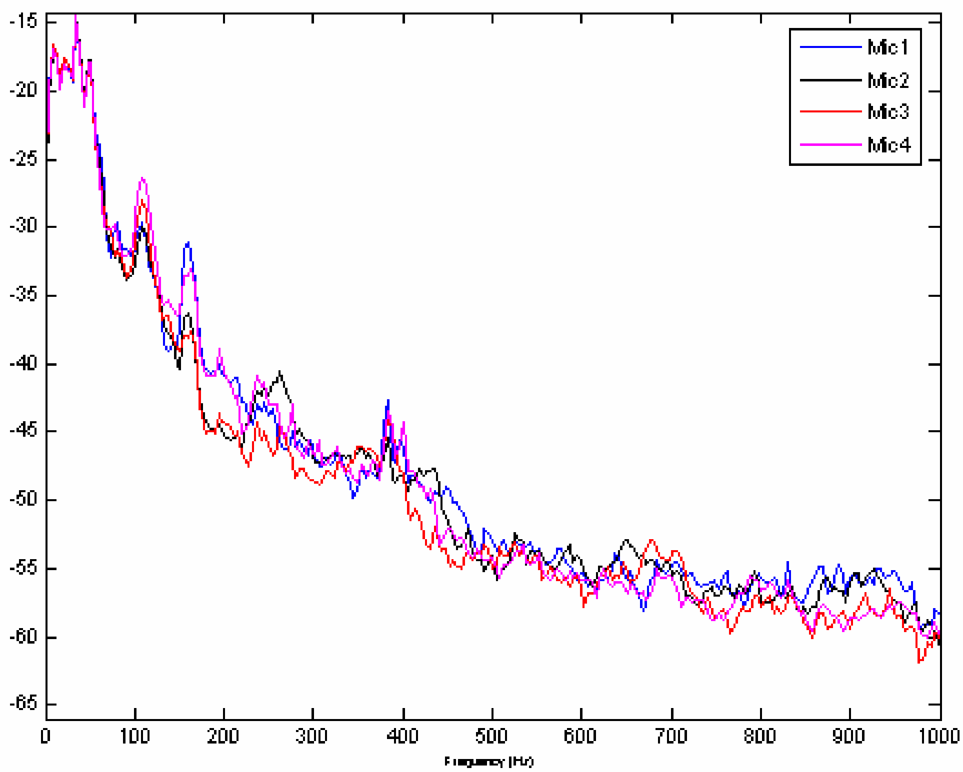

Figure 4.24: Driving 50 MPH normalized 0-1 kHz PSD.

The lower frequency data has a higher power than it did in the 30 MPH test. The engine appears to be at approximately 2000 RPM during this test, which would account for the 100 Hz noise spike. The biggest difference versus the 30 MPH Test is that the linear decrease seems to level off at -60dB.

4.2.7 30-50MPH Acceleration Driving Test

The acceleration test differs from the first tests in that the car is not travelling at the same velocity. The acceleration test is useful in illustrating the uses of the spectrogram in analysis.

4.2.1.9 Spectral Analysis

The PSD plots show mostly lower frequency noise. The noise levels are somewhere in between what is seen for the 30 MPH and 50 MPH graphs.

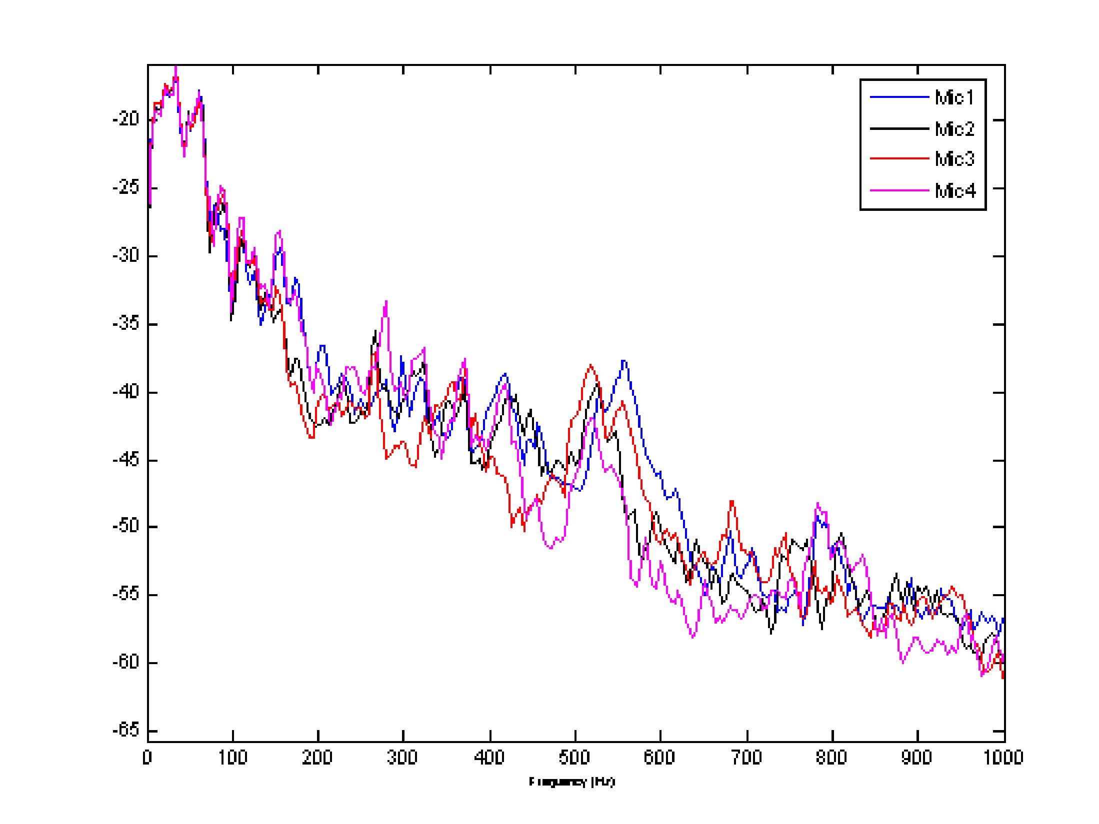

Figure 4.25: Accelerating 30-50 MPH normalized 0-1 kHz PSD.

Figure 4.25 shows a high level of frequencies at 70 Hz and below and moderate frequency content up till approximately 150 Hz. The lower band would seem to indicate the noise from the car's exterior. The second band indicates the engine noise, as there is a linear progression that shifts from 80 Hz to 150 Hz.

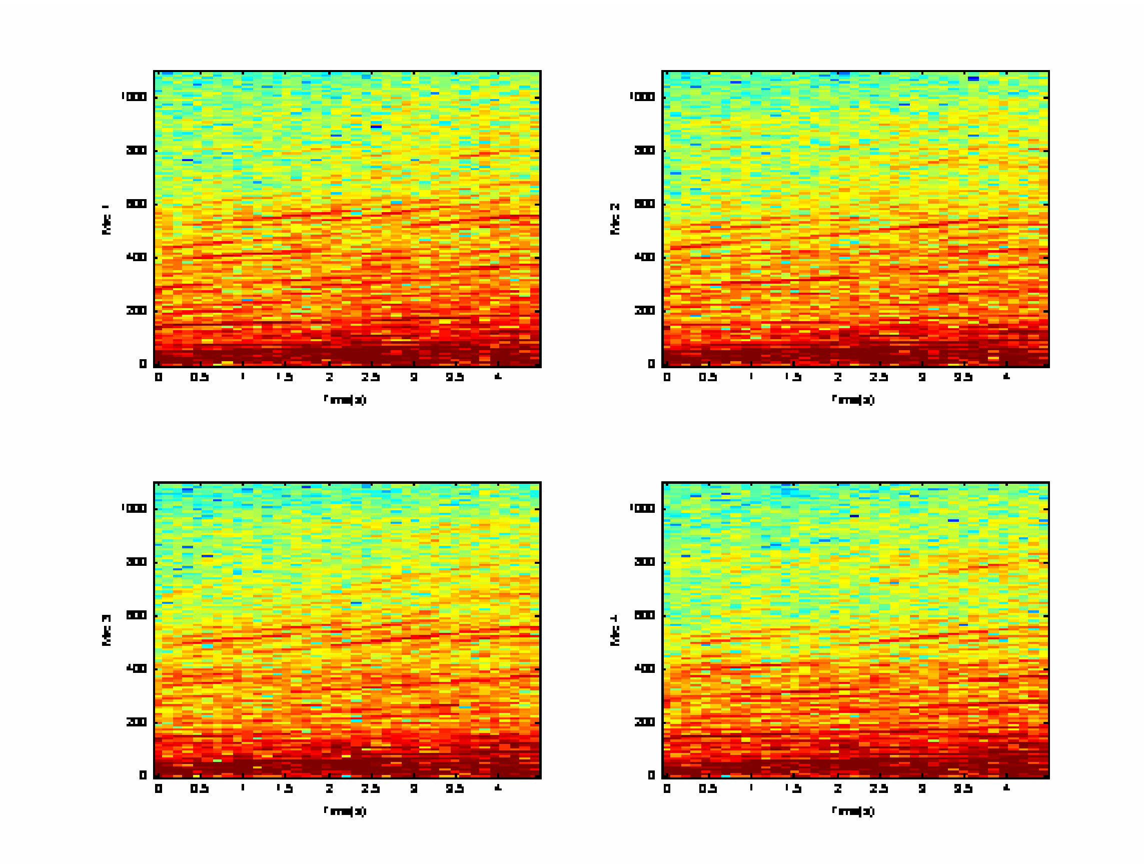

Figure 4.26: Accelerating 30 to 50 0-1 kHz spectrogram.

As can be seen from Figure 4.26, there is a shift to higher frequencies over the course of the automobile acceleration. This data confirms the general pattern of the frequency shift that was seen in the power spectral density plot.

4.2.8 Summary and Interpretation of the Results

The car tests showed a number of things. First, it proved that the system designed and tested in the laboratory functioned as expected in the automobile. Second, completing the tests proved to the team that the automation software worked correctly and made the procedure relatively quick and easy. Finally, it proved that the analysis methods used show expected results such as RPM to fundamental frequency and increase in noise and lower frequencies when driving. For the detailed reports on all three cars, please refer Appendix A, B, and C.

5 Conclusions and Recommendations

This chapter discusses the research and results that came from designing and testing of the system. The second part of this chapter will discuss recommendations for future improvements to the project.

5.1 Conclusions

The goal of this project was to improve upon the noise acquisition system developed in [7]. Improving on the system involved creating a list of requirements as laid out in the methodology. Some of the requirements that came from the goals involved portability and durability of the suitcase. Set-up and quality recording were important for in automobile usage. The final requirement was that the software should be entirely automated. This section outlines the overall design improvements.

5.1.1 Noise Acquisition System

One of the biggest motivations for this project was improved portability of the system to and from the automobile. The new system is primarily stored within a single suitcase. The weight of the entire suitcase is approximately twenty-five pounds. Only the microphone array bar needs to be stored outside the suitcase. The suitcase holds all the microphones in a container that is removable from the box. The inverter is attached by Velcro to the suitcases upper section. The rest of the equipment is already permanently mounted in the suitcase. All the necessary parts to make an automotive recording are enclosed in this single suitcase allowing it to meet the standards for portability.

Alongside the importance of portability is durability. The system was designed in such a manner that it can be "knocked" around and still function with out any connections coming loose. The first method to preventing damage was having the system enclosed within the suitcase. The suitcase will take most of the denting if it is dropped and will prevent the Plexiglas from cracking. Inside the case, the Plexiglas is supported by four metal rods to prevent any danger of collapsing of the supports. The Plexiglas chosen has 3/8'' thickness to prevent any risk of bowing. Also to prevent damage to the microphone connectors there are rubber gaskets around each of the holes in the suitcase.

The second phase of system involved the in-automobile use and recording. The system set-up time is well within the required range. Normal set-up takes less than ten minutes. With experience and knowledge of the system, the set-up can be completed in less than five minutes. The setup has two different forms; the first is having the suitcase and entire system rest on the passengers lap. The second form, which was chosen for testing in this project, was having the suitcase placed in the backseat with the laptop handled by the passenger in front.

One of the focuses of project was improving upon the audio data acquisition. The validation tests proved that system did not contain any unwanted harmonics originating from 60 Hz. Several tests were performed to prove that each component in the system was electrically sound as well. Three car tests were performed to validate and analyze car noise. Each test performed well, and there was no evidence in the spectrograms or power spectral density graphs of any abnormalities.

5.1.2 Graphical User Interface

The biggest change from previous projects is the automation software. All work is done though the graphical user interface (GUI) except for the recordings. The graphical user interface takes data input into the interface and converts it into an output .html file. The GUI allows the user to have control of all the data that goes into the report as mentioned in the methods section.

The GUI has a protocol for the user choosing which car tests to perform. There are eight different tests to perform, and the user can chose as few or as many tests as they wish to perform. Each test has a text prompt associated with it explaining the test and the procedure to create the correct recording. This feature creates more organization of the data and allows the user to have more understanding of how each test was designed to work.

The GUI alleviates the issue of having to the run the audio data manually through Matlab. The GUI improves upon the previous Matlab code by having the user chose the types of graphs that will be placed into the .html report. The choices are categorized under the following three styles: spatial, temporal, or spectral. DOA analysis is fully integrated into the code for the first time. All the parameters necessary to calculate DOA are integrated into the GUI. The GUI features DOA on up to three different frequencies.

The final feature the GUI offers for improving the overall system is the file structure and nomenclature. Every time that a report is created it prompts the user to locate the audio files associated with each test and microphone. As each file is selected the program renames it according to each test and microphone. Each audio file associated with the test is in a folder named “Audio Data”. Every graph generated is named by the test performed and graph type, and placed in a "Figures" folder. Both of these folders fall in a subdirectory of the main folder. The main folder is named after the car and date of report creation. This feature creates a file system to simplify finding the tests and its associated graphs and audio files.

The end result of all the programming is the final .html report. This report contains all the graphs and links to the audio files from the selected tests. Each car will have a unique report. Each test has built in links for easy navigation. The major improvement here is that even though each plot is saved individually, this report is easily printable and categorizes each plot by test and has the plots in a specific order.

5.1.3 General Conclusions

The only issue that was not resolvable with the system was the issue of a daylight visible display. The cost of a daylight visible display was out of the budget range of this project. Instead, a sunshield was constructed from an extra part of the suitcase. The sides were sewn on. In the prototype testing, there was no need to use the sunshield, but it was created as an option to use on bright days.

Another general conclusion is that the best indicators of the trends for each type of test performed on the car are the power spectral density and correlation plots. The data changes greatly from test to test for these types of plots. Spectrograms change some with changes, but only show general trends, and little direct data was taken from these plots.

The Direction of Arrival plots do not appear to be extremely useful in the automobile environment. In the validation testing some of the results were promising and display the code works. In the automobile, the tests may not be extremely useful. Most plots point in several directions, and could indicate that the frequency maybe reflecting off of glass, or have several separate occurrences of the frequency through out the car. Another consideration when using the DOA is that the frequency to search for must be chosen before the user examines the PSD most of the time, meaning the value is arbitrarily chosen.

5.2 Recommendations

While most of the goals were met from the requirement list for the project, this does not mean there is not room for improvement. Many of these recommendations may not be realizable immediately, but these changes would be helpful in improving the flexibility of the system.

5.2.1 System Improvements

One of the modifications mentioned above was obtaining a daylight visible display. The price for such displays was approximately $1,000 and was not feasible with the price for the rest of the project's equipment. This would also help to obviate the need for the current laptop. An original goal of this system was to have a computer placed along the audio recording equipment in the suitcase. With technology's exponential increase, a rearranging of the suitcase along with some of the new technology's mini computers, the laptop could be eliminated, allowing for more room in the upper section of the suitcase.

The other system issue involved microphone windscreens. The current windscreens do an adequate job of filtering the wind during the 30MPH test, but there was some popping on the acceleration with the windows down test. Because of this, neither of the tests was included in the main section of the report, however; the plot results are in the appendix. The best solution to this problem would be adding more windscreens on the inside of the microphones. The issue was not as prevalent previously because the microphone array was smaller. Having an array to be able to implement DOA needs to be at least 1m long, which places the outer most microphones right next to the window.

5.2.2 Software Improvements

The rest of the problems and recommendations relate to ways to improve the coding of the project. The first improvement recommendation is to improve the current test structure to a more user friendly process. Although each test can be changed relatively quickly, there is code that would be able to do it in a more compact way. The prompting, naming structure, and text in the dropdown box are currently not declared in the same area, finding the code and process to do this would greatly improve the ability to add and remove tests from the program.

All recording of audio data was done through Cakewalk Sonar as mentioned above. This was one automation issue that was not able to be solved in this project. Matlab was unable to handle simultaneous four channel recording. This issue is one that would make the audio recording process even easier. If some program that is either compatible with Matlab, or easier to use than Sonar was found, it would be helpful to the learning curve of this project.

Another feature in Matlab that could be useful was the tabbing function. The tabbing function is used in several GUI's, and was considered for this project. It appears the current GUI designer in Matlab does not contain a tabbing GUI feature, but an experienced Matlab user may be able to modify the interface. If each portion of the test was separated into a different tab, it would allow for less compaction and require a smaller overall sized GUI.

Finally, from a graph and plot standpoint, the power spectral density and spectrogram plots would benefit from having more options of frequencies on the graph. This process is difficult, but it may be useful to have a 5 kHz plot or some graph ending approximately at that frequency. A semi-log plot may also be useful to see the various frequencies and effects. The 1000 Hz plot is nice for lower frequencies, but anything beyond 1000 Hz is harder to distinguish.

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Appendix A—2000 Jeep Cherokee April 13, 2005

Bose Corporation/WPI SpinLab Report Generator

13-Apr-2005 15:32:22

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Chapter 1. General Information

Tester Names: Jeffrey Ford, George Roscoe, Joseph Vaughn

Location. Rt. 31, Worcester, MA, 01609

Weather: Cloudy

Wind: 5-10 MPH

Road Conditions: Slightly damp.

Comments: Tests went well.

Chapter 2. Car Information

Vehicle: 2000 Jeep Cherokee

Transmission: Automatic

Tires: Goodyear

Chapter 3. Test One: Car Idle

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Play Car Idle Mic 2.wav
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Play Car Idle Mic 3.wav
Recording Four
Play Car Idle Mic 4.wav

Power Spectral Density (0 to 20 kHz)

Figure 3.1. Non-Normalized PSD 0-20kHz, Amplitude in dB

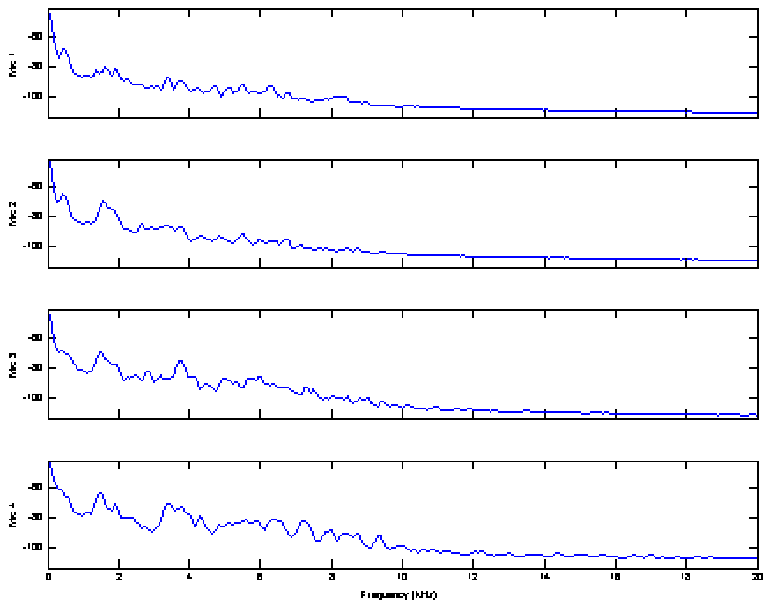
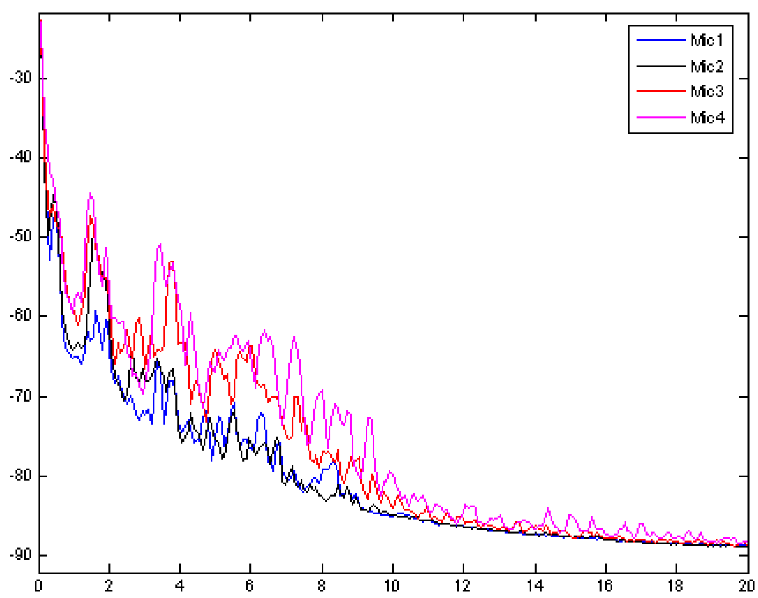


Figure 3.2. Normalized PSD 0-20kHz, Amplitude in dB



Power Spectral Density (0 to 1kHz)

Figure 3.3. Non-Normalized PSD 0-1kHz, Amplitude in dB

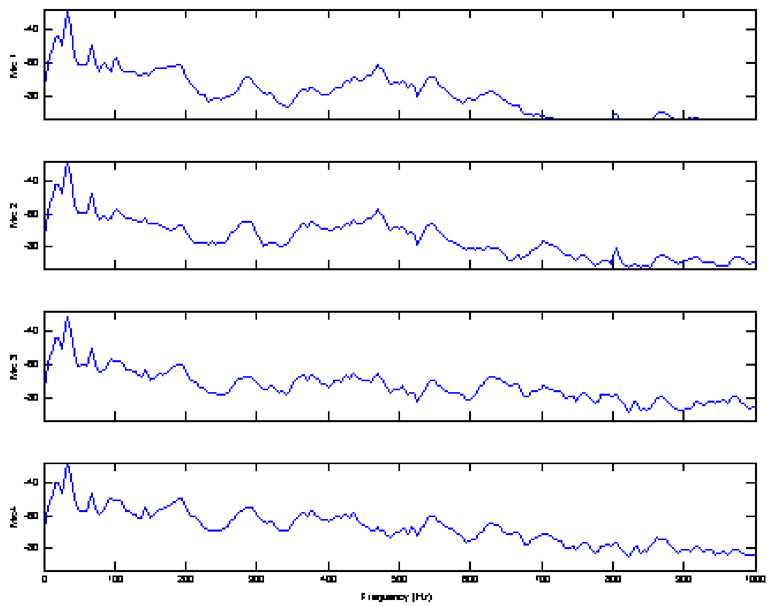
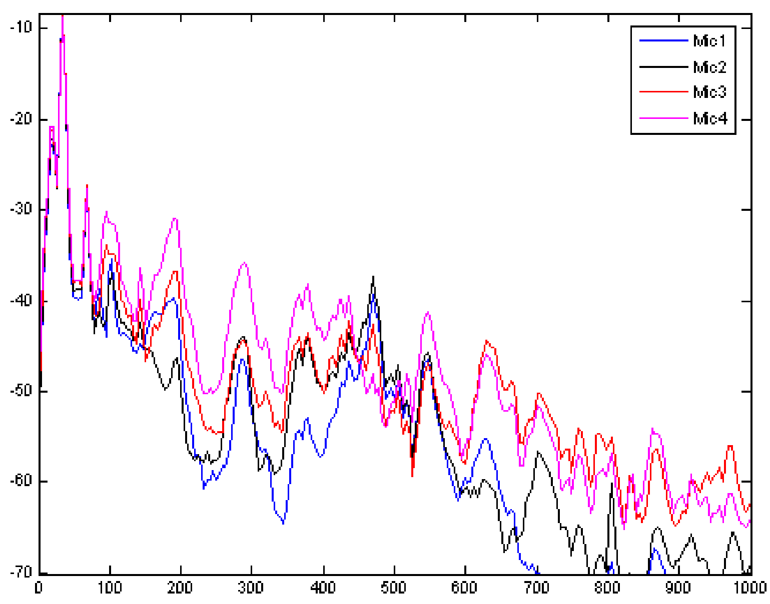
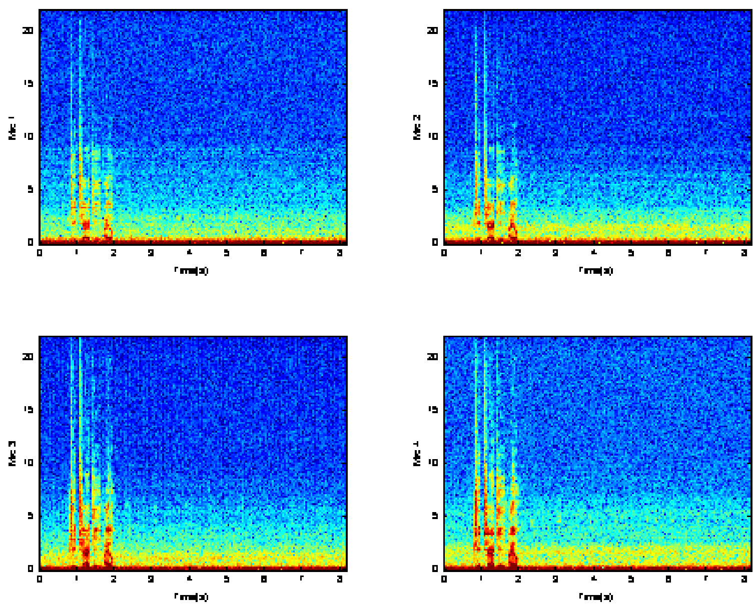


Figure 3.4. Normalized PSD 0-1kHz, Amplitude in dB



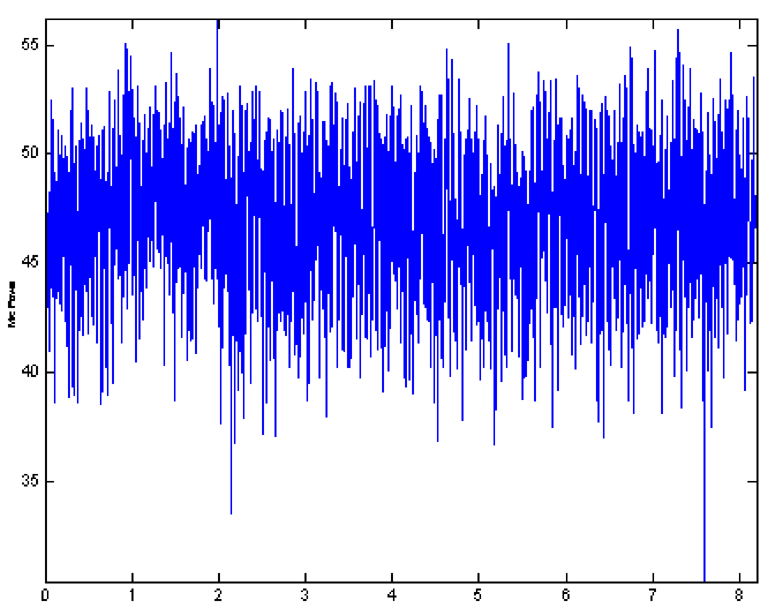
Spectrogram (0 to 20 kHz)

Figure 3.5. Spectrogram 0-20kHz, Frequency in kHz



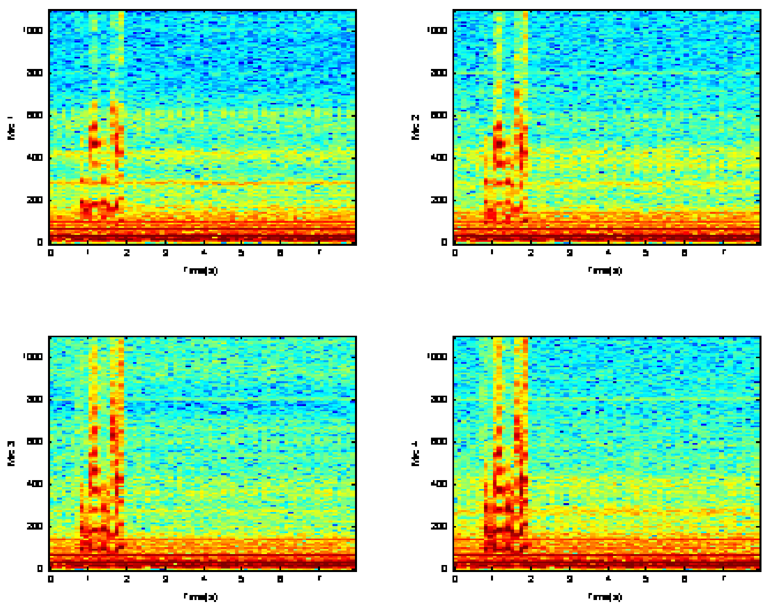
Power vs. Time

Figure 3.6. Power vs. Time, Amplitude in Normalized dB



Spectogram (0 to 1kHz)

Figure 3.7. Spectrogram 0-1kHz, Frequency in Hz



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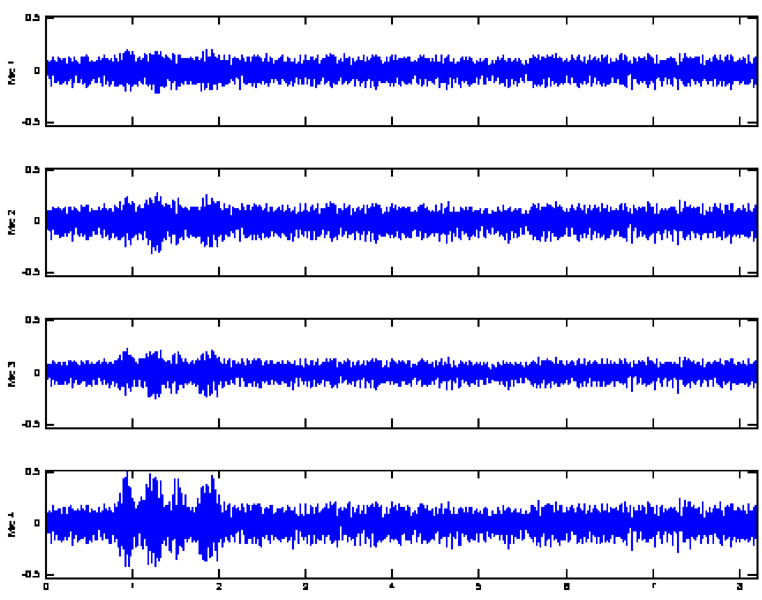

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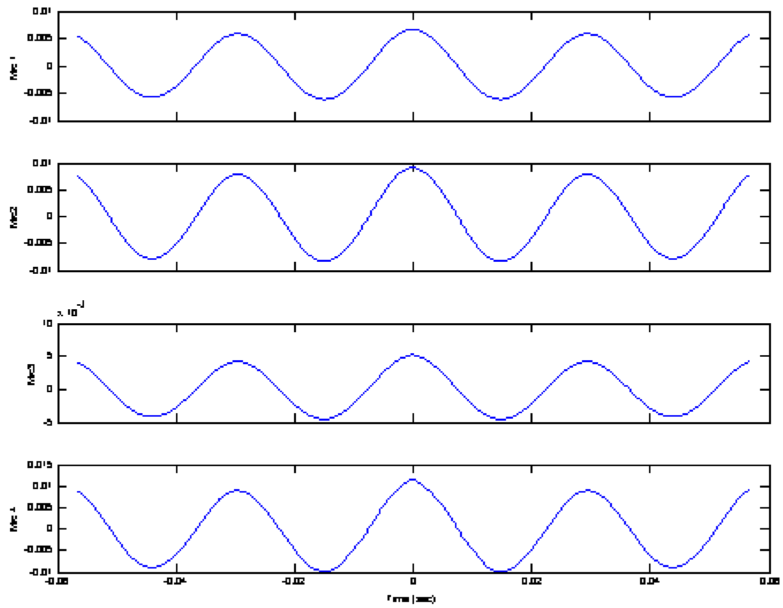
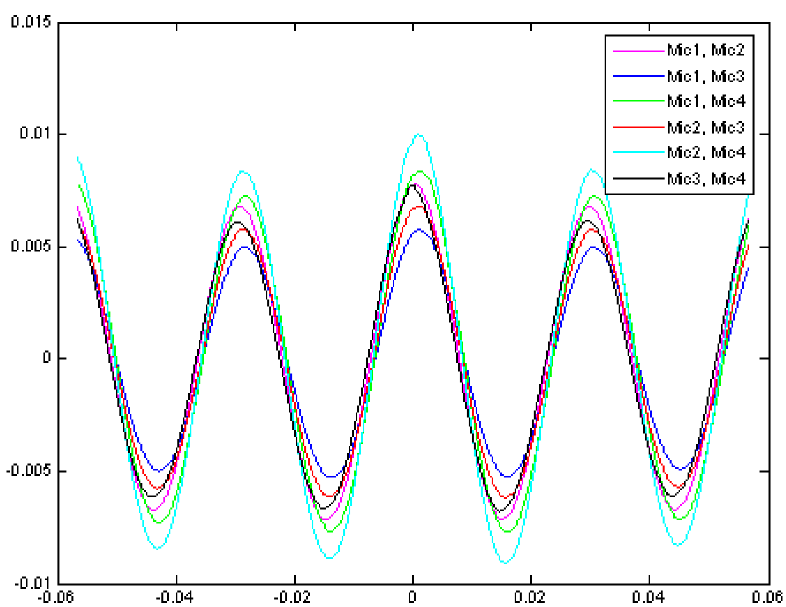


Crosscorrelation

Figure 3.10. CrossCorrelation



Direction of Arrival 200 Hz

Figure 3.11. DOA 200 Hz

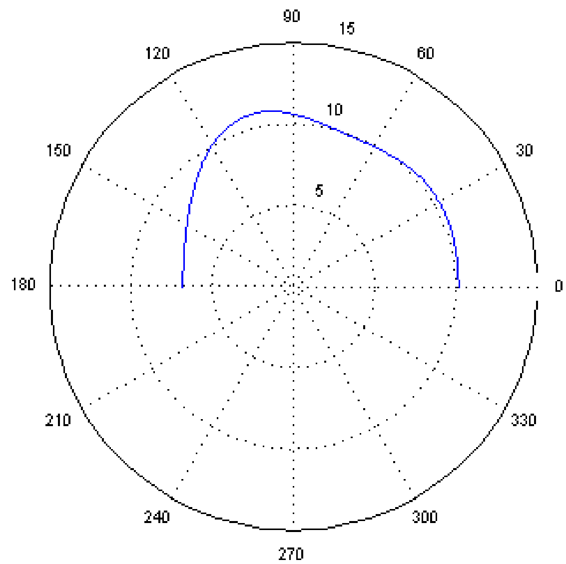


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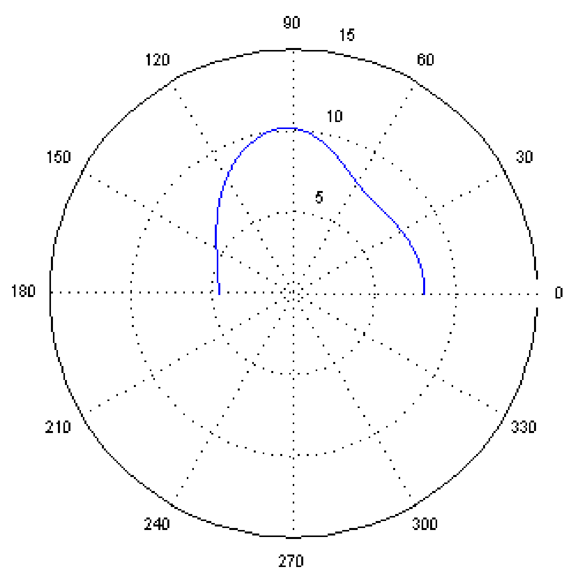
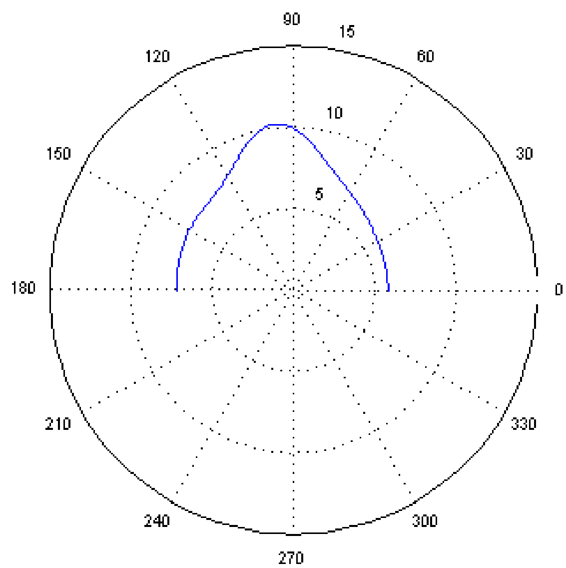
Figure 3.12. DOA 300 Hz



Direction of Arrival 400 Hz

Figure 3.13. DOA 400 Hz



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Recording Two
Play Idle 3000 RPM Mic 2.wav
Recording Three
Play Idle 3000 RPM Mic 3.wav
Recording Four
Play Idle 3000 RPM Mic 4.wav

Power Spectral Density (0 to 20 kHz)

Figure 4.1. Non-Normalized PSD 0-20kHz, Amplitude in dB

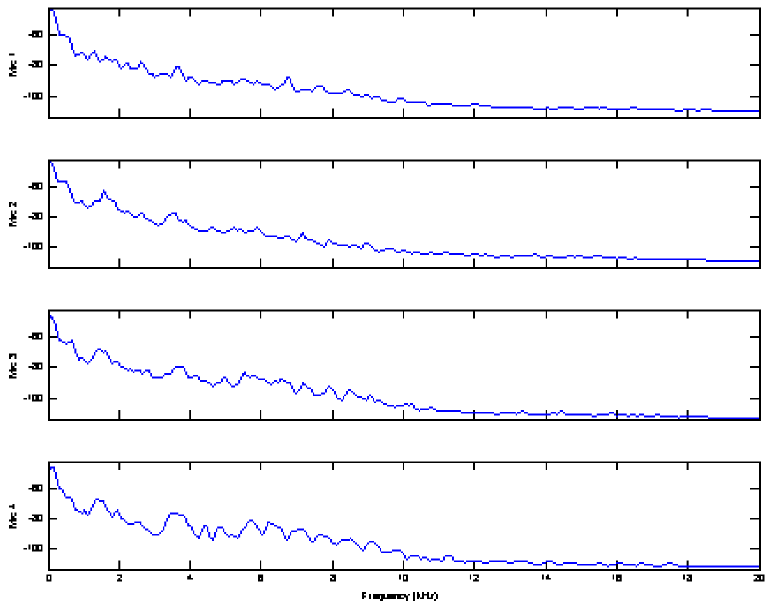
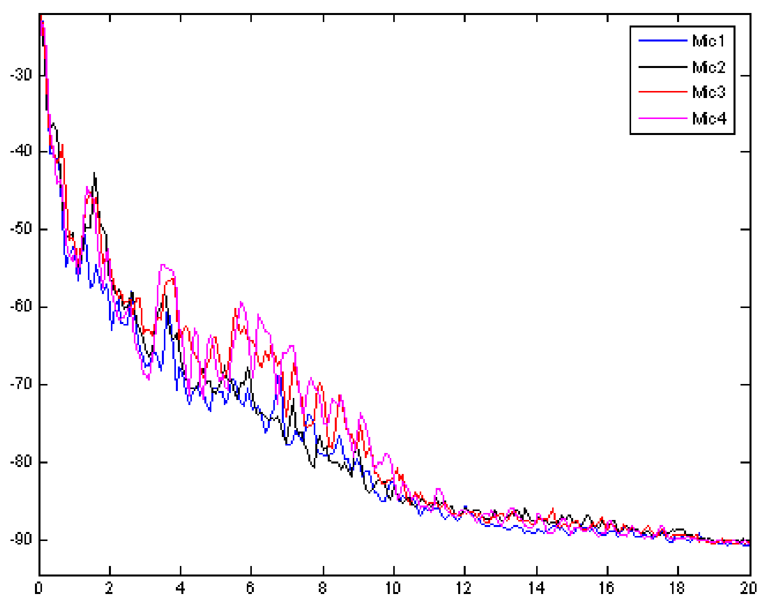


Figure 4.2. Normalized PSD 0-20kHz, Amplitude in dB



Power Spectral Density (0 to 1kHz)

Figure 4.3. Non-Normalized PSD 0-1kHz, Amplitude in dB

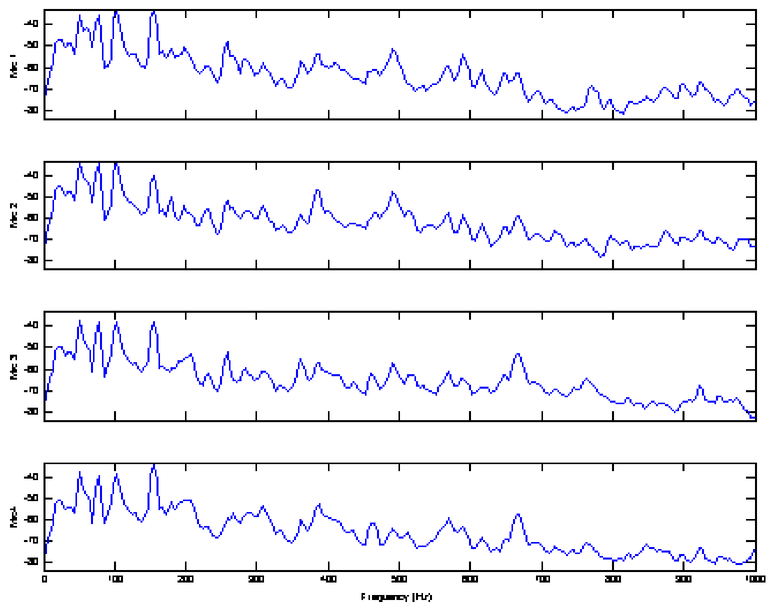
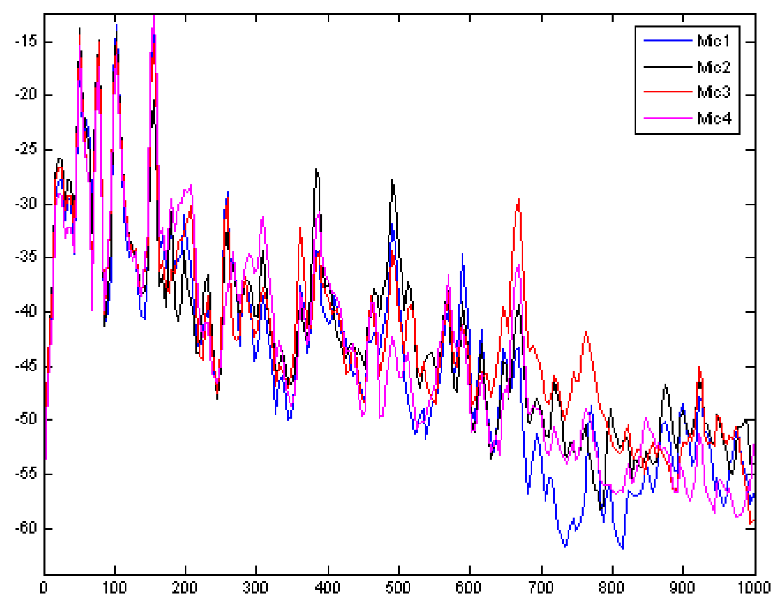
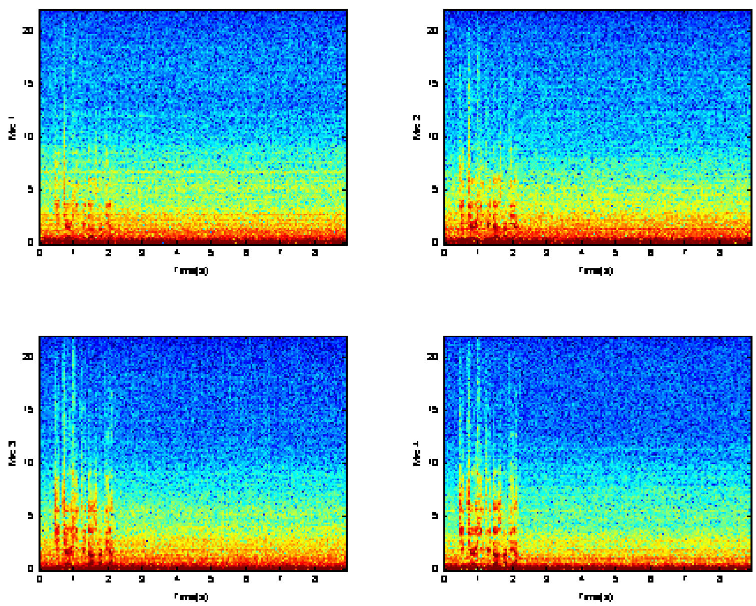


Figure 4.4. Normalized PSD 0-1kHz, Amplitude in dB



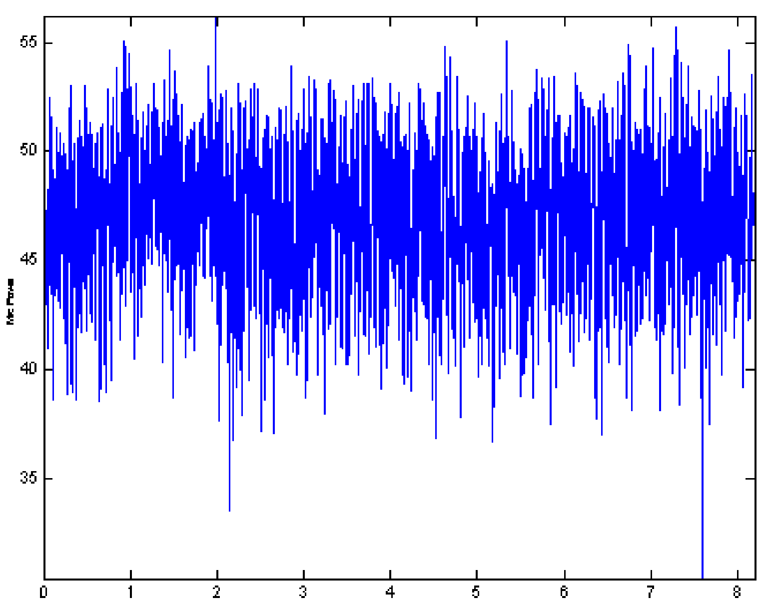
Spectrogram (0 to 20 kHz)

Figure 4.5. Spectrogram 0-20kHz, Frequency in kHz



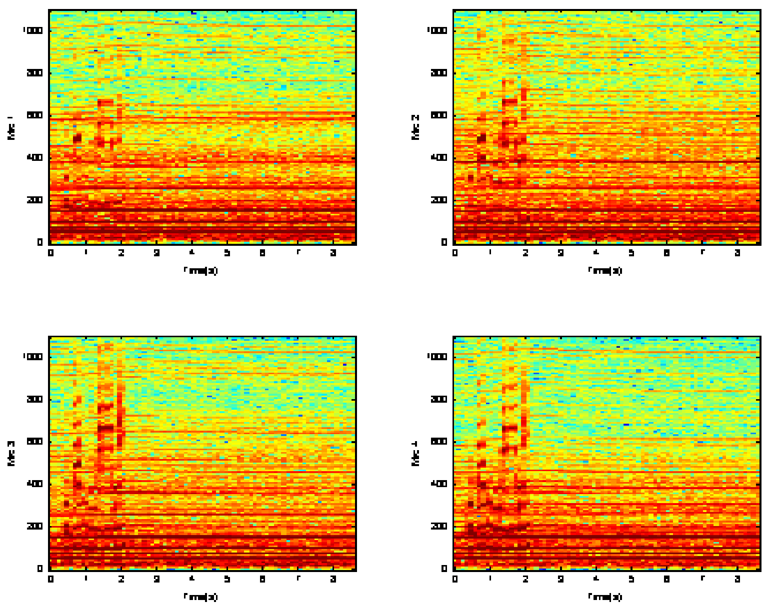
Power vs. Time

Figure 4.6. Power vs. Time, Amplitude in Normalized dB



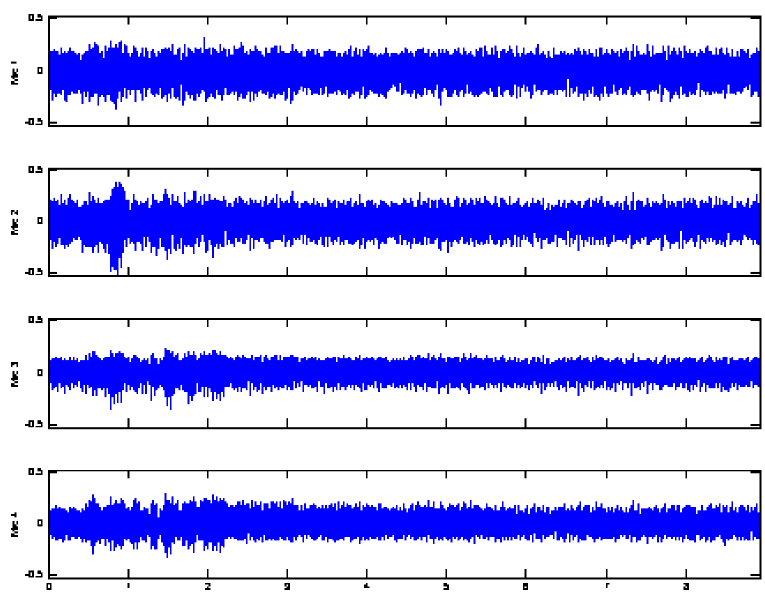
Spectogram (0 to 1kHz)

Figure 4.7. Spectrogram 0-1kHz, Frequency in Hz



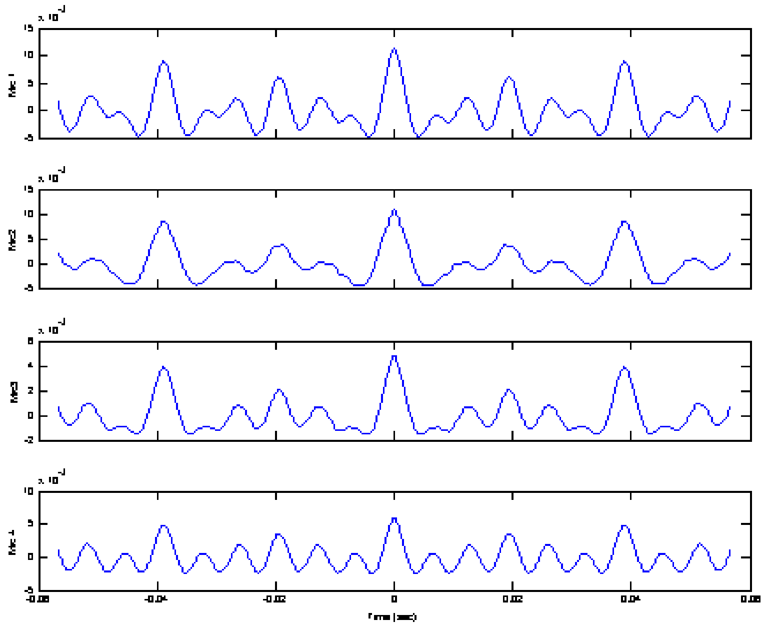
Time Plot

Figure 4.8. Time Graph



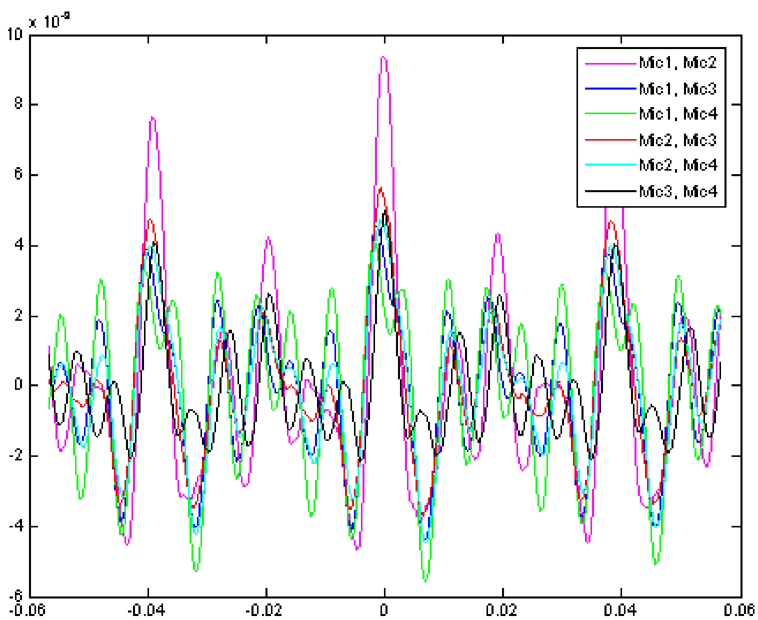
Autocorrelation

Figure 4.9. Autocorrelation Graph



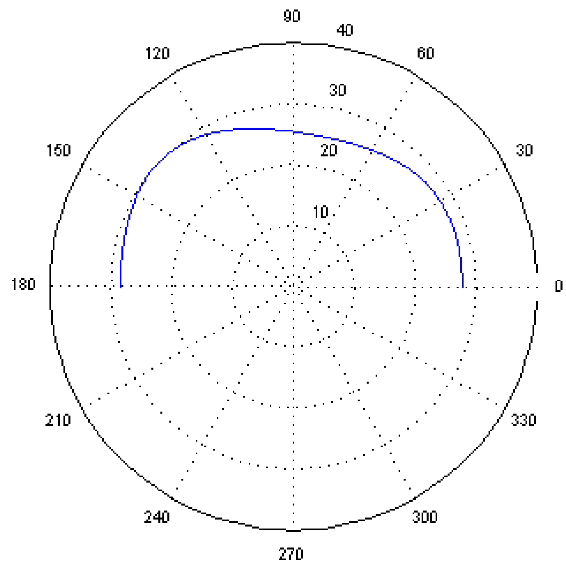
Crosscorrelation

Figure 4.10. CrossCorrelation



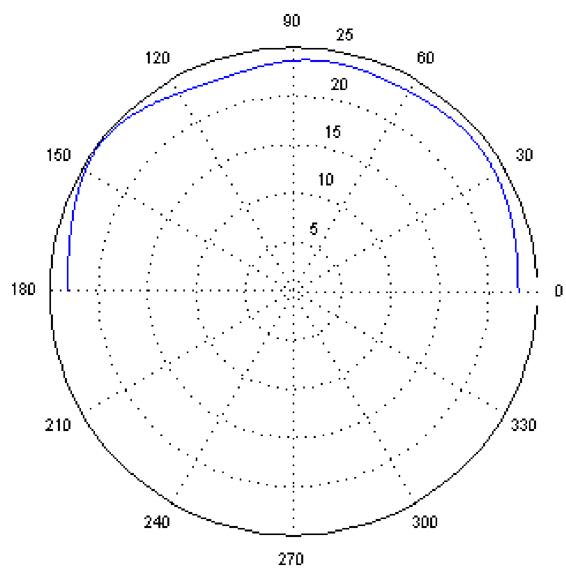
Direction of Arrival 200 Hz

Figure 4.11. DOA 200 Hz



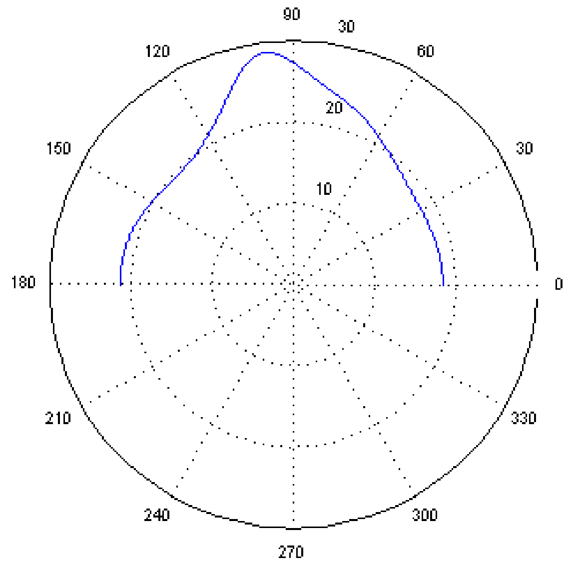
Direction of Arrival 300 Hz

Figure 4.12. DOA 300 Hz



Direction of Arrival 400 Hz

Figure 4.13. DOA 400 Hz



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Power Spectral Density (0 to 20 kHz)

Figure 5.1. Non-Normalized PSD 0-20kHz, Amplitude in dB

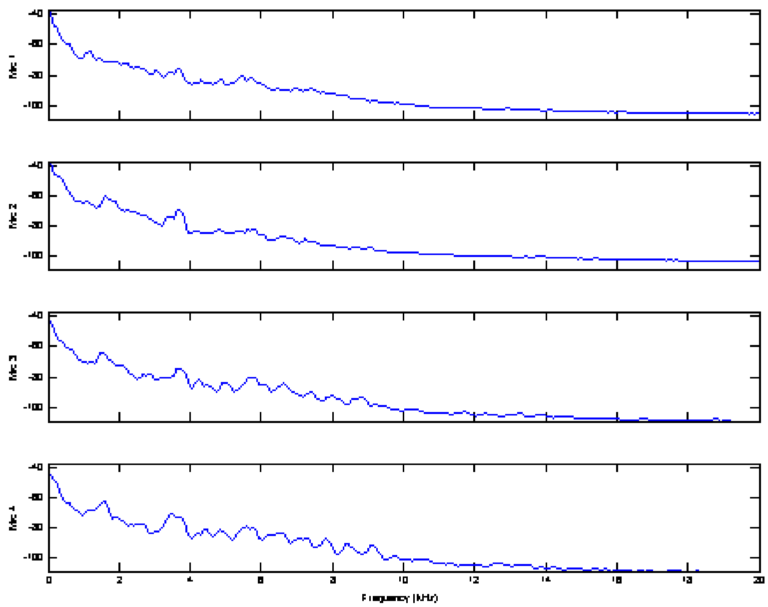
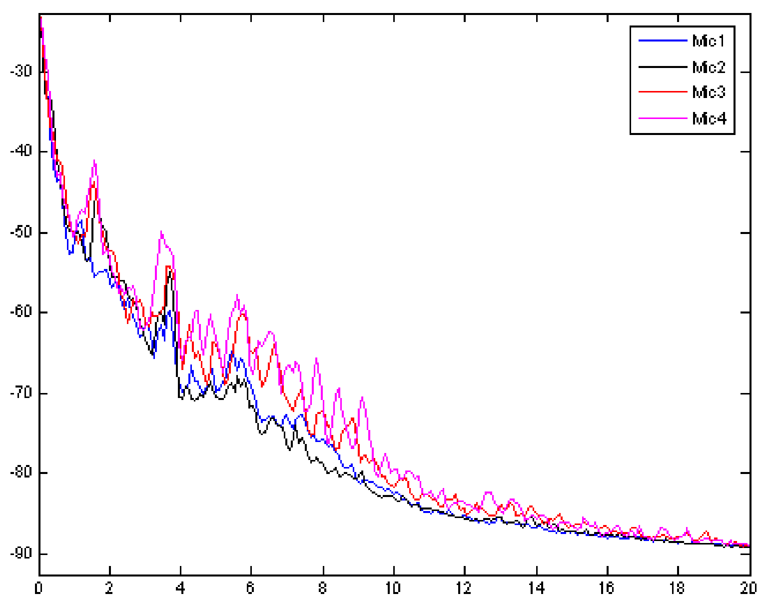


Figure 5.2. Normalized PSD 0-20kHz, Amplitude in dB



Power Spectral Density (0 to 1kHz)

Figure 5.3. Non-Normalized PSD 0-1kHz, Amplitude in dB

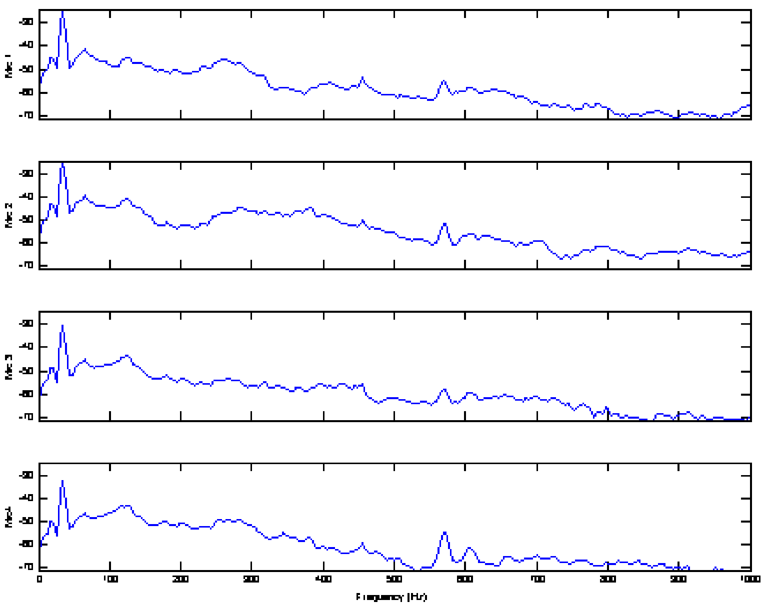
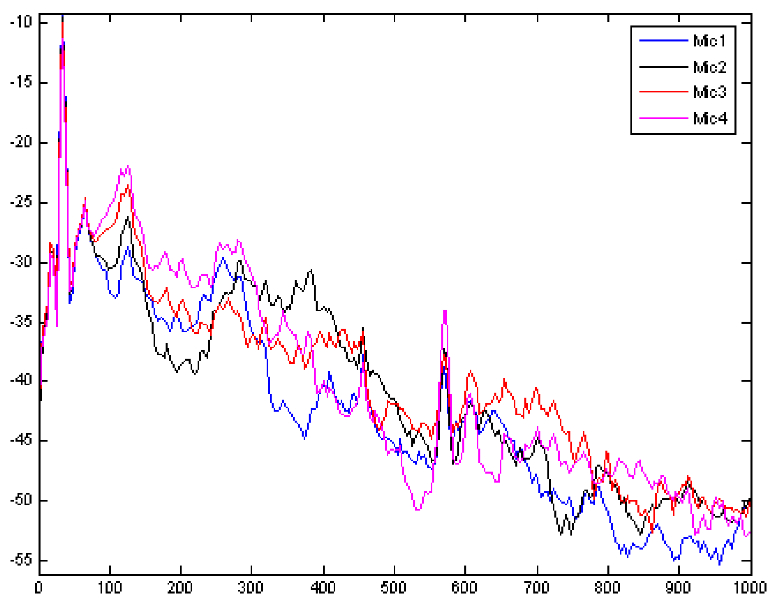
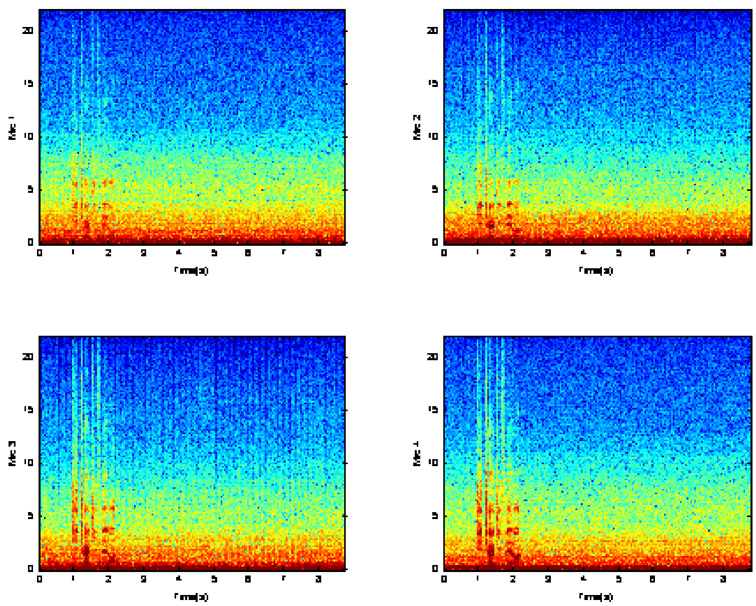


Figure 5.4. Normalized PSD 0-1kHz, Amplitude in dB



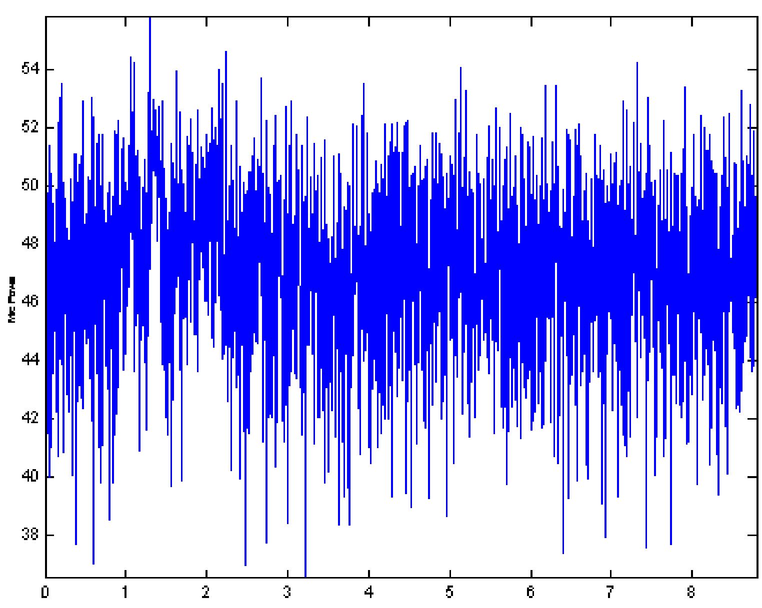
Spectrogram (0 to 20 kHz)

Figure 5.5. Spectrogram 0-20kHz, Frequency in kHz



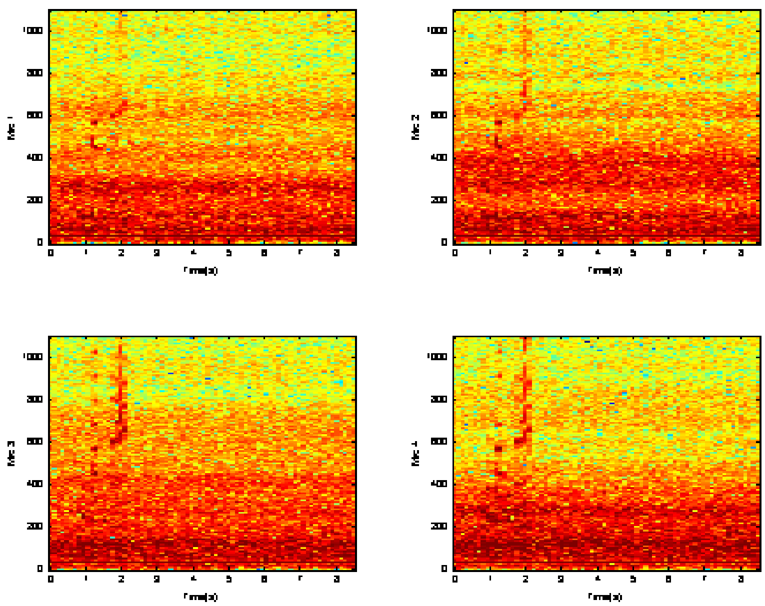
Power vs. Time

Figure 5.6. Power vs. Time, Amplitude in Normalized dB



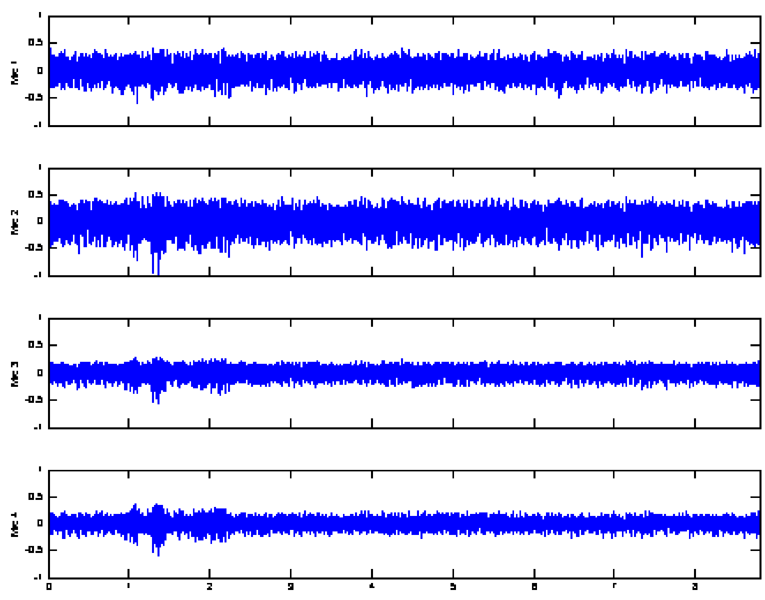
Spectogram (0 to 1kHz)

Figure 5.7. Spectrogram 0-1kHz, Frequency in Hz



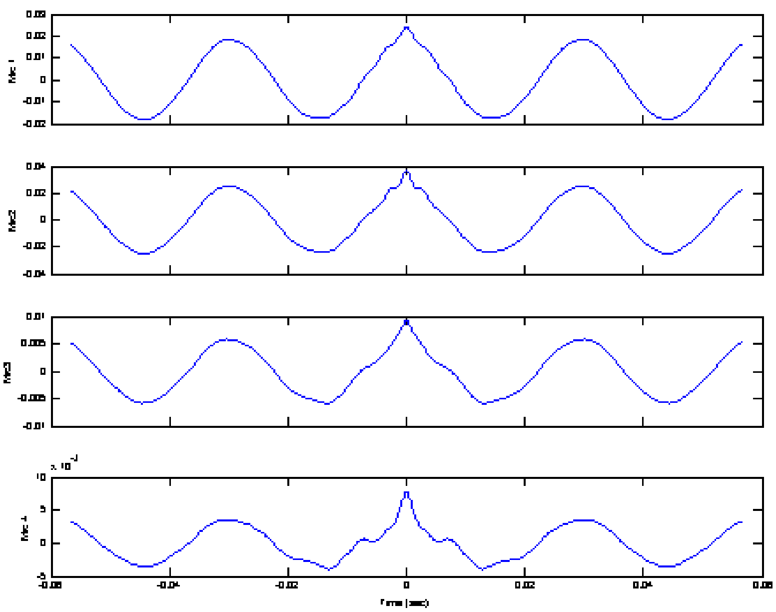
Time Plot

Figure 5.8. Time Graph



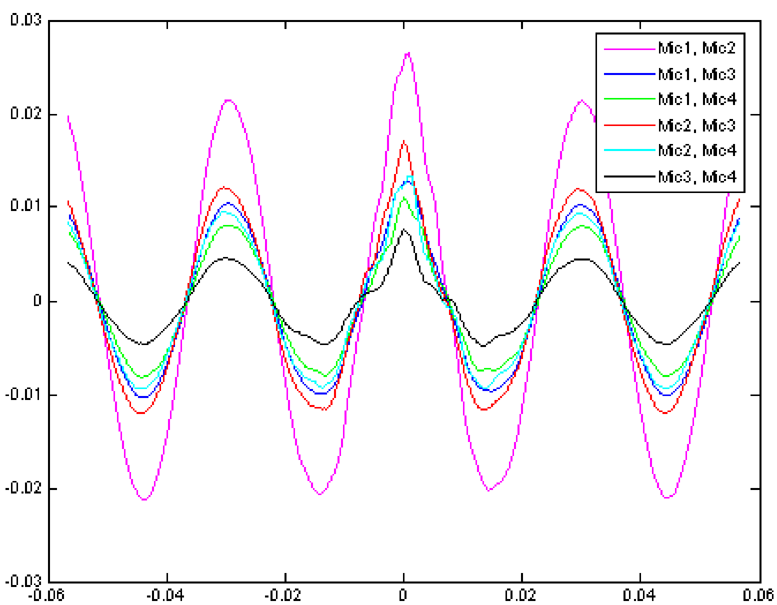
Autocorrelation

Figure 5.9. Autocorrelation Graph



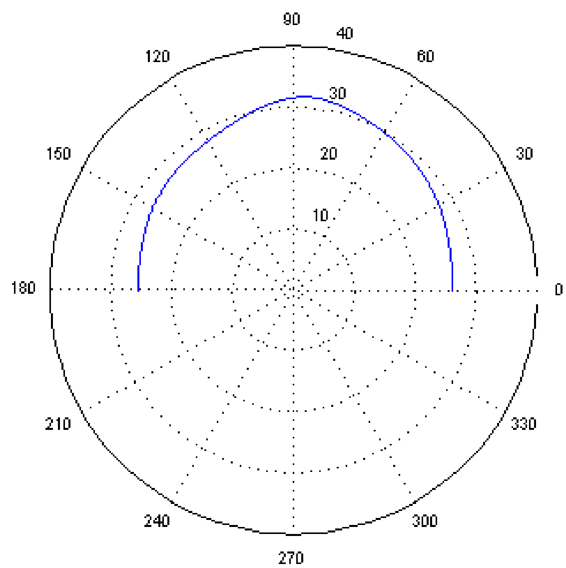
Crosscorrelation

Figure 5.10. CrossCorrelation



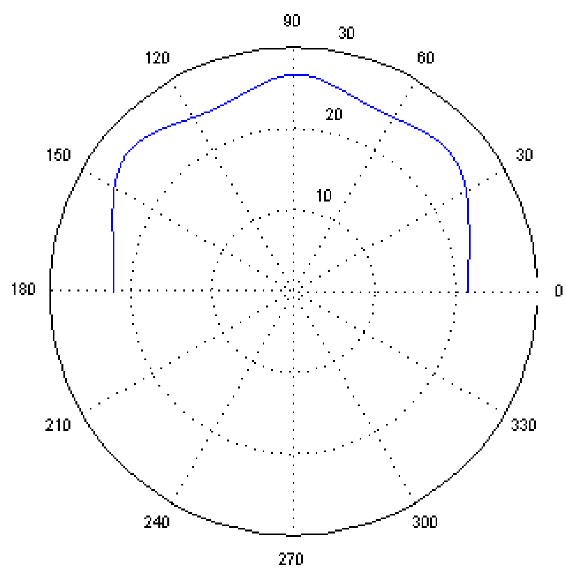
Direction of Arrival 200 Hz

Figure 5.11. DOA 200 Hz



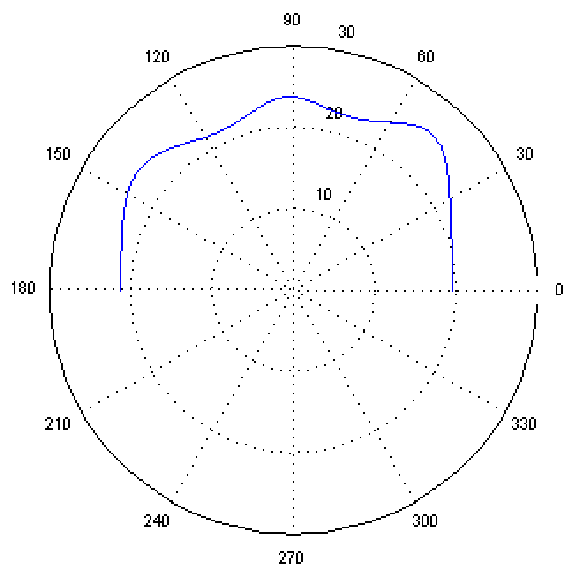
Direction of Arrival 300 Hz

Figure 5.12. DOA 300 Hz



Direction of Arrival 400 Hz

Figure 5.13. DOA 400 Hz



Chapter 6. Test Four: Driving 30 MPH

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Power Spectral Density (0 to 20 kHz)

Figure 6.1. Non-Normalized PSD 0-20kHz, Amplitude in dB

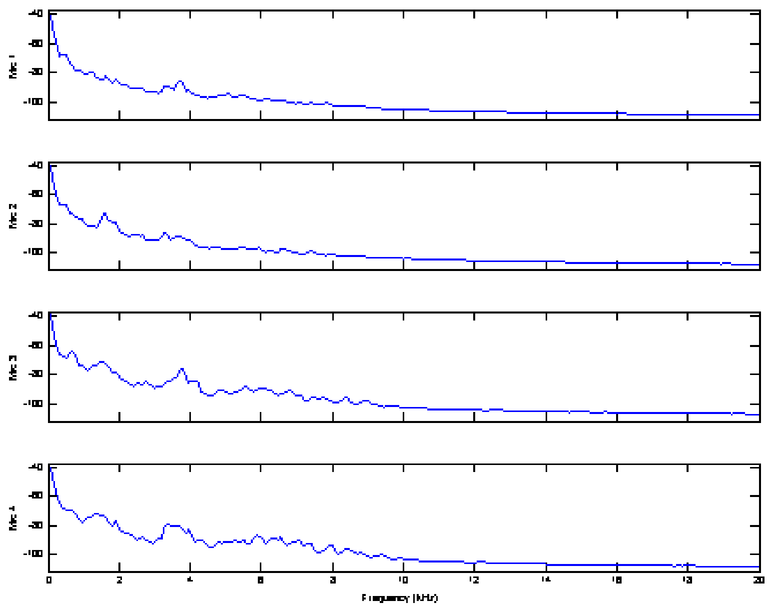
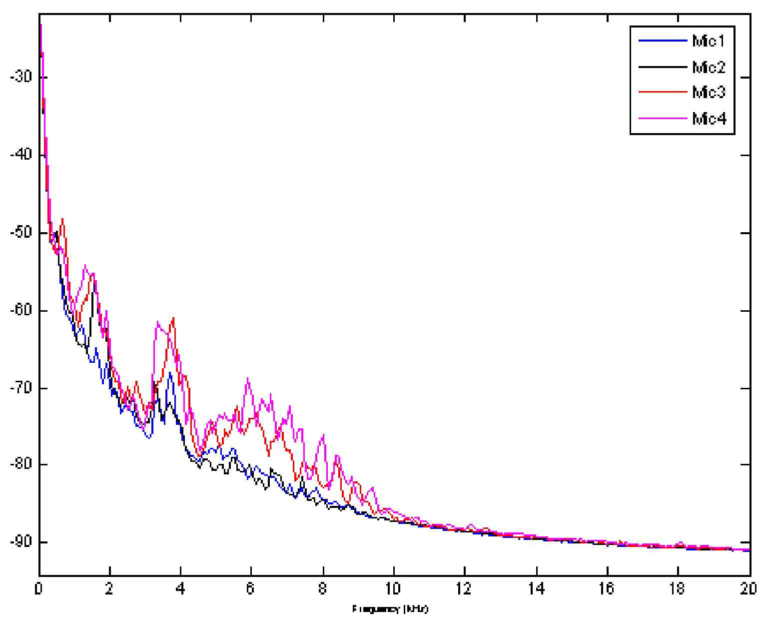


Figure 6.2. Normalized PSD 0-20kHz, Amplitude in dB



Power Spectral Density (0 to 1kHz)

Figure 6.3. Non-Normalized PSD 0-1kHz, Amplitude in dB

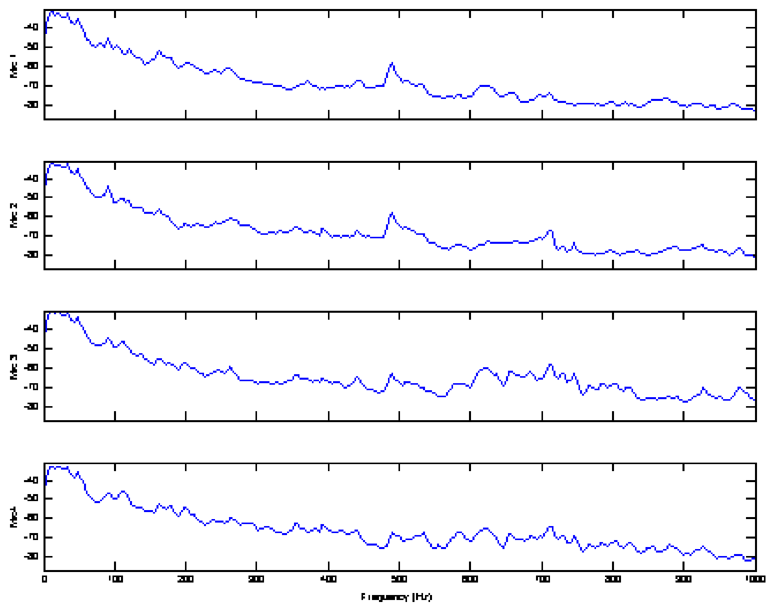
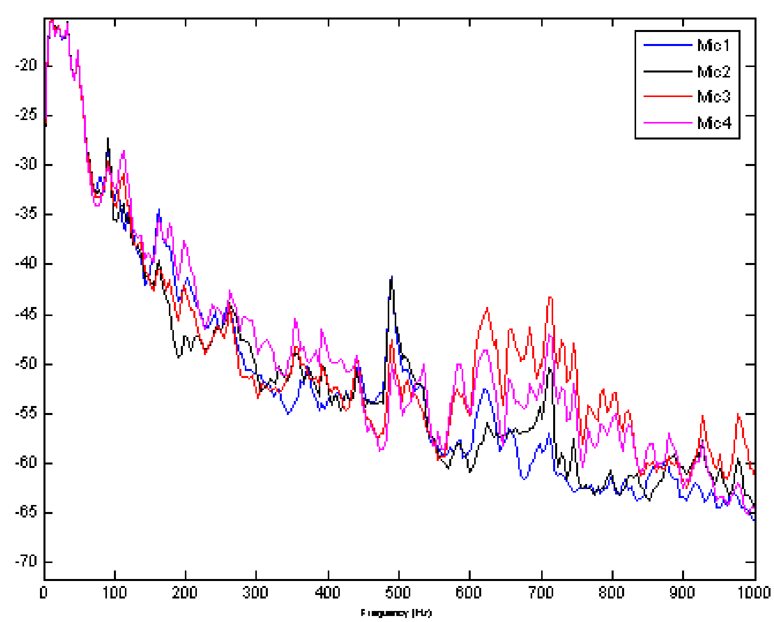
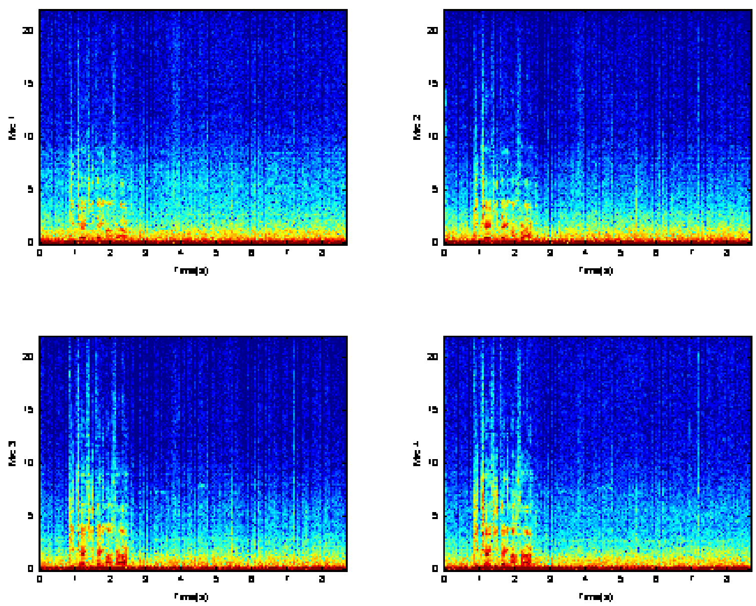


Figure 6.4. Normalized PSD 0-1kHz, Amplitude in dB



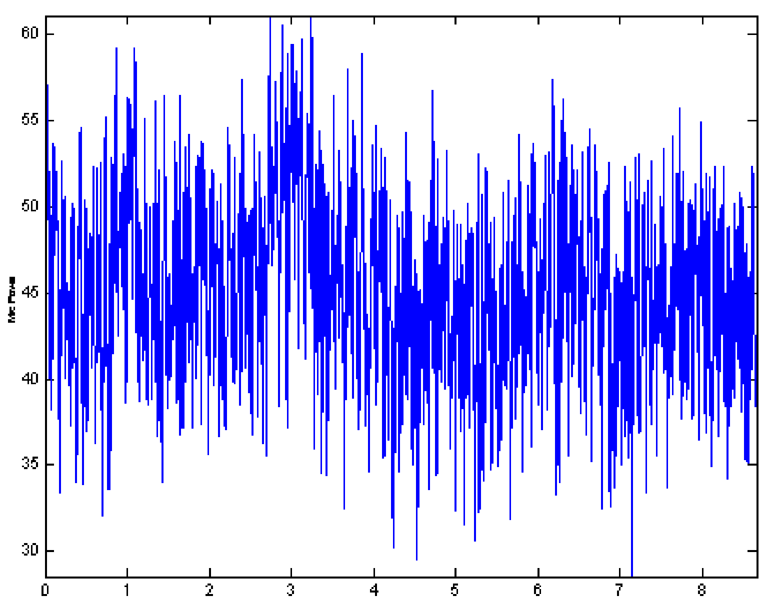
Spectrogram (0 to 20 kHz)

Figure 6.5. Spectrogram 0-20kHz, Frequency in kHz



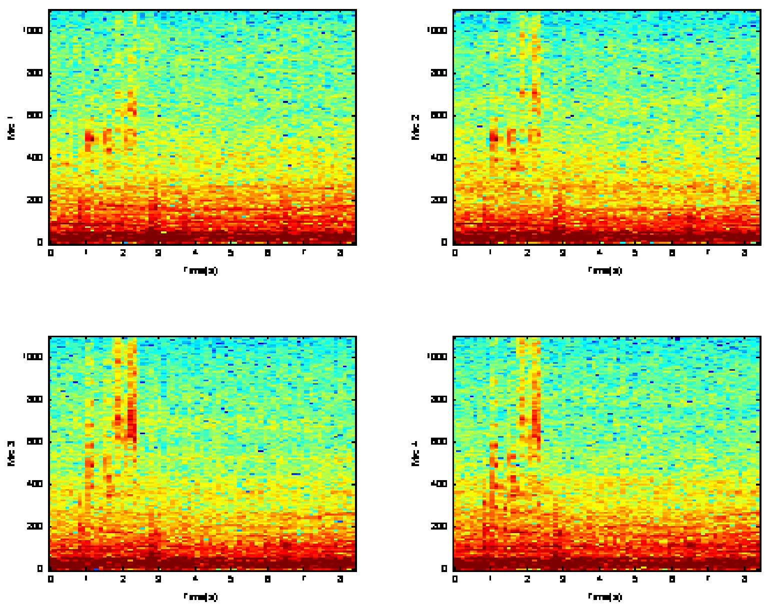
Power vs. Time

Figure 6.6. Power vs. Time, Amplitude in Normalized dB



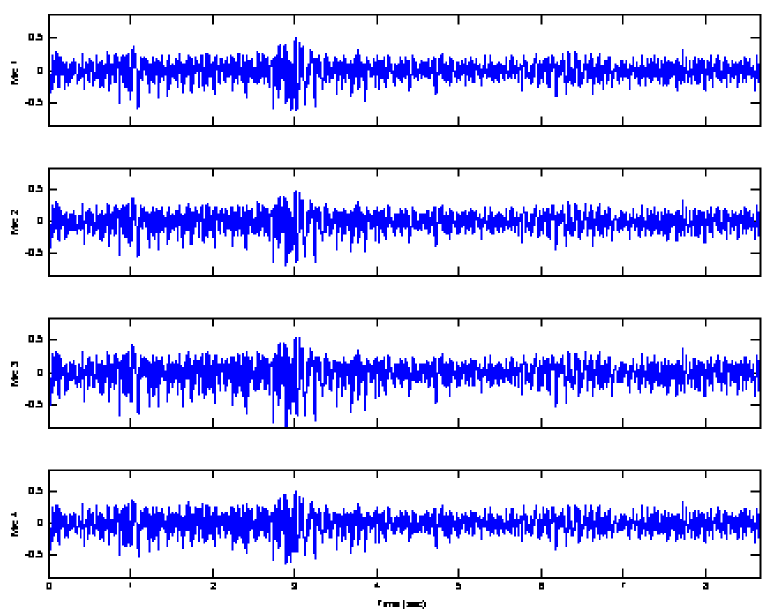
Spectogram (0 to 1kHz)

Figure 6.7. Spectrogram 0-1kHz, Frequency in Hz



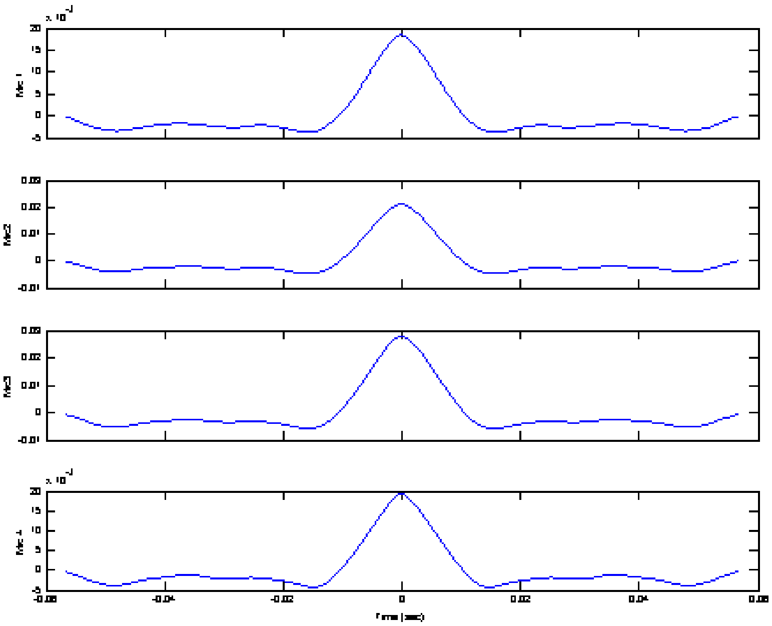
Time Plot

Figure 6.8. Time Graph



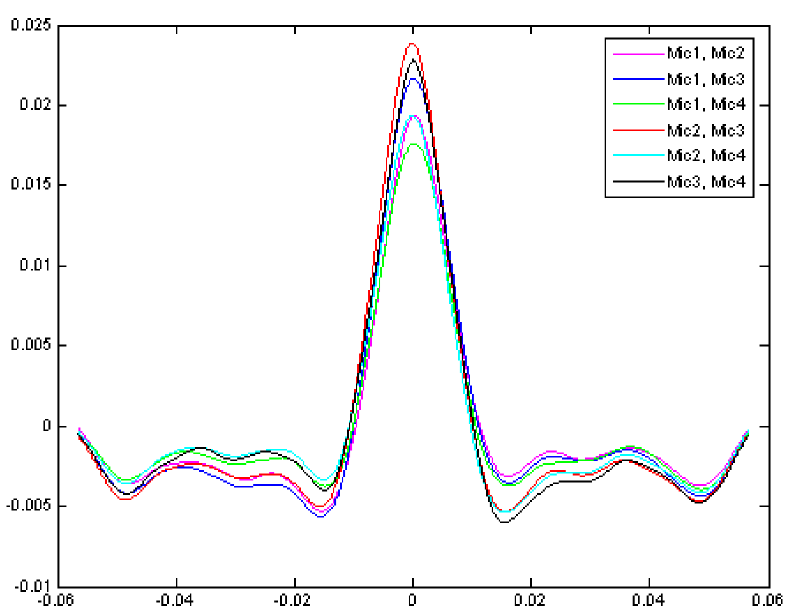
Autocorrelation

Figure 6.9. Autocorrelation Graph



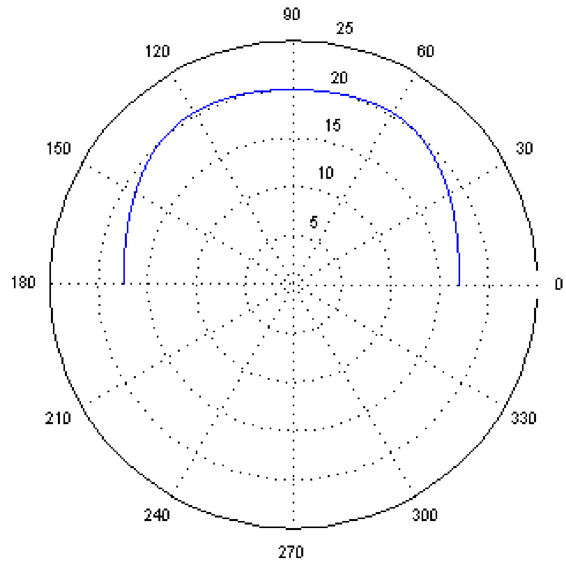
Crosscorrelation

Figure 6.10. CrossCorrelation



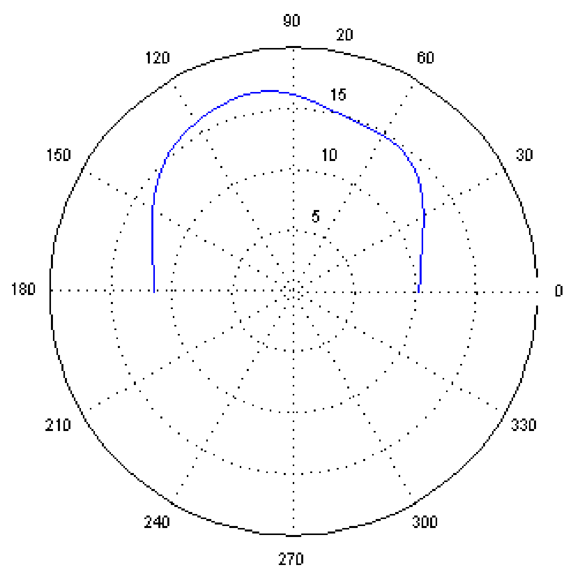
Direction of Arrival 200 Hz

Figure 6.11. DOA 200 Hz



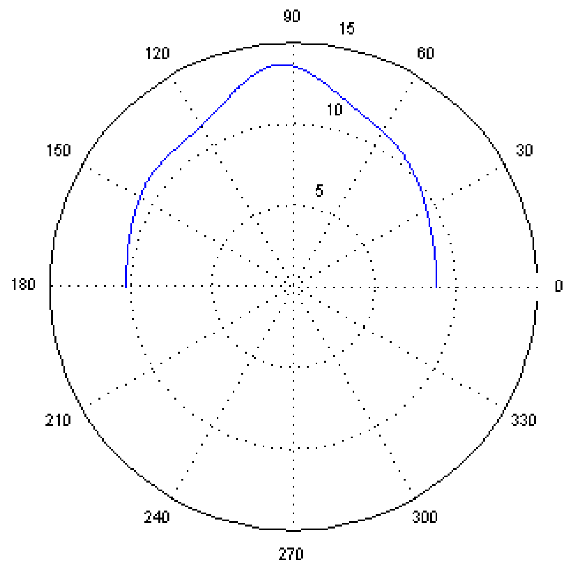
Direction of Arrival 300 Hz

Figure 6.12. DOA 300 Hz



Direction of Arrival 400 Hz

Figure 6.13. DOA 400 Hz



Chapter 7. Test Five: Driving 30 MPH, windows down

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Power Spectral Density (0 to 20 kHz)

Figure 7.1. Non-Normalized PSD 0-20kHz, Amplitude in dB

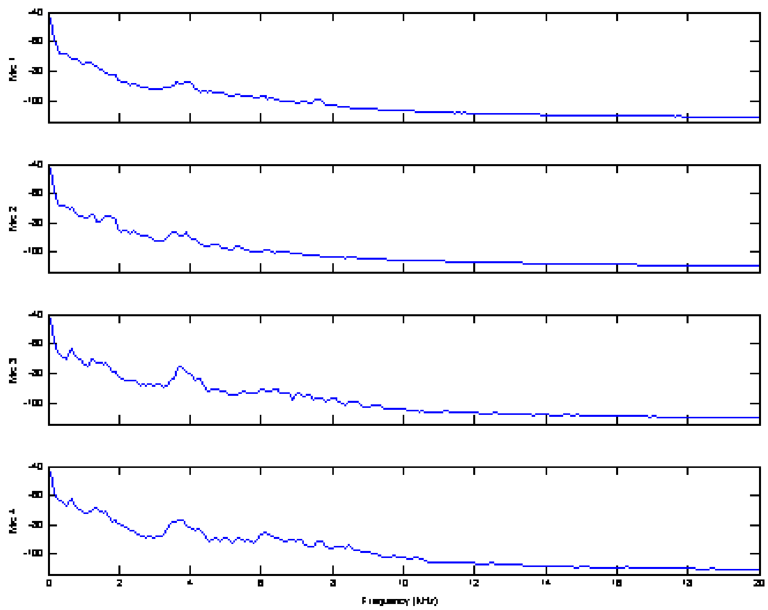
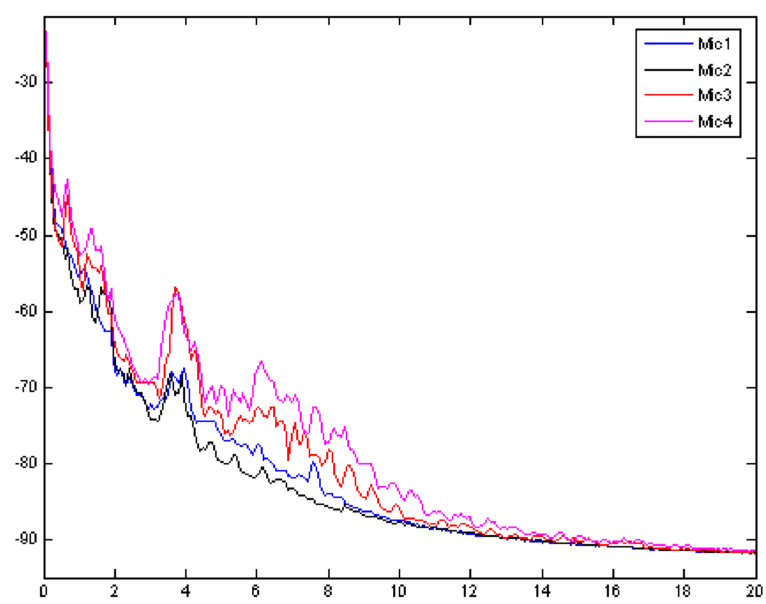


Figure 7.2. Normalized PSD 0-20kHz, Amplitude in dB



Power Spectral Density (0 to 1kHz)

Figure 7.3. Non-Normalized PSD 0-1kHz, Amplitude in dB

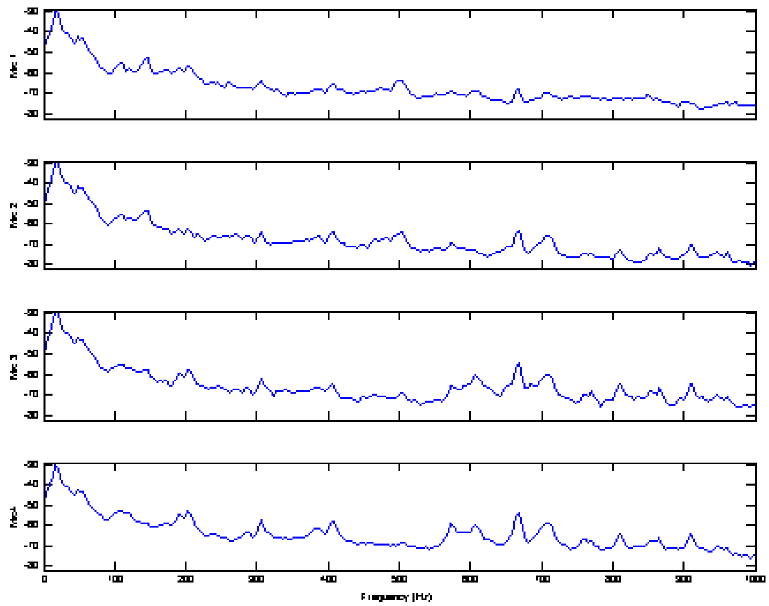
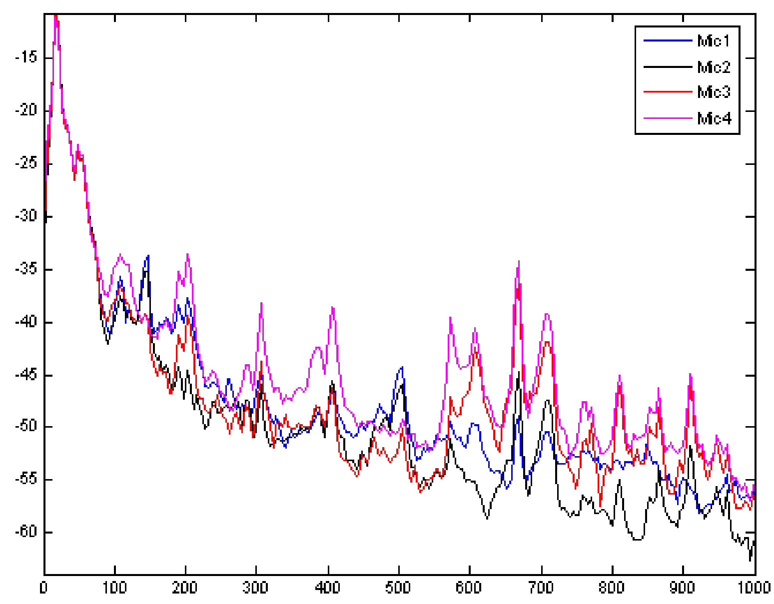
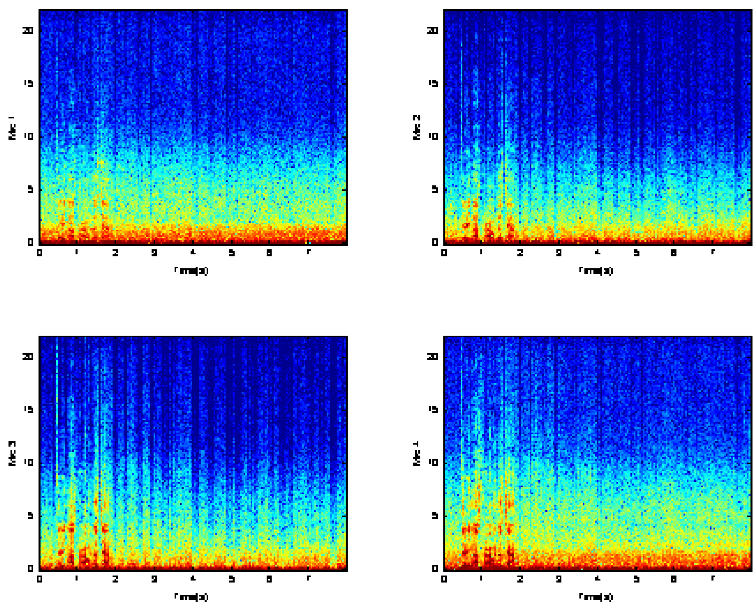


Figure 7.4. Normalized PSD 0-1kHz, Amplitude in dB



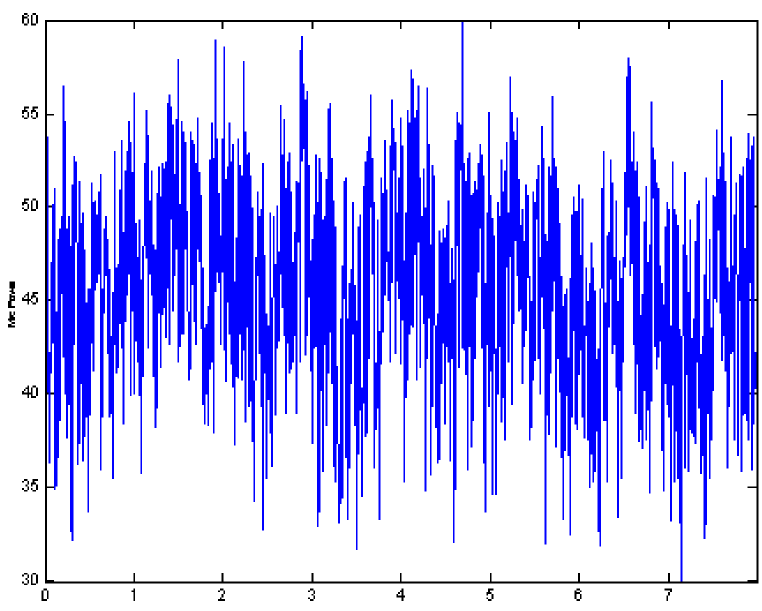
Spectrogram (0 to 20 kHz)

Figure 7.5. Spectrogram 0-20kHz, Frequency in kHz



Power vs. Time

Figure 7.6. Power vs. Time, Amplitude in Normalized dB



Spectogram (0 to 1kHz)

Figure 7.7. Spectrogram 0-1kHz, Frequency in Hz

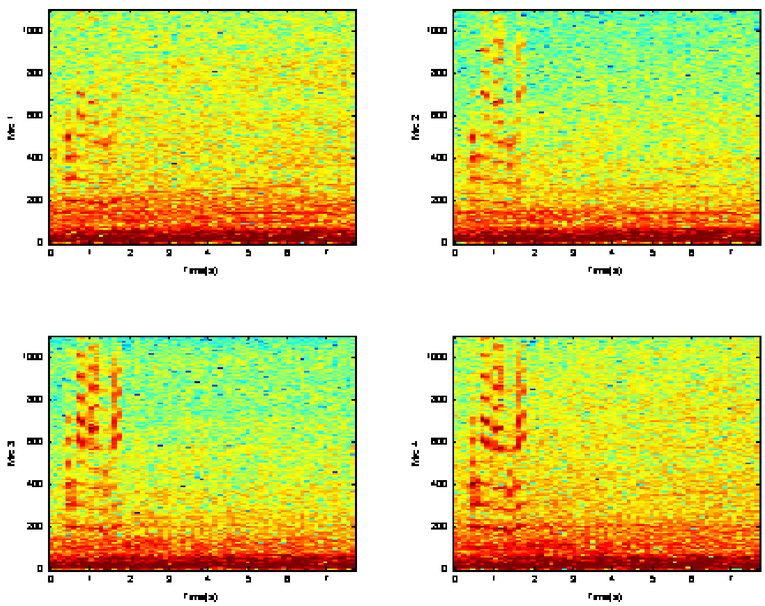


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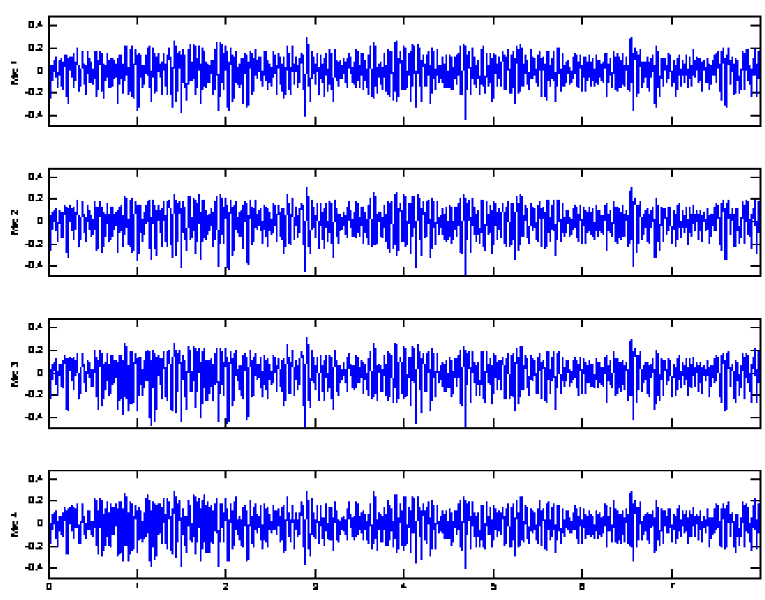
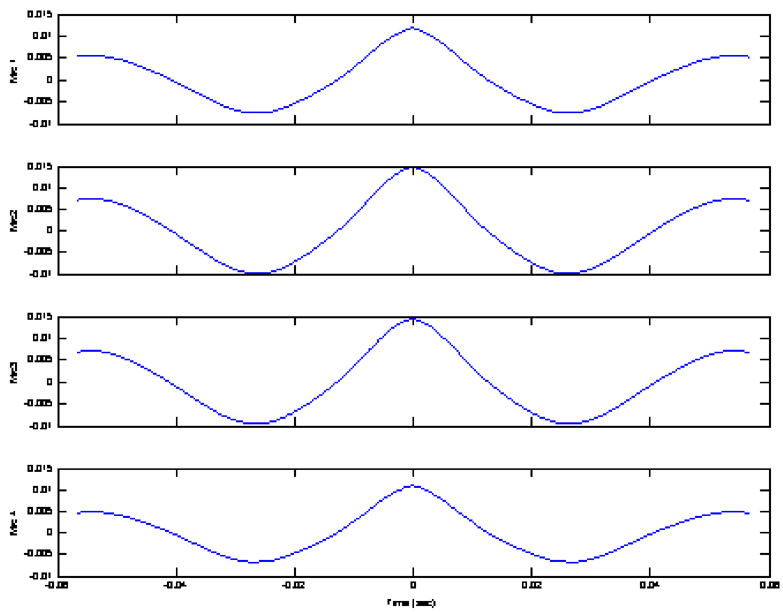
Figure 7.8. Time Graph



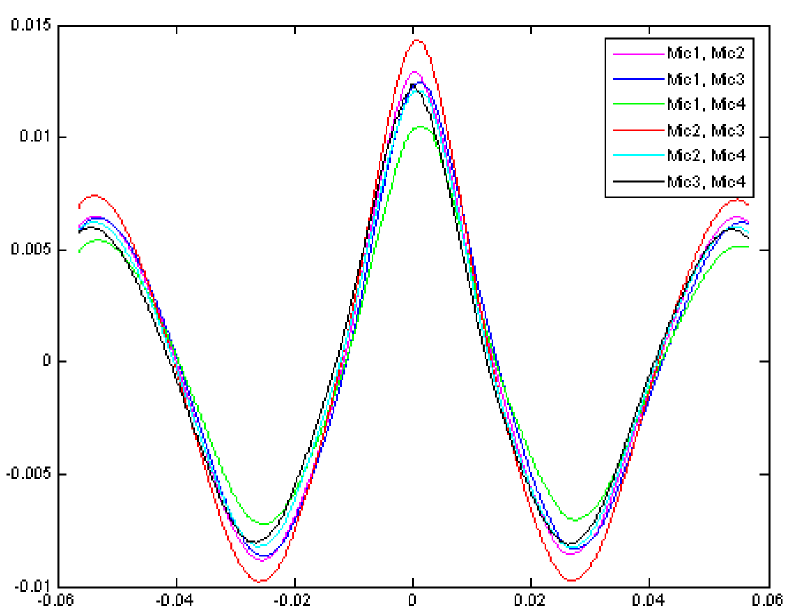
Autocorrelation

Figure 7.9. Autocorrelation Graph



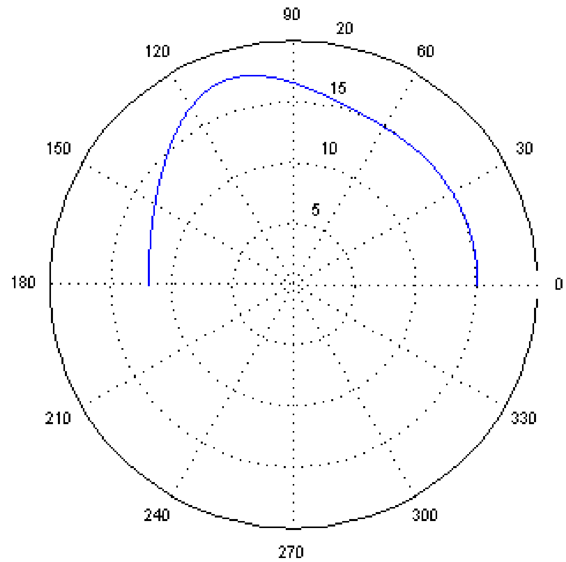
Crosscorrelation

Figure 7.10. CrossCorrelation



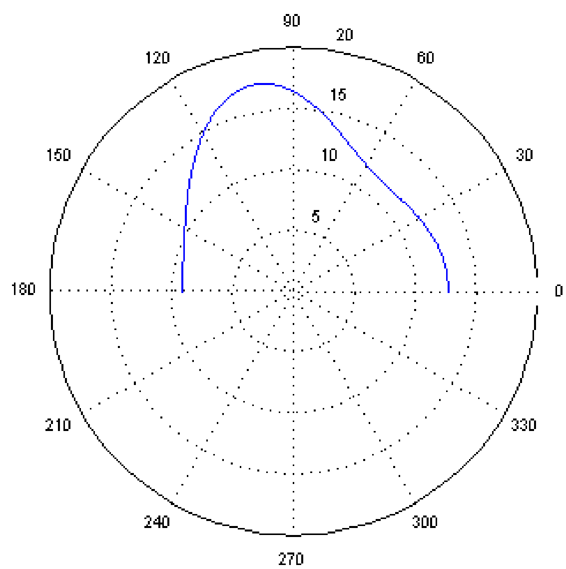
Direction of Arrival 200 Hz

Figure 7.11. DOA 200 Hz



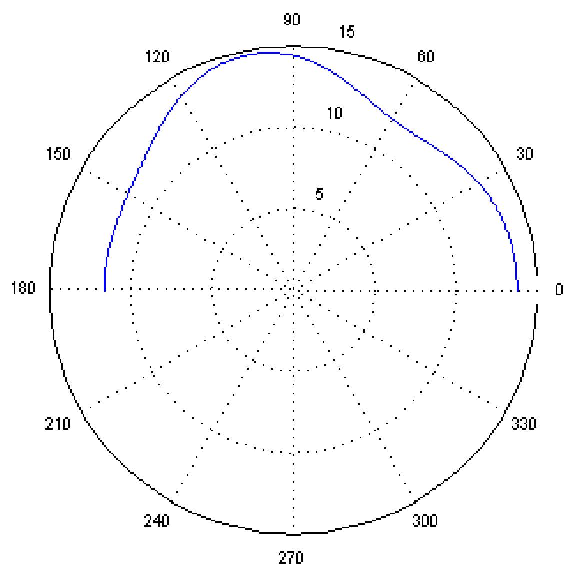
Direction of Arrival 300 Hz

Figure 7.12. DOA 300 Hz



Direction of Arrival 400 Hz

Figure 7.13. DOA 400 Hz



Chapter 8. Test Six: Accelerating 30-50 MPH

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Play Accelerating 30-50 MPH Mic 4.wav

Power Spectral Density (0 to 20 kHz)

Figure 8.1. Non-Normalized PSD 0-20kHz, Amplitude in dB

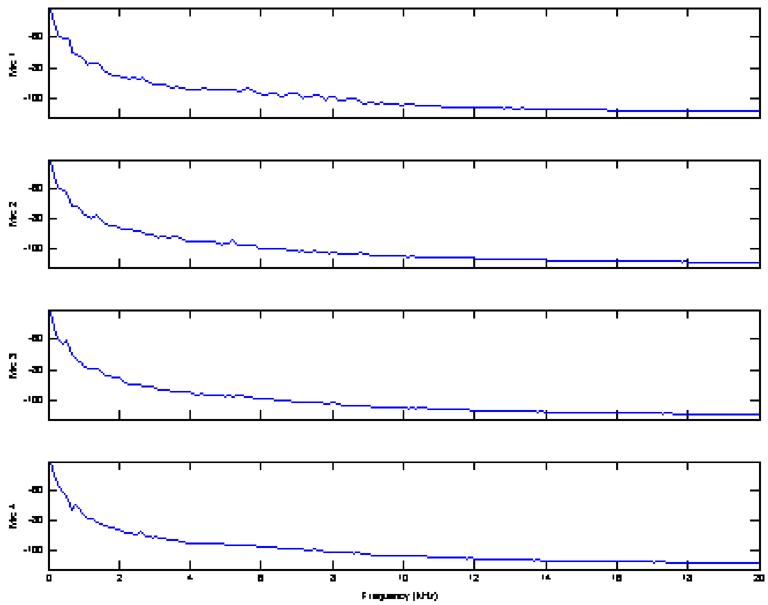
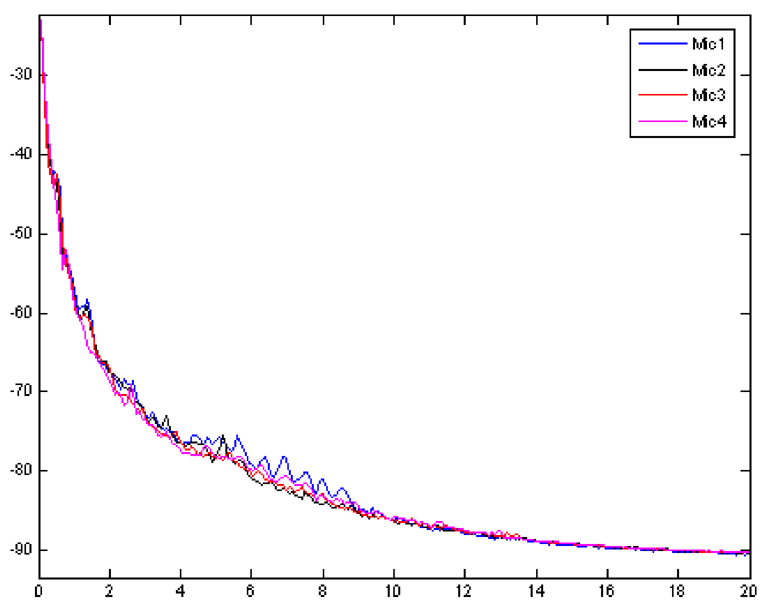


Figure 8.2. Normalized PSD 0-20kHz, Amplitude in dB



Power Spectral Density (0 to 1kHz)

Figure 8.3. Non-Normalized PSD 0-1kHz, Amplitude in dB

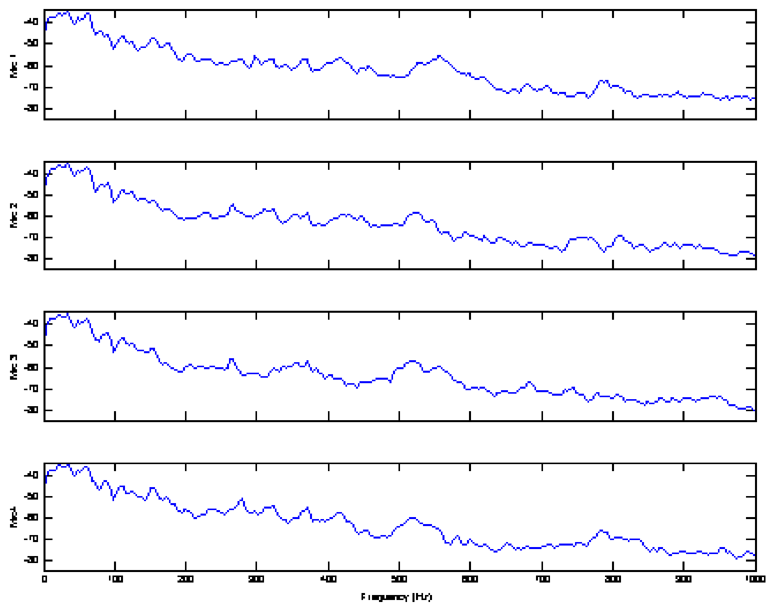
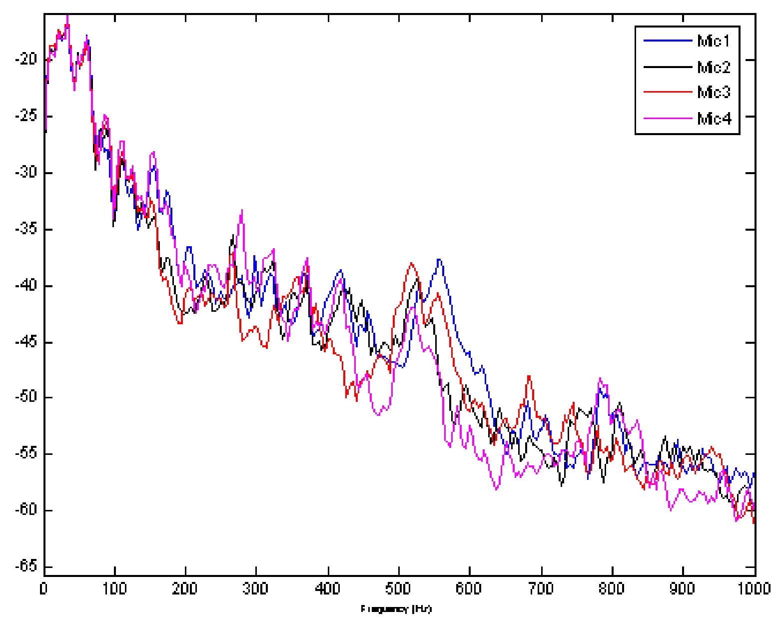
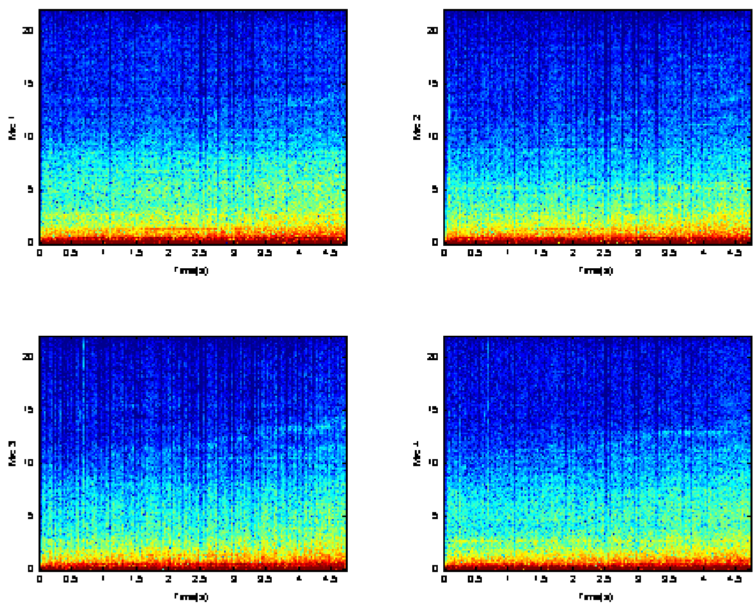


Figure 8.4. Normalized PSD 0-1kHz, Amplitude in dB



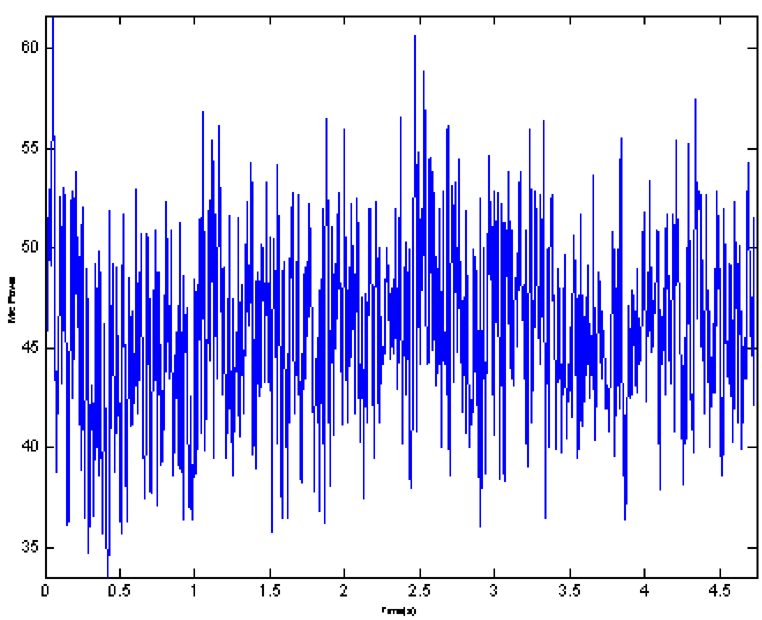
Spectrogram (0 to 20 kHz)

Figure 8.5. Spectrogram 0-20kHz, Frequency in kHz



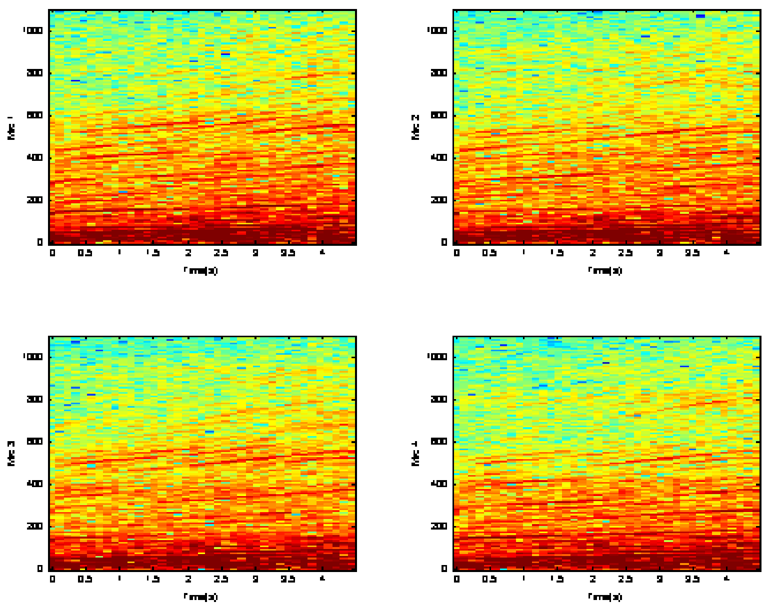
Power vs. Time

Figure 8.6. Power vs. Time, Amplitude in Normalized dB



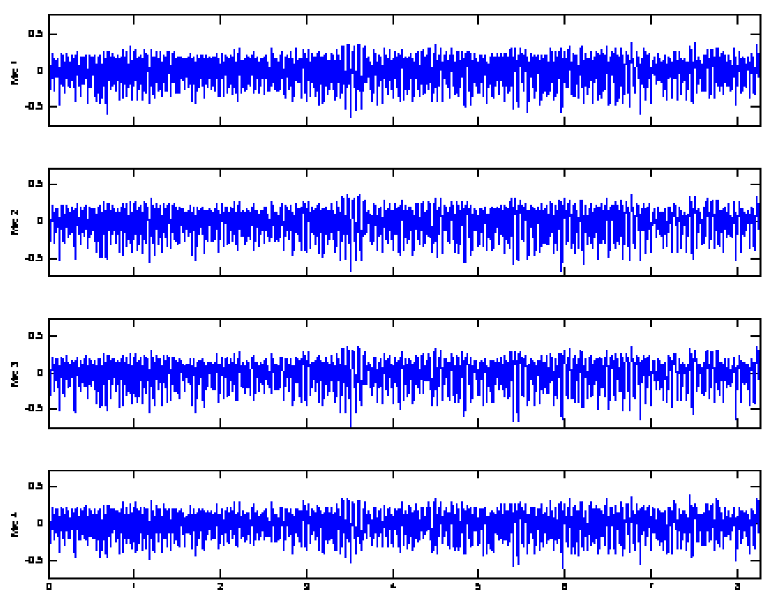
Spectogram (0 to 1kHz)

Figure 8.7. Spectrogram 0-1kHz, Frequency in Hz



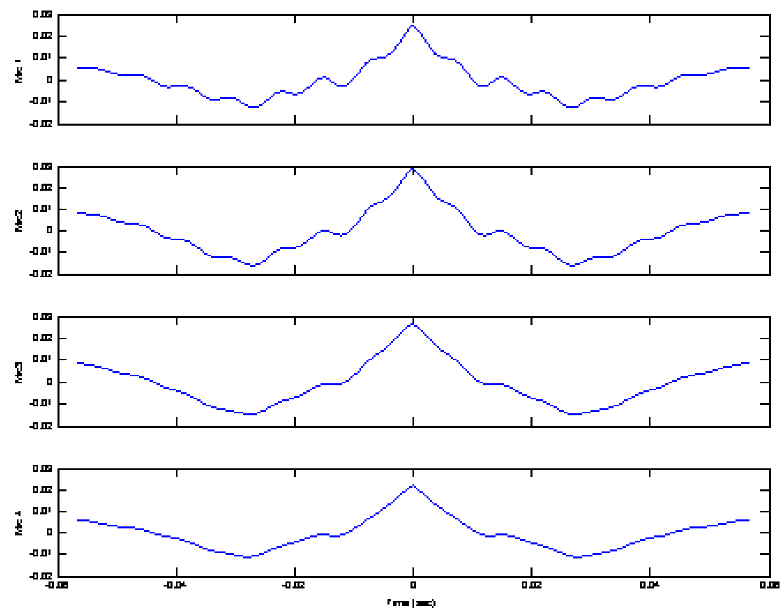
Time Plot

Figure 9.8. Time Graph



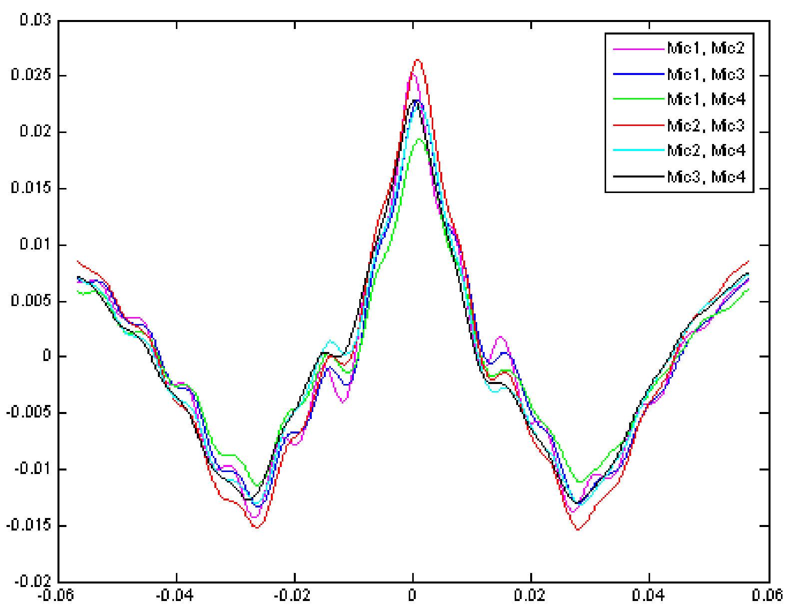
Autocorrelation

Figure 9.9. Autocorrelation Graph



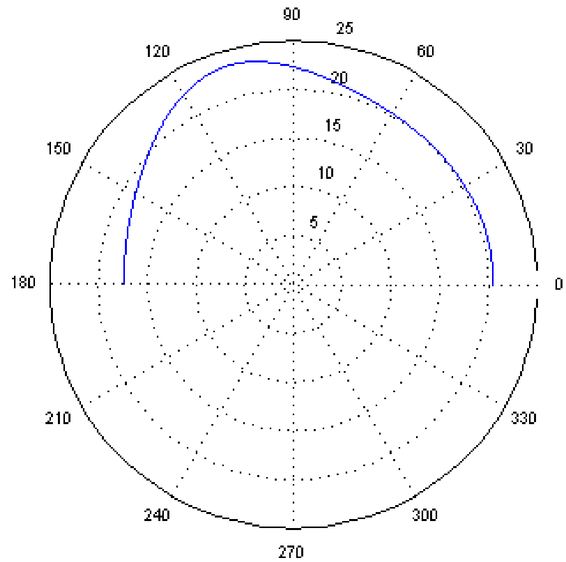
Crosscorrelation

Figure 9.10. CrossCorrelation



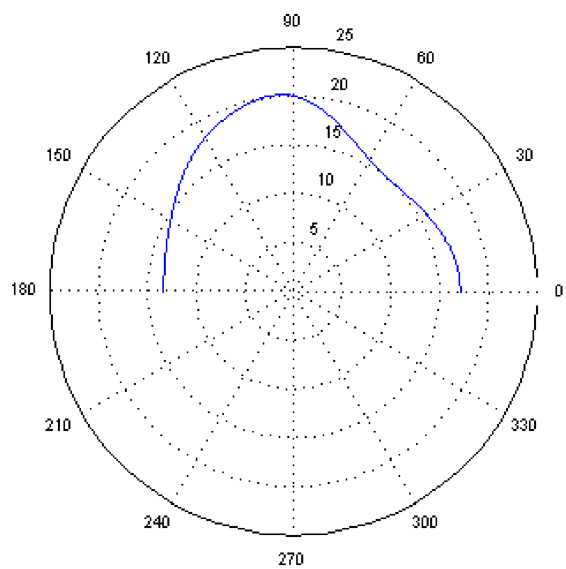
Direction of Arrival 200 Hz

Figure 9.11. DOA 200 Hz



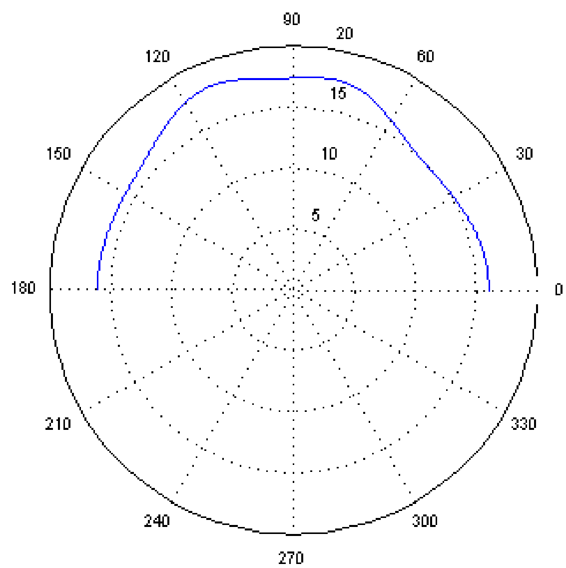
Direction of Arrival 300 Hz

Figure 9.12. DOA 300 Hz



Direction of Arrival 400 Hz

Figure 9.13. DOA 400 Hz



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Play Driving 50 MPH Mic 2.wav

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Recording Four

Play Driving 50 MPH Mic 4.wav

Power Spectral Density (0 to 20 kHz)

Figure 10.1. Non-Normalized PSD 0-20kHz, Amplitude in dB

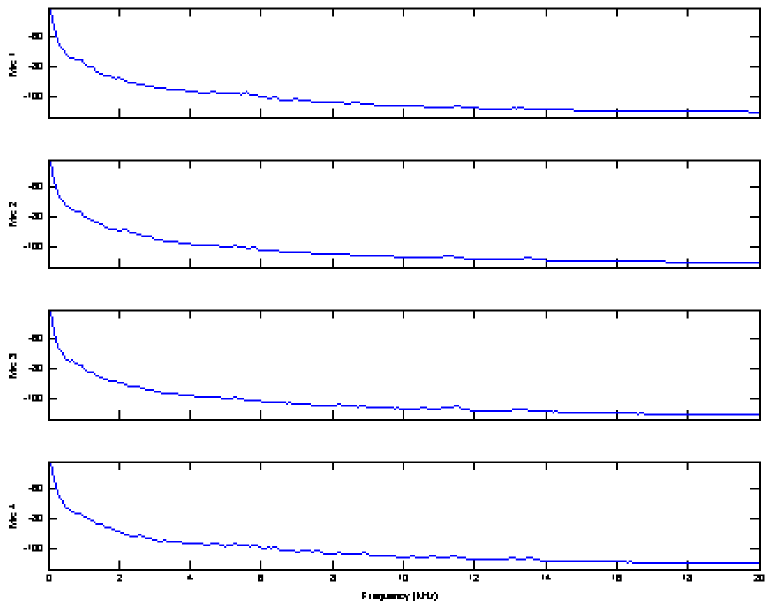
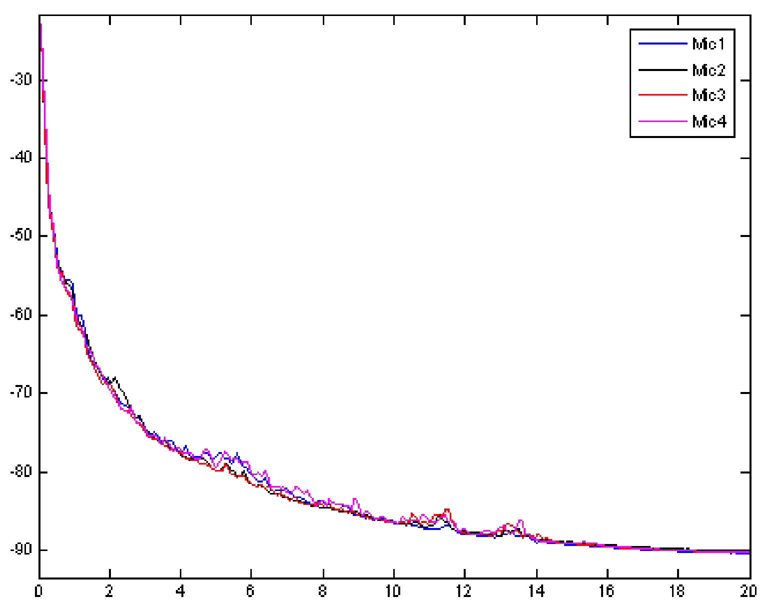


Figure 10.2. Normalized PSD 0-20kHz, Amplitude in dB



Power Spectral Density (0 to 1kHz)

Figure 10.3. Non-Normalized PSD 0-1kHz, Amplitude in dB

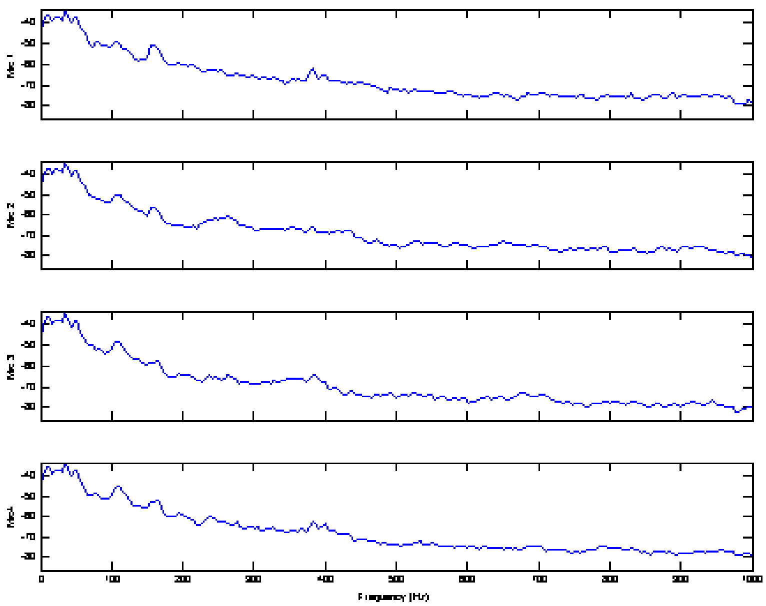
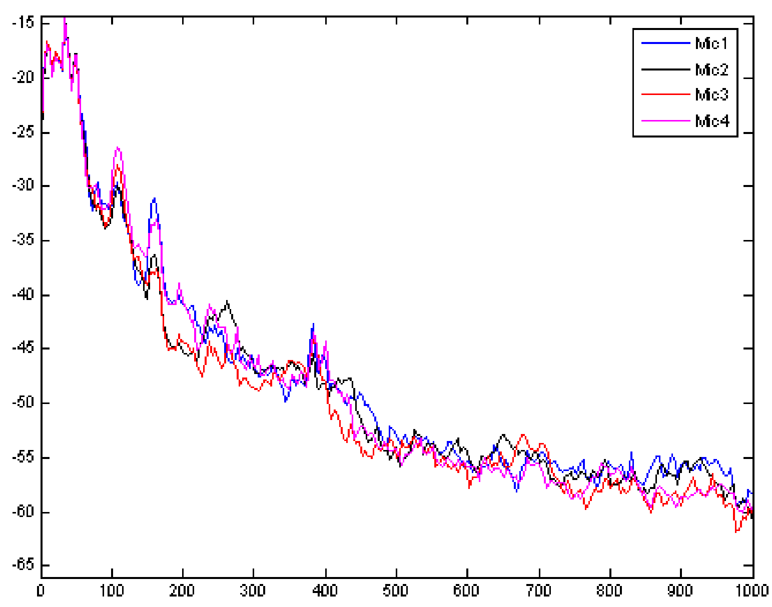
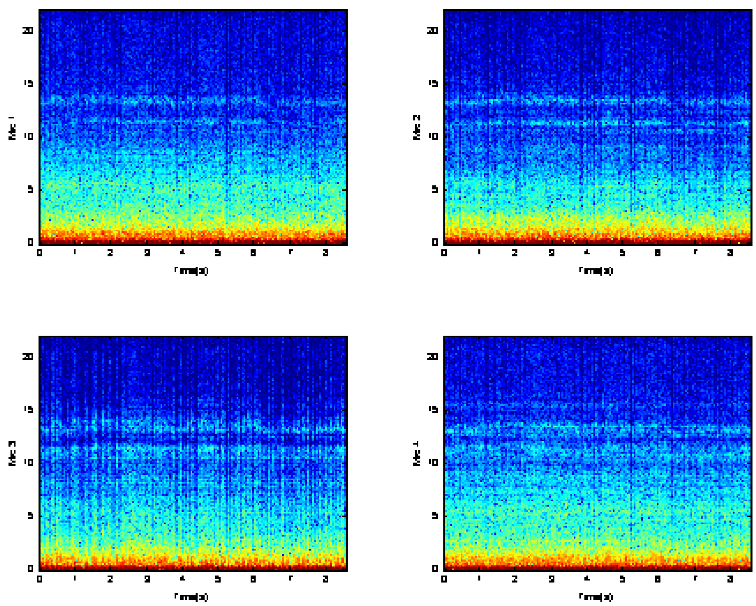


Figure 10.4. Normalized PSD 0-1kHz, Amplitude in dB



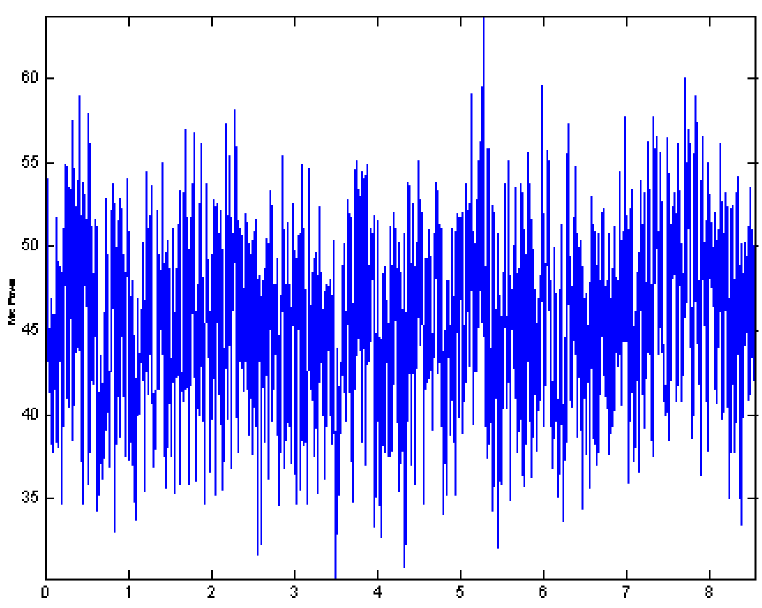
Spectrogram (0 to 20 kHz)

Figure 10.5. Spectrogram 0-20kHz, Frequency in kHz



Power vs. Time

Figure 10.6. Power vs. Time, Amplitude in Normalized dB



Spectogram (0 to 1kHz)

Figure 10.7. Spectrogram 0-1kHz, Frequency in Hz

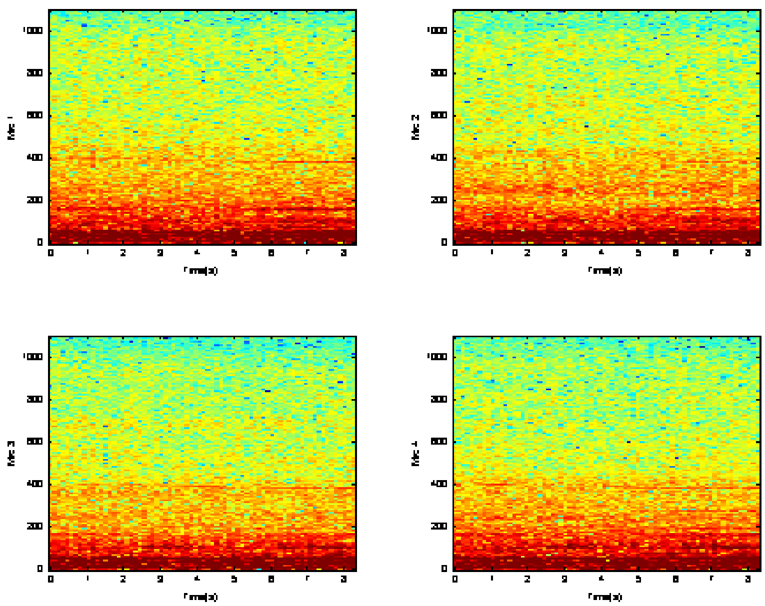


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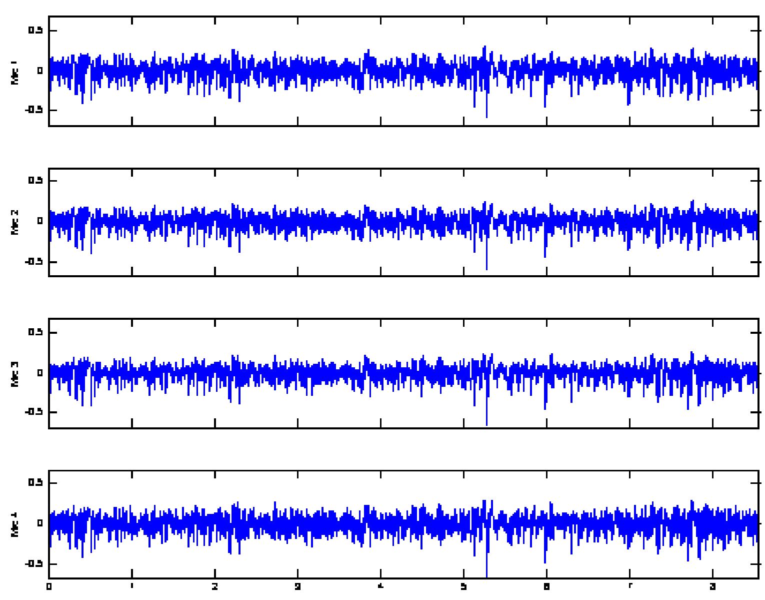
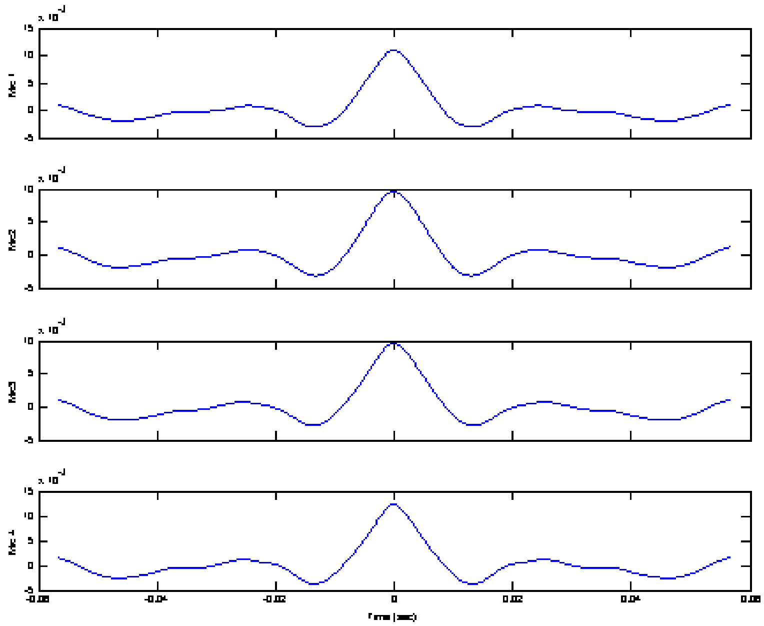
Figure 10.8. Time Graph



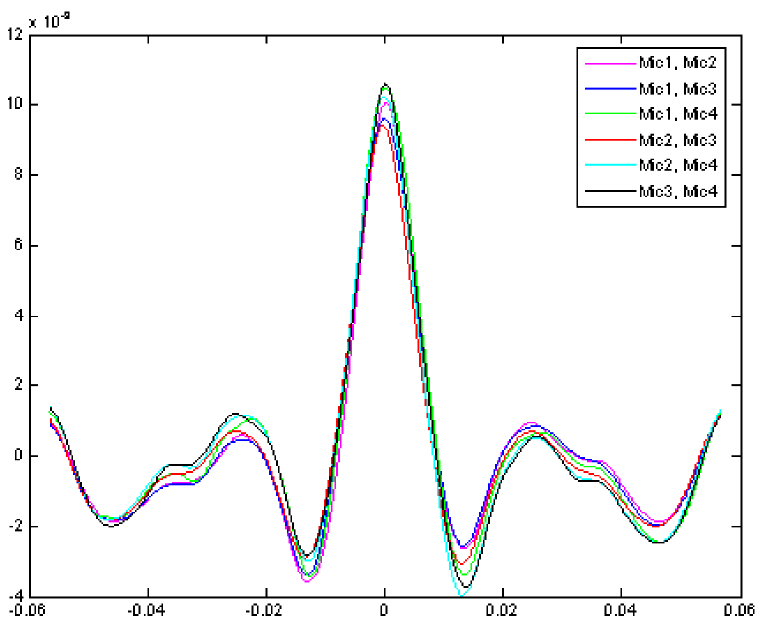
Autocorrelation

Figure 10.9. Autocorrelation Graph



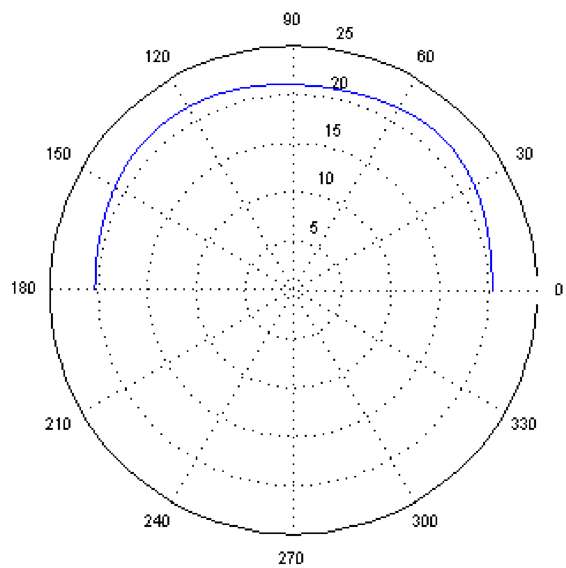
Crosscorrelation

Figure 10.10. CrossCorrelation



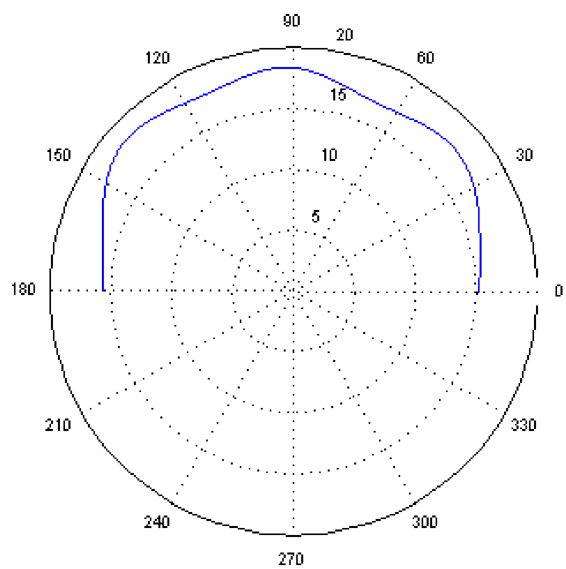
Direction of Arrival 200 Hz

Figure 10.11. DOA 200 Hz



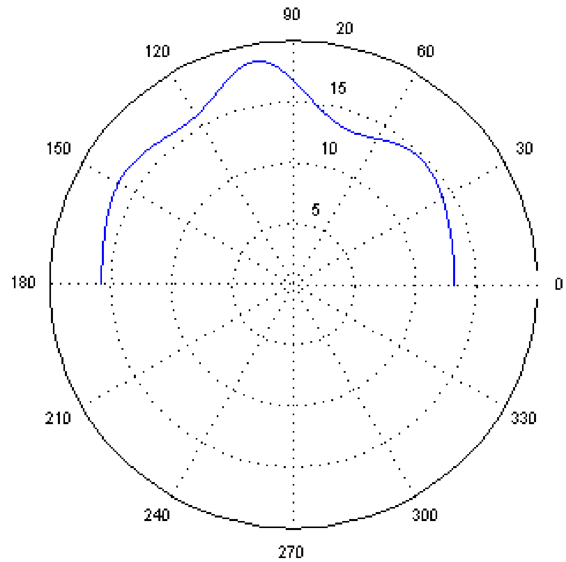
Direction of Arrival 300 Hz

Figure 10.12. DOA 300 Hz



Direction of Arrival 400 Hz

Figure 10.13. DOA 400 Hz



Chapter 11. Definition of Plots

Time Domain Plot. The time domain plot represents the data recorded by the microphone in the time domain.

Power Spectral Density. Power spectral density (PSD) is a useful analysis tool to use when examining signals. This tool shows the power at each frequency. In this report, Welch's method is used to find the PSD. The vertical axis gives the magnitude in W/Hz. The horizontal axis is frequency in Hz.

Autocorrelation. Autocorrelation is defined as A measure of the similarity between a signal and a time-shifted replica of itself; a special case of cross-correlation. If the length of the signal is enough to encompass several pitch periods of speech, the autocorrelation function will also show peaks at multiples of the pitch period. By identifying these peaks, the fundamental frequency can be determined. If there are no peaks, then it is known that there is an interval without speech.

Direction of Arrival. The direction of arrival (DOA) for a microphone takes into consideration several factors. In an array of microphones it is important to consider that the speed of sound travel is 340m/s. In this short time, the system takes 44.1K samples in a second. Direction of Arrival therefore takes into account direction as well as the associated time delay when examining an acoustical signal. The DOA examines a range of ? and plots based on power.

Spectrogram. A sound spectrogram, also known as a sonogram, is a visual representation of an acoustic signal. In the spectrogram itself, the vertical axis represents frequency. All of the spectra computed by the Fourier transform are displayed parallel to this vertical, or y-axis. The horizontal axis represents time. A color scale is used to display the magnitudes.

Power vs. Time. Similar to the power sepctral density graph, this graph sums up all the power at any given time. This graph is independent of frequency.

Appendix B—1995 Honda Civic April 15 2005

Bose Corporation/WPI SpinLab Report Generator

23-Apr-2005 12:22:30

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Chapter 1. General Information

Tester Names: Joseph Vaughn George Roscoe Jeff Ford

Location. Rt 122 and Rt 56

Weather: Sunny

Wind: 5-10 MPH

Road Conditions: Clear

Comments: Test went well

Chapter 2. Car Information

Vehicle: 1995 Honda Civic

Transmission: Automatic

Tires:

Chapter 3. Test One: Car Idle

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Power Spectral Density (0 to 20 kHz)

Figure 3.1. Non-Normalized PSD 0-20kHz, Amplitude in dB

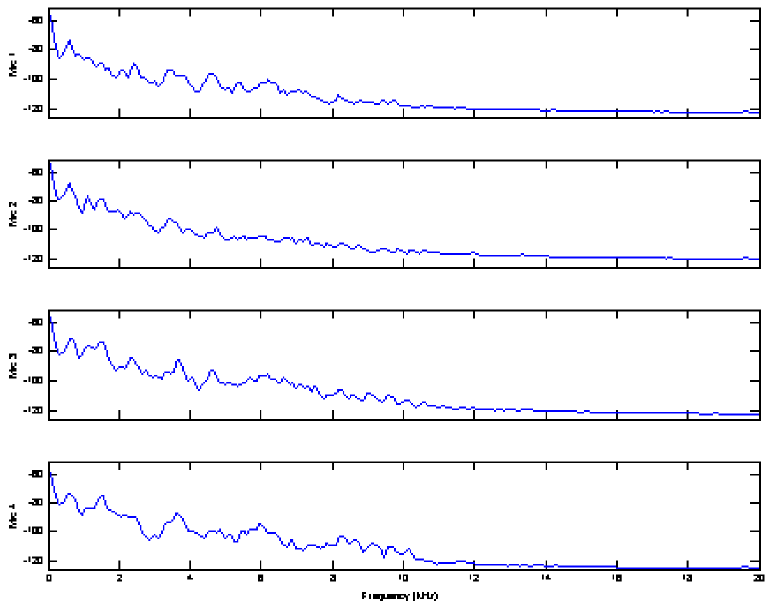
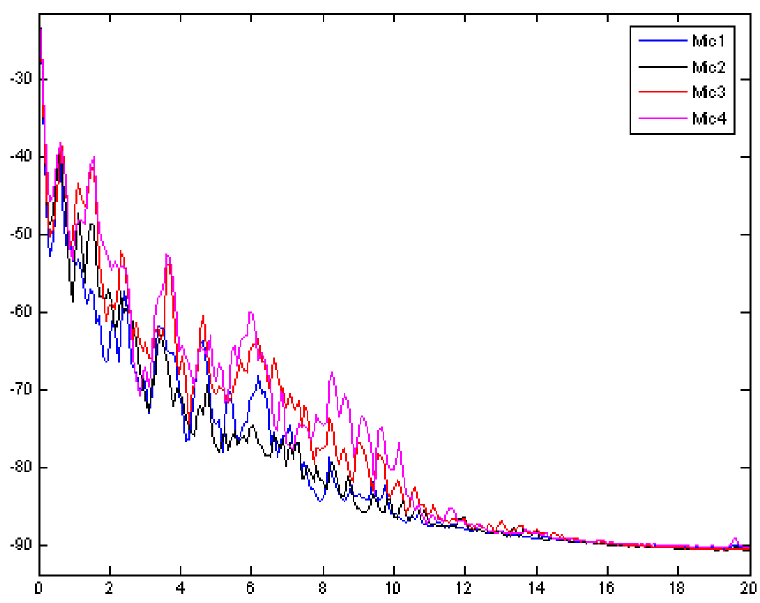


Figure 3.2. Normalized PSD 0-20kHz, Amplitude in dB



Power Spectral Density (0 to 1kHz)

Figure 3.3. Non-Normalized PSD 0-1kHz, Amplitude in dB

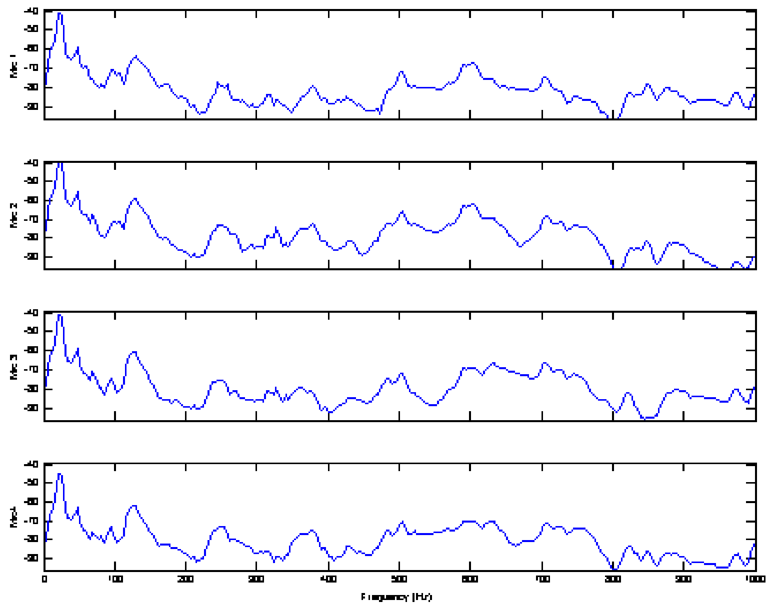
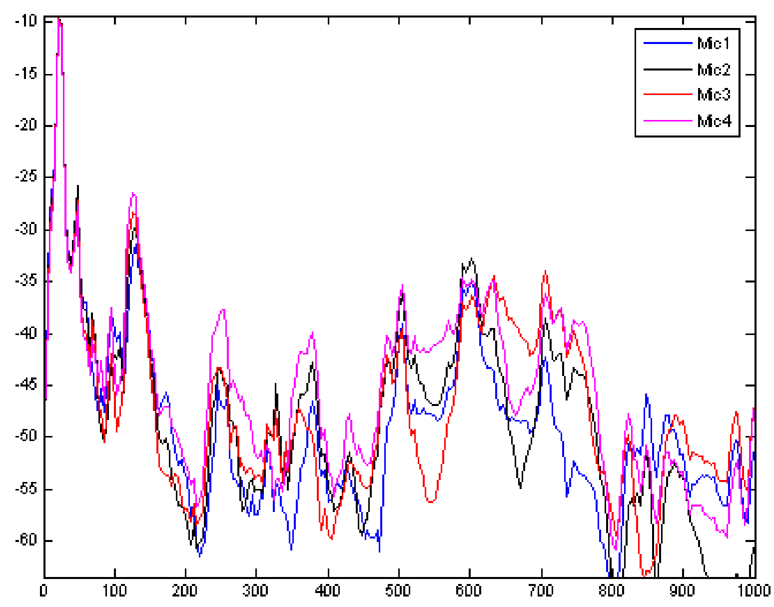
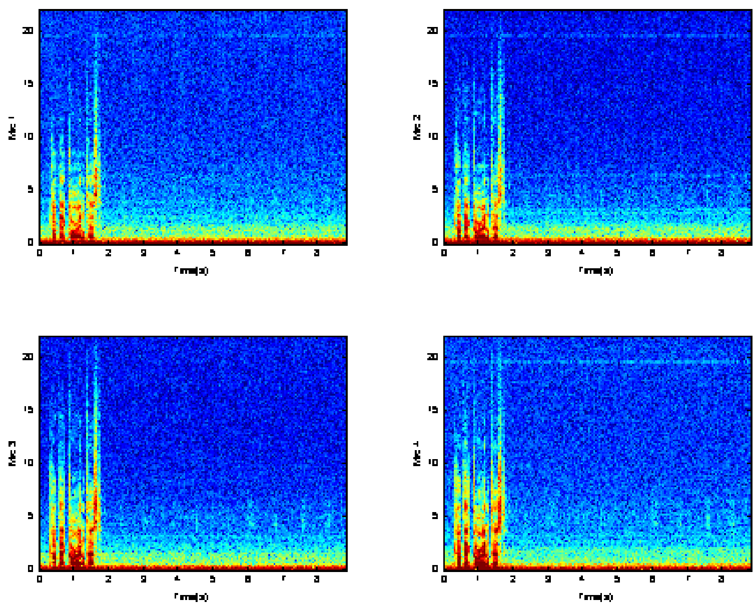


Figure 3.4. Normalized PSD 0-1kHz, Amplitude in dB



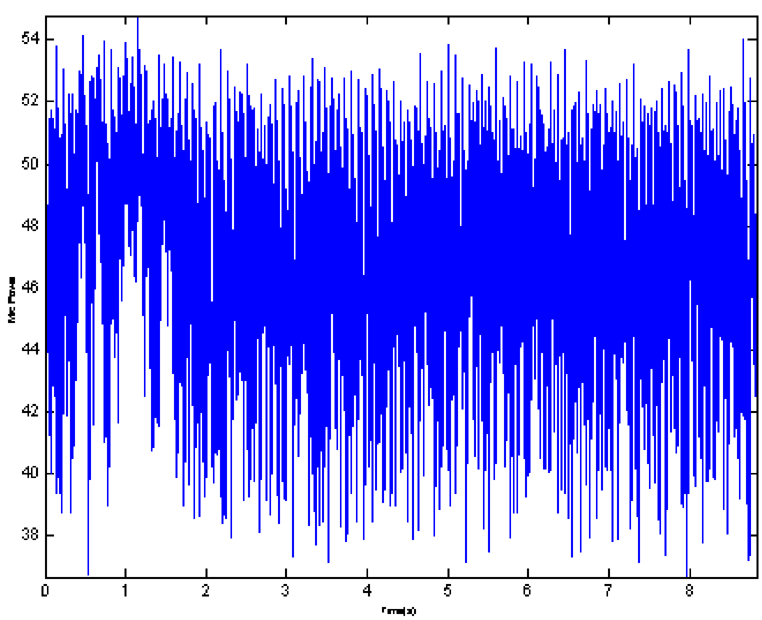
Spectrogram (0 to 20 kHz)

Figure 3.5. Spectrogram 0-20kHz, Frequency in kHz



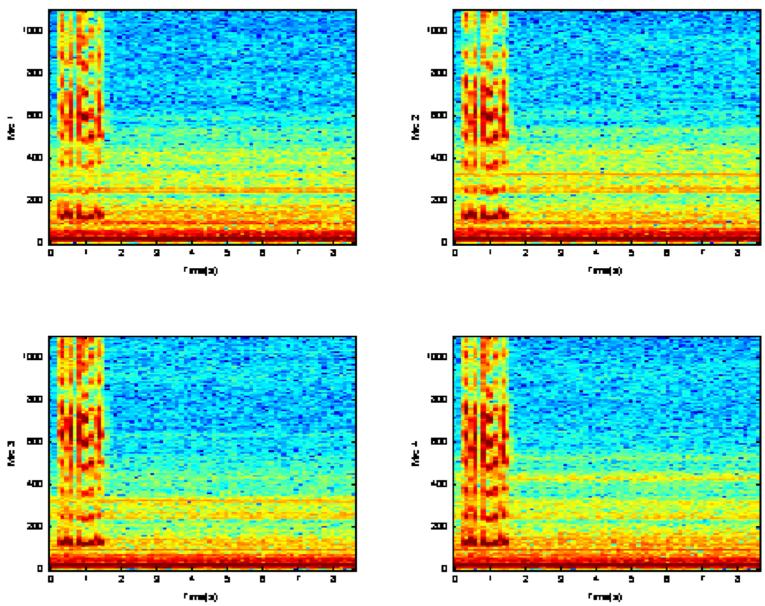
Power vs. Time

Figure 3.6. Power vs. Time, Amplitude in Normalized dB



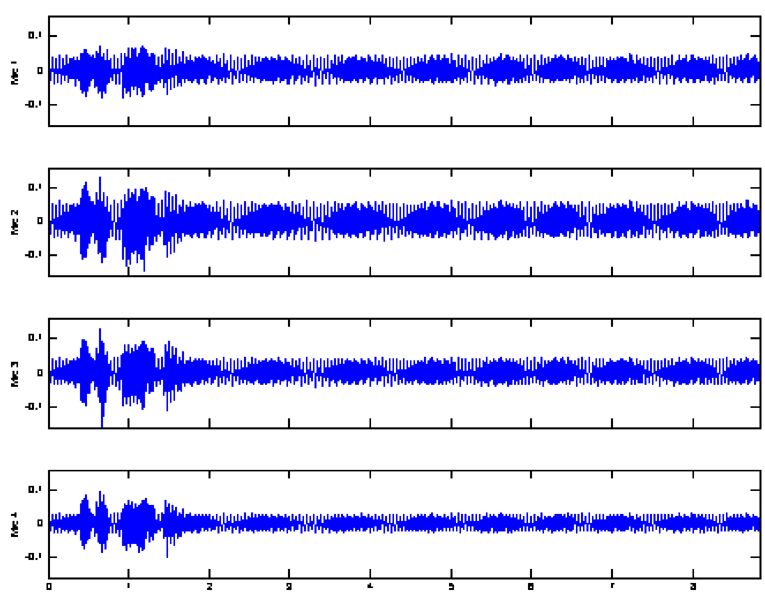
Spectogram (0 to 1kHz)

Figure 3.7. Spectrogram 0-1kHz, Frequency in Hz



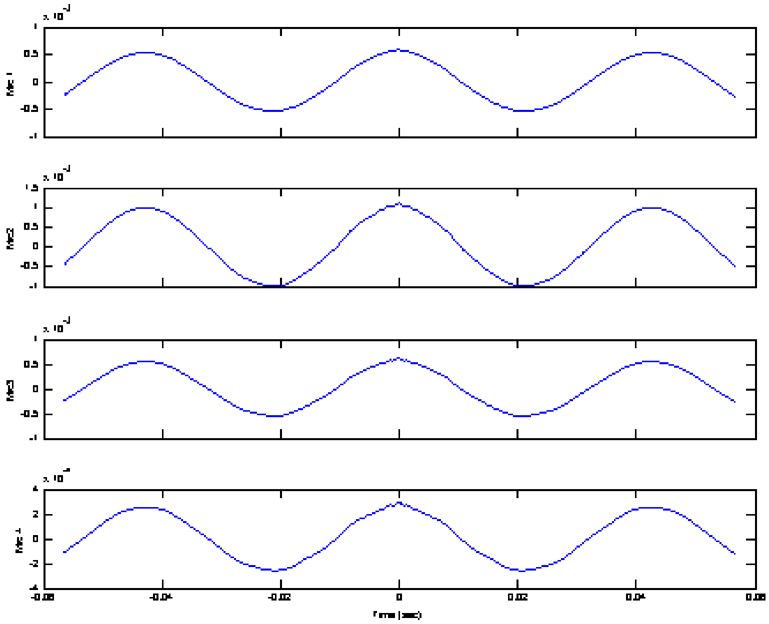
Time Plot

Figure 3.8. Time Graph



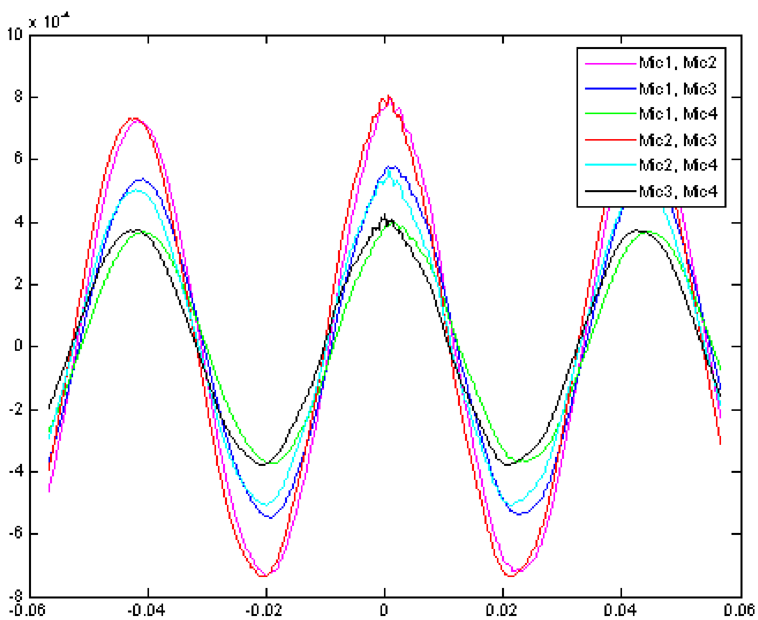
Autocorrelation

Figure 3.9. Autocorrelation Graph



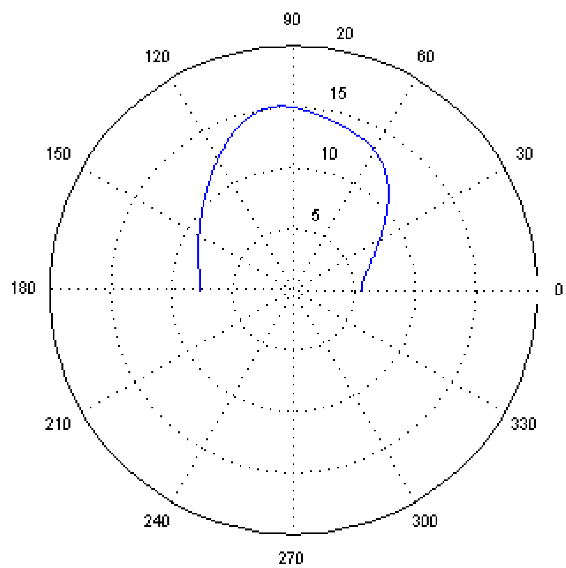
Crosscorrelation

Figure 3.10. CrossCorrelation



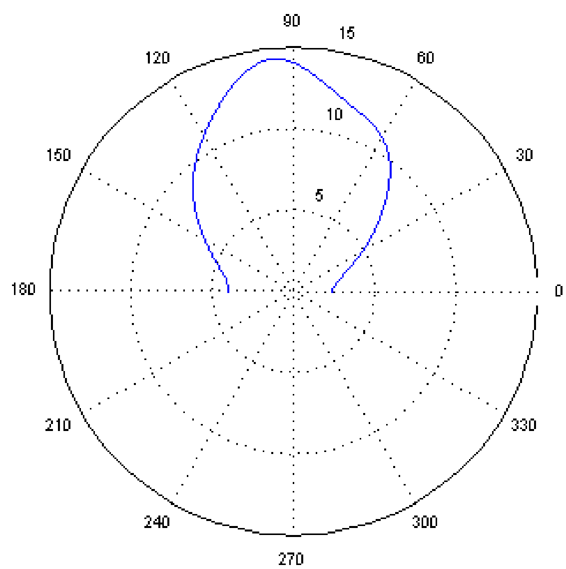
Direction of Arrival 200 Hz

Figure 3.11. DOA 200 Hz



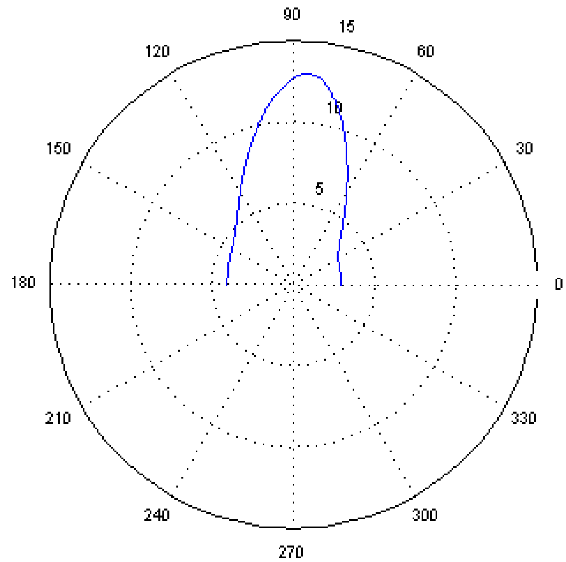
Direction of Arrival 300 Hz

Figure 3.12. DOA 300 Hz



Direction of Arrival 400 Hz

Figure 3.13. DOA 400 Hz



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Power Spectral Density (0 to 20 kHz)

Figure 4.1. Non-Normalized PSD 0-20kHz, Amplitude in dB

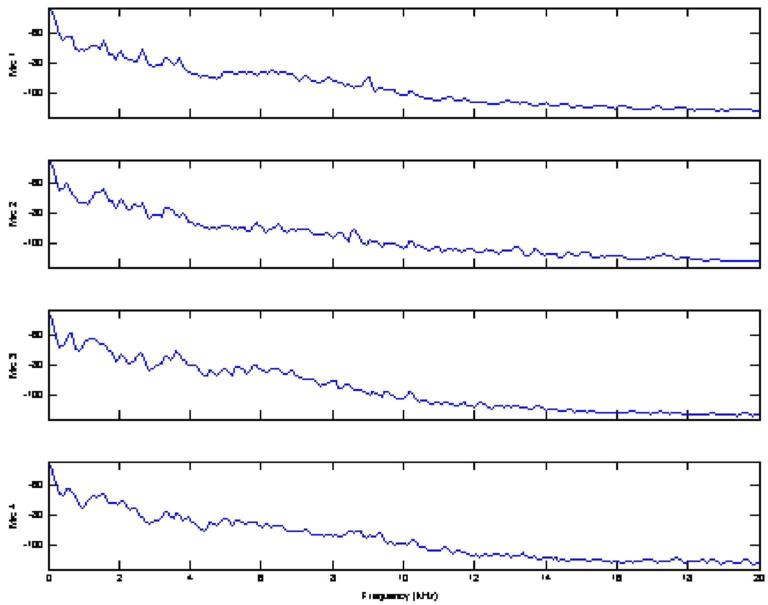


Figure 4.2. Normalized PSD 20kHz, Amplitude in dB

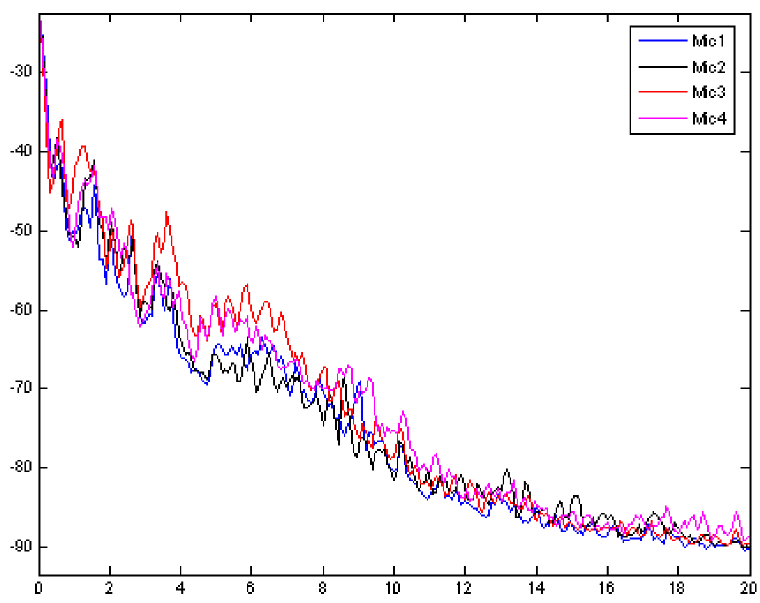


Figure 4.3. Non-Normalized PSD 0-1kHz, Amplitude in dB

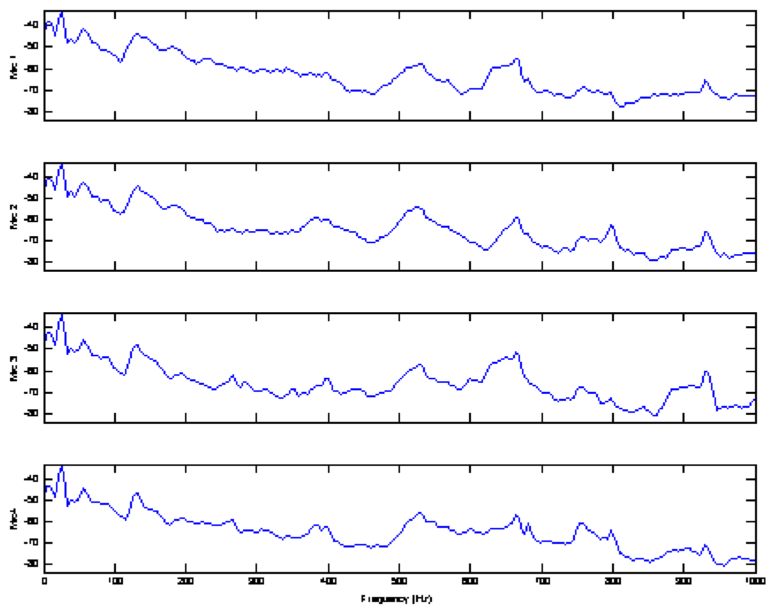
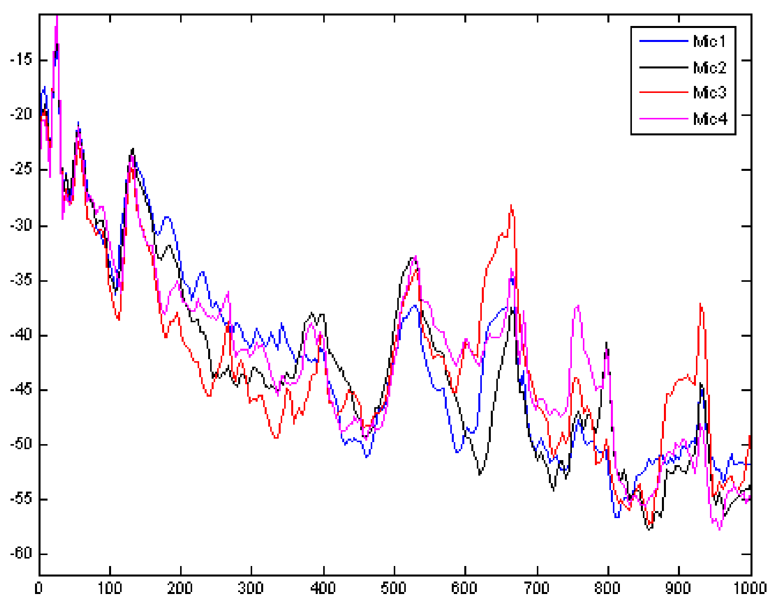
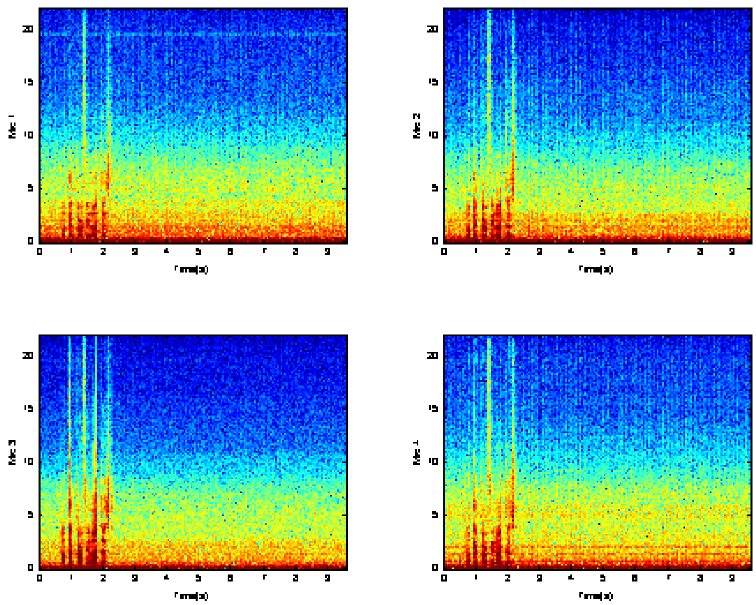


Figure 4.4. Normalized PSD 0-1kHz, Amplitude in dB



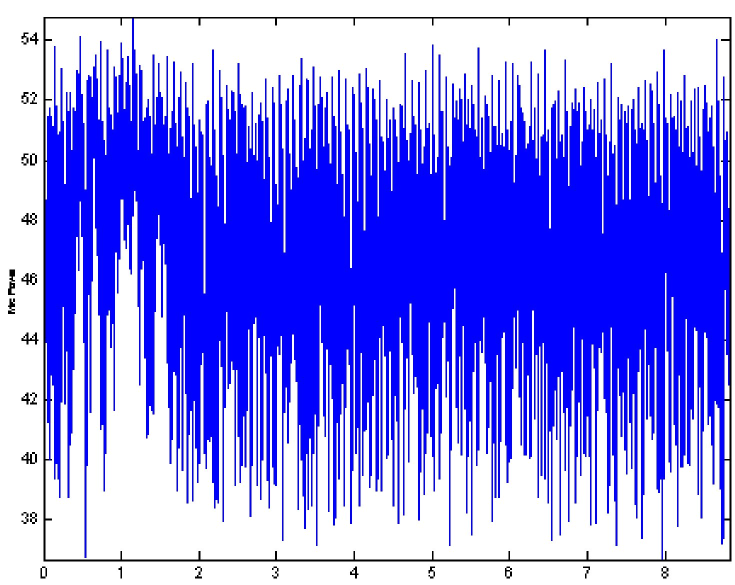
Spectrogram (0 to 20 kHz)

Figure 4.5. Spectrogram 0-20kHz, Frequency in kHz



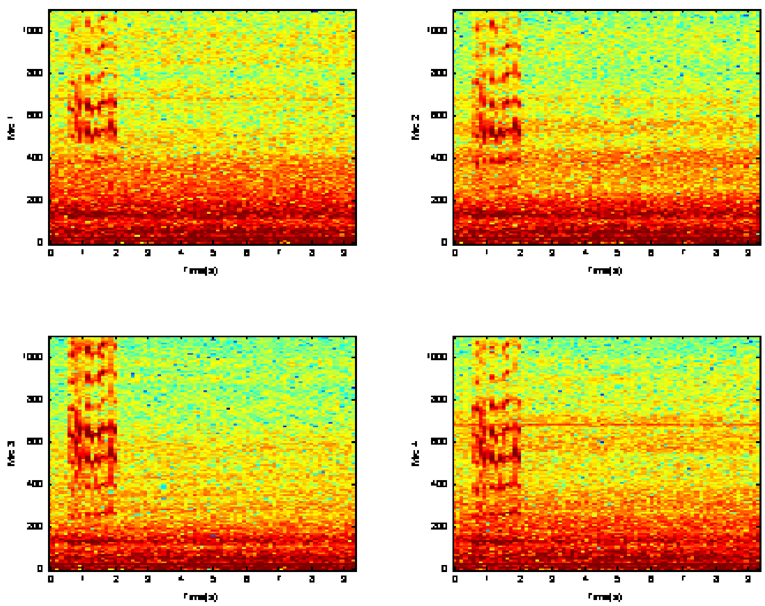
Power vs. Time

Figure 4.6. Power vs. Time, Amplitude in Normalized dB



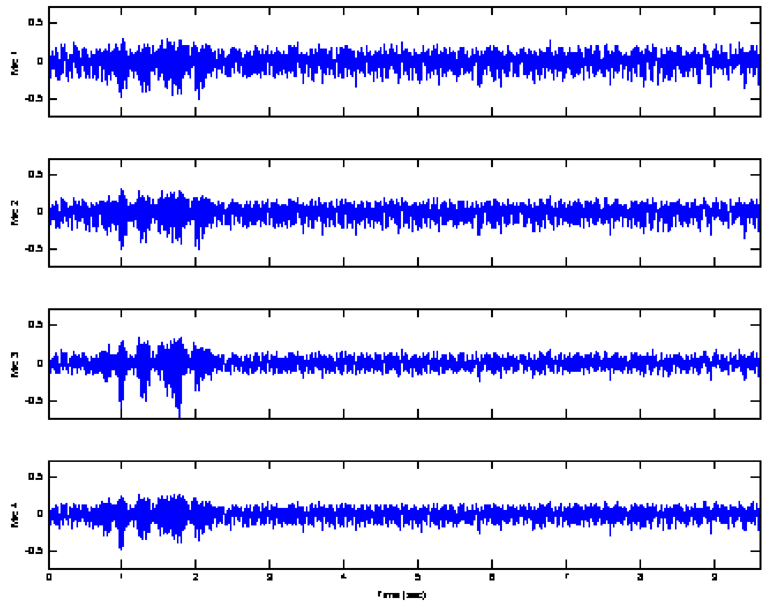
Spectogram (0 to 1kHz)

Figure 4.7. Spectrogram 0-1kHz, Frequency in Hz



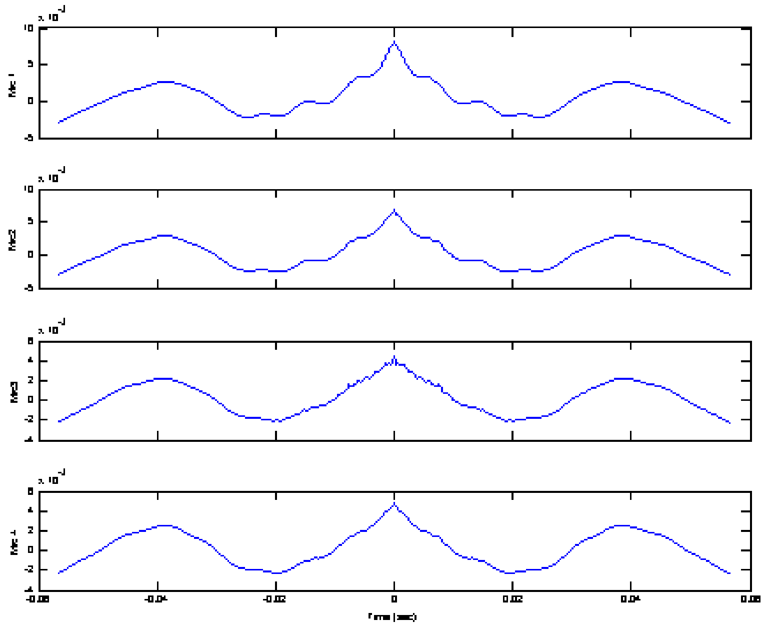
Time Plot

Figure 4.8. Time Graph



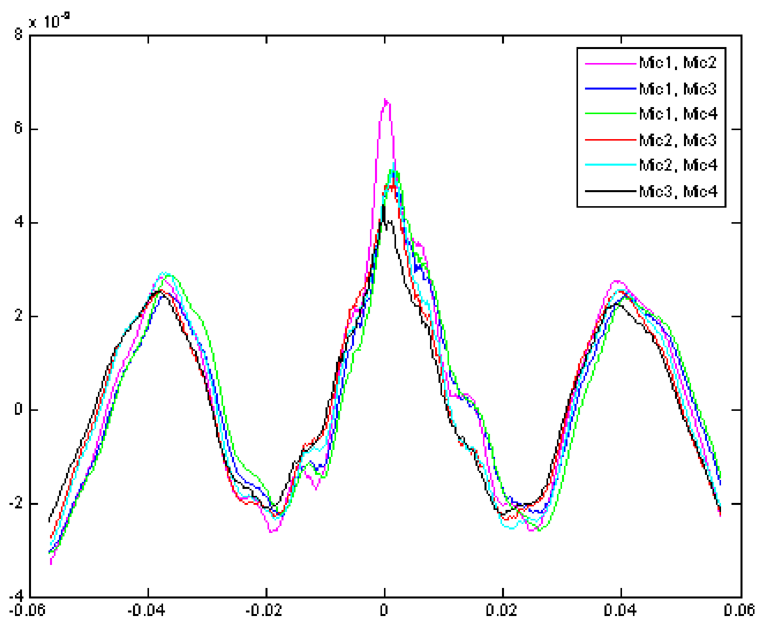
Autocorrelation

Figure 4.9. Autocorrelation Graph



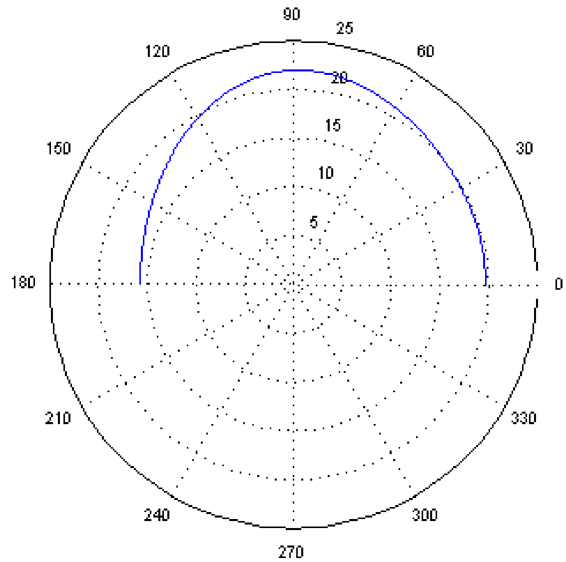
Crosscorrelation

Figure 4.10. CrossCorrelation



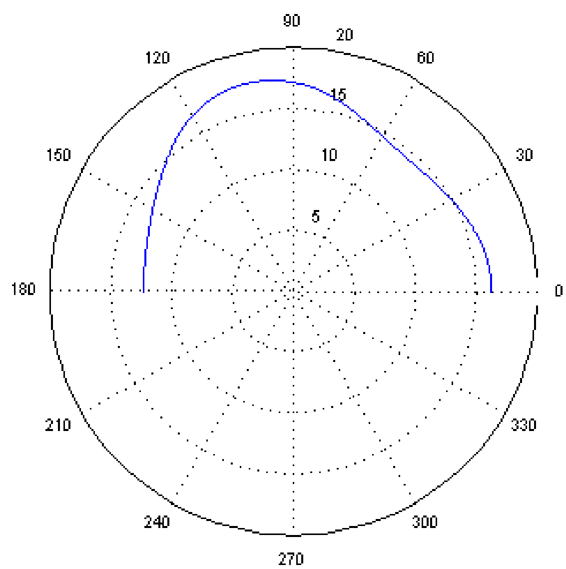
Direction of Arrival 200 Hz

Figure 4.11. DOA 200 Hz



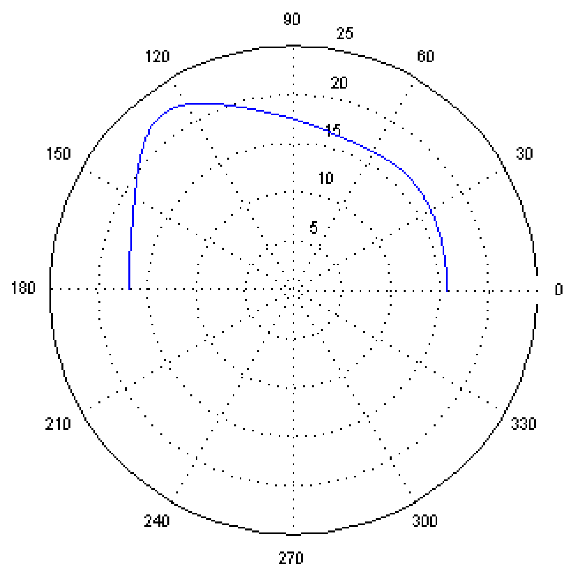
Direction of Arrival 300 Hz

Figure 4.12. DOA 300 Hz



Direction of Arrival 400 Hz

Figure 4.13. DOA 400 Hz



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Play Idle 3000 RPM Mic 4.wav

Power Spectral Density (0 to 20 kHz)

Figure 5.1. Non-Normalized PSD 0-20kHz, Amplitude in dB

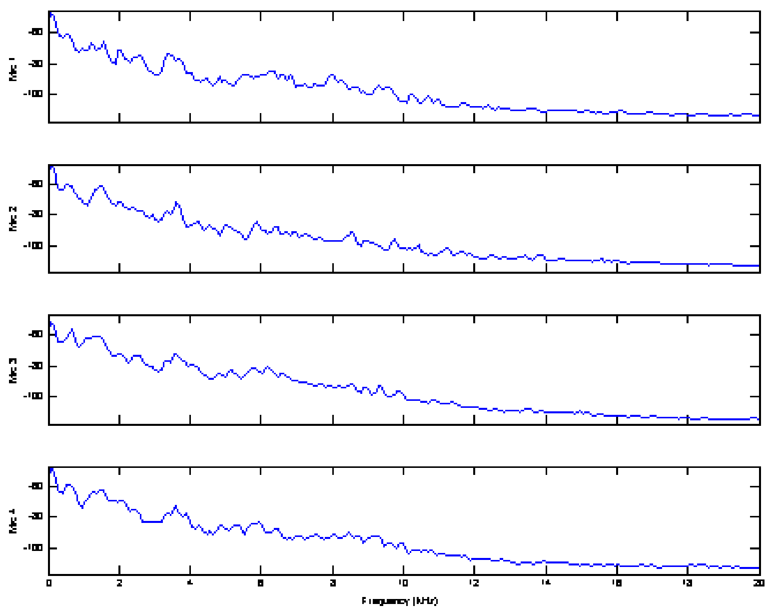
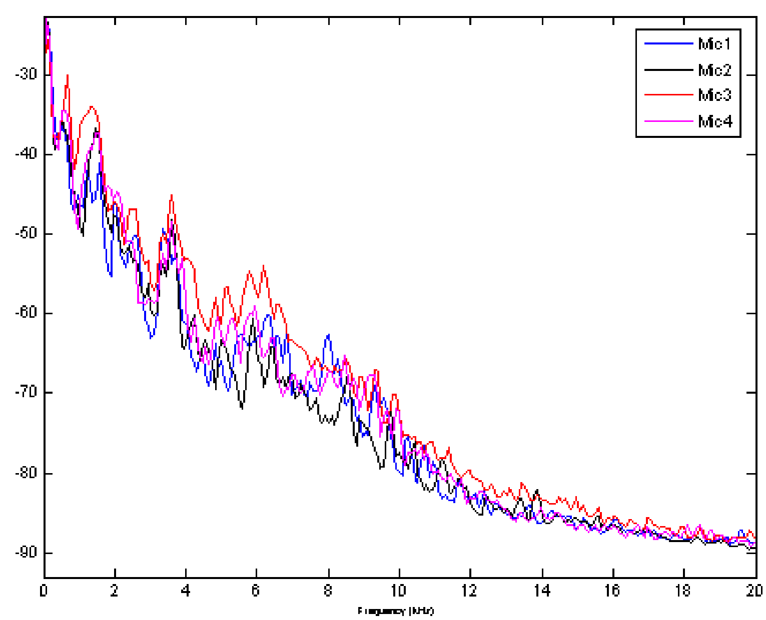


Figure 5.2. Normalized PSD 0-20kHz, Amplitude in dB



Power Spectral Density (0 to 1kHz)

Figure 5.3. Non-Normalized PSD 0-1kHz, Amplitude in dB

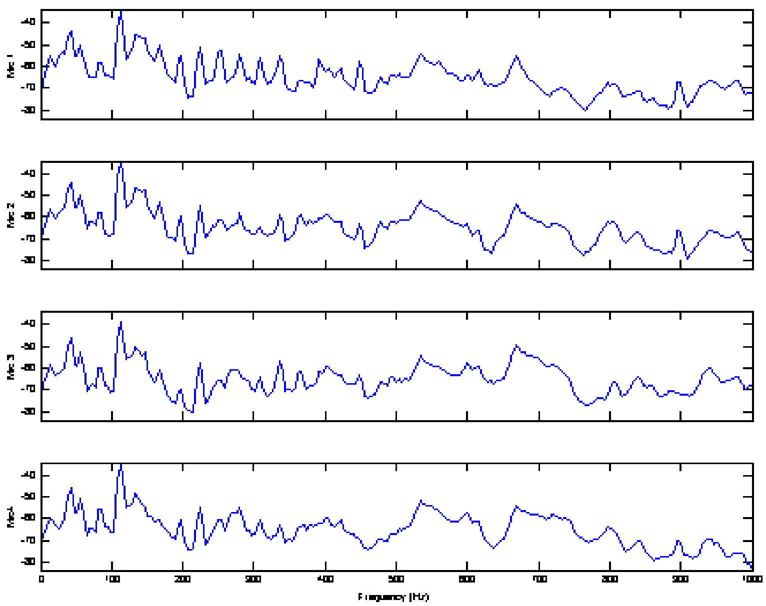
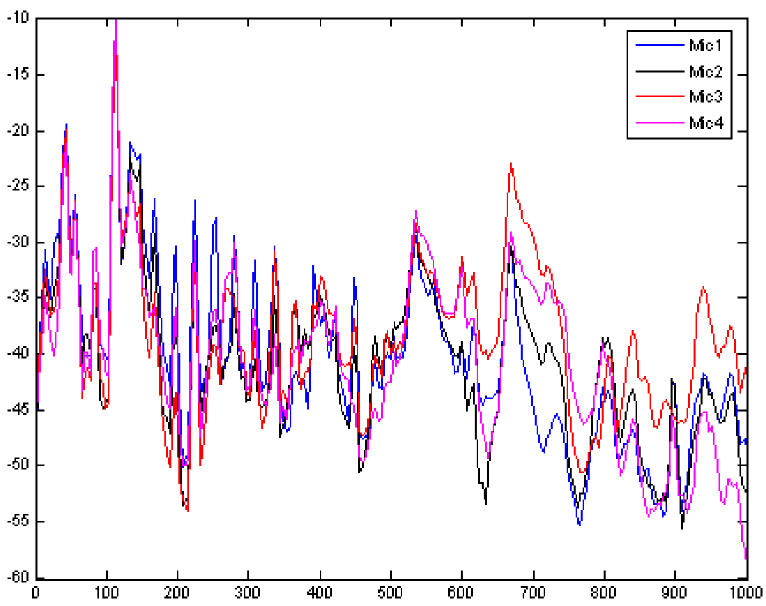
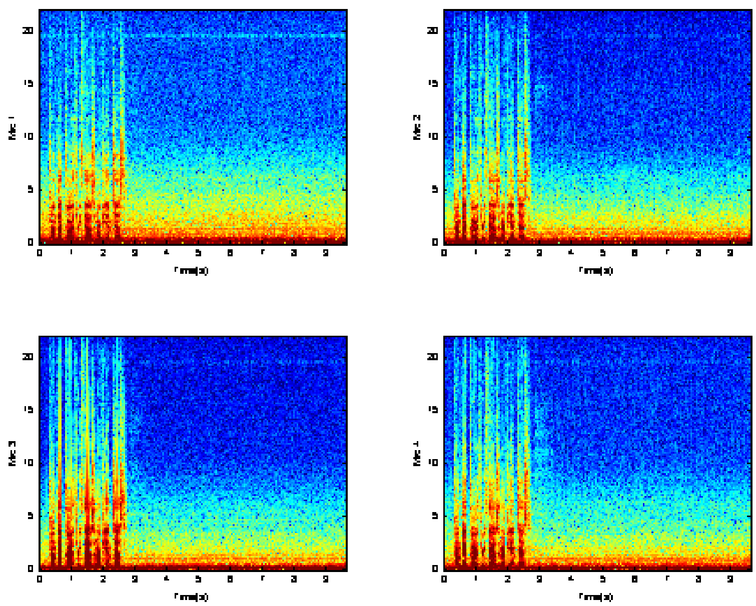


Figure 5.4. Normalized PSD 0-1kHz, Amplitude in dB



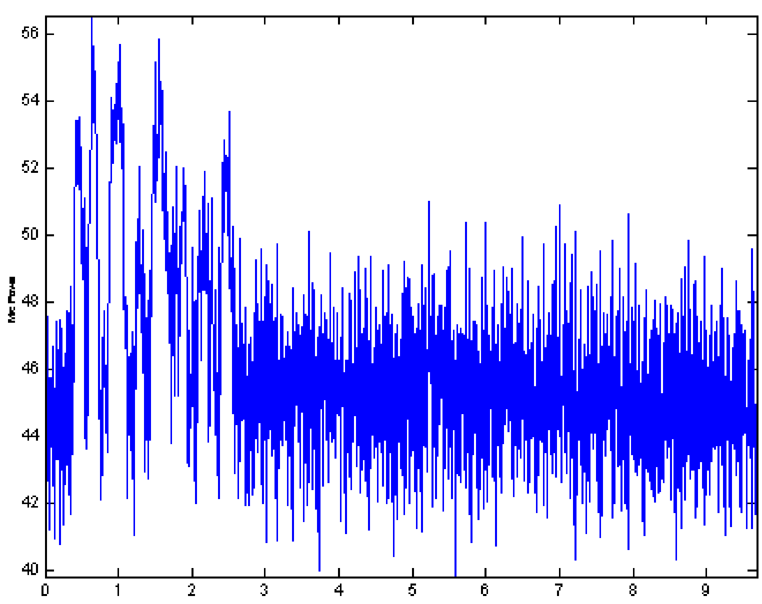
Spectrogram (0 to 20 kHz)

Figure 5.5. Spectrogram 0-20kHz, Frequency in kHz



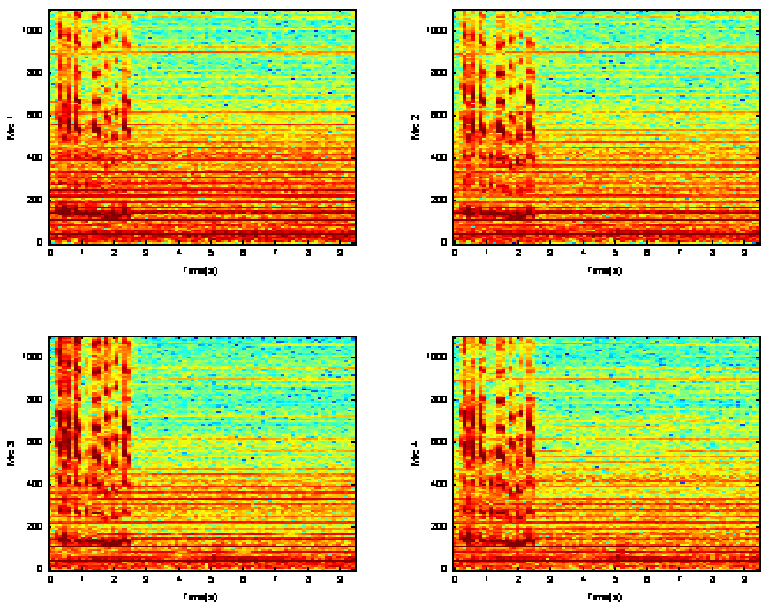
Power vs. Time

Figure 5.6. Power vs. Time, Amplitude in Normalized dB



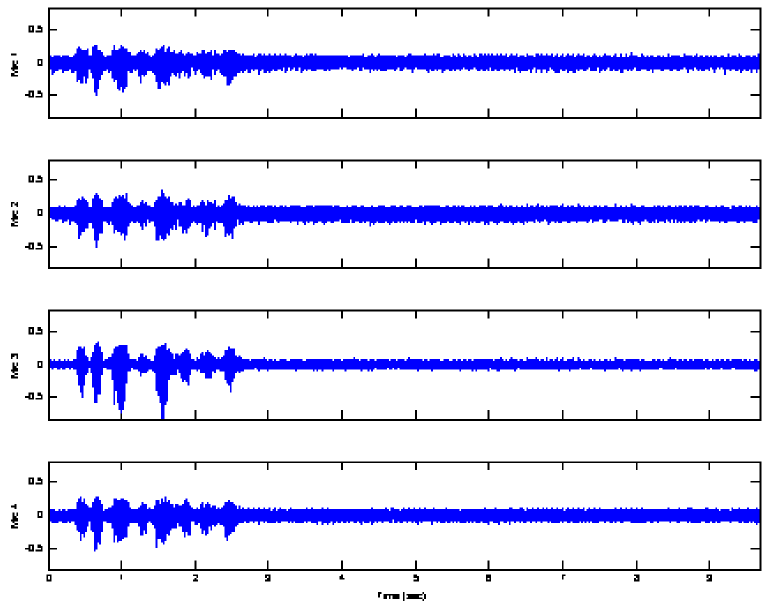
Spectogram (0 to 1kHz)

Figure 5.7. Spectrogram 0-1kHz, Frequency in Hz



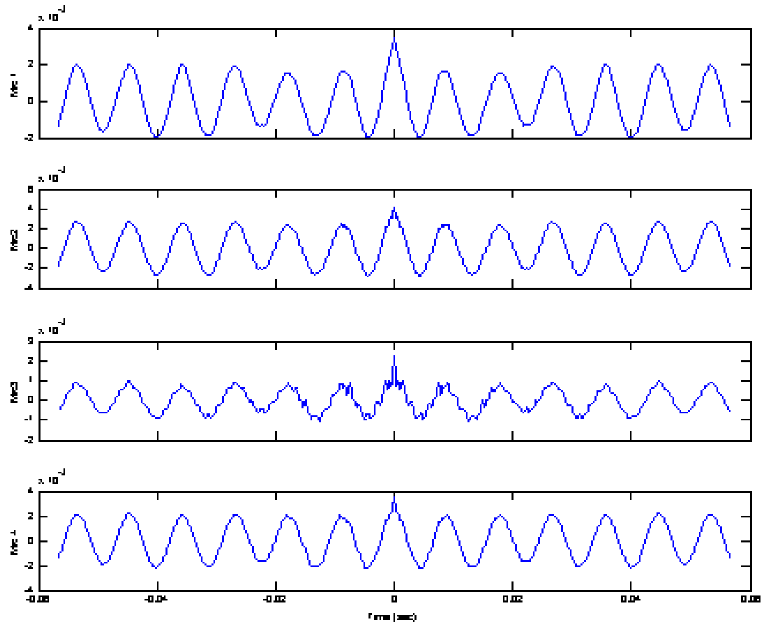
Time Plot

Figure 5.8. Time Graph



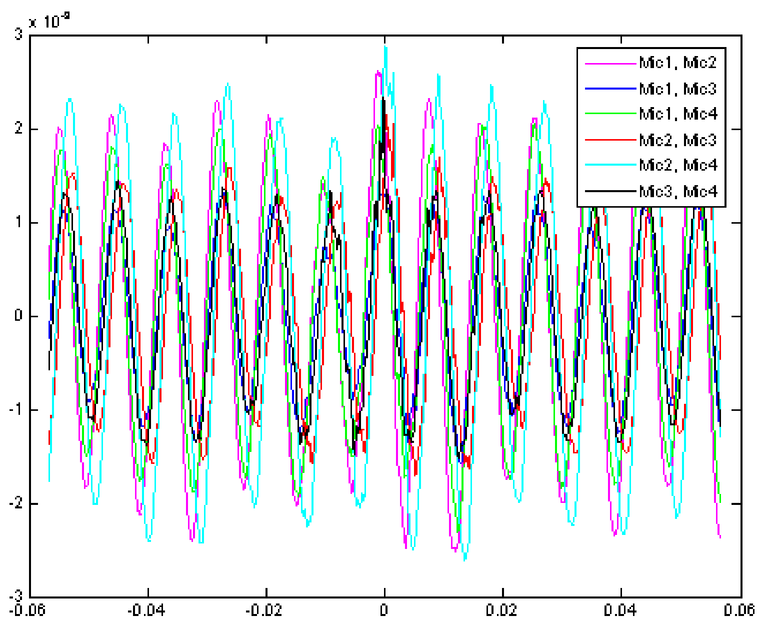
Autocorrelation

Figure 5.9. Autocorrelation Graph



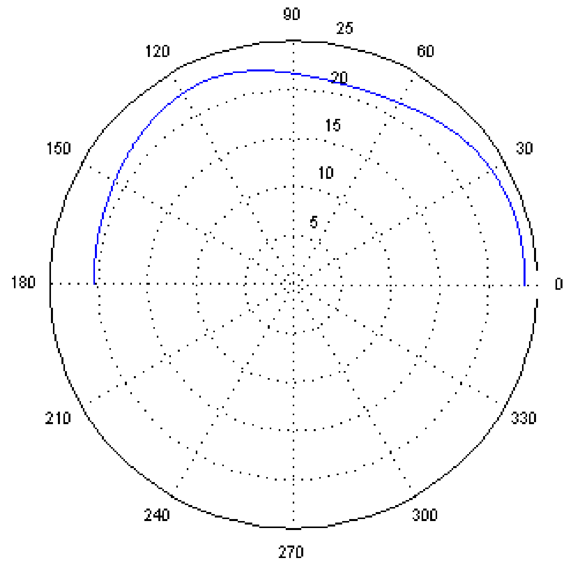
Crosscorrelation

Figure 5.10. CrossCorrelation



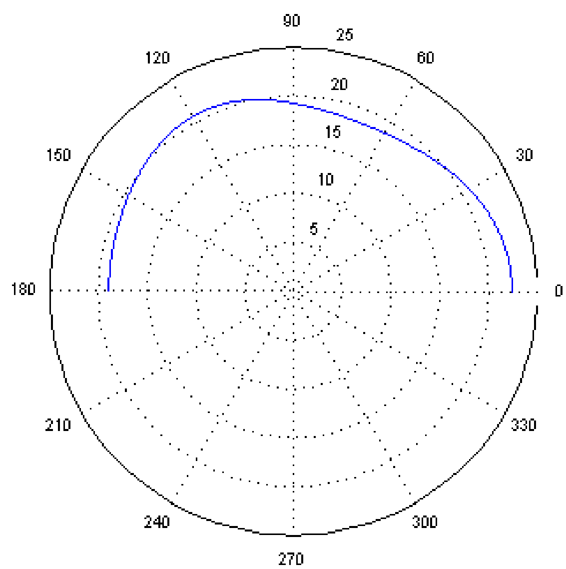
Direction of Arrival 200 Hz

Figure 5.11. DOA 200 Hz



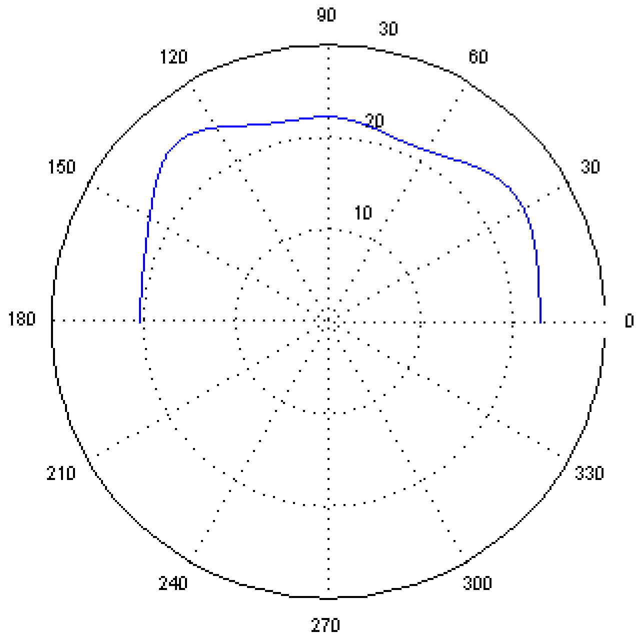
Direction of Arrival 300 Hz

Figure 5.12. DOA 300 Hz



Direction of Arrival 400 Hz

Figure 5.13. DOA 400 Hz



Chapter 6. Test Four: Driving 30 MPH

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Power Spectral Density (0 to 20 kHz)

Figure 6.1. Non-Normalized PSD 0-20kHz, Amplitude in dB

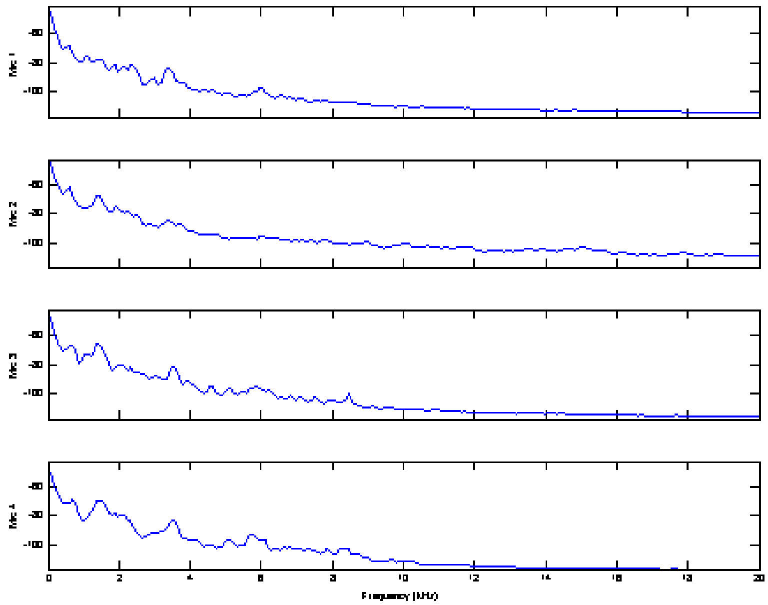
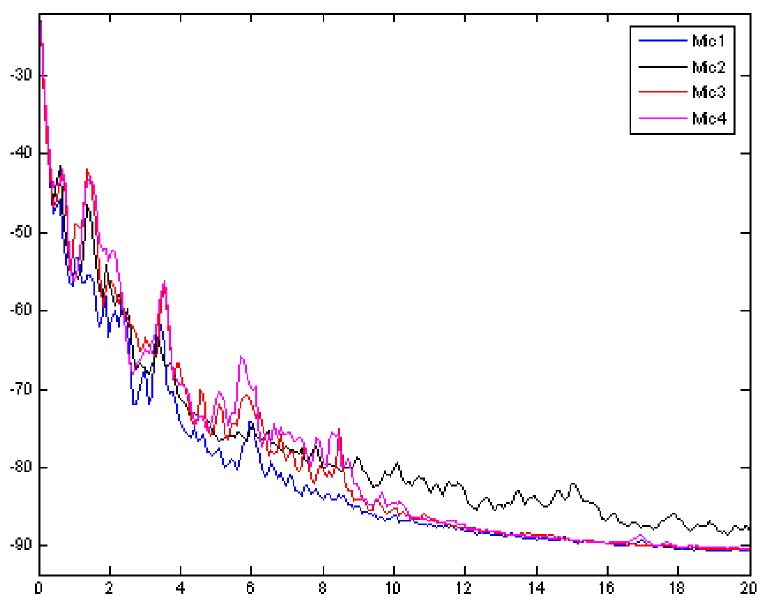


Figure 6.2. Normalized PSD 0-20kHz, Amplitude in dB



Power Spectral Density (0 to 1kHz)

Figure 6.3. Non-Normalized PSD 0-1kHz, Amplitude in dB

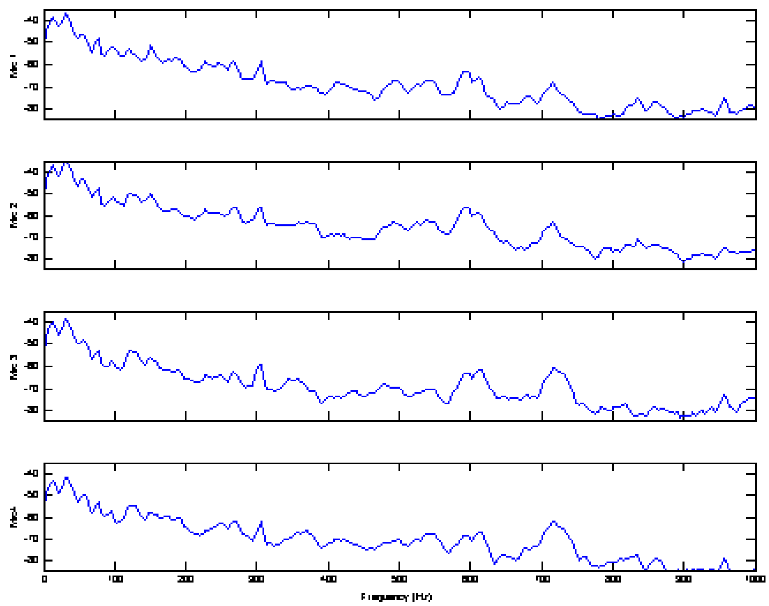
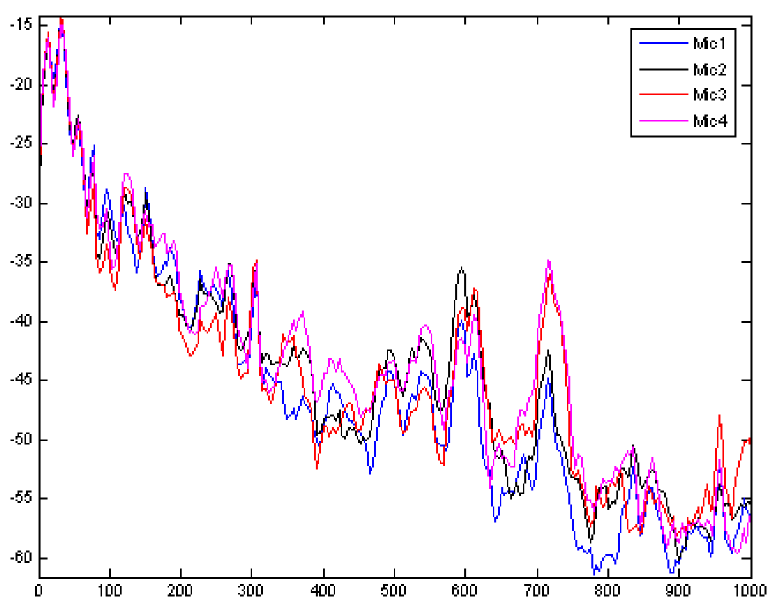
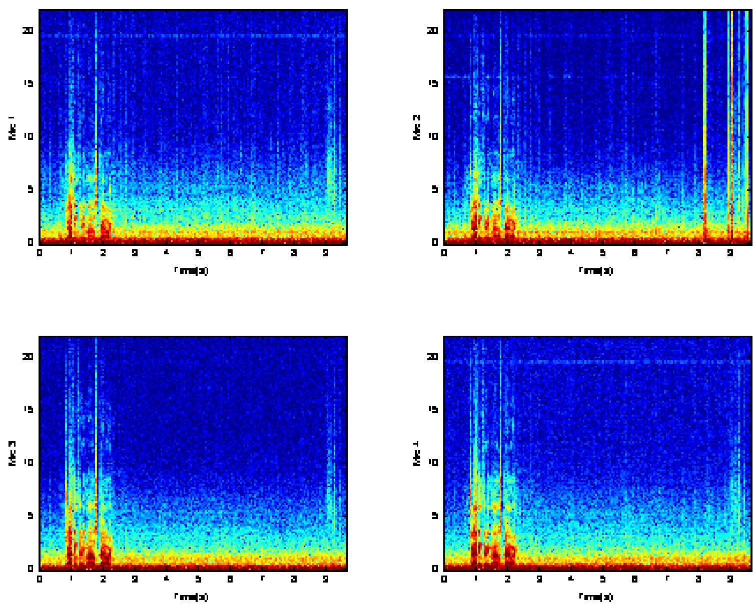


Figure 6.4. Normalized PSD 0-1kHz, Amplitude in dB



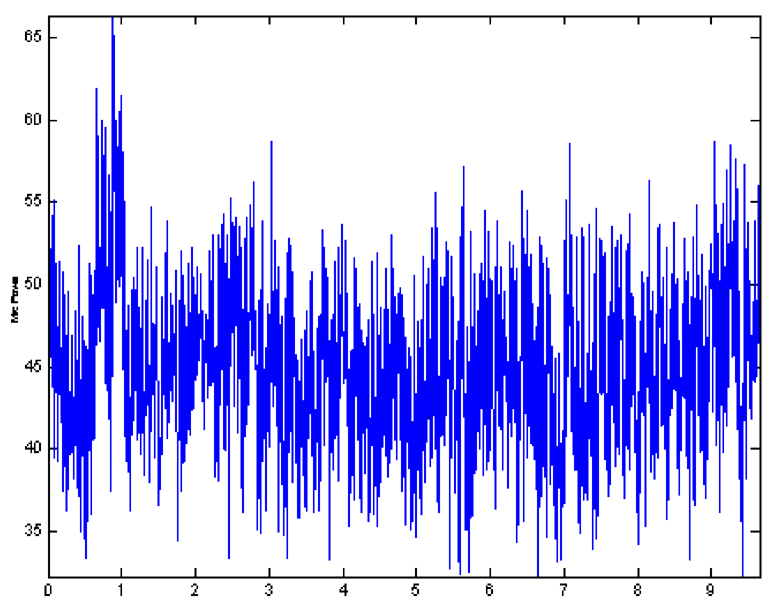
Spectrogram (0 to 20 kHz)

Figure 6.5. Spectrogram 0-20kHz, Frequency in kHz



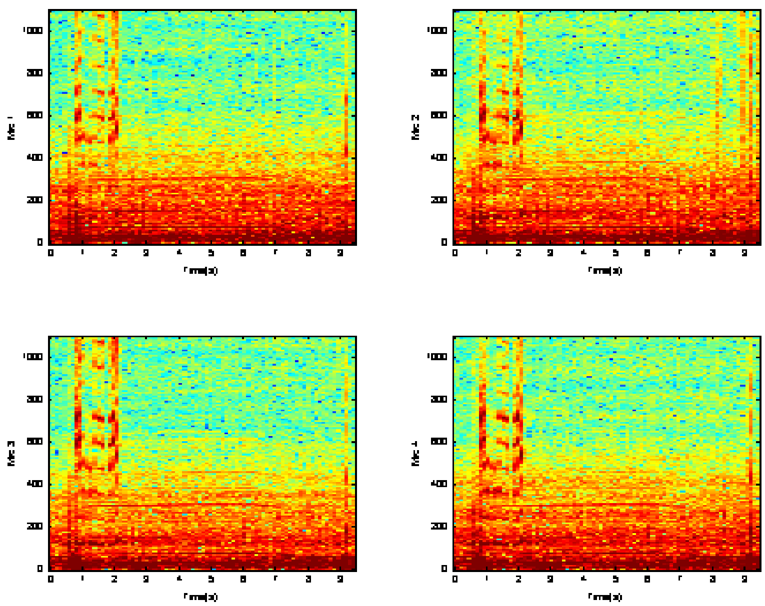
Power vs. Time

Figure 6.6. Power vs. Time, Amplitude in Normalized dB



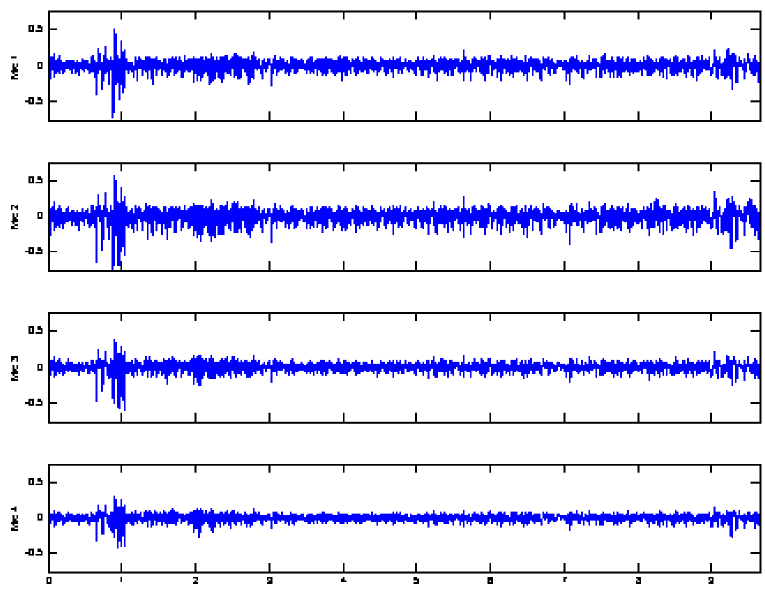
Spectogram (0 to 1kHz)

Figure 6.7. Spectrogram 0-1kHz, Frequency in Hz



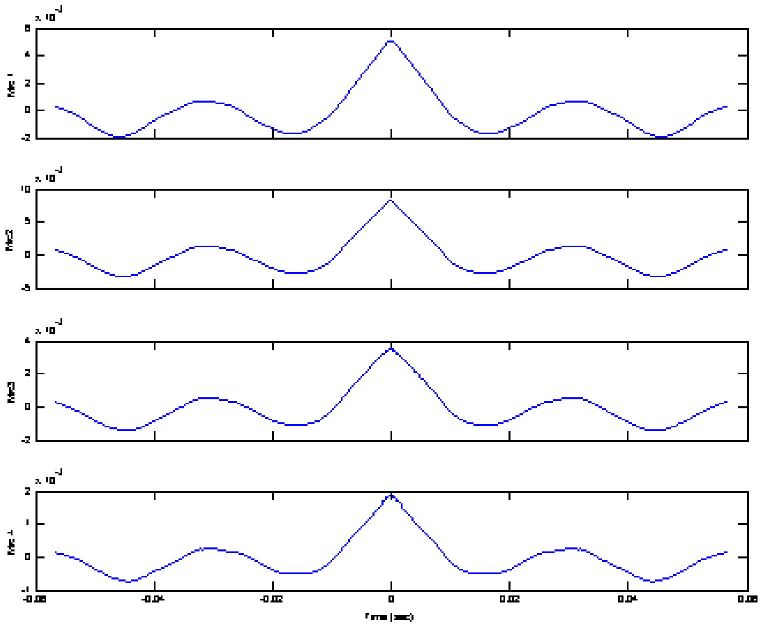
Time Plot

Figure 6.8. Time Graph



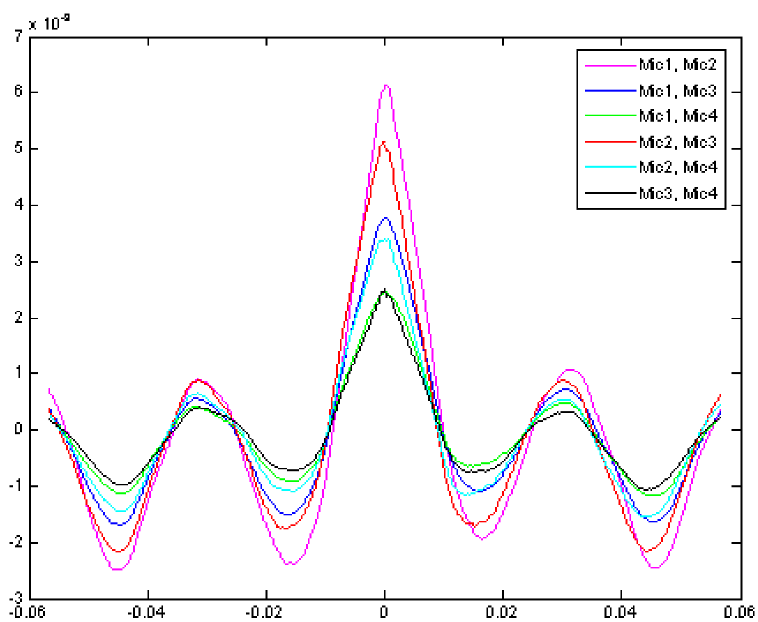
Autocorrelation

Figure 6.9. Autocorrelation Graph



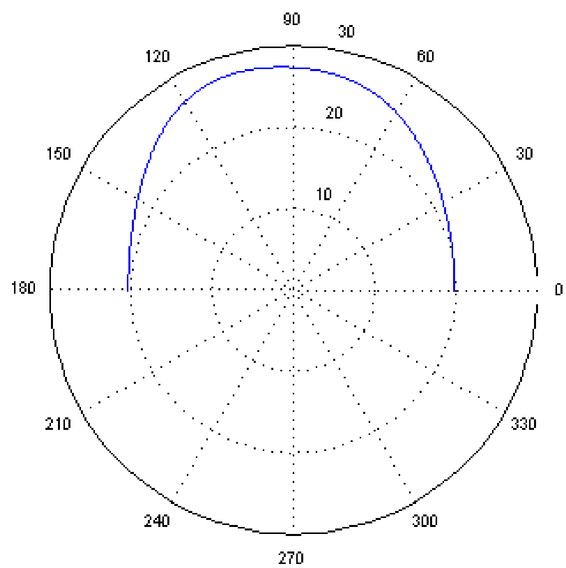
Crosscorrelation

Figure 6.10. CrossCorrelation



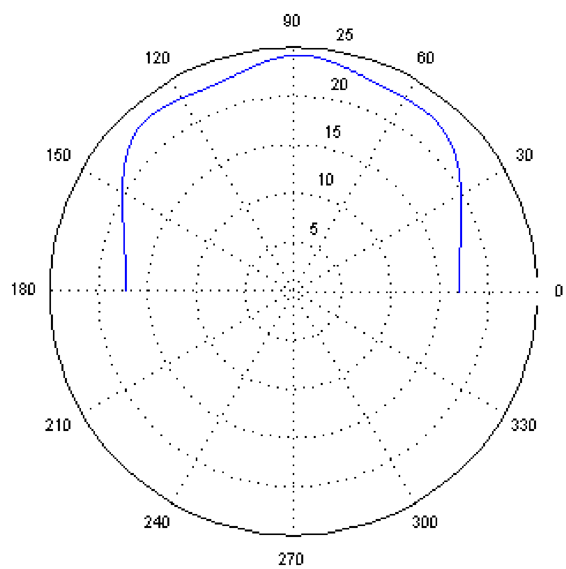
Direction of Arrival 200 Hz

Figure 6.11. DOA 200 Hz



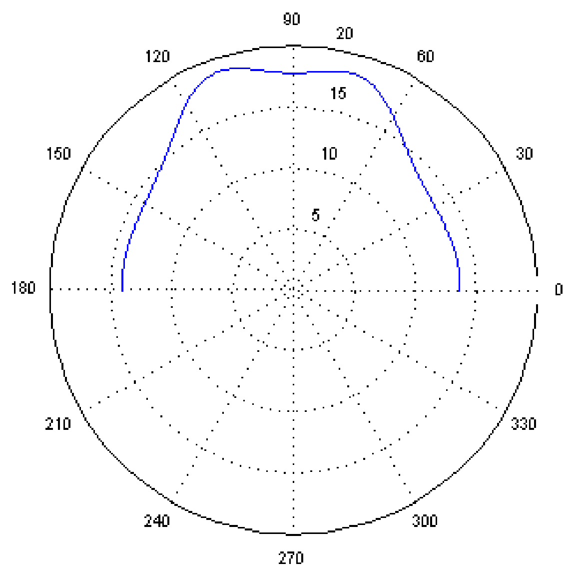
Direction of Arrival 300 Hz

Figure 6.12. DOA 300 Hz



Direction of Arrival 400 Hz

Figure 6.13. DOA 400 Hz



Chapter 7. Test Five: Driving 50 MPH

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`Recording Four`
Play Driving 50 MPH Mic 4.wav

Power Spectral Density (0 to 20 kHz)

Figure 7.1. Non-Normalized PSD 0-20kHz, Amplitude in dB

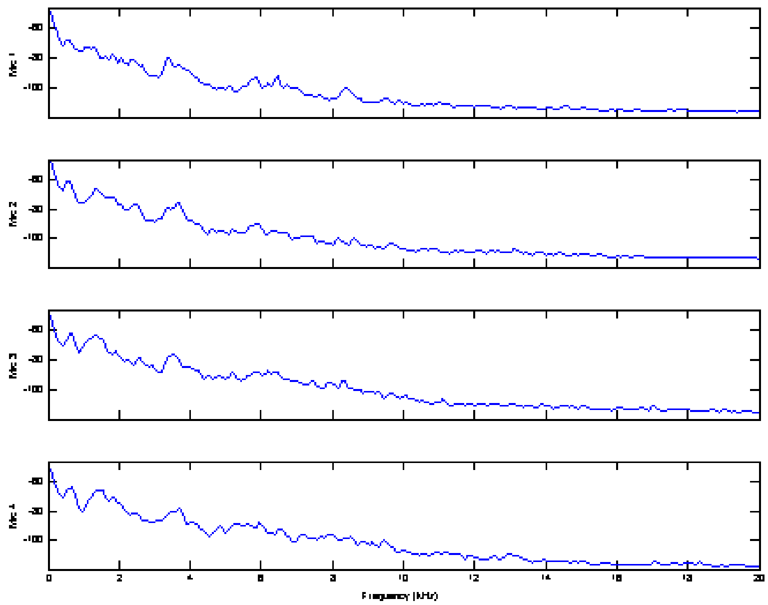
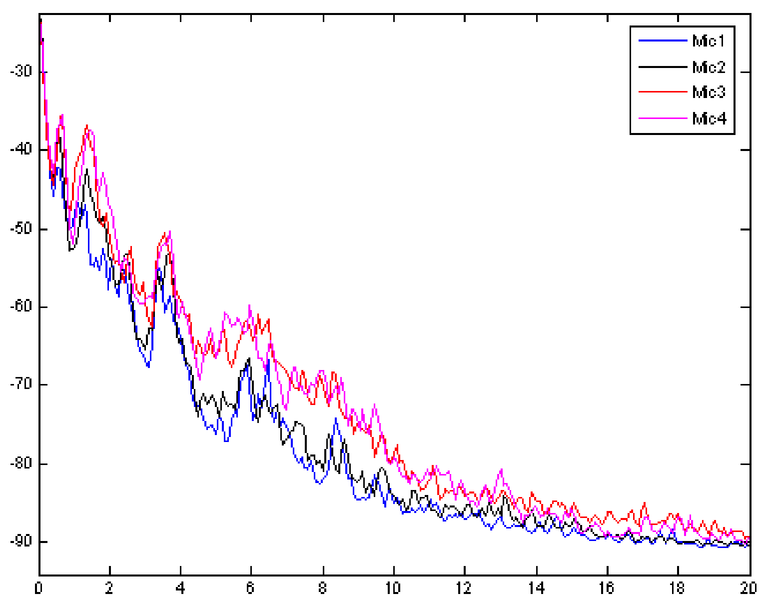


Figure 7.2. Normalized PSD 0-20kHz, Amplitude in dB



Power Spectral Density (0 to 1kHz)

Figure 7.3. Non-Normalized PSD 0-1kHz, Amplitude in dB

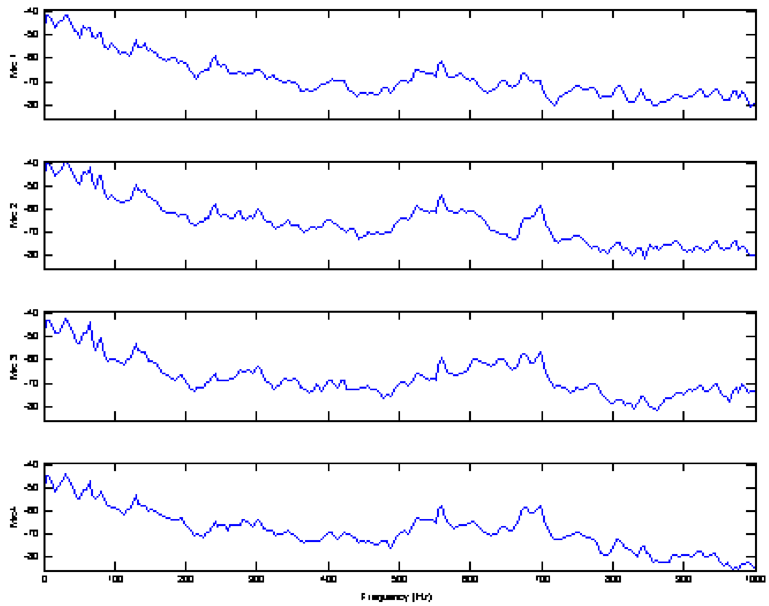
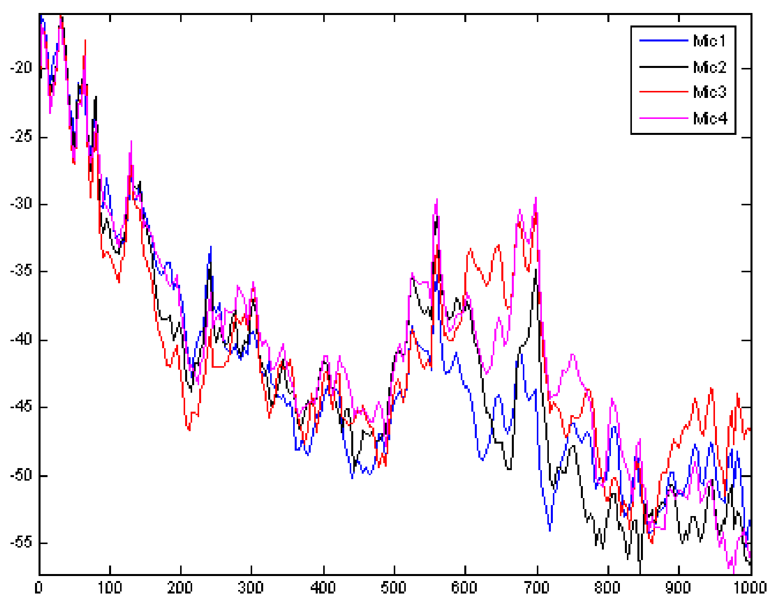
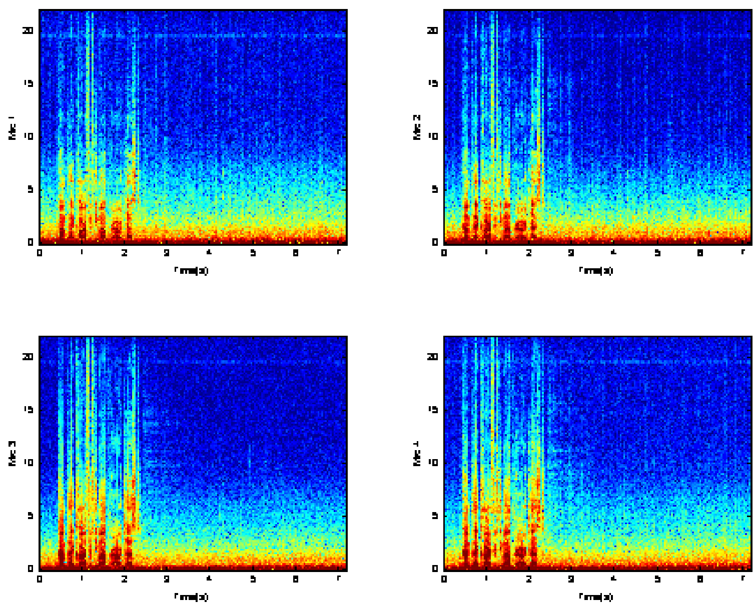


Figure 7.4. Normalized PSD 0-1kHz, Amplitude in dB



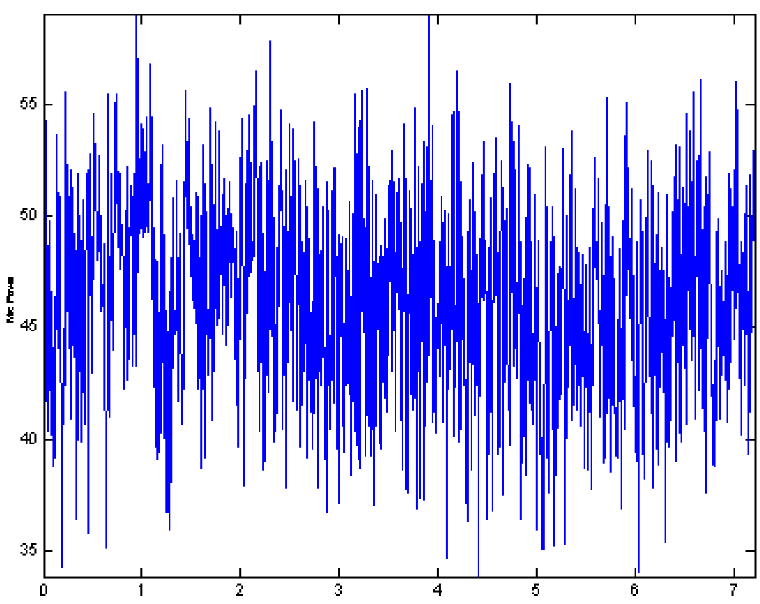
Spectrogram (0 to 20 kHz)

Figure 7.5. Spectrogram 0-20kHz, Frequency in kHz



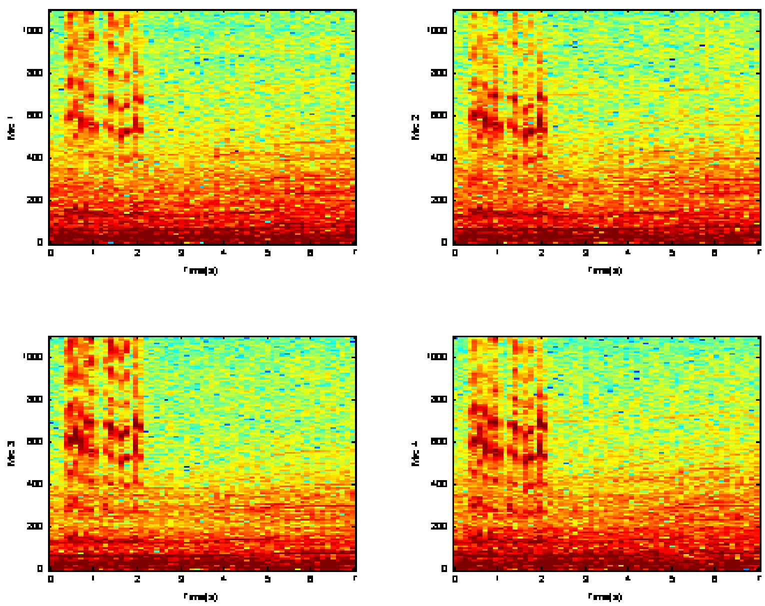
Power vs. Time

Figure 7.6. Power vs. Time, Amplitude in Normalized dB



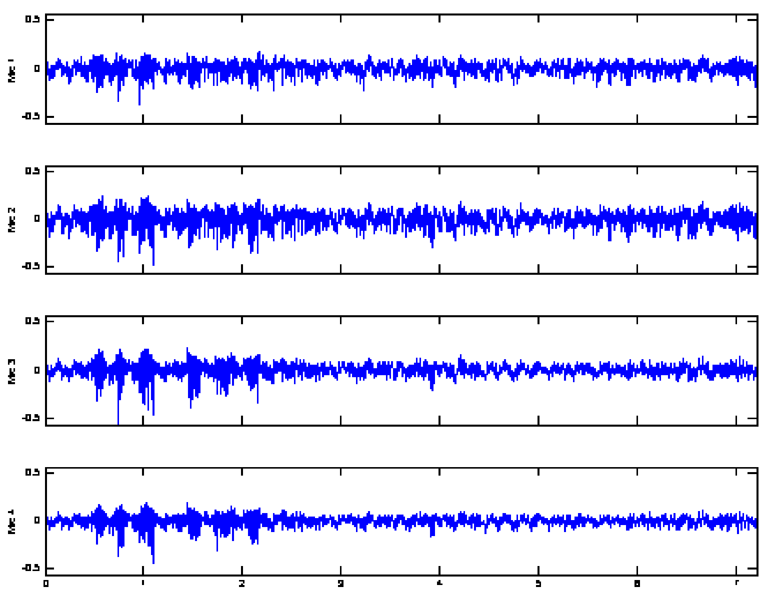
Spectogram (0 to 1kHz)

Figure 7.7. Spectrogram 0-1kHz, Frequency in Hz



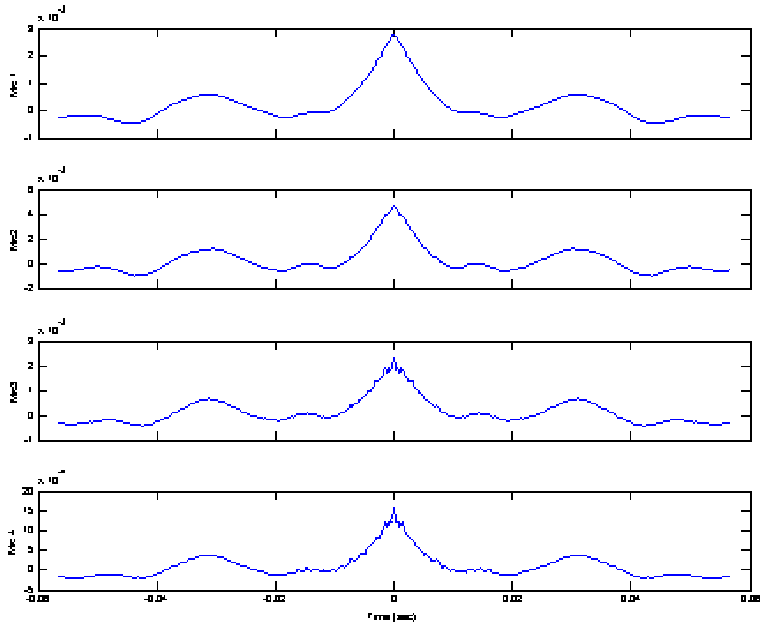
Time Plot

Figure 7.8. Time Graph



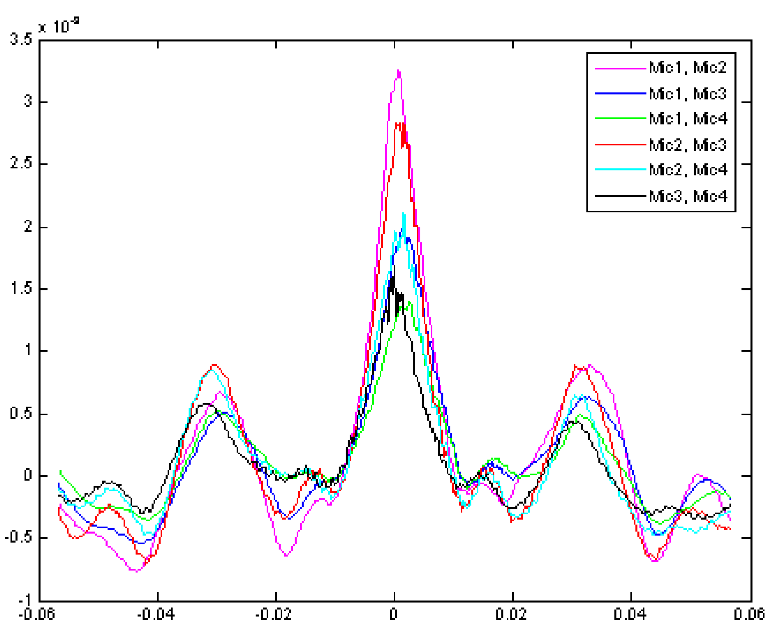
Autocorrelation

Figure 7.9. Autocorrelation Graph



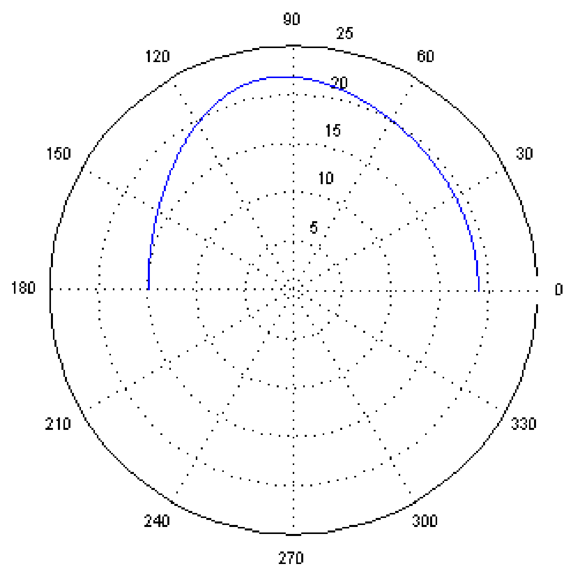
Crosscorrelation

Figure 7.10. CrossCorrelation



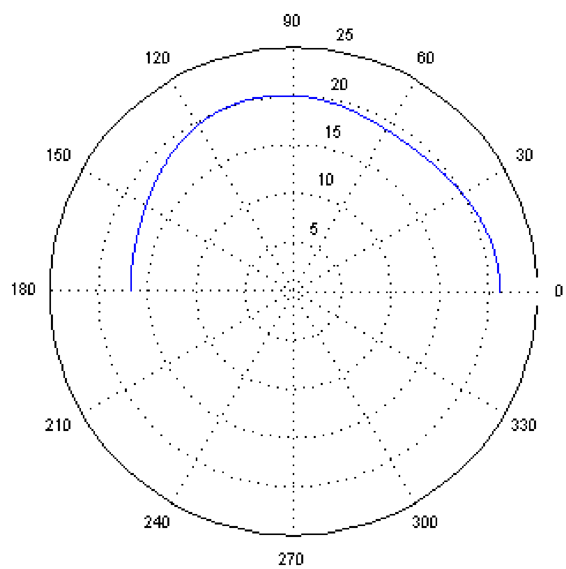
Direction of Arrival 200 Hz

Figure 7.11. DOA 200 Hz



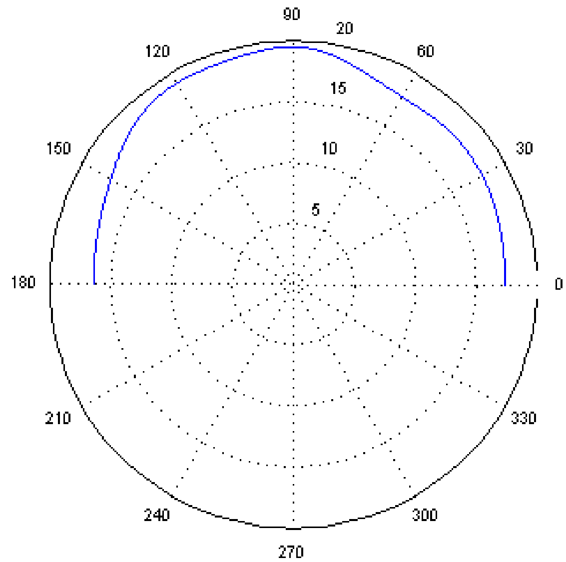
Direction of Arrival 300 Hz

Figure 7.12. DOA 300 Hz



Direction of Arrival 400 Hz

Figure 7.13. DOA 400 Hz



Chapter 8. Test Six: Driving 30 MPH, windows down

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Power Spectral Density (0 to 20 kHz)

Figure 8.1. Non-Normalized PSD 0-20kHz, Amplitude in dB

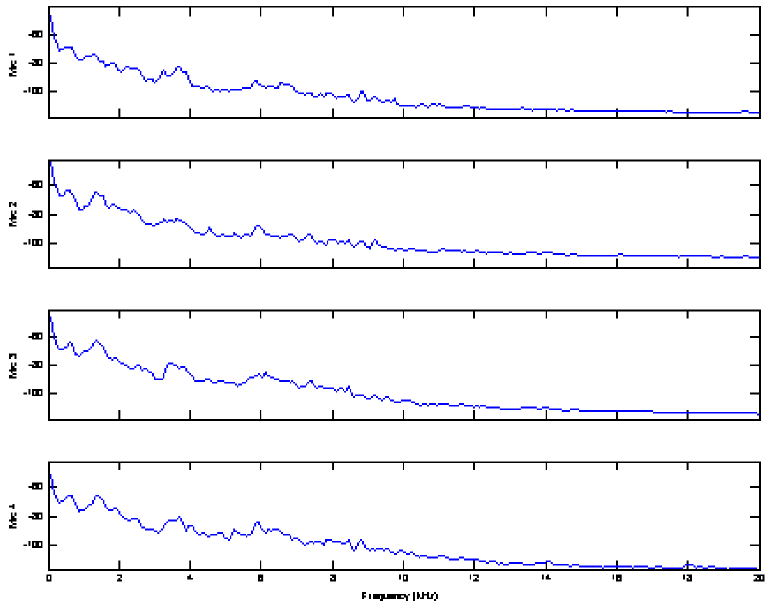
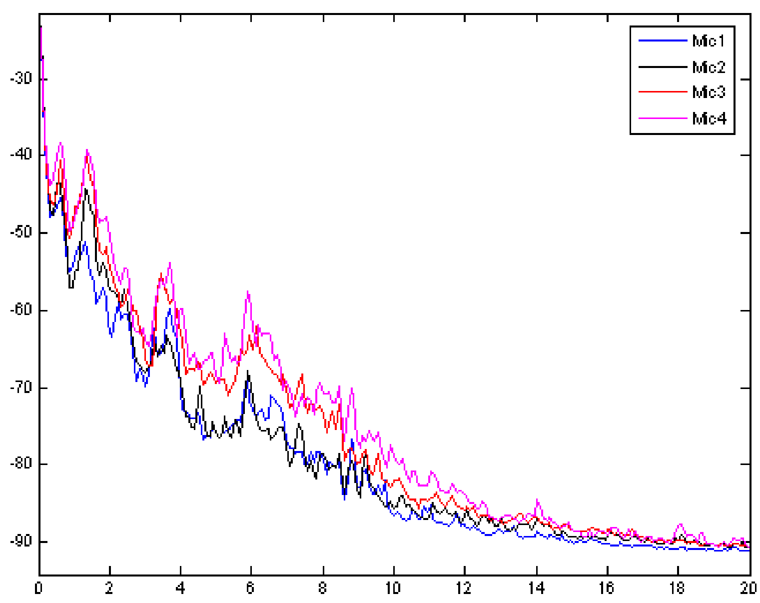


Figure 8.2. Normalized PSD 0-20kHz, Amplitude in dB



Power Spectral Density (0 to 1kHz)

Figure 8.3. Non-Normalized PSD 0-1kHz, Amplitude in dB

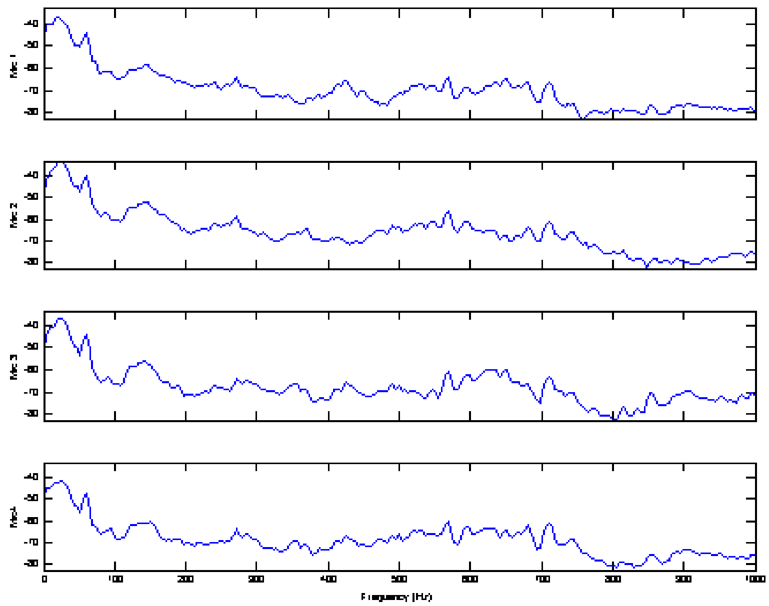
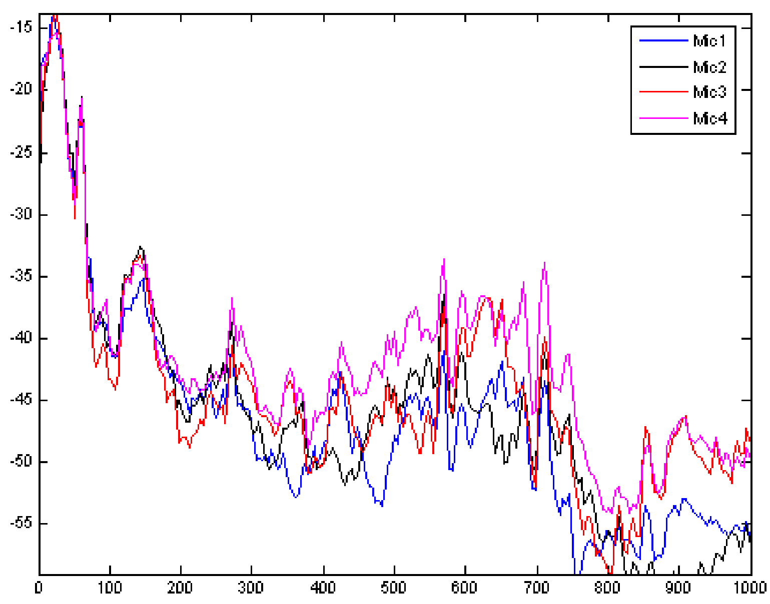
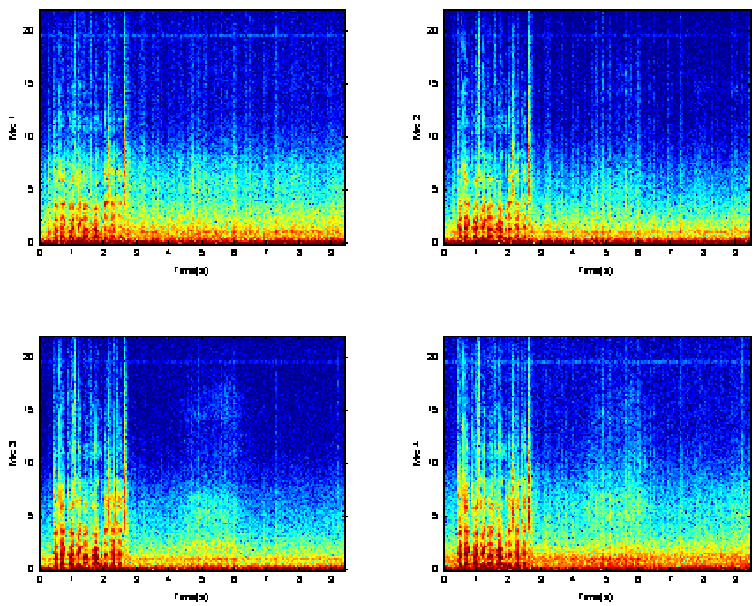


Figure 8.4. Normalized PSD 0-1kHz, Amplitude in dB



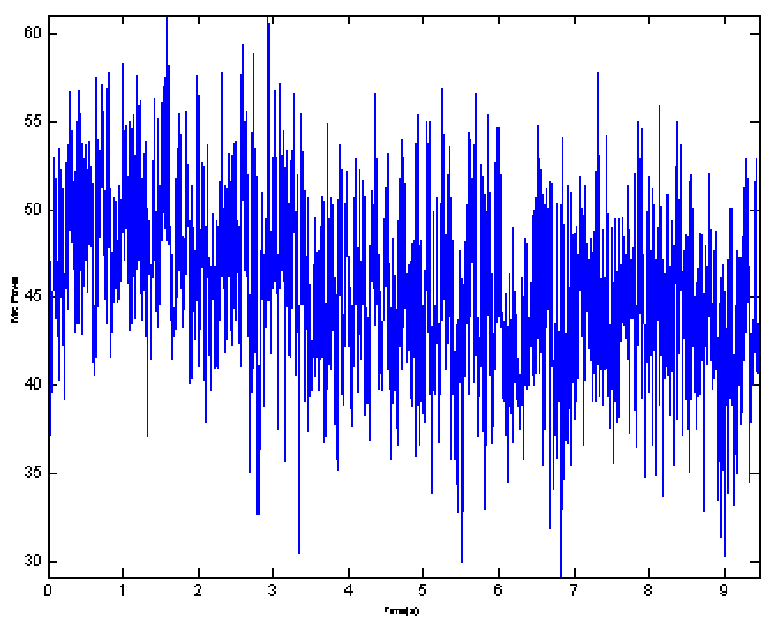
Spectrogram (0 to 20 kHz)

Figure 8.5. Spectrogram 0-20kHz, Frequency in kHz



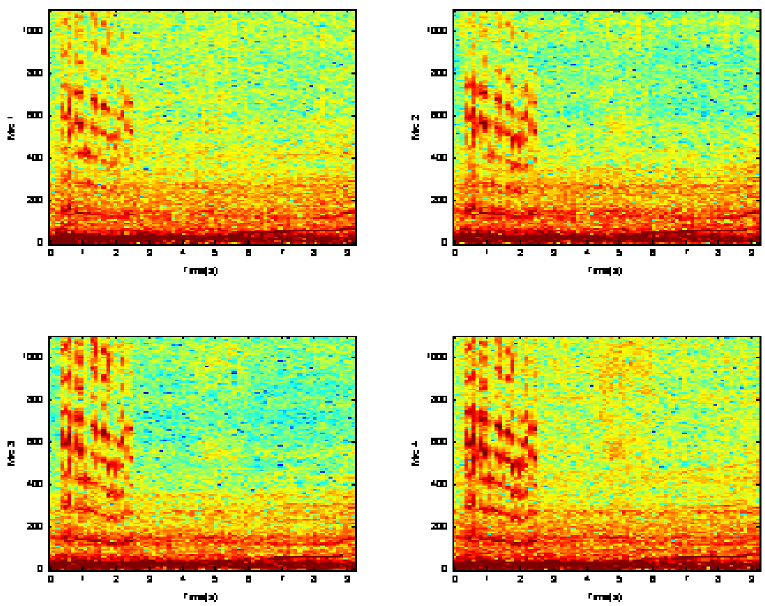
Power vs. Time

Figure 8.6. Power vs. Time, Amplitude in Normalized dB



Spectogram (0 to 1kHz)

Figure 8.7. Spectrogram 0-1kHz, Frequency in Hz



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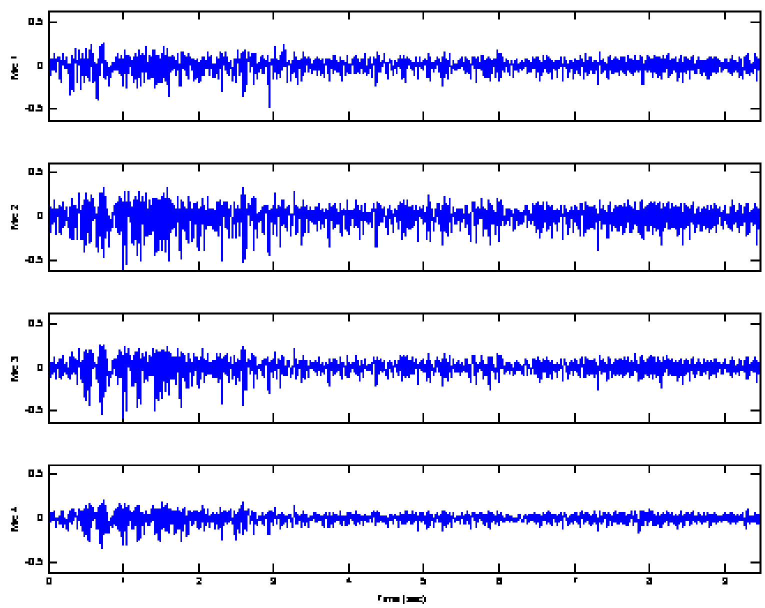
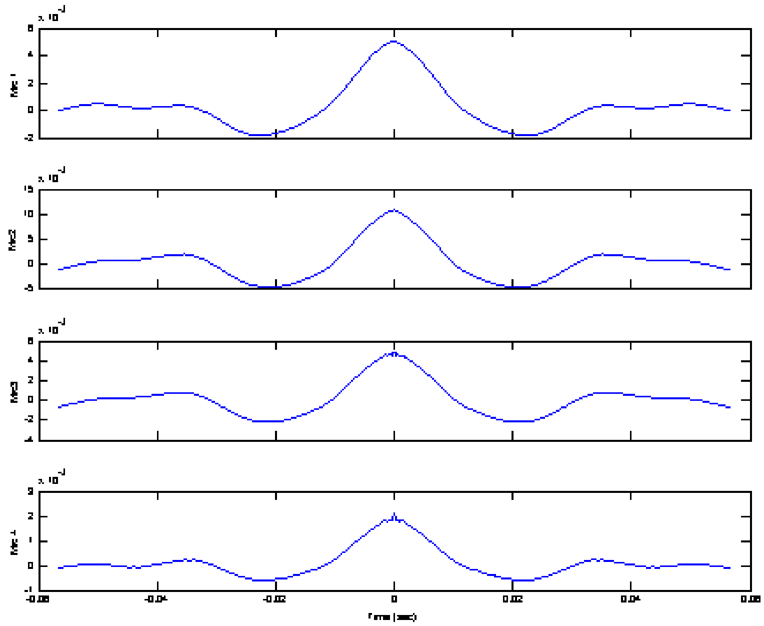


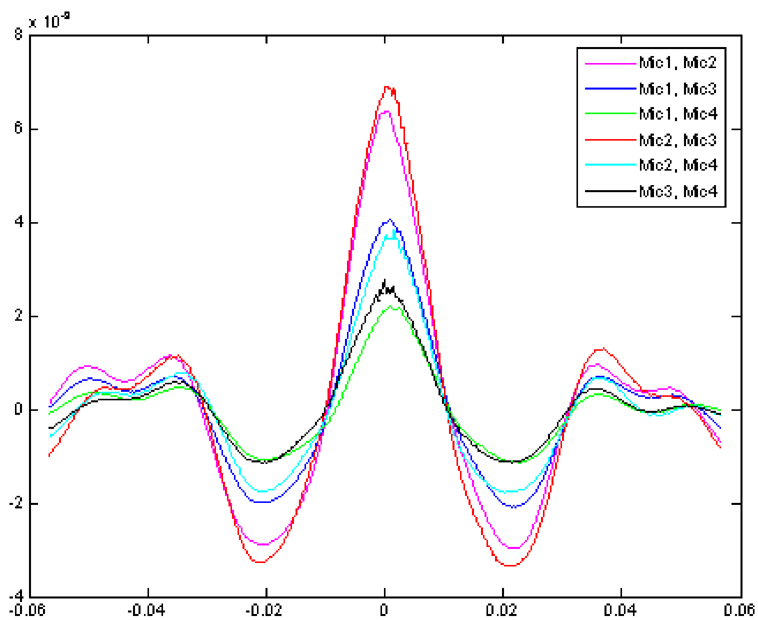
Autocorrelation

Figure 8.9. Autocorrelation Graph



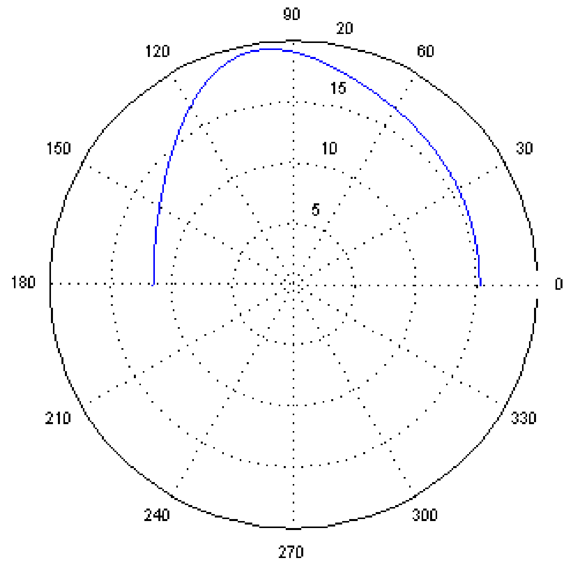
Crosscorrelation

Figure 8.10. CrossCorrelation



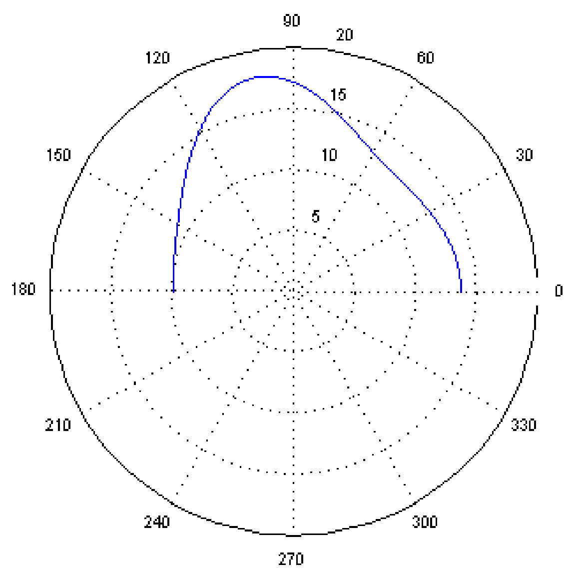
Direction of Arrival 200 Hz

Figure 8.11. DOA 200 Hz



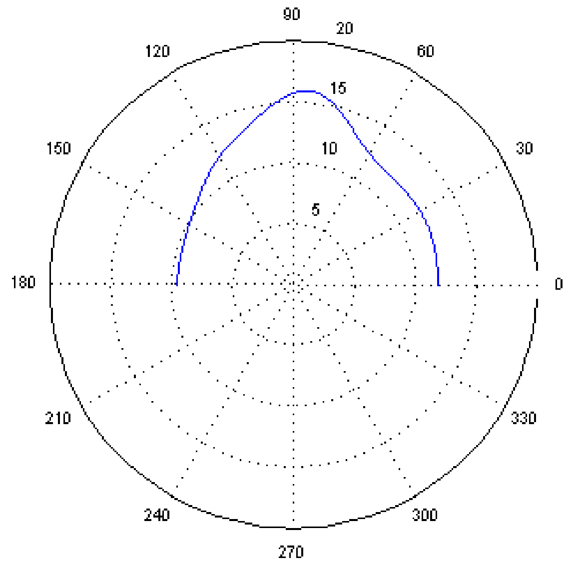
Direction of Arrival 300 Hz

Figure 8.12. DOA 300 Hz



Direction of Arrival 400 Hz

Figure 8.13. DOA 400 Hz



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Play Accelerating 30-50 MPH Mic 4.wav

Power Spectral Density (0 to 20 kHz)

Figure 9.1. Non-Normalized PSD 0-20kHz, Amplitude in dB

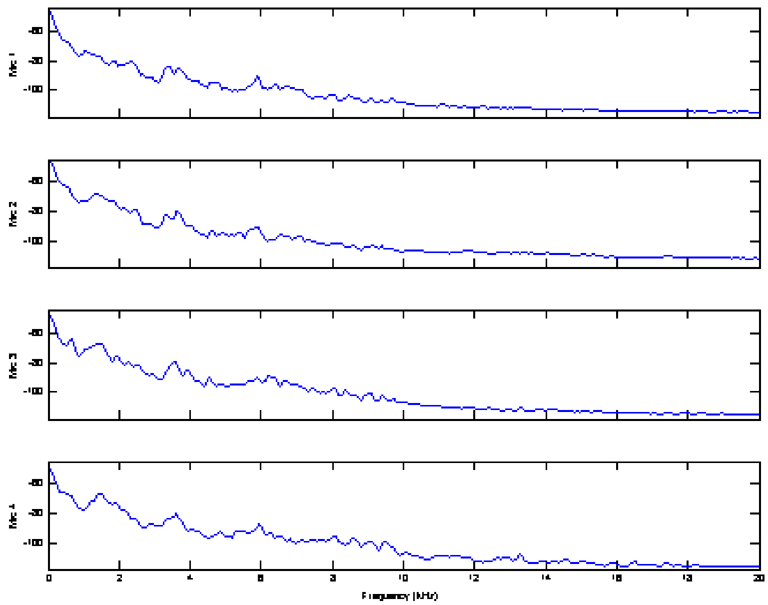
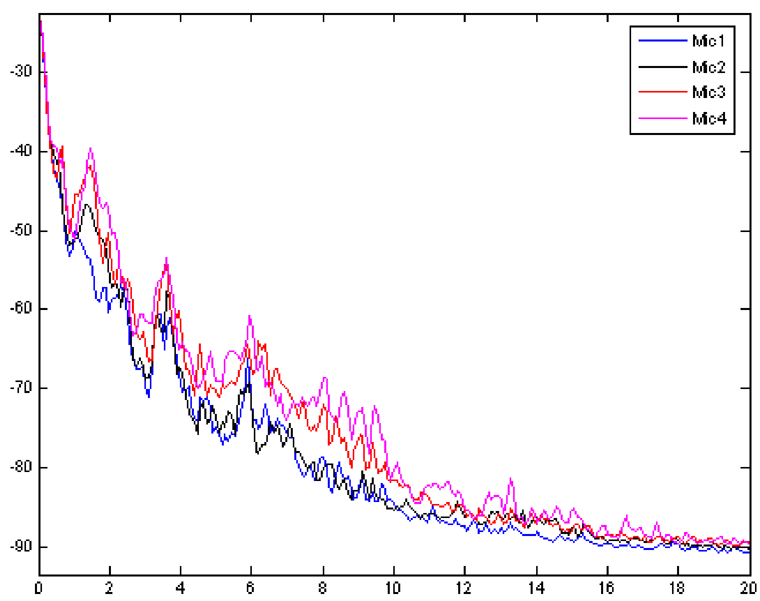


Figure 9.2. Normalized PSD 0-20kHz, Amplitude in dB



Power Spectral Density (0 to 1kHz)

Figure 9.3. Non-Normalized PSD 0-1kHz, Amplitude in dB

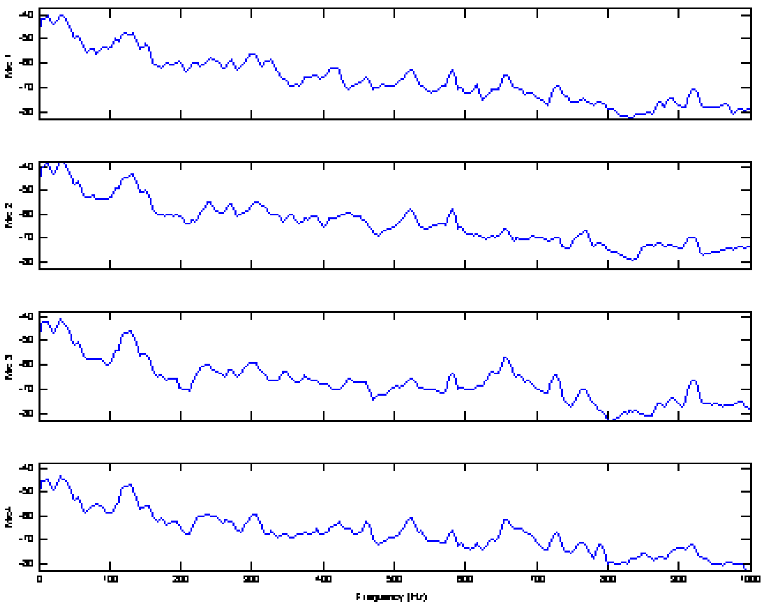
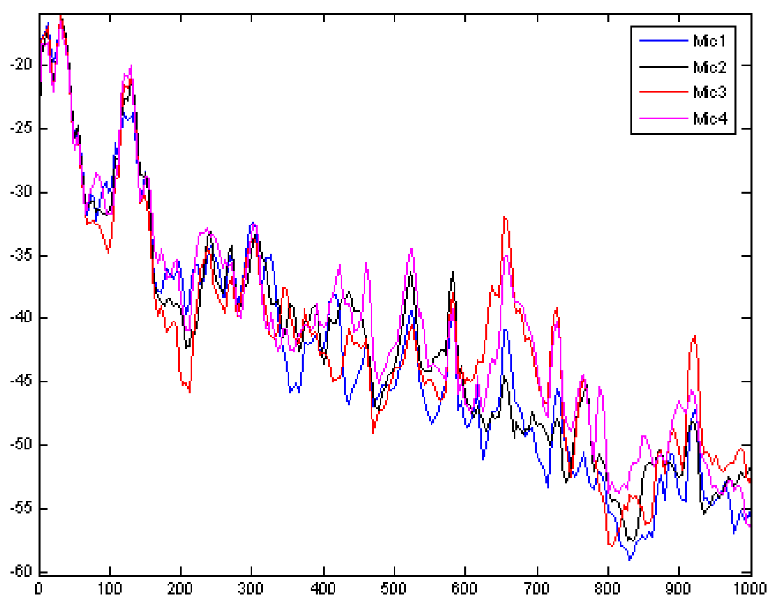
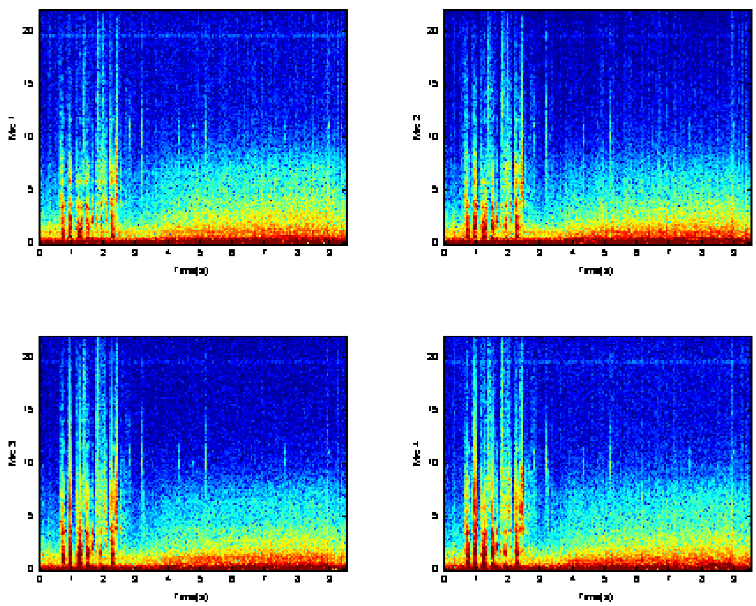


Figure 9.4. Normalized PSD 0-1kHz, Amplitude in dB



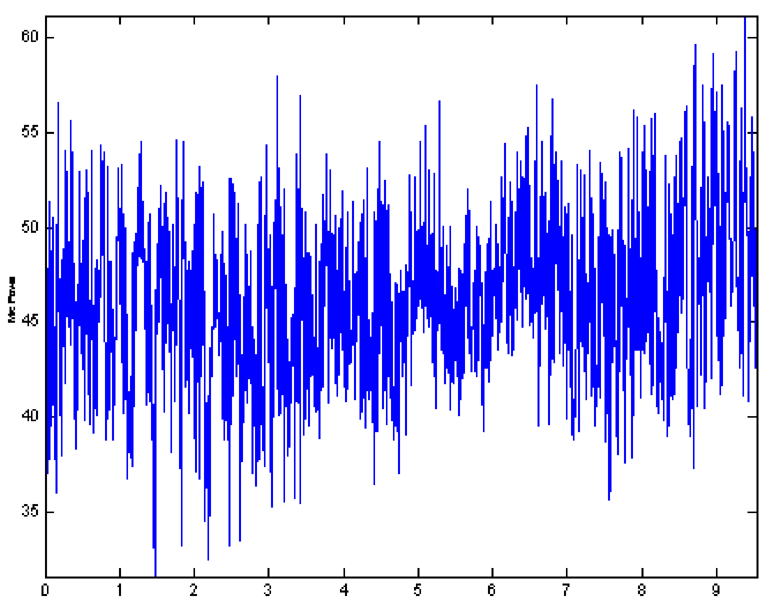
Spectrogram (0 to 20 kHz)

Figure 9.5. Spectrogram 0-20kHz, Frequency in kHz



Power vs. Time

Figure 9.6. Power vs. Time, Amplitude in Normalized dB



Spectogram (0 to 1kHz)

Figure 9.7. Spectrogram 0-1kHz, Frequency in Hz

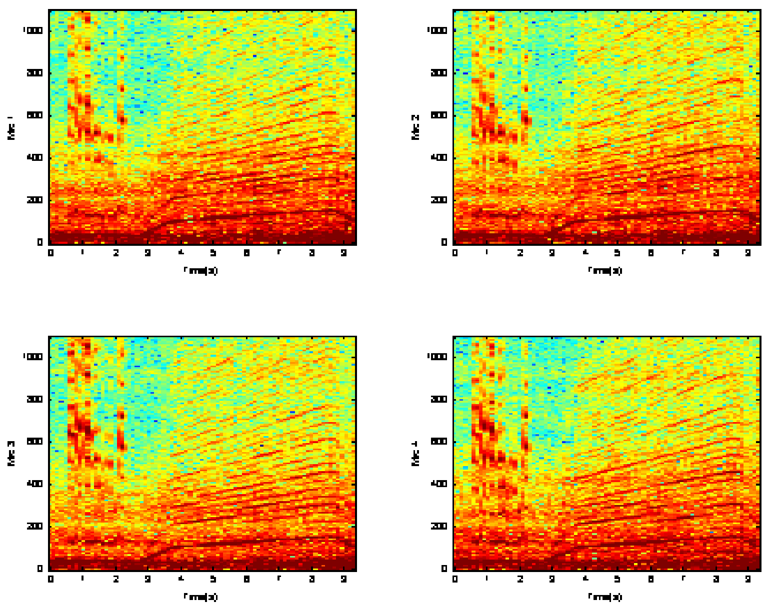


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Figure 9.8. Time Graph

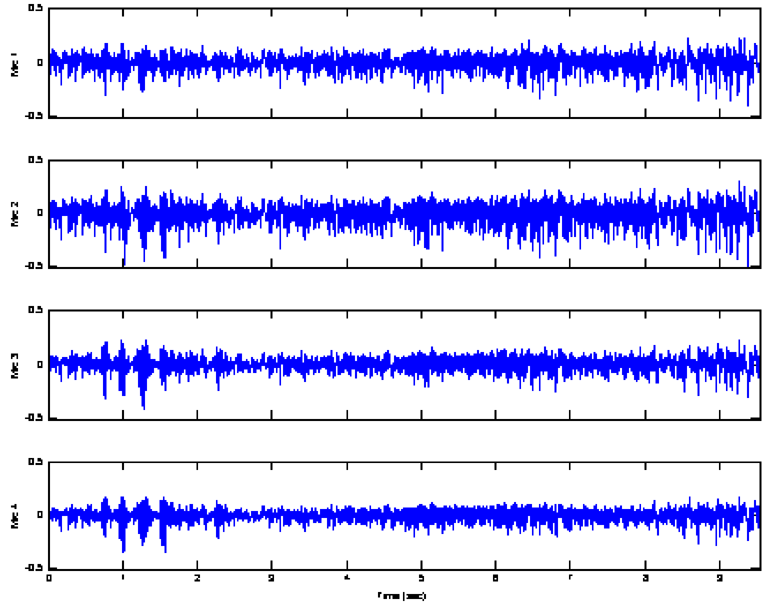

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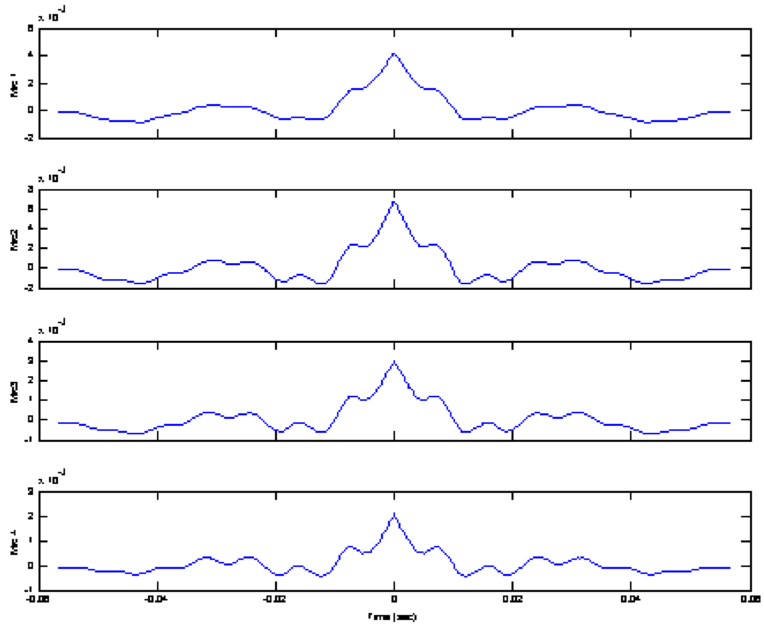
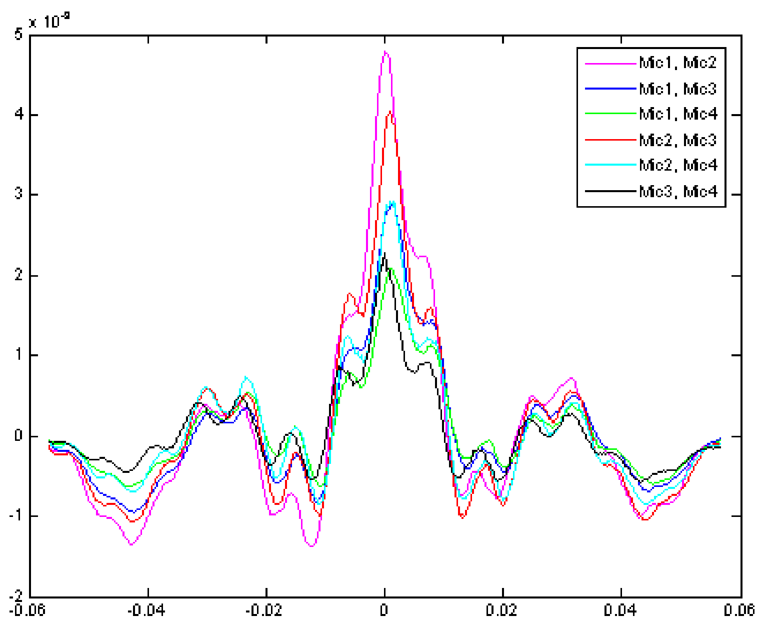
Figure 9.9. Autocorrelation Graph



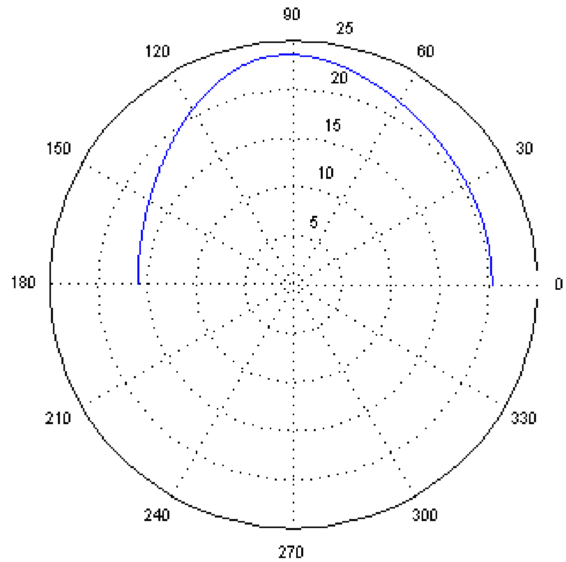
Crosscorrelation

Figure 9.10. CrossCorrelation



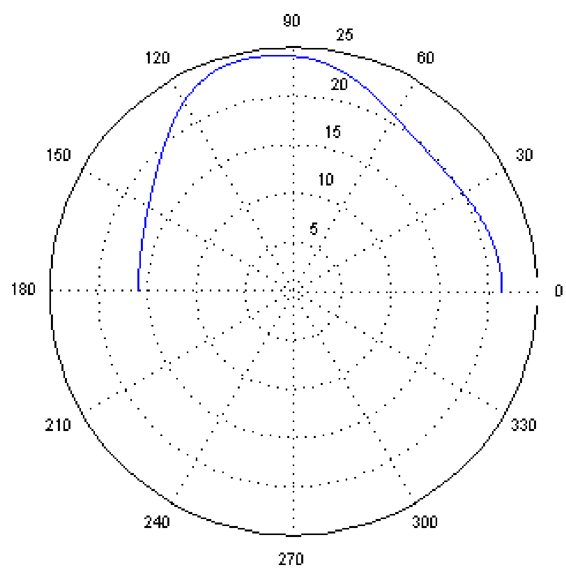
Direction of Arrival 200 Hz

Figure 9.11. DOA 200 Hz



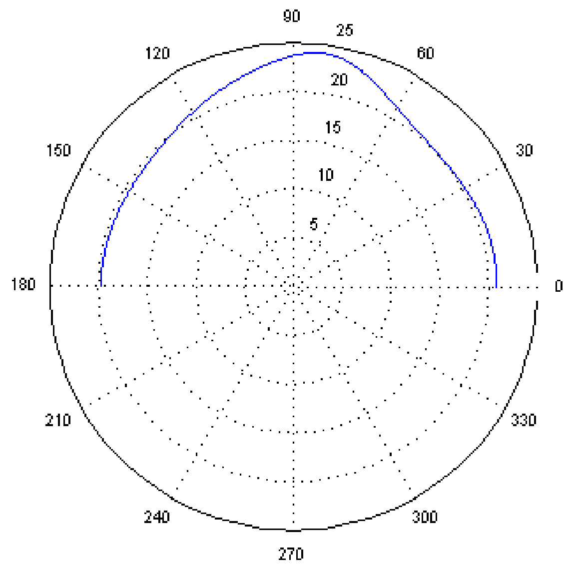
Direction of Arrival 300 Hz

Figure 9.12. DOA 300 Hz



Direction of Arrival 400 Hz

Figure 9.13. DOA 400 Hz



Chapter 10. Test Eight: Accelerating 30-50 MPH, windows down

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Power Spectral Density (0 to 20 kHz)

Figure 10.1. Non-Normalized PSD 0-20kHz, Amplitude in dB

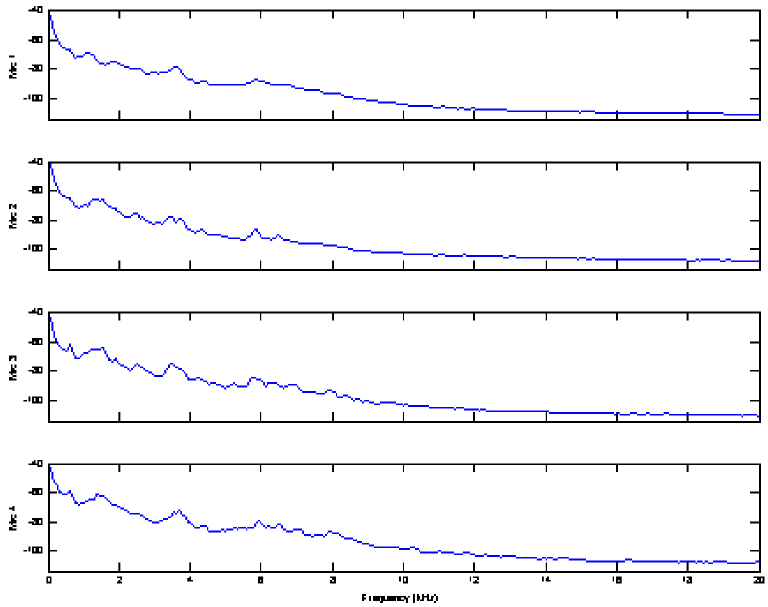
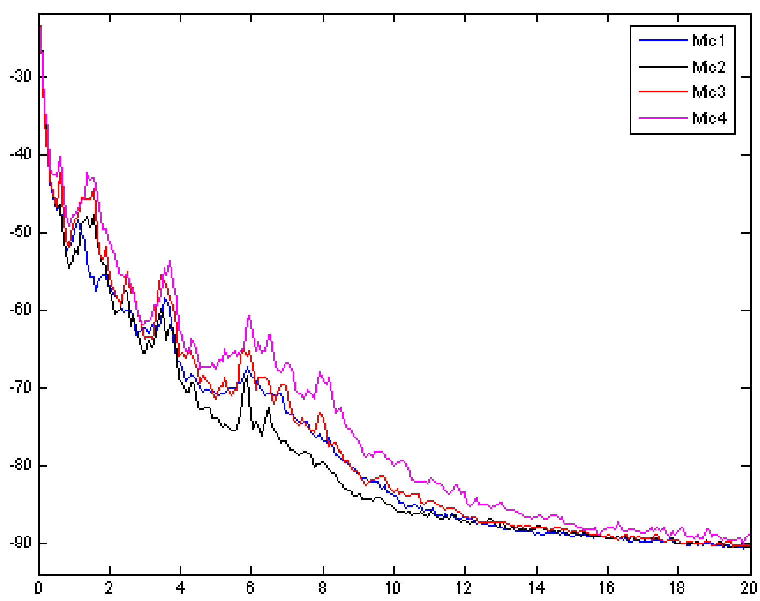


Figure 10.2. Normalized PSD 0-20kHz, Amplitude in dB



Power Spectral Density (0 to 1kHz)

Figure 10.3. Non-Normalized PSD 0-1kHz, Amplitude in dB

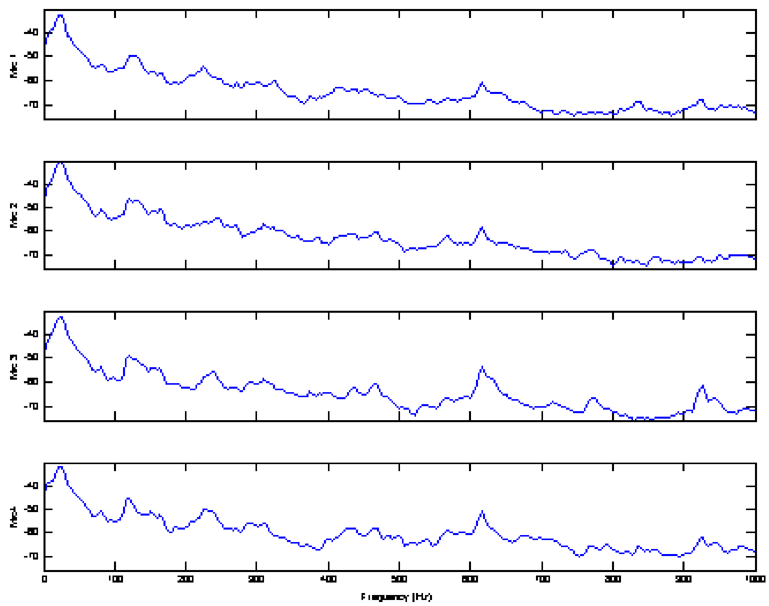


Figure 10.4. Normalized PSD 0-1kHz, Amplitude in dB

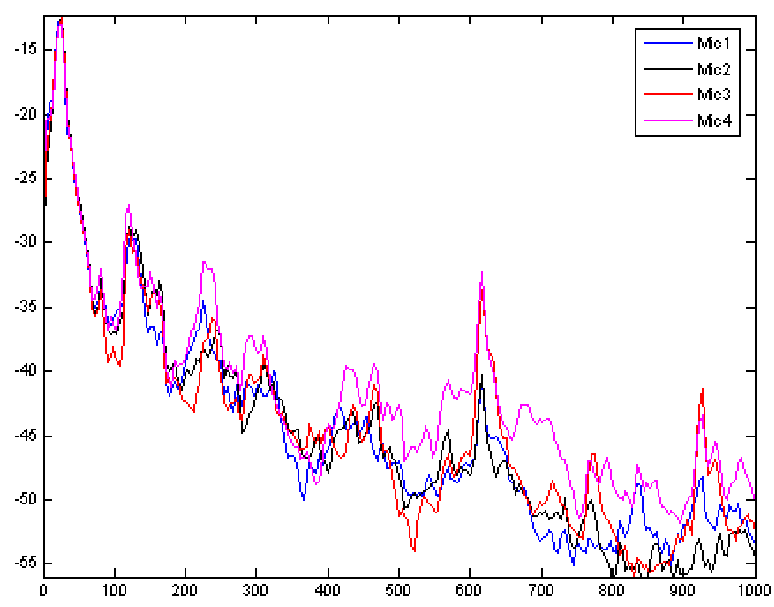


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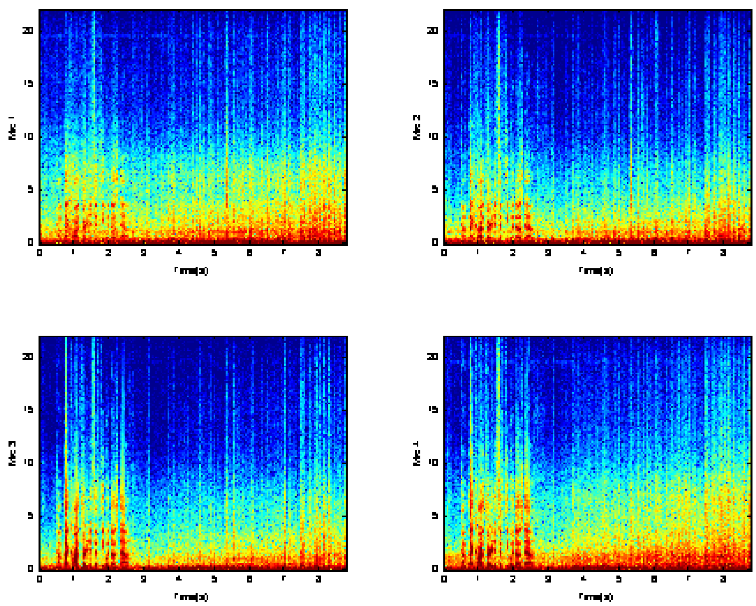
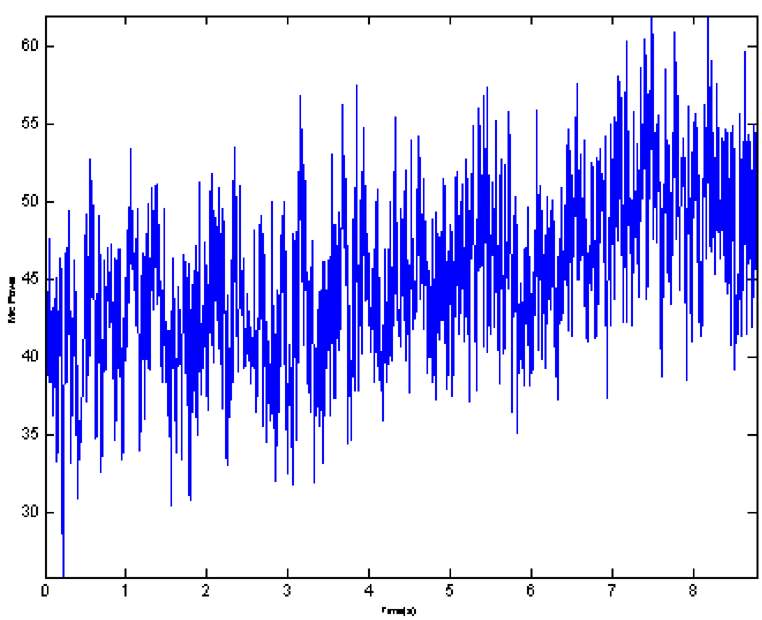
Figure 10.5. Spectrogram 0-20kHz, Frequency in kHz



Power vs. Time

Figure 10.6. Power vs. Time, Amplitude in Normalized dB



Spectogram (0 to 1kHz)

Figure 10.7. Spectrogram 0-1kHz, Frequency in Hz

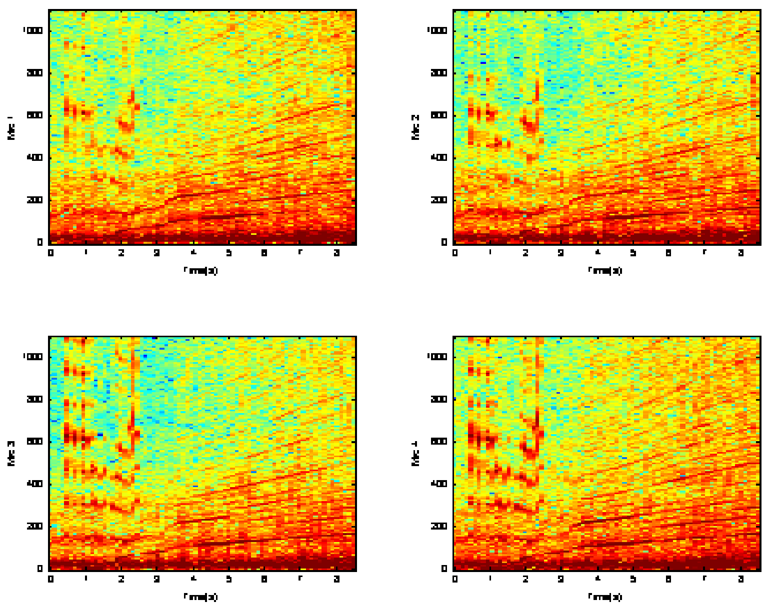


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Figure 10.8. Time Graph

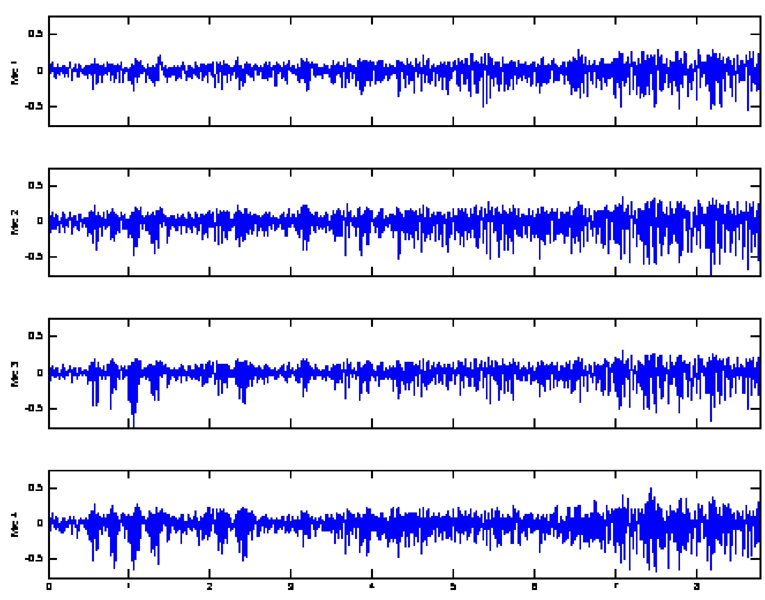

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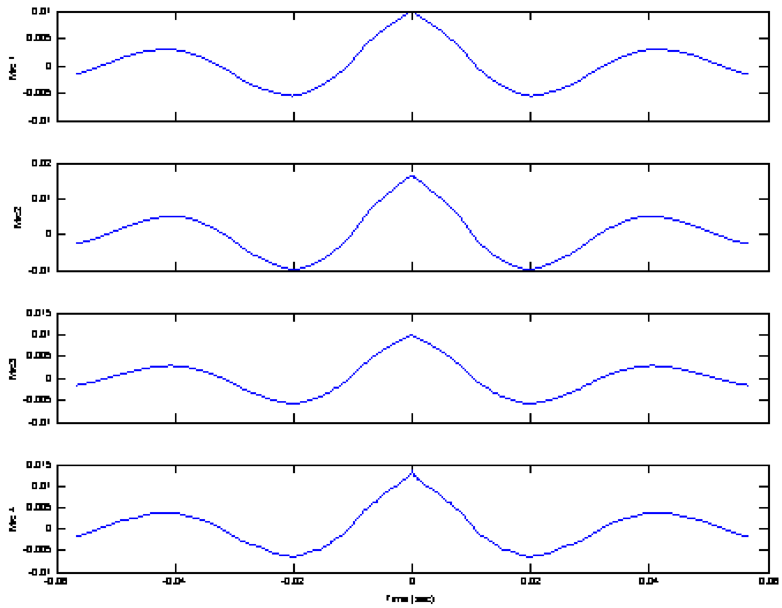
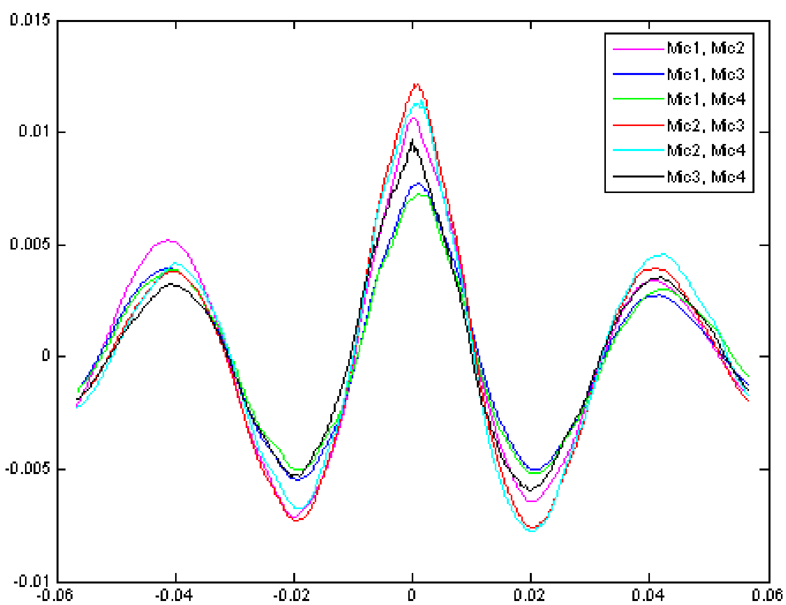
Figure 10.9. Autocorrelation Graph



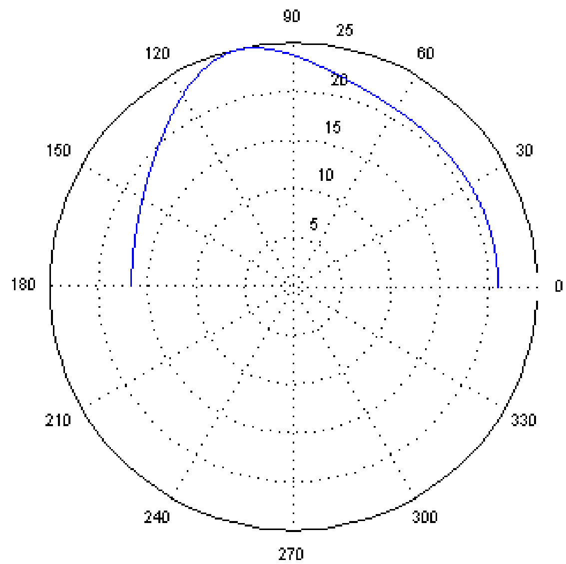
Crosscorrelation

Figure 10.10. CrossCorrelation



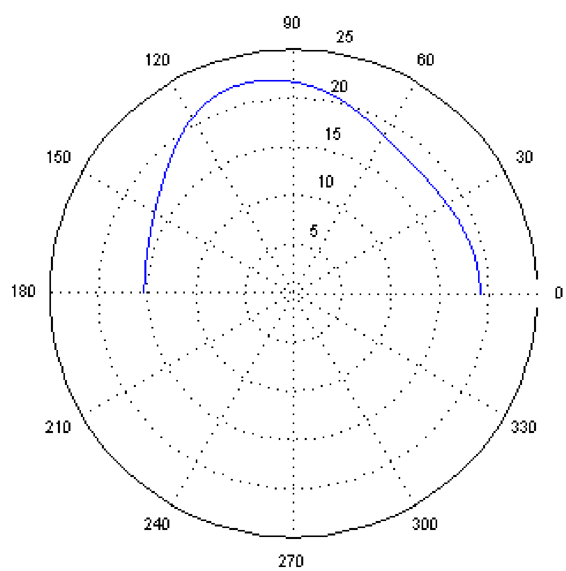
Direction of Arrival 200 Hz

Figure 10.11. DOA 200 Hz



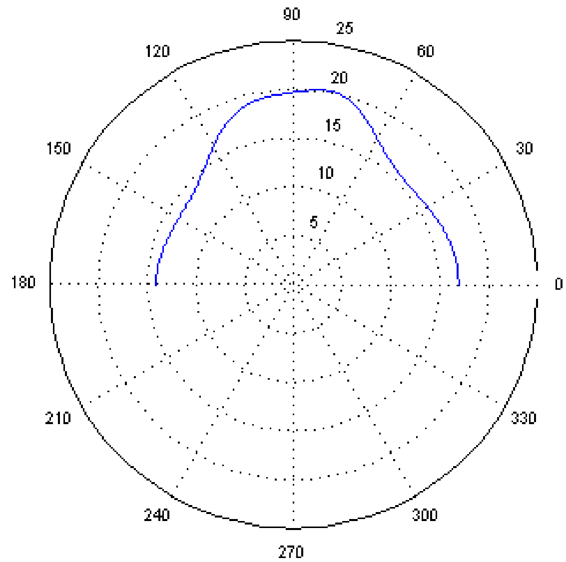
Direction of Arrival 300 Hz

Figure 10.12. DOA 300 Hz



Direction of Arrival 400 Hz

Figure 10.13. DOA 400 Hz



Chapter 11. Definition of Plots

Time Domain Plot. The time domain plot represents the data recorded by the microphone in the time domain.

Power Spectral Density. Power spectral density (PSD) is a useful analysis tool to use when examining signals. This tool shows the power at each frequency. In this report, Welch's method is used to find the PSD. The vertical axis gives the magnitude in W/Hz. The horizontal axis is frequency in Hz.

Autocorrelation. Autocorrelation is defined as A measure of the similarity between a signal and a time-shifted replica of itself; a special case of cross-correlation. If the length of the signal is enough to encompass several pitch periods of speech, the autocorrelation function will also show peaks at multiples of the pitch period. By identifying these peaks, the fundamental frequency can be determined. If there are no peaks, then it is known that there is an interval without speech.

Direction of Arrival. The direction of arrival (DOA) for a microphone takes into consideration several factors. In an array of microphones it is important to consider that the speed of sound travel is 340m/s. In this short time, the system takes 44.1K samples in a second. Direction of Arrival therefore takes into account direction as well as the associated time delay when examining an acoustical signal. The DOA examines a range of ? and plots based on power.

Spectrogram. A sound spectrogram, also known as a sonogram, is a visual representation of an acoustic signal. In the spectrogram itself, the vertical axis represents frequency. All of the spectra computed by the Fourier transform are displayed parallel to this vertical, or y-axis. The horizontal axis represents time. A color scale is used to display the magnitudes.

Power vs. Time. Similar to the power sepctral density graph, this graph sums up all the power at any given time. This graph is independent of frequency.

Appendix C—1992 Buick Regal April 5, 2005

Bose Corporation/WPI SpinLab Report Generator

13-Apr-2005 00:03:07

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Chapter 1. General Information

Tester Names: Jeffrey Ford, George Roscoe, Joseph Vaughn

Location. Rt. 122 and Rt. 56, Paxton/Leicester MA

Weather: Sunny

Wind: 0-5 MPH

Road Conditions: Clear

Comments: Tests went well.

Chapter 2. Car Information

Vehicle: 1992 Buick Regal

Transmission: Automatic

Tires: Goodyear

Chapter 3. Test One: Car Idle

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Power Spectral Density (0 to 20 kHz)

Figure 3.1. Non-Normalized PSD 0-20kHz, Amplitude in dB

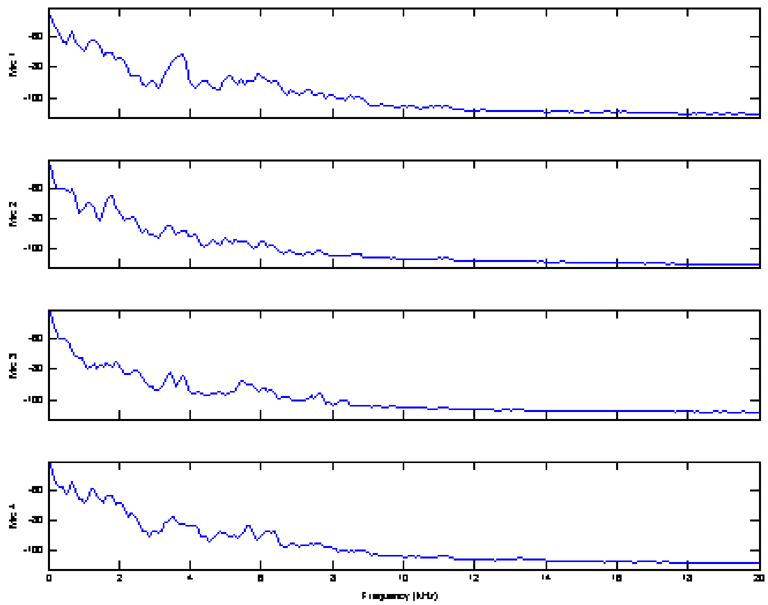
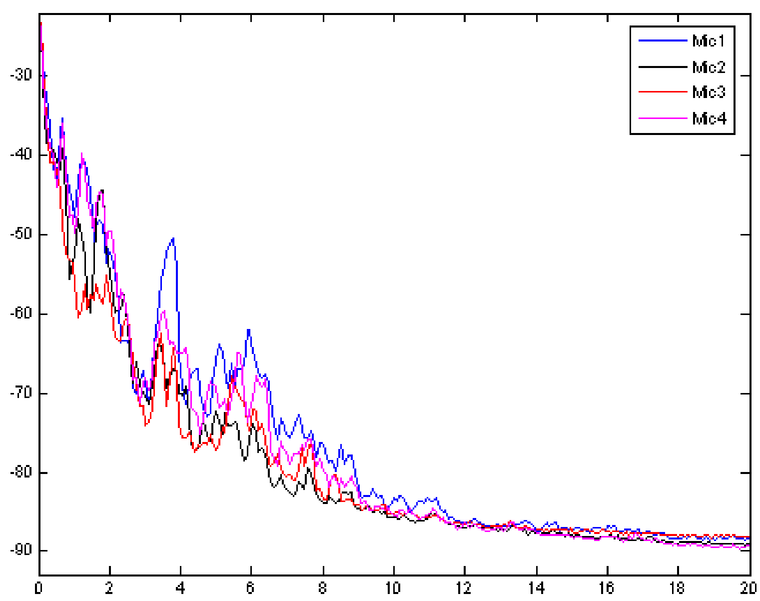
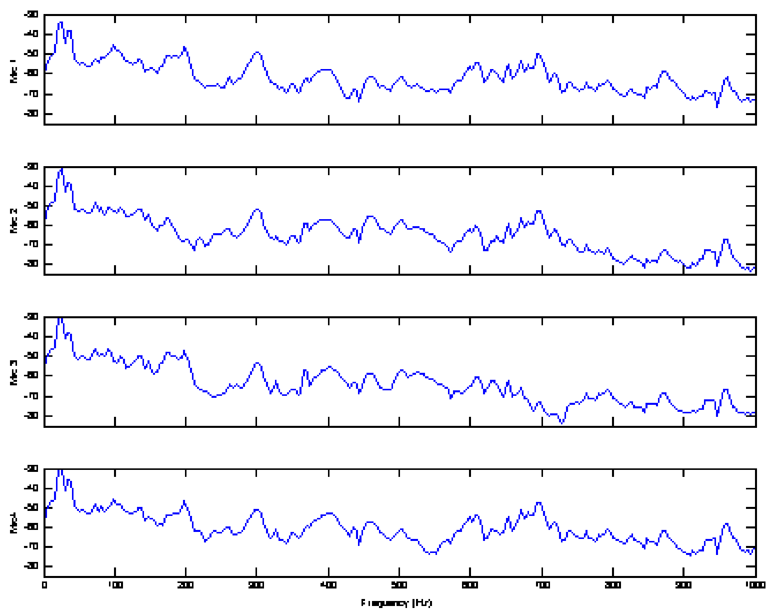


Figure 3.2. Normalized PSD 0-20kHz, Amplitude in dB



Power Spectral Density (0 to 1kHz)

Figure 3.3. Non-Normalized PSD 0-1kHz, Amplitude in dB



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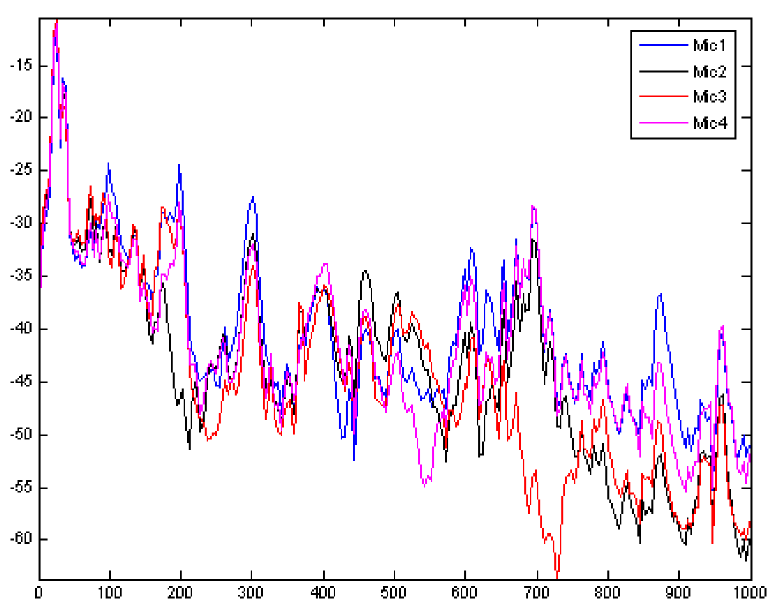
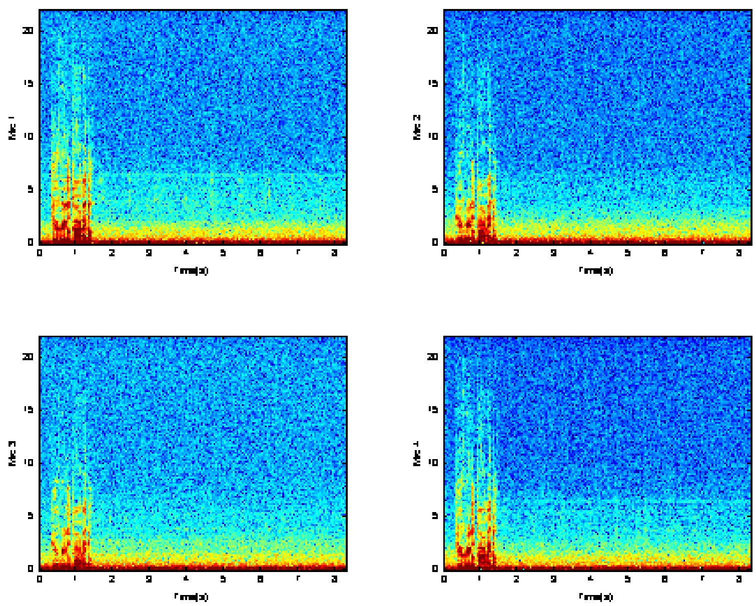


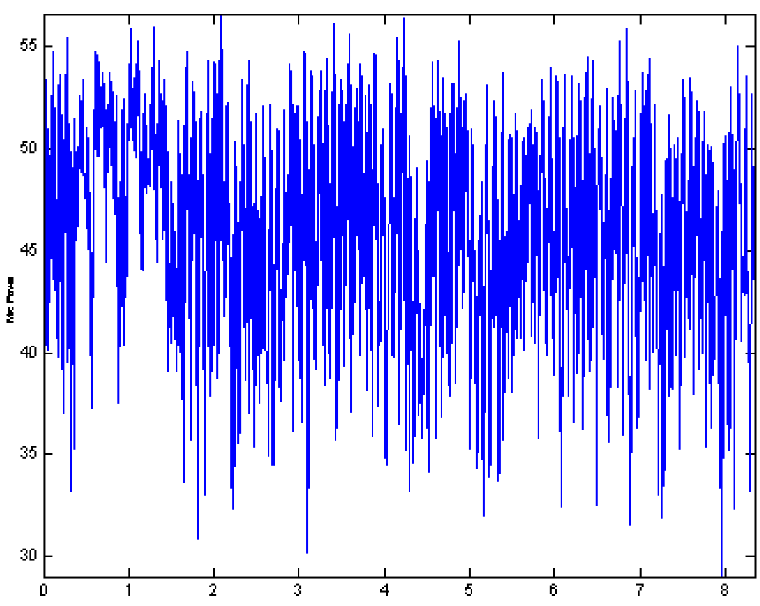
Spectrogram (0 to 20 kHz)

Figure 3.5. Spectrogram 0-20kHz, Frequency in kHz



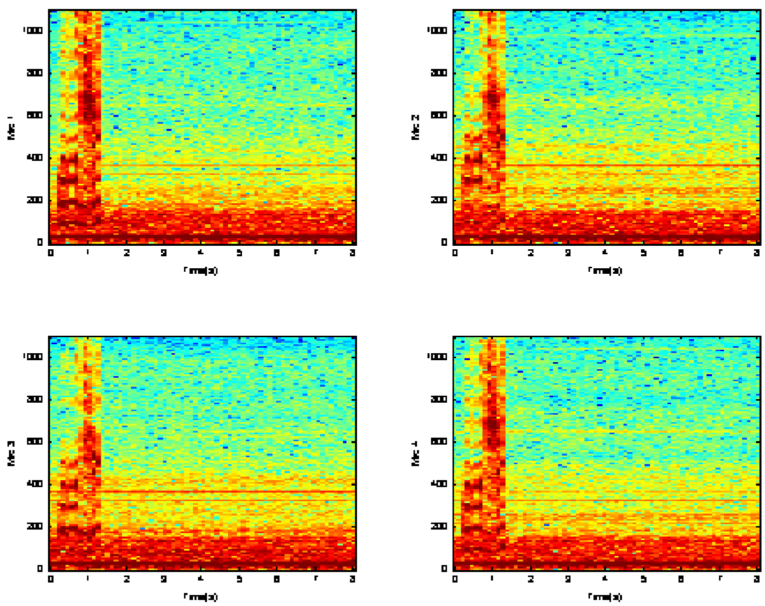
Power vs. Time

Figure 3.6. Power vs. Time, Amplitude in Normalized dB



Spectogram (0 to 1kHz)

Figure 3.7. Spectrogram 0-1kHz, Frequency in Hz



Time Plot

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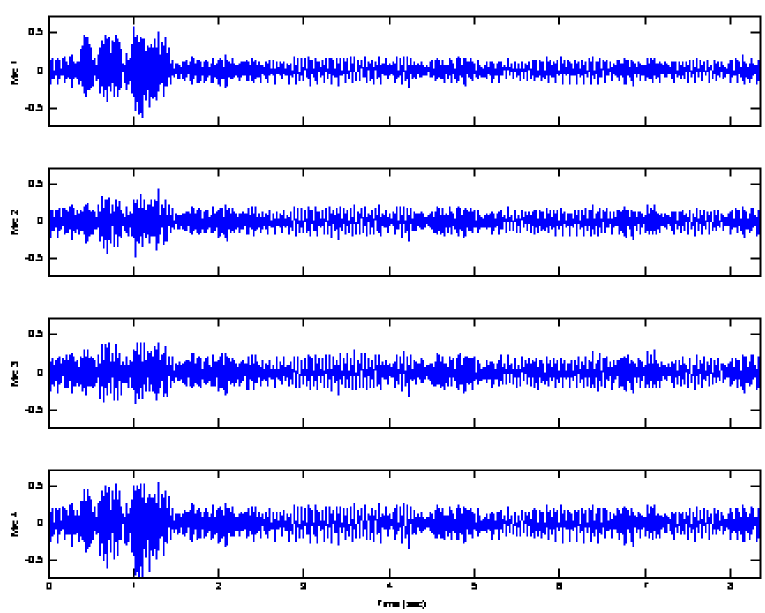
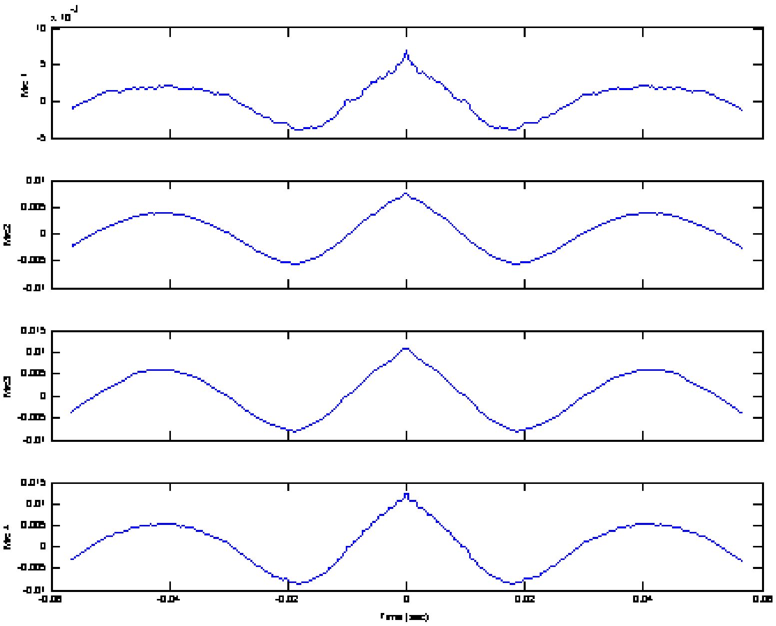


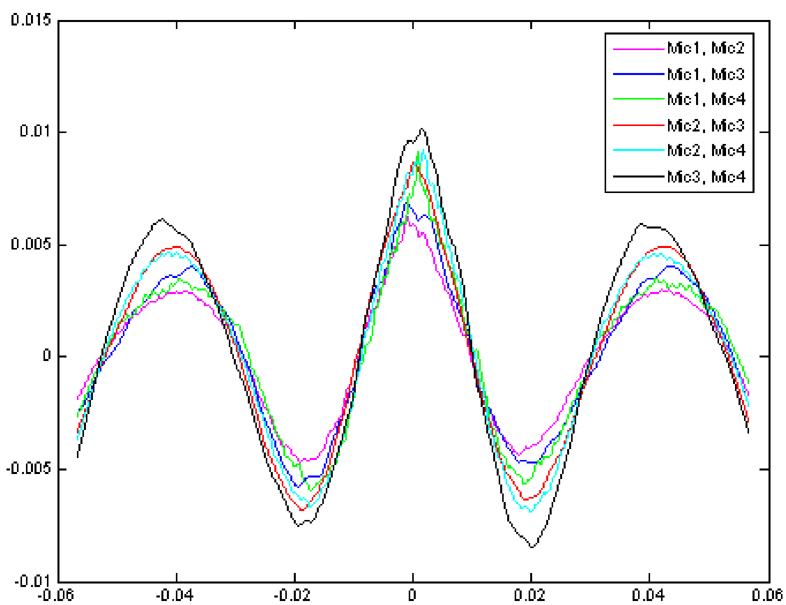
Autocorrelation

Figure 3.9. Autocorrelation Graph



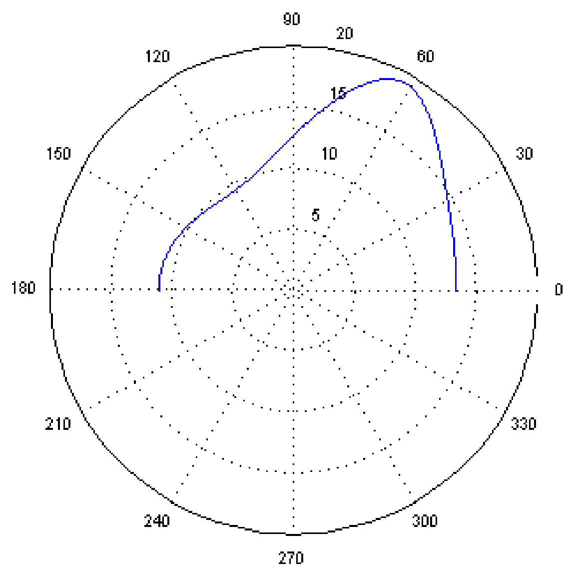
Crosscorrelation

Figure 3.10. CrossCorrelation



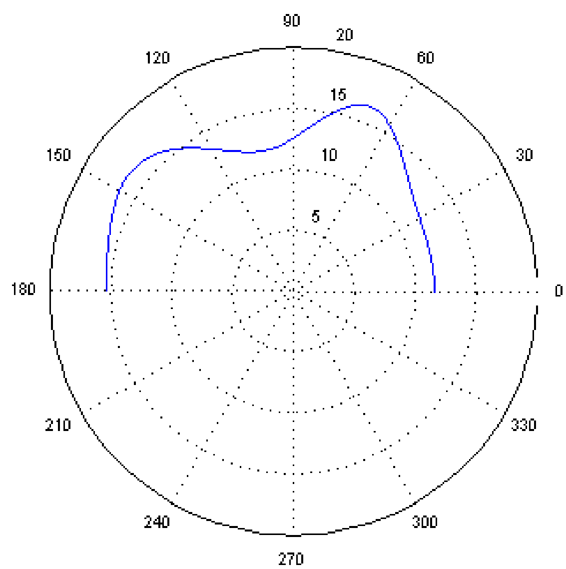
Direction of Arrival 200 Hz

Figure 3.11. DOA 200 Hz



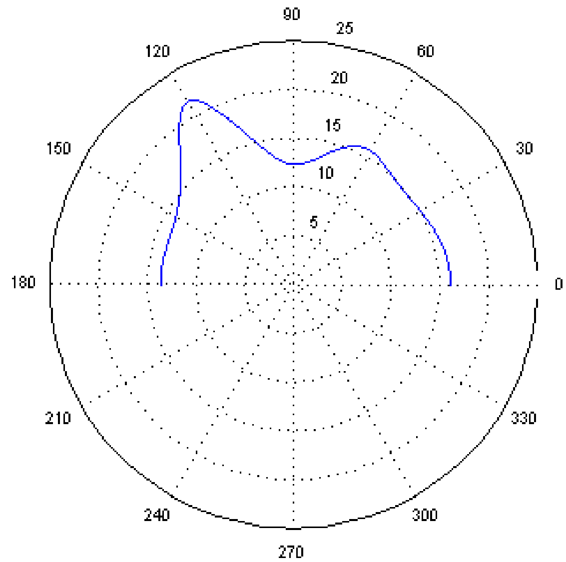
Direction of Arrival 300 Hz

Figure 3.12. DOA 300 Hz



Direction of Arrival 400 Hz

Figure 3.13. DOA 400 Hz



Chapter 4. Test Two: Idle 3000 RPM

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Play Idle 3000 RPM Mic 4.wav

Power Spectral Density (0 to 20 kHz)

Figure 4.1. Non-Normalized PSD 0-20kHz, Amplitude in dB

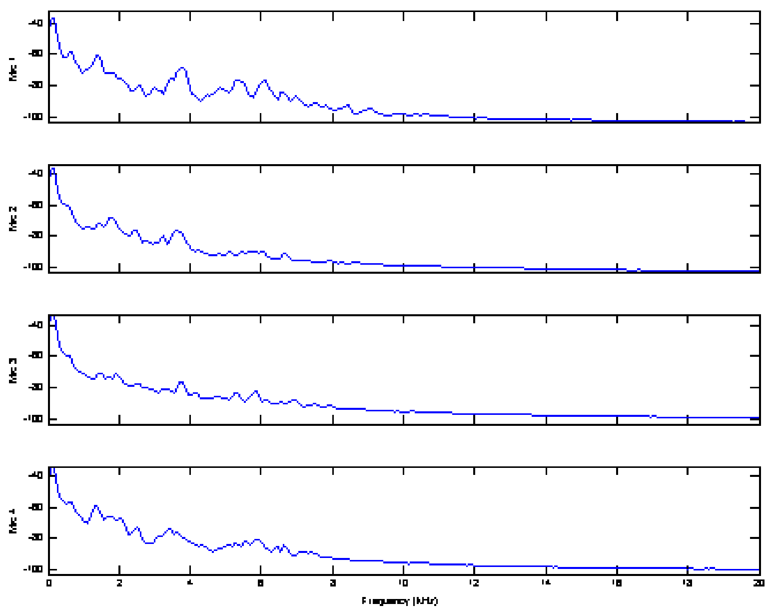
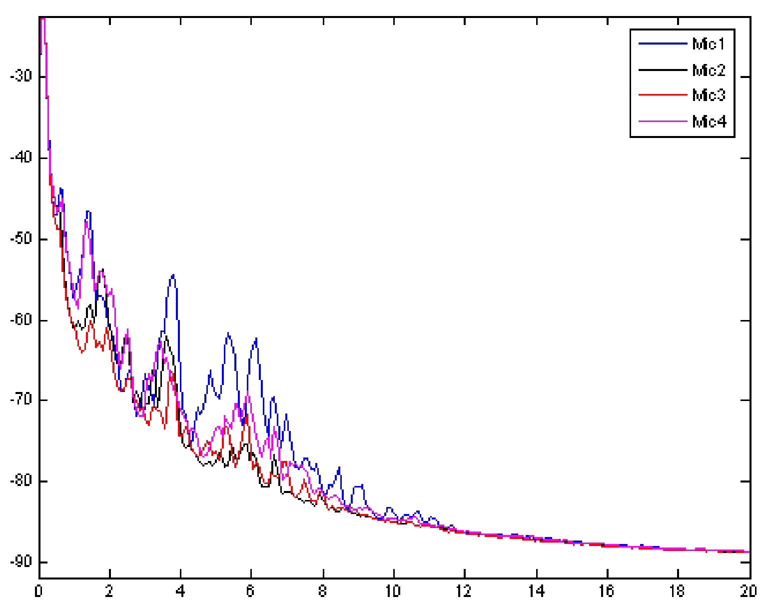


Figure 4.2. Normalized PSD 0-20kHz, Amplitude in dB



Power Spectral Density (0 to 1kHz)

Figure 4.3. Non-Normalized PSD 0-1kHz, Amplitude in dB

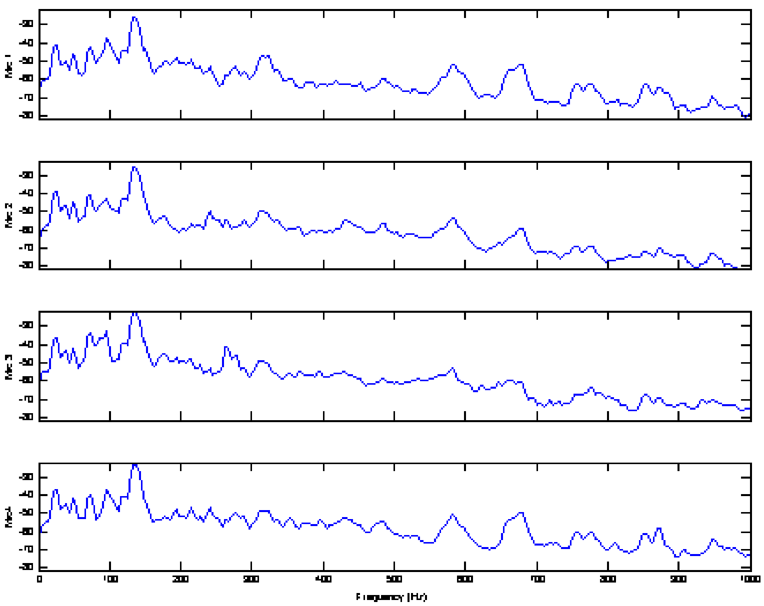
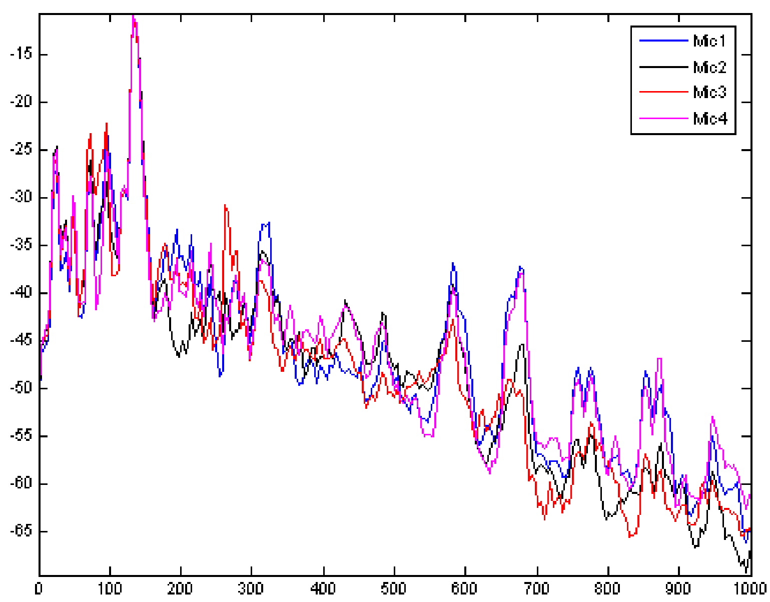
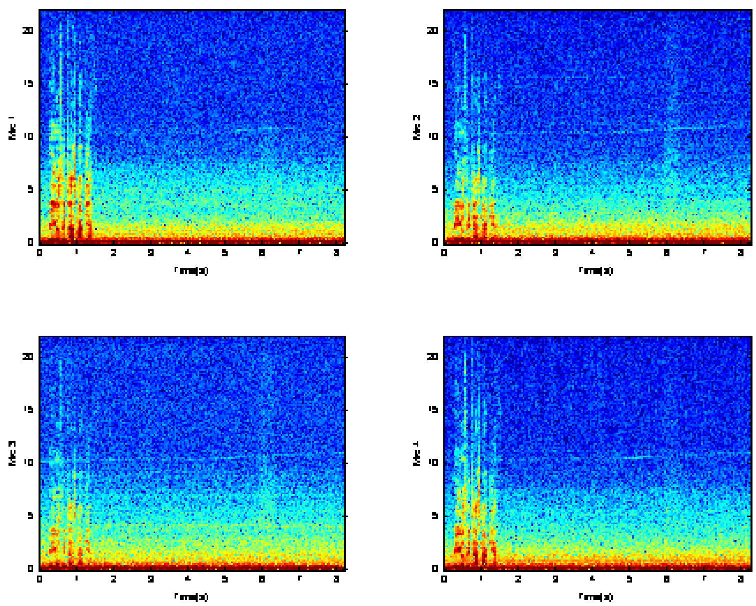


Figure 4.4. Normalized PSD 0-1kHz, Amplitude in dB



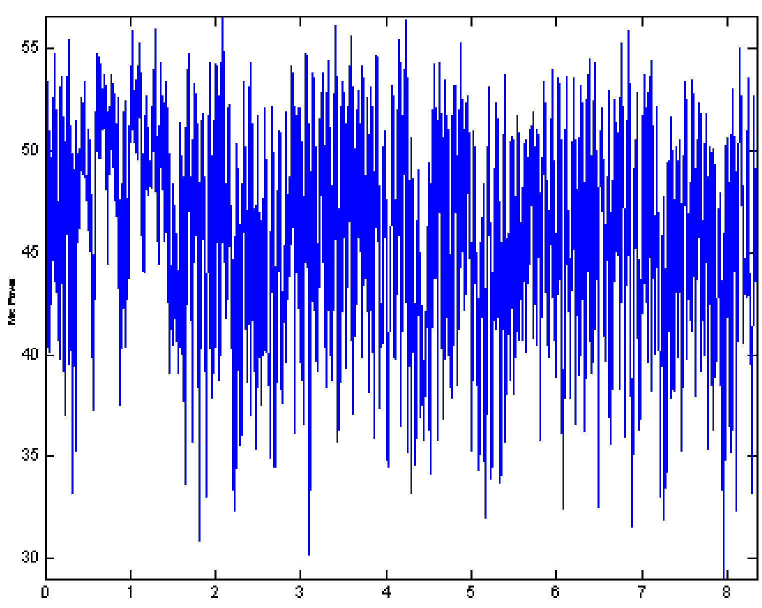
Spectrogram (0 to 20 kHz)

Figure 4.5. Spectrogram 0-20kHz, Frequency in kHz



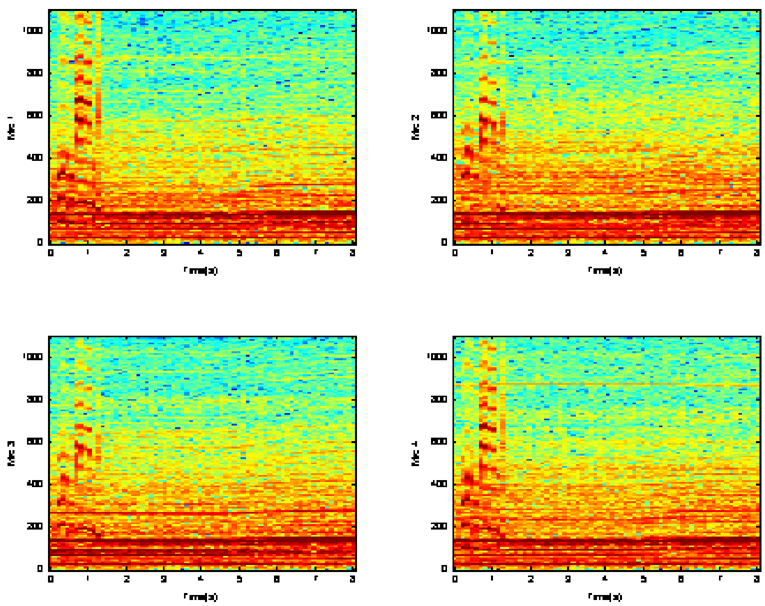
Power vs. Time

Figure 4.6. Power vs. Time, Amplitude in Normalized dB



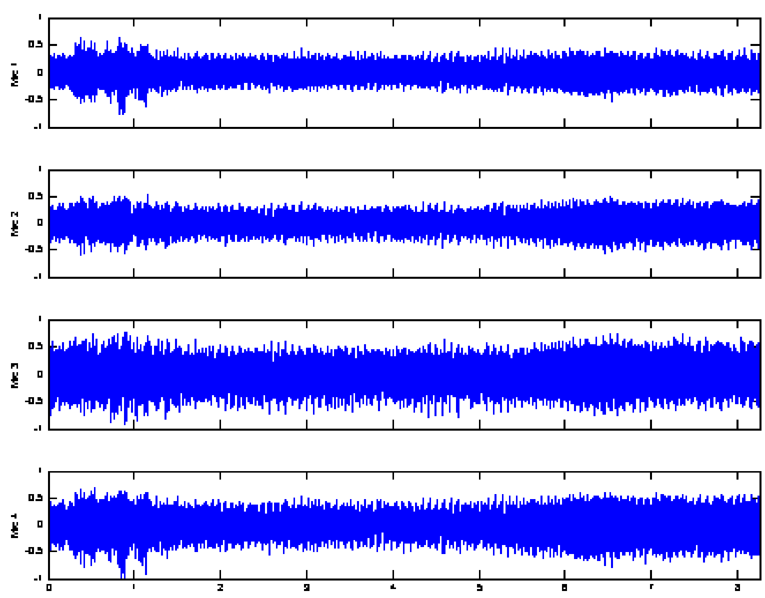
Spectogram (0 to 1kHz)

Figure 4.7. Spectrogram 0-1kHz, Frequency in Hz



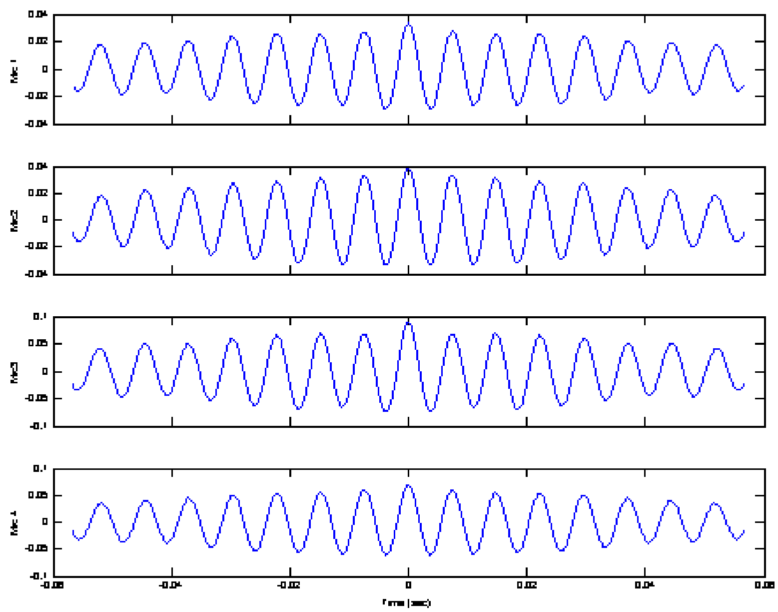
Time Plot

Figure 4.8. Time Graph



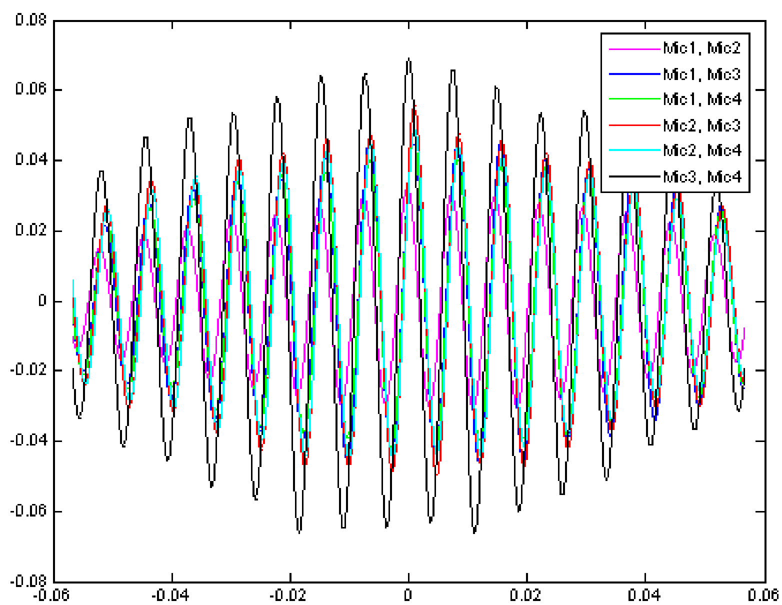
Autocorrelation

Figure 4.9. Autocorrelation Graph



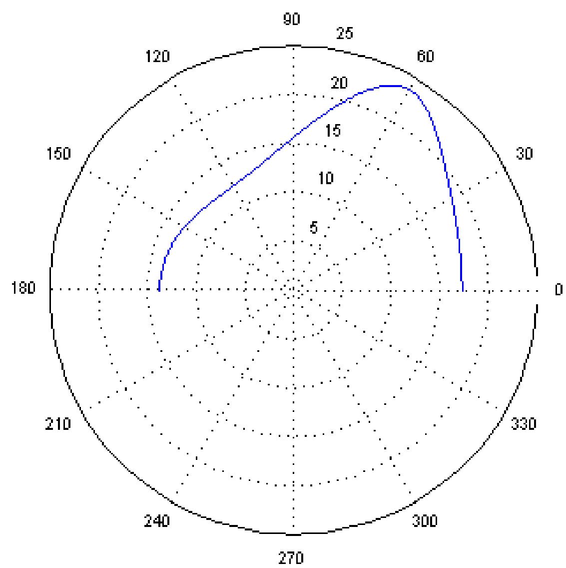
Crosscorrelation

Figure 4.10. CrossCorrelation



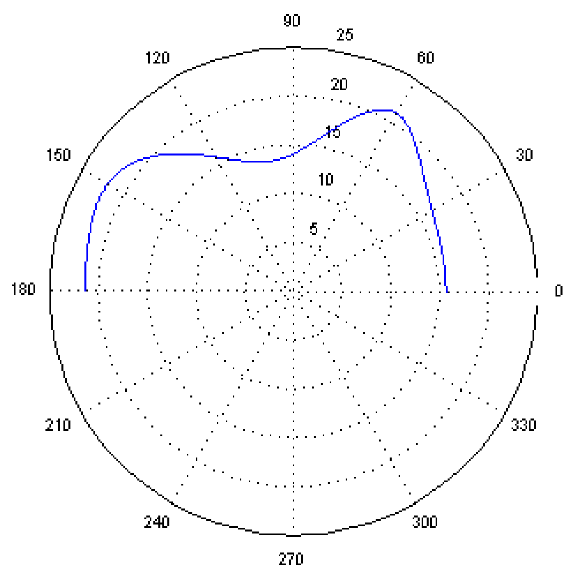
Direction of Arrival 200 Hz

Figure 4.11. DOA 200 Hz



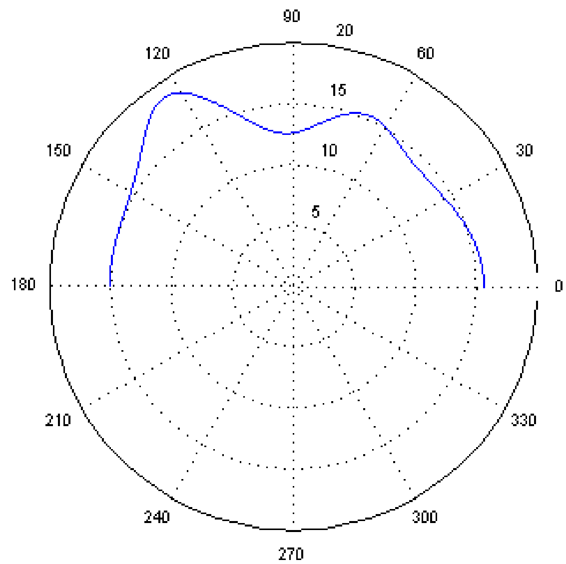
Direction of Arrival 300 Hz

Figure 4.12. DOA 300 Hz



Direction of Arrival 400 Hz

Figure 4.13. DOA 400 Hz



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Power Spectral Density (0 to 20 kHz)

Figure 5.1. Non-Normalized PSD 0-20kHz, Amplitude in dB

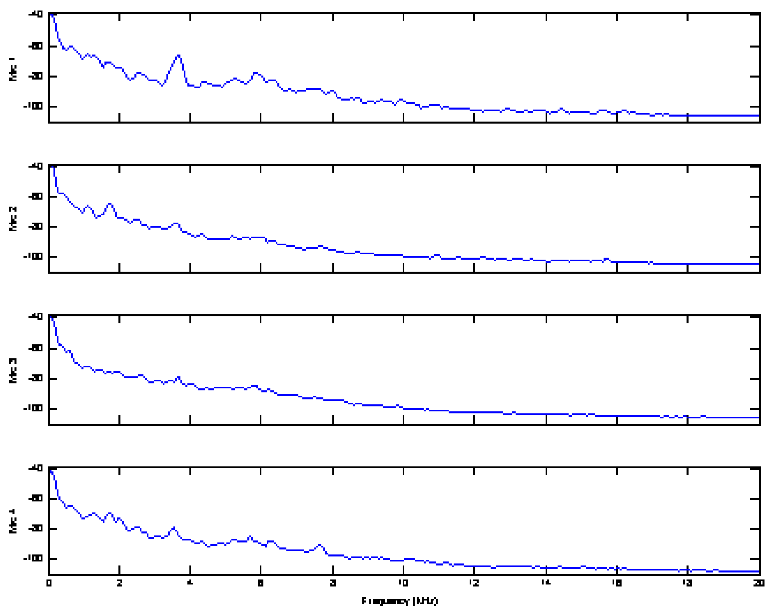
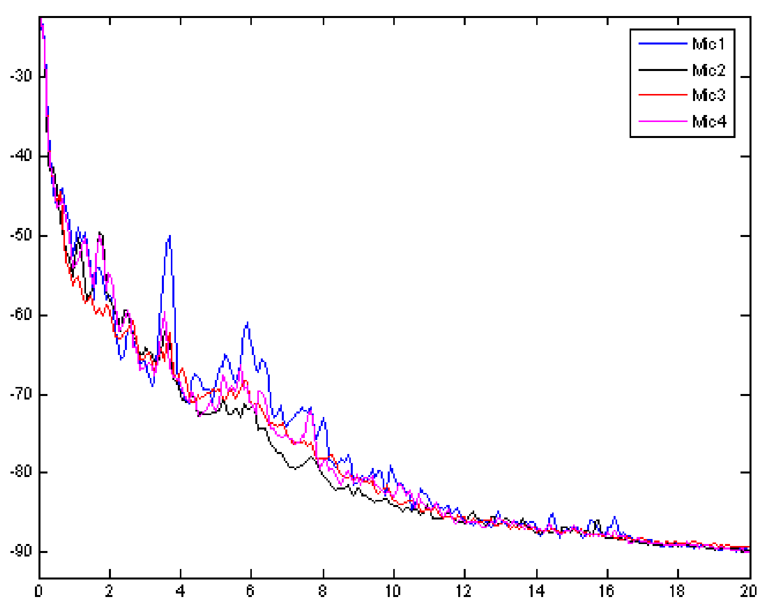


Figure 5.2. Normalized PSD 0-20kHz, Amplitude in dB



Power Spectral Density (0 to 1kHz)

Figure 5.3. Non-Normalized PSD 0-1kHz, Amplitude in dB

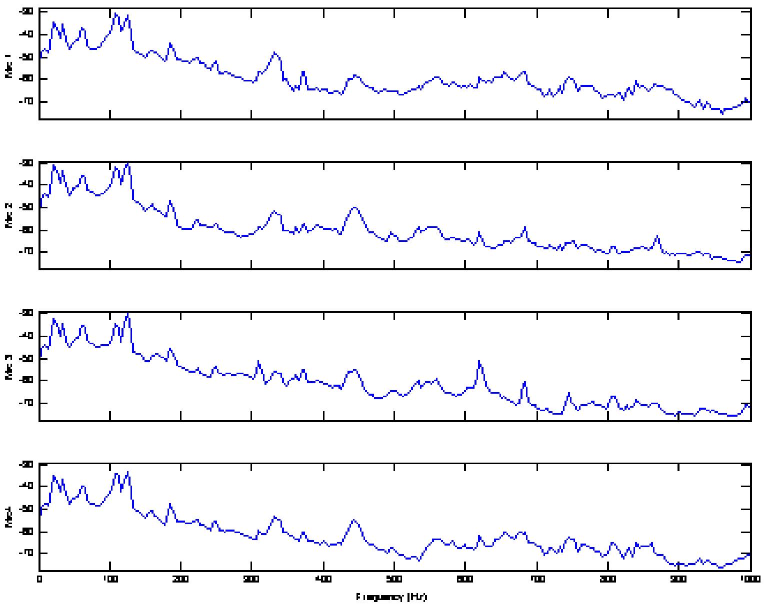
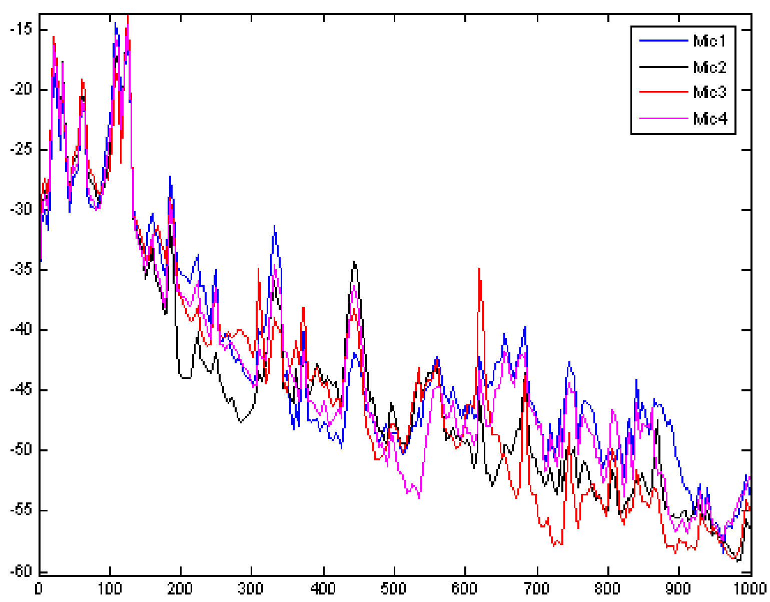
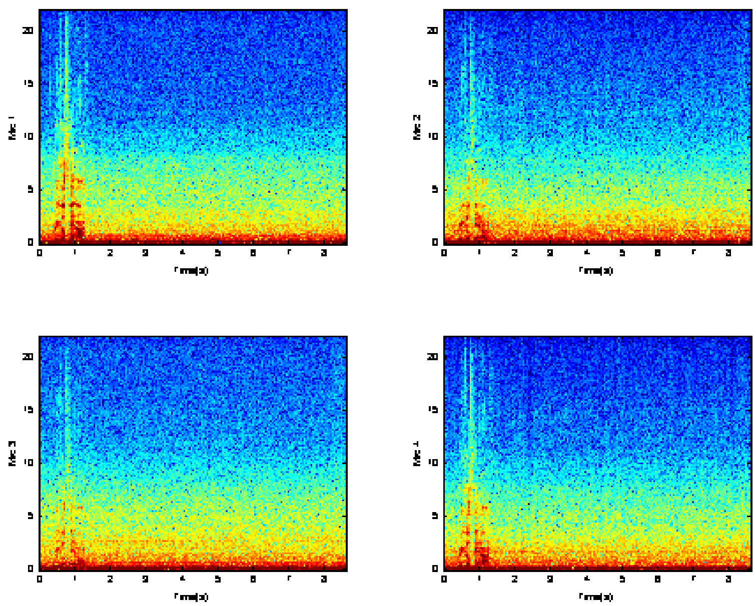


Figure 5.4. Normalized PSD 0-1kHz, Amplitude in dB



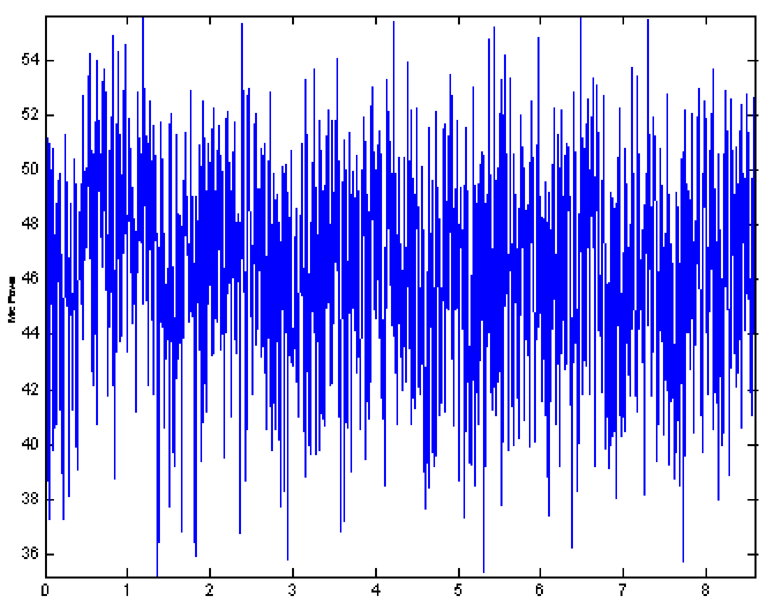
Spectrogram (0 to 20 kHz)

Figure 5.5. Spectrogram 0-20kHz, Frequency in kHz



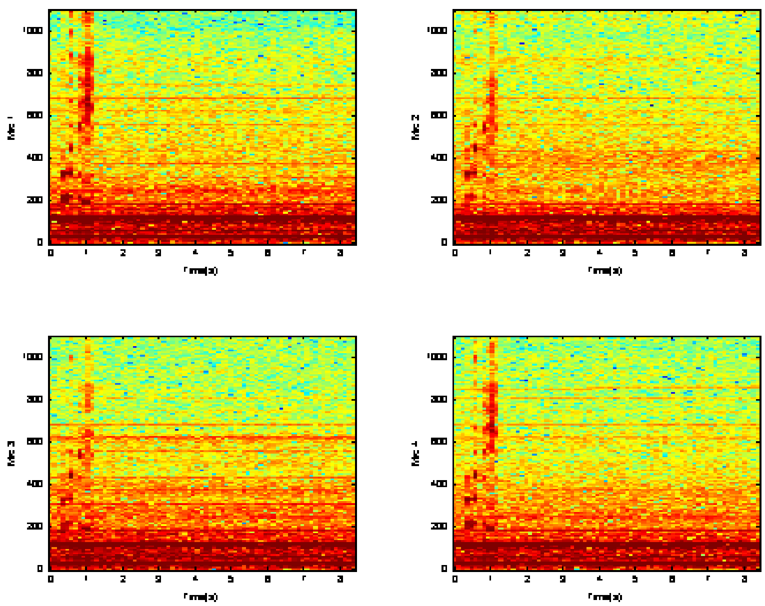
Power vs. Time

Figure 5.6. Power vs. Time, Amplitude in Normalized dB



Spectogram (0 to 1kHz)

Figure 5.7. Spectrogram 0-1kHz, Frequency in Hz



Time Plot

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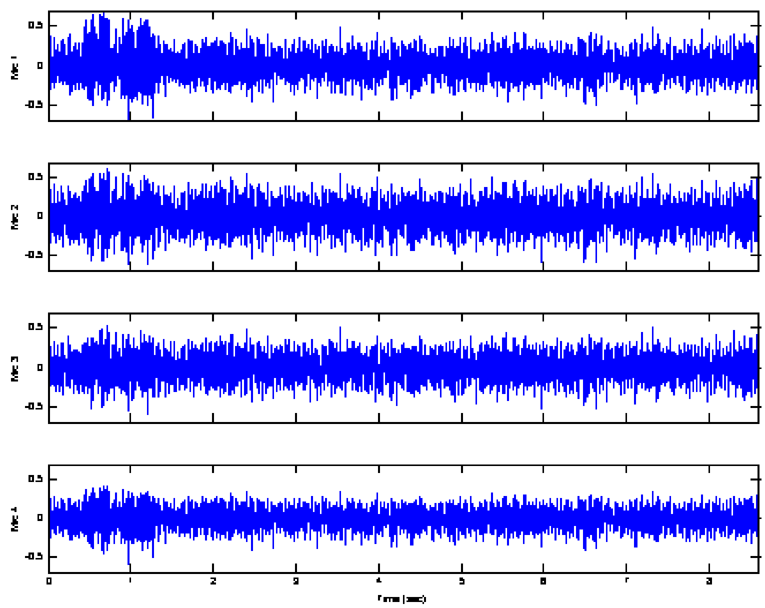
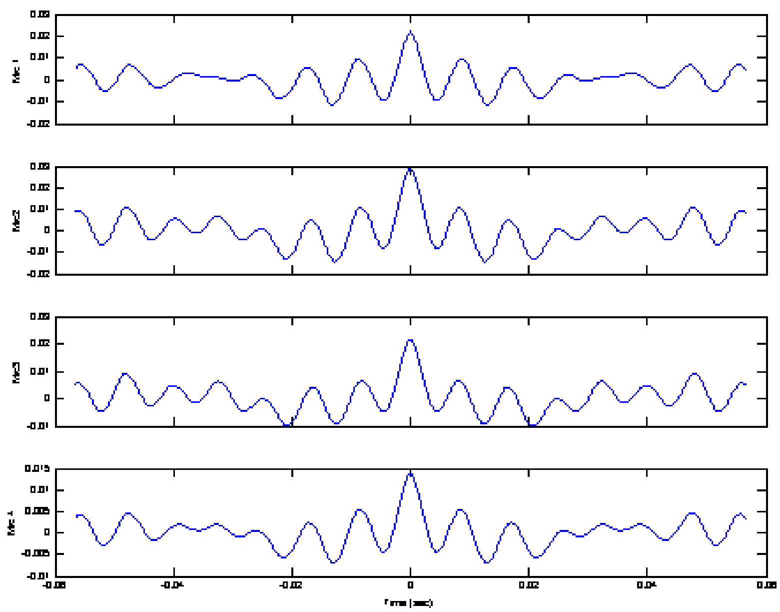


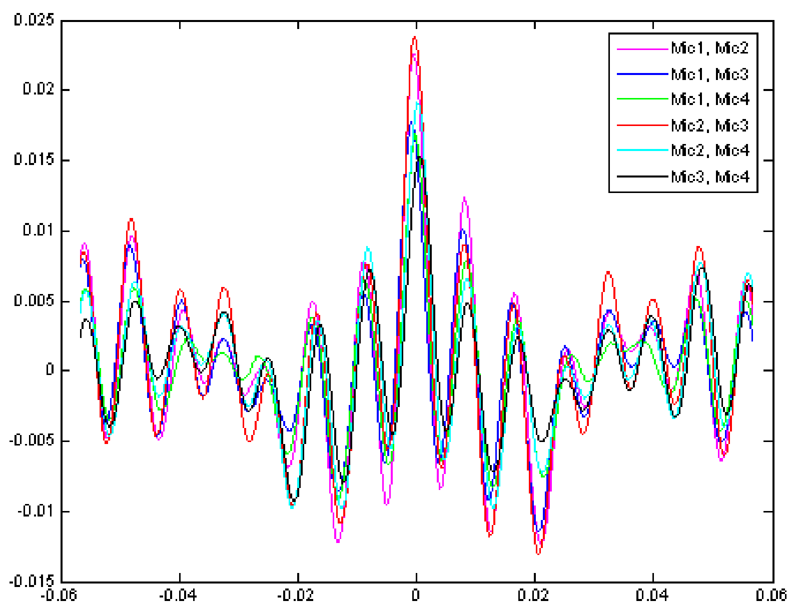
Autocorrelation

Figure 5.9. Autocorrelation Graph



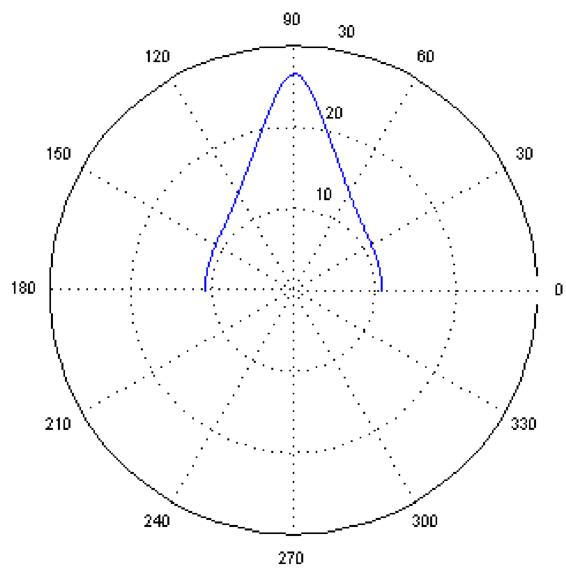
Crosscorrelation

Figure 5.10. CrossCorrelation



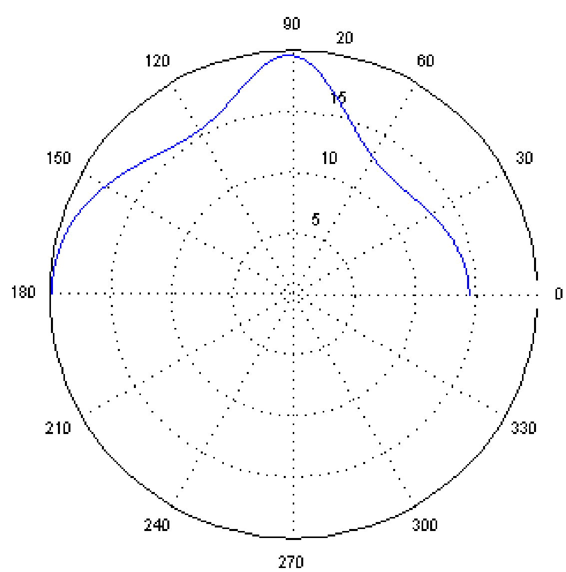
Direction of Arrival 200 Hz

Figure 5.11. DOA 200 Hz



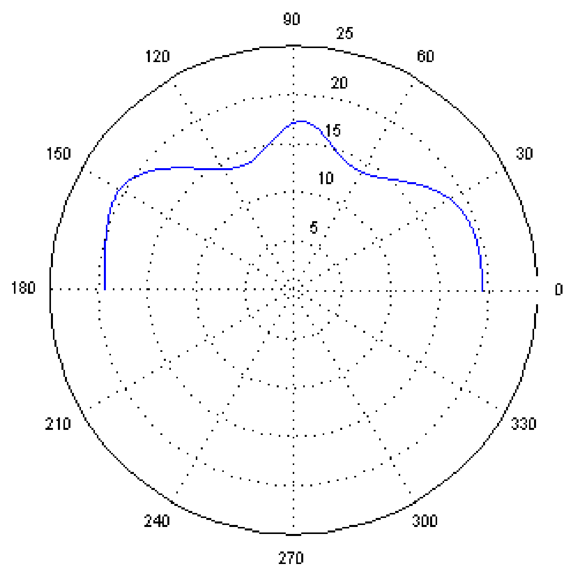
Direction of Arrival 300 Hz

Figure 5.12. DOA 300 Hz



Direction of Arrival 400 Hz

Figure 5.13. DOA 400 Hz



Chapter 6. Test Four: Driving 30 MPH

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Power Spectral Density (0 to 20 kHz)

Figure 6.1. Non-Normalized PSD 0-20kHz, Amplitude in dB

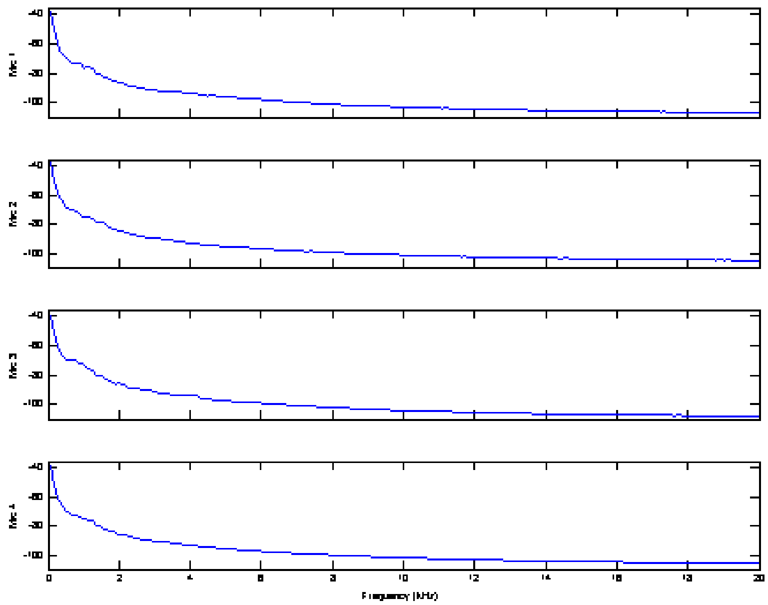
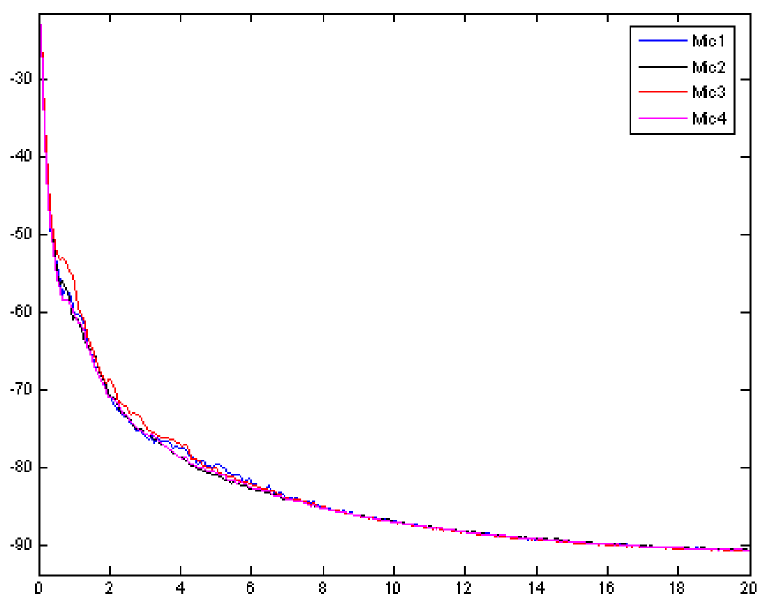


Figure 6.2. Normalized PSD 0-20kHz, Amplitude in dB



Power Spectral Density (0 to 1kHz)

Figure 6.3. Non-Normalized PSD 0-1kHz, Amplitude in dB

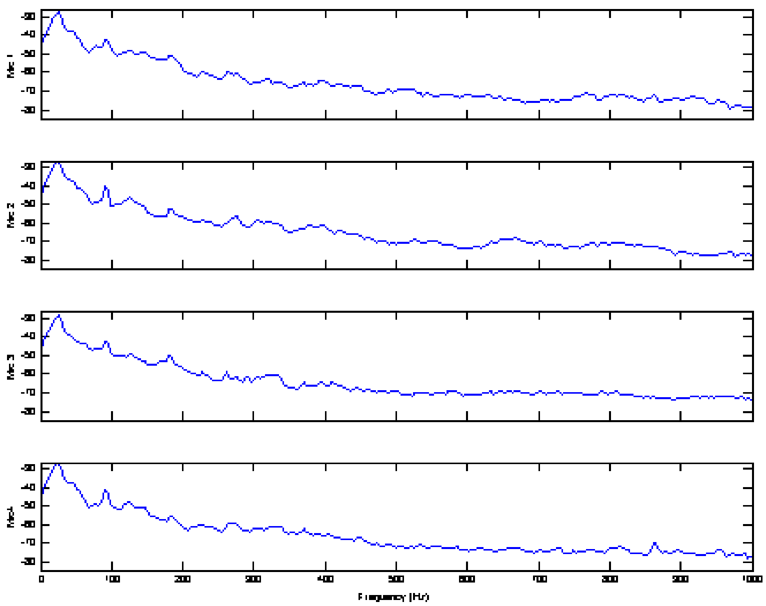
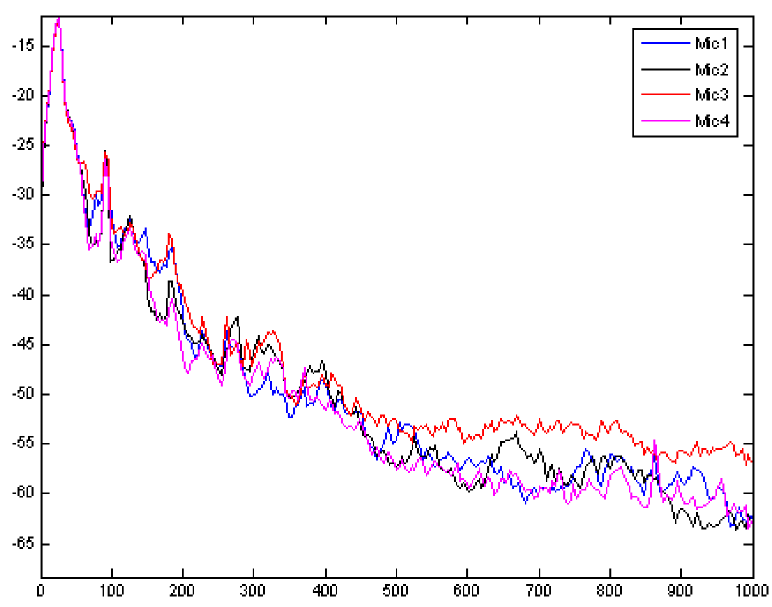
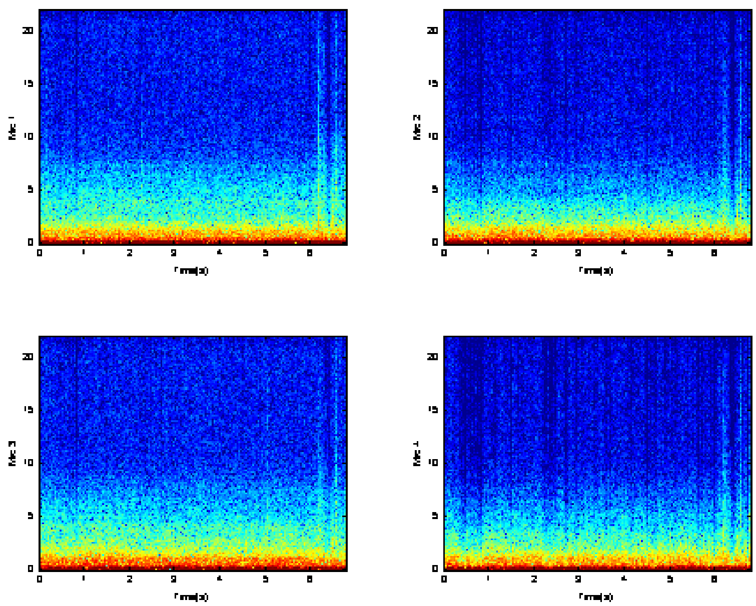


Figure 6.4. Normalized PSD 0-1kHz, Amplitude in dB



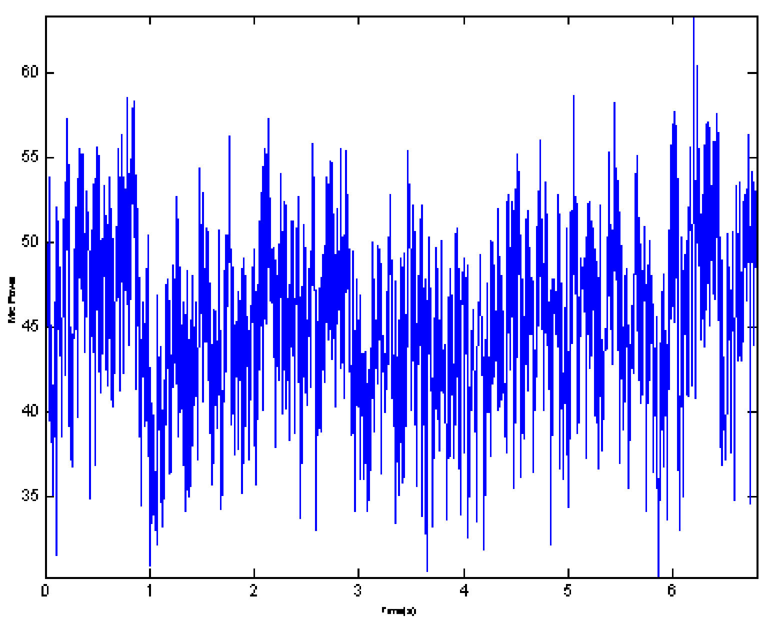
Spectrogram (0 to 20 kHz)

Figure 6.5. Spectrogram 0-20kHz, Frequency in kHz



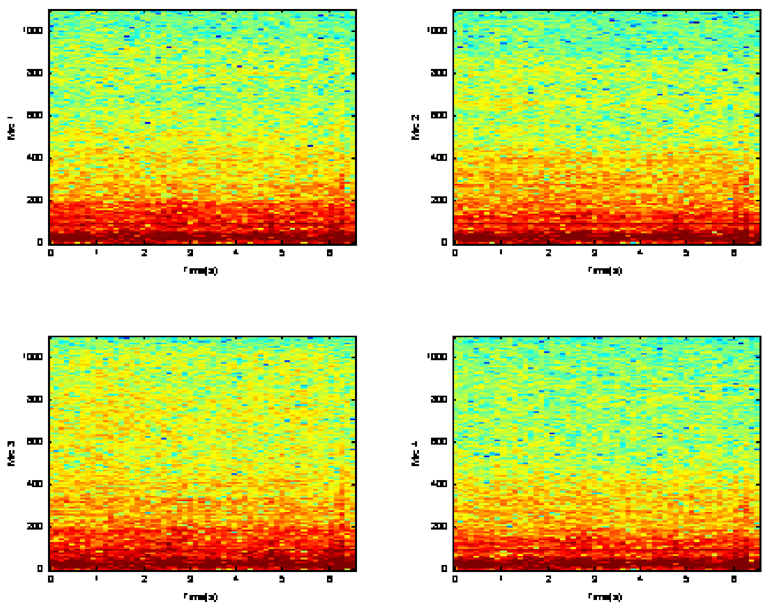
Power vs. Time

Figure 6.6. Power vs. Time, Amplitude in Normalized dB



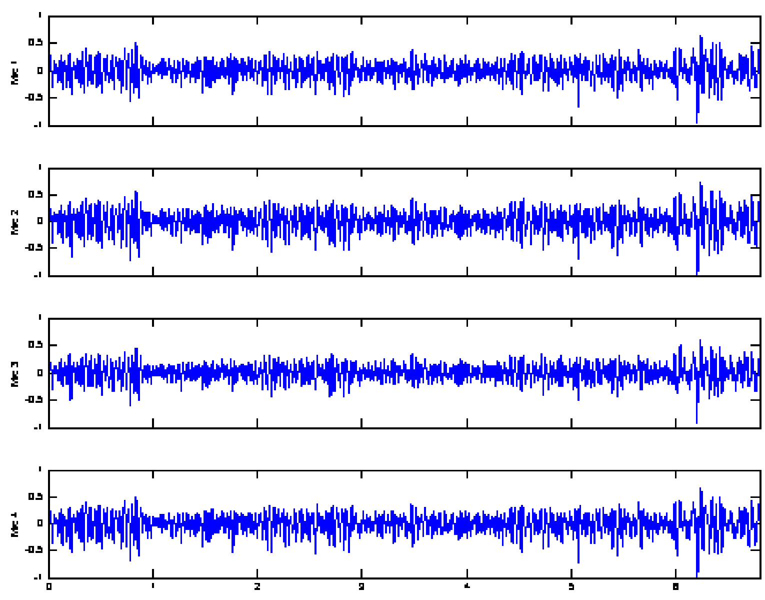
Spectogram (0 to 1kHz)

Figure 6.7. Spectrogram 0-1kHz, Frequency in Hz



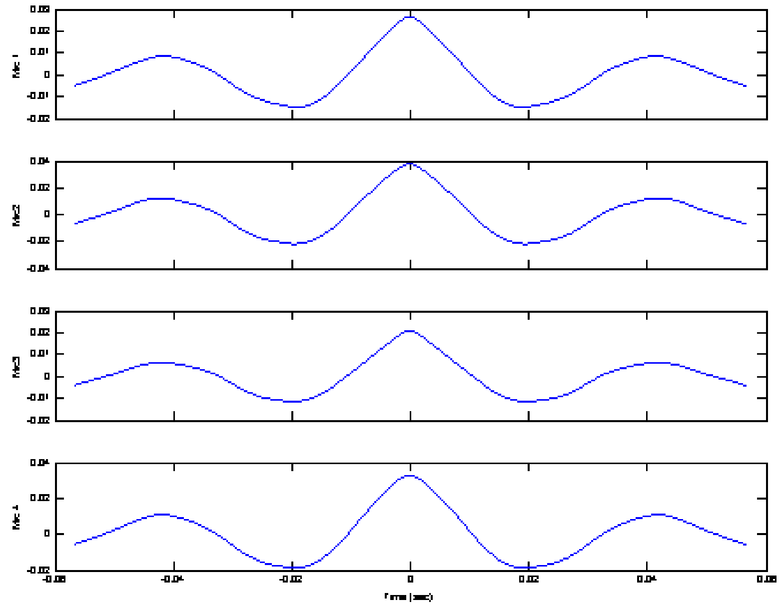
Time Plot

Figure 6.8. Time Graph



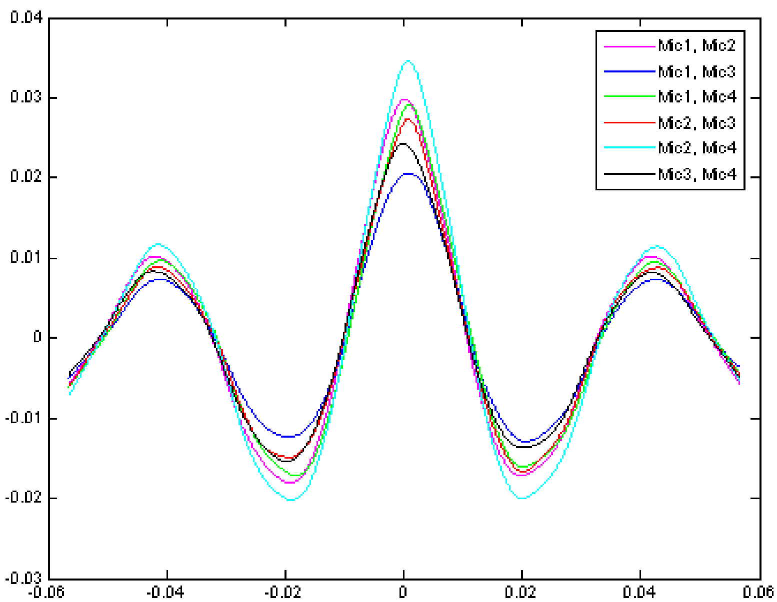
Autocorrelation

Figure 6.9. Autocorrelation Graph



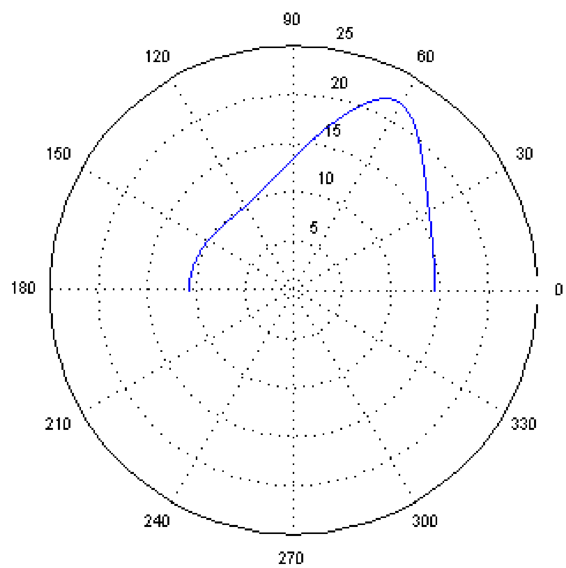
Crosscorrelation

Figure 6.10. CrossCorrelation



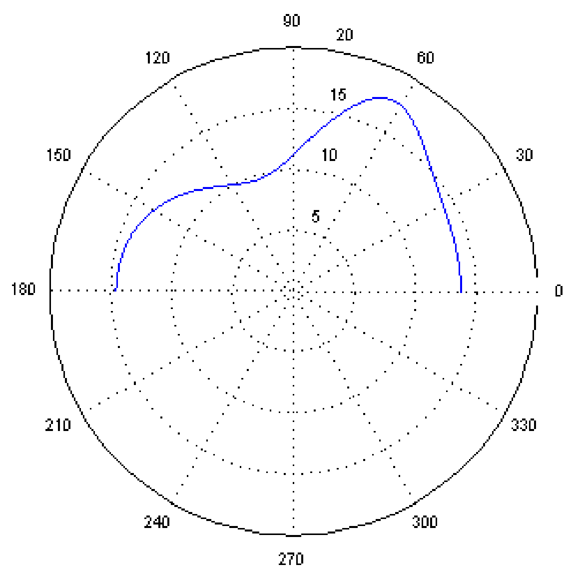
Direction of Arrival 200 Hz

Figure 6.11. DOA 200 Hz



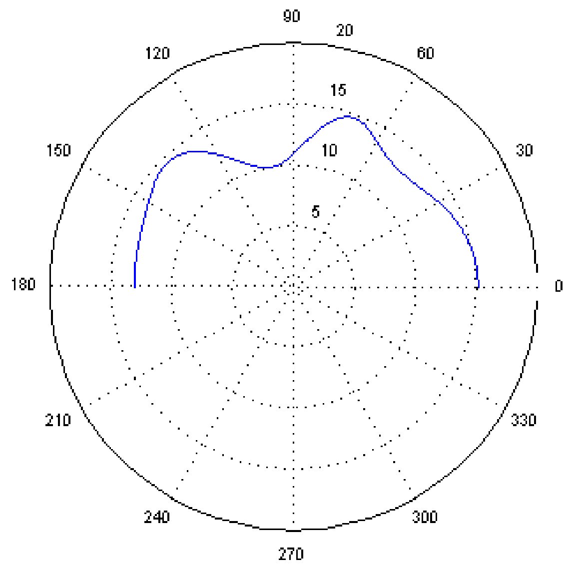
Direction of Arrival 300 Hz

Figure 6.12. DOA 300 Hz



Direction of Arrival 400 Hz

Figure 6.13. DOA 400 Hz



Chapter 7. Test Five: Driving 30 MPH, windows down

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Power Spectral Density (0 to 20 kHz)

Figure 7.1. Non-Normalized PSD 0-20kHz, Amplitude in dB

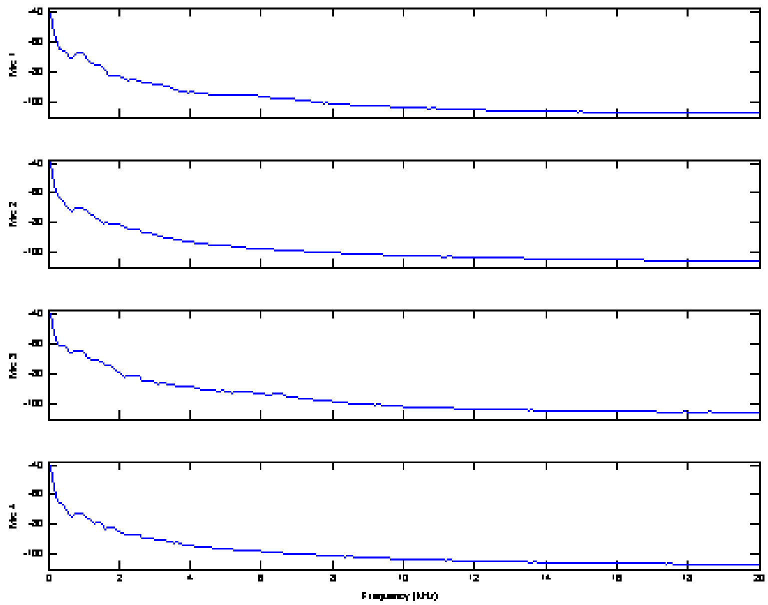
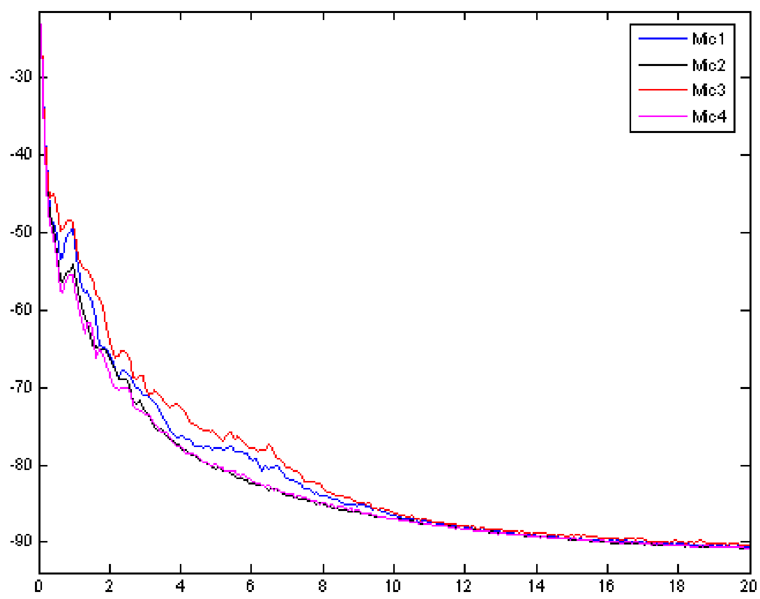


Figure 7.2. Normalized PSD 0-20kHz, Amplitude in dB



Power Spectral Density (0 to 1kHz)

Figure 7.3. Non-Normalized PSD 0-1kHz, Amplitude in dB

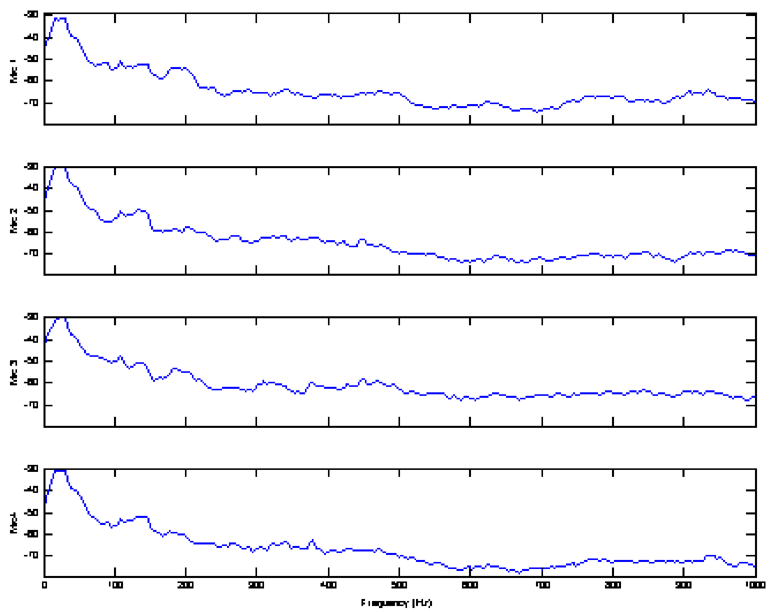
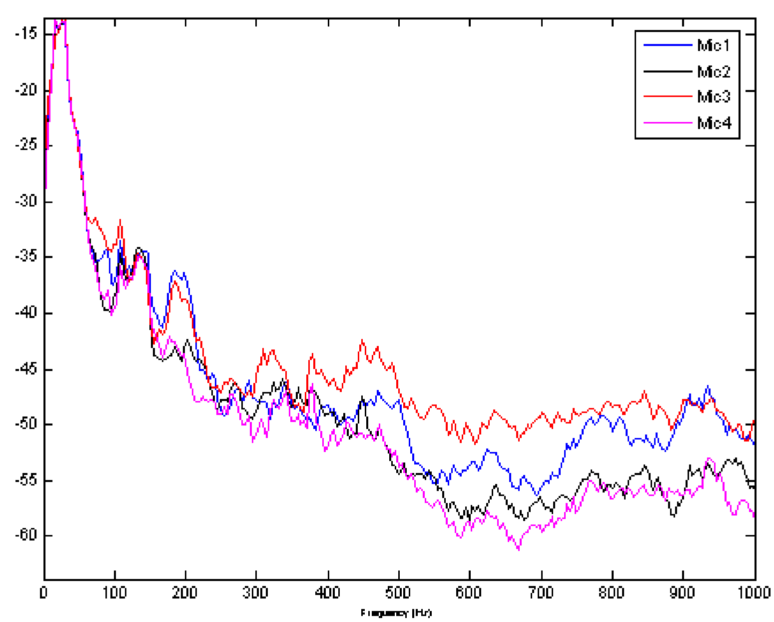
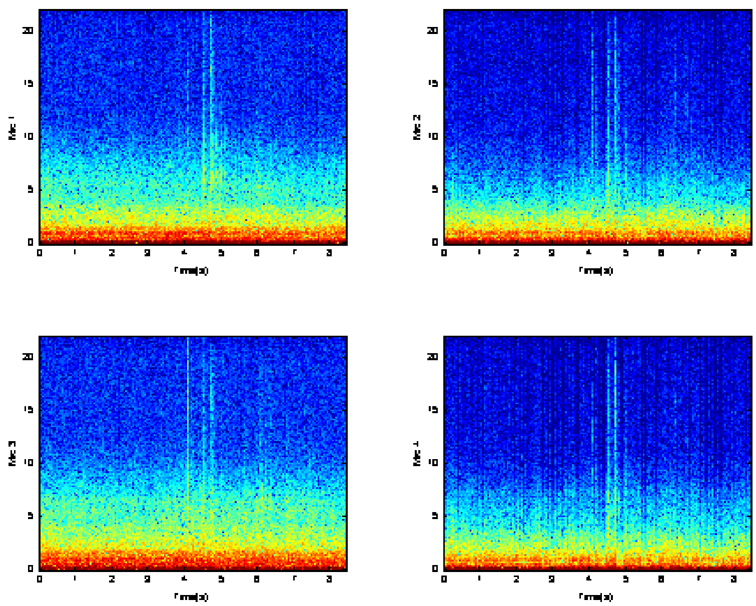


Figure 7.4. Normalized PSD 0-1kHz, Amplitude in dB



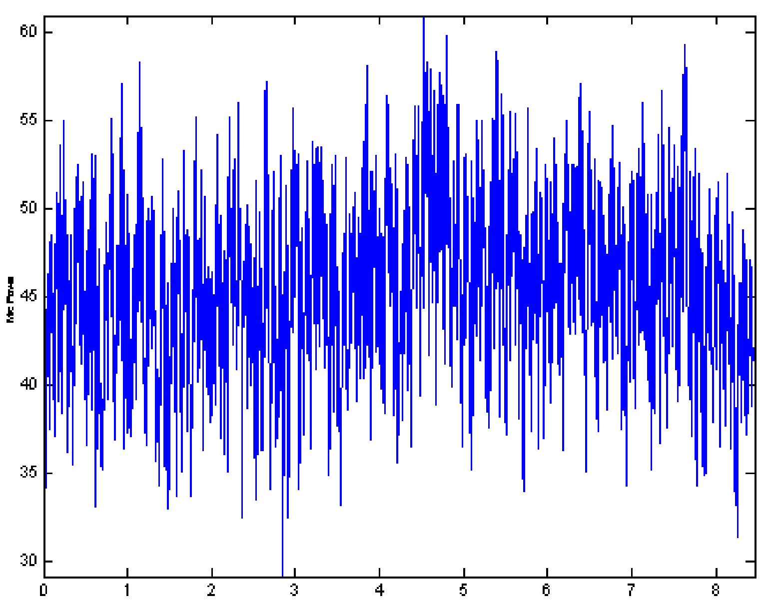
Spectrogram (0 to 20 kHz)

Figure 7.5. Spectrogram 0-20kHz, Frequency in kHz



Power vs. Time

Figure 7.6. Power vs. Time, Amplitude in Normalized dB



Spectogram (0 to 1kHz)

Figure 7.7. Spectrogram 0-1kHz, Frequency in Hz

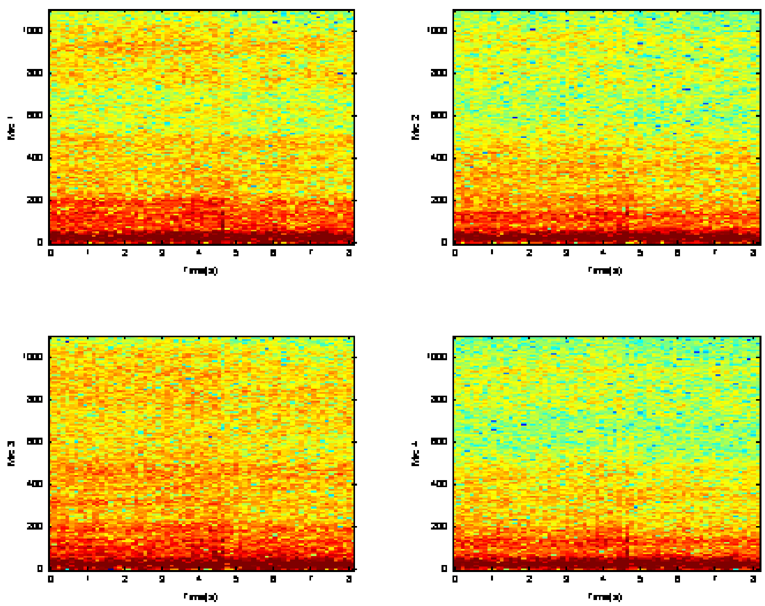


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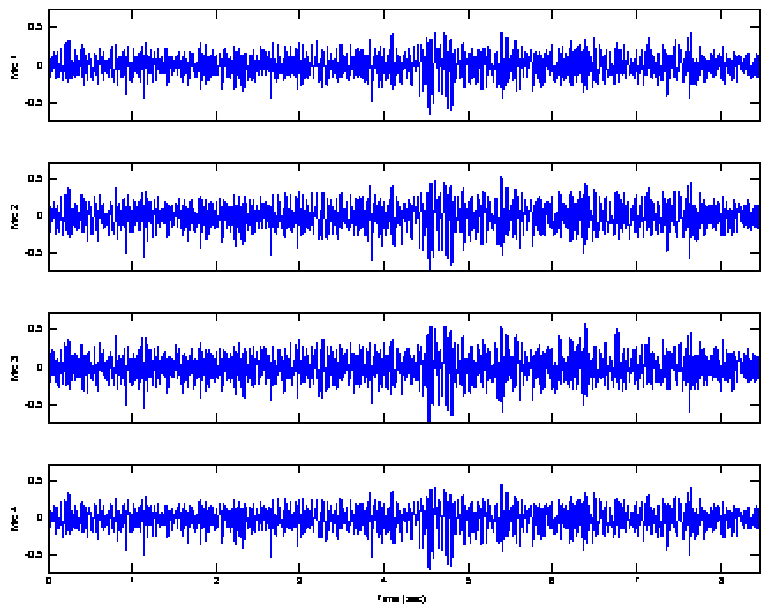
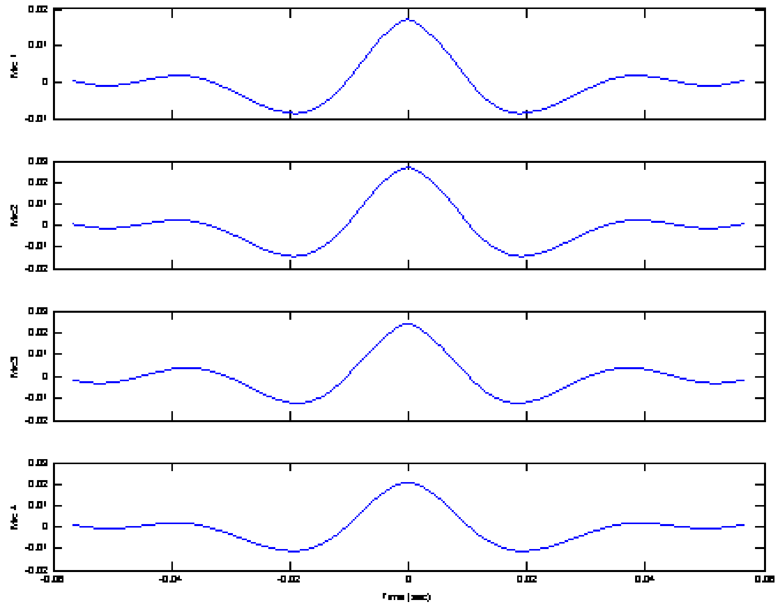
Figure 7.8. Time Graph



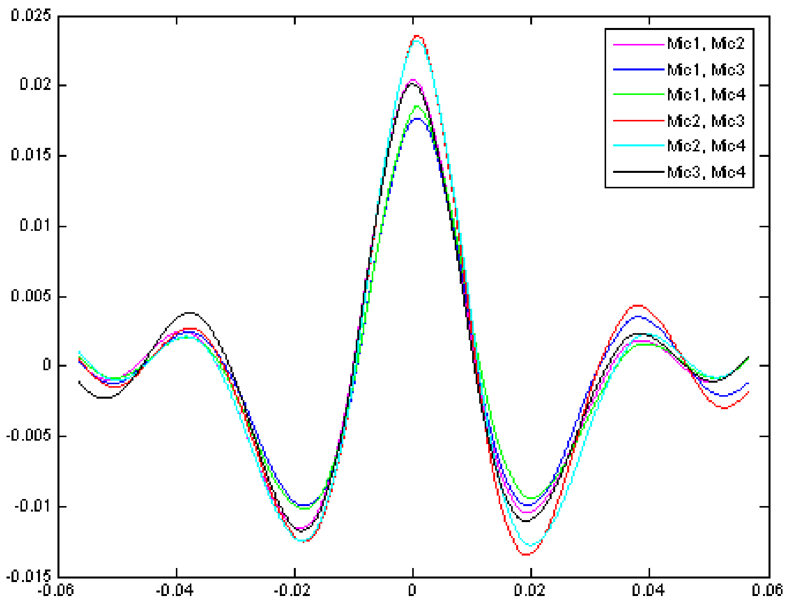
Autocorrelation

Figure 7.9. Autocorrelation Graph



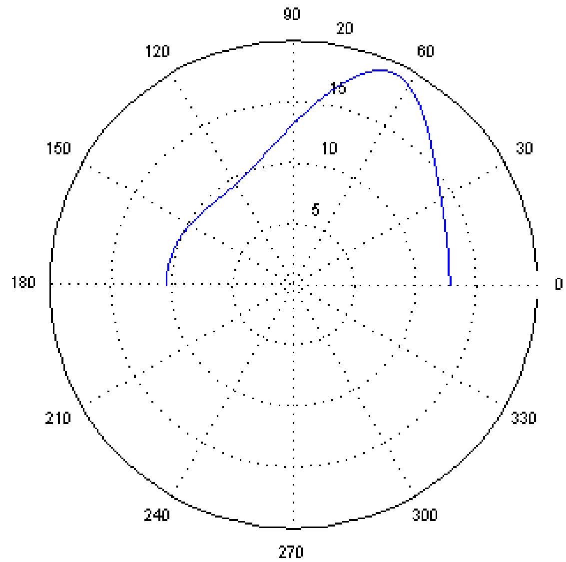
Crosscorrelation

Figure 7.10. CrossCorrelation



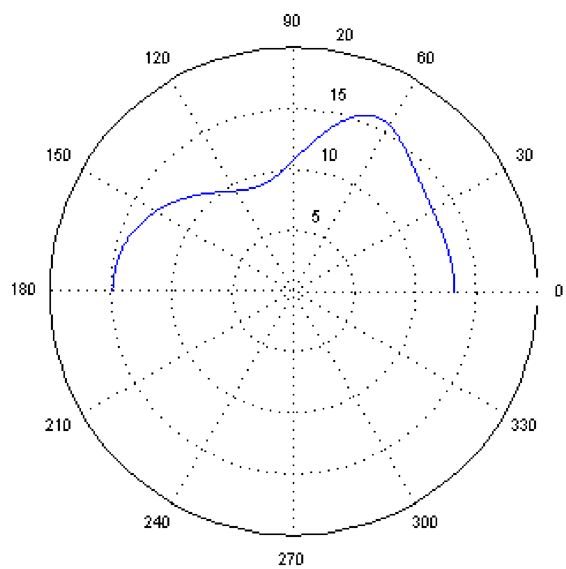
Direction of Arrival 200 Hz

Figure 7.11. DOA 200 Hz



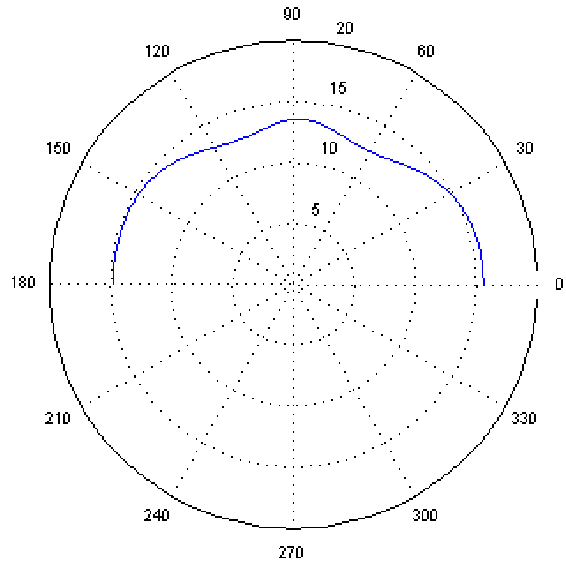
Direction of Arrival 300 Hz

Figure 7.12. DOA 300 Hz



Direction of Arrival 400 Hz

Figure 7.13. DOA 400 Hz



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Recording Four
Play Accelerating 30-50 MPH Mic 4.wav

Power Spectral Density (0 to 20 kHz)

Figure 8.1. Non-Normalized PSD 0-20kHz, Amplitude in dB

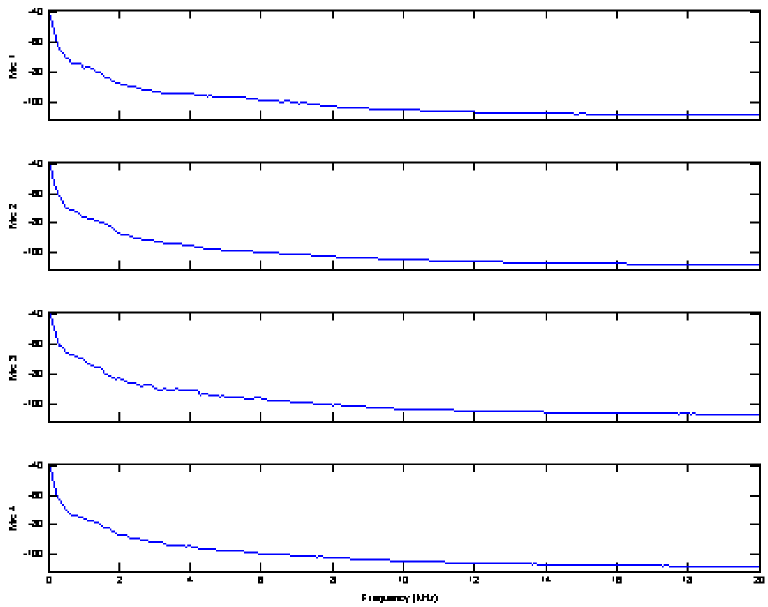
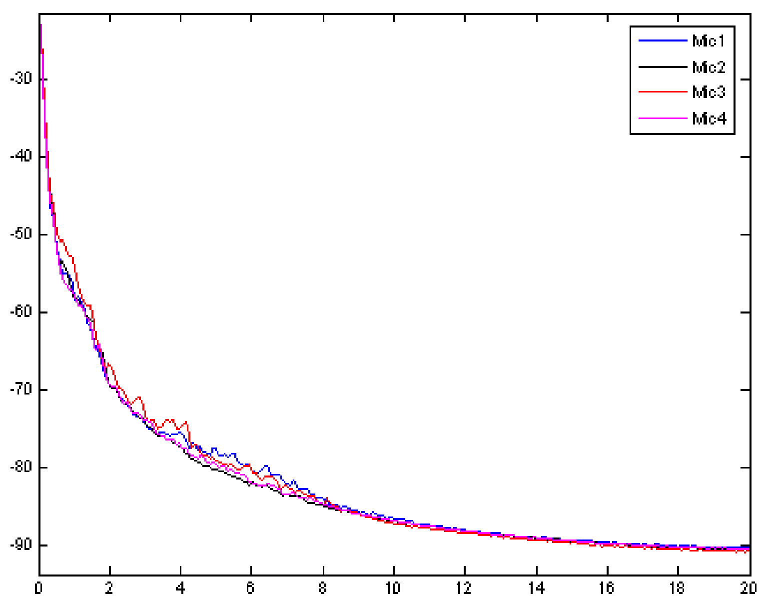


Figure 8.2. Normalized PSD 0-20kHz, Amplitude in dB



Power Spectral Density (0 to 1kHz)

Figure 8.3. Non-Normalized PSD 0-1kHz, Amplitude in dB

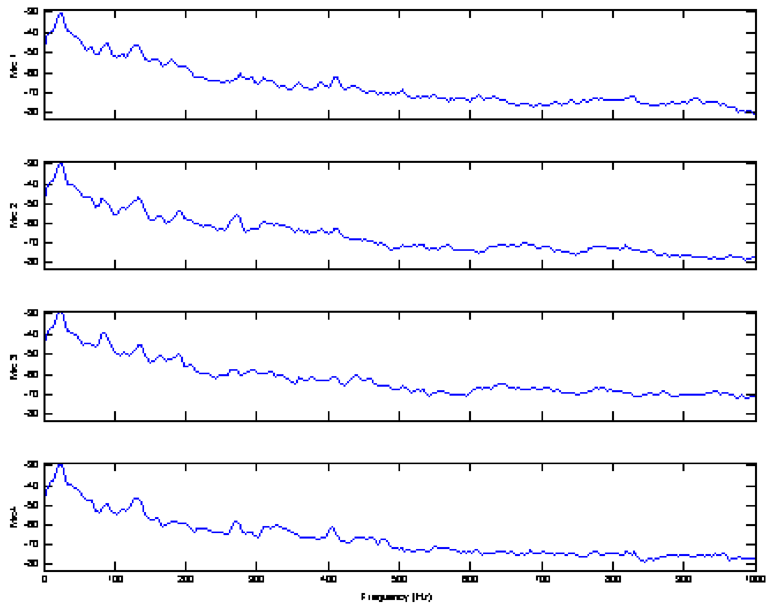
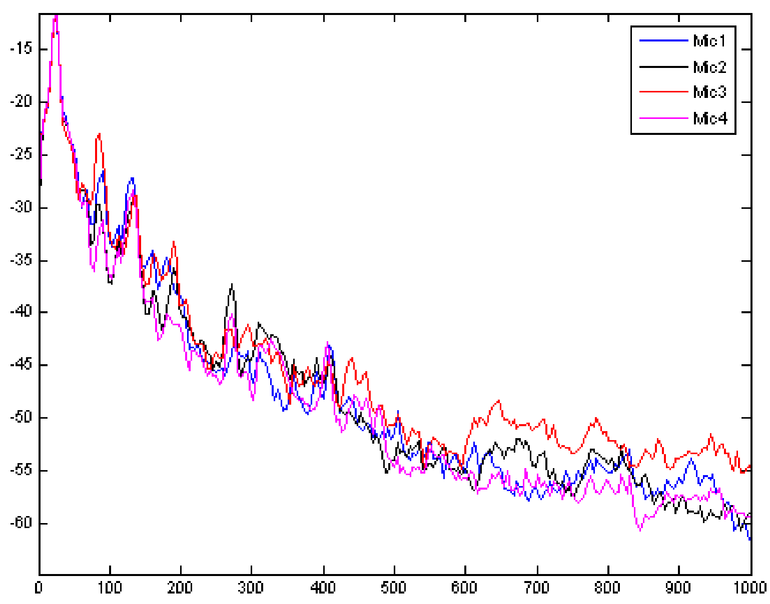
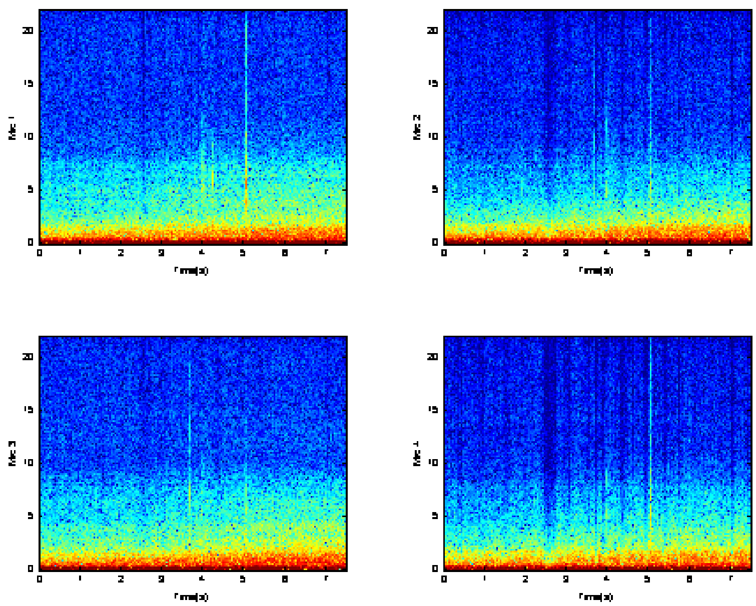


Figure 8.4. Normalized PSD 0-1kHz, Amplitude in dB



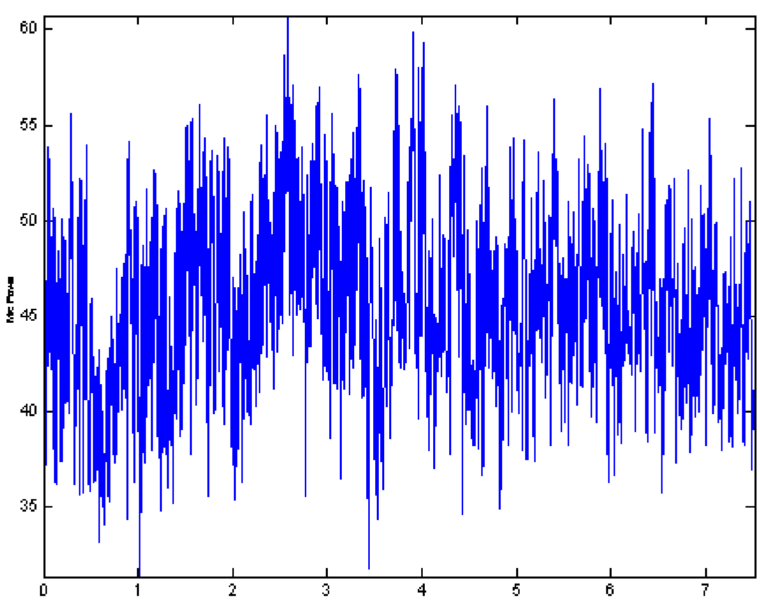
Spectrogram (0 to 20 kHz)

Figure 8.5. Spectrogram 20kHz, Frequency in kHz



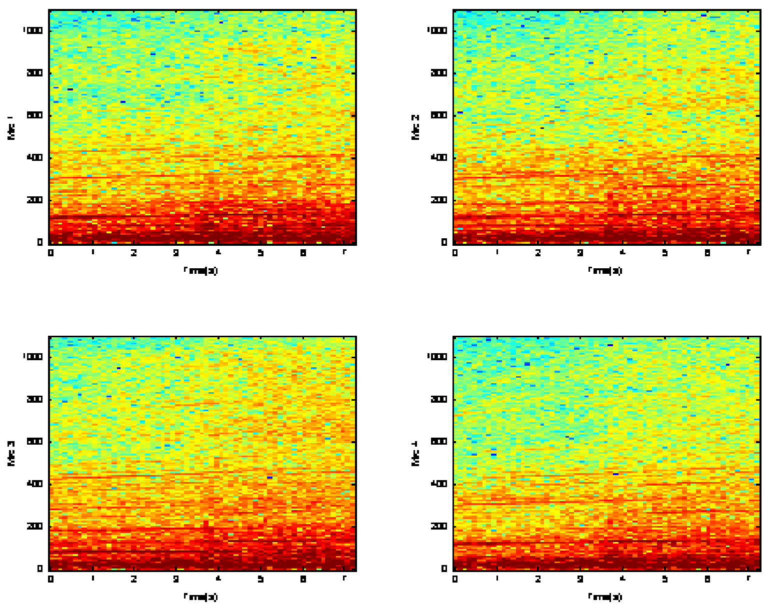
Power vs. Time

Figure 8.6. Power vs. Time, Amplitude in Normalized dB



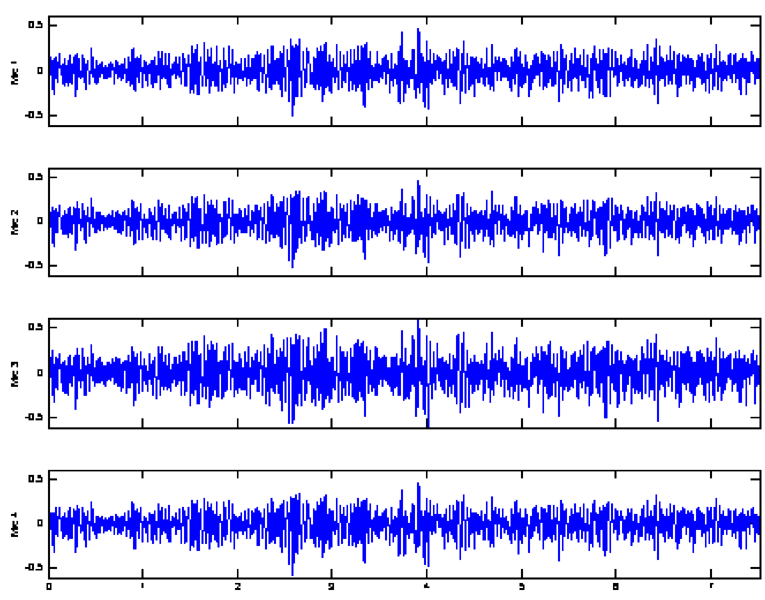
Spectogram (0 to 1kHz)

Figure 8.7. Spectrogram 0-1kHz, Frequency in Hz



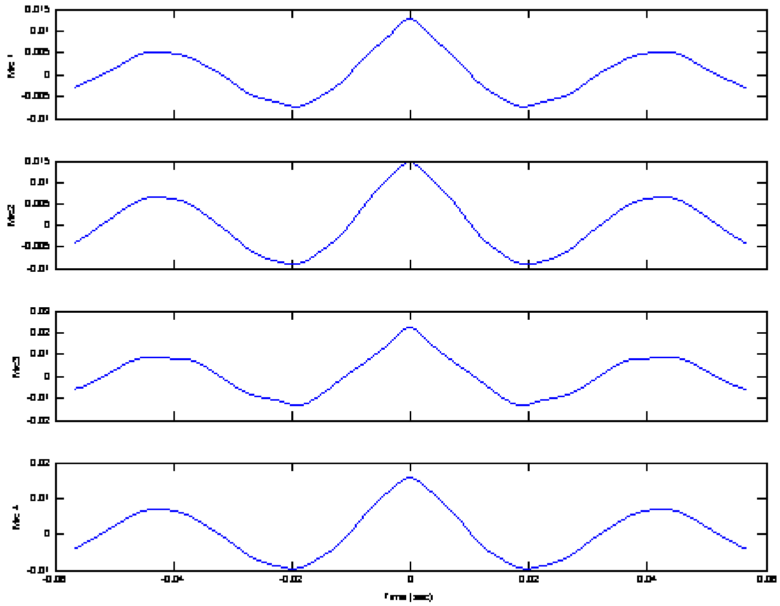
Time Plot

Figure 8.8. Time Graph



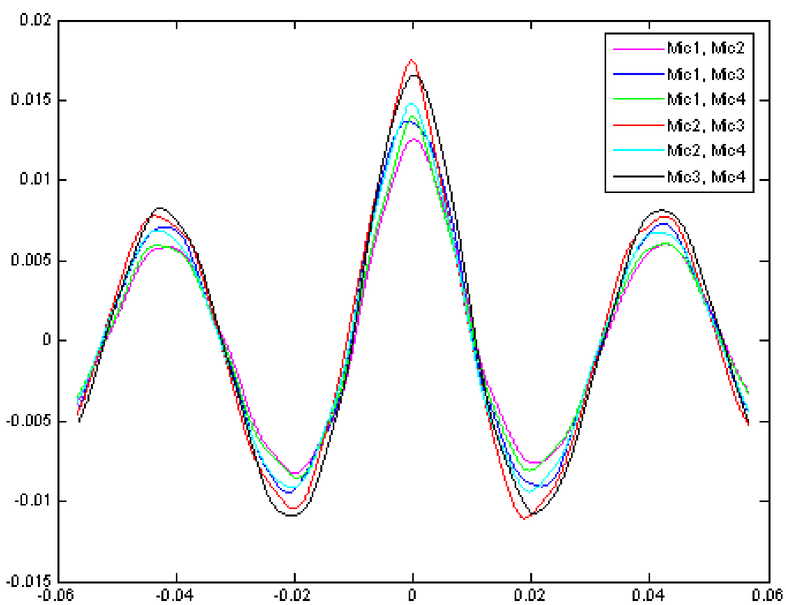
Autocorrelation

Figure 8.9. Autocorrelation Graph



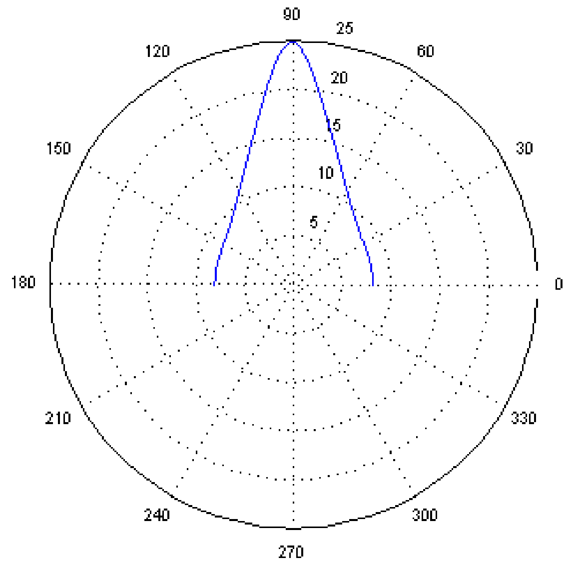
Crosscorrelation

Figure 8.10. CrossCorrelation



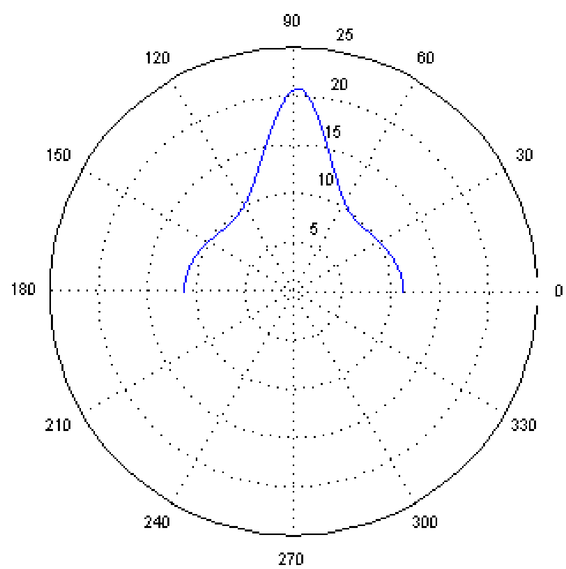
Direction of Arrival 200 Hz

Figure 8.11. DOA 200 Hz



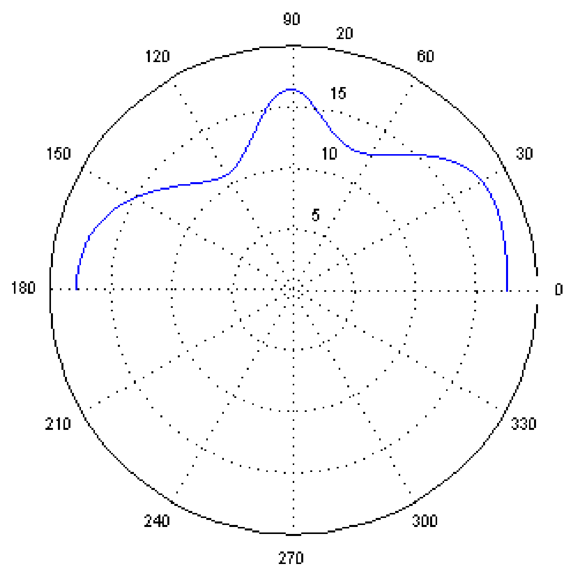
Direction of Arrival 300 Hz

Figure 8.12. DOA 300 Hz



Direction of Arrival 400 Hz

Figure 8.13. DOA 400 Hz



Chapter 9. Test Seven: Accelerating 30-50 MPH, windows down

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Audio Recordings

`Recording One`

Play Accelerating 30-50 MPH, windows down Mic 1.wav

`Recording Two`

Play Accelerating 30-50 MPH, windows down Mic 2.wav

`Recording Three`

Play Accelerating 30-50 MPH, windows down Mic 3.wav

`Recording Four`

Play Accelerating 30-50 MPH, windows down Mic 4.wav

Power Spectral Density (0 to 20 kHz)

Figure 9.1. Non-Normalized PSD 0-20kHz, Amplitude in dB

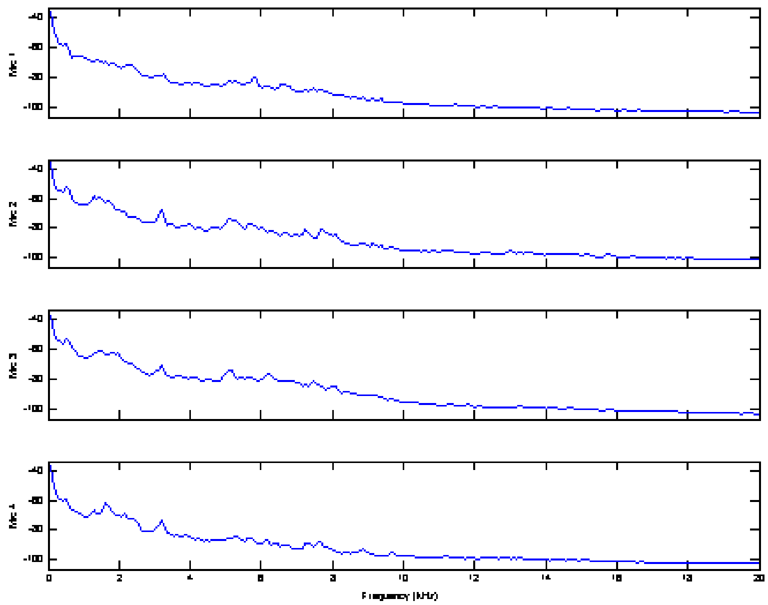
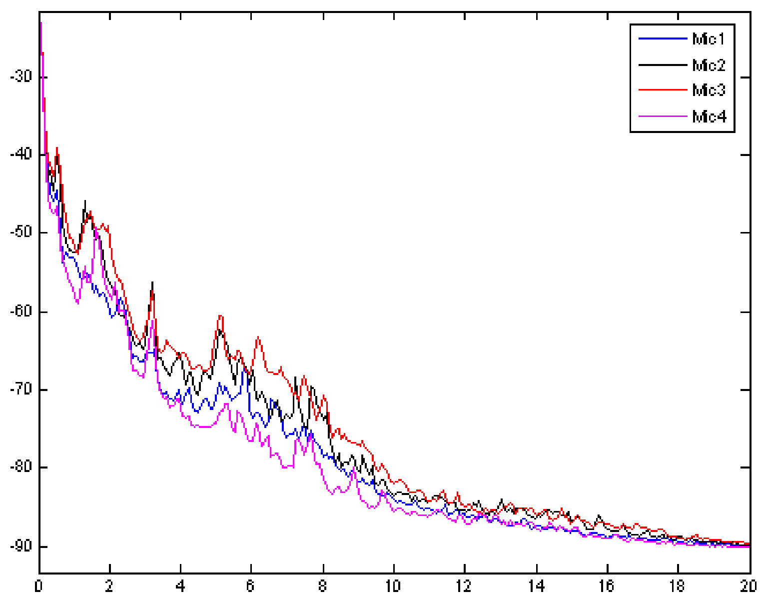


Figure 9.2. Normalized PSD 0-20kHz, Amplitude in dB



Power Spectral Density (0 to 1kHz)

Figure 9.3. Non-Normalized PSD 0-1kHz, Amplitude in dB

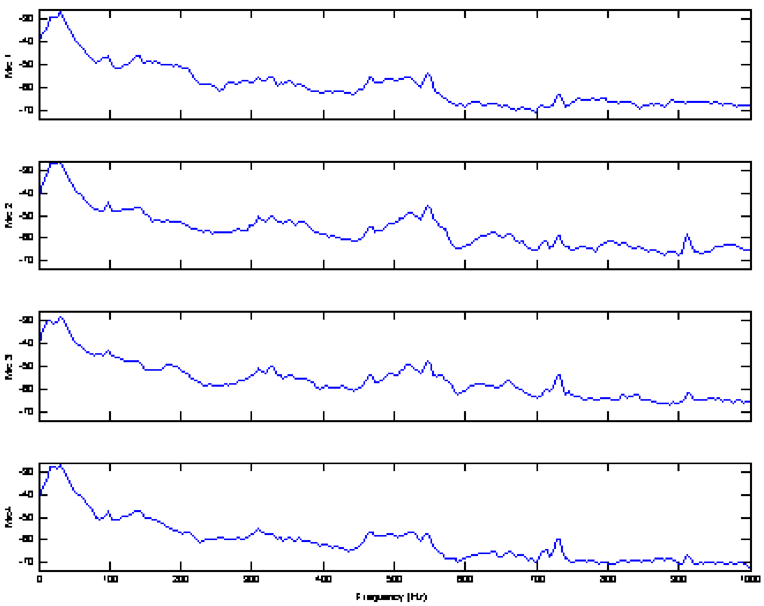
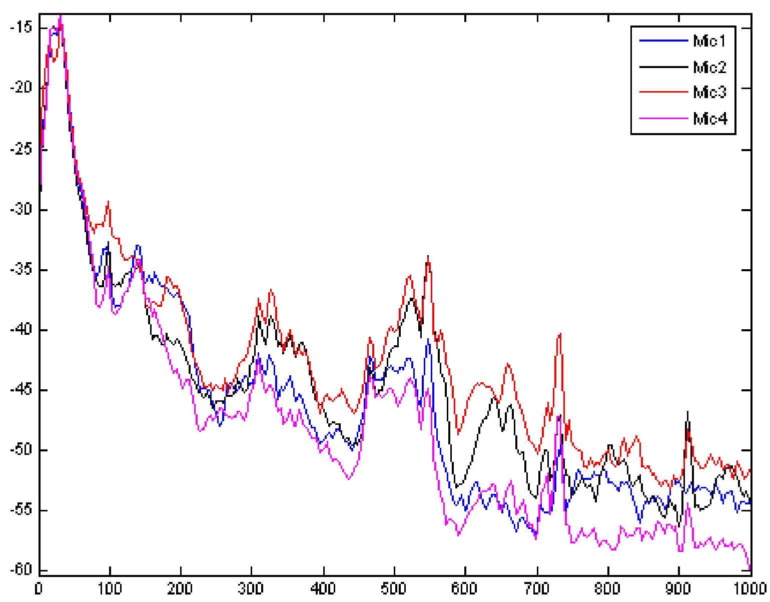
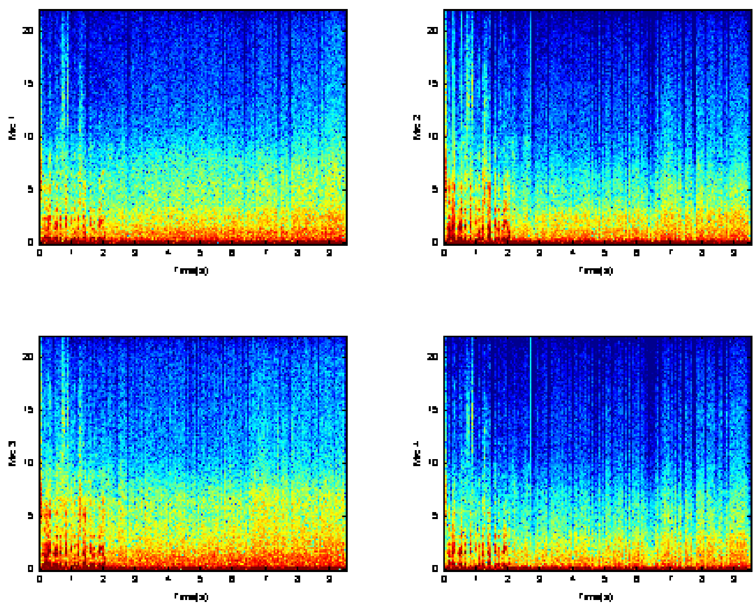


Figure 9.4. Normalized PSD 0-1kHz, Amplitude in dB



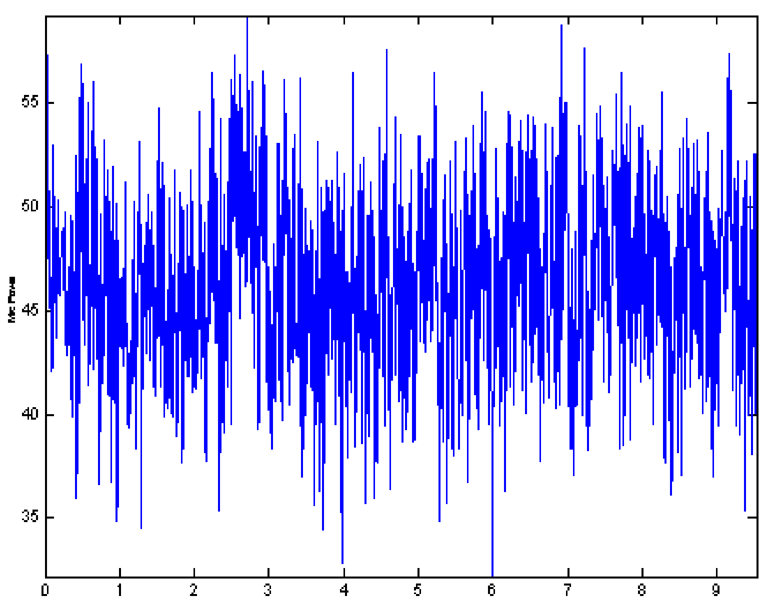
Spectrogram (0 to 20 kHz)

Figure 9.5. Spectrogram 0-20kHz, Frequency in kHz



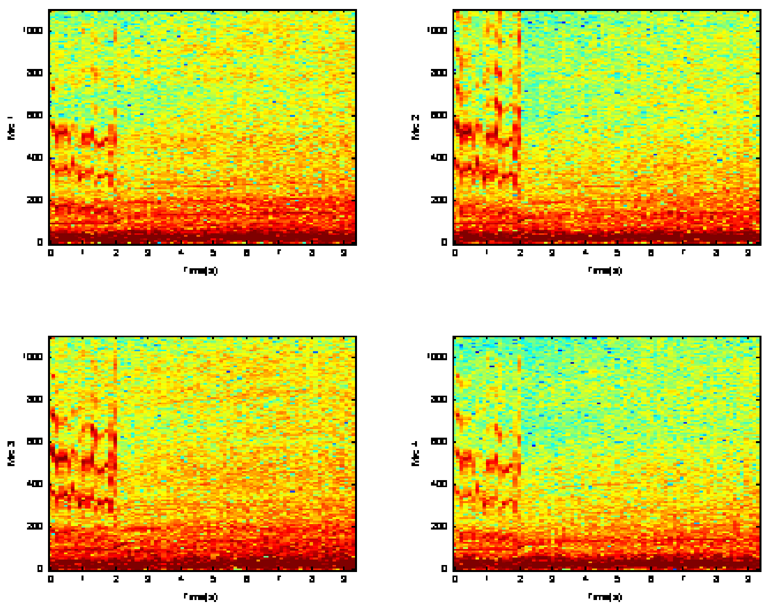
Power vs. Time

Figure 9.6. Power vs. Time, Amplitude in Normalized dB



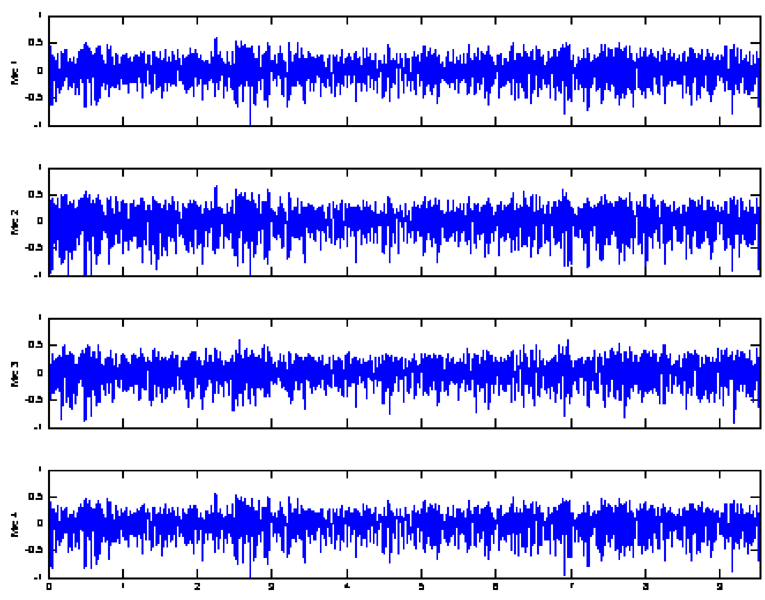
Spectogram (0 to 1kHz)

Figure 9.7. Spectrogram 0-1kHz, Frequency in Hz



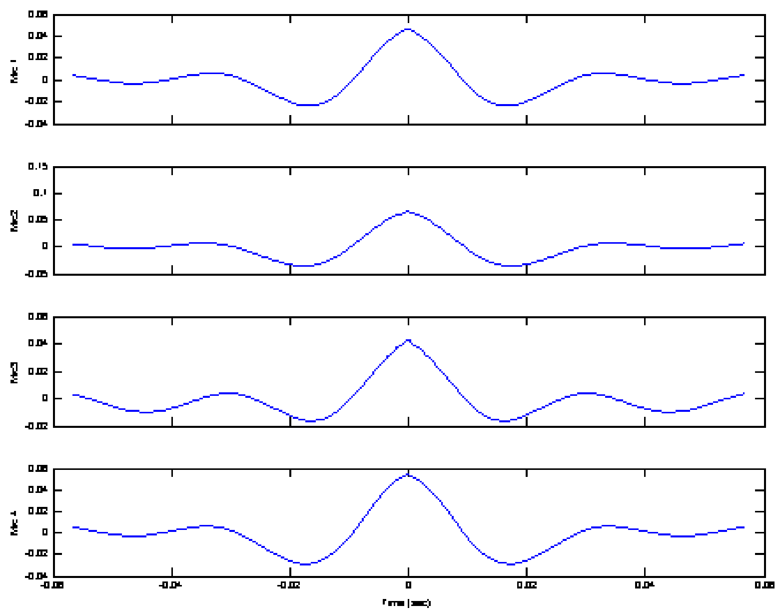
Time Plot

Figure 9.8. Time Graph



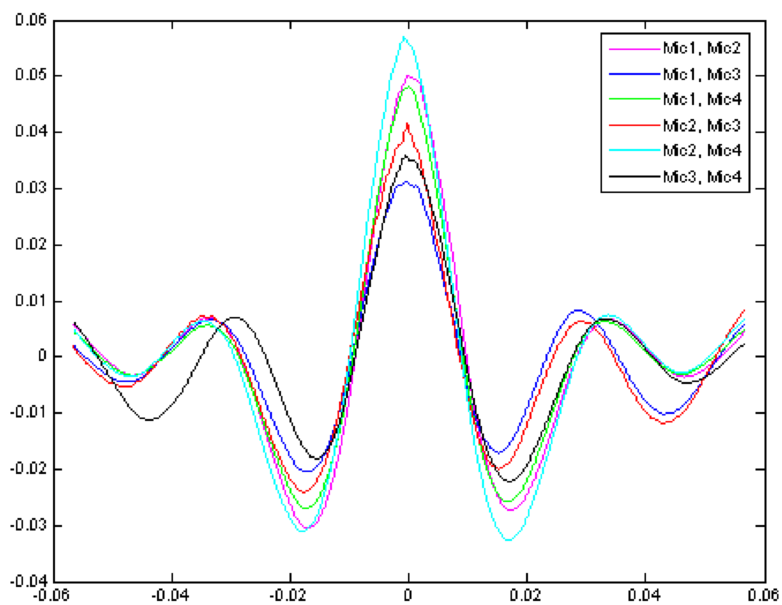
Autocorrelation

Figure 9.9. Autocorrelation Graph



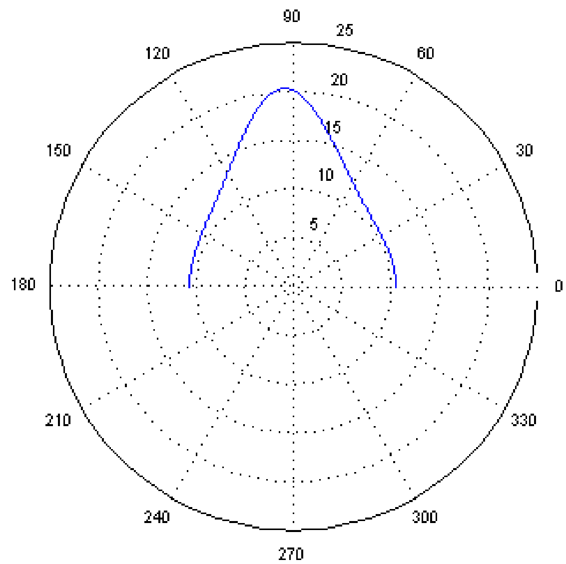
Crosscorrelation

Figure 10. CrossCorrelation



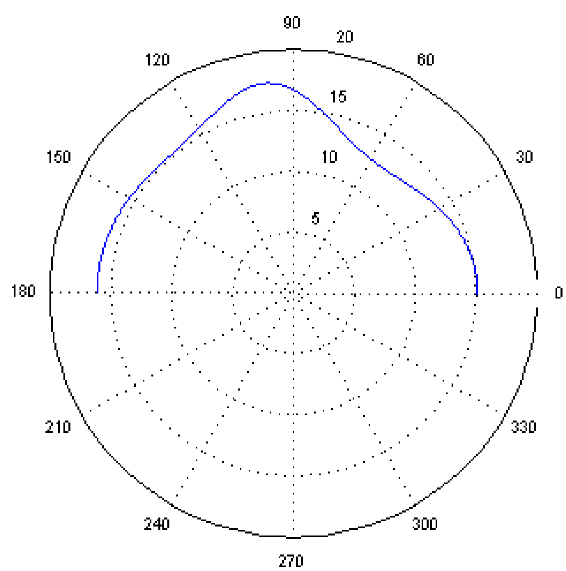
Direction of Arrival 200 Hz

Figure 9.11. DOA 200 Hz



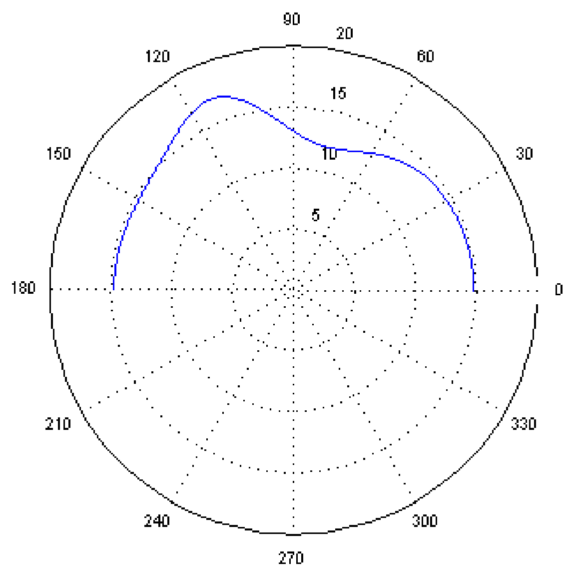
Direction of Arrival 300 Hz

Figure 9.12. DOA 300 Hz



Direction of Arrival 400 Hz

Figure 9.13. DOA 400 Hz



Chapter 10. Test Eight: Driving 50 MPH

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Audio Recordings

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Play Driving 50 MPH Mic 1.wav
`Recording Two`
Play Driving 50 MPH Mic 2.wav
`Recording Three`
Play Driving 50 MPH Mic 3.wav
`Recording Four`
Play Driving 50 MPH Mic 4.wav

Power Spectral Density (0 to 20 kHz)

Figure 10.1. Non-Normalized PSD 0-20kHz, Amplitude in dB

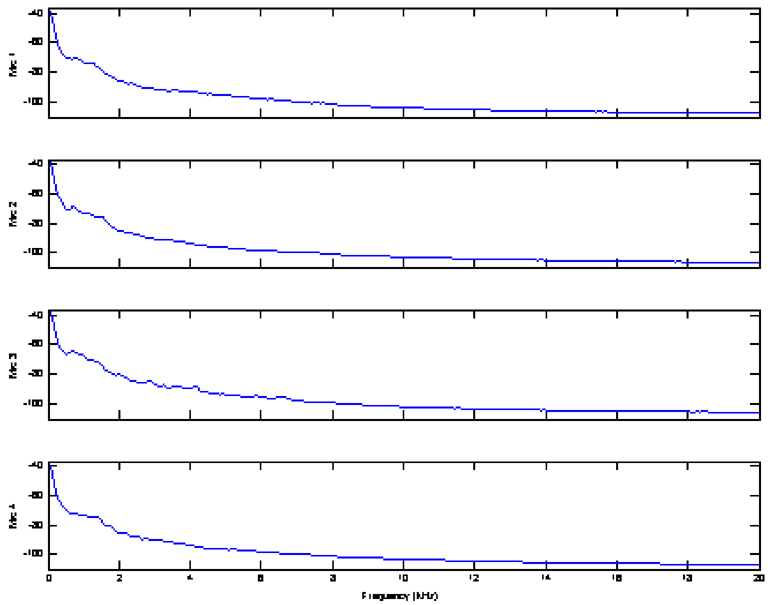
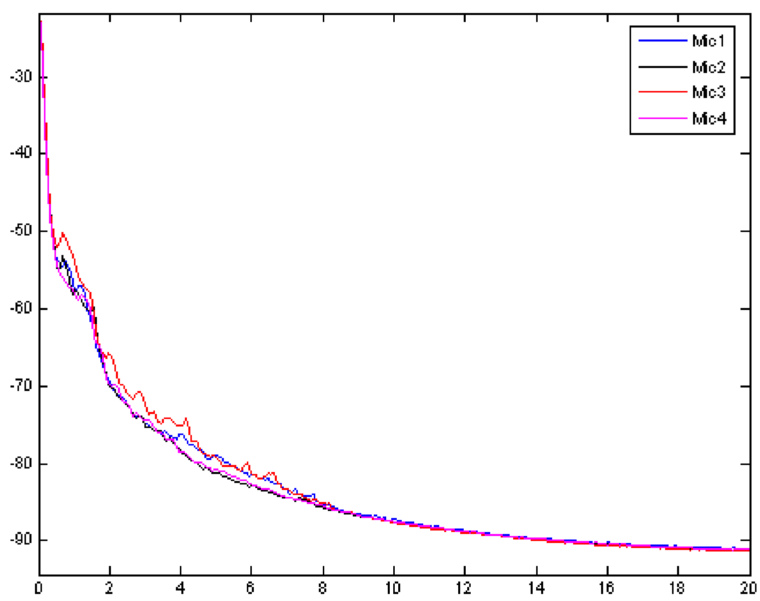


Figure 10.2. Normalized PSD 0-20kHz, Amplitude in dB



Power Spectral Density (0 to 1kHz)

Figure 10.3. Non-Normalized PSD 0-1kHz, Amplitude in dB

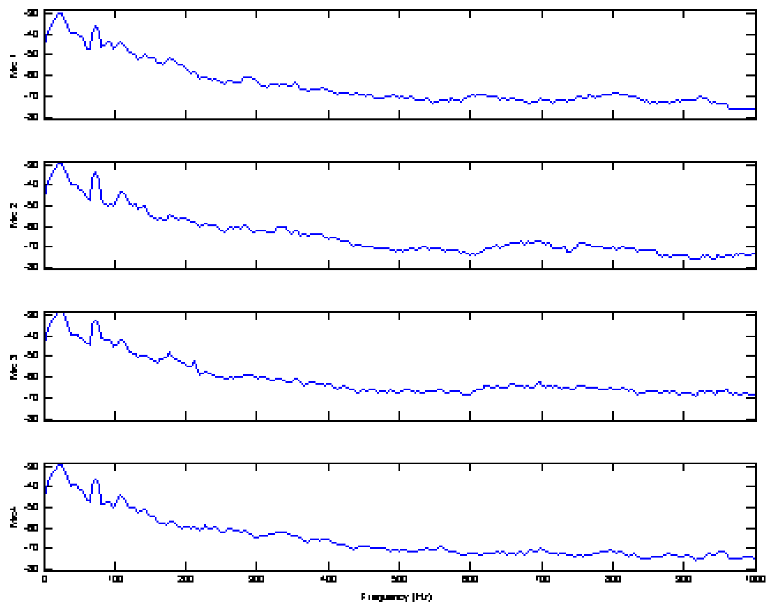
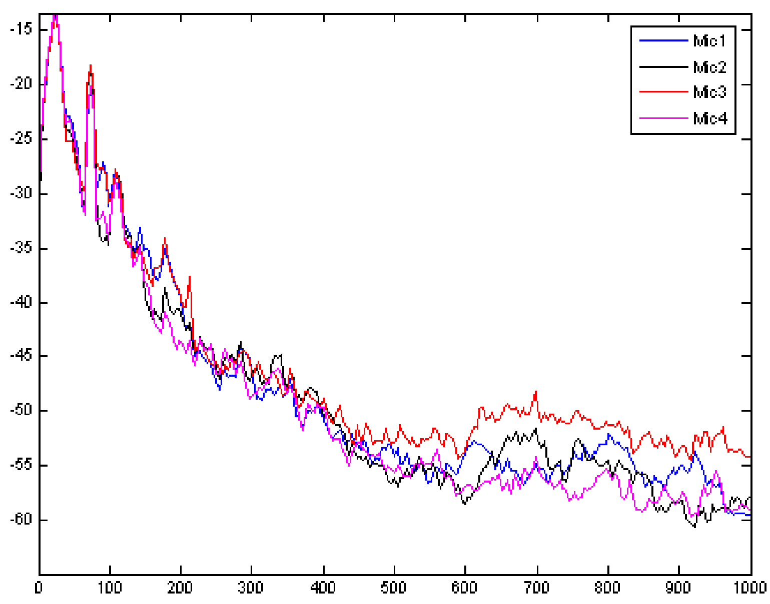
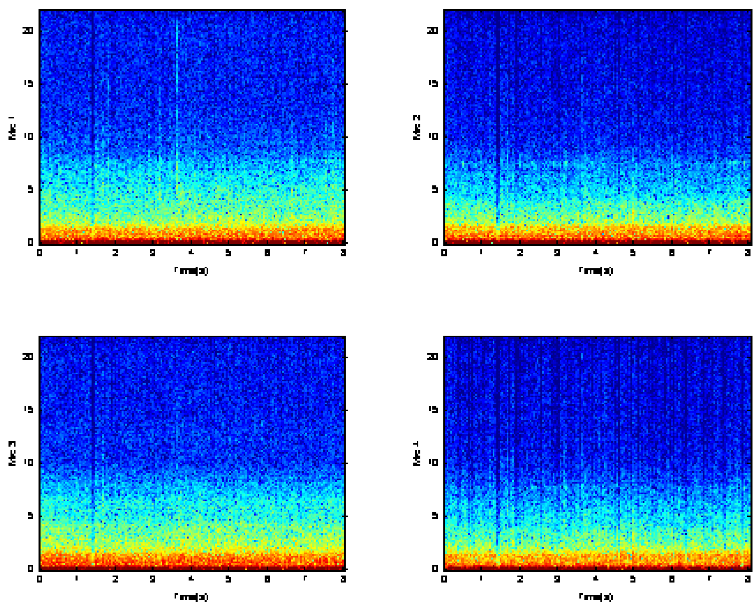


Figure 10.4. Normalized PSD 0-1kHz, Amplitude in dB



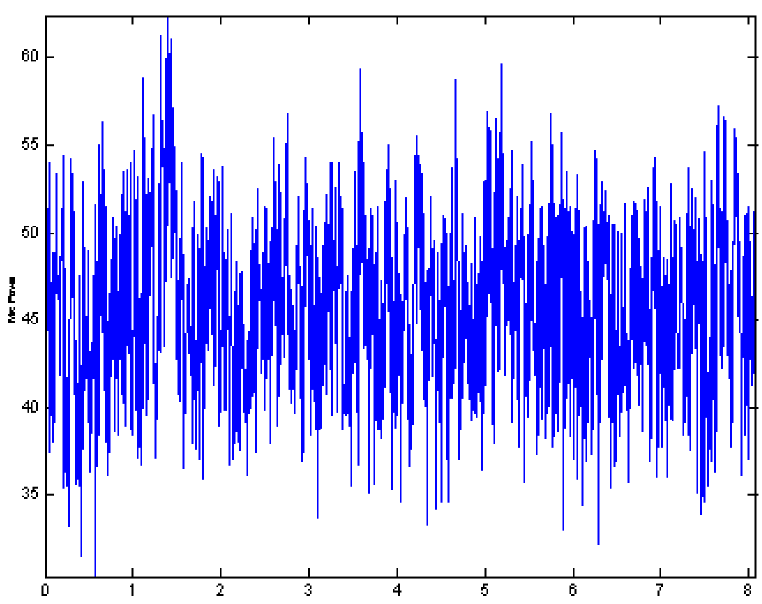
Spectrogram (0 to 20 kHz)

Figure 10.5. Spectrogram 0-20kHz, Frequency in kHz



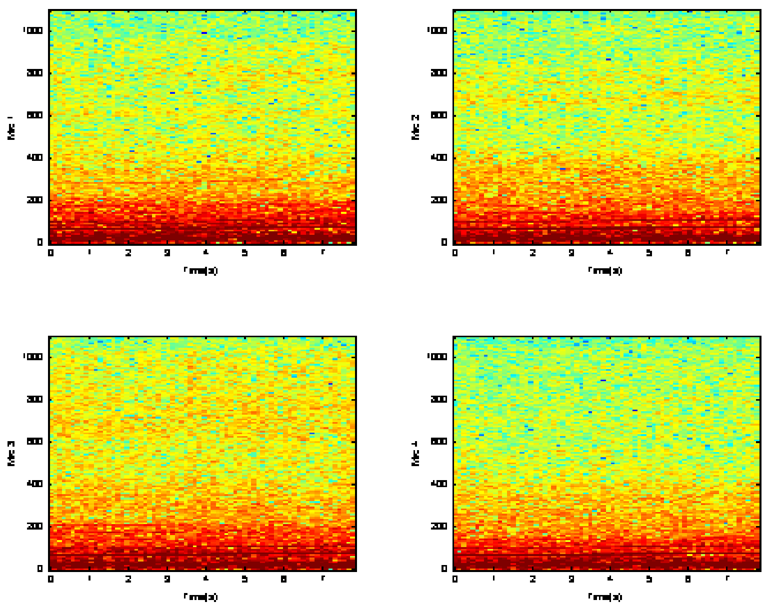
Power vs. Time

Figure 10.6. Power vs. Time, Amplitude in Normalized dB



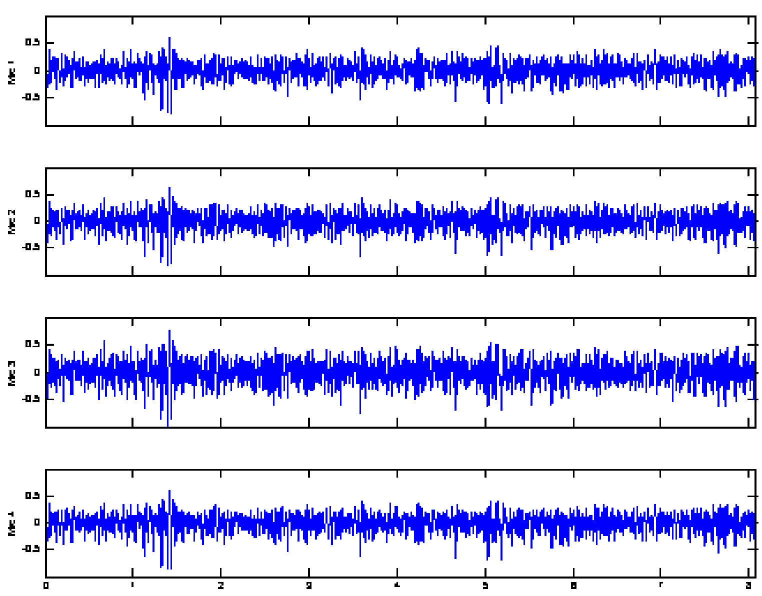
Spectogram (0 to 1kHz)

Figure 10.7. Spectrogram 0-1kHz, Frequency in Hz



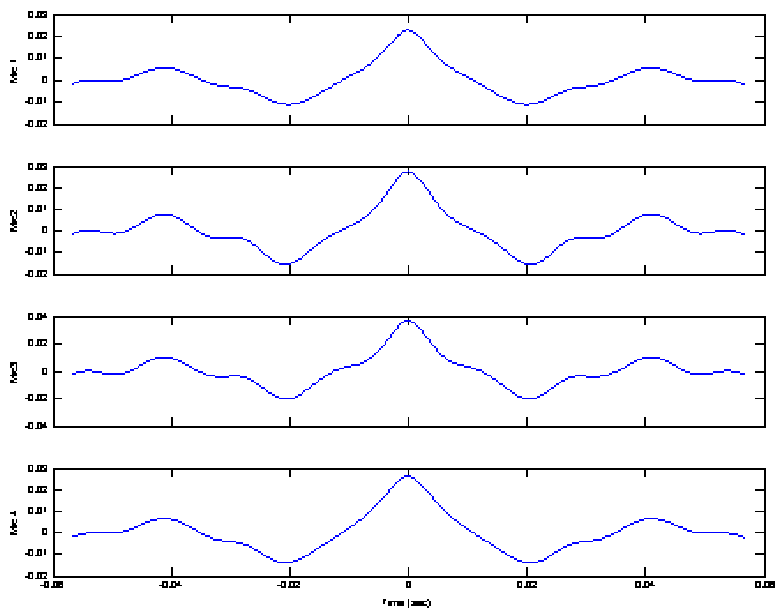
Time Plot

Figure 10.8. Time Graph



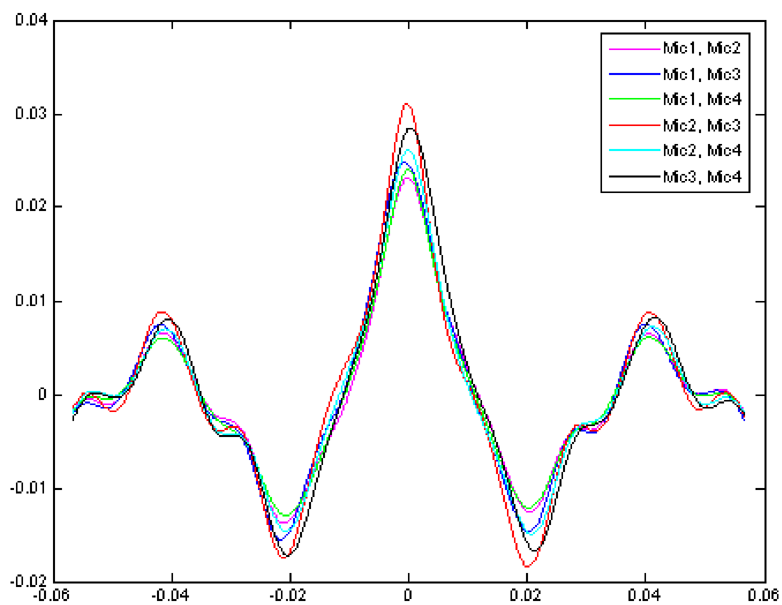
Autocorrelation

Figure 10.9. Autocorrelation Graph



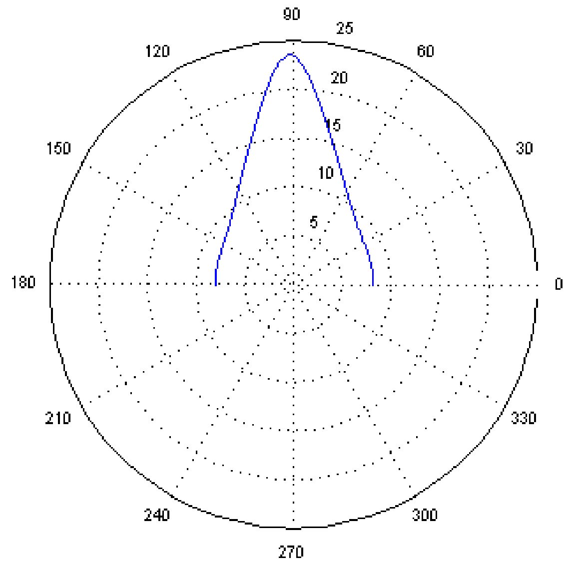
Crosscorrelation

Figure 10.10. CrossCorrelation



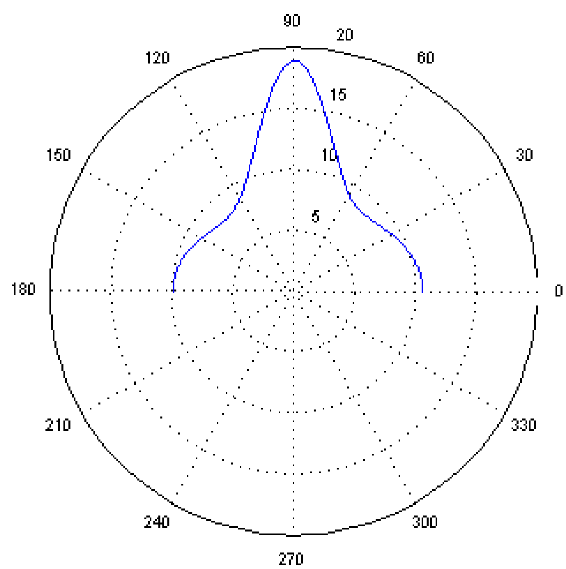
Direction of Arrival 200 Hz

Figure 10.11. DOA 200 Hz



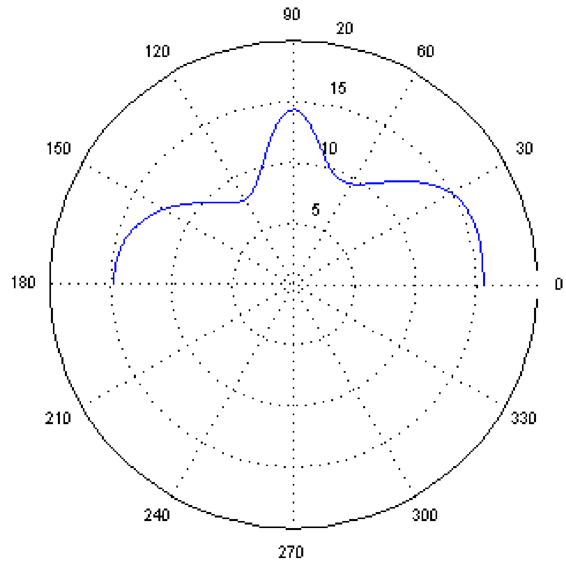
Direction of Arrival 300 Hz

Figure 10.12. DOA 300 Hz



Direction of Arrival 400 Hz

Figure 10.13. DOA 400 Hz



Chapter 11. Definition of Plots

Time Domain Plot. The time domain plot represents the data recorded by the microphone in the time domain.

Power Spectral Density. Power spectral density (PSD) is a useful analysis tool to use when examining signals. This tool shows the power at each frequency. In this report, Welch's method is used to find the PSD. The vertical axis gives the magnitude in W/Hz. The horizontal axis is frequency in Hz.

Autocorrelation. Autocorrelation is defined as A measure of the similarity between a signal and a time-shifted replica of itself; a special case of cross-correlation. If the length of the signal is enough to encompass several pitch periods of speech, the autocorrelation function will also show peaks at multiples of the pitch period. By identifying these peaks, the fundamental frequency can be determined. If there are no peaks, then it is known that there is an interval without speech.

Direction of Arrival. The direction of arrival (DOA) for a microphone takes into consideration several factors. In an array of microphones it is important to consider that the speed of sound travel is 340m/s. In this short time, the system takes 44.1K samples in a second. Direction of Arrival therefore takes into account direction as well as the associated time delay when examining an acoustical signal. The DOA examines a range of ? and plots based on power.

Spectrogram. A sound spectrogram, also known as a sonogram, is a visual representation of an acoustic signal. In the spectrogram itself, the vertical axis represents frequency. All of the spectra computed by the Fourier transform are displayed parallel to this vertical, or y-axis. The horizontal axis represents time. A color scale is used to display the magnitudes.

Power vs. Time. Similar to the power sepctral density graph, this graph sums up all the power at any given time. This graph is independent of frequency.