GUNSHOT SPOTTING SYSTEM

By

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FINAL PROJECT REPORT

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CERTIFICATION OF APPROVAL

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TRONOH, PERAK

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CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

MOHD FARIS BIN AHMAD

ABSTRACT

There are various ways to detect the location of the gunshot. When a gun is fired, it produces a loud distinctive sound known as a gunshot with certain frequencies. The gunshot travels to all directions and reaches every different point along the way of its travelling at different time, this provides us the information to locate the gunshot. This is called the Gunshot Spotting System. Gunshot spotting system consists of three microphones placed along a straight line with equal distance apart, a filter, time recorder and a program to calculate the location. The purpose of this report is to explain in detail the concept of the gunshot locating system. The design of the system involves microphones, USB sound cards, filters, time recorders and processing software.

ACKNOWLEDGEMENTS

First of all, I would like to thank the almighty god, who gave me the discipline and courage to finish this project. Without his blessings, the project might not have been completed. I would also like to thank both my parents for their encouragements and financial support. Without their support I would have a difficult time finishing this project.

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I will not forget to thank my friends Hazilah Hamzah, who helped in developing the project, Ahmad Nizar, Zaim Aiman and Ishrat who stood by me during the long nights of the project and gave me ideas and feedbacks on the project.

Finally, I would like to thank Universiti Teknologi PETRONAS for providing me the necessary research opportunities and the environment to develop this project.

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LIST OF ABREVIATIONS

CPU	central processing unit
FFT	fast Fourier transform
PC	personal computer
USB	Universal Serial Bus
MATLAB	Matrix Laboratory

CHAPTER 1
INTRODUCTION

1.1 Background of Study

Gunshot spotting system is an ingenious crime solving system. The system is designed to locate the gunshot and notify the user using microphones and a computer software. In the following sections, there will be discussions on the theory, literature review and methodology behind Gunshot Spotting System. The system can be applied in the environment where gunfire normally occur or at locations which needs higher level of security.

1.2 Problem Statement

Are gun crimes really a major problem these days? Unfortunately the answer is affirmative. Despite remarkable progress in law enforcement and decreasing crime rates throughout the 90s, in 2002 the FBI reported some 18,000 homicides in United States, of which 12,000 involving the use of a gun [1]. Even though the gun crime in Malaysia is rare, the same cannot be said for third world countries. That comes to 33 homicides involving guns per day, or a little more than one every forty-four minutes. These figures do not include attempted homicides, of which there are, by some estimates, perhaps five to six times as many compared to homicides in a day. Homicide-related gunfire is not the only reason for the illegal discharge of weapons. The current technology in Malaysia relies on post-incident reports to investigate the case relating to gun crimes. By the time the police arrive at the crime scene, it is almost impossible to determine the shooter. The situation can be prevented if, the police are able to arrive sooner to rescue the gunshot victim and the murderer can be known from the victim before he dies.

1.3 Objective and Scope of Study

In order to address the problem stated above a system is designed to provide the solution of the security system by detecting and locating the gunshot allowing police officer in tackling gun crime. A formula based on this method is derived to identify the coordinate of the gunshot with respect to the center microphone which will later be known as Microphone B. For this purpose, a processing system is created to calculate the location of the gunshot and display the location on the screen. Owing to the time constraint, this project will focus on the urban environment where the factors involving humidity, wind and temperature will be ignored.

CHAPTER 2
LITERATURE REVIEW AND THEORY

2.1 Literature Review

2.1.1 Shot Spotter Gunshot Locating System

ShotSpotter GLS is a similar gunshot spotting system used in United States to detect gunshot in urban areas. ShotSpotter GLS uses patented technology and the principle of triangulation to accurately detect and locate gunfire and explosions within seconds [1].Shot Spotter uses 10 to 12 sensors spaced evenly throughout each square-mile section of the city it's covering, and each sensor is capable of hearing the sound of gunfire within a 3-km radius [10].Using a built-in GPS system as an accurate time source, three sensors work together to triangulate the location from which a shot was fired.

When a shot is fired somewhere in the city, Sensor 1 picks up the sound of the shot. Since each acoustic sensor has a range of about 2 miles, all we know right now is that the shot was fired within a 2-mile radius of Sensor 1.

One second later, a second sensor picks up the sound waves of a gunshot. If sound in this city travels at about 340 meters per second, we now know that the shot was fired approximately 340 meters away from Sensor 2 than from Sensor 1. We can draw a circle representing the perception radius of Sensor 2 overlapping the perception radius of Sensor 1. Since both sensors picked up the sound waves, the shot must have been fired within the overlapping coverage areas. Where the two circles intersect, there are two possible locations for our gunshot.

To figure out which of these two points is the location from which the shot was fired, we need to find a third sensor that picked up the sound of the shot. A third sensor, located to the south of Sensors 1 and 2, picked up the sound waves a half-second after Sensor 2 detected them. This would put the origin of the sound about 170 meters of a mile farther from Sensor 3 than from Sensor 2.

According to ShotSpotter, the system is accurate to 25 meters. Police officials in D.C. say the system has cut the "shots fired" response time in half. Shot Spotter also records all detected gunfire and corresponding locations for later forensic use. The cost of implementation for the Shot Spotter system can range from hundreds of thousands of dollars for a small area to millions of dollars to cover an entire city the size of D.C.

For this project, the Gunshot Spotting System has an advantage over ShotSpotter in terms of accuracy. ShotSpotter is only able to locate the gunshot in a postulated region where the three circles overlap. Shot Spotter has an accuracy of up to 25 meters where else the Gunshot Spotting System can locate the source of the gunshot accurately.

2.1.2 Boomerang

Boomerang is a Gunshot Location Detection System developed by DARPA and BBN Technologies primarily for use against snipers on mobile vehicles such as the Humvee, Stryker, and MRAP combat vehicles [2]. Boomerang acoustic gunshot detection system is designed to operate in noisy vehicular environment.

The Boomerang unit attaches on a mast to the rear of a vehicle and uses an array of seven small microphone sensors. The sensors detect and measure both the muzzle blast and the supersonic shock wave from a supersonic bullet travelling through the air [13]. Each microphone detects the sound at slightly different times. Boomerang then uses sophisticated algorithms to compute the direction a bullet is coming from, distance above the ground and range to the shooter in less than one second.

The Boomerang system is even more sophisticated and robust compared to the Shot Spotter as it requires 7 microphones to detect the location of the gunshot. The boomerang is concentrated on moving vehicles and can calculate not only the angle and distance; it can even calculate the distance above ground level.

2.2 Theory

2.2.1 Preliminary

In this section there will be explanations on the general knowledge and terms used throughout this report.

2.2.1.1 Trigonometry

Trigonometry is a study on triangles and the relationship between their sides and the angles between sides. For example, if one angle of a triangle is 90 degrees and one of the other angles is known, the third is thereby fixed, because the three angles of any triangle add up to 180 degrees. The two acute angles therefore add up to 90 degrees which means they are complementary angles. The shape of a triangle is completely determined, except for similarity, by the angles. Once the angles are known, the ratios of the sides are determined, regardless of the overall size of the triangle. If the length of one of the sides is known, the other two are determined.

2.2.1.2 Speed of Sound

The speed of sound is the distance travelled during a unit of time by a sound wave propagating through an elastic medium. In dry air at 20 °C, the speed of sound is about 340 meters per second. This is 1,236 kilometers per hour, or about one kilometer in three seconds or approximately one mile in five seconds.

2.2.2 Gunshot Spotting System Theory

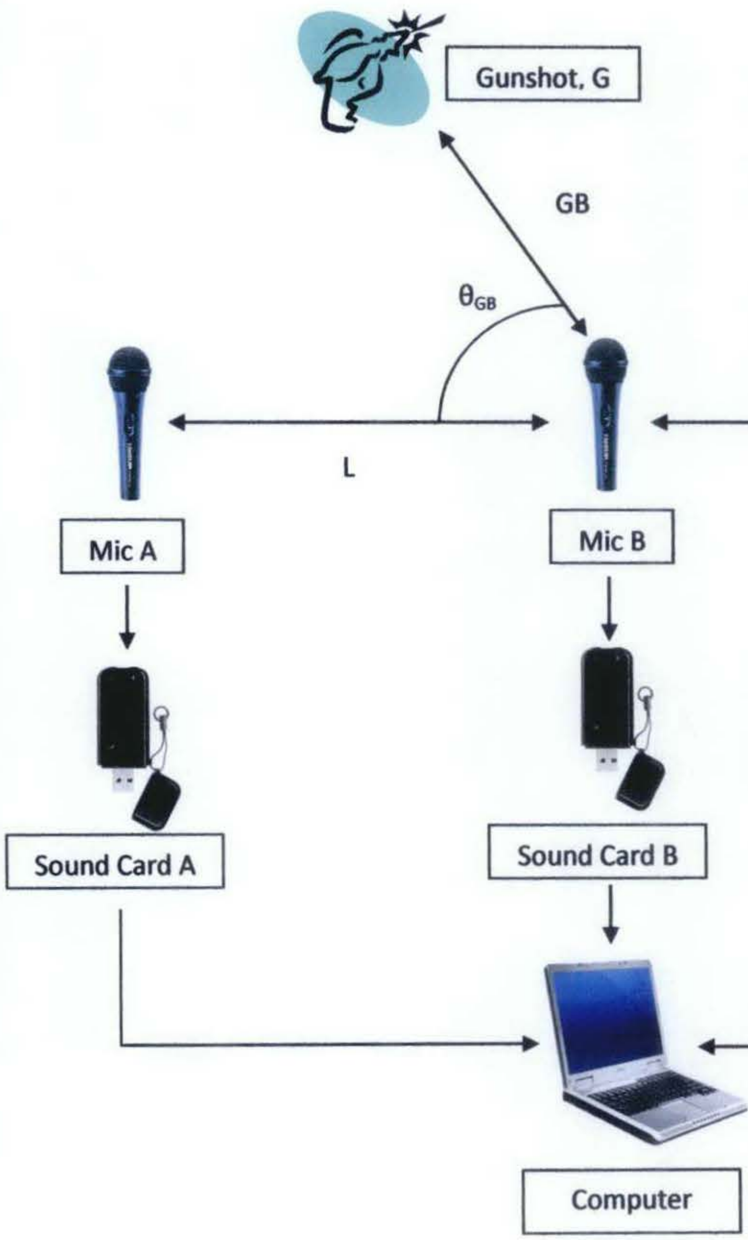


Figure 1: Gunshot Spotting System Setup

The diagram above shows the arrangement of an array of microphones connected to either an external sound card or straight to the computer microphone input to detect the gunshot location. This is the Gunshot Spotting System setup. The system consists of three microphones, three USB sound cards and a processing system which includes a sound filter and a time recorder.

There are several types of microphones that may be used for the project. These microphones are connected to a special sound filter allowing a certain frequency range of gunfire to pass through. Then the pulse sound triggers the time recorder and the instantaneous time that the sound arrives at the microphone will be recorded. The time recorder must be really precise in order to differentiate the small time difference between the microphones. The more precise the time recorders are, the more accurate the location of the gunshot will be. Once the time differences are known, the exact location of the gunshot can be calculated.

The theory behind this system is based on the variation distance between each microphone to the gunshot, so that the time at which the sound wave captured by each microphone is different and this provides the information to calculate the exact location of the source. The distance from the microphone B to the gun shot location, is derived below.

V = THE SPEED OF SOUND AT SEA LEVEL = 340 m/s

L = THE LENGTH BETWEEN MICROPHONES

GA = THE DISTANCE BETWEEN MICROPHONE A AND GUNSHOT

GB = THE DISTANCE BETWEEN MICROPHONE B AND GUNSHOT

GC = THE DISTANCE BETWEEN MICROPHONE C AND GUNSHOT

t = THE TIME GUNSHOT OCCURS

t_A = THE TIME GUNSHOT ARRIVES AT MICROPHONE A

t_B = THE TIME GUNSHOT ARRIVES AT MICROPHONE B

t_C = THE TIME GUNSHOT ARRIVES AT MICROPHONE C

Δt_{AB} = THE TIME DIFFERENCE BETWEEN MICROPHONE A AND B

Δt_{BC} = THE TIME DIFFERENCE BETWEEN MICROPHONE B AND C

$$\frac{GA}{t_A - t} = V\,, \qquad \frac{GB}{t_B - t} = V, \qquad \frac{GC}{t_C - t} = V$$

Using trigonometry,

$$GA^2 = L^2 + GB^2 - 2LGBcos\theta_B \tag{1}$$

$$GC^2 = L^2 + GB^2 + 2LGBcos\theta_B \tag{2}$$

$$t_A - t = \frac{GA}{V}, \qquad t_B - t = \frac{GB}{V}, \qquad t_C - t = \frac{GC}{V}$$

$$\Delta t_{AB} = t_A - t - (t_B - t) = t_A - t_B = \frac{1}{V}(GA - GB)$$

$$V\Delta t_{AB} = GA - GB$$

$$GA = V\Delta t_{AB} + GB$$

$$\Delta t_{BC} = t_B - t_C = \frac{1}{V}(GB - GC)$$

$$GC = -V\Delta t_{BC} + GB$$

Insert GA into equation (1)

$$(V\Delta t_{AB} + GB)^2 = L^2 + GB^2 - 2LGBcos\theta_B \quad (3)$$

$$GB^2 + V^2\Delta t_{AB}{}^2 + 2GBV\Delta t_{AB} = L^2 + GB^2 - 2LGBcos\theta \quad (4)$$

Insert GC into equation (2)

$$(-V\Delta t_{BC} + GB)^2 = L^2 + GB^2 + 2LGBcos\theta$$

$$GB^2 + V^2\Delta t_{BC}{}^2 - 2GBV\Delta t_{BC} = L^2 + GB^2 + 2LGBcos\theta \quad (5)$$

Add equation (4) and (5)

$$V^2\Delta t_{AB}{}^2 + 2GBV\Delta t_{AB} + V^2\Delta t_{BC} - 2GBV\Delta t_{BC}$$
$$= L^2 - 2LGBcos\theta + L^2 + 2\mathrm{LGBcos}\theta$$

$$V^2\Delta t_{AB}{}^2 + 2GBV\Delta t_{AB} + V^2\Delta t_{BC}{}^2 - 2GBV\Delta t_{BC} = 2L^2$$

$$GB(2V\Delta t_{AB} - 2\,V\Delta t_{BC}) = 2L^2 - V^2\Delta t_{AB}{}^2 - V^2\Delta t_{BC}{}^2$$

Hence, the formula for GB is,

$$GB = \frac{2L^2 - V^2\Delta t_{AB}{}^2 - V^2\Delta t_{BC}{}^2}{2V\Delta t_{AB} - 2V\Delta t_{BC}}$$

The angle opened from microphone A to the gunshot with respect to microphone B is given by:

From the previous equation,

Minus (5) from equation (4)

$$V^2 \Delta t_{AB}{}^2 + 2GBV\Delta t_{AB} - V^2 \Delta t_{BC}{}^2 + 2GBV\Delta t_{BC}$$
$$= L^2 - 2LGBcos\theta - L^2 - 2\text{LGBcos}\theta$$

$$V^2 \Delta t_{AB}{}^2 + 2GBV\Delta t_{AB} - V^2 \Delta t_{BC}{}^2 + 2GBV\Delta t_{BC} = -4LGBCOS\theta$$

Hence the formula for θ_{GB} is

$$\theta_{GB} = cos^{-1} \frac{V(V^2 \Delta t_{AB} \Delta t_{BC} - L^2)(\Delta t_{AB+} \Delta t_{BC})}{L[2L^2 - V^2(\Delta t_{AB}{}^2 + \Delta t_{BC}{}^2)]}$$

The microphones are aligned in a straight line at equal distance L. The range of L is shown below.

$$0.034\, meter < L < EFFECTIVE\ MICROPHONE\ RANGE$$

Since the time recorder has the sensitivity of up to about 0.1 milliseconds and the velocity of sound is 340 m/s. Therefore the minimum length between each microphone is given by.

0.0001s x 340m/s ~= 0.034 meter

If L is smaller than 0.034, the system will not be sensitive enough to differentiate the time difference received by each microphone. If L is larger than the effective microphone range, there will be no overlapping for the detection to take place. This is the limitation of the project.

CHAPTER 3
METHODOLOGY

3.1 Procedure Identification

The procedure identification flow is shown in Figure 5.

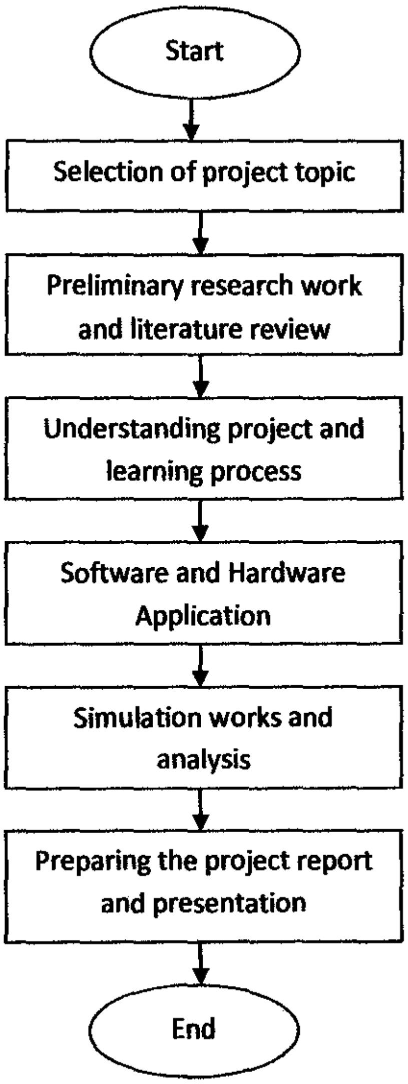


Figure 2: Procedure Identification Flow of the Project

In the beginning of the semester, the titles for the Final Year Project had to be chosen or proposed. After the project title was chosen or approved, preliminary research work and literature review was done on the project title. The next task was to understand more regarding the project and learn from the literature reviews and researches. After understanding about the project, the actual software and hardware application was done. Next step was to simulate the process of the project. The last step of the procedure is to prepare the project report and presentation.

3.2 Tools and Equipments Required

Hardware Requirement

i. Microphones
ii. 3 USB sound cards
iii. Personal Computer
iv. Air Gun

Software Requirement

i. MATLAB
ii. Simulink

3.3 Process Flow

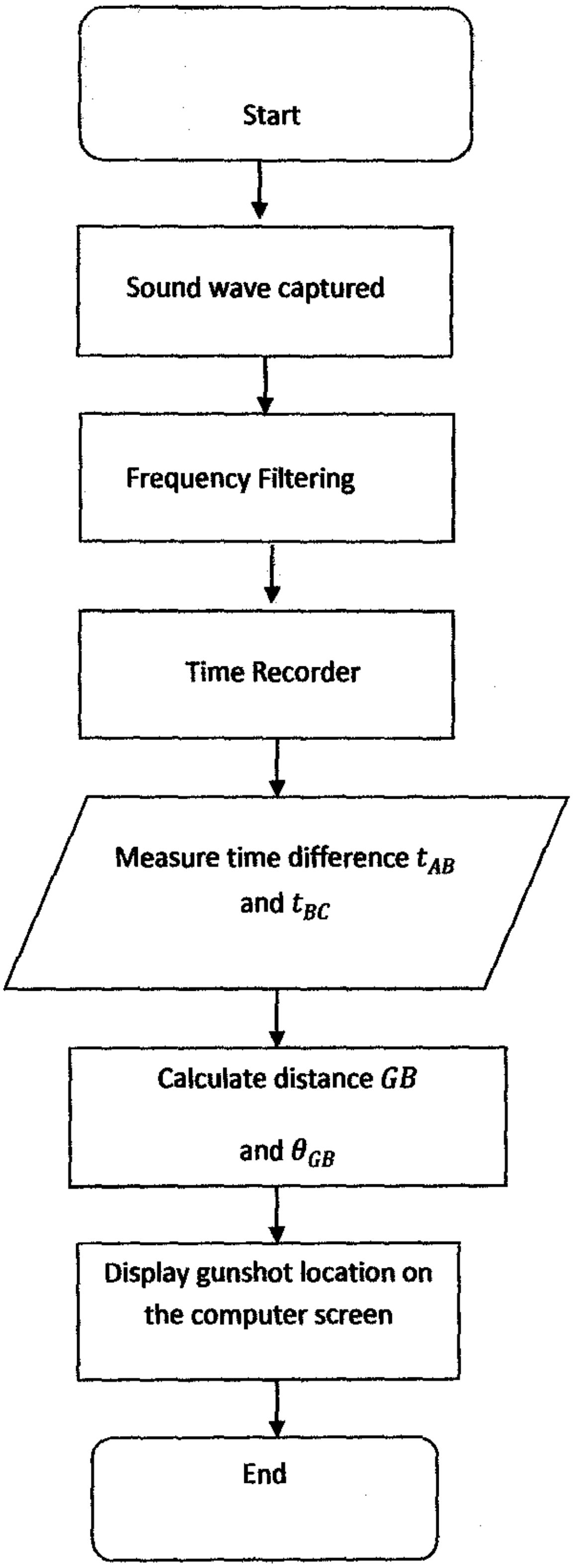


Figure 3: Process Flow

When a signal enters the program through the three microphones, the program will show the waveforms of the signal. From this waveform, the processing system will filter out frequencies which are not produced by gunshot. If the system detects a gunshot frequency, it will automatically measure the time the sound arrives at the microphone. Since the length between each microphone, L is fixed and the velocity of sound is 340 m/s, using, t_{AB} and, t_{BC} the software will perform the calculation of the location of the sound source in terms of the distance and angle from microphone B. When the length and the angle are found, the output will be displayed on the computer screen. The function of each block in the process flow will be explained in detail in the following sections.

3.4 Capturing Sound Wave

3.4.1 Microphones

The type of microphone used in this project is the omnidirectional or also known as nondirectional microphone. The microphone's response is generally considered to be a perfect sphere in three dimensional spaces. This is the most common type of microphone and since it can detect sound from every angle, it is the perfect microphone for the project.

However due to budget constrictions, a normal computer microphones will be used for this project. Computer microphones are not as sensitive as other microphones though it is the most affordable omnidirectional microphone. However computer microphones do not produce consistent results. The same sound would produce different output in MATLAB.

Every microphone has an effective range. The effective range is the range of the region that the microphone can detect any sound within the region. The figure below shows an example of the effective range of the microphones. However the actual range of the microphone may vary.

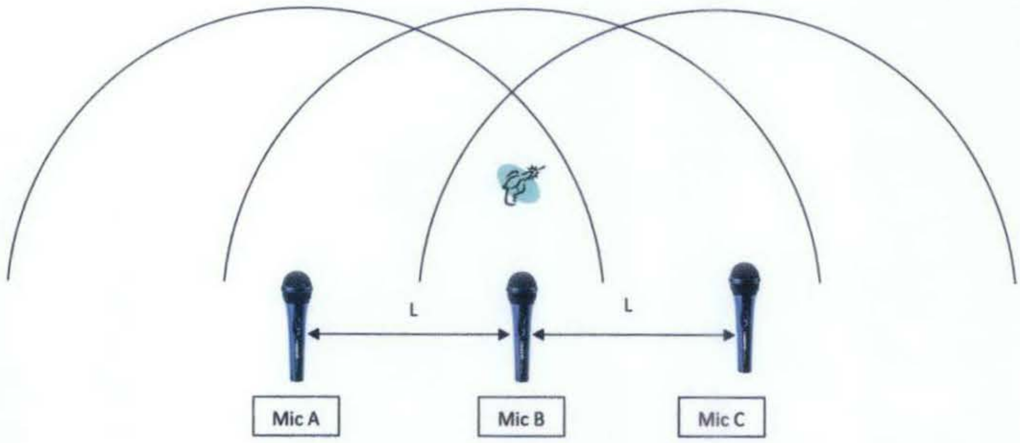


Figure 4: Microphone range

On the figure above, we can see there are three separate semi circles. The extreme left semi-circle represents microphone A's effective range, the middle semi-circle represents microphone B's effective range and finally left semi circles represents microphone C's effective range. The system is able to locate gunshots at the region where the effective range from each microphone overlap. The figure below shows the exact location of the overlapping ranges in yellow.

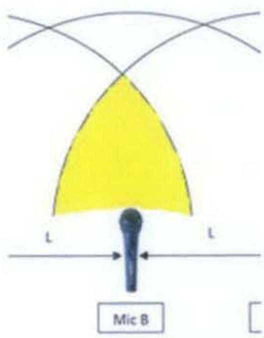


Figure 5: Overlapping Range

Figure below shows the audio signal recorded from a microphone. The audio signal below is from the sound of a banging. The microphone is able to record the sound from a distance up to 10 meters. Thus the effective range for the microphone is 10 meters.

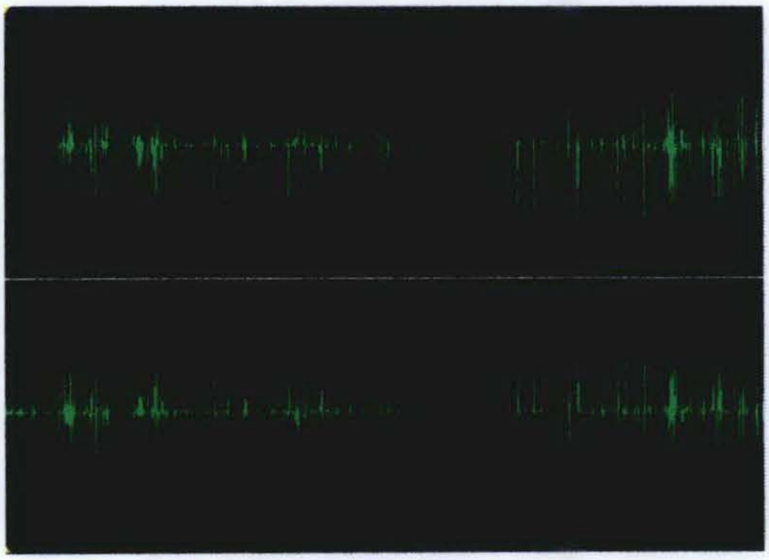


Figure 6: Banging Audio Signal

3.4.2 USB Sound Card

USB sound card is an external sound card which connect microphone to computer [3]. Creative Sound Blaster X-Fi Go is a high end USB sound card which will be perfect for this project however due to budget restrictions, a normal USB Sound Card can be used for this project. Three USB Sound card is connected to three different microphones. The existing PC sound card will not be connected to a microphone. The USB sound card is a plug and play device. However the device does have its disadvantages. Since each Sound card can only take an input from one microphone, it has to be connected to three different USB ports. If the PC does not have enough USB ports, a USB hub is needed to connect all three USB Sound cards.

Three USB sound cards are used is because the time is very sensitive in nature in this system and the precision of the time recording is crucial in this project. Therefore the three microphones must be connected to the computer simultaneously. Furthermore, most computers only have a single built in sound card which will only accept connection from a single microphone.

The figure below shows the input from 3 separate microphones simultaneously. This proves that it is possible to receive 3 separates inputs simultaneously.

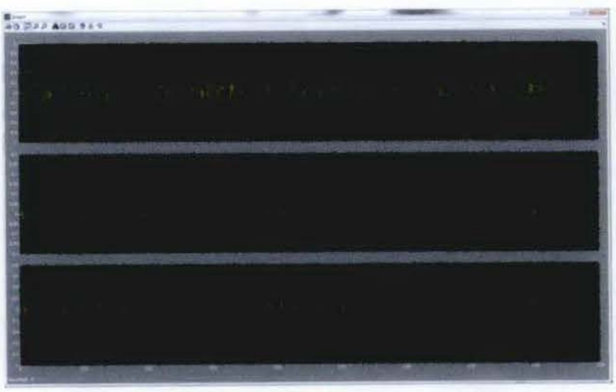


Figure 7: 3 Sound Wave from 3 microphones

3.5 Frequency Filtering

Frequency filtering or sound filters are important to remove noises from the sound. The main purpose of the sound filter in this project is to ensure that only the gunshot will trigger the time recorder and avoid false alarms. The frequency of a gunshot is around 130Hz to 3 kHz [6]. However since the project uses a toy gun or a fake gun, the sound filter will be used for filtering out noises only. For this project, a band pass filter will be used.

A band pass filter is built by combining a low pass filter and a high pass filter. A band pass filter is a frequency filter that will only pass certain range of frequencies through it [7]. The low pass filter will determine the lower cutoff frequency and the high pass filter will determine the higher cutoff frequency. In other words, by combining both low and high pass filter, only the desired range of the frequencies will enter into the system [8]. The gunshot wave in frequency domain is needed to identify the frequency range of the gunshot. By knowing this frequency, we can use is to filter out other frequencies. For the figure below, the gunshot wave is shown in frequency domain. The x axis shows frequency and the y axis is normalized magnitude.

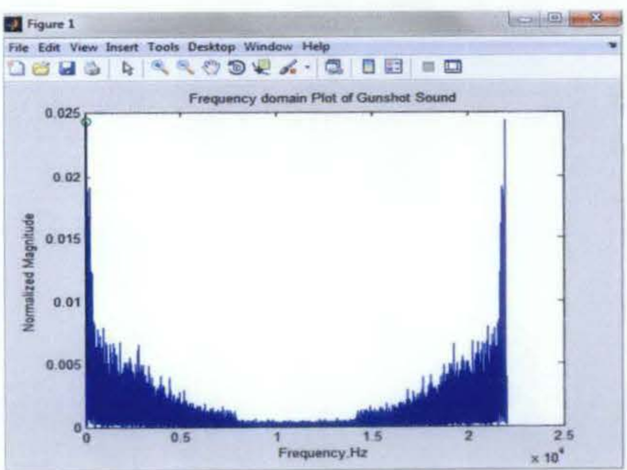


Figure 8: Gunshot Wave in Frequency Domain

The band pass filter block in Simulink can easily filter out any frequency range [9] and will automatically detect noises and automatically removes the noise. The Figure below shows the audio wave from a microphone input. The top wave shows the wave from a filtered audio wave and the second wave shows the wave directly from a single microphone input.

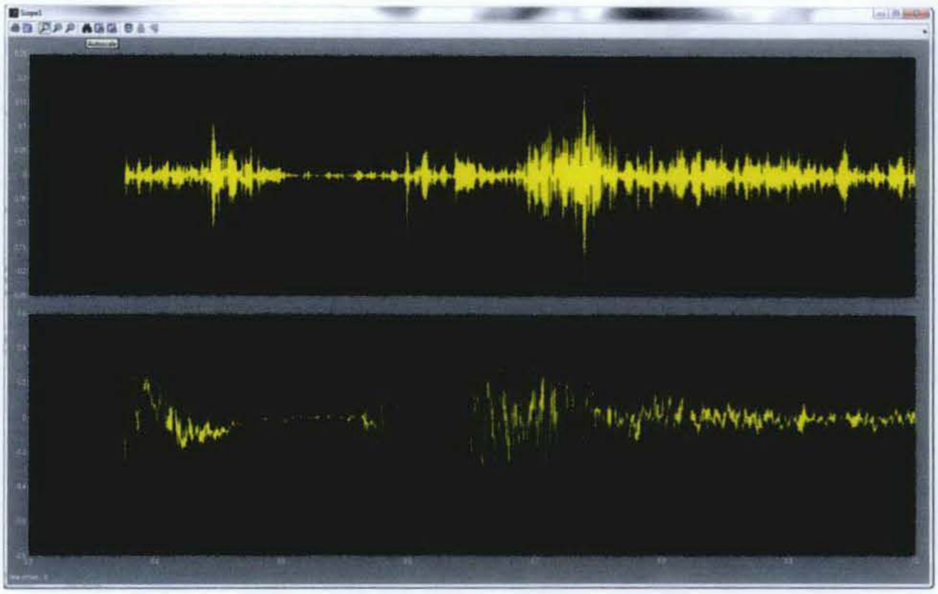


Figure 9: Filtered and Unfiltered Sound Wave

The two waves above came from the same exact source. Once it is clear that the filter was able to perform filtration from a single source, the next phase is to connect three simultaneous filters to three microphones. The Figure below shows the audio wave from 3 separate microphone inputs.

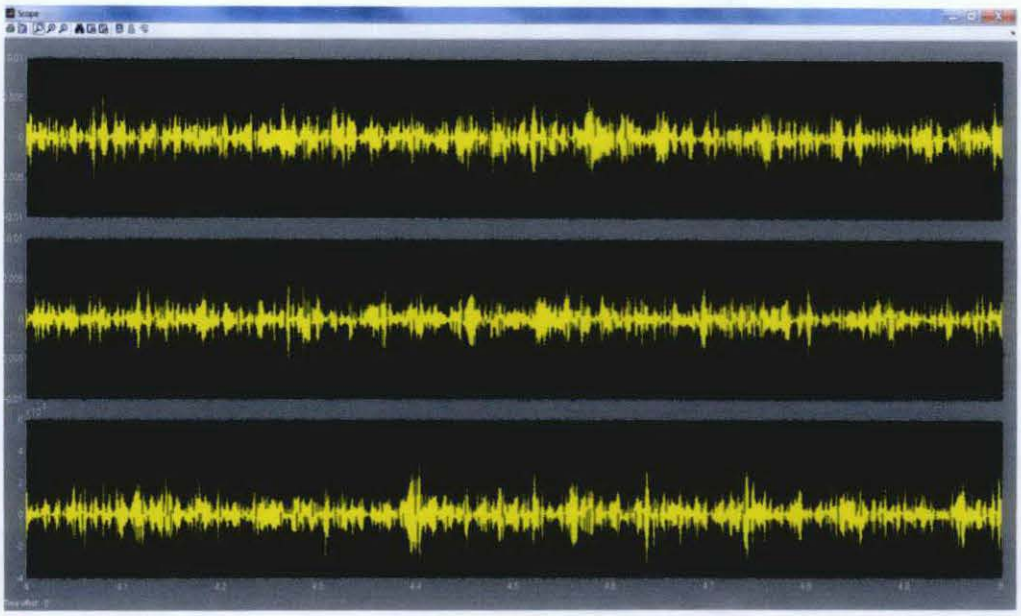


Figure 10: Filtered Sound Waves

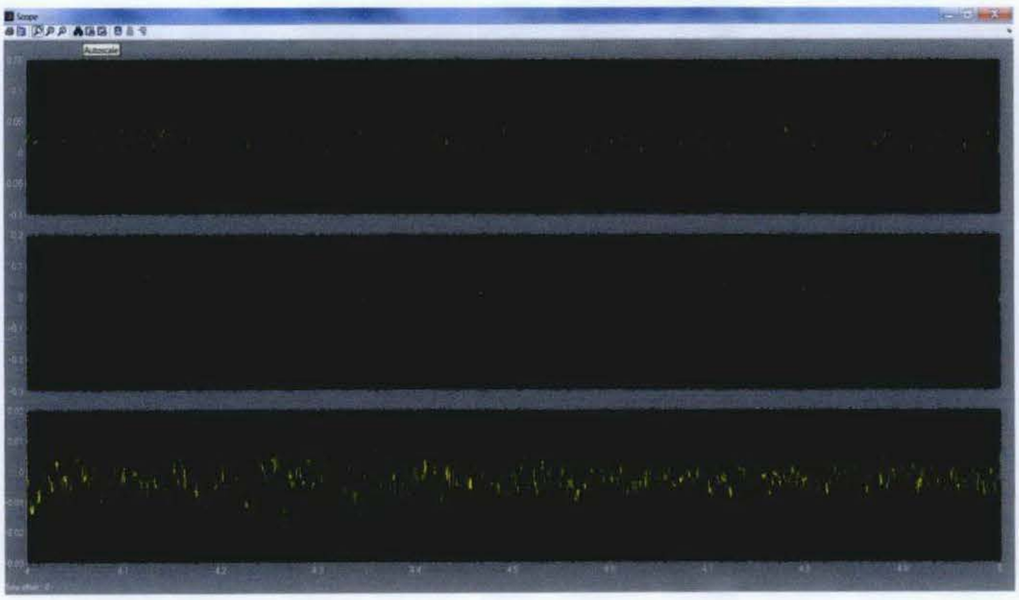


Figure 11: Unfiltered Sound Waves

3.6 Time Recorder

To measure the time of the sound captured by the microphone, we need to record the time by using a time recorder. The time recorder will be activated by Simulink and the time will be recorded subsequently. The data is then sent to MATLAB workspace.

The figure below shows a gunshot wave from a recorded gunshot audio file. By loading the audio file, MATLAB is able to show the gunshot wave graphically. In the figure, the gunshot wave is shown in time domain. The time domain graph is needed to get the peak time. The x axis shows the time and the y axis is the amplitude.

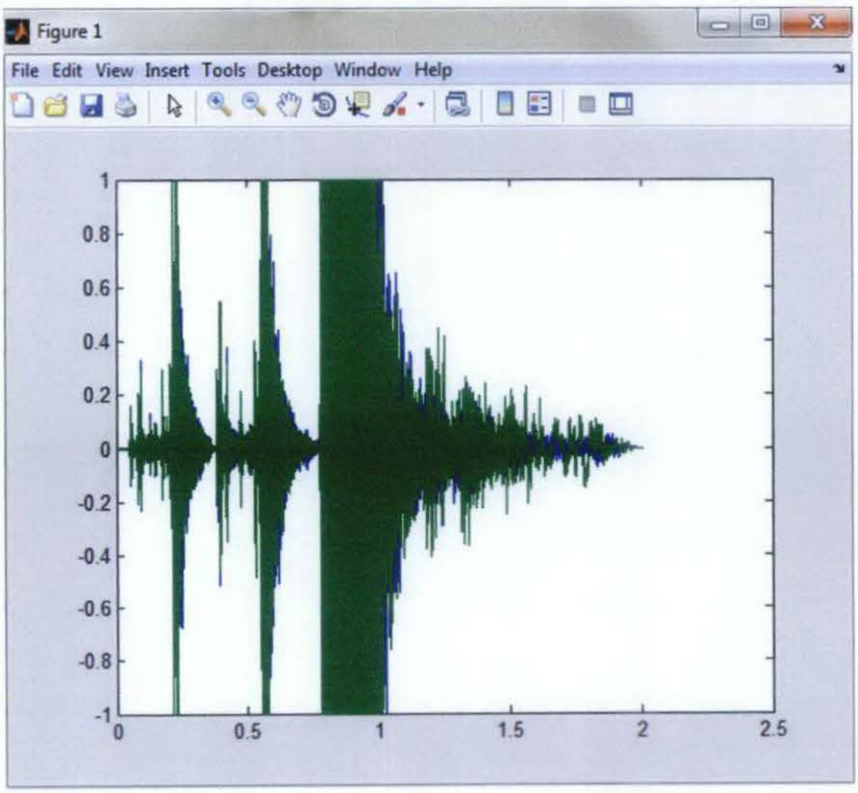


Figure 12: Gunshot Wave in Time Domain

From the MATLAB workspace, we can see a very long list of recorded data. This list is long due to the sample rate of the microphone. For example, if the sound is recorded for 10 seconds and the sample rate is 5000 samples per second, there will be a total of 50,000 samples from each microphone.

From the data in workspace, MATLAB will automatically determine the maximum amplitude from the workspace. From the maximum amplitude, MATLAB will then determine the corresponding index. The corresponding index of the maximum amplitude can be translated into peak time which will be used to calculate the location of the gunshot. For example, the maximum amplitude index from workspace A is X, and the sample rate is 5000 the peak time is

$$X \times \frac{1}{5000} = X/5000\, seconds$$

Therefore, the peak time from microphone A is X/5000. When the peak time from microphone B and C is calculated from the same formula, we then use these results to calculate the location of the gunshot.

It is important that the time recorder is calibrated first before it is used to ensure that the time recorder is working perfectly. Calibration process is a comparison between measurements where one of known magnitude or correctness made or set with one device and another measurement made in as similar a way as possible with a second device [14]. Every time a measurement is performed, there is an actual result and an expected result. Due to random and non-random variability, the actual result often differs from the expected result. Calibration works to either fix the non-random variability or account for it in such a way that the difference between the actual and expected results is negligible.

To calibrate the time recorder, all three microphones must be placed as close as possible and a test shot is fired. Ideally, the time recorder should record the exact same peak time, thus Δt_{AB} and Δt_{BC} should be zero.

When a lot of sampling for peak time is taken, the error is calculated through the root mean square with respect to the actual time which is calculated by the ratio between distance and the speed of sound. The peak time is then adjusted by imposing the error factor to compensate the actual error. For example, if the peak time of a microphone is measured to be T seconds, the modified value is equal to T+ΔT, where ΔT is the error factor. The error factor ΔT has the order of10^{-2}, since the speed of sound is of the order of 3×10^2 m/s, this produces error ~ 10 meters. In this project, the allowable error is 0.1% or 1 microsecond which is equivalent to 0.34 meters.

By using the processing system as a time recorder, the time accuracy is up to 0.1milliseconds. It would be costly if hardware time recorder is used. The time recorder application is very robust and the audio data parameters such as sampling rate and number of bits per one sample can be modified during the runtime. This application is the base for the audio processing system used in this project.

The figure below shows the results from the calibration process in MATLAB.

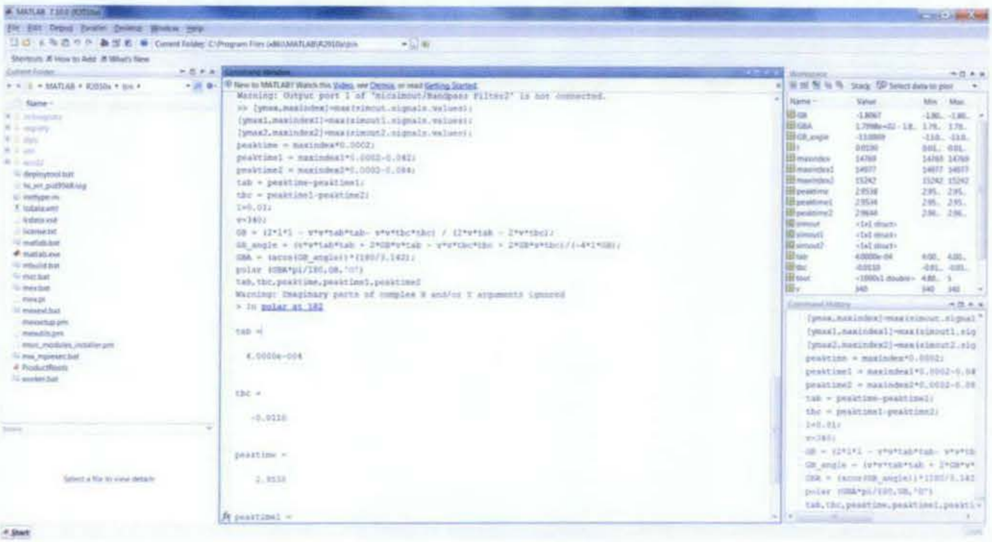


Figure 13: Calibration Results in MATLAB

The figure below shows the extracted results from the calibration process in MATLAB.

```
tab =

  4.0000e-004

tbc =

  -0.0110
```

Figure 14: Extracted MATLAB results

3.7 Processing System

As mentioned previously, MATLAB is the most important part of this project. MATLAB is used from connecting the hardware to the computer all the way to displaying the location of the gunshot on a map. MATLAB is normally used for advanced mathematics [5]. Simulink is a part of MATLAB tool which has most of the functions in MATLAB but it has several functions that MATLAB does not, making it vital for this project. MATLAB with help of Simulink will perform tasks mentioned earlier which includes connecting the USB sound cards and microphone, filtering out noises from the surrounding, measuring the time the gunshot arrives at the microphone, calculating the location of the gunshot by using the formulas and lastly displaying the location of the gunshot [12].

In this project, the first part of the processing system is done by Simulink. The first part consists of connecting the USB sound cards and microphone, filter the sound and transfer the data to MATLAB.

Figure below shows the connection of the 3 microphones in MATLAB Simulink with the help of USB soundcards. The 3 Simulink blocks on the left is the analog input block which represents each USB sound cards. On the analog input block, only one channel out of two channels should be used for each analog input block. The Simulink block diagram on the right is the scope block diagram which is used to display the results on a graph. The results are shown in the results and discussions section.

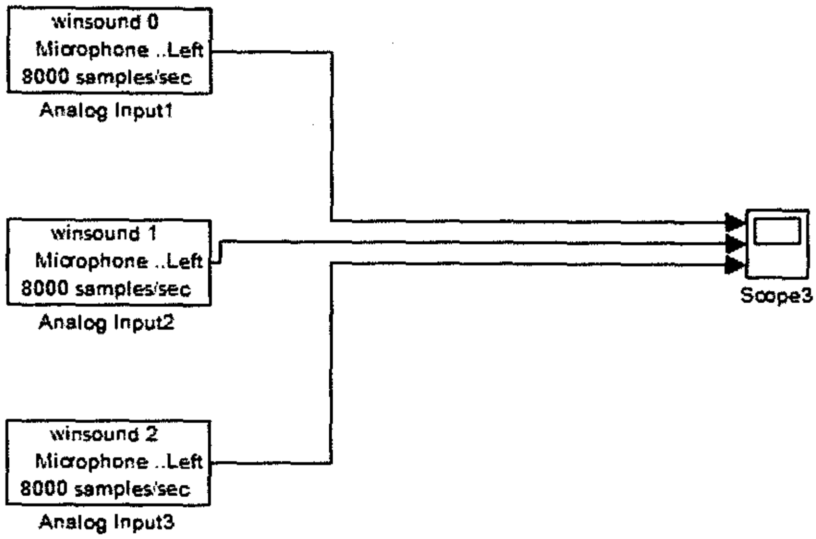


Figure 15: 3 Sound Card Connections in Simulink

The figure below shows the implementation of band pass filter block in Simulink from a single source. The outcome of the band pass filter is displayed in the results section.

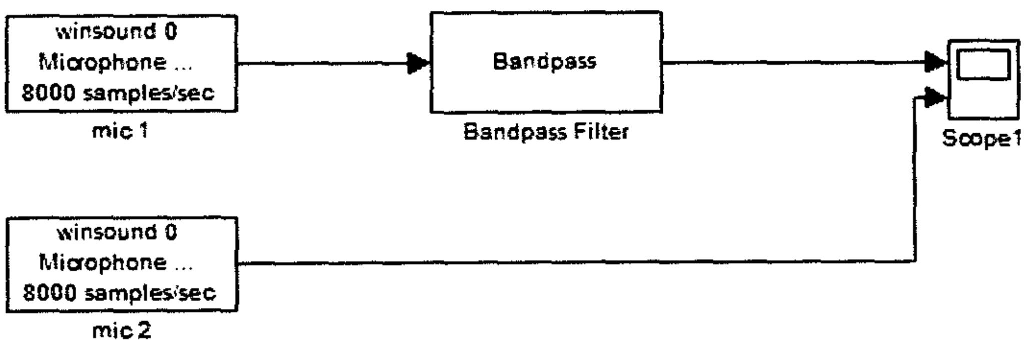


Figure 16: Band Pass Filter in Simulink

The next step is to connect the Simulink to MATLAB. To achieve this, a simout block diagram is used. Simout will send the data to MATLAB's workspace. The figure below shows a block diagram of simout.

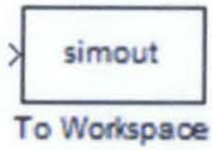


Figure 17: Simout block diagram

The final Simulink block diagram is a combination of sound card connections, band pass filter and simout block diagram. The final Simulink block diagram is shown in the figure below.

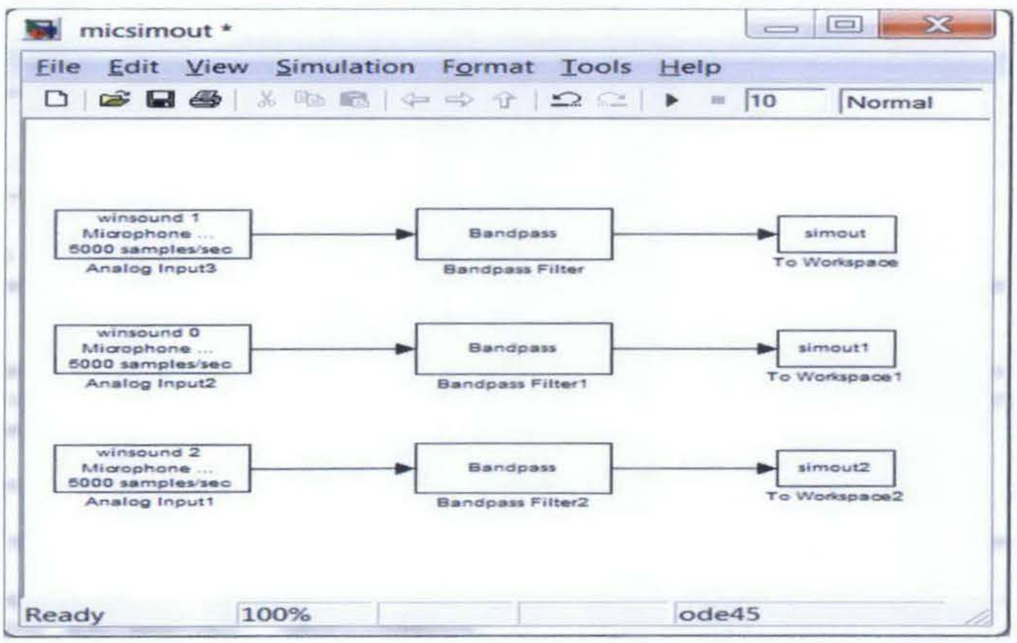


Figure 18: Complete Simulink Block Diagram

Once Simulink has finished its task, MATLAB comes to work. MATLAB interprets the data provided by Simulink as mentioned in the time recorder section and performs the calculation based on the formulas derived in the previous section. The figure below shows the MATLAB workspace with the data from Simulink.

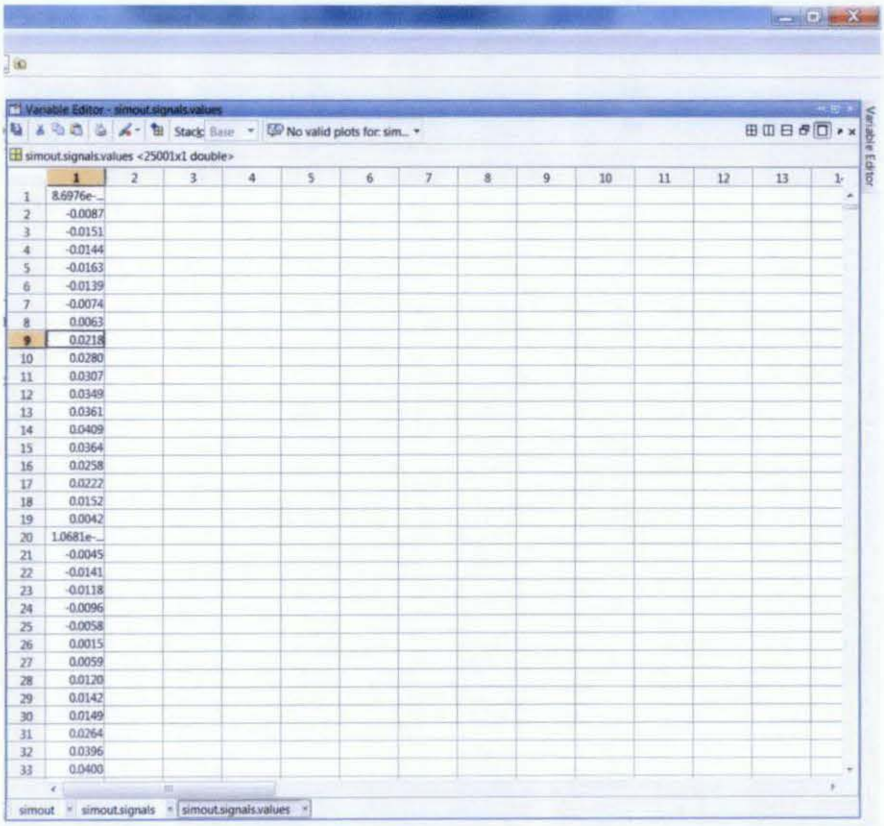


Figure 19: MATLAB Workspace

The figure below shows the MATLAB with the programming codes to extract the data from the workspace, interpret the data and perform the calculation task.

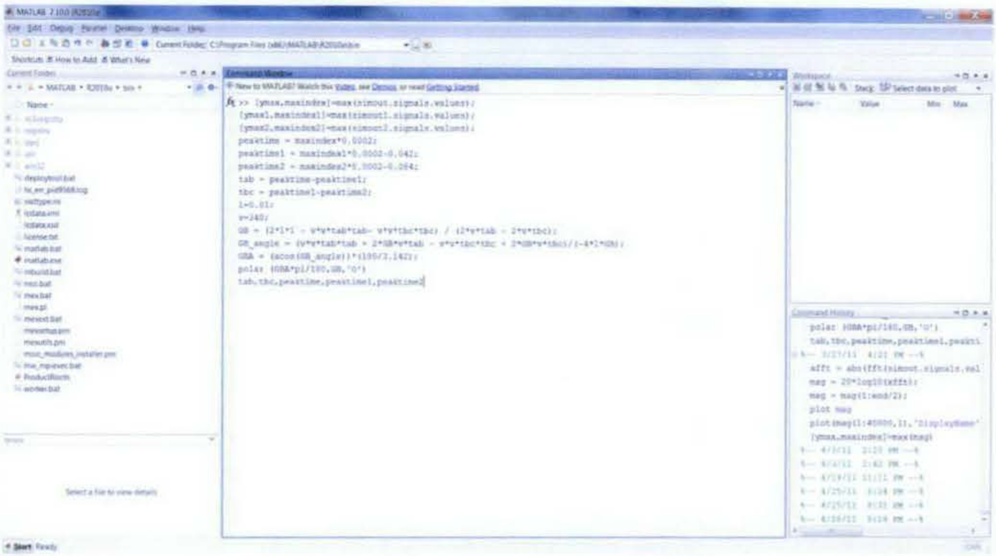


Figure 20: MATLAB

When the calculation is done and the location of the gunshot is known, MATLAB displays the distance and angle of the gunshot and location of the gunshot in a virtual map of the area as shown in the figure below.

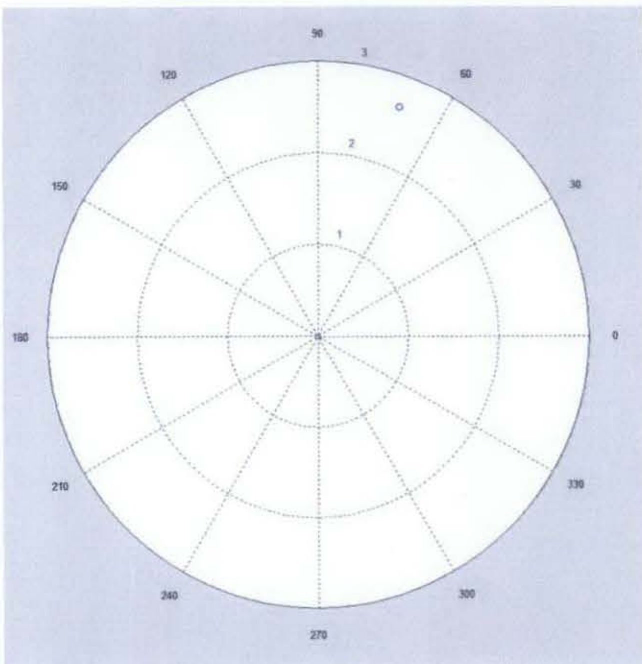


Figure 21: Simulation Map Example

The figure below shows the mapping simulation from MATLAB. In the figure below, 'o' represents the location of the gunshot. For this simulation, a carefully calculated value for each peak time is used. In this map, we can see that the gunshot is located between 120 degrees and 150 degrees and the distance is between 4 meters and 5 meters.

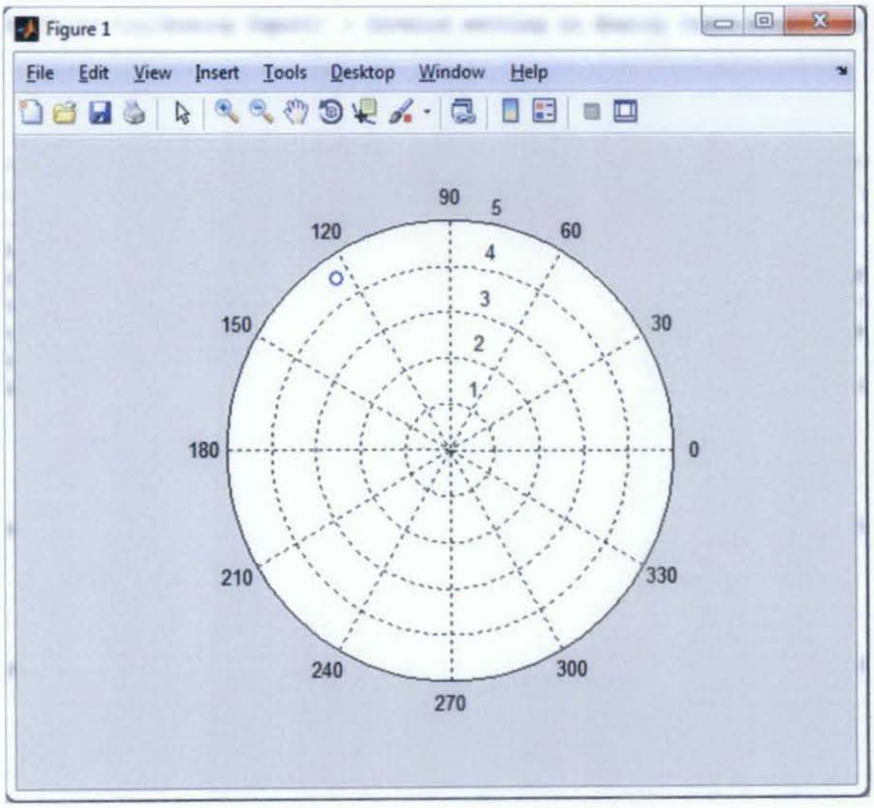


Figure 22: Mapping Simulation

When it is clear that the system is able to handle the mapping simulation, the next phase is to perform an experiment. The first experiment was done in my own room.

For this experiment, the distance from one microphone to another is set to be 0.3 meters. The figure below shows the results of the experiment. After performing the experiment, MATLAB immediately produced the output. The figure below shows the actual results from an experiment done in my room.

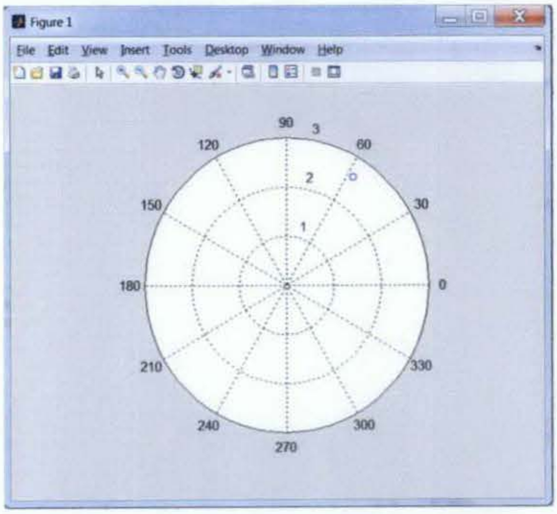


Figure 23: Mapping Results

Figure 24: MATLAB Results

```
GB =

  2.6189

GBA =

  57.4390
```

Figure 25: Extracted MATLAB Results

Next stage of the experiment was to perform the experiment in an open area.

For this experiment, the distance from one microphone to another is set to be 3 meters. The experiment was performed using an audio cable extender because the microphone cable was only 1 meter in length. However since the audio cable extender does affect the data speed, the calibration must be performed again to ensure there will be no errors. Once the calibration is done, we can proceed to the experiment. The figure below shows the results of the experiment.

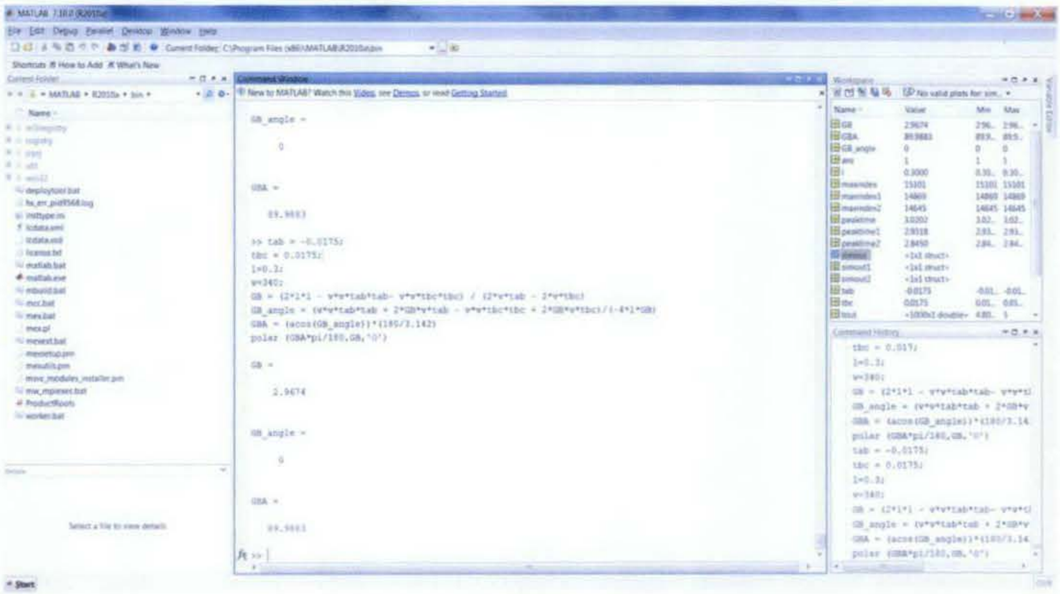


Figure 26: MATLAB Results

The figure below shows the extracted results from MATLAB.

GB =

2.9674

GBA =

89.9883

Figure 27: Extracted MATLAB Results

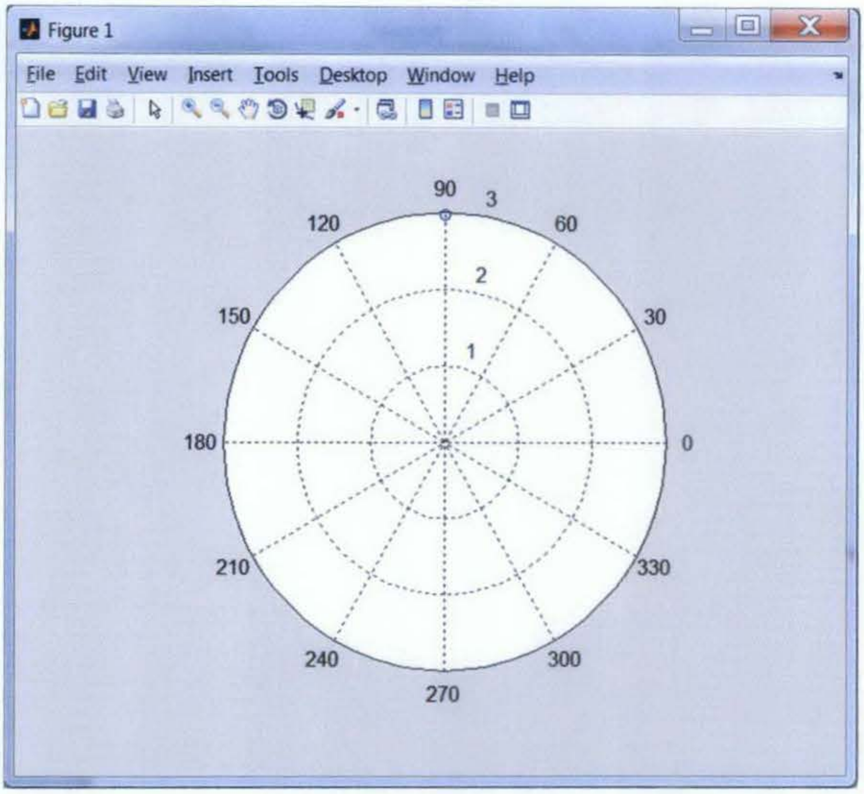


Figure 28: Mapping Results for Open area experiment

CHAPTER 4
RESULTS AND DISCUSSIONS

4.1 Results

In this section, we summarize the results of the work done this project.

4.1.1 Gunshot Spotting System results comparison

The figure below shows the results of the system taken at different angles and distance. Each graph represents the results from different angles and each graph shows the distance from 0.5 to 2.5 meters with an interval of 0.5 meters.

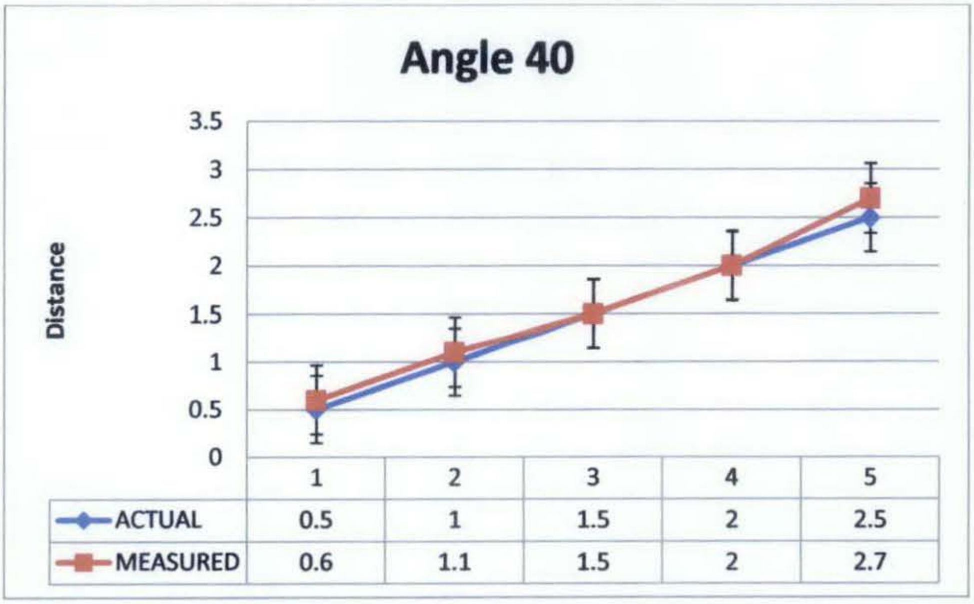
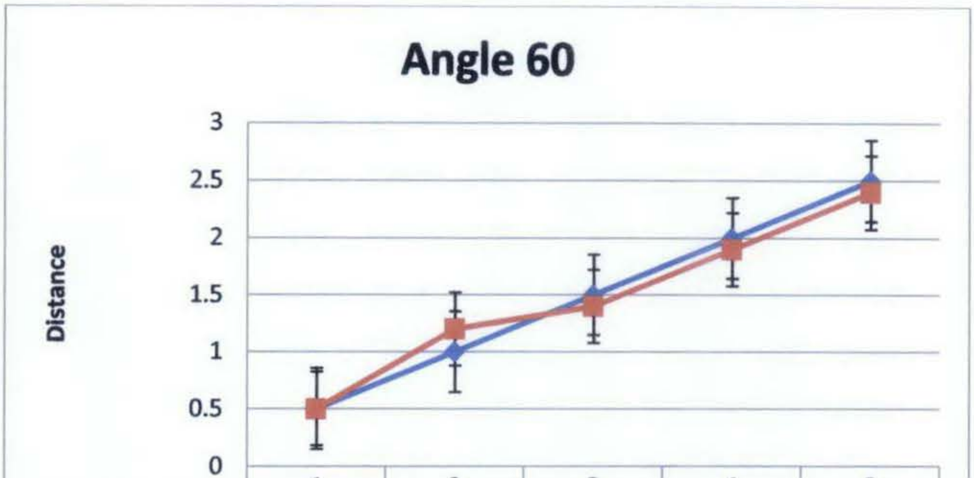
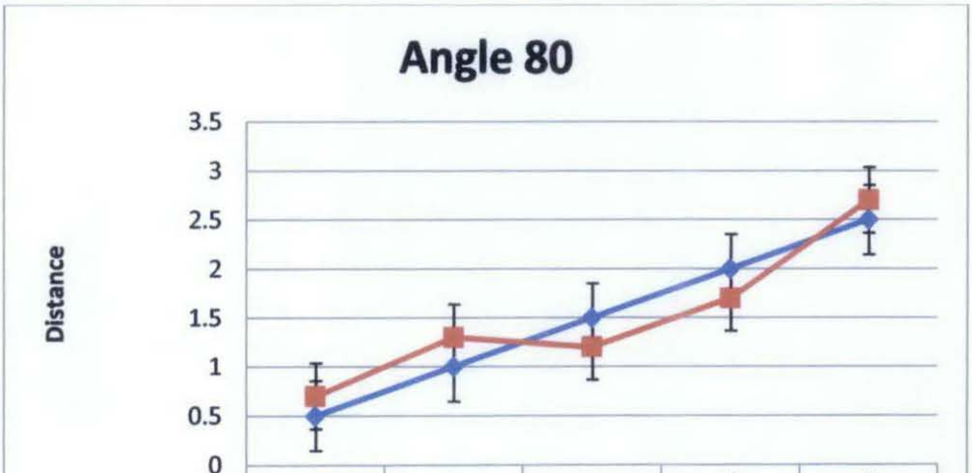


Figure 29: Gunshot Spotting System results at 40 degrees



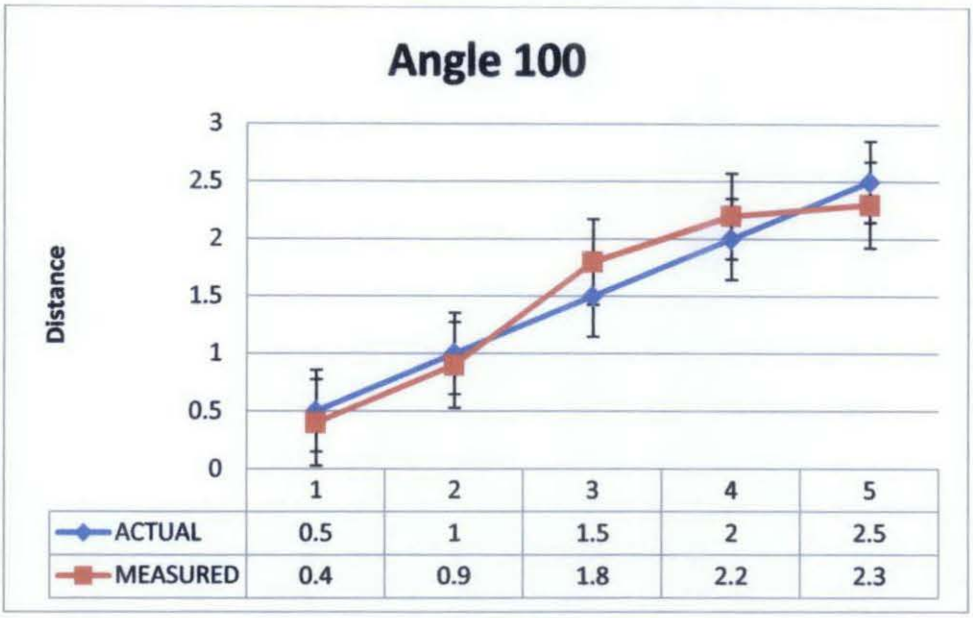
	1	2	3	4	5
ACTUAL	0.5	1	1.5	2	2.5
MEASURED	0.5	1.2	1.4	1.9	2.4

Figure 30: Gunshot Spotting System results at 60 degrees



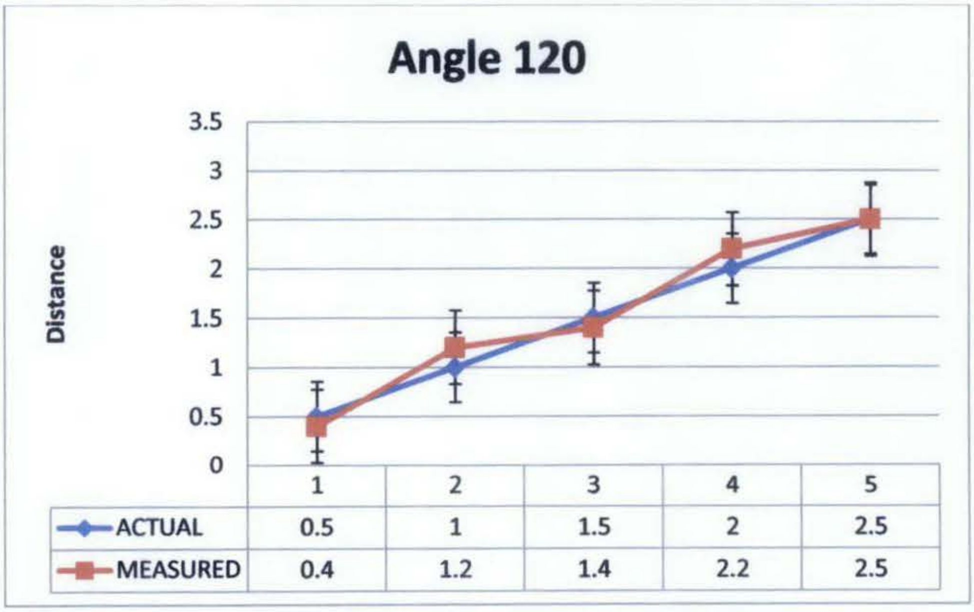
	1	2	3	4	5
ACTUAL	0.5	1	1.5	2	2.5
MEASURED	0.7	1.3	1.2	1.7	2.7

Figure 31: Gunshot Spotting System results at 80 degrees



	1	2	3	4	5
ACTUAL	0.5	1	1.5	2	2.5
MEASURED	0.4	0.9	1.8	2.2	2.3

Figure 32: Gunshot Spotting System results at 100 degrees



	1	2	3	4	5
ACTUAL	0.5	1	1.5	2	2.5
MEASURED	0.4	1.2	1.4	2.2	2.5

Figure 33: Gunshot Spotting System results at 120 degrees

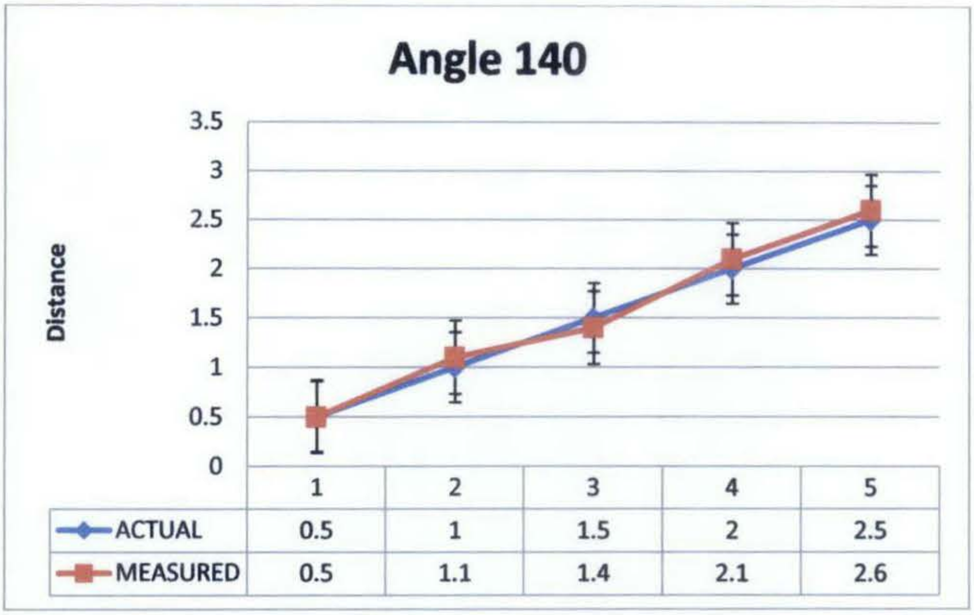


Figure 34: Gunshot Spotting System results at 140 degrees

The figure below shows the results of the system taken at different distances and angles. Each graph represents the results from different distance and each graph shows the angles from 40 to 140 degrees with an interval of 20 degrees.

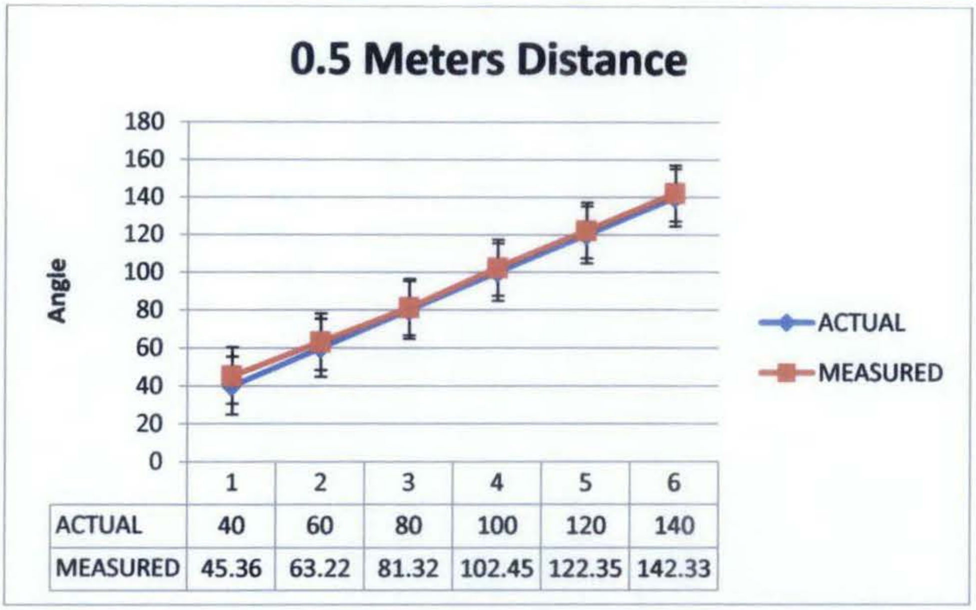


Figure 35: Gunshot Spotting System results at 0.5 meters

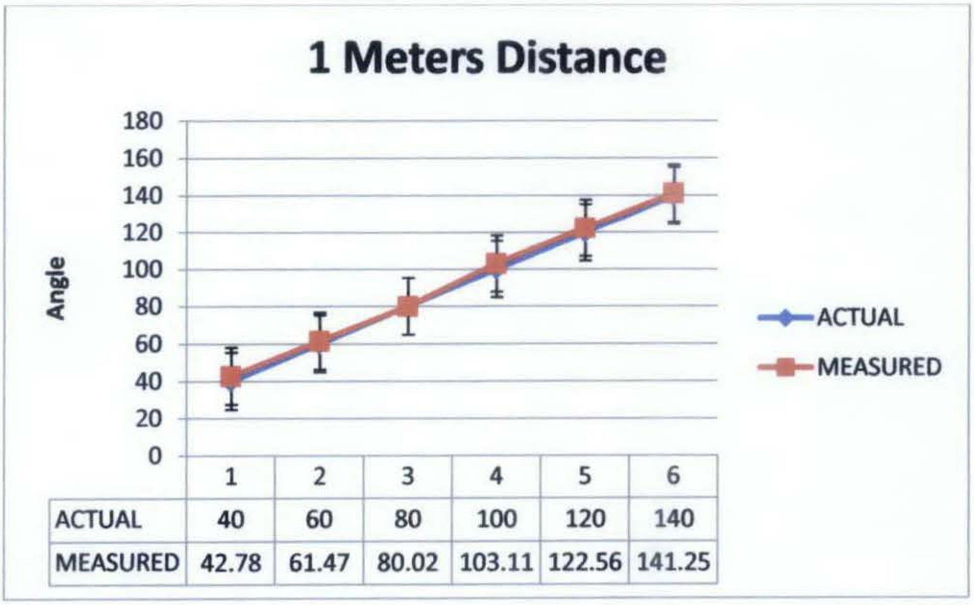


Figure 36: Gunshot Spotting System results at 1 meter

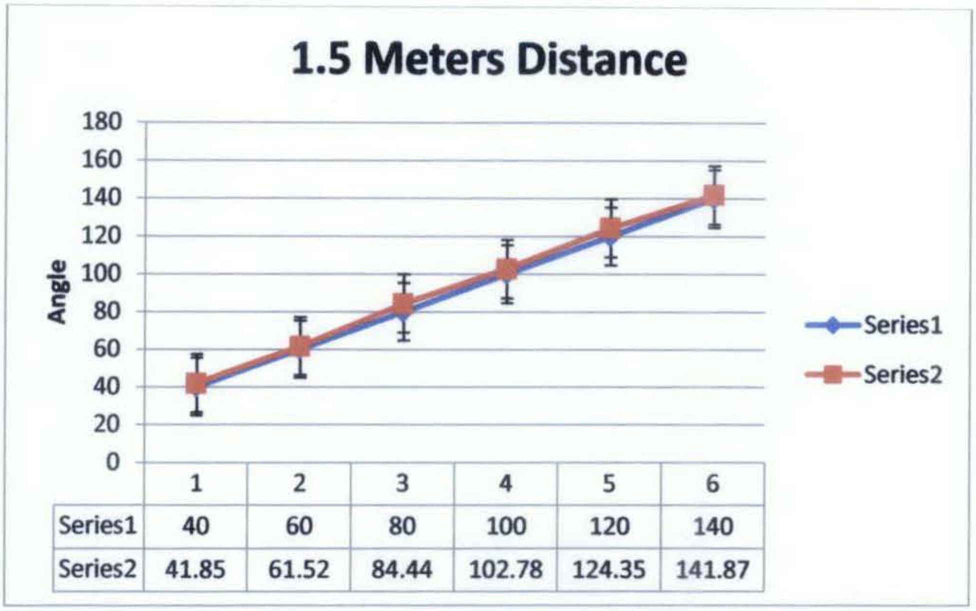


Figure 37: Gunshot Spotting System results at 1.5 meters

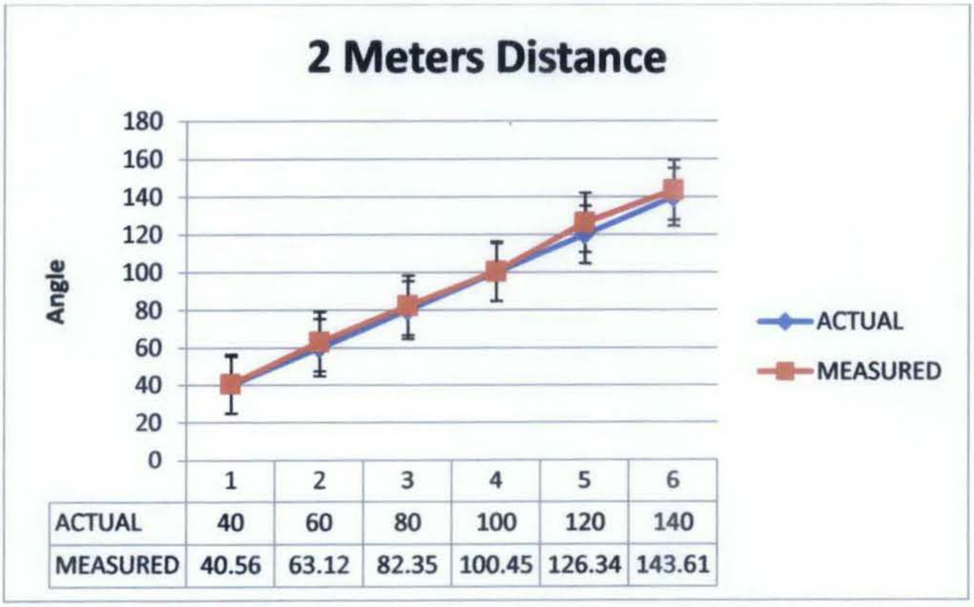


Figure 38: Gunshot Spotting System results at 2 meters

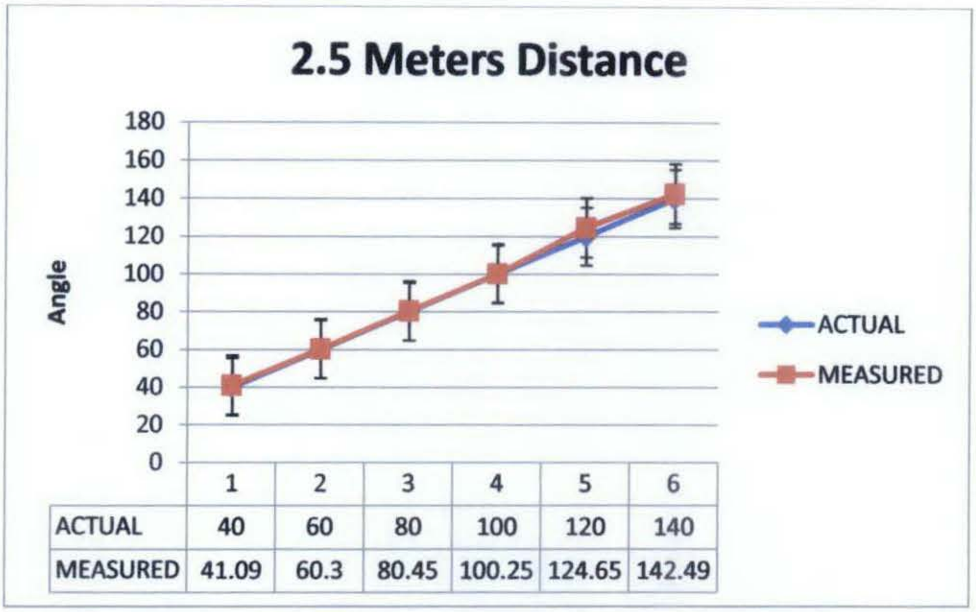


Figure 39: Gunshot Spotting System results at 2.5 meters

The figure below shows the error chart for different position inside the effective area, the radius of the position starts from 0.5m (labeled as 1 at the horizontal axis) up to 2.5m (labeled as 5 at the horizontal axis) with 0.5m interval, where the Series 1 for 40°, Series 2 for 60°, Series 3 for 80°, Series 4 for 100°, Series 5 for 120°, Series 6 for 140°.

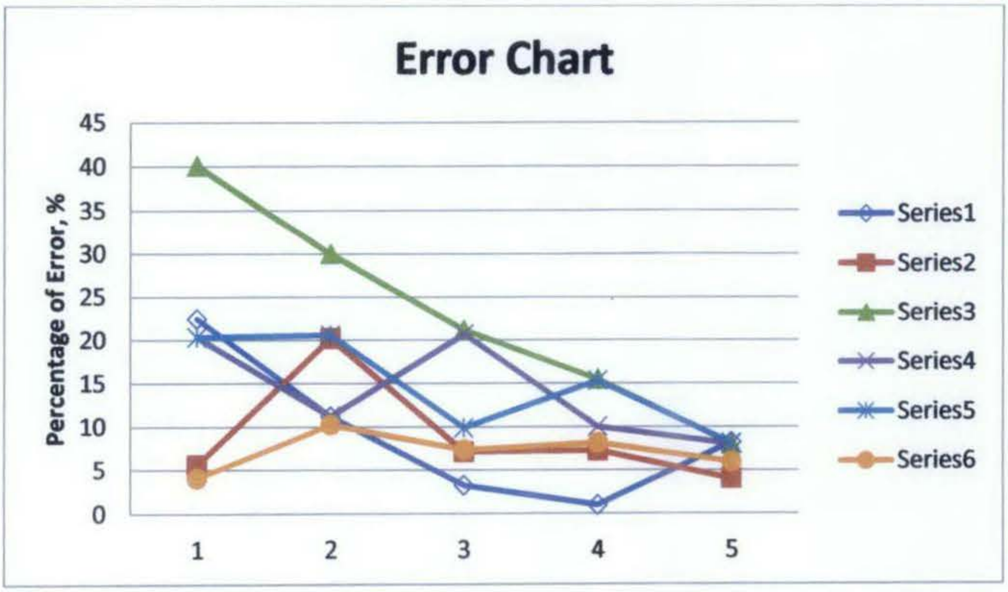


Figure 40: Error Chart

4.2 Discussions

This section we discuss the outcome performance measures of the Gunshot Spotting System and the problems encountered by the system.

According to figures 29-39 above, we see that the blue line represents the actual value and the brown line represents the measured value. The tables for the actual and measured values, the discrepancy distance L and the percentage error are given in the appendix B. The discrepancy distance L is determined based on the triangle law of cosines

$$L = \sqrt{{R_A}^2 + {R_M}^2 - 2R_A R_M \cos(\theta_A - \theta_M)}$$

Where R_A is the actual radius, R_M is the measured radius, θ_A is the actual angle and θ_M is the measured angle. The percentage error is calculated by

$$\text{Error} = \frac{L}{R_A} \times 100\%$$

We see that the performance of the system at 40° and 60° are nearly agreed with the actual location. However in the range of 80°-120° the system is comparatively less accurate. Though, the values at 140° are satisfaction within 4%.

In the error chart, the percentage of error reduces with distance at 40°. At 60°, the average error is almost constant along the distance except a single spike at 1 meter. At 80°, we see that when the distance is 0.5 meters, the percentage of error is huge however it decreases substantially with distance beyond this point.

At 100° the percentage varying along the distance, however the percentage error tends to decrease. At 120°, outcome behaved similarly with the one along 100°. And finally at the angle 140°, the percentage error is relatively low. This shows that the system performed very well at 140°.

According to appendix B the lowest percentage error occurs at 40°, 2 meters away from the origin. The distance of the measure value from the actual value is just 0.02 meters which accounts to 0.98% of error. The highest percentage error occurred at 80° with the distance 0.5 meter. This accounted to the error of 40.09% with the discrepancy 0.2 meters.

By comparing the angles with the distance show that the accuracy of the system increases with distance. This is shown in the graphs in which the distance at 0.5 meters suffers with high error. The error is reduced from 1 meter through 2 meters and lastly 2.5 meters give the least error. The accuracy is determined by the percentage error.

From this observation, we see that the system perform well when receiving signals from the left or right but performs poorly in the middle. And the system performs better when receiving the sound from far distance.

There are factors that affect the accuracy of the system such as temperature and humidity. Both these factors affect the speed of sound which is used to calculate the location of the gunshot. The higher the temperature and humidity, the faster the speed of sound will be. However due to time constraints, these factors are not considered in the project.

CHAPTER 5

CONCLUSIONS AND RECOMENDATIONS

5.1 Conclusions

Gunshot Spotting System is an interesting project which could benefit us with a great value of our safety in the community. The gunshot spotting system is designed using an array of microphones to detect the gunshot. An omnidirectional computer microphone was chosen for the project because it is affordable. These microphones are then connected to a band pass filter to filter out frequencies other than gunshot frequencies. When a gunshot is detected, the time recorder will be activated and the time difference will be calculated. The time recorder is required to have a sensitivity of at least 1ms and since it would be really expensive to build a hardware version of the time recorder, thus we opted to use a software version time recorder. Next the processing system will calculate the location of the gunshot and display the calculated location of the source on the computer screen.

5.2 Recommendations

The performance of the system can be improved, by using a microphone with higher sensitivity. A microphone with higher sensitivity able capture the sound within the larger effective range and thus, larger area can be covered to detect the gunshot.

If a CCTV is integrated in to the Gunshot Spotting System, the crime scene can be recorded. Using this as evidence, the police officer can trace the identity of the shooter.

The system can be installed on a moving vehicle such as army trucks or tanks in the jungle provided that the system can differentiate if the sound is coming from the front or back of the microphones. The Gunshot Spotting System is designed to capture gunshot in front of the microphones.

There are several factors that may affect the accuracy of the system such as wind, temperature and humidity as mentioned earlier. These factors will be considered in the future improvement of the system.

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APPENDICES

APPENDIX A
GANTT CHART

Activities / Week	1	2	3	4	5	6	7	Mid Semester Break	8	9	10	11	12	13	14
Topic selection	■														
Preliminary research		■	■	■											
Submission of Preliminary Report				■											
Mathematical Formula	■	■	■	■	■										
Microphone experiments			■	■	■	■	■		■	■	■				
Filter Design			■	■	■	■	■		■	■	■				
Programming			■	■	■	■	■		■	■	■				
Processing System									■	■	■				
System Integration									■	■	■				
User Interface												■	■		
System Testing														■	■
Preparation for Interim Report										■	■	■	■	■	■
Submission of Interim Report										■	■	■	■	■	■
Oral presentation										■	■	■	■	■	■

APPENDIX B

MATLAB RESULTS

	DISTANCE (METERS)		ANGLE (DEGREES)			
NO	ACTUAL	MEASURED	ACTUAL	MEASURED	L (METERS)	% ERROR
1	0.5	0.6	40	45.36	0.11	22.47
2	1	1.1	40	42.78	0.11	11.22
3	1.5	1.5	40	41.85	0.05	3.23
4	2	2	40	40.56	0.02	0.98
5	2.5	2.7	40	41.09	0.21	8.24

	DISTANCE (METERS)		ANGLE (DEGREES)			
NO	ACTUAL	MEASURED	ACTUAL	MEASURED	L (METERS)	% ERROR
1	0.5	0.5	60	63.22	0.03	5.62
2	1	1.2	60	61.47	0.20	20.20
3	1.5	1.4	60	61.52	0.11	7.14
4	2	1.9	60	63.12	0.15	7.29
5	2.5	2.4	60	60.3	0.10	4.03

	DISTANCE (METERS)		ANGLE (DEGREES)			
NO	ACTUAL	MEASURED	ACTUAL	MEASURED	L (METERS)	% ERROR
1	0.5	0.7	80	81.32	0.20	40.09
2	1	1.3	80	80.02	0.30	30.00
3	1.5	1.2	80	84.44	0.32	21.17
4	2	1.7	80	82.35	0.31	15.47
5	2.5	2.7	80	80.45	0.20	8.04

	DISTANCE (METERS)		ANGLE (DEGREES)			
NO	ACTUAL	MEASURED	ACTUAL	MEASURED	L (METERS)	% ERROR
1	0.5	0.4	100	102.45	0.10	20.36
2	1	0.9	100	103.11	0.11	11.25
3	1.5	1.8	100	102.78	0.31	20.69
4	2	2.2	100	100.45	0.20	10.03
5	2.5	2.3	100	100.25	0.20	8.01

	DISTANCE (METERS)		ANGLE (DEGREES)			
NO	ACTUAL	MEASURED	ACTUAL	MEASURED	L (METERS)	% ERROR
1	0.5	0.4	120	122.35	0.10	20.33
2	1	1.2	120	122.56	0.21	20.59
3	1.5	1.4	120	124.35	0.15	9.91
4	2	2.2	120	126.34	0.31	15.32
5	2.5	2.5	120	124.65	0.20	8.11

	DISTANCE (METERS)		ANGLE (DEGREES)			
NO	ACTUAL	MEASURED	ACTUAL	MEASURED	L (METERS)	% ERROR
1	0.5	0.5	140	142.33	0.02	4.07
2	1	1.1	140	141.25	0.10	10.26
3	1.5	1.4	140	141.87	0.11	7.37
4	2	2.1	140	143.61	0.16	8.17
5	2.5	2.6	140	142.49	0.15	5.97

	DISTANCE (METERS)		ANGLE (DEGREES)			
NO	ACTUAL	MEASURED	ACTUAL	MEASURED	L (METERS)	% ERROR
1	0.5	0.6	40	45.36	0.11	22.47
2	0.5	0.5	60	63.22	0.03	5.62
3	0.5	0.7	80	81.32	0.20	40.09
4	0.5	0.4	100	102.45	0.10	20.36
5	0.5	0.4	120	122.35	0.10	20.33
6	0.5	0.5	140	142.33	0.02	4.07

	DISTANCE (METERS)		ANGLE (DEGREES)			
NO	ACTUAL	MEASURED	ACTUAL	MEASURED	L (METERS)	% ERROR
1	1	1.1	40	42.78	0.11	11.22
2	1	1.2	60	61.47	0.20	20.20
3	1	1.3	80	80.02	0.30	30.00
4	1	0.9	100	103.11	0.11	11.25
5	1	1.2	120	122.56	0.21	20.59
6	1	1.1	140	141.25	0.10	10.26

	DISTANCE (METERS)		ANGLE (DEGREES)			
NO	ACTUAL	MEASURED	ACTUAL	MEASURED	L (METERS)	% ERROR
1	1.5	1.5	40	41.85	0.05	3.23
2	1.5	1.4	60	61.52	0.11	7.14
3	1.5	1.2	80	84.44	0.32	21.17
4	1.5	1.8	100	102.78	0.31	20.69
5	1.5	1.4	120	124.35	0.15	9.91
6	1.5	1.4	140	141.87	0.11	7.37

	DISTANCE (METERS)		ANGLE (DEGREES)			
NO	ACTUAL	MEASURED	ACTUAL	MEASURED	L (METERS)	% ERROR
1	2	2	40	40.56	0.02	0.98
2	2	1.9	60	63.12	0.15	7.29
3	2	1.7	80	82.35	0.31	15.47
4	2	2.2	100	100.45	0.20	10.03
5	2	2.2	120	126.34	0.31	15.32
6	2	2.1	140	143.61	0.16	8.17

	DISTANCE (METERS)		ANGLE (DEGREES)			
NO	ACTUAL	MEASURED	ACTUAL	MEASURED	L (METERS)	% ERROR
1	2.5	2.7	40	41.09	0.21	8.24
2	2.5	2.4	60	60.3	0.10	4.03
3	2.5	2.7	80	80.45	0.20	8.04
4	2.5	2.3	100	100.25	0.20	8.01
5	2.5	2.5	120	124.65	0.20	8.11
6	2.5	2.6	140	142.49	0.15	5.97

APPENDIX C

MATLAB PROGRAMMING CODE FOR ROOM EXPERIMENT

```
[ymax,maxindex]=max(simout.signals.values);

[ymax1,maxindex1]=max(simout1.signals.values);

[ymax2,maxindex2]=max(simout2.signals.values);

peaktime = maxindex*0.0002;

peaktime1 = maxindex1*0.0002-0.042;

peaktime2 = maxindex2*0.0002-0.084;

tab = peaktime-peaktime1;

tbc = peaktime1-peaktime2;

l=0.3;

v=340;

GB = (2*l*l - v*v*tab*tab- v*v*tbc*tbc) / (2*v*tab - 2*v*tbc);

GB_angle = (v*v*tab*tab + 2*GB*v*tab - v*v*tbc*tbc + 2*GB*v*tbc)/(-4*l*GB);

GBA = (acos(GB_angle))*(180/3.142);

polar (GBA*pi/180,GB,'O')
```

APPENDIX D

MATLAB PROGRAMMING CODE FOR OPEN AREA EXPERIMENT

```
[ymax,maxindex]=max(simout.signals.values);

[ymax1,maxindex1]=max(simout1.signals.values);

[ymax2,maxindex2]=max(simout2.signals.values);

peaktime = maxindex*0.0002;

peaktime1 = maxindex1*0.0002-0.042;

peaktime2 = maxindex2*0.0002-0.084;

tab = peaktime-peaktime1;

tbc = peaktime1-peaktime2;

l=3;

v=340;

GB = (2*l*l - v*v*tab*tab- v*v*tbc*tbc) / (2*v*tab - 2*v*tbc);

GB_angle = (v*v*tab*tab + 2*GB*v*tab - v*v*tbc*tbc + 2*GB*v*tbc)/(-4*l*GB);

GBA = (acos(GB_angle))*(180/3.142);

polar (GBA*pi/180,GB,'O')
```

APPENDIX E

MATLAB PROGRAMMING CODE BEFORE CALIBRATION

```
[ymax,maxindex]=max(simout.signals.values);

[ymax1,maxindex1]=max(simout1.signals.values);

[ymax2,maxindex2]=max(simout2.signals.values);

peaktime = maxindex*0.0002;

peaktime1 = maxindex1*0.0002;

peaktime2 = maxindex2*0.0002;

tab = peaktime-peaktime1;

tbc = peaktime1-peaktime2;

l=3;

v=340;

GB = (2*l*l - v*v*tab*tab- v*v*tbc*tbc) / (2*v*tab - 2*v*tbc);

GB_angle = (v*v*tab*tab + 2*GB*v*tab - v*v*tbc*tbc + 2*GB*v*tbc)/(-4*l*GB);

GBA = (acos(GB_angle))*(180/3.142);

polar (GBA*pi/180,GB,'O')
```