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ECHO-LESS RANGE FINDING SYSTEM

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Abstract

The aim of this research was to investigate a low-cost, ranging finding system, incorporating SONAR and RF-Beacon technology to determine distances for mobile robotic navigation. This hybrid system measures the propagation of an audible sound wave from a SONAR transmitter to a SONAR beacon. Rather than relying on the sound wave to be reflected back to the transmitter, a radio signal is used for the time-of-flight (TOF) measurement.

The first objective of this research was to investigate the variety of range finding methodologies that employ the TOF measurements currently used for mobile robotic navigation and review the application methodologies and limitations. The second part of the project is to develop a low cost system for indoor mobile vehicle navigation, which can be easily implemented with microcontrollers and PCs. The final part of this research involved the observation and examination of the hybrid system to check for accuracy and also made a comparison with other systems. The system developed is a working system with a reasonable accuracy. It certainly provides one more options for locating indoor mobile vehicle position.

Presented in this thesis is an in-depth discussion on the development and design process required for the hybrid SONAR system. The research conducted in this project found that the combination of SONAR and RF-Beacon technology can provide an inexpensive system for distance measurement that assists to obtain a mobile vehicle's location.

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Table of Contents

1	Introduction	1
2	Literature Review	3
2.1	Introduction.....	3
2.2	Global Positioning Systems	4
2.2.1	GPS Data Acquisition in different Environments	5
2.2.2	GPS with Dead Reckoning	6
2.3	Map-Based Positioning.....	8
2.3.1	Metric Based Mapping	8
2.3.2	Topological Based Mapping.....	9
2.4	Sound Navigation and Ranging (SONAR).....	11
2.4.1	Active Sonar Basics.....	11
2.4.2	Ultrasonic Sensors	12
2.4.3	Ultrasonic Localisation.....	12
2.4.4	Case Study: Mobile Robot Localisation Using Sonar	14
2.5	Light Detection and Ranging (LIDAR).....	16
2.5.1	Continuous Wave Ranging Basics (CWR).....	16
2.5.2	Pulse Ranging Basics (PR).....	17
2.5.3	Aerial LIDAR and Map-Based Positioning.....	18
2.6	Literature Review Summary.....	19
2.7	Literature Review Conclusions.....	20
3	Hybrid SONAR Test System for Range Finding	21
3.1	Mathematics for Beacon Trilateration	21
3.2	SONAR Test System Development.....	23
3.2.1	Key Components of SONAR Test System.....	25
3.2.2	Resolution of the SONAR Test System.....	26
3.3	Summary.....	27
4	Frequency Detection Design and Implementation	28
4.1	Target Frequency Selection	28
4.1.1	Circuit Design for a Target Frequency	29
4.1.2	Circuit Design of the Audio Amplifier.....	31
4.2	Signal Conditioning	33
4.2.1	Circuit Design for Microphone Pre-Amplifier	33

4.2.2	Circuit Design for the Band-Pass Filter.....	35
4.2.3	Circuit Design for Burst Noise Suppression.....	38
4.3	Target Frequency Detection.....	41
4.3.1	Circuit Design for Phase Locked Loop Circuit	41
4.3.2	Frequency Response Calibration	45
4.4	Decibel Level Calibration.....	45
5	Frequency Confirmation using Radio Signals.....	47
5.1	Synopsis of Radio Communication Fundamentals.....	47
5.1.1	Binary Information Generation and Modulation	48
5.2	Radio Transmitter/Receiver Pair Selection.....	49
5.2.1	ZW3100/ZW3102 Wireless Module	49
5.2.2	PICHRT111 - Radio Transceiver Module.....	50
5.3	Radio Module Integration with Microcontroller	50
5.3.1	PICAXE Microcontroller.....	51
5.3.2	ZW3100/ZW3102 integration with PICAXE Microcontroller.....	51
5.3.3	PICHRT111 integration with PICAXE Microcontroller.....	53
5.4	Radio Module Performance Evaluation.....	54
5.4.1	Performance Evaluation Methodology	54
5.4.2	ZW3100/ZW3102 Evaluation Results.....	55
5.4.3	PICHRT111 Evaluation Results	56
5.4.4	Evaluation Summary	57
5.5	PICHRT111 Integration with Frequency Detection Circuitry.....	58
5.5.1	Stop Trigger with Radio Transmission Triggers	58
6	Real-Time Data Acquisition.....	61
6.1	Microcontroller for Real-Time Data Acquisition	61
6.1.1	PICAXE Time Measurement Resolution	62
6.2	Pulse Generation	64
6.2.1	Circuit Design for Pulse Generation.....	65
6.3	Microcontroller Data Transmission	66
6.3.1	PICAXE communication with LabVIEW Interface.....	66
7	System Integration and Control.....	69
7.1	SONAR Transmitter System Control	69
7.1.1	Target Frequency Generation Control.....	69
7.1.2	Real-Time Data Acquisition Control.....	70

7.1.3	Radio Confirmation Control	71
7.1.4	SONAR Transmitter Integration with LabVIEW Interface.....	71
7.1.5	SONAR Transmitter Power Supply.....	73
7.2	SONAR Beacon System Integration.....	75
7.2.1	SONAR Beacon Power Supply	75
7.3	SONAR System Assembly	77
7.3.1	SONAR Transmitter Test Rig	77
7.3.2	SONAR Beacon Test Rig	78
8	Examination of the SONAR System	79
8.1	SONAR Distance Theory	79
8.1.1	Distance vs. Time	79
8.2	Experiment 1 - Test on Linear Distance Change	82
8.2.1	Experiment 1 - Results and Data Analysis	83
8.3	Experiment 2 - Test on Orientation Change	90
8.3.1	Experiment 2 - Results and Data Analysis	92
8.4	Experiment 3 - Test on Elevation Change	97
8.4.1	Experiment 3 - Results and Data Analysis	98
9	Conclusions and Recommendations.....	103
9.1	Comparisons with Reviewed Range Finding Systems	103
9.2	Future Development Considerations	105
	References	106
	Appendix A	108
	Appendix B.....	115
	Appendix C.....	133

List of Figures

Figure 2-1 Simplified Diagram of GPS operation.....	4
Figure 2-2 Results from Willgoss and Rosenfeld, 2003.....	7
Figure 2-3 Results from Willgoss and Rosenfeld, 2003.....	7
Figure 2-4 Example of a Grid-Based Map	9
Figure 2-5 Example of a Topographical Map	10
Figure 2-6 Active sonar illustrations	12
Figure 2-7 Generalised Ultrasonic Localisation.....	13
Figure 2-8 Misalignment of transmitter receiver pair adapted from H.R. Everett (1995)	14
Figure 2-9 Mapped indoor environment adapted from Drumheller (1985)	15
Figure 2-10 Sonar Segments to obtain a contour of an indoor environment adapted from Drumheller (1985).....	15
Figure 2-11 CWR Phase difference measurement from (Lohani, n.d).....	17
Figure 2-12 Time of travel measurement between transmitted and return pulse from (Lohani, n.d)	18
Figure 2-13 Prior Map compared to Local Map from Donamukkala et al. (2003)	19
Figure 3-1 Model Indoor Environment	22
Figure 3-2 Solving for x	22
Figure 3-3 Non-Rectangular Room Example for Trilateration	23
Figure 3-4 Simplified SONAR System Components for Range Finding.....	24
Figure 3-5 Time between Triggers	24
Figure 3-6 Components for SONAR Transmitter	26
Figure 3-7 Counting clock edges to determine time-of-flight for a sound WAVE.....	27
Figure 4-1 Sine Wave Generator Circuit.....	29
Figure 4-2 Sine Wave Generator PCB	30
Figure 4-3 Generated Sine Wave (ABOVE) compared to Pure Sine (BELOW).....	30
Figure 4-4 Audio Amplifier Circuit	31
Figure 4-5 Speaker	31
Figure 4-6 Sine Wave Amplifier Prototype Circuit Board.....	32
Figure 4-7 Input Generated Sine Wave (Lower Curve) compared to Amplified Sine Waveform (Upper Curve) with R7 set to 2 KOhm	32
Figure 4-8 Amplified Sine Waveform (a) with R7 = 4 KOhm, (b) R7 = 6 KOhm.....	32

Figure 4-9 Amplified Sine Waveform (a) with $R7 = 8 \text{ KOhm}$, (b) $R7 = 10 \text{ KOhm}$	33
Figure 4-10 Signal Conditioning Block Diagram	33
Figure 4-11 Cross-Section of a Condenser Microphone (“Condenser,” n.d).....	34
Figure 4-12 Pre-Amplifier Circuit Schematic	35
Figure 4-13 Pre-Amplifier Prototype Circuit Board	35
Figure 4-14 Idealised frequency response of a band-pass filter adapted from Franco (1988)	36
Figure 4-15 State Variable Filter Circuit Schematic	36
Figure 4-16 Pre-Amplified Ambient noise passed through Band-pass Filter	37
Figure 4-17 Pre-Amplified Sine Wave passed through Band-pass filter	37
Figure 4-18 Example of Burst Noise.....	38
Figure 4-19 Burst Suppression Circuit Schematic	39
Figure 4-20 Burst Suppression Prototype Circuit Board.....	39
Figure 4-21 Noise Burst Suppressed by SSM2167 Circuit	40
Figure 4-22 Signal Conditioning of a Sine wave coupled with Burst Noise.....	41
Figure 4-23 Phase Locked Loop Circuit Diagram	43
Figure 4-24 NE567 PPL Centre Frequency f_0	43
Figure 4-25 Phase Locked Loop and State Variable Filter Prototype Circuit Board	43
Figure 4-26 PPL Circuit adjusting phase adjust phase	44
Figure 4-27 PPL Centre frequency Adjustment –(a) 180 degrees out of phase, (b) 3.6 Degrees out of phase, (c) in phase.....	44
Figure 5-1 Simplified Radio Trigger Block Diagram	47
Figure 5-2 ZW3100 and ZW3102 Modules	49
Figure 5-3 PICHRT111 Radio Transducer.....	50
Figure 5-4 PICAXE-08M Microcontroller with Experimenter Board	51
Figure 5-5 (a) ZW3100 in Experimenter Board, (b) ZW3102 in Experimenter Board	52
Figure 5-6 PICAXE-08M pin configuration for ZW3100	52
Figure 5-7 PICAXE-08M pin configuration for ZW3102	52
Figure 5-8 (a) PICHRT111 in Experimenter Board configured as Radio Transmitter, (b) PICHRT111 in Experimenter Board configured as Radio Receiver.....	53
Figure 5-9 PICAXE-08M pin configuration for PICHRT111 as Radio Transmitter	54
Figure 5-10 PICAXE-08M pin configuration for PICHRT111 as Radio Receiver	54
Figure 5-11 ZW3000 and ZW3002 transmission errors.....	56
Figure 5-12 PICHRT111 Demodulated received radio signal	56

Figure 5-13 PICHRT111 Transmission and Reception delay	57
Figure 5-14 Microcontroller decoding ASCII data and turning on LED	57
Figure 5-15 Level Detector Circuit Schematic.....	59
Figure 5-16 Detailed Block Diagram of SONAR Beacon with Radio Confirmation	60
Figure 6-1 Square-Pulse Generation Simplified.....	64
Figure 6-2 NOR Gate used to generate Square-PULSE.....	64
Figure 6-3 Pulse Generation Circuit Schematic	65
Figure 6-4 Response time of Pulse Generator Circuit.....	65
Figure 6-5 Communication link between Microcontroller and Computer	67
Figure 6-6 Screenshot of LabVIEW program used for serial Communication.....	67
Figure 7-1 Frequency Generation Control Diagram	70
Figure 7-2 Real-Time Data Acquisition Control Diagram.....	70
Figure 7-3 Radio Confirmation Control Diagram	71
Figure 7-4 Block Diagram of SONAR Transmitter System	72
Figure 7-5 Screenshot of LabVIEW Interface.....	73
Figure 7-6 Interface Circuit Schematic	74
Figure 7-7 Power distribution.....	74
Figure 7-8 Power Supply Circuit Schematic	76
Figure 7-9 SONAR Transmitter Test Rig	78
Figure 7-10 SONAR Beacon Test Rig	78
Figure 8-1 Theoretical Time vs. Distance	81
Figure 8-2 Experiment 1 Apparatus Setup	82
Figure 8-3 Converted time measurements for 0.5 metres	85
Figure 8-4 Averaged Times vs. Distance	86
Figure 8-5 Experiment 2 Apparatus Setup	90
Figure 8-7 Distance measurements for a 10 degrees.....	94
Figure 8-8 Averaged Times vs. Distance	95
Figure 8-9 Sound Wave Propagation in Relation to Accuracy	96
Figure 8-10 Experiment 3 Apparatus Setup	97
Figure 8-11 Distance measurements for an Elevation of 1.5m	100
Figure 8-12 Linear Distance vs. Averaged Vertical Height	101
Figure 8-13 Right angled triangle.....	102

1 Introduction

With recent advances in navigation systems for mobile robotics, the need for a cheap, reliable and adaptable localisation system is growing rapidly. A number of mobile robotic projects involve indoor applications, requiring systems to provide the mobile robot with current positioning information relative to its environment. In determining position, navigation and localisation systems use a variety of techniques and technologies to acquire distance information.

Positioning systems such as **S**ound **N**avigation and **R**anging (SONAR) are mainly used for underwater navigation; however, these systems can also be used in the air, although for mobile robotic localisation applications this is often overlooked in favour of the more commonly used obstacle avoidance approach. Another technology utilised in mobile robotic navigation is **R**adio **F**requency **B**eacons (RF-Beacon), such as the widely popular **G**lobal **P**osition **S**ystems (GPS). However, application of these in mobile robotics is limited to outdoor navigation, as both systems measure the time it takes for a wave (sound wave or electromagnetic wave) emitted from a transducer to travel to an object and back again.

Single return SONAR systems that operate in this manner are susceptible to noise (Smith, 2001), and accurate distance measurements require that the path of the sound wave to the target is not obstructed. On the other hand, while RF-Beacons are not susceptible to interference from objects in the path of a direct line between the emitted wave and the target, building such custom RF-Beacons systems for indoor applications can be expensive. Additionally, the distances normally associated with RF-Beacon systems such as GPS range in the hundreds of kilometres, and thus are not suitable for indoor applications.

The aim of this research is to investigate a low-cost system incorporating SONAR and RF-Beacon technology to determine distances for mobile robotic navigation. This hybrid system measures the propagation of an audible sound wave from a SONAR transmitter to a SONAR beacon. Rather than relying on the sound wave to be reflected back to the transmitter, a radio signal is used for the time-of-flight (TOF) measurement.

The first objective of this research is to investigate the variety of distance finding methodologies that employ the TOF measurements currently used for mobile robotic navigation. A review of GPS, SONAR and Light Detection and Navigation (LIDAR) systems is conducted in this research. The application methodologies used in mobile robotic navigation and the limitations of each system were reviewed. The findings showed GPS and LIDAR systems are expensive and only suitable for very large outdoor areas of operation. In contrast, SONAR systems were found to be relatively inexpensive and often used for indoor environments. The SONAR systems reviewed employed ultrasonic frequencies and suffered from line-of-sight issues. All the systems reviewed had to be paired with other sensor technology to make a complete guidance system. Following the review of varying technologies, the research focused on outlining the methodology and implementation process for developing a hybrid SONAR system, with the goal of overcoming the limitations of the reviewed range finding systems. Presented in the follow chapters of this research is an in-depth discussion on the development and design considerations of the necessary components required for the SONAR system. The research conducted in this thesis found the combination of SONAR and RF-Beacon technology for distance measurement is plausible. The final segment of this researched involved the observation and examination of the hybrid system to check for accuracy and ensure the system overcomes the limitations of the reviewed systems.

The structure of the thesis closely follows the process outlined in this Chapter. In Chapter Two, the literature review is reported in detail with a focus on navigation systems that employ TOF methodologies for distance measurement, with the evaluation of these technologies. Chapter Three contains research into the fundamentals of trilateration, and a project proposal outlining the design of a hybrid SONAR system. The design considerations and implementations of the SONAR systems hardware, firmware and software components are covered in Chapters Four through Seven. Outlined in Chapter Eight are the experimental methodologies and procedures for testing the SONAR System, as well as a report and analysis of the results. Finally, Chapter Nine contains the evaluation of the SONAR system, discussion, conclusions drawn from the findings in this research and recommendations for further improving the system.

2 Literature Review

2.1 Introduction

The ultimate goal in mobile robotic development is to create a truly autonomous mobile robot with no human input. To achieve this, in terms of navigation, autonomous robot projects often incorporate several guidance systems. The work environment and intended application of the mobile robot may render some navigation techniques useless or ineffective. Furthermore some navigation techniques require alterations to the work environment such as the addition of magnetic guide lines, or radio frequency identification tags to be embedded into the workshop floor and can be expensive to alter an already established plant or facility.

Navigation Systems have been in development for decades in the robotic industry and can be divided into two categories, Path Finding and Localisation. Path Finding Systems enable an autonomous mobile robot to plan or plot a course to a goal destination. Localisation Systems enable an autonomous mobile robot to determine its current position or location relative to its current environment. Path Finding and Localisation Systems are as important as each other with many technologies and methodologies overlapping.

Localisation systems for mobile robots can be categorised into two distinct types **Independent Localisation** and **Dependant Localisation**. Independent Localisation relies on a combination of onboard sensors to compute the robots current position in an environment and does not require information from external sources. Dependant Localisation systems requires external information to be sent to the mobile robot to compute its current position in an environment.

2.2 Global Positioning Systems

Global Positioning Systems or GPS can be categorised as a dependant localisation system. A popular navigation system for outdoor use, a mobile robot is fitted with a GPS receiver and localisation is based on information received from satellites (Borenstein, Everett, Feng, 1996). The GPS implements complicated trilateration techniques based on the time-of-flight (TOF) of coded spread-spectrum radio signals transmitted by four to six satellites. This information results in an absolute 3-dimensional (3-D) position of the GPS receiver (Borenstein et al., 1996).

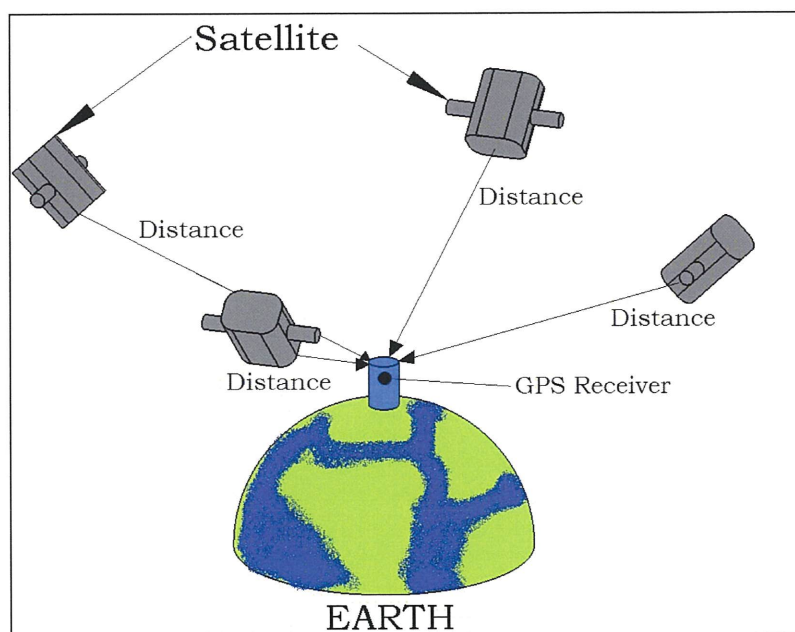


Figure 2-1 Simplified Diagram of GPS operation

There are a number of GPS receiver manufacturers and there is a relationship between cost and accuracy of the receiver (Willgoss & Billingsley, 2003). Low cost receivers process the information every second and there is an unpredictable time delay due to the rate at which the information is received from a satellite and the processing time of that information by the GPS receiver. Accuracy can be affected by a few meters with occasional excursions to greater than 10 meters (Willgoss & Billingsley, 2003).

2.2.1 GPS Data Acquisition in different Environments

In an experiment conducted by Panzieri, Pascucci, and Ulivit, (n.d), a low cost GPS receiver was tested at two points (A and B). A robot with a GPS receiver gathered data at different times of the day from both locations. Point A was an open parking lot with few obstructions and Point B was in-between two buildings. The GPS receiver took 900 samples in a 1 second period. Some of the data obtained is presented in Table 2-1 and Table 2-2.

Table 2-1 Satellite Availability at Point A

Satellite Number	First Acquisition	Second Acquisition	Overall Percentage
4	0	11	0.6
5	0	53	2.9
6	197	127	18.0
7	685	282	53.7
8	18	427	27.7

Table 2-2 Satellite Availability at Point B

Satellite Number	First Acquisition	Second Acquisition	Third Acquisition	Overall Percentage
3	180	0	0	6.6
4	401	298	121	30.3
5	319	602	697	59.9
6	0	0	82	3.0

The minimum number of satellites required for complete 3-D localisation is four which is realised for points A and B. The experiment does reveal that more satellites are detected by the GPS receiver in an open environment (Point A). According to the data, on average more samples are attained when the robot was located at Point A. More samples will result in better overall accuracy. The buildings located at Point B effected the wave propagation of radio signals and fewer samples were recorded.

It is common to combine GPS system with other systems should the GPS work intermittently or fail. It is therefore essential to combine the GPS receiver data with other sensor information to create an effective guidance system.

2.2.2 GPS with Dead Reckoning

Navigation by dead reckoning works by calculating a mobile robots position and orientation over time by integrating its velocity with respect to time as defined in Bekey (2005), and is often referred to as odometry data. In the research conducted by Willgoss and Rosenfeld (2003), two GPS receivers were combined with a dead reckoning system to establish a high precision guidance system. The goal of the research was to investigate the accuracy of a mobile robots actual position by blending GPS and odometry data.

Once the GPS receivers have acquired the appropriate information and established the robots position, that information is then combined with odometry information to determine the robots exact location. If the GPS receivers fail for any reason, it is then possible to use the last known odometry information to establish the robots position. A mathematical model was simulated in MATLAB to simulate the results of odometry with GPS using a Kalman Filter (Welch & Bishop, 2006). The simulated model was provided with the distance travelled by the wheels and steering angle of the mobile robot at 0.1 second intervals (odometry information) and the GPS information at 1 second intervals. A goal destination was input into the simulation. The blending coefficient β (Welch & Bishop, 2006), was used to calculate the relative proportions of GPS and odometry depending on which was most trustworthy at the time. The coefficient took the form of:

Equation 2.1
$$\beta = \exp (K*D)$$

Where K is proportionality constant and D is the Euclidian distance from the actual to the predicted position of the mobile robot (Willgoss & Rosenfeld, 2003). The simulated results depended on the information being out of date by 4 seconds. The model was then subjected to variances in odometry and GPS information to simulate real world conditions. The MATLAB model was then put into practise using a robotic test platform. The robot used by the project is a flexible test bed with a 10 micro

accuracy for wheel position. The robot was then instructed to travel 3 meters east and 1 meter south Figure 2-2 and 2 meters north and 3 meters east Figure 2-3.

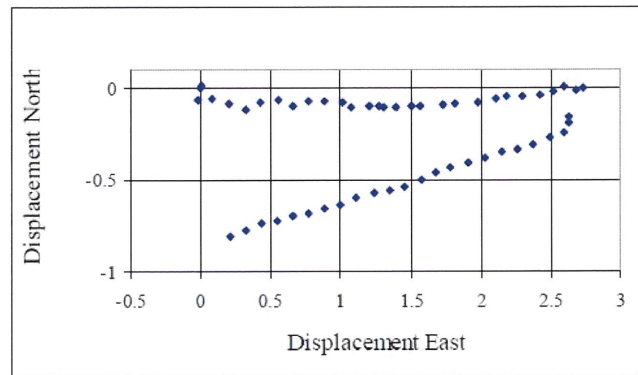


Figure 2-2 Results from Willgoss and Rosenfeld, 2003

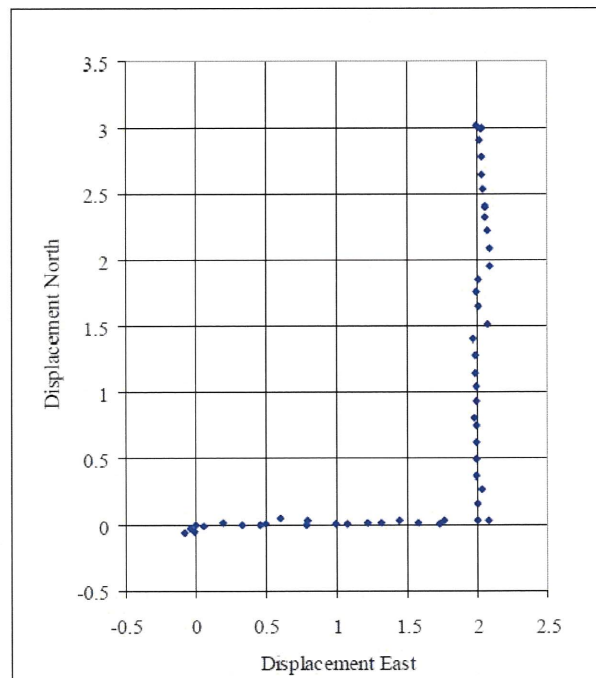


Figure 2-3 Results from Willgoss and Rosenfeld, 2003

In the first test, the mobile robot stopped 25 centimetres short of the target path, and in the second test, remained within 5 centimetres of the predetermined path. The accuracy of this system is limited to the estimations made by GPS data. The level of the ground was assumed to be uniform for these tests although some areas were uneven and had gradual slope that may affect the accuracy of the algorithms used to calculate the robots position. The weight distribution of the robot could also throw off the odometry readings ultimately affecting the positioning data. Time delays and GPS sample errors as discussed in Willgoss and Rosenfeld (2003), are not taken into account as samples

are only taken with a set delay. Autonomous control of a mobile robot was achieved with centimetre accuracy with the fusion of odometry and GPS information.

2.3 Map-Based Positioning

Map-Based Positioning (Mapping) is a real-time technique that involves the creation and use of digital maps and models of indoor environments for autonomous mobile robotic guidance and navigation. There are two types of mapping techniques. The most common method used is grid-based mapping (Bekey, 2005). The second type of mapping technique used is topographical-based maps. Both techniques are often coupled with odometry data and other range sensor data.

2.3.1 Metric Based Mapping

A metric-based map consists of an evenly spaced grid where each grid represents an obstacle or area of free space that the mobile robot can travel within. Consider the example grid-based map of an indoor environment in Figure 2-4. For a mobile robot, the dark grey areas represent a fixed object or a wall. The mobile robot must avoid collision with these objects and walls when navigating from room to room.

Objects are not always fixed and therefore continuous range sensor data is required to allow a mobile robot to navigate to a desired location within the map without colliding into objects. This will also ensure that if the map data has changed the sensors onboard will allow the robot to stop and calculate a new path. The data from the sensors can also be used to self localise to determine current position and orientation (Borenstein et al., 1996). Grid-based methods produce accurate maps, but their complexity and large data requirement often prohibits efficient planning and problem solving in large-scale indoor environments (Bekey, 2005).

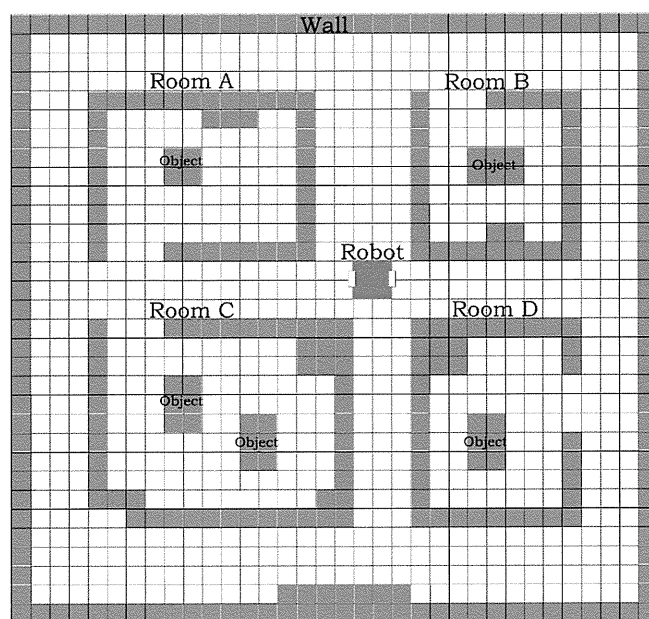


Figure 2-4 Example of a Grid-Based Map

2.3.2 Topological Based Mapping

Topological-based mapping replicates a mobile robot environment by graphs (Borenstein et al., 1996), and relies on the location of key landmarks in the environment and not the distance between landmarks (Bekey, 2005). In a topographical map a distinct landmark in the environment is referred to as a Node. There can be any number of nodes where each node is connected to the next node by a series arcs as shown in Figure 2-5. Topological based maps contain less data than the grid-based counter-part.

A mobile robot is programmed to travel a path along a set number of nodes to a set destination. The mobile robot is limited to areas near or around node locations. Furthermore, sensors designed to recognise nodes may miss a node or confuse one node for another. Map construction is made difficult in large environments as the requirement for more nodes is increased.

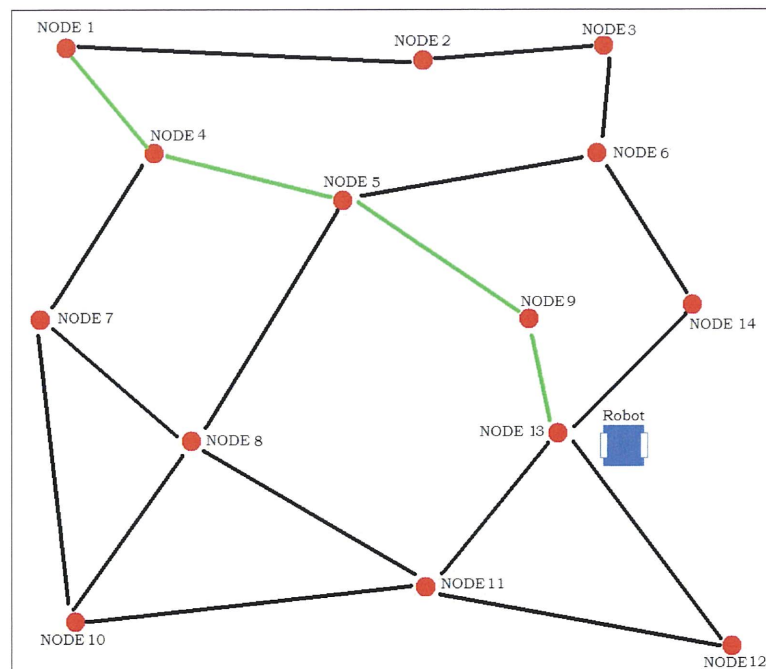


Figure 2-5 Example of a Topographical Map

If a mobile robot is given the topographical map shown Figure 2-5, the mobile robot can travel to NODE 1 via the indicated green path but not limited to that exact path. The robot will first have to identify the closest node using predetermined sensor technology. Using the information found in the topographical map the robot must then decide the best path from that node to the goal destination node.

The mobile robot will require a significant amount of processing power depending on the path finding algorithm used. Topographical-based mapping also requires algorithms to determine current position relative to current node and the ability to model the environment based on the information in the map.

A critical issue outlined in Borenstein et al. (1996, p. 206) is the selection of sensors for the applications and target environment. The sensing capability to utilize this mapping technique can come at the expense of cost.

2.4 Sound Navigation and Ranging (SONAR)

Sound navigation and ranging, more commonly known as SONAR, is an umbrella term used to describe methodologies for measuring distances, detecting objects and navigation: based on the propagation of sound waves through a given medium. Typically, SONAR is used for underwater applications as sound travels 4.4 times faster in water than in air (Tucker, 1966). SONAR is not limited to underwater applications and can function in air which can be suitable for indoor mobile robot applications. SONAR is divided into two types, **Passive** and **Active**. Passive systems listen to sounds waves generated by a target whereby the information can then be interpreted. Generally limited to aquatic environments (Tucker, 1966) and is regularly used by marine biologist to detect the presence or absence of marine life. Active SONAR is commonly used in industrial automation. A typical example is mobile robotic applications.

2.4.1 Active Sonar Basics

The fundamentals of SONAR are clearly presented in text books. The key point is the use of sound to measure a distance. A transmitter emits a sound pulse where the distance r is calculated by the length of time t taken for the sound pulse to be transmitted to and reflected back from an object and detected by a receiver (see Figure 2-6). The speed of sound is denoted by c , thus the following formula is derived by Smith, (2001, p. 114).

Equation 2.2
$$r = ct/2$$

This principle of SONAR provided the platform for SONAR based range sensors. These sensors are now widely used in robotic applications, intelligent control and industrial automation.

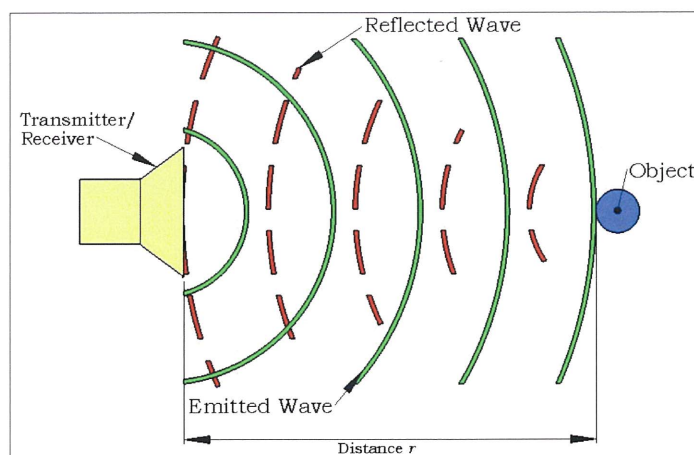


Figure 2-6 Active sonar illustrations

2.4.2 Ultrasonic Sensors

According to Everett (2002), a popular active SONAR technique for indoor mobile robotics is ultrasonic ranging. Commonly used for collision detection and avoidance, ultrasonic sensors return the distance to the nearest object. Ultrasonic sensors can be used in localisation systems to locate a mobile robots current position in small to medium sized indoor environment (Smith, 2001).

An ultrasonic sensor is an optoelectronic transducer which converts a physical measurement by the emission and reception of acoustic energy as defined by Smith (2001). Generally an ultrasonic sensor consists of two parts, a transmitter that outputs high frequency pulse train (normally 45kHz), and a receiver that detects the pulses and outputs an electric signal either based on frequency phase shift due to a reflections or TOF of the ultrasonic pulse. The TOF measurement method of operation is referred to as pulse-echo mode in Smith, (2001, p. 114).

2.4.3 Ultrasonic Localisation

To determining an autonomous robots position in a small indoor environment, ultrasonic trilateration schemes are used (Everett, 1995) that are similar to the GPS. This is where instead of a GPS receiver being fitted to the mobile robot a master

ultrasonic receiver module is fitted with several slave ultrasonic transmitters to operate as beacons instead of geostationary satellites (Borenstein et al., 1996, p. 154).

It is then possible to calculate the 2-dimensional Cartesian coordinates of the robot if certain variables are already known, such as the dimensions of the room and relative positions of the slave beacons in the room (Everett, 1995). Figure 2-7 illustrates a generalised setup of an ultrasonic trilateration scheme using 1 master receiver and 3 slave transmitters. Thus by use of trigonometry, if $L1$ and $L2$ are known, then it is possible to calculate the X and Y coordinates of the master ultrasonic receiver relative to the origin $0,0$ based on the distance data of A , B , and C .

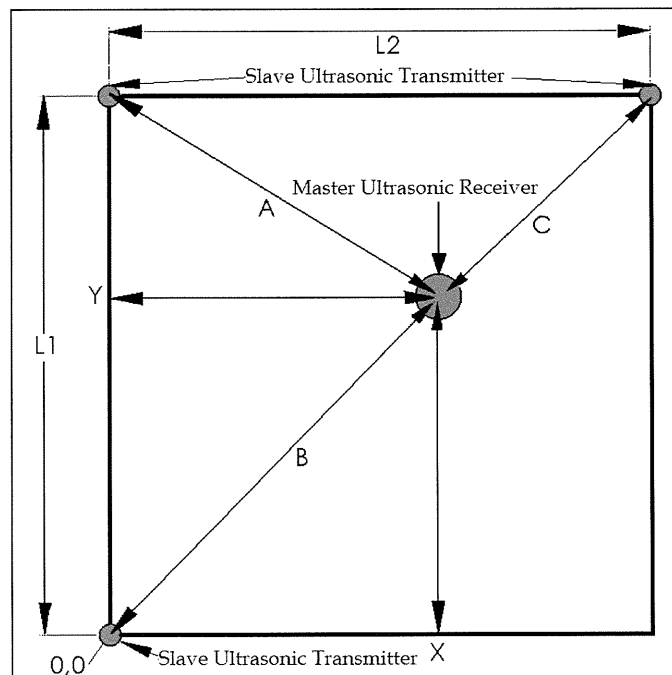


Figure 2-7 Generalised Ultrasonic Localisation

A limiting factor of ultrasonic trilateration suggested by Everett (1995) is the use of the system in multiple rooms requiring a network of ultrasonic beacons creating complex and costly scenarios. Everett (1995) also mentions the physical dimensions of the ultrasonic transducers limit the width of the transmitted and received wave. This is problematic when the receivers or transmitters are off axis as shown in Figure 2-8, resulting in inaccurate range measurements.

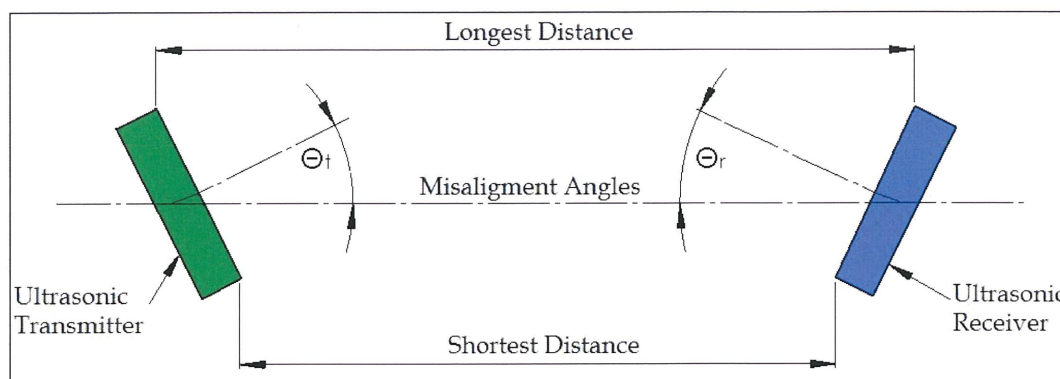


Figure 2-8 Misalignment of transmitter receiver pair adapted from H.R. Everett (1995)

2.4.4 Case Study: Mobile Robot Localisation Using Sonar

The case study describes a method in which range data from a sonar device is used to determine the 2-dimensional position of a mobile robot in an indoor environment based on map data investigated by Drumheller (1985). The goal of the study was to design a method to allow a mobile robot to calculate its position and orientation in an indoor environment based on the known dimensions of the indoor environment. There are two requirements for the method; firstly the mobile robot needs to be provided with a model of the operating environment. Secondly, a sonar device is needed for range finding. In this case study, a Polaroid Ultrasonic Rangefinder was used.

Each wall in the indoor environment is numbered from 1 to 6 as shown in Figure 2-9. The robot then obtains a sonar trace of the room in the form of straight line segments using the ultrasonic sensor. This is called “sonar segments” as defined in Drumheller (1985, p. 3), and the data is then feed into an algorithm to filter out erroneous data. The sonar segments are then converted into wall contours by joining the ends of the segments contours (see Figure 2-10). The calculated contours are paired with the environment model (length and relationships to other walls) to attain the orientation and position of the mobile robot. The studied showed that localisation could be realised quickly and a less noisy sensor would improve accuracy. The study fails to discuss moving obstacles and how that may interfere with data collection and sonar segment creation. Not discussed in the study was the height at which the ultrasonic sensor was mounted. The height may vary the data acquired from the sensor and wall contours may

not be accurate. The study has shown that the system developed is appropriate for laboratory conditions and not real world applications.

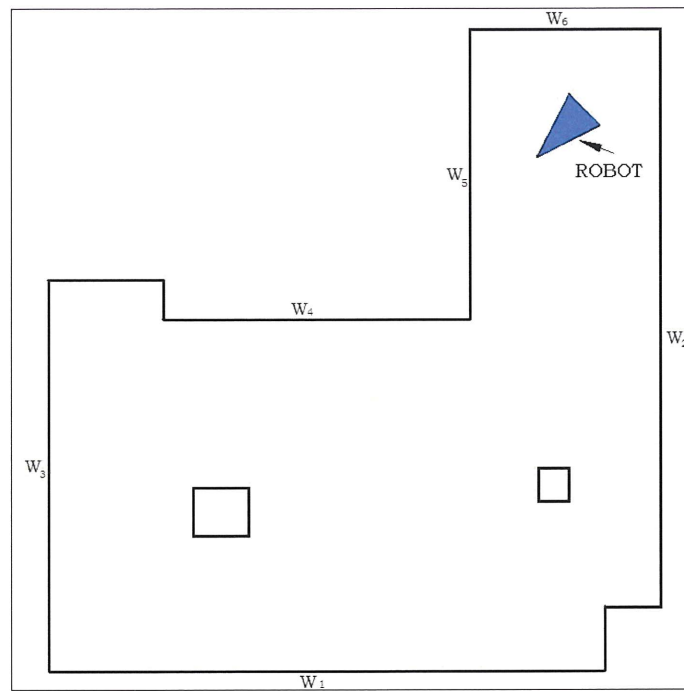


Figure 2-9 Mapped indoor environment adapted from Drumheller (1985)

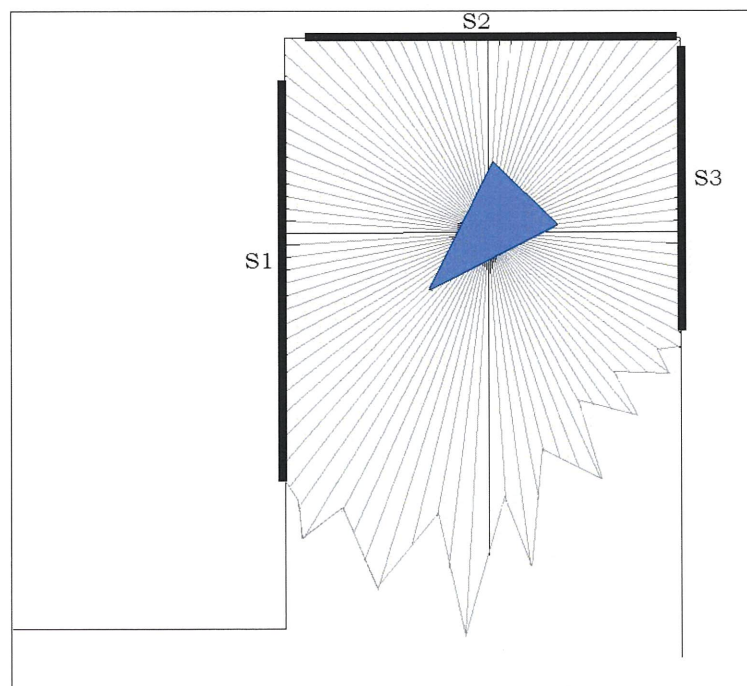


Figure 2-10 Sonar Segments to obtain a contour of an indoor environment adapted from Drumheller (1985)

2.5 Light Detection and Ranging (LIDAR)

Light Detection and Ranging (LIDAR) or Laser Detection and Ranging (LADAR) is a light-based time-of-flight ranging system (Borenstein et al., 1996) where an optical sensing technology measures the properties of scattered light to find range of a distant target (Smith, 2001). There are two methods for determining range, Continuous Wave Ranging (CWR) and Pulse Ranging (PR). Both ranging techniques require an emitter and detector (Smith, 2001). The average LIDAR unit is priced at \$1000+ NZD and has an operational area of 20 km sq.

2.5.1 Continuous Wave Ranging Basics (CWR)

In the case of CWR a laser beam is used to measure the distance between transmitter and reflector as shown in Figure 2-11, by measuring the phase difference between the transmitted and reflected wave (Lohani, n.d). The time of travel is calculated by,

$$\text{Equation 2.3} \quad TL = nT + (\Phi/2\pi)*T$$

T is the time taken for light to travel one wavelength and Φ is the phase difference. The total number of full wavelengths is represented by n and is the only unknown. Therefore range R is given by,

$$\text{Equation 2.4} \quad R = (TL/2)*c$$

Where c is the speed of light. So for $n = 0$,

$$\text{Equation 2.5} \quad R = (nT + (\Phi/2\pi) T/2)*c$$

Equation 2.5 Simplifies to,

$$\text{Equation 2.6} \quad R = (c/4 \pi) (\Phi/f)$$

Range accuracy is reliant on the resolution of phase difference measurement and on the wavelength. CWR systems are highly accurate; however the maximum range that can be measured is limited due to the high cost and difficulty in generating continuous high

energy waves. The CWR technique is not commonly employed by systems for mobile robotics.

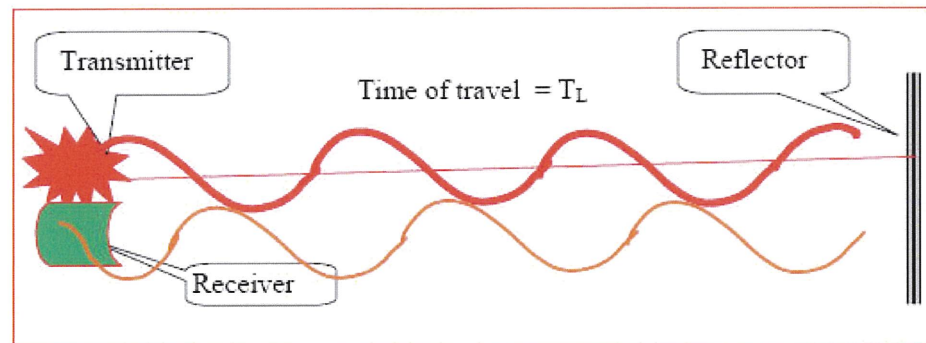


Figure 2-11 CWR Phase difference measurement from (Lohani, n.d)

2.5.2 Pulse Ranging Basics (PR)

Pulsing Ranging measures the time-of-flight T_L between the leading edges of a transmitted and received beam of light as shown in Figure 2-12. Range R is solved by Equation 2.7.

Equation 2.7
$$R = (T_L/2) c$$

The accuracy of a PR system depends on the accuracy of the time-of-flight measurement, which is limited by the precision of the clock used in the system (Lohani, n.d) and the maximum range depends on the amount of energy in the laser pulse and the sensitivity of the receiver. This is to ensure the reflected pulse can distinguished from noise from atmospheric influences (Lohani, n.d).

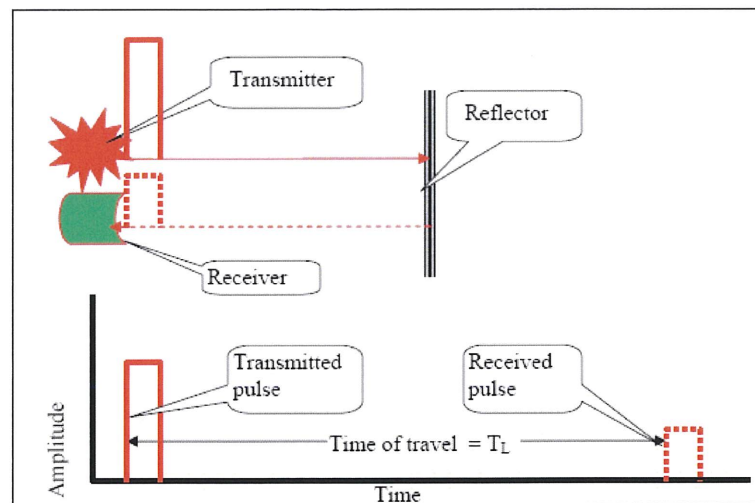


Figure 2-12 Time of travel measurement between transmitted and return pulse from (Lohani, n.d)

2.5.3 Aerial LIDAR and Map-Based Positioning

Aerial or Airborne LIDAR is a mapping technique used to measure the distance between a laser range sensor (normally 400 metres above ground) and the surface of the target environment resulting in a topographical map (Lohani, n.d.). This technique can be used for a wide variety of applications including outdoor mobile robotics. The findings in Donamukkala, Hebert, and Vandapel, (2003) show the use of high resolution aerial LIDAR range data to create topographical maps for autonomous mobile robot navigation in natural environments.

The mobile robot used in Donamukkala et al. (2003) was equipped with a three dimensional (3-D) laser sensor, an inertial navigation unit and a GPS receiver. The first challenge addressed in Donamukkala et al. (2003) is dealing with large volumes of data attained from the aerial LIDAR data, secondly distinguishing between the terrain surface and vegetation in the area. The method investigated in Donamukkala et al. (2003) involved obtaining a surface map from an aerial sweep using LIDAR to create a topographical map of the work environment. The map is then loaded into the mobile robot and is referred to as the prior map. A 3-D local map is created from the on-board 3-D laser sensor and localisation is achieved by matching interest points from the prior map with the local map (see Figure 2-13). The results obtained from Donamukkala et al. (2003) showed that vegetation obstructs and masks the terrain contours from the

aerial LIDAR data. This misleading information was a major problem for the navigation system. Complicated algorithms were used to filter vegetation from the aerial LIDAR data; and a large amount processing power is required for both the filtering process and map matching algorithms.

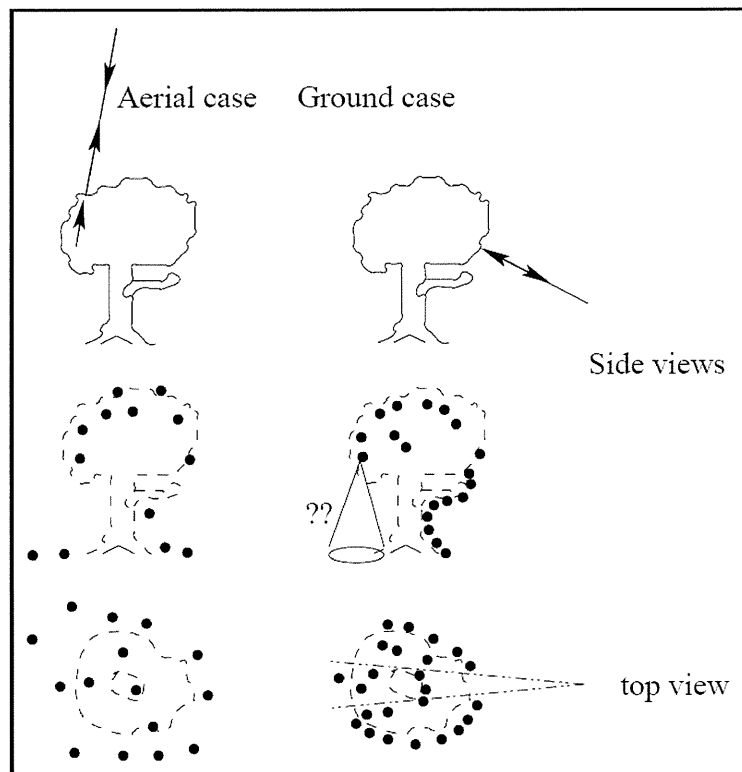


Figure 2-13 Prior Map compared to Local Map from Donamukkala et al. (2003)

2.6 Literature Review Summary

There are a number of techniques that employ time-of-flight ranging for mobile robotic navigation. GPS systems coupled with dead-reckoning data are very accurate for outdoor applications and sensor fusion can create reliable configurations for mobile robots. However, this system is only useful for outdoor mobile robotics and GPS receivers have a tendency to give erroneous data in densely populated areas.

The second TOF system reviewed in this chapter is SONAR. Sound travels slower than a broad spectrum radio wave, therefore the equipment required for ultrasonic TOF measurements is cheaper. The limitations of ultrasonic sensors are due to line of sight

issues and ultrasonic trilateration techniques are limited to the physical dimensions of the emitter, resulting in narrow sound wave broadcast hindering the accuracy of the system.

LIDAR systems for indoor projects are expensive and impractical as most LIDAR systems are suited to work in extremely large outdoor environments. Mapping with TOF sensors for mobile robot location is highly accurate; however results depend on the quality of the sensors used. Mapping systems work for static indoor environments where the introduction of external objects not referenced in the map, will cause complications for the navigation system.

2.7 Literature Review Conclusions

Time-of-flight systems are an accurate method for determining distances. It is clear that there is a relationship between price and accuracy. Current available TOF systems are limited to outdoor applications, nonflexible operation, or too expensive to be tailored for an indoor environment. The mobile robotic world would benefit from a cheap, non line of sight, TOF system for distance measurement. The proposed system should have little impact in existing areas and be easily incorporated into any system. Audible sound waves do not suffer from narrow wave emission therefore it is plausible to design a TOF system using audible sound frequencies.

3 Hybrid SONAR Test System for Range Finding

Based on the literature study, this research proposes a system that uses audible sound frequencies for distance measurement. This chapter first focuses on the mathematics related to the trilateration calculations based on three distances from beacons of known locations in an indoor environment of known dimensions. Then the methodologies implemented are discussed. The last part of this chapter is the development of a hybrid SONAR system for distance measurement.

3.1 Mathematics for Beacon Trilateration

The area of an indoor environment with dimensions of length I and width L is presented in Figure 3-1. Three beacons are placed in the corners of the room so that the locations of each Beacon (the green circle in Figure 3-1) are known. The mobile robot (the blue box in Figure 3-1) is arbitrarily placed in the room. The two components to calculate are the distance from the origin 0.0 located at Beacon 3 in the Figure to the robot in the x -direction and secondly, the distance from the origin to mobile robot in the y -direction. Length A is the distance between Beacon 3 and the robot, length B is the distance between Beacon 1 and the robot and length C is the distance between Beacon 2 and the robot. The lengths of A , B , and C would be provided by their respective beacons and are considered known variables. Angles Φ and β are the only unknown variables. Angle Φ and β can be solved using the following equations;

$$\text{Equation 3.1} \quad \cos \Phi = (L^2 + C^2 - A^2) / 2LC$$

$$\text{Equation 3.2} \quad \Phi = \cos^{-1} (L^2 + C^2 - A^2) / 2LC)$$

$$\text{Equation 3.3} \quad \cos \beta = (I^2 + C^2 - B^2) / 2IC$$

$$\text{Equation 3.4} \quad \beta = \cos^{-1} (I^2 + C^2 - B^2) / 2IC$$

Once angle Φ and β are obtained, the right angle triangle rule will give the solution for X (see Figure 3-2).

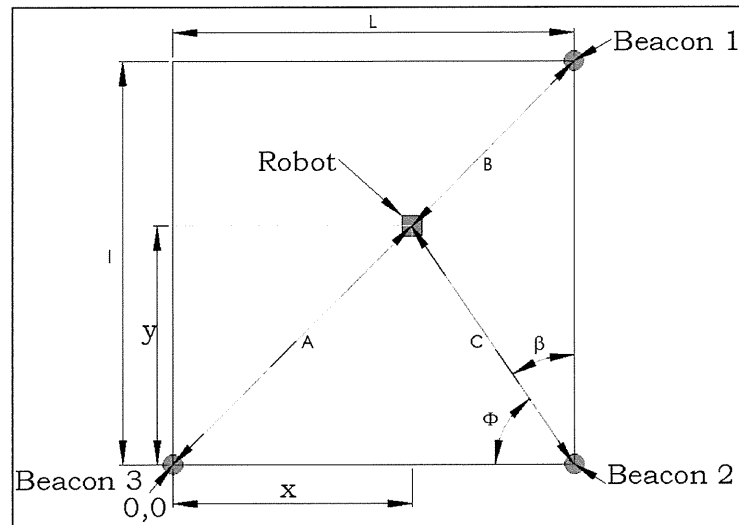


Figure 3-1 Model Indoor Environment

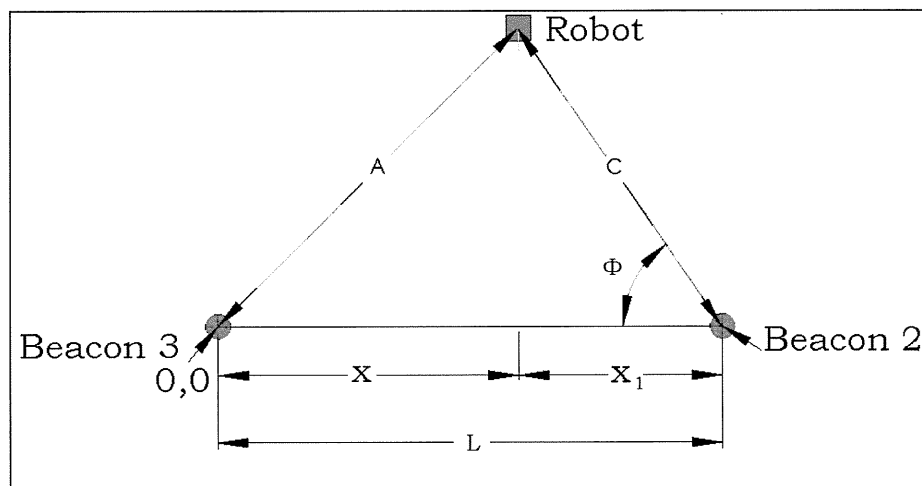


Figure 3-2 Solving for x

Equation 3.5

$$X1 = C / \cos \Phi$$

Equation 3.6

$$X = L - (C / \cos \Phi)$$

Length Y is calculated the same way, except Φ is substituted for β . It is possible to solve for lengths X and Y by using only two beacons and modifying Equation 3.6 by substituting cosine for sine, thus only one angle is required. However, only using two beacons may lead to errors. In theory angles Φ and β must equal to 90° . If only two beacons are used and if there is an error in lengths A , B or C , it will not be possible to check for errors. By using three beacons, it is possible to check the sum of angles Φ and β as the sum of the angles calculated by the three beacons should be around 90° , if the sum is significantly different to 90° , then an error has occurred.

In summary it is possible to determine an objects position based on the distances to three positions of known locations. However, for rooms with a non-rectangular shape, to implement this trilateration method requires a modification. Figure 3-3 presents a non-rectangular room. It is possible to impose a rectangle denoted by the red bounding box. Point *e* is an example of extrapolating distance *C* as the location of the beacons is already known. Lengths *X* and *Y* can then be calculated by the addition of ΔX and ΔY respectively to Equation 3.5. Further geometric equations are needed for rooms with different shapes and internal wall angles that are not right angles as shown (see in Figure 3-3).

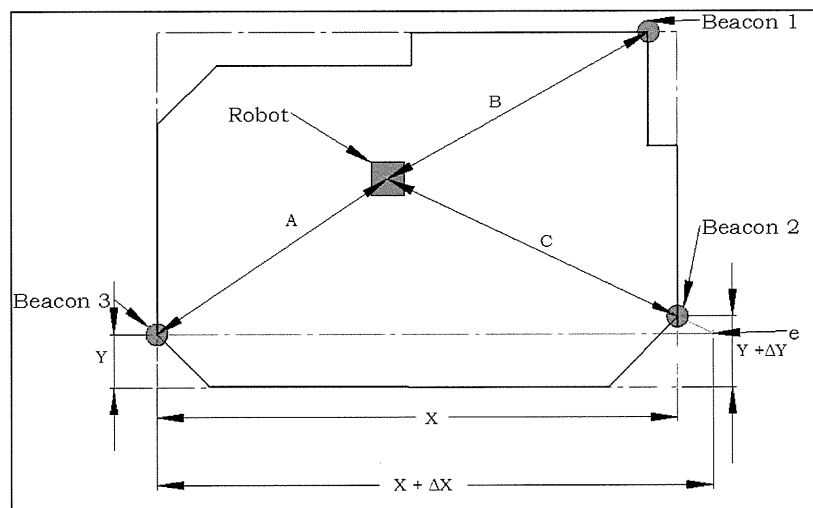


Figure 3-3 Non-Rectangular Room Example for Trilateration

3.2 SONAR Test System Development

A sound wave travels uniformly at 340.29ms^{-1} through open air at room temperature on the assumption that the open air particle density and humidity is relatively low. A SONAR TOF range finding technique works on the assumption that, the amount of time taken to reach an object is the same amount of time taken to be reflected back. Equation 3.8 is adapted from Smith (2001, p 114) as investigated in Chapter 2.

Equation 3.7
$$d = v * t/2$$

Where, *d* = distance

v = speed of sound

t = time of flight

The aim of this research is to solve for d based on the time taken for a sound wave to travel to an object without taking into account the reflected wave. The TOF Equation now becomes;

Equation 3.8
$$d = v * t$$

To solve for d it is necessary to determine t . The proposed SONAR system consists of a SONAR Transmitter and a SONAR Beacon (see Figure 3-4). A sound pulse is emitted from the SONAR Transmitter and simultaneously a timer is started. When the sound wave is detected by the SONAR Beacon, a radio signal is used to act as a pseudo reflected wave which will stop the timer.

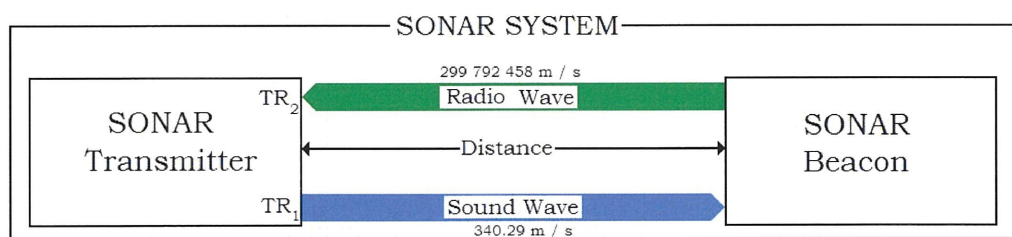


Figure 3-4 Simplified SONAR System Components for Range Finding

The time-of-flight measurement (Figure 3-5) is achieved by measuring the time between trigger 1 (TR_1) and trigger 2 (TR_2) where, TR_1 is the instant the sound pulse is produced and TR_2 is the instant the radio signal is received from the SONAR Beacon. Distance d can be calculated from Equation 3.7 where t is the difference between TR_2 and TR_1 . Radio signals travel at the speed of light and can be considered to have negligible influence on the overall time taken for the sound wave to travel from the SONAR Transmitter to the SONAR Beacon.

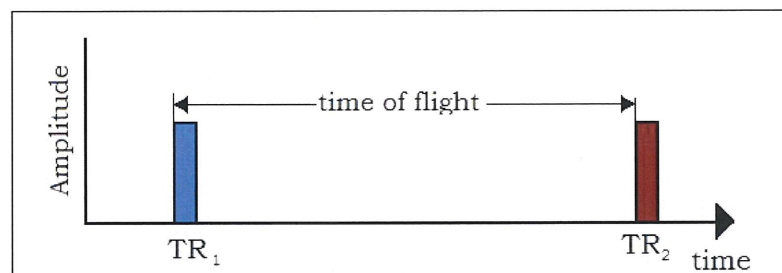


Figure 3-5 Time between Triggers

The system is made up of two parts. The first part is the **SONAR Transmitter** which consists of three modules:

1. **Frequency Generation** – Create an audible sound wave of target frequency for the SONAR Beacon to detect.
2. **Radio Confirmation** – Creates interrupts for the timing circuitry
3. **Timing Circuitry** – Time the difference between TR_1 and TR_2 and outputs the information to a computer.

The second part of the system is the **SONAR Beacon** which also consists of two modules:

1. **Frequency Detection** – Processes all audio signals within range searching for the target frequency.
2. **Radio Confirmation** – Transmits the appropriate information to the SONAR Transmitter for the timing circuitry

3.2.1 Key Components of SONAR Test System

The methodology implemented in this research is to determine the Cartesian coordinates of a mobile robot in an indoor environment. A computer is used to model the mobile robot and acquire data from the SONAR Beacon. Seen in Figure 3-6 are the key components for the operation and control of the SONAR System. The computer will delegate when the sound pulse is produced and will have direct communication with the timing circuitry and the timing data. Also demonstrated in Figure 3-6 are the key components required for the SONAR Beacon which is independent from the SONAR Transmitter.

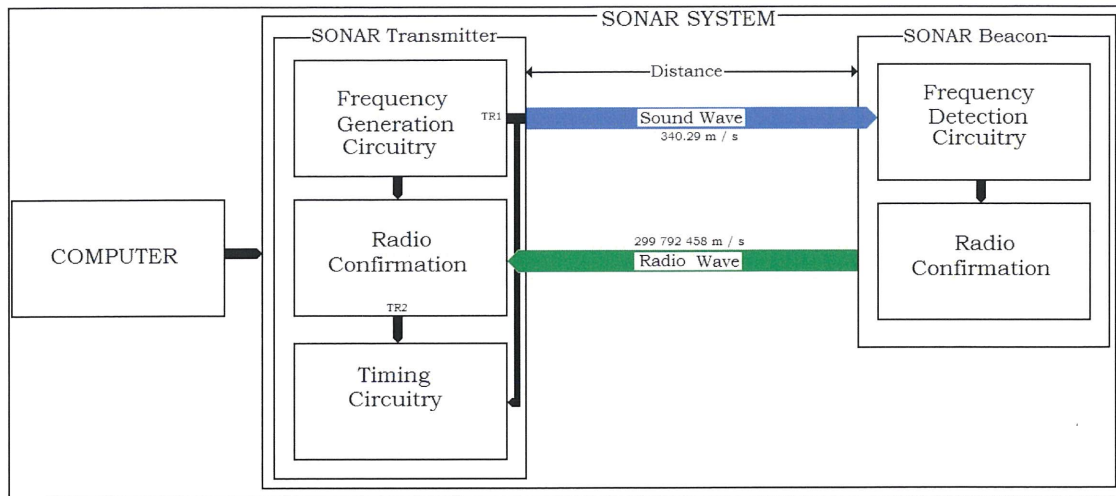


Figure 3-6 Components for SONAR Transmitter

3.2.2 Resolution of the SONAR Test System

The maximum resolution of the SONAR system depends on the amount of energy or the volume of the sound wave emitted and the sensitivity of the frequency detection circuitry. The maximum resolution of the test system was selected based on the distance not more than 10 meters. Similar to Pulse Ranging in LIDAR systems the minimum resolution is determined by the accuracy of the time-of-flight measurement.

Time measurement is achieved by counting the rising edges of a digital clock pulse as shown in Figure 3-7. Each count of the clock pulse represents a unit of time. Multiplying the count by the period of the clock frequency gives time t in Equation 3.8. If we assume the desired minimum resolution to be 1 centimetre, then the frequency of the clock is determined by Equation 3.9 where f is the clock frequency and t is the period.

Equation 3.9
$$f = 1/t$$

Equation 3.10
$$t = 1/f$$

Period t , is time t in Equation 3.8 thus combed Equation 3.10 gives,

Equation 3.11
$$d = v * 1/f$$

Equation 3.12
$$f = v / d$$

The desired minimum resolution is 1cm. Therefore $d = 1$ and $v = 340.29\text{ms}^{-1}$, thus;

$$f = 340.29 / 0.01$$

$$f = 34029 \text{ Hz}$$

$$f = 34 \text{ kHz}$$

Therefore minimum clock frequency required is 34 kHz for a desired 1 cm resolution.

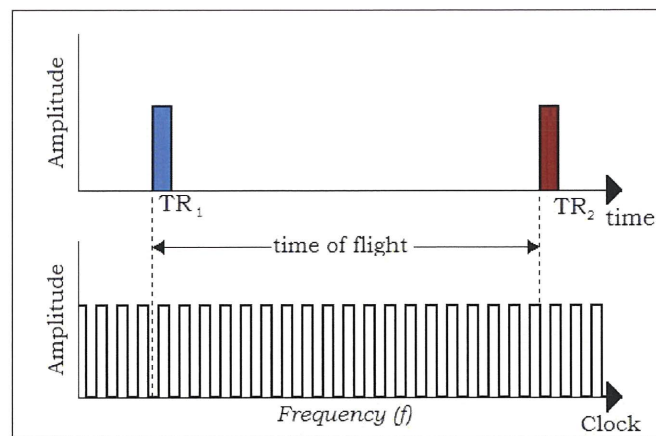


Figure 3-7 Counting clock edges to determine time-of-flight for a sound WAVE

3.3 Summary

In theory it is possible to determine distances by combining SONAR methodologies and radio technology. The key concept is to use radio waves as feedback and not reflected waves. This system design ideology is to minimise the line of sight flaws normally associated with TOF distance measurement methodologies. Audible sound frequencies transmit waves that project at wider angles than that of ultrasonic frequencies therefore it is theorised that the SONAR Beacon will not have to be directly in line of sight of the SONAR Transmitters to achieve accurate measurements.

Furthermore, most machines and robots have an audible sound system for giving warning alert. The hybrid SONAR system can be incorporated into such systems by adjusting the Frequency Detection Circuitry to suit distance measurement. Therefore, this SONAR system should not be a significant cost to a robot system.

4 Frequency Detection Design and Implementation

This chapter will centre on frequency generation and frequency detection components of the SONAR system. The main discussion will focus on the design considerations, circuit design and implementation for the target frequency, sound wave production, signal conditioning and frequency detection modules.

4.1 Target Frequency Selection

In order to detect sound waves it is important to first choose a suitable target frequency. The wavelength of sound energy is proportional to the speed of the wave (Everett, 1995, p. 222) and shown by;

Equation 4.1 $\lambda = c / f$

Where, λ = wavelength

c = speed of sound

f = operating frequency

Small wavelengths achieve higher resolution according to Everett (1995). For the purposes of this research a target frequency of 2 kHz is used. The calculated wavelength would be approximately 17 centimetres; therefore the theoretical minimum distance that can be measured is 17 centimetres.

When producing a mono tone sound a sinusoidal, square or triangle waveform can be used. Square waves are a combination of odd frequency harmonics of the 2 kHz range producing a sharp and piecing sound that can cause irritation when experimenting. A triangle wave only contains integer harmonic frequencies resulting in a sharper pitch (Franco, 1988), where a sine waveform creates a smooth mono-tone.

4.1.1 Circuit Design for a Target Frequency

The first component is a circuit to produce an audible sound wave at the target frequency with adjustable amplitude for volume. The objective of the target frequency circuit is to produce a sound pulse for a finite amount of time that will be able to be heard at least 10 meters away. The oscillator circuit design is based on the Twin-T-Bridge Oscillator circuit which consists of a resistor and capacitor network. The Twin-T-Bridge circuit produces a low distortion sine wave; where R1-C1-R2 creates a low pass filter and C3-R5-C2 creates a high pass filter. Both R1-C1-R2 and C3-R5-C2 resemble like a “T” shape (see Figure 4-1). The values of R and C are determined by Equation 4.2 for the target frequency $f = 2$ kHz.

Equation 4.2
$$f = \frac{1}{2\pi RC}$$

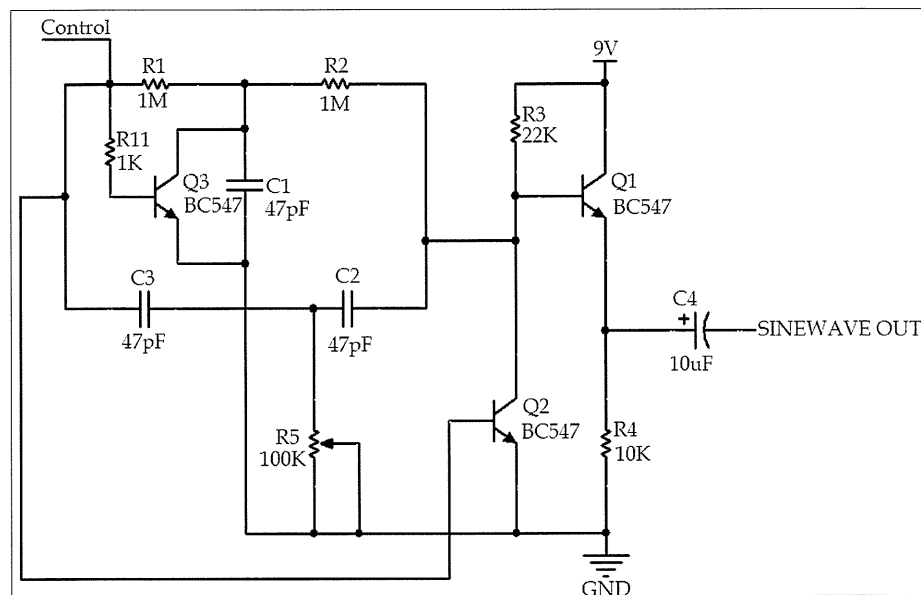


Figure 4-1 Sine Wave Generator Circuit

Transistor Q3 shown in Figure 4-1 is used to bypass capacitor C1 to ground. When Q3 is saturated the circuit is off. When Q3 is not saturated the circuit will turn on. This is used to control the circuit so that when logic high is fed into the gate of Q3 the circuit is off. When logic low is fed into Q3, the voltage is allowed to pass through C1 switching the circuit on. The manufactured prototype circuit board (PCB) is shown in Figure 4-2.

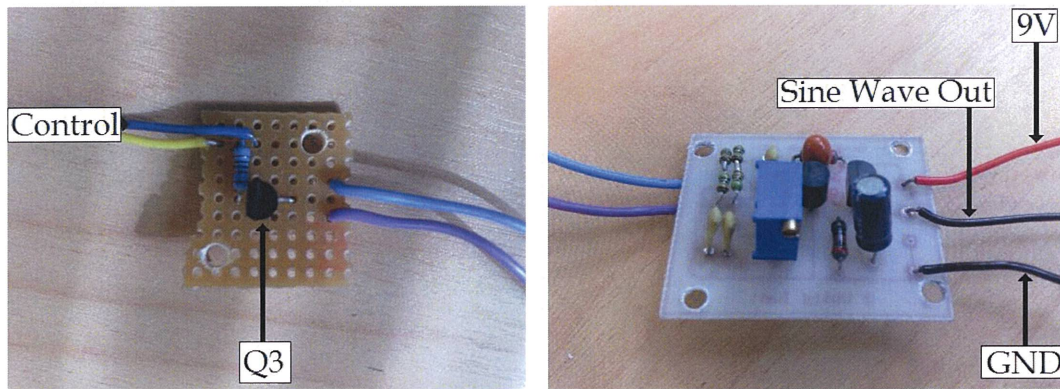


Figure 4-2 Sine Wave Generator PCB

The outcome of the circuit is compared with a function generator. An Agilent 33220A 20 MHz Function/Arbitrary Waveform Generator is used to generate a pure 2 kHz sine wave. The sine wave is compared to the sine wave produced by the Twin-T-Bridge circuit as shown in Figure 4-3. The waveforms are captured by a Tektronix TDS1012 Two Channel Oscilloscope. The Twin T-Bridge circuit produces a similar waveform. However there is a distortion in the negative portion of the wave when compared to the pure sine waveform. This is due to the accuracy of the components and the 3 dB roll off in the low pass and filter. The distortion has no affect on the overall application of the system.

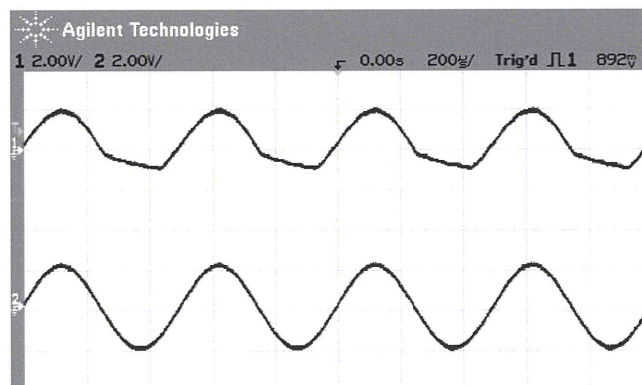


Figure 4-3 Generated Sine Wave (ABOVE) compared to Pure Sine (BELOW)

4.1.2 Circuit Design of the Audio Amplifier

The sine wave produced by the Twin T-Bridge circuit is amplified to be outputted from a speaker. The LM386 is a Low Voltage Audio Amplifier and a low cost integrated circuit (IC). This IC is used to create an audio amplifier circuit. The LM386 is stable with the overall amplification circuit requiring only few components. The gain is determined by resistor R1 and capacitor C8 on pin 1 and 8 on the circuit schematic shown in Figure 4-4. The circuit is adapted from the LM386 datasheet found in Appendix C. To achieve a gain of 200 requires the value of R1 to be 1.2 kOhm and C8 to be 10 uF. This means that any input signal fed into pin 3 is multiplied 200 times. The amplified waveform is then outputted via pin 5 to an 8 Ohm speaker shown in Figure 4-5. The speaker has been modified from a set of desktop computer speakers and has the ability to output the desired frequencies. The manufactured audio amplifier PCB is shown in Figure 4-6.

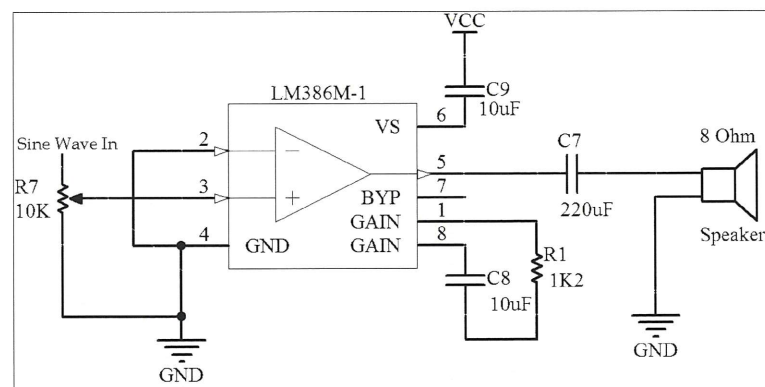


Figure 4-4 Audio Amplifier Circuit



Figure 4-5 Speaker

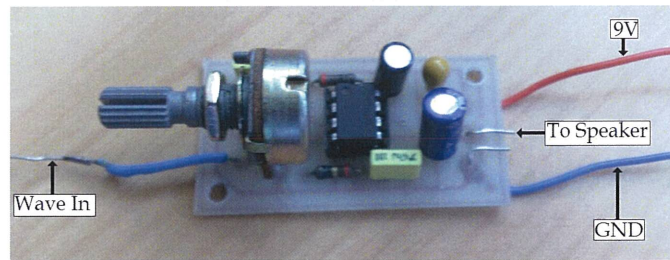


Figure 4-6 Sine Wave Amplifier Prototype Circuit Board

The amplified waveform is captured and compared with the input waveform. The results are shown in Figure 4-7 to 4-9. The amplitude of the amplified signal is depends on the value of the variable resistor R7. The result shown in Figure 4-7 shows that the amplified sine wave is not really a sinusoidal when R7 is set to 2 kOhm. As R7 is gradually increased the amplified waveform becomes more sinusoidal (see Figure 4-8). As R7 is set above 6 KOhm the amplified waveform becomes square (see Figure 4-9). The frequency is not affected by the increased amplitude. However the pitch of the audio signal is increased.

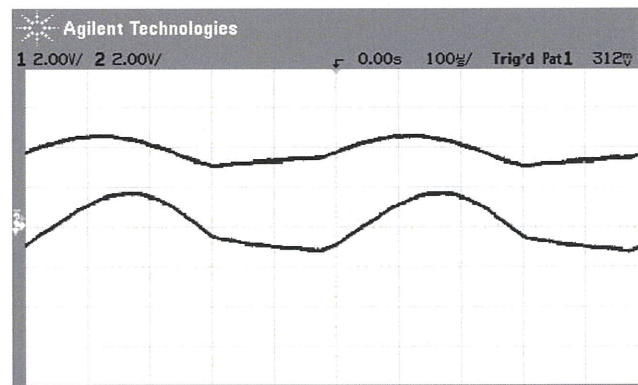


Figure 4-7 Input Generated Sine Wave (Lower Curve) compared to Amplified Sine Waveform (Upper Curve) with R7 set to 2 KOhm

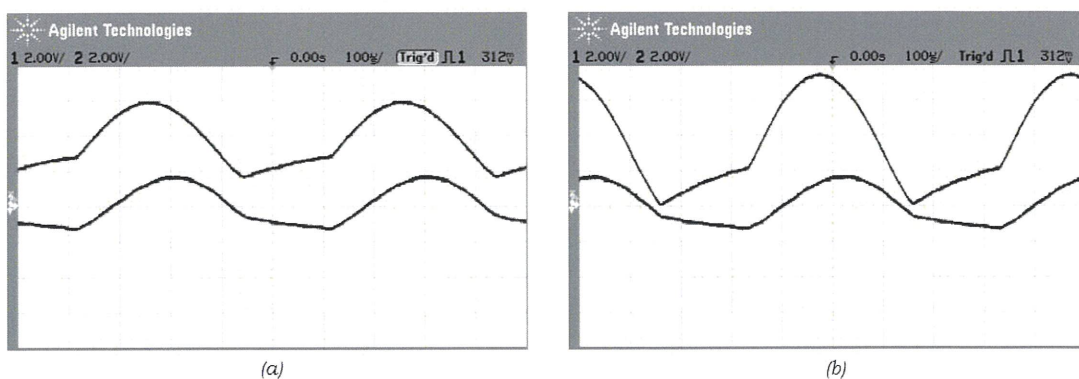


Figure 4-8 Amplified Sine Waveform (a) with R7 = 4 KOhm, (b) R7 = 6 KOhm

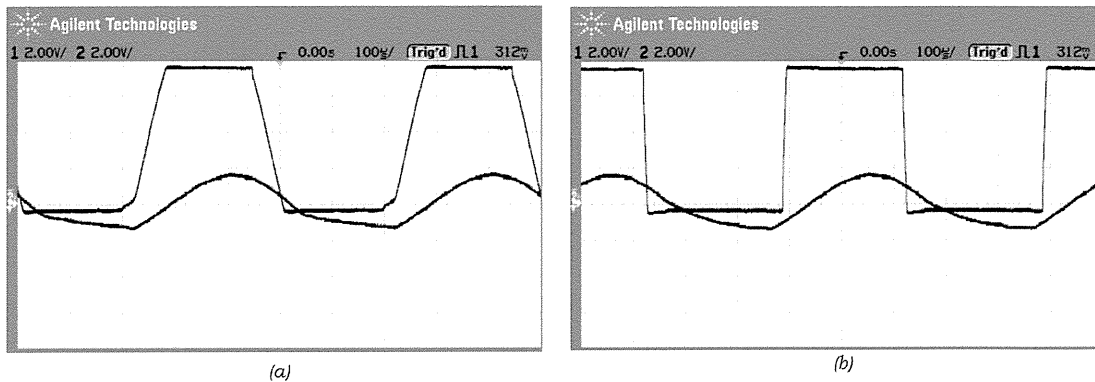


Figure 4-9 Amplified Sine Waveform (a) with $R7 = 8 \text{ KOhm}$, (b) $R7 = 10 \text{ KOhm}$

4.2 Signal Conditioning

The SONAR Beacon is designed to process all audio signals within range and distinguish between noise and the target frequency. Before the target frequency can be processed however, a signal conditioning component is required to filter and clean all audio signals detected by the SONAR Beacon. If the audio signal is weak the beacon will not function properly. Therefore any signals detected also need to be amplified before the signal can be filtered. The signal conditioning component consists of three circuit modules, which are pre-amplifier, band-pass filter and burst suppression. Figure 4-10 illustrates the signal process procedure.

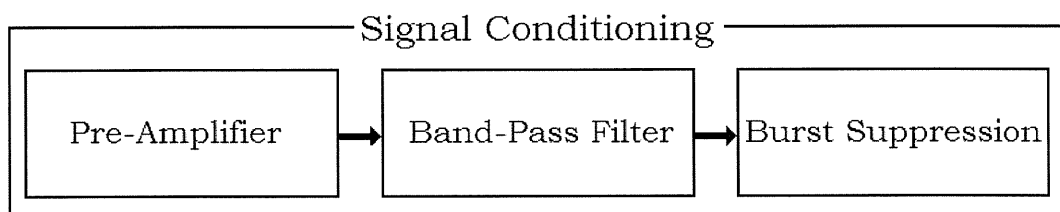


Figure 4-10 Signal Conditioning Block Diagram

4.2.1 Circuit Design for Microphone Pre-Amplifier

The pre-amplifier circuit amplifies all audio signals within range of the microphones frequency response specifications. A standard condenser microphone has a frequency range of 20 Hz to 20 kHz.

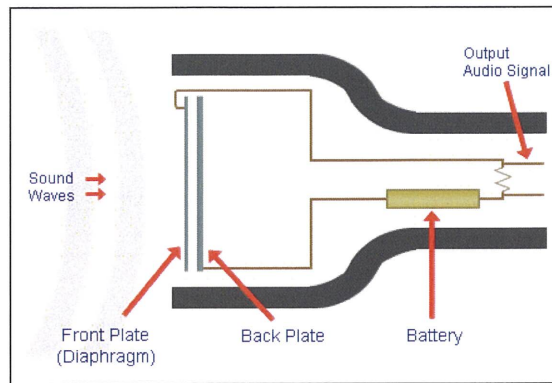


Figure 4-11 Cross-Section of a Condenser Microphone (“Condenser,” n.d)

A condenser microphone (cross-section shown in Figure 4-11) consists of a capacitor made up of two plates that hold voltage between them (“Condenser,” n.d.). The two plates are made of a very light material which acts as the diaphragm. As sound waves strike the diaphragm, it vibrates changing the distance between the two plates and therefore changing the capacitance. As the plates vibrate closer together, capacitance increases as the current is charged up. When the plates are further apart, capacitance decreases as the current is discharged.

The energy in a sound wave decays at a rate that is inversely with the square of the distance from the source (“Sound,” n.d.). The pre-amplifier circuit increases the overall sensitivity of the SONAR Beacon by amplifying all audio signals within the frequency range of the condenser microphone. In theory increased sensitivity increases the maximum distance measurement, where the SONAR Beacon can be placed further away from the SONAR Transmitter.

A LM833 – Dual Audio Operational Amplifier IC is used to create the pre-amplifier circuit shown in Figure 4-12. The LM833 IC attenuates direct current (DC) signals and has a wide dynamic range allowing signals to be amplified over 140 dB. Audio signals are pre-amplified by the first operational amplifier (op-amp) and the gain is determined by the logarithmic potentiometer R20. The signal is then amplified by a gain factor of 3 by the second op-amp on the LM833 IC. The gain factor is determined by the ratio of R9 and R7. The amplified signal is then passed out from C6 which eliminates all DC components from the audio signal. The manufactured PCB is shown in Figure 4-13.

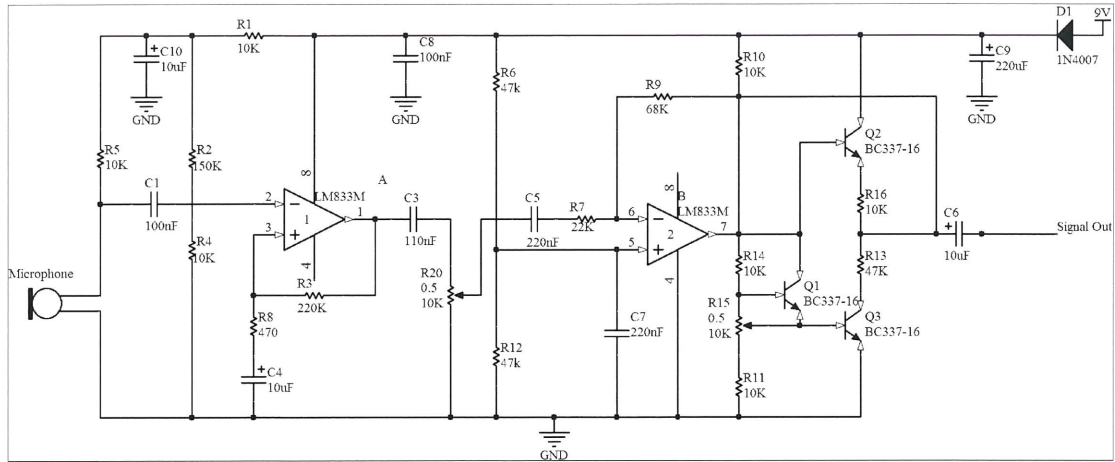


Figure 4-12 Pre-Amplifier Circuit Schematic

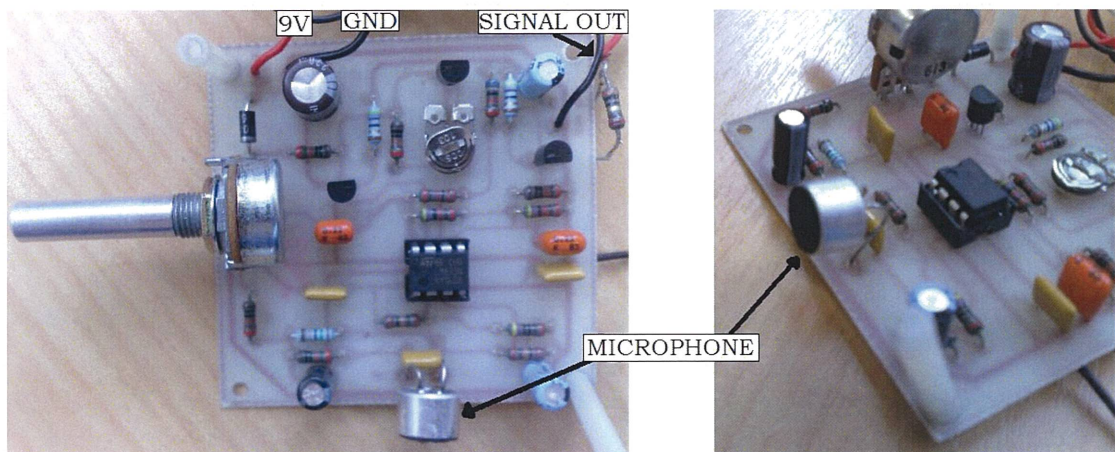


Figure 4-13 Pre-Amplifier Prototype Circuit Board

4.2.2 Circuit Design for the Band-Pass Filter

To make frequency detection easier, it is important to filter out as much unwanted information as possible. Other audio signals present such as people talking, a lawn mower in the background or even a radio playing music will be amplified. A Band-Pass filter is used to allow the target frequency to pass unaltered for further processing while simultaneously attenuating unwanted frequencies.

The band-pass filter could be thought of as both a high pass and low pass filter; where frequencies above and below (f_H and f_L respectively) the target frequency (also known as the centre frequency f_C) are filtered out. This is known as the *frequency response* of the filter. The *frequency band* is the range of frequencies that is allowed to pass through

the filter unaltered and is determined by $f_H - f_L$. An idealised response of a band-pass filter in the time domain is shown in Figure 4-14.

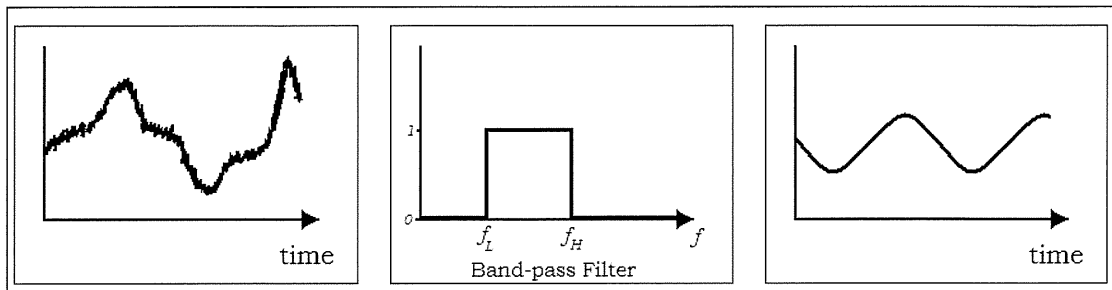


Figure 4-14 Idealised frequency response of a band-pass filter adapted from Franco (1988)

The circuit provided in the TL064CN - Low Power Junction Gate Field-Effect Transistor Quad Operational Amplifier - datasheet found in Appendix C is modified to design the required state variable filter circuit (Figure 4-15). The state variable filter designed consists of four filters (High-pass, Low-pass, Band-pass and Notch Filter). For the purposes of this research, the Band-pass filter on the state variable filter circuit is used. Equation 4.2 in section 4.1.1 is used to calculate the width of the frequency band and the values of resistor R2 and capacitor C1 so that f_H is +50 Hz of the target frequency and f_L is -50 Hz of the target 2 kHz frequency.

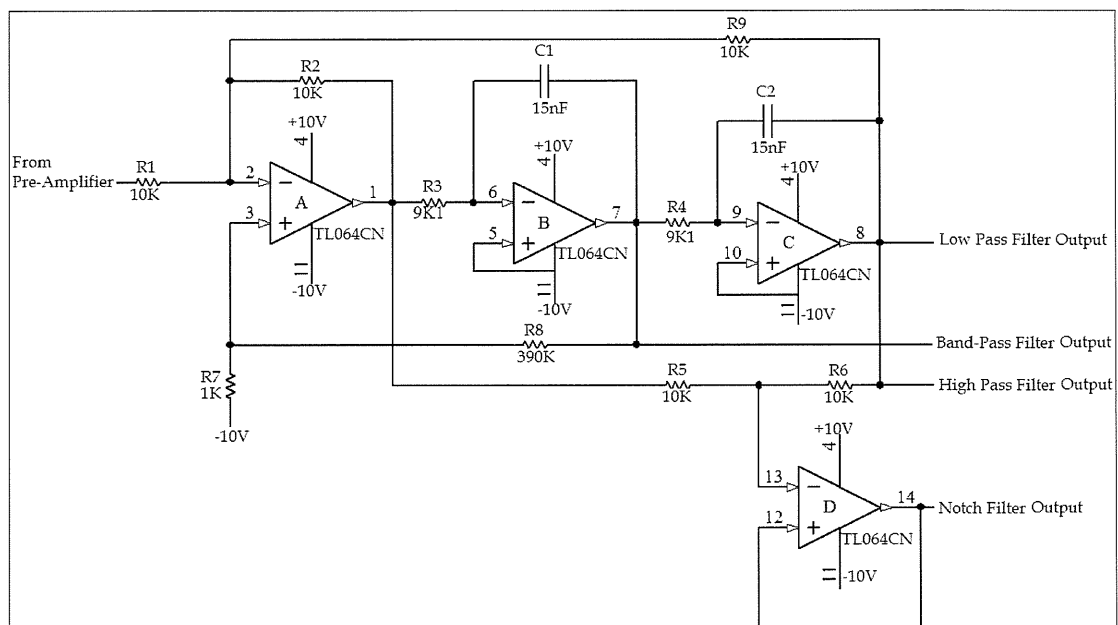


Figure 4-15 State Variable Filter Circuit Schematic

The pre-amplifier also amplifies ambient noise that may contain harmonic frequencies similar to the target frequency. Presented in Figure 4-16 is the attenuation of ambient noise frequencies by the Band-Pass-Filter. Presented in Figure 4-17 is the test results by placing the SONAR Transmitter module a metre away from the beacon.

On the left in Figure 4-17, amplified sine wave is distorted due to the combination of the target frequency and ambient noise. When the signal is fed into the Band-Pass filter, the noise is cleaned and the outcome is shown on the right in Figure 4-17. The filter attenuates all frequencies outside the frequency band. The waveform is sinusoidal with no distortions. Using the Tektronix TDS1012 Two Channel Oscilloscope, the frequency of the waveform is measured and the value is 1.988 kHz. Therefore the filter has no effect on the target frequency or amplitude.

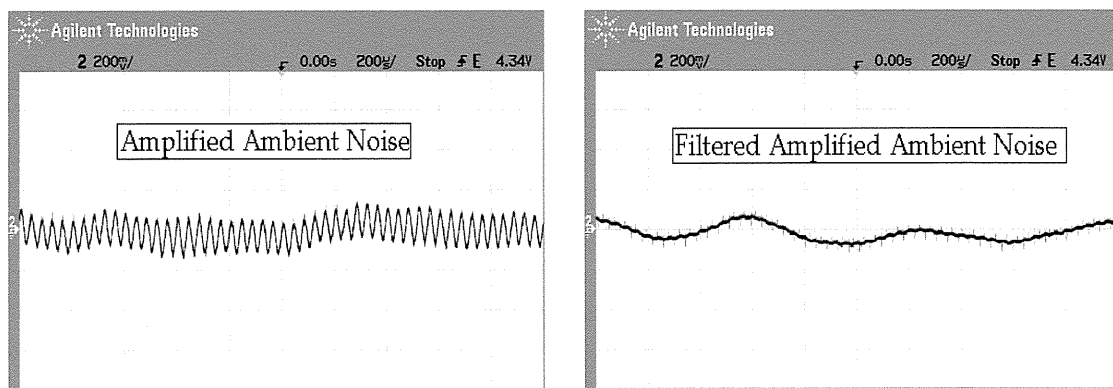


Figure 4-16 Pre-Amplified Ambient noise passed through Band-pass Filter

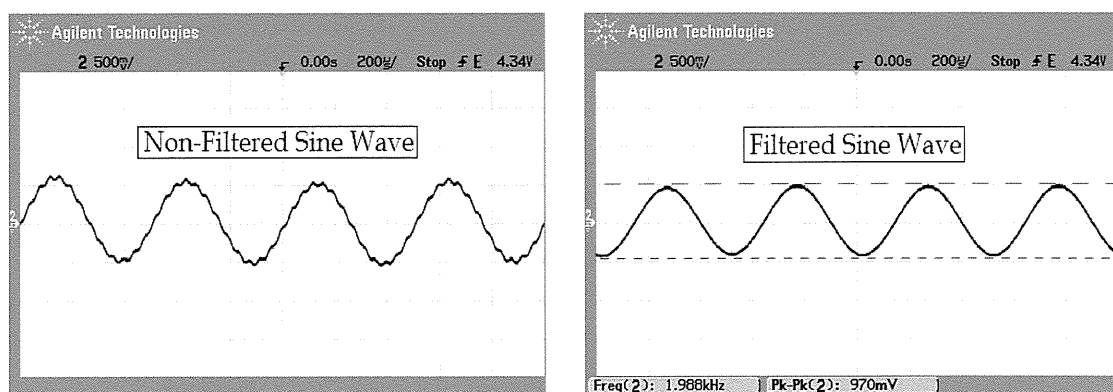


Figure 4-17 Pre-Amplified Sine Wave passed through Band-pass filter

4.2.3 Circuit Design for Burst Noise Suppression

It is not realistic to assume a mobile robot will operate in low level noise environment. It is important to plan for burst and other abrupt noises. Burst noises may occur when a door is slammed or by an object falling. Loud burst of noises contain frequency harmonics that are close to target frequency. This may cause the circuitry to be overloaded resulting in false frequency detection. Shown in Figure 4-18 is an example of a burst noise created by slamming a book on a desk near the Pre-amplifier circuit and how random bursts of noise “punch” through the Band-Pass Filter circuit.

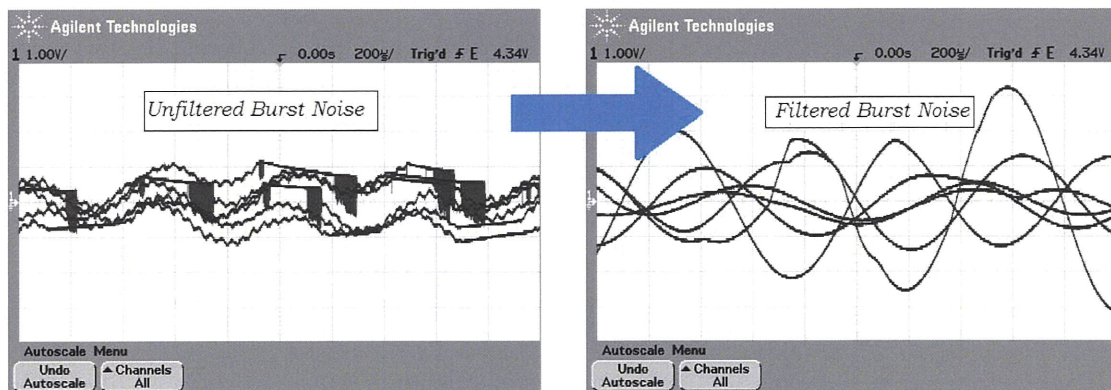


Figure 4-18 Example of Burst Noise

The next circuit designed in the signal conditioning module is a Burst Noise Suppressing circuit. In order to build the circuit a SSM2167 - Low Voltage Microphone Preamplifier with Variable Compression and Noise Gating - IC is used. The SSM2167 features adjustable noise gate threshold and compression ratios. The circuit design shown in Figure 4-19 is taken from the SSM2167 datasheet found in Appendix C as the IC is designed for complete microphone signal conditioning. The manufactured Burst Noise Suppressing circuit PCB is shown in Figure 4-20.

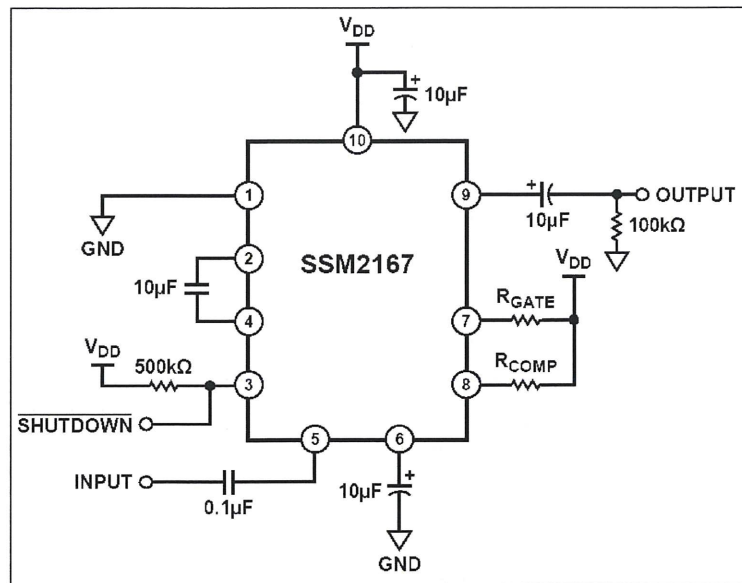


Figure 4-19 Burst Suppression Circuit Schematic

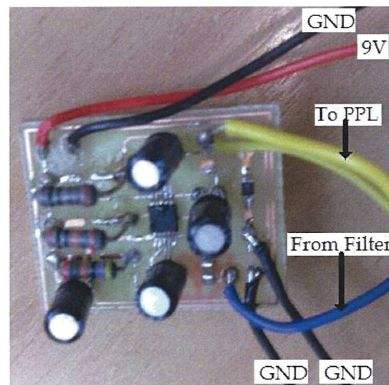


Figure 4-20 Burst Suppression Prototype Circuit Board

The Noise Gate Threshold configures the minimum input signal voltage level known as the downward expanded voltage or V_{DE} . Any input below V_{DE} will be expanded by a magnitude of -3dB and therefore ignored by the circuit. The Noise Gate Threshold is determined by the value of R_{GATE} ; 1 kOhm was selected, thus any signals below -48 dBV will have a -3dB gain applied to it. Setting the compression ratio will change the scaling of signals fed into the input. By selecting 75 kOhm for R_{COMP} the compression ratio is then set to 5:1. This means input voltages above the Noise Gate threshold are compressed by a factor of 5 so that any burst noises will be compressed.

The Burst Noise Suppression circuit *clips* signals that may cause erroneous triggers. The filtered burst noise waveform from Figure 4-18 is fed into the Burst Noise Suppression circuit, shown in Figure 4-21. When input signals exceed V_{DE} the signal is compressed, represented by the signal flat line at the 3 volts in the figure. Voltages

below V_{DE} have a -3dB gain applied to the signal to an average of 0.8 volts shown in the figure. Burst noise still has a tendency to trigger the Frequency Detection circuitry (discussed in Chapter 5) however the overall performance limits a good proportion of unwanted frequencies due to burst noise.

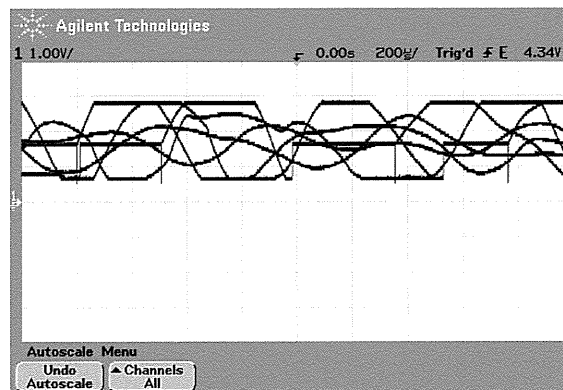


Figure 4-21 Noise Burst Suppressed by SSM2167 Circuit

In order for the SONAR Beacon to function, the frequency detection circuitry must lock onto the target frequency for a set amount of time. Burst noise can sometime overload the frequency detection circuitry and the frequency lock can be lost. Using the Agilent 33220A 20 MHz Function/Arbitrary Waveform Generator, a pure 2 kHz sine wave was generated with a peak-to-peak voltage of 4V and is output through a speaker. When a sharp burst sound was made by slamming a book onto a desk, the combined sound signal was captured by the SONAR Beacon. The pre-amplified signal appears noisy and random and non-sinusoidal.

When the signal is passed through the band-pass filter, the waveform reflects a misshapen sinusoidal waveform varying in amplitude as shown in Figure 4-22. Furthermore the Burst Noise Suppression circuit inhibits any burst noise frequencies from completely distorting the sine wave as shown in the same figure. A smooth constant amplitude waveform is produced. The peaks of the sine wave have been limited by the Burst Noise Suppression circuit. The frequency of the waveform is unchanged. This design suggests that when the frequency detection circuitry has locked on to the target frequency any abrupt noises will not break the lock.

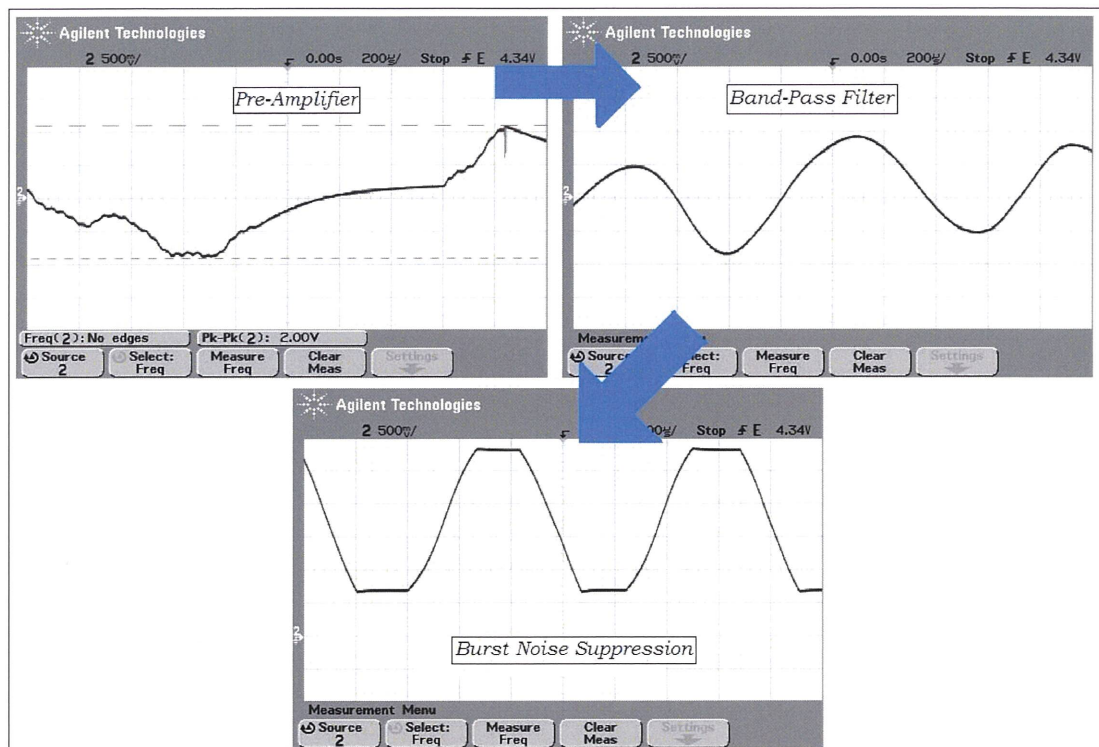


Figure 4-22 Signal Conditioning of a Sine wave coupled with Burst Noise

4.3 Target Frequency Detection

The most crucial part of the hybrid SONAR Beacon is to confirm that the target frequency has been detected. The circuit on SONAR Beacon must have the functionality to analyse a signal that has passed through signal conditioning modules and determine if the signal is sent from the SONAR Transmitter and is received by SONAR Beacon.

4.3.1 Circuit Design for Phase Locked Loop Circuit

A Phase Locked Loop (PLL) circuit is designed to detect the target frequency. A PLL IC is configured as a phase detector. The phases of two input signals are compared. When the frequencies of the two input signals are identical, a logic output is produced (Best, 2007, p. 13). The first input signal is defined as the centre frequency f_0 and is established on the PLL IC by Equation 4.3 found in Mims (1979). The second input frequency is the target frequency fed into the PLL circuit from the signal conditional module. The PLL adjusts the phase of the centre frequency to match that of the target

frequency. The rate at which the PPL adjusts the centre frequency phase is dependant on the operational speed which is set by minimising the capacitor values C4 and C5 shown in the circuit schematic in Figure 4-23 by Equation 4.4¹ and Equation 4.5 respectively.

$$\text{Equation 4.3} \quad f_o = (1.1) / (R * C)$$

$$\text{Equation 4.4} \quad C4 = 260 / f_o$$

$$\text{Equation 4.5} \quad C5 = 130 / f_o$$

For small values of C4 the sensitivity to noise and extraneous signals is increased. This will result in false phase matching. The centre frequency is calculated to match the target frequency by Equation 4.3.

Target Frequency $f = 2 \text{ kHz} = 2000 \text{ Hz} = f_o$ and select $C = 47 \times 10^{-9} \text{ F}$, solve for R ;

$$\text{Equation 4.3} \quad R = (1.1) / (C * f_o)$$

$$R = (1.1) / (47 \times 10^{-9} * 2000)$$

$$R = 11702.13 \text{ Ohm}$$

$$R = 11.7 \text{ kOhm}$$

In the circuit schematic R from Equation 4.6 is a combination of a fixed resistor R4 and variable resistor R6. This is to allow for fine tuning of the centre frequency to match the target frequency exactly. The circuit designed for the SONAR Beacon uses a NE567 PPL IC that can be used to detect frequencies in the order of 0.01 Hz to 500 kHz. Using the values calculated for R and C , the PPL IC produces a square wave shown in Figure 4-24 with the centre frequency measured to be 2 kHz. Figure 4-25 is the PCB containing the PPL circuit, State Variable Filter circuit discussed in section 4.2.2 and power supply circuit to be discussed in Chapter 7.

¹ Equations 4.4 and 4.5 in the NE567 Datasheet found in Appendix C

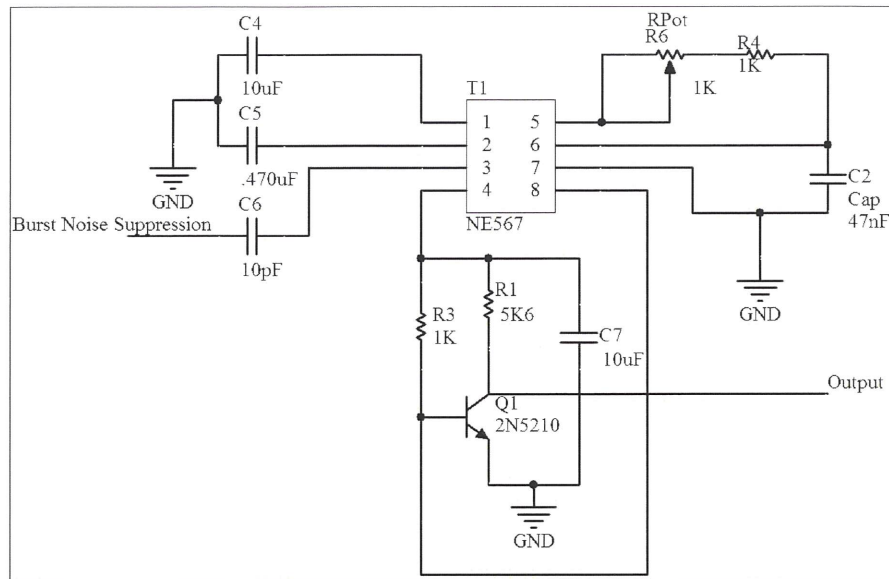


Figure 4-23 Phase Locked Loop Circuit Diagram

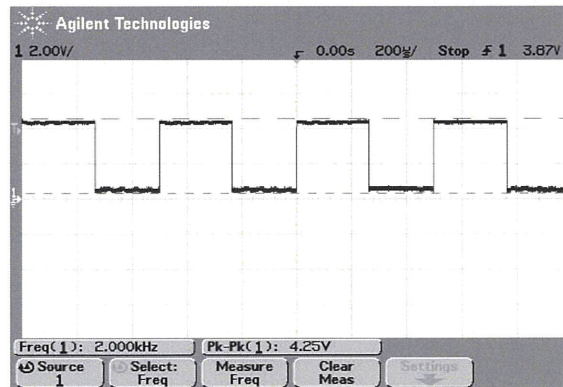


Figure 4-24 NE567 PPL Centre Frequency f_0

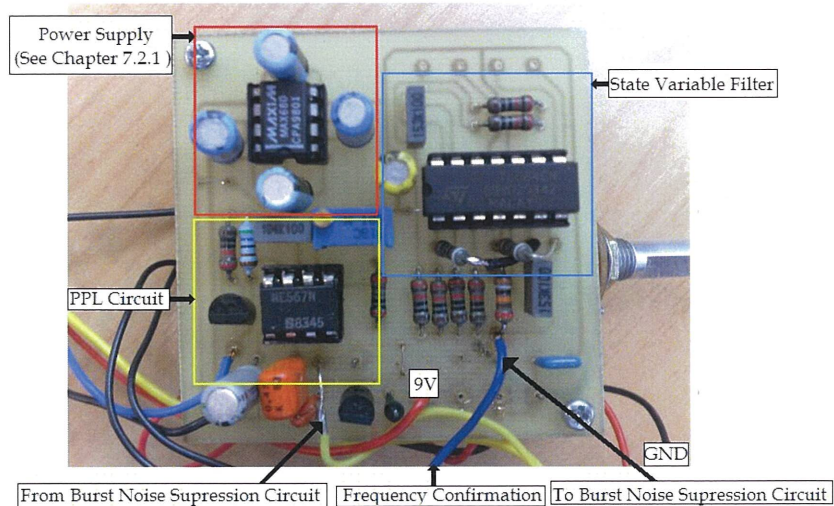


Figure 4-25 Phase Locked Loop and State Variable Filter Prototype Circuit Board

To test the PPL circuit PCB board, an Agilent 33220A 20 MHz Function/Arbitrary Waveform Generator was used to produce a pure 2 kHz sine wave with a peak-to-peak voltage of 4V. The signal was sent a speaker. The sinusoidal waveform shown in Figure 4-26 is the sinusoidal waveform signal passed through signal conditioning circuitry and is fed into the PPL circuit. The series of square waves in Figure 4-27 illustrates the PPL IC adjusting the phase of the centre frequency to match the target frequency's phase. Once the PPL circuit detects a phase match, a logic High is output from PIN 4 on the NE567 PPL.

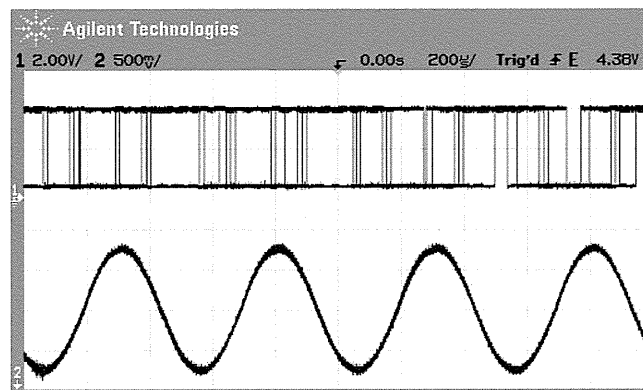


Figure 4-26 PPL Circuit adjusting phase adjust phase

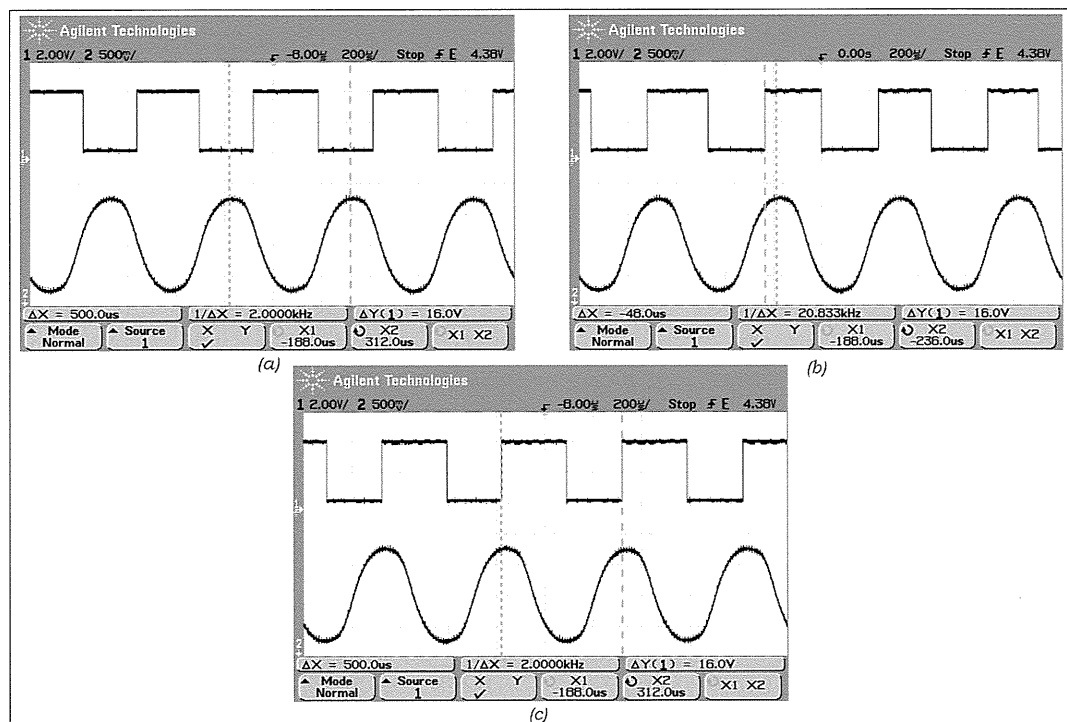


Figure 4-27 PPL Centre frequency Adjustment –(a) 180 degrees out of phase, (b) 3.6 Degrees out of phase, (c) in phase

It is important to note that the time taken to shift the centre frequency phase to match that of the target frequency signal is not predictable. This issue is addressed in Chapter 6.

4.3.2 Frequency Response Calibration

The Frequency Detection Circuitry response is affected by $R6^2$ in the PPL circuit, which is used to adjust the centre frequency. The Agilent 33220A 20 MHz Function/Arbitrary Waveform Generator Function Generator was used to calibrate the centre frequency from 10 metres away by outputting a 2 kHz sine wave from a speaker at 100 dB. The variable resistor R6 was then adjusted till the PPL circuit locked onto the target frequency. The PPL circuit will lock onto the target frequency when the centre frequency is between 1.8 kHz and 2.1 kHz. When adjusted to these centre frequencies the PPL circuit is more susceptible to burst noise. The closer the centre frequency is set to the target frequency, the less likely the PPL circuit to lose the lock.

4.4 Decibel Level Calibration

The hybrid SONAR system needs to be calibrated to operate at the maximum distance of 10 metres. The SONAR Transmitter contains a variable resistor to adjust the volume of the transmitted sound wave. It is important to set the SONAR Transmitter to an optimal decibel level so that the Frequency Detection Circuitry can detect the emitted sound pulse and confirm the target frequency.

Using The Agilent 33220A 20 MHz Function/Arbitrary Waveform Generator, a 2 kHz sine was produced and output through a speaker 10 meters away from the Frequency Detection Circuitry. The peak-to-peak amplitude of the 2 kHz wave was increased by 500 mV increments and the decibel levels next to the speaker were recorded by a condenser microphone. The result is presented in Table 4-1.

² Section 4.1.3, Figure 4.18

Table 4-1 Decibel Level with change in amplitude

Amplitude (Vrms)	Speaker (dB)	Microphone (dB)	2 kHz Detected?
0	40.5	40.5	NO
0.5	85.9	47.6	YES
1	92.5	47.9	YES
1.5	96.1	48.4	YES
2	98.8	50.9	YES
2.5	100.5	54.5	YES
3	102.5	59.6	YES
3.5	103.5	66.4	YES

The room in which the calibration took place recorded ambient sounds between 40.5 dB and 44.2 dB which are within normal parameters of a quiet living room or office space (Teknik, n.d.). The test shows that the Frequency Detection Circuitry would sporadically acknowledge the 2 kHz wave when the decibel level was adjusted from 40.5 to 85.9 dB where the pitch of the sound is the equivalent of standing 1 metre away from an alarm clock (Teknik, n.d.). All amplitudes above 90 dB were detected correctly by the Frequency Detection Circuitry. Decibel levels in the vicinity of 100 dB are the equivalent of standing next to a subway train. At 10 meters away the 100 dB pulse is recorded at 66 dB which is above the sound level of a conventional conversation. Outputting sound pulses at high decibel levels can be harmful to human hearing as suggested by Teknik, (n.d.), if near the system for an extended period of time. From the data collected a 92 dB to 98 dB decibel level is sufficient to trigger the Frequency Detection Circuitry. Continuous or loud bursts of noise in the vicinity of the microphone that are in the order of 75 dB or above (equivalent to a vacuum cleaner ("Sound," n.d.)), cause the Phase-Locked Loop circuit to lose the lock on the target frequency. Conversational speech (60 dB) and noise created by foot steps ("Sound," n.d.) had no effect on the circuitry performance when testing was conducted. The optimal decibel level for SONAR Transmitter is 95 dB. The sound level meter was placed near the SONAR Transmitters' speaker and the variable resistor R7³ was adjusted so that the reading on the meter read 95 dB. The noise generated by the speaker has a nominal decibel level of 60 dB when 5 metres away from the speaker and 50 dB when 10 metres away. This decibel level is the equivalent of conversational speech and close to the ambient noise decibel levels. This means that a sound pulse emitted at 95 dB at the source is not distributive to human hearing.

³ Discussed in Chapter 4.1.2

5 Frequency Confirmation using Radio Signals

The addition of a radio component is an important part in the development of the SONAR system explored in this research. The radio receiver creates the stop trigger⁴ for the timing circuitry. Shown in Figure 5-1 is a block diagram demonstrating the implementation of radio signals to trigger for the timing circuitry. This chapter will evaluate two pre-assembled radio modules from two separate manufacturers. The findings concluded in this chapter will determine the radio module used for the SONAR system.

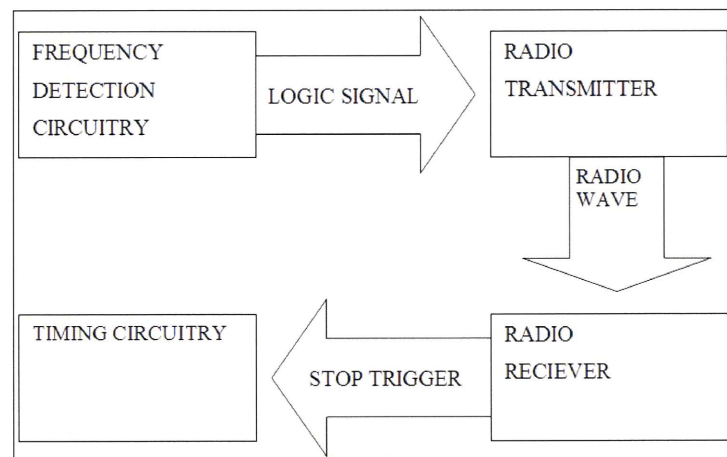


Figure 5-1 Simplified Radio Trigger Block Diagram

5.1 Synopsis of Radio Communication Fundamentals

Radio is the transmission of information by the modulation of electromagnetic waves with frequencies below those of visible light (Haslett, 2008). Radio waves travel at the speed of light approximately 3.0×10^8 metres per second (Haslett, 2008). Information is transmitted by systematically altering (modulating) some property of the radio wave, such as phase, amplitude or frequency.

A radio system normally includes a transmitter and receiver. The transmitter generates alternating current of a desired carrier frequency. The transmitter contains a system to

⁴ Discussed in Chapter 3, Section 2.1

modulate the carrier frequency to transmit information where the signal is converted into an electromagnetic wave (radio wave) by an antenna. The radio wave is intercepted by a receiver designed to respond to the carrier frequency. The receiver's antenna captures the energy of the wave and converts the wave into an oscillating electrical current. The receiver, demodulates the signal to retrieve the original information transmitted (Haslett, 2008).

5.1.1 Binary Information Generation and Modulation

Radio waves can be used to transmit binary information: The American Standard Code for Information Interchange (ASCII) can thus be utilized. ASCII is a method where each character in the English alphabet is encoded into an 8-bit binary number. ASCII codes are used to represent text in computer-based control and communication equipment that use text ("ASCII", n.d.). Microcontrollers are also commonly used to handle the generation encoding and decoding of ASCII characters. In this research, a microcontroller is used to transmit ASCII characters from the SONAR Beacon to the SONAR Transmitter to create a signal named TR₂ for the timing circuitry.

The radio modules explored in this chapter modulate information by employing **A**mplitude **S**hift **K**eying (ASK) or **F**requency **S**hift **K**eying (FSK). Both ASK and FSK can be used to modulate radio waves to transmit binary information. ASK pulses the sinusoidal carrier frequency so that one of the binary states is represented by the presence of the carrier while the other is represented by its absence (Hussain, 2005). FSK Modulation discretely alters the carrier waves' frequency based on the information transmitted. Binary information is represented by two frequencies where "1" is called the mark frequency and the "0" is called the space frequency (Hussain, 2005). Haslett (2008), provides an in depth explanation of both ASK and FSK modulation.

5.2 Radio Transmitter/Receiver Pair Selection

The Transmitter/Receiver pair must transmit binary information reliably over a distance of 10 metres with as little delay as possible. The information transmitted will be used as a pseudo reflected sound wave to trigger the timing circuitry. The two Radio Transmitter/Receiver pairs investigated in this Chapter are;

- ZW3100 (Radio Transmitter) and ZW3102 (Radio Receiver) Pair
- PICHRT111 - Radio Transceiver

5.2.1 ZW3100/ZW3102 Wireless Module

The ZW3100 Radio Transmitter and ZW3102 Radio Receiver (see Figure 5-2) are pre-built wireless modules that operate on the 433 MHz frequency band. The modules incorporate ASK modulation for applications requiring short data bursts in one direction for trigger pulses. The radio modules do not come with an antenna and the user had to design one according to the specifications provided in the datasheet found in Appendix C.

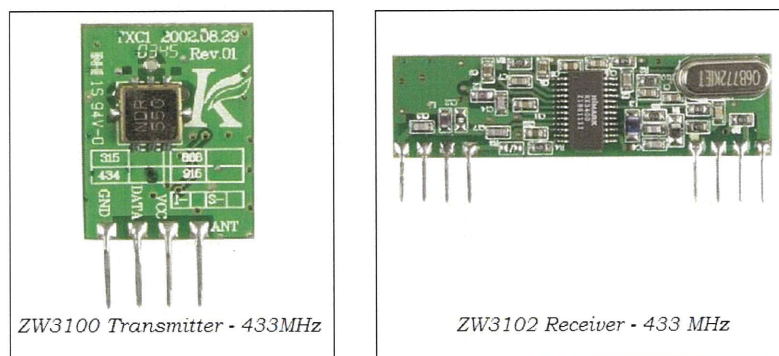


Figure 5-2 ZW3100 and ZW3102 Modules

5.2.2 PICHRT111 - Radio Transceiver Module

The second radio module examined in this chapter is the PICHRT111 Radio Transceiver (see Figure 5-3) that can be configured to act as either, a radio transmitter or radio receiver. The modules feature 2-way half-duplex transmission; where information can be transmitted and received on the same module, but not at the same time. The modules are pre-assembled and supplied with a screw-on frequency tuned right-angled antennas shown in the figure. The PICHRT111 modules operational frequencies are software configurable and can operate in the 300 MHz, 434 MHz and 900 MHz frequency band. Information transmitted and received is modulated by the FSK protocol. The PICHRT111 also features an onboard MAX232 IC which will (depending on the configuration) convert serial ASCII information to and from transistor-to-transistor logic (TTL) levels.

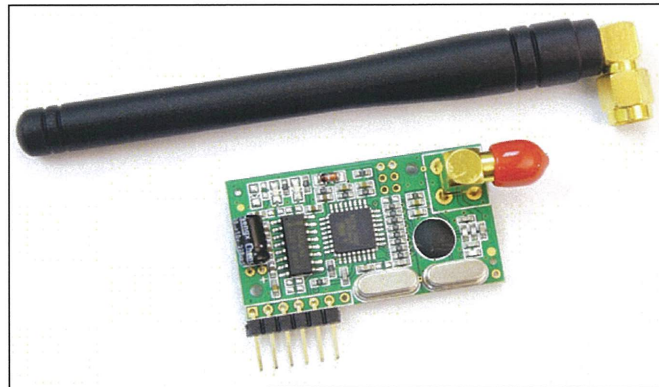


Figure 5-3 PICHRT111 Radio Transducer

5.3 Radio Module Integration with Microcontroller

A microcontroller manages the generation, encoding and decoding of ASCII. The binary character information is output from the microcontroller via serial communication methodology to the radio transmitter. The transmitted radio wave is received by the corresponding radio receiver and the information is then decoded by the respective microcontroller.

5.3.1 PICAXE Microcontroller

The PICAXE brand of microcontrollers is used to generate and encode data for the radio modules investigated in this chapter. The PICAXE microcontroller can be integrated with the radio modules via the Experimenter Board provided with the PICAXE-08M microcontroller shown in Figure 5-4. The Experimenter Board serves two purposes, firstly to supply power to the microcontroller and radio module. Secondly, the board has three indicator light emitting diodes (LED) which are utilised in the testing of the radio modules discussed in section 5.4. The PICAXE-08M is a versatile 8 pin IC that is programmed in BASIC. The IC features a universal asynchronous receiver/transmitter (UART) component (Lincoln. D, 2006) used for serial communication between the radio modules and microcontroller. The following section will outline the wiring methodology and integration of the microcontroller to radio modules examined in this chapter.

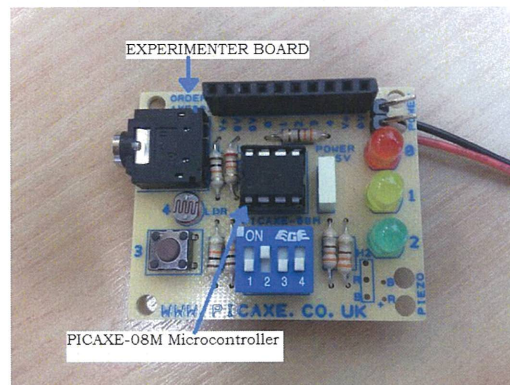


Figure 5-4 PICAXE-08M Microcontroller with Experimenter Board

5.3.2 ZW3100/ZW3102 integration with PICAXE Microcontroller

The PICAXE-08M microcontroller is integrated with the ZW3100 and ZW3102 modules by directly plugging the modules into the Experimenter Board header socket shown below in Figure 5-5; where power is also supplied to the radio modules. Information is wired directly from the microcontroller pins as shown in the Figures 5-6 and 5-7 respectively. Also shown in Figure 5-5 is the custom antennas designed from solid core copper wire insulated in purple plastic to specification found in the ZW3100

datasheet in Appendix C. The unused pins on the ZW3102 module were de-soldered to prevent shorting.

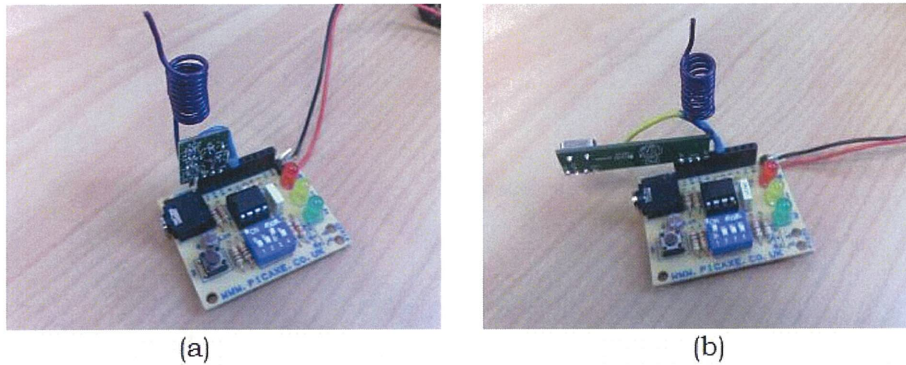


Figure 5-5 (a) ZW3100 in Experimenter Board, (b) ZW3102 in Experimenter Board

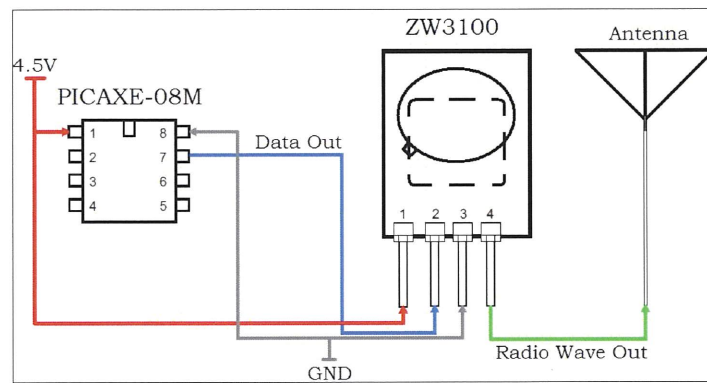


Figure 5-6 PICAXE-08M pin configuration for ZW3100

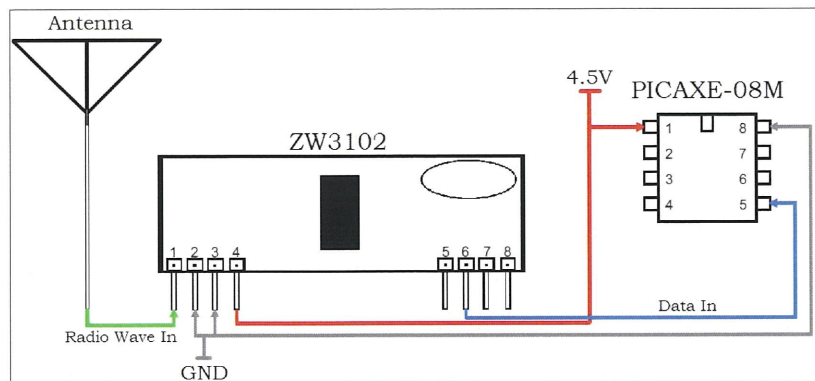


Figure 5-7 PICAXE-08M pin configuration for ZW3102

5.3.3 PICHRT111 integration with PICAXE Microcontroller

The PICHRT111 Radio Transceiver is also plugged directly into the Experimenter Board when the module is configured as a radio transmitter. An extra module must be added to the Experimenter Board before one of the PICHRT111 can be configured as a radio receiver. The onboard MAX232 IC converts TTL signals from logic high 5V and logic low 0V to +9V high and -9V low. These output voltages will damage the PICAXE-08M microcontroller when the PICHRT111 is used as a radio receiver, as the microcontroller only accepts a maximum input voltage of 5V. A voltage divider is required from the PICHRT111 transceiver module to the data input pin on the microcontroller to prevent damage (see Figure 5-8).

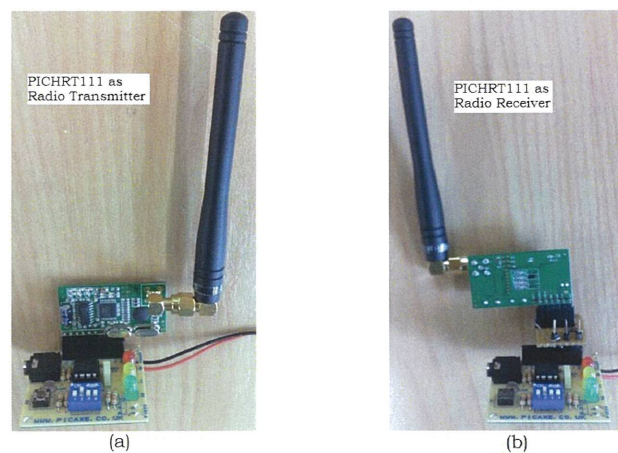


Figure 5-8 (a) PICHRT111 in Experimenter Board configured as Radio Transmitter, (b) PICHRT111 in Experimenter Board configured as Radio Receiver

Shown in Figure 5-9 is the wiring configuration for the PICHRT111 to act as a radio transmitter. The output PIN0 on the PICAXE-08M is wired directly to the PICHRT111 module. Similar to the ZW3100 modules, power to the modules is supplied by the Experimenter Board. Shown in Figure 5-10 is the wiring configuration for the PICHRT111 to act as a radio receiver with the addition of a voltage divider to step-down the output data voltage from the radio module. The values of R1 and R2 are provided in Lincoln (2006, p. 86).

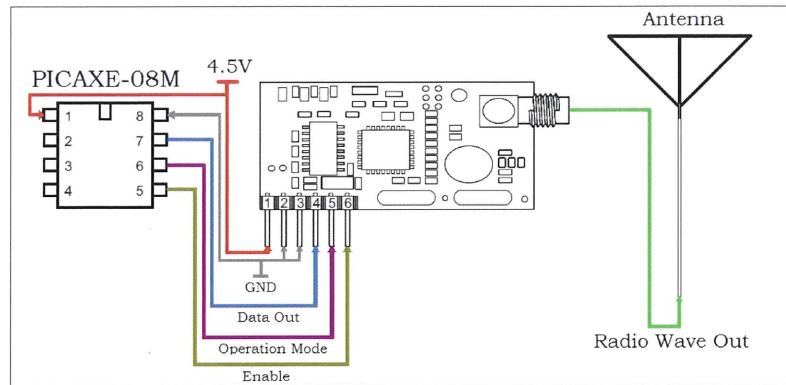


Figure 5-9 PICAXE-08M pin configuration for PICHRT111 as Radio Transmitter

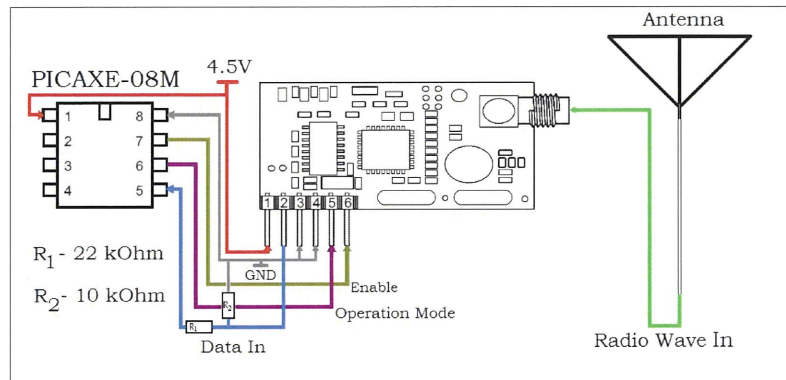


Figure 5-10 PICAXE-08M pin configuration for PICHRT111 as Radio Receiver

5.4 Radio Module Performance Evaluation

The two radio modules studied must adhere to three important criteria. The first criteria is that the radio modules must operate from at least 10 metres apart. Secondly, when the target frequency is detected by the SONAR Beacon, the logic signal from the frequency detection circuitry must trigger the radio modules as soon as possible. Lastly, the radio receiver modules must interpret transmitted information accurately and with minimum latency.

5.4.1 Performance Evaluation Methodology

In order to test the performance of the radio modules, both the receiver and transmitter are placed 10 metres apart. The respective microcontrollers are programmed to output the ASCII character “D” every 2.5 seconds. The receiving microcontrollers are programmed to turn on an LED on the Experimenter Board when the respective

receivers pick up the transmitted ASCII character. The amount of times the LED is turned on in a 30-second period is recorded. In theory the LED should only illuminate 12 times in the 30 second period. This test will examine the radio modules transmission latency and information reception reliability.

5.4.2 ZW3100/ZW3102 Evaluation Results

The BASIC code⁵ programmed into the microcontroller outputted the ASCII character three times in succession every 2.5 seconds. This is a redundancy measure so that if the radio receiver missed the first transmission of the character, the second and third would be received straight after. The receiving microcontroller is programmed to respond to the reception of only one ASCII character. In the 30 second interval the LED was triggered 5, 22, and 18 times per test as shown in Table 5-1.

Further analysis of the received radio signal is shown in Figure 5-11 shows that the ZW3102 module is highly susceptible to noise and the reception of information was sporadic and unreliable. The upper waveform is the transmitted demodulated radio signal and the lower waveform is the received demodulated radio signal. Bounded in the red box is the radio noise that the ZW3102 module has demodulated and bound in the green lines is the desired information. The ambient radio noise triggered the PICAXE-08M microcontroller to accept false information and thus triggered the LED more times than it should of. Even though the custom antenna was designed to specifications, the performance of the ZW3100 modules was extremely poor.

Table 5-1 ZW3100 and ZW3102 Results

Attempt	Number of times LED was illuminated
1	15
2	22
3	18

⁵ ZW3102 Receive Code and ZW3100 Send Code found in Appendix A

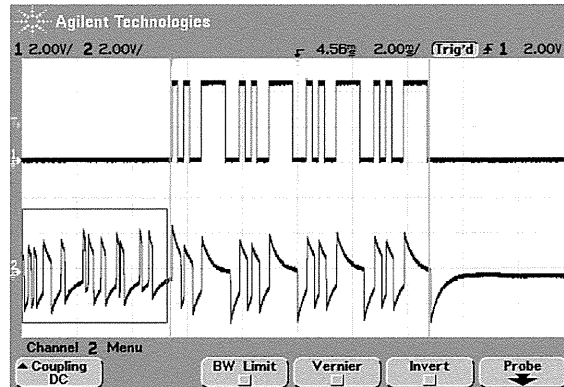


Figure 5-11 ZW3000 and ZW3002 transmission errors

5.4.3 PICHRT111 Evaluation Results

Test results for the PICHRT111 transceiver module shown in Table 5-2 show that the PICHRT111 modules illuminated the LED 12 times. It is clear that the PICHRT111 modules are more stable for both transmission and reception of radio signals. The provided antenna makes the units less susceptible to noise as shown in Figure 5-12. The demodulated received radio signal is passed through the MAX232 IC before inputting into the microcontroller. The transmitting microcontroller was programmed to transmit the ASCII character “D” once as opposed to thrice as with the ZW3100 modules as radio noise was not a factor and did not disrupt any data transmissions.

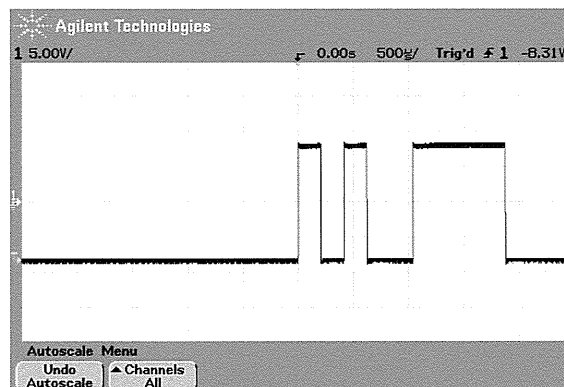


Figure 5-12 PICHRT111 Demodulated received radio signal

Table 5-2 PICHRT111 Results

Attempt	NO# LED illuminated
1	12
2	12
3	12

Further analysis shows there is a time delay between the transmission of the non-modulated data and the received demodulated data. The 6.2 millisecond delay shown in Figure 5-13 is constant for all distances up to 10 metres and is due to the MAX232 processing time. The time taken for the microcontroller to decode the ASCII character from the radio receiver and turn on the LED is about 120 microseconds as shown in Figure 5-14. The delay is constant and can be taken into account for time measurements for the SONAR system.

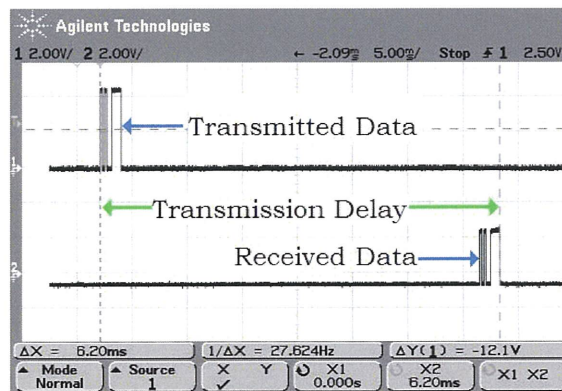


Figure 5-13 PICHRT111 Transmission and Reception delay

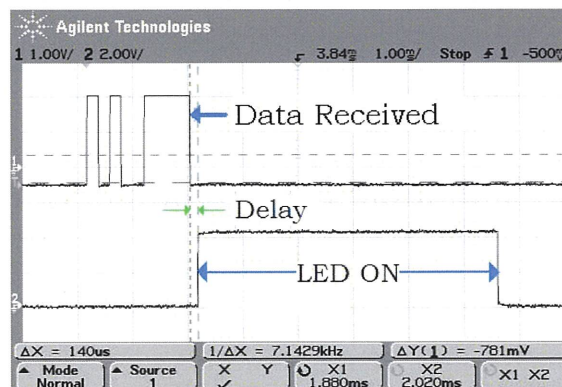


Figure 5-14 Microcontroller decoding ASCII data and turning on LED

5.4.4 Evaluation Summary

Comparing the cost to benefits, the PICHRT111 is selected for the hybrid SONAR system. The transmission latency of the PICHRT111 is the only disadvantage to the module. However, the delay is consistent; it can be factored into any timing operations required. A cost-benefit analysis in Table 5-3 would suggest that the reliability and performance outweigh the expenditure of the units.

Table 5-3 Cost-Benefit Table

	Radio Module	
	ZW3100/ZW3102	PICHRT111
COST	\$31.80 NZD⁶	\$75 NZD⁷
OVERALL PERFORMANCE	POOR	GOOD

5.5 PICHRT111 Integration with Frequency Detection Circuitry

The PICHRT111 needs to transmit useful information back to the timing circuitry at the exact time of frequency detection. However, the PPL circuit works by shifting the phase of the centre frequency to match that of the target frequency. The time taken for the PPL circuit to do this is unpredictable. If the stop trigger is created by the output of the PPL circuit, the time measured for distance will not be accurate due to the unpredictable processing time of the PPL circuit. However, the stop trigger can be triggered from another point in the Frequency detection circuitry. When the target frequency has passed through the Burst Noise Suppression circuitry, a particular voltage level can be output. It is possible to create the stop trigger for the timing circuitry by using two radio signals. The first radio signal will stop the timing circuit; the second radio signal will confirm that the target frequency has been detected.

5.5.1 Stop Trigger with Radio Transmission Triggers

The first radio transmission will transmit the stop trigger TR₂ and is generated by a Level Detector circuit shown below in Figure 5-15. The Burst Noise Suppression Circuitry outputs a voltage level when the target frequency is detected. By using a LM358N - Low Power Dual Operational Amplifier - when the voltage from the Burst Suppression Circuitry is above or equal to the voltage generated by the variable resistor shown in the figure. Logic high will be outputted from the LM358N IC to trigger the

⁶ Price for both the ZW3100 and ZW3102 in New Zealand Currency

⁷ Price for two PICHRT111 Modules in New Zealand Currency

PICAXE-08M microcontroller programmed⁸ to output an ASCII character to the PICHRT111 transmitter to stop the timing circuitry.

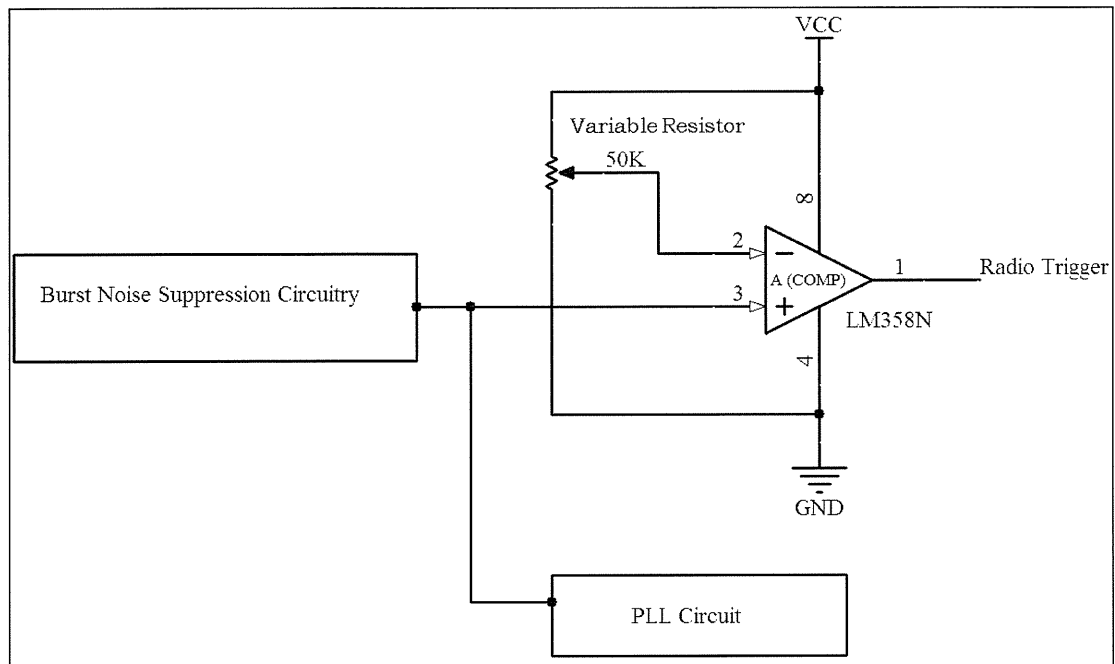


Figure 5-15 Level Detector Circuit Schematic

It is possible for ambient noise and burst noise to cause a radio trigger; this issue is addressed by having a second radio transmitter. The timing event should only be triggered when the SONAR Beacon has detected the target frequency. Therefore a second radio transmitter and receiver pair is used to confirm that the first radio signal was triggered by the target frequency and this is denoted as the confirmation trigger.

A second PICAXE-08M microcontroller and PICHRT111 pair is used to trigger from the PPL circuit. As mentioned before the PPL processing time is not consistent and therefore the microcontroller is programmed to wait for confirmation that the target frequency has been detected then output an ASCII character via radio signal back to the timing circuitry to indicate that the recorded time is valid. The transmission of this radio signal is not time critical. If the time recorded was triggered by burst noise, then the confirmation signal will not be transmitted. The timing circuit will disregard the recorded time and request another distance sample.

⁸ PICHRT111 Send and Receive Code Appendix A

The block diagram in Figure 5-16 illustrates the systematic process of the Radio Trigger and Confirmation Trigger in the SONAR Beacon.

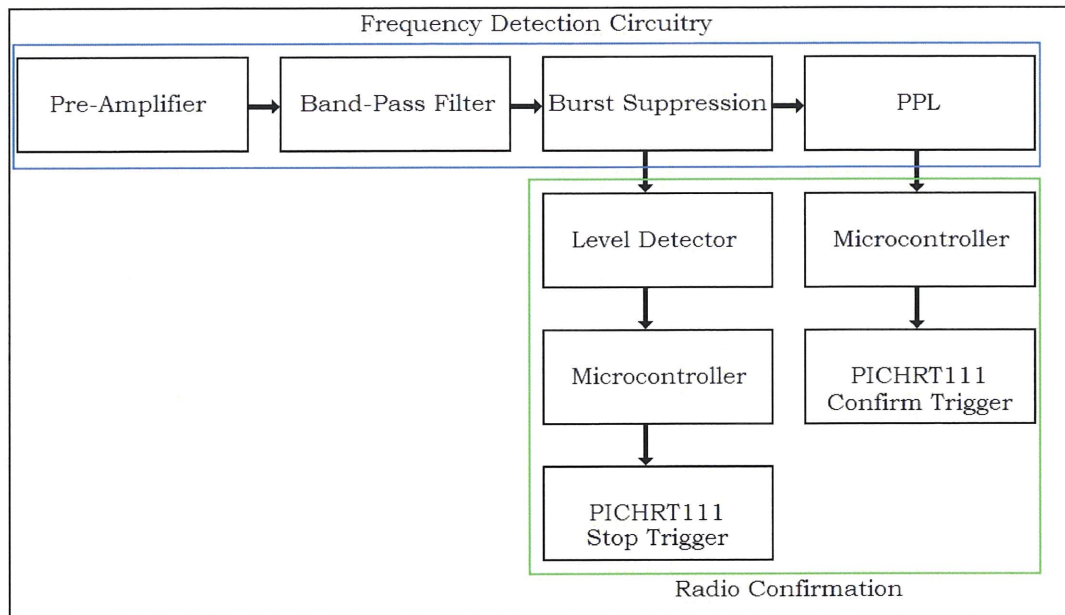


Figure 5-16 Detailed Block Diagram of SONAR Beacon with Radio Confirmation

6 Real-Time Data Acquisition

The time component of the hybrid SONAR system developed in this research will measure the **time-of-flight** (TOF) of a sound wave in one direction. This chapter will discuss the methodology used to acquire real-time data using a microcontroller. This will include the generation of a digital square-pulse required for the microcontroller to time, interpret the real-time data and the conversion of the information into relevant distance measurements.

6.1 Microcontroller for Real-Time Data Acquisition

The TOF can be measured using software or hardware. Software timing would require a computer to be available whenever a time measurement is required by the SONAR system. Real-time data acquisition accuracy is limited by other processes running on the computer. Data acquisition acquired by dedicated hardware is more accurate as the hardware is only concerned with the timing process. The information acquired from hardware can be output to a variety of microcontrollers or computers using different methodologies. Real-time data acquisition between two events and the interpretation of information can be implemented by a single microcontroller. The PICAXE-08M microcontroller has a predefined BASIC command for timing procedures. The SONAR system takes advantage of the “*pulsin*” command (Lincoln, 2006, p. 69) for real-time data acquisition. The *pulsin* BASIC command achieves time measurement by counting the rising edges of an internal digital clock pulse (software configured) for the duration of a digital square-pulse fed into a designated input pin on the microcontroller. Each count of the clock pulse represents a unit of time. Multiplying the count by the period of the clock frequency will result in the time measurement.

6.1.1 PICAXE Time Measurement Resolution

Discussed in Chapter 3.2.2, the method used in this research to measure time depends on the frequency of the internal digital clock used by the microcontroller (see Equation 3.12). The PICAXE-08M utilizes a clock frequency of 200 kHz for the *pulsin* command. The equation developed in Chapter 3.2.2 is applied to the 200 kHz clock pulse. Each count of the clock pulse is 5 microseconds. The theoretical minimum distance d , which can be measured by the microcontroller, is calculated by Equation 6.1. The average theoretical value used for the speed of sound is 340.29ms^{-1} .

Equation 6.1 $d = v * t$

$$t = 1/f$$

Where f is the clock frequency, thus

$$d = 340.29 \times 1 / 200\,000$$

$$d = 0.00170145 \text{ metres}$$

$$d = 1.701 \text{ millimetres}$$

The *pulsin* command is designed with an automatic timeout function at 0.32768 seconds. Thus the theoretical maximum distance that can be measured by the microcontroller is determined by Equation 6.1 for time $t = 0.32768$;

$$d = 340.29 \times 0.32768$$

$$d = 111.5062272 \text{ metres}$$

For the purposed of this research the SONAR system needs to function at a maximum of 10 meters. The theoretical maximum resolution is more than adequate. The theoretical time taken for a sound wave to travel from 0.5 metres to 10 metres is determined by reformulating Equation 6.1 into Equation 6.2. Time is relative to the number of counts and is calculated by multiplying the theoretical time by the inverse of the clock frequency, see Equation 6.3. The results are tabulated in Table 6-1.

Equation 6.2 $t = d / v$

Equation 6.3 $Count = f / t$

Using the Agilent Function/Arbitrary Waveform Generator, the theoretical pulse widths were simulated and fed into a PICAXE-08M microcontroller. The microcontroller is then programmed to output the simulated pulse width measurements (counts) into a computer via a serial port. The REVOLUTION PICAXE Program Editor is equipped with a “Terminal” option that allows ASCII information to be read from a designated COM Port on a computer. The PICAXE microcontroller is programmed⁹ to output the counts in ASCII and read into the Terminal.

The experiment is designed to compare the theoretical count values to the microcontroller measured counts to monitor real-time performance. The results shown in Table 6-1 verify an average error of 0.4% that is consistent throughout the data collection for the experiment. The error percentage is so low that it will have no effect on the accuracy of the overall time measurement.

Table 6-1 Microcontroller Experiment Results Table

Theoretical Pulse Width (s)	Theoretical Distance (m)	Theoretical Counts (0.5us per count)	Actual Counts (0.5us per count)	Error (%)
0.001469	0.5	294	295	0.34
0.002939	1.0	588	590	0.34
0.004408	1.5	882	884	0.23
0.005877	2.0	1175	1179	0.34
0.007347	2.5	1469	1473	0.27
0.008816	3.0	1763	1767	0.23
0.010285	3.5	2057	2064	0.34
0.011755	4.0	2351	2364	0.55
0.013224	4.5	2645	2656	0.42
0.014693	5.0	2939	2951	0.41
0.016163	5.5	3233	3246	0.40
0.017632	6.0	3526	3542	0.45
0.019101	6.5	3820	3837	0.45
0.020571	7.0	4114	4133	0.46
0.02204	7.5	4408	4427	0.43
0.023509	8.0	4702	4723	0.45
0.024979	8.5	4996	5018	0.44
0.026448	9.0	5290	5313	0.43
0.027917	9.5	5583	5608	0.45
0.029387	10.0	5877	5904	0.46

⁹ BASIC *pulsin* code found in Appendix A

6.2 Pulse Generation

In order to utilize the PICAXE-08M microcontroller a square-pulse needs to be generated to obtain a distance measurement. The rising edge of the square-pulse is generated when the sine wave generator module is set low (TR_1) and the falling edge is generated when the Radio Wave module outputs logic high (TR_2) (see Figure 6-1).

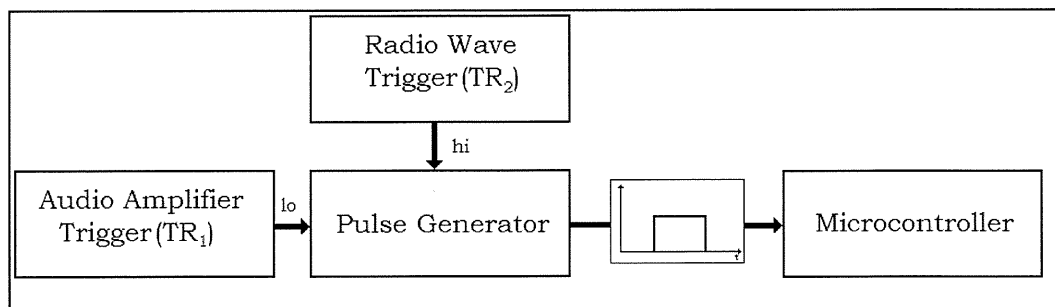


Figure 6-1 Square-Pulse Generation Simplified

The correct combination of signals will be controlled by a logic gate to create a square-pulse and is determined by the truth table shown in Table 6-2. A NOR Gate (Hewes, 2009) will provide the appropriate output required to create a square pulse from the available input signals TR_1 and TR_2 (See Figure 6-2).

Table 6-2 Truth Table for Pulse Generation

TR_1	TR_2	OUTPUT	Desired Effect
0	0	1	Creates rising edge of square pulse
0	1	0	Creates falling edge of square pulse
1	0	0	No effect on output
1	1	0	No effect on output

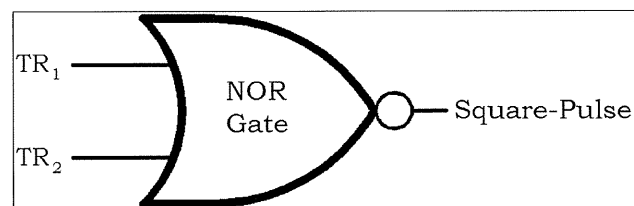


Figure 6-2 NOR Gate used to generate Square-PULSE

6.2.1 Circuit Design for Pulse Generation

A MC14011BCP - Quad 2-Input NAND Gate – IC is used to create the desired pulse, where all four gates are used to replicate the function of a NOR gate. The circuit schematic shown in Figure 6-3 requires that the inputs be tied to ground by resistors R1 and R2. This is to stop the input from “floating” high.

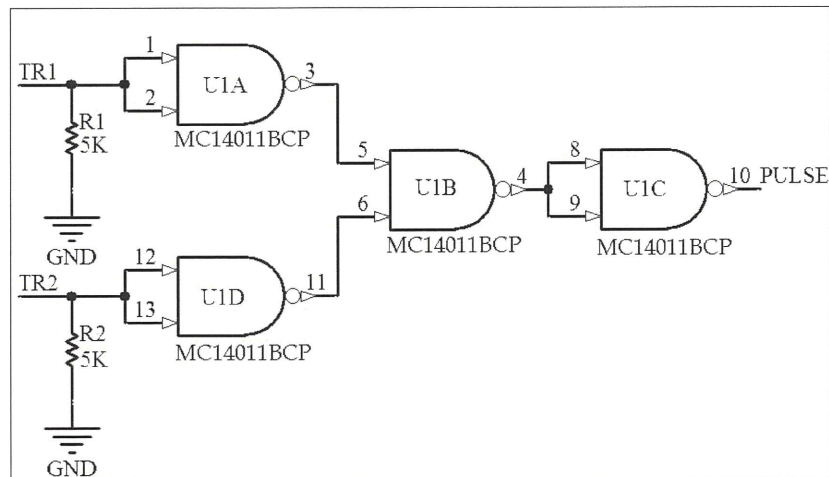


Figure 6-3 Pulse Generation Circuit Schematic

The response time was tested by inputting a square pulse into the TR_1 input to simulate actual operation. The response time is measured to be 180 nanoseconds in response to a changing input shown in Figure 6-4 for the rising and falling edges of the generated-square pulse.

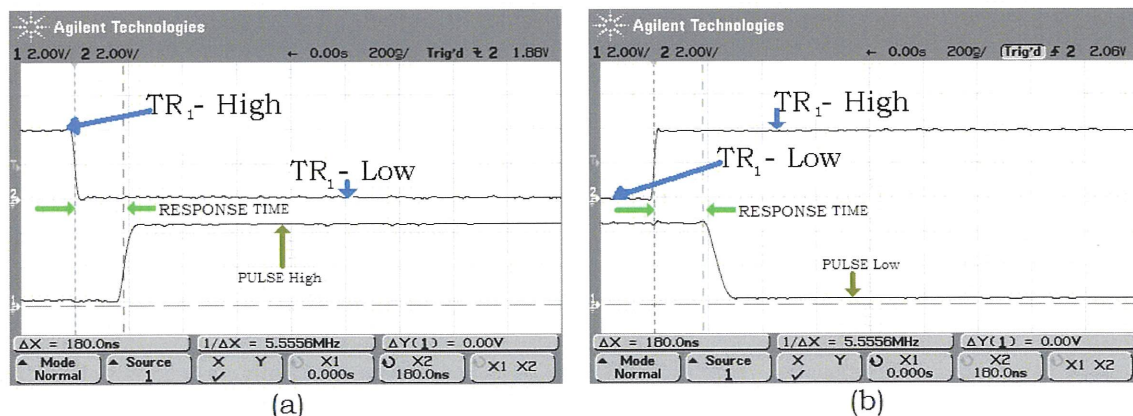


Figure 6-4 Response time of Pulse Generator Circuit

The response to an input falling edge and rising edge are almost the same and is not a factor in the timing measurement as the delays cancel each other.

6.3 Microcontroller Data Transmission

Once the square-pulse is measured by the microcontroller the information is stored in internal memory of the PICAXE-08M. The information can be output from the microcontroller via serial communication methodology to another microcontroller or computer for further processing. For this research the information stored on the microcontroller is passed to a computer.

6.3.1 PICAXE communication with LabVIEW Interface

Communication between the PICAXE-08M microcontroller and computer is established by serial communication using the RS232 port and LabVIEW as the software interface. Once the information is transferred from the microcontroller to LabVIEW interface program, algorithms can be used to process data into distance measurements.

The microcontroller has predefined BASIC commands found in Lincoln (2006), to output serial information from any of the input/output (I/O) pins available on the PICAXE-08M microcontroller. In exactly the same way information is transmitted to the radio modules discussed in Chapter 5, information can be transmitted from the microcontroller to the computer via a custom RS232 cable as defined Lincoln (2006). The interface program¹⁰ compiled in LabVIEW takes advantage of the *Virtual Instrument Software Architecture* (VISA) used to configure the Communication Port (COM Port). This allows information to be accepted and sent via serial communication from computer to microcontroller. The PICAXE-08M, only supports 2-way half-duplex transmission of information, thus information can be only received or transmitted at one time.

The LabVIEW interface has to send a request first to receive information from the microcontroller. The interface program (screenshot of the LabVIEW program in Figure

¹⁰ LabVIEW Code found in Appendix A

6-5) is used to communicate with the microcontroller¹¹ and request information by sending the ASCII characters “GO”. Upon receiving the “GO” characters, the microcontroller then uses the *pulsin* command to measure a square-pulse fed into PIN3 as shown in Figure 6-6. The raw data (counts) stored in internal memory is converted into ASCII characters and then sent to the computer with the LabVIEW program by using the *serout* BASIC command.

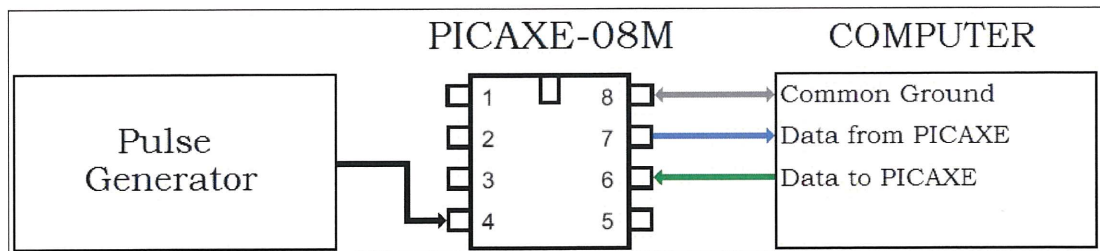


Figure 6-5 Communication link between Microcontroller and Computer

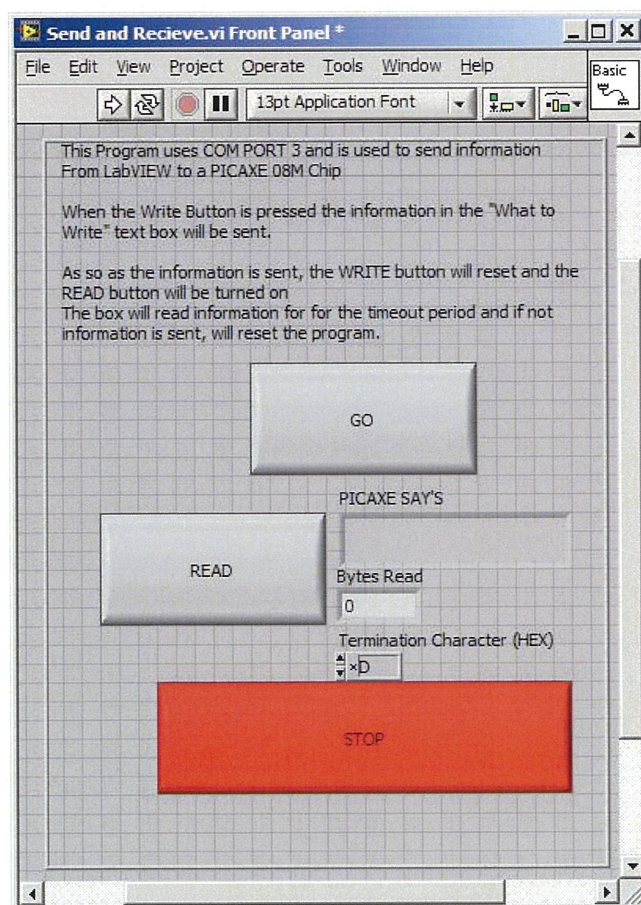


Figure 6-6 Screenshot of LabVIEW program used for serial Communication

¹¹ BASIC Communication Code found in Appendix C

The data received is the physical number of counts of the clock for the period of the pulse. The information can then be converted into a time and therefore into a distance measurement. The interpretation of the information is discussed in Chapter 7.

7 System Integration and Control

The hybrid SONAR system consists of two main parts - the SONAR Transmitter and SONAR Beacon - that consist of multiple modules. This chapter will focus on the integration of the modules and the methodologies employed to control and power the two parts.

7.1 SONAR Transmitter System Control

The SONAR Transmitter consists of three components, where each component is controlled by a PICAXE-08M microcontroller. The three components are the **T**arget **F**requency **G**eneration (TFG), **R**eal-Time **D**ata **A**cquisition (RTDA) and the **R**adio **C**onfirmation module (RAC). The TFG and RTDA modules are activated simultaneously by a computer via the LabVIEW interface. The RAC module is wired directly to the appropriate microcontrollers.

7.1.1 Target Frequency Generation Control

As discussed in Chapter 4, the TFG module requires a logic low to turn on. Shown in Figure 7-1 is the wiring configuration to connect a PICAXE-08M microcontroller to the TFG module. The LabVIEW interface is programmed to send the ASCII characters “GO” to trigger the microcontroller. The microcontroller is programmed¹² to turn on the TFG circuit 10 milliseconds after receiving the “GO” command. The 10 millisecond delay is a time buffer designed to accommodate any discrepancies in the time taken for the command to be sent from the computer to the microcontroller. Secondly, the buffer allows the TFG and RTDA modules to synchronise.

¹² TFG Microcontroller BASIC Code in Appendix A

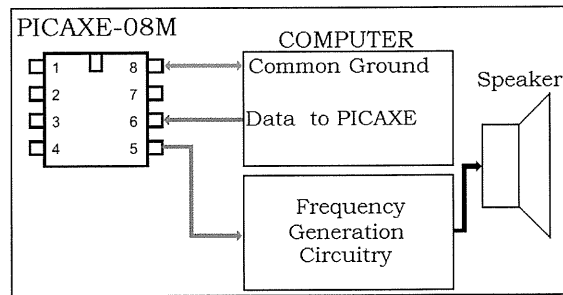


Figure 7-1 Frequency Generation Control Diagram

7.1.2 Real-Time Data Acquisition Control

Discussed in Chapter 6, the RTDA module is wired to the computer via custom RS232 cable. The same “GO” ASCII command used to trigger the TFG module is used to trigger the RTDA module. The RTDA microcontroller is programmed¹³ with a 9 millisecond buffer to allow for transmission discrepancies and synchronization. The flow of data to and from the microcontrollers is shown in Figure 7-2. Taking advantage of the timeout function of the pulsln command, the 9 millisecond buffer is to ensure that the timing command has started before the creation of TR₁ so that the time measurement is not lost.

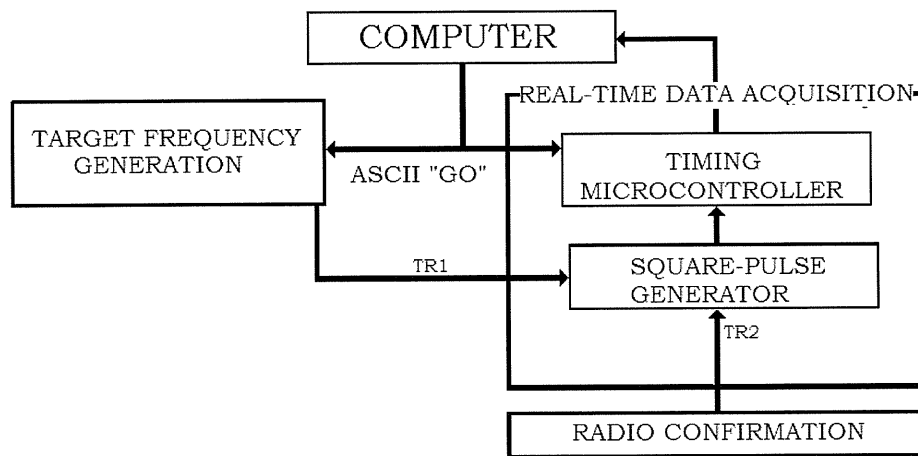


Figure 7-2 Real-Time Data Acquisition Control Diagram

¹³ RTDA Microcontroller BASIC Code in Appendix A

7.1.3 Radio Confirmation Control

The RAC module does not need any controlling. However the respective microcontrollers do require programming¹⁴ to receive the correct data. Mentioned in Chapter 6, the confirmation radio signal is not a time critical event. Therefore on the reception of the confirmation radio signal the microcontroller is programmed with a slight delay before logic high is output to the timing microcontroller. The flow diagram shown Figure 7-3 illustrates the data flow from radio receiver to timing module.

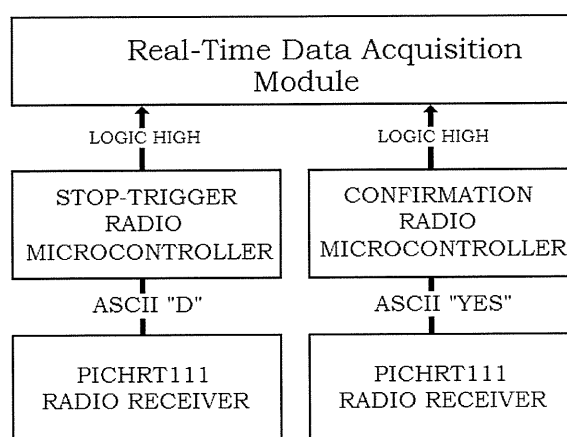


Figure 7-3 Radio Confirmation Control Diagram

7.1.4 SONAR Transmitter Integration with LabVIEW

Interface

Shown in Figure 7-4 is the flow of data between the SONAR Transmitter components and computer. Information is passed from the computer to the TGF and RTDA modules via the RS232 port using a custom serial cable (see Figure 7-9). The serial cable plugs directly into an interface board that is connected to the appropriate microcontrollers. The LabVIEW interface¹⁵ (screenshot of program seen in Figure 7-5) takes advantage of the VISA functions, as discussed in Chapter 6. The program is designed to take a user defined amount of samples and store the counts in a designated word document.

¹⁴ RAC microcontroller BASIC code found in Appendix A

¹⁵ LabVIEW Interface code in Appendix A

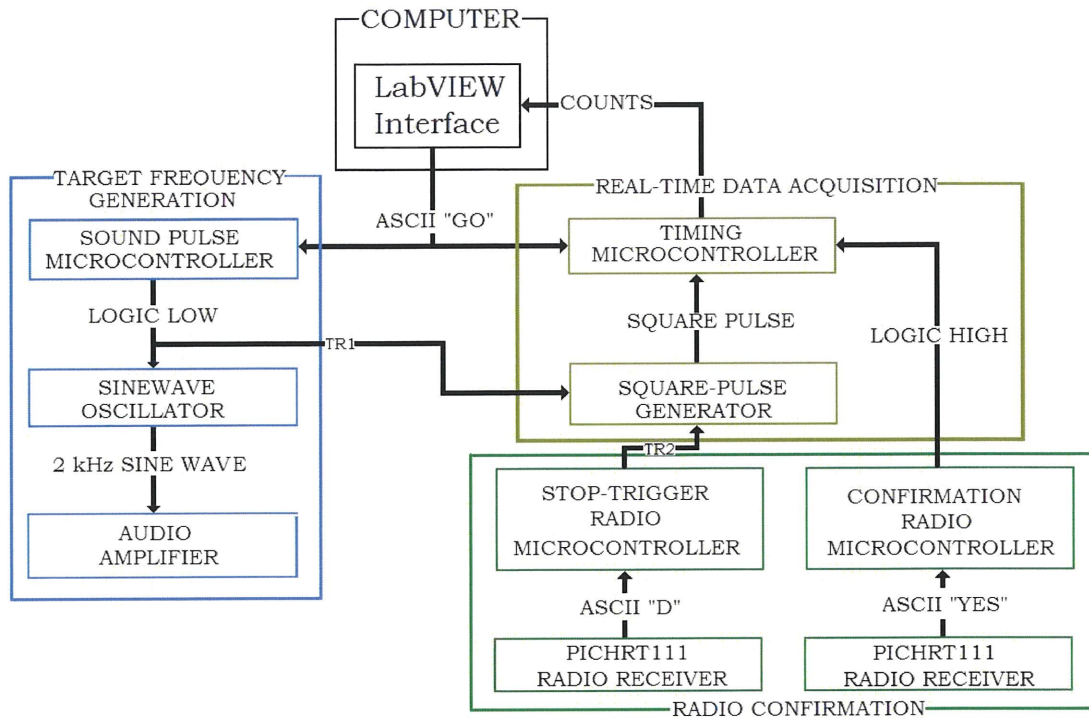


Figure 7-4 Block Diagram of SONAR Transmitter System

The method of operation for the LabVIEW interface program is described as follows:

1. Choose word document filename for data to be stored in.
2. Enter the amount of samples required in samples field in LabVIEW interface.
3. Press GO button in LabVIEW interface.
4. ASCII character "GO" is sent to TFG and RTDA microcontrollers
5. Upon reception of ASCII "GO" the 9 millisecond delay is invoked before the RTDA microcontroller begins to measure a square pulse on the designated pin.
6. Upon reception of ASCII "GO" the 10 millisecond delay is invoked before the TFG microcontroller simultaneously triggers Sine Wave Oscillator and TR₁ is created.
7. RTDA module awaits TR₂ from SONAR Beacon.
8. Upon reception of confirmation signal from SONAR Beacon, the measured pulse count is output to the LabVIEW interface and stored in designated word file.
9. If confirmation signal is false, then "false count" is sent instead.
10. The process is repeated till the number of samples has been acquired.

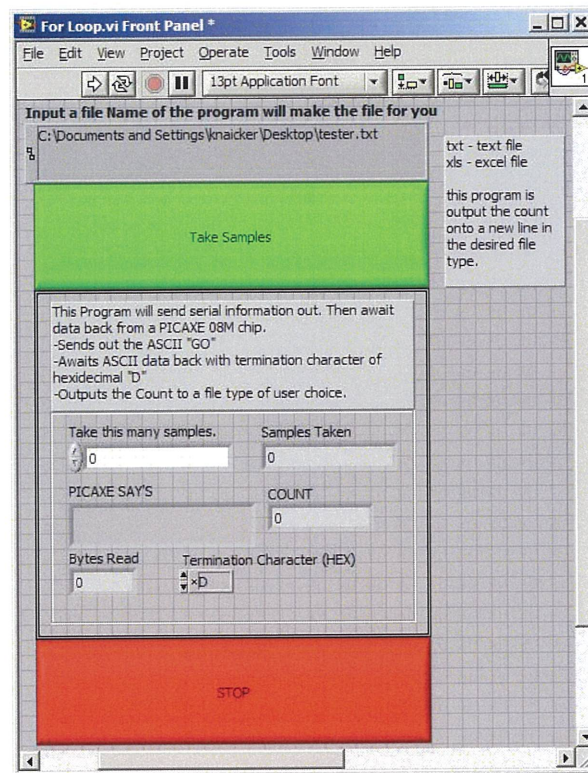


Figure 7-5 Screenshot of LabVIEW Interface

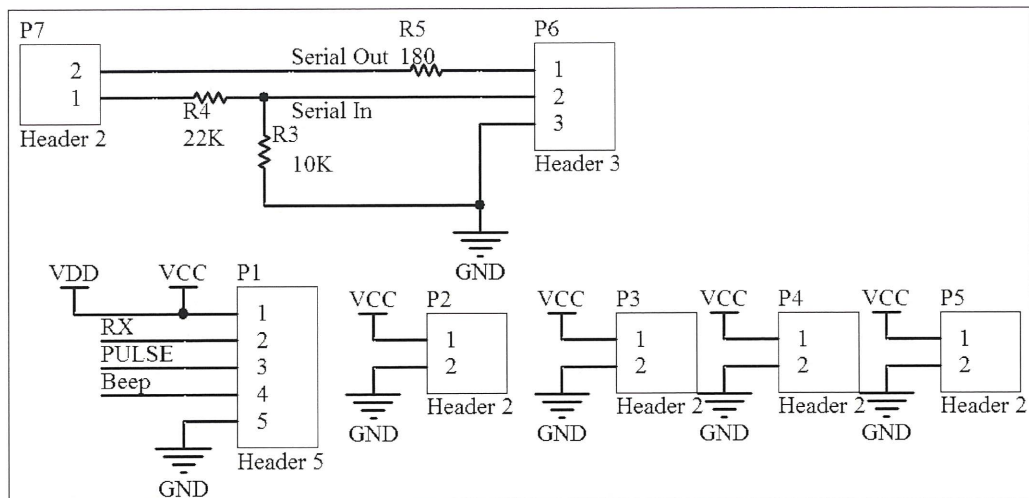
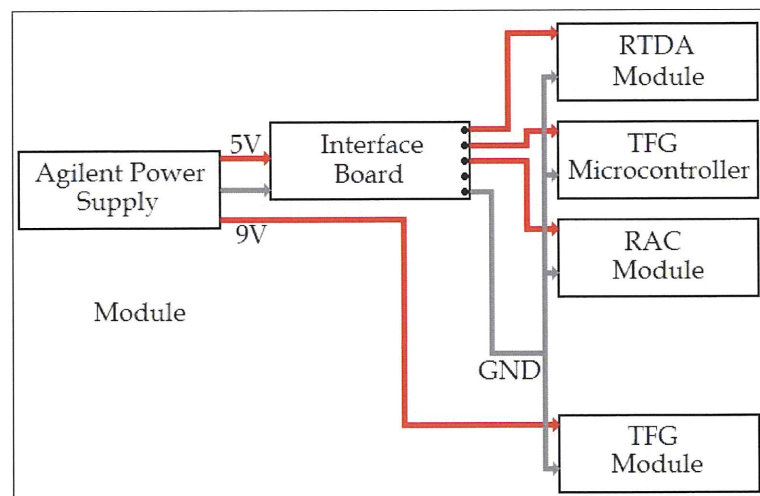
7.1.5 SONAR Transmitter Power Supply

Power is required for the individual modules of the SONAR Transmitter. Only the TFG module requires a different operating voltage. The voltage requirements shown in Table 7-1 are met by the Agilent E3631A Triple Output DC Power Supply. The 6 volt output on the Agilent power supply is adjust to output 5 volts and connected to an interface board (the interface board circuit schematic is shown in Figure 7-6) that distributes power among the 5V modules. The +25 volt output is set to 9V and connected directly to the TFG components requiring 9V. A common ground is established by connected the negative terminals of the power supply together as shown in Figure 7-7.

Table 7-1 Operating Voltage Requirement

MODULE	Operating voltage (V)
Sine Wave Oscillator	9V
Audio Amplifier	9V
Square Pulse Generator	5V
PICHRT111	5V
Microcontroller	5V

NOTE: In total there are 4 microcontrollers and 2 PICHRT11 modules on the SONAR Transmitter.

**Figure 7-6 Interface Circuit Schematic****Figure 7-7 Power distribution**

7.2 SONAR Beacon System Integration

The SONAR Beacon is a wireless module that will be placed away from the SONAR Transmitter. A power supply is required to power the individual modules for the SONAR Beacon. However each module has different voltage requirements. Instead of using multiple batteries to accommodate the variance in voltages required, one rechargeable 12V, 9AH Seal Lead Acid battery is used.

7.2.1 SONAR Beacon Power Supply

Table 7-2 outlines the voltage requirement for each module in the SONAR Beacon. In order to supply the appropriate voltages to the units a combination of a voltage regulator and voltage converters are used to supply power to the modules on the SONAR Beacon. The first step is to step down the voltage from 12V to 9V to supply the Pre-amplifier, Burst Noise Suppression and Level Detector circuitry. This is achieved by making use of a LM317T 3-Terminal Adjustable Regulator. The output voltage of 9 volts (V_{Out}) is determined by Equation 7.1 from the LM317T datasheet found in Appendix C. Setting R2 at 240 Ohms, R3 can then be adjusted to output 9V found in the LM317T datasheet.

Equation 7.1
$$V_{OUT} = 1.25V (1 + R3/R2) + I_{ADJ}*(R2)$$

The 9V is then fed into a LM78L05¹⁶ 3-Terminal Positive 5V Regulator to power the Phase Locked-Loop circuit and PICAXE-08M microcontroller. The regulator will accept voltages up to 10V and typically output 5V. As defined in the datasheet Capacitor C10 is required to limit high frequency noise and C5 is required to filter the 9V input voltage. Finally to power the Band-Pass Filter the 5V is also fed into a MAX680¹⁷ +5V to +/-10V converter which converts an input voltage of 5V to the required -10/+10V required for the circuit. The MAX680 requires four 4.7 microfarad

¹⁶ LM78L05 Datasheet found in Appendix C

¹⁷ MAX680 Datasheet found in Appendix C

capacitors as suggested in the datasheet. Shown in Figure 7-8 is the circuit schematic of all three power supplies and their appropriate voltage outputs.

Table 7-2 Operating Voltage Requirement

MODULE	Operating voltage (V)
Pre-Amplifier	9
Band-Pass Filter	-10 / +10
Burst Noise Suppression	9
Phase Locked-Loop	5
Level Detector	9
Microcontroller	5

NOTE: The PIC18F1440 radio module powers off the microcontroller experimenter board.

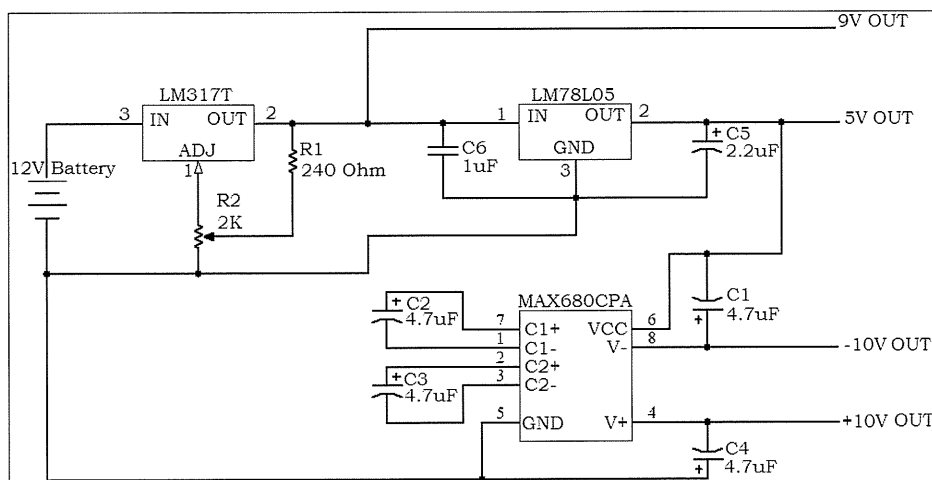


Figure 7-8 Power Supply Circuit Schematic

The current consumption of the SONAR Beacon is measured by connecting a multimeter in series with each module. The current required by each module in the SONAR Beacon is outlined in Table 7-3 and in the worst case scenario (where the SONAR Beacon is continuous transmitting) all the modules roughly consume 120mA. In theory the SONAR Beacon can operated for 90 hours on a fully charge battery. However, in real world applications, the SONAR Beacon would be wired to the mains for indoor applications. Power from the sealed lead acid battery is suitable to attained results for experiments to be discussed in Chapter 8.

Table 7-3 Current Consumption

MODULE	Operating voltage (mA)
Pre-Amplifier	12
Band-Pass Filter	8
Burst Noise Suppression	11
Phase Locked-Loop	13
Level Detector	5
Microcontroller*	51 - 70

* With PICHRT111 Radio module connected. 50mA not transmitted. 70mA transmitting information

7.3 SONAR System Assembly

Before the SONAR system can be evaluated the system needs to be physically integrated. This is achieved by mounting each PCB module onto a piece of wood. Once the system modules are mounted the experiments outlined in Chapter 8 can be carried out.

7.3.1 SONAR Transmitter Test Rig

The SONAR Transmitter designed in this research is modular so that, any faults can be traced back to the individual module. Each module is mounted onto a block of wood as shown in Figure 7-9. Also shown in the figure is the aforementioned custom serial cable.

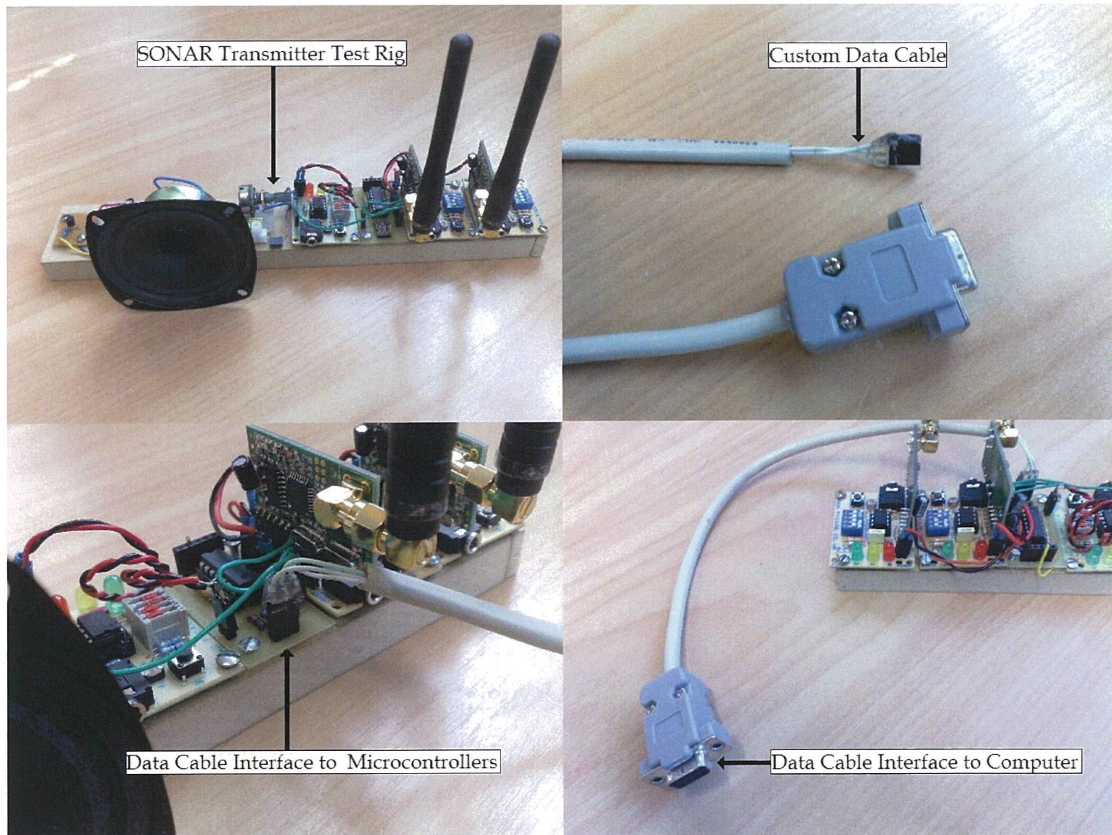


Figure 7-9 SONAR Transmitter Test Rig

7.3.2 SONAR Beacon Test Rig

Similarly to the SONAR Transmitter, the SONAR Beacon is also modular, to make fault finding easier. Each module is mounted onto a block of wood as shown in Figure 7-10.

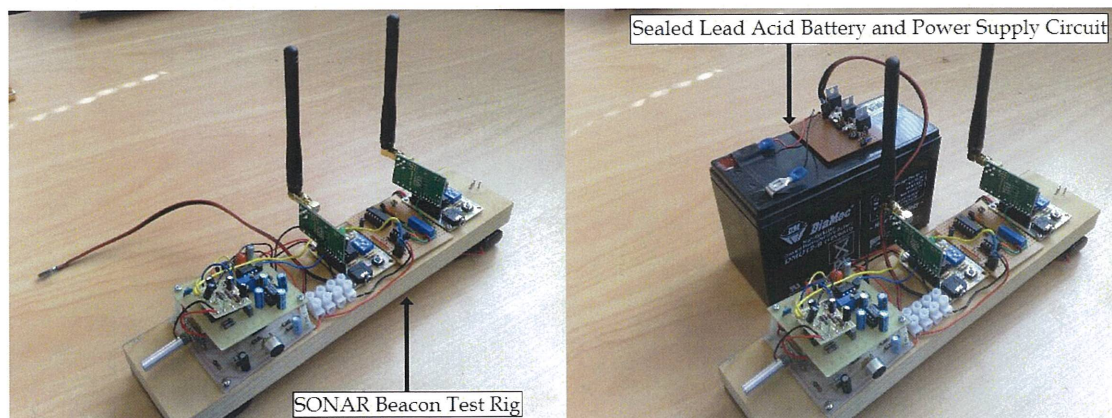


Figure 7-10 SONAR Beacon Test Rig

8 Examination of the SONAR System

The SONAR system is tested for accuracy before it can be used for any real-world applications. The testing results were compared to theoretical data to gauge the accuracy. In order to test the accuracy and performance of the system three experiments were conducted to test different aspects of the system. The linear accuracy of the system was tested first, by changing the distance between the SONAR Transmitter and SONAR Beacon. The second test analysed the effect of the orientation of the SONAR Transmitter to the SONAR Beacon. The third experiment conducted examined the accuracy of the distance measurement as the SONAR Beacon is placed at different elevations to the SONAR Transmitter.

8.1 SONAR Distance Theory

The laboratory chosen to test the SONAR system measures 12 metres by 7 metres by 3 metres. The ambient temperature, humidity and air particle density at the time of the experiments are assumed to have no effect on the speed of sound.

8.1.1 Distance vs. Time

As discussed in Chapter 3, the aim of this research was to create a system to measure distance based on the speed of sound. The formula derived in Chapter 3.2.2¹⁸ is used (Equation 8.1) to calculate the theoretical data required to compare against the experimental data collected. Data representation is made more meaningful by converting the calculated times from microseconds to milliseconds.

¹⁸ Equation 3.9

Equation 8.1 $d = v * t$

Where, d = distance (metres)

v = speed of sound (340.29 ms^{-1})

t = time (seconds)

Therefore, time in milliseconds should be

$$t = d * 1/340.29\text{ms}^{-1}$$

$$t = d * 0.0029387$$

$$t = d * 0.0029387 * 1000$$

Equation 8.2 $t = d * 2.9387$

For a straight line, it can be represented by:

$$y = mx + c$$

Where x and y are the coordinates of the points that satisfy the function and so lie on a straight line graph. The gradient of the straight line is represented by m and c is the 'y intercept' of the straight line graph. Clearly, the graph of Equation 8.2 is a straight line with a gradient of 2.9387. As c is zero, this line passes through the origin. According to Equation 8.2, for a distance d , there is a corresponding time t . Let's name the time obtained by Equation 8.2 the theoretical time, Then Table 8-1 presents the theoretical times corresponding to the distance change from 0.5m to 10m with 0.5m increments. The corresponding graph is illustrated in Figure 8.1. The data presented in Table 8-1 and the graph in Figure 8-1 is used as the base to compare and analyse the experimental data and outcome obtained from the following three experiments.

Table 8-1 Results Table

Distance (m)	Theoretical Time (ms)
0.5	1.469
1.0	2.939
1.5	4.408
2.0	5.877
2.5	7.347
3.0	8.816
3.5	10.285
4.0	11.755
4.5	13.224
5.0	14.693
5.5	16.163
6.0	17.632
6.5	19.101
7.0	20.571
7.5	22.040
8.0	23.509
8.5	24.979
9.0	26.448
9.5	27.917
10.0	29.387

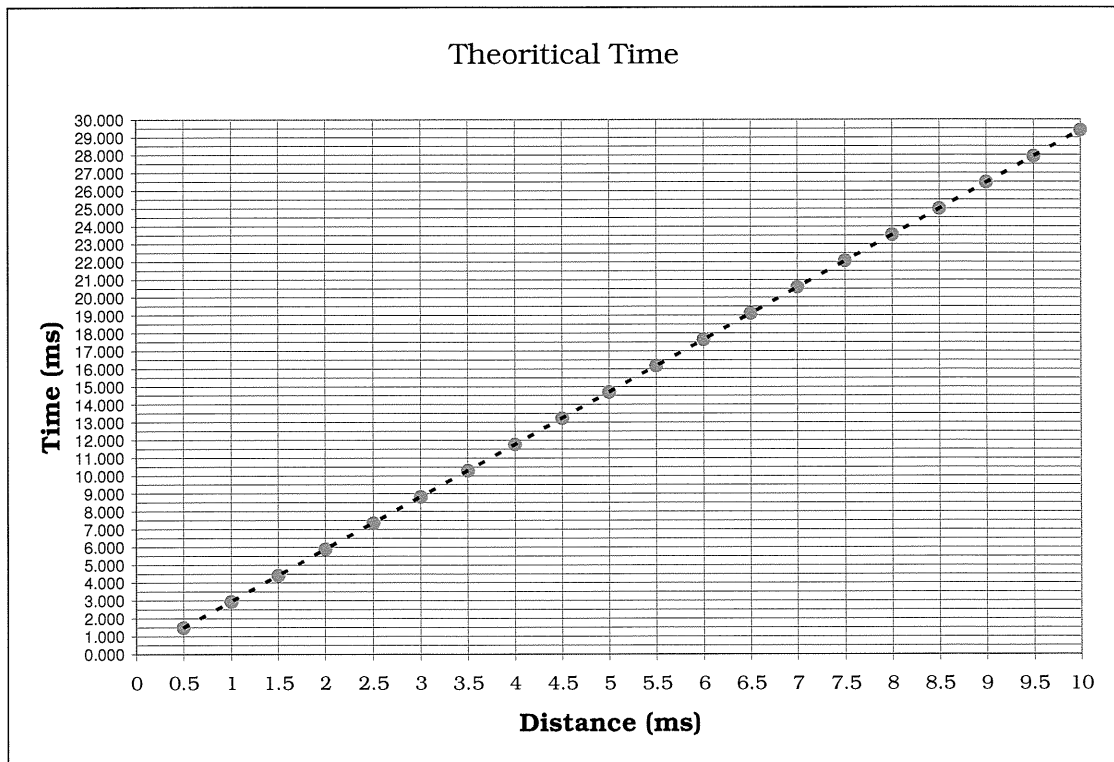


Figure 8-1 Theoretical Time vs. Distance

8.2 Experiment 1 - Test on Linear Distance Change

Aim: To test the distance measurement accuracy of the SONAR system when the distance changes from 0.5 metres to 10 metres.

Hypothesis: It is predicted that the distance measurements will be askew by a finite amount due to the delay caused by the radio modules and microcontroller processing time.

Figure 8-2 is the setup for Experiment 1. The SONAR Transmitter's speaker and the SONAR Beacon are facing each other. The signal comes from the speaker. The response from the SONAR Beacon is recorded in the computer.

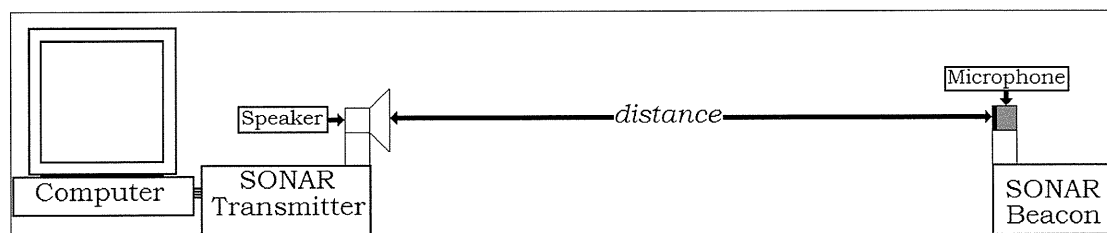


Figure 8-2 Experiment 1 Apparatus Setup

Procedure and Data Collection:

1. Connect SONAR Transmitter to computer using LabVIEW Interface
2. Place SONAR Beacon 0.5 metres away from the SONAR Transmitter in a direct line from the speaker and microphone, insure both the SONAR Transmitter speaker and SONAR Beacon microphone are at the same height and record the distance using the LabVIEW interface taking 100 samples.
3. Move SONAR Beacon in 0.5-meter increment away from SONAR Transmitter to a maximum of 10 metres, record the distance at each 0.5-meter interval and take 100 samples for each 0.5-metre distance increment using the LabVIEW interface.

8.2.1 Experiment 1 - Results and Data Analysis

Part of the raw data collected in Experiment 1 is shown in Table 8-2. The complete raw data set can be found in Appendix B. The table consists of the count data attained from the timing microcontroller as discussed in Chapter 6.

Table 8-2 Experiment 1 Raw Count Data

DISTANCE	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5	7	7.5	8	8.5	9	9.5	10
1	1700	2177	2491	2875	3063	3514	3856	4251	4387	5425	4811	5916	5579	5867	5433	6471	7569	7151	7494	7368
2	1622	2237	2403	2588	3091	3243	3518	3846	4253	4382	4818	5106	5510	5569	5879	6154	6563	6919	7037	7496
3	1844	2012	2496	2689	2895	3242	3517	3838	4253	4380	4812	4266	4568	4847	5976	6258	6459	6934	7041	7480
4	1836	2232	2275	2691	3092	3038	3517	3851	4247	4377	4807	5113	5508	5578	5870	6258	6555	6934	7460	7487
5	1714	2034	2406	1946	2876	3360	3496	3848	4247	5425	4829	5105	5511	5589	5876	6168	6572	6003	7147	6777
6	1827	2031	2182	2701	2896	3242	3518	3850	4245	5427	4819	5090	5313	5577	5148	6257	6566	7774	7037	7490
7	1613	1106	2403	2591	3091	3036	3528	3848	4262	4386	4821	5094	5315	5594	5146	6261	6573	7170	6337	7263
8	1841	2139	2404	2691	3090	1875	3530	3847	4241	4379	4799	5101	5915	5568	5871	6158	6571	7672	7037	7383
9	1621	2012	2494	2688	3078	3244	3511	3858	4263	4378	4806	5105	5512	5576	5138	6266	5725	7033	7146	7487
10	1840	2018	2180	2686	2897	3266	3530	3860	4249	4371	4825	4258	5323	5580	5976	5416	6566	7667	6332	7265
11	1727	2139	2171	2692	2899	3040	3530	3857	4264	4400	4816	5092	5317	5571	5139	6263	5733	6108	7128	7380
12	1611	2014	2182	2699	3094	2538	3532	3857	4256	4386	4815	5113	5315	5580	5130	6156	6568	7780	6305	7488
13	1608	2141	2176	2687	3091	3041	3508	3853	4245	4392	4826	5089	4576	5570	5884	5427	6567	7037	6921	7383
14	1838	2140	2402	2682	3093	3035	3531	3858	4268	4376	4826	5105	5507	5590	5872	5437	5744	6000	7044	7492
15	1620	2144	2383	2592	2893	3250	3526	3837	4263	4376	4808	4282	5320	5593	5860	6165	5727	7668	7041	6750
16	1612	2034	2500	2690	3092	3242	3508	3851	4256	4387	4811	5113	5320	5595	5880	6165	6471	7035	7455	7485
17	1839	2041	2500	2684	3092	3253	3512	3848	4240	4388	4820	5099	5313	5581	5873	6143	6559	6003	7261	7263
18	1616	2234	2494	2699	3100	3038	3526	3866	4255	4385	4813	5108	5324	5594	5129	6261	6464	7166	7459	7483
19	1826	2016	2180	2687	2875	3041	3508	3854	4247	4398	3966	5088	4566	5587	5875	6164	6466	5006	7461	7489
20	1823	2017	2400	2596	2895	3262	3506	3865	4251	4394	4810	5103	5512	5689	5139	6161	6474	5995	7150	7497
21	1837	2012	2178	2592	3096	3036	2816	3864	4253	4379	4825	5098	5323	5582	5140	6152	6476	7169	7463	7493
22	1843	2237	2276	2694	2897	3260	3521	3866	4240	4385	4808	4005	5315	5569	5881	6165	6569	6135	7047	7490
23	1607	2038	2172	2674	2899	3260	3508	3839	1272	4397	4811	4279	5917	5569	5870	6266	5732	7033	7149	7386
24	1825	2141	2496	2684	3079	3242	3517	3851	4247	4394	4820	5114	5515	5584	5873	6264	6566	6128	7042	6777
25	1615	2022	2179	2698	3087	3265	3517	3850	4258	4378	4829	5100	5325	5587	5139	6165	6569	7779	6541	7388
26	1610	2037	2169	2589	3096	3243	3514	3852	4247	4377	4818	5090	5313	5598	5977	5442	6569	6004	7460	7266
27	1612	2240	2173	2591	3093	3040	3516	3862	4268	4375	4825	5105	5323	5589	5862	6153	5733	7028	7143	7266
28	1611	2037	2171	2595	3089	3040	3624	3849	4257	4377	4819	5089	5314	5579	5882	6262	6465	7773	6438	7264
29	1938	2237	2401	2700	2875	3037	3515	3863	4264	4373	4808	5111	5508	4855	5977	6168	6471	7781	2940	7486
30	1714	2016	2173	2590	2892	3247	3516	3861	4269	4384	4824	5110	5325	4865	5873	6169	5731	7776	6127	7490
31	1624	2235	2174	2589	2897	3033	3510	3852	4255	4384	4826	4286	5914	4849	5873	6170	6574	7868	7143	7483
32	1836	2017	2497	2702	3083	3264	3528	3850	4062	4375	4808	5099	5507	5578	5876	6266	6465	7778	7472	7484
33	1618	2015	2404	2590	2894	3254	3523	3847	4255	4371	4821	5106	5917	5586	5864	6155	6465	7025	7259	6781
34	1616	2122	2499	2591	2899	3243	3524	3846	4267	4396	3972	5111	5317	5585	5134	6170	6464	7033	7257	7482
35	1823	2232	2177	2691	2895	3044	3520	3841	4249	4384	4816	5095	5319	5586	5140	6164	6568	7775	6291	6646
36	1619	2013	2169	2691	2901	3263	3507	3844	4238	4396	4806	5113	5507	5595	5869	6163	6468	7774	1096	7488
37	1606	2039	2496	2586	3092	3038	3506	3859	4251	4374	4808	5098	5511	5588	5146	5421	6571	7566	7042	7490
38	1838	2012	2171	2593	3085	3268	3516	3841	4255	4375	4827	5090	5515	5585	5880	6163	6564	7667	7147	7261
39	1608	2016	2401	2686	3099	3045	3520	3121	4247	4371	4815	5114	5513	5573	5880	6261	6466	7568	7455	7483
40	1845	2019	2181	2584	3082	3039	3518	3843	4256	4400	4826	5086	5320	5594	5873	6167	6575	7031	7149	7380
41	1836	2017	2170	2698	2846	3358	3529	3851	4247	4387	4805	5094	5507	5569	5864	6153	6568	7572	7043	7266
42	1609	2040	2403	2691	2877	3259	3507	3843	4252	4375	4803	5100	5325	5574	5884	6265	5745	6002	7264	7370
43	1608	2239	2398	2691	2892	3245	3521	3851	4255	4375	4822	5096	5327	5584	5132	6262	6563	7035	6296	7365
44	1932	2016	2183	2677	3087	3036	3533	3849	4248	4378	4812	5098	5324	5593	5885	6167	6562	7027	7273	7485
45	1824	2031	2275	2696	2901	3358	3503	3860	4261	4377	4819	5093	5327	5584	5869	5422	5732	7025	6304	7481
46	1845	2017	2174	2692	2903	3039	3503	3844	4250	4378	4819	5097	5509	5597	5867	6169	6461	7777	7041	7484
47	1617	2018	2169	2594	2901	3264	3505	3849	4262	4387	4824	4013	4559	5580	5862	6266	6467	7018	3997	7382
48	1844	2031	2177	2698	3094	3265	3531	3845	4254	5422	4807	5114	5318	4839	5883	6165	6564	7033	7273	6681
49	1714	2235	2173	2695	3085	3268	3515	3858	4258	4374	4804	5099	5916	5595	5878	6261	6573	6007	6438	7485

As discussed in Chapter 6.1.1, a single count equates to 5 microseconds, which is determined by the microcontroller's clock frequency. All of the raw data collected in Experiment 1 is converted into a time measurement by Equation 8.3 (derived in Chapter 6.1.1). Only part of the converted data is tabulated in Table 8-3. The complete table of the raw data collected in Experiment 1 that has been converted into a time measurement can be found in Appendix B. The times shown in Table 8-3 have been scaled to milliseconds.

Equation 8.3

$$5\mu\text{s} * \text{counts} = \text{time}$$

Table 8-3 Samples of the RAW data converted into times

DISTANCE	0.5	1	1.5	2	2.5	3	3.5	4	4.5
Sample 1	8.500	10.885	12.455	14.375	15.315	17.570	19.280	21.255	21.935
Sample 2	8.110	11.185	12.015	12.940	15.455	16.215	17.590	19.230	21.265
Sample 3	9.220	10.060	12.480	13.445	14.475	16.210	17.585	19.190	21.265
Sample 4	9.180	11.160	11.375	13.455	15.460	15.190	17.585	19.255	21.235
Sample 5	8.570	10.170	12.030	9.730	14.380	16.800	17.480	19.240	21.235
Sample 6	9.135	10.155	10.910	13.505	14.480	16.210	17.590	19.250	21.225
Sample 7	8.065	5.530	12.015	12.955	15.455	15.180	17.640	19.240	21.310
Sample 8	9.205	10.695	12.020	13.455	15.450	9.375	17.650	19.235	21.205
Sample 9	8.105	10.060	12.470	13.440	15.390	16.220	17.555	19.290	21.315
Sample 10	9.200	10.090	10.900	13.430	14.485	16.330	17.650	19.300	21.245
Sample 11	8.635	10.695	10.855	13.460	14.495	15.200	17.650	19.285	21.320
Sample 12	8.055	10.070	10.910	13.495	15.470	12.690	17.660	19.285	21.280
Sample 13	8.040	10.705	10.880	13.435	15.455	15.205	17.540	19.265	21.225
Sample 14	9.190	10.700	12.010	13.410	15.465	15.175	17.655	19.290	21.340
Sample 15	8.100	10.720	11.915	12.960	14.465	16.250	17.630	19.185	21.315
Sample 16	8.060	10.170	12.500	13.450	15.460	16.210	17.540	19.255	21.280
Sample 17	9.195	10.205	12.500	13.420	15.460	16.265	17.560	19.240	21.200
Sample 18	8.080	11.170	12.470	13.495	15.500	15.190	17.630	19.330	21.275
Sample 19	9.130	10.080	10.900	13.435	14.375	15.205	17.540	19.270	21.235
Sample 20	9.115	10.085	12.000	12.980	14.475	16.310	17.530	19.325	21.255
Sample 21	9.185	10.060	10.890	12.960	15.480	15.180	14.080	19.320	21.265
Sample 22	9.215	11.185	11.380	13.470	14.485	16.300	17.605	19.330	21.200
Sample 23	8.035	10.190	10.860	13.370	14.495	16.300	17.540	19.195	6.360
Sample 24	9.125	10.705	12.480	13.420	15.395	16.210	17.585	19.255	21.235
Sample 25	8.075	10.110	10.895	13.490	15.435	16.325	17.585	19.250	21.290
Sample 26	8.050	10.185	10.845	12.945	15.480	16.215	17.570	19.260	21.235
Sample 27	8.060	11.200	10.865	12.955	15.465	15.200	17.580	19.310	21.340
Sample 28	8.055	10.185	10.855	12.975	15.445	15.200	18.120	19.245	21.285
Sample 29	9.690	11.185	12.005	13.500	14.375	15.185	17.575	19.315	21.320

Figure 8-3 presents the 100 recorded times acquired for each 0.5 metre increment. The majority of the times lie between 8 milliseconds and 9.5 milliseconds. Each distance measurement has been charted this way and can be found in Appendix B.

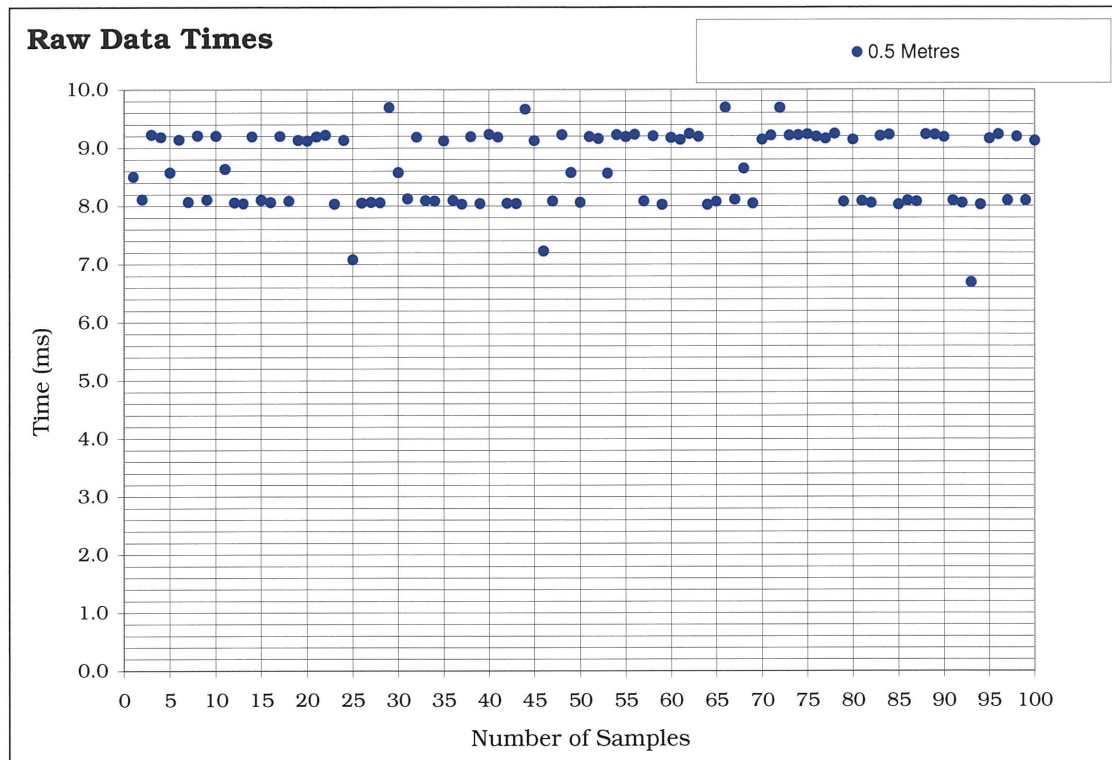


Figure 8-3 Converted time measurements for 0.5 metres

The times from Experiment 1 are averaged and tabulated in Table 8-4. Included in the table are the theoretical times from Table 8-1 and the variance. The variance is the difference between the theoretical time and averaged time for that particular distance. The averaged variance is 7.269 milliseconds throughout the data. The averaged times are plotted against the theoretical data shown in Figure 8-4. Using Microsoft Excel 2003 a trend-line is applied to the averaged data set and the trend-line equation is also shown in the figure.

Table 8-4 Experiment 1 Averaged Time Data

Distance (m)	Theoretical Time (milliseconds)	Averaged Times (milliseconds)	Variance
0.5	1.469	8.660	7.191
1.0	2.939	10.284	7.345
1.5	4.408	11.505	7.097
2.0	5.877	13.181	7.304
2.5	7.347	14.988	7.641
3.0	8.816	15.722	6.906
3.5	10.285	17.516	7.231
4.0	11.755	19.284	7.529
4.5	13.224	20.991	7.767
5.0	14.693	21.831	7.138
5.5	16.163	23.756	7.593
6.0	17.632	24.979	7.347
6.5	19.101	27.039	7.938
7.0	20.571	27.424	6.853
7.5	22.040	28.675	6.635
8.0	23.509	30.424	6.915
8.5	24.979	31.799	6.820
9.0	26.448	35.485	9.037
9.5	27.917	33.805	5.888
10.0	29.387	36.586	7.199

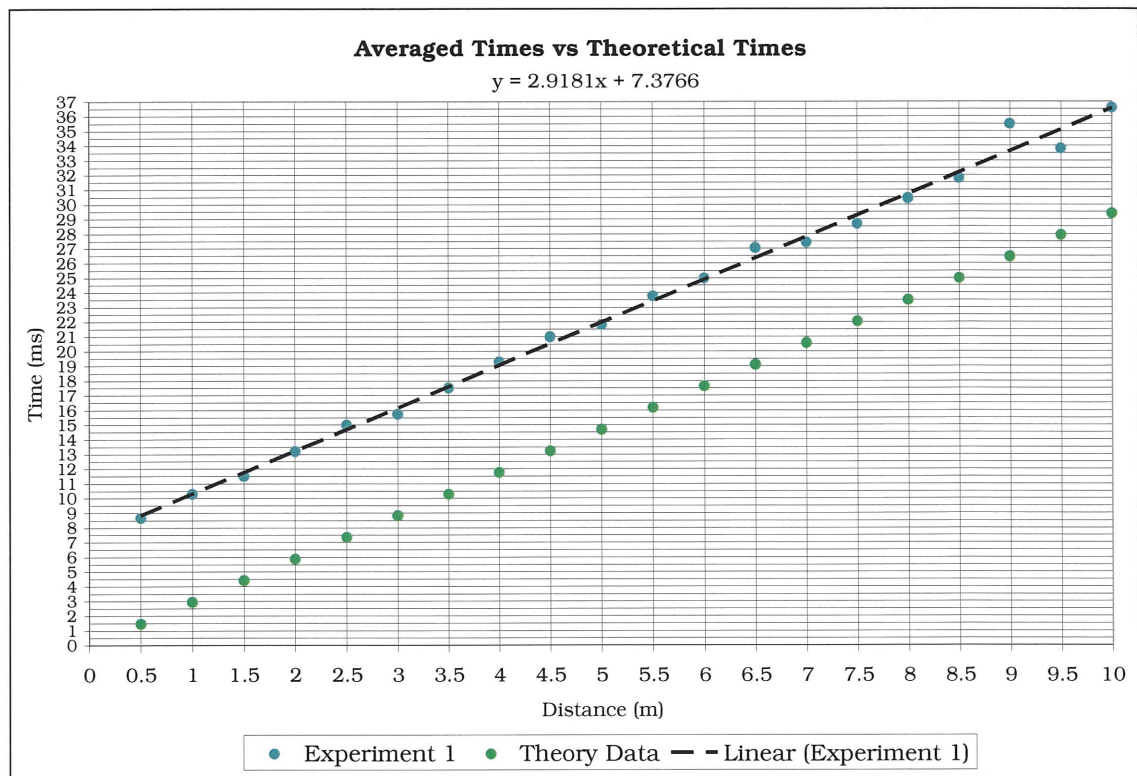


Figure 8-4 Averaged Times vs. Distance

The trend-line equation (Equation 8.4) describes the linear relationship between the raw data collected in the experiment and distance.

$$\text{Equation 8.4} \quad y = 2.9181 * x + 7.3766$$

Where, y = time

x = distance

By changing the nomenclature to terms already in use (Equation 8.5) the trend-line equation becomes more meaningful for the analysis of the results in Experiment 1.

$$\text{Equation 8.5} \quad t = d * 2.9181 + 7.3766$$

The basic theory of a straight line equation (mentioned in section 8.1.1) can be applied to Equation 8.5. The gradient in the equation is relative to the speed of sound at the time of the experiment.

$$v = 1 / 2.9181$$

$$v = 342.69 \text{ ms}^{-1}$$

It was assumed at the time of the Experiment 1 that the temperature, humidity and air particle density had no affect on the speed of sound in the Laboratory. The data collected would suggest that these elements were a factor and that the speed of sound at the time of the experiments was greater than the assumed average speed used to calculate the theoretical data.

As predicted in the hypothesis the times recorded were askew by a finite amount. This is proven in Equation 8.5 by the y -intercept. The y -intercept derived by the Microsoft Excel program is closer to the median of the data set and while similar to the averaged time variance calculated from Table 8-4 they are not equal. The time delay is a combination of factors including radio transmission latency (discussed in Chapter 5), time to condition the audio signal on the SONAR Beacon and the microcontrollers processing time.

From Equation 8.5 a generic formula to convert the raw count data into a distance measurement can be derived by rearranging the equation.

$$t = d * 2.9181 + 7.3766$$

Equation 8.6

$$d = (t - 7.3766) / 2.9181$$

Time t in Equation 8.6 needs to be put in terms of counts. Equation 8.6 is combined with Equation 8.3 to give,

$$d = ((5us * counts) - 7.3766) / 2.9181$$

Equation 8.7

$$d = ((0.005 * counts) - 7.3766) / 2.9181$$

Or

$$d = ((0.005 * counts) - 7.3766) * v$$

Where, v is the speed of sound in the operating environment. The results collected in Experiment 1 have lead to the formulation of Equation 8.7 that can now be applied to the raw data attained from the system. Equation 8.7 is used to calculate the distances from the raw count data collected in Experiment 1. The results are tabulated in Table 8-5. Only part of the converted data is tabulated. The complete table of distance measurements can be found in Appendix B.

The data collected in the experiments suggest the accuracy between the actual distance and measured distances by the system is within $\pm 2\%$. Experiment 1 has shown that the SONAR system has a good level of accuracy.

Table 8-5 Sample of RAW data converted to a distance measurement

DISTANCE	0.5	1	1.5	2	2.5	3	3.5	4	4.5
Sample 1	0.385	1.202	1.740	2.398	2.720	3.493	4.079	4.756	4.989
Sample 2	0.251	1.305	1.590	1.907	2.768	3.029	3.500	4.062	4.759
Sample 3	0.632	0.920	1.749	2.080	2.433	3.027	3.498	4.048	4.759
Sample 4	0.618	1.297	1.370	2.083	2.770	2.678	3.498	4.071	4.749
Sample 5	0.409	0.957	1.595	0.806	2.400	3.229	3.462	4.065	4.749
Sample 6	0.603	0.952	1.211	2.100	2.434	3.027	3.500	4.069	4.746
Sample 7	0.236	-0.633	1.590	1.912	2.768	2.674	3.517	4.065	4.775
Sample 8	0.627	1.137	1.591	2.083	2.767	0.685	3.521	4.064	4.739
Sample 9	0.250	0.920	1.745	2.078	2.746	3.031	3.488	4.083	4.777
Sample 10	0.625	0.930	1.207	2.074	2.436	3.068	3.521	4.086	4.753
Sample 11	0.431	1.137	1.192	2.085	2.439	2.681	3.521	4.081	4.778
Sample 12	0.232	0.923	1.211	2.097	2.774	1.821	3.524	4.081	4.765
Sample 13	0.227	1.141	1.201	2.076	2.768	2.683	3.483	4.074	4.746
Sample 14	0.621	1.139	1.588	2.068	2.772	2.672	3.522	4.083	4.785
Sample 15	0.248	1.146	1.555	1.913	2.429	3.041	3.514	4.047	4.777
Sample 16	0.234	0.957	1.756	2.081	2.770	3.027	3.483	4.071	4.765
Sample 17	0.623	0.969	1.756	2.071	2.770	3.046	3.490	4.065	4.737
Sample 18	0.241	1.300	1.745	2.097	2.784	2.678	3.514	4.096	4.763
Sample 19	0.601	0.926	1.207	2.076	2.398	2.683	3.483	4.076	4.749
Sample 20	0.596	0.928	1.584	1.920	2.433	3.061	3.479	4.095	4.756
Sample 21	0.620	0.920	1.204	1.913	2.777	2.674	2.297	4.093	4.759
Sample 22	0.630	1.305	1.372	2.088	2.436	3.058	3.505	4.096	4.737
Sample 23	0.226	0.964	1.194	2.054	2.439	3.058	3.483	4.050	-0.348
Sample 24	0.599	1.141	1.749	2.071	2.748	3.027	3.498	4.071	4.749
Sample 25	-0.103	0.937	1.206	2.095	2.762	3.067	3.498	4.069	4.768
Sample 26	0.231	0.962	1.189	1.908	2.777	3.029	3.493	4.072	4.749
Sample 27	0.234	1.310	1.195	1.912	2.772	2.681	3.497	4.089	4.785
Sample 28	0.232	0.962	1.192	1.919	2.765	2.681	3.682	4.067	4.766
Sample 29	0.793	1.305	1.586	2.098	2.398	2.676	3.495	4.091	4.778
AVAREAGE	0.419	1.012	1.451	2.002	2.636	2.803	3.484	4.098	4.592

8.3 Experiment 2 - Test on Orientation Change

Aim: Analyse the accuracy of the distance measurement made by the SONAR System by moving the SONAR Beacon around the SONAR Transmitter at a 1 metre radius.

Hypothesis: The distance measurements will become less accurate as the SONAR Beacon approaches a 90 degree angle to the SONAR Transmitters speaker.

Experiment 2 only carries out the measurements from 0 to 180 degrees anti-clockwise. This is because moving the beacon clockwise from 0 to 180 degrees will produce the same results. Therefore, mirroring the graph of the data obtained by moving the beacon anti-clockwise will give the information of moving the beacon from 0 to 360 degrees. However, it is important to note that the SONAR Transmitter speaker does not move and remains facing the same position throughout the entire experiment.

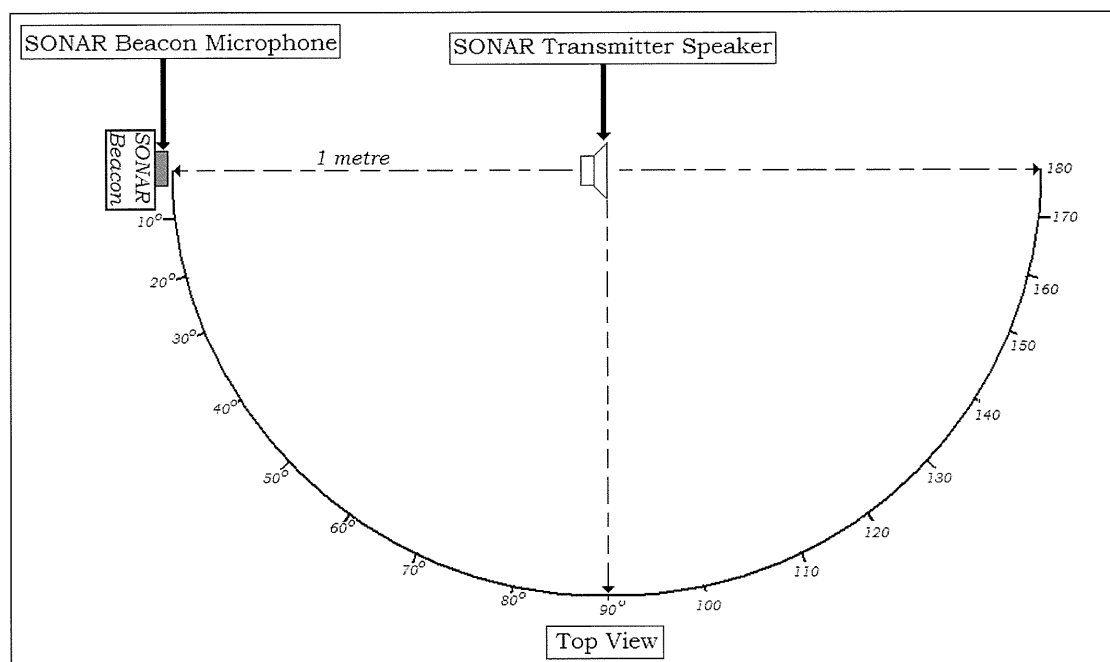


Figure 8-5 Experiment 2 Apparatus Setup

Procedure and Data collection:

1. Place the SONAR Beacon 1 metre away from the SONAR Transmitter so that the speaker is facing away from the microphone as shown in Figure 8-5. Take 100 distance measurements using the LabVIEW interface.
 2. Use a protractor to place the SONAR Beacon at a 10-degree increment as shown in Figure 8-5 and keep the distance between the SONAR Beacon and SONAR Transmitter at 1 metre. The microphone on the SONAR Beacon should be aligned tangentially to the 1m radius.
 3. Repeat steps 1 and 2 until data has been collected for angles from 0° to 180° as shown in Figure 8-5.
-

8.3.1 Experiment 2 - Results and Data Analysis

Part of the raw data collected in Experiment 2 is shown in Table 8-6. The complete raw data set can be found in Appendix B. The table consists of the count data attained from the timing microcontroller as discussed in Chapter 6.

Table 8-6 Raw Data from Experiment 2

Degrees	0	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180
1	2051	2070	2118	2008	2131	2048	2018	2091	2052	1937	2043	2125	1950	2094	2022	2132	2064	2058	2093
2	2060	2067	2108	2105	2020	2133	2101	2094	2142	2128	1946	2108	2138	2014	2102	2012	2073	2059	2001
3	2066	2062	2109	2100	2122	2140	2098	2092	2153	2039	2174	2105	2142	2100	2097	2114	2068	2065	2095
4	2069	2072	2102	2084	2115	2136	2096	1722	2063	2122	2162	2103	2138	2031	2081	2107	2078	2068	2102
5	2062	2058	2118	1992	2131	2113	2095	2110	2128	2132	2147	2102	2115	2113	1989	2123	2064	2061	2107
6	2070	2082	2118	2089	2131	2029	2023	2195	2152	2137	2138	2030	2031	2122	2086	2123	1988	2069	2094
7	2054	2078	2100	2104	2113	2033	2103	2186	2132	2117	2053	2025	2035	2119	2101	2105	2084	2053	2107
8	2082	2071	2099	2105	2112	2035	2116	2101	2130	2115	2053	2108	2037	2113	2102	2104	2077	2081	2110
9	2067	2064	2092	2091	2105	2039	2115	2182	2054	2039	2134	2105	2041	2014	2088	2097	2070	2066	2008
10	2057	2080	2119	2084	2132	2133	2115	2089	2137	2122	2141	2103	2135	2021	2081	2124	2086	2056	2102
11	2069	2057	2110	2016	2123	2140	2009	2004	2147	2132	2156	2016	2142	2103	2013	2115	2063	2068	2000
12	2060	2076	2098	2092	2111	2029	2118	2006	2152	2137	2158	2125	2031	2111	2089	2103	2082	2059	1691
13	2059	2067	2021	2004	2034	2030	2120	2007	2148	2133	2159	2127	2032	2103	2001	2026	2073	2058	2216
14	2064	2069	1411	2088	1424	2039	2018	2002	2052	2037	2154	2022	2041	2015	2085	1416	2075	2063	2088
15	2075	2064	2114	2110	2127	2123	2101	2093	2049	2034	2145	2103	2125	2025	2107	2119	2070	2074	2114
16	2077	2058	2098	2105	2111	2120	2098	2016	2146	2131	2158	2100	2122	2122	2102	2103	2064	2076	2093
17	1984	2071	2012	2094	2025	2139	2096	2187	2150	2135	2139	2123	2141	2100	2091	2017	2077	1983	2002
18	2060	1984	2101	2089	2114	2048	2095	2091	2059	2044	2155	2106	2140	2017	2086	2106	1990	2059	2002
19	2053	1964	2112	2095	2125	2133	2023	2094	2158	2043	2132	2121	2126	2030	2092	2117	1970	2052	2080
20	2062	2056	2097	2084	2110	2140	2103	2092	2148	2133	2059	2100	2119	2125	2081	2102	2062	2061	2106
21	2051	2070	2118	2008	2131	2136	2116	1722	2062	2037	2043	2025	2050	2090	2005	2123	2076	2050	2093
22	2060	2067	2007	2105	2020	2113	2115	2110	2152	2127	2046	2108	2135	2014	2102	2012	1965	2059	2001
23	2066	2062	2109	2100	2122	2029	2115	2195	2163	2138	2144	2105	2142	2100	2097	2114	2068	2065	2095
24	2069	2072	2102	2084	2115	2033	2009	2086	2053	2048	1674	2103	2138	2031	2081	2107	2078	2068	2102
25	2062	2058	2118	1992	2131	2035	2118	2101	2138	2113	2062	2102	2115	2113	1989	2123	2064	2061	2107
26	2070	2082	2118	2089	2131	2039	2120	2182	2142	2137	2147	2030	2031	2122	2086	2123	2088	2069	2094
27	2054	2078	2100	2104	2113	2133	2015	2189	2142	2117	2138	2110	2035	2119	2101	2105	2084	2053	2107
28	2082	2071	2099	2105	2112	2140	2096	2004	2120	2115	2053	2123	2037	2113	2102	2104	2077	2081	2110
29	2067	2064	2092	2091	2105	2029	2093	2206	2064	2039	2134	2122	2041	2110	2088	2097	2070	2066	2008
30	2057	2080	2119	2084	2132	2030	2116	2017	2127	2122	2141	2122	2135	2021	2081	2124	2086	2056	2102
31	2069	2057	2110	2016	2123	2039	2099	2012	2057	2132	2156	2016	2142	2103	2013	2115	2063	2068	2000
32	2060	2076	2098	2092	2111	2123	2114	2193	2142	2137	2158	2125	2031	2111	2089	2103	2082	2059	1691
33	2059	2067	2021	2004	2034	2120	2093	2006	2158	2133	2159	2127	2032	2103	2001	2026	2073	2058	2216
34	2064	2069	1411	2088	1424	2139	2115	2187	2142	2037	2154	2022	2041	2015	2085	1416	1975	2063	2088
35	2075	2064	2114	2110	2127	2138	2009	2003	2059	2034	2145	2103	2125	2025	2107	2119	2070	2074	2114
36	2077	2058	2098	2105	2111	2124	2118	2180	2036	2131	2158	2100	2122	2122	2102	2103	2064	2076	2093
37	2051	2070	2118	2008	2131	2117	2120	2107	2160	2037	2043	2025	2050	2090	2005	2123	2076	2050	2093
38	2060	2067	2007	2105	2020	2039	2015	2189	2049	2127	2046	2108	2135	2014	2102	2012	2073	2059	2001
39	2066	2062	2109	2100	2122	2133	2096	2204	2068	2138	2144	2105	2142	2100	2097	2114	2068	2065	2095
40	2069	2072	2102	2084	2115	2140	2093	2026	2038	2048	1674	2103	2138	2031	2081	2107	2078	2068	2102
41	2062	2058	2118	1992	2131	2029	2116	2027	2052	2113	2062	2102	2115	2113	1989	2123	2064	2061	2107
42	2070	2082	2118	2089	2131	2030	2099	2012	2162	2137	2147	2030	2031	2122	2086	2123	2088	2069	2094
43	2054	2078	2100	2104	2113	2039	2114	2193	2133	2117	2138	2110	2035	2119	2101	2105	1984	2053	2107
44	2082	2071	2099	2105	2112	2123	2093	2006	2083	2115	2053	2123	2037	2113	2102	2104	2077	2081	2110
45	2067	2064	2092	2091	2105	2120	2115	2187	2108	2039	2134	2122	2041	2110	2088	2097	2070	2066	2008
46	2057	2080	2119	2084	2132	2139	2115	2003	2072	2122	2141	2122	2135	2021	2081	2124	2086	2056	2102
47	2069	2057	2110	2016	2123	2138	2009	2180	2102	2132	2156	2016	2142	2103	2013	2115	2063	2068	2000

All of the raw data collected in Experiment 2 is converted into a distance measurement by Equation 8.7. Only part of the converted data is tabulated in Table 8-7. The complete table can be found in Appendix B.

Table 8-7 Sample of RAW data from Experiment 2 converted in a distance measurement

Degrees	0	10	20	30	40	50	60	70	80	90
Sample 1	0.986	1.018	1.100	0.913	1.123	0.981	0.930	1.055	0.988	0.791
Sample 2	1.002	1.013	1.084	1.079	0.933	1.127	1.072	1.060	1.142	1.118
Sample 3	1.012	1.005	1.085	1.070	1.108	1.139	1.067	1.057	1.161	0.966
Sample 4	1.017	1.022	1.073	1.043	1.096	1.132	1.064	0.423	1.007	1.108
Sample 5	1.005	0.998	1.100	0.885	1.123	1.093	1.062	1.087	1.118	1.125
Sample 6	1.019	1.039	1.100	1.052	1.123	0.949	0.938	1.233	1.159	1.134
Sample 7	0.992	1.032	1.070	1.077	1.093	0.956	1.075	1.218	1.125	1.099
Sample 8	1.040	1.020	1.068	1.079	1.091	0.959	1.098	1.072	1.122	1.096
Sample 9	1.014	1.008	1.056	1.055	1.079	0.966	1.096	1.211	0.992	0.966
Sample 10	0.997	1.035	1.102	1.043	1.125	1.127	1.096	1.052	1.134	1.108
Sample 11	1.017	0.996	1.087	0.926	1.110	1.139	0.914	0.906	1.151	1.125
Sample 12	1.002	1.029	1.066	1.057	1.089	0.949	1.101	0.909	1.159	1.134
Sample 13	1.000	1.013	0.934	0.906	0.957	0.950	1.105	0.911	1.153	1.127
Sample 14	1.009	1.017	-0.111	1.050	-0.088	0.966	0.930	0.902	0.988	0.962
Sample 15	1.028	1.008	1.094	1.087	1.117	1.110	1.072	1.058	0.983	0.957
Sample 16	1.031	0.998	1.066	1.079	1.089	1.105	1.067	0.926	1.149	1.123
Sample 17	0.872	1.020	0.919	1.060	0.942	1.137	1.064	1.219	1.156	1.130
Sample 18	1.002	0.871	1.071	1.052	1.094	0.981	1.062	1.055	1.000	0.974
Sample 19	0.990	0.837	1.090	1.062	1.113	1.127	0.938	1.060	1.170	0.973
Sample 20	1.005	0.994	1.064	1.043	1.087	1.139	1.075	1.057	1.153	1.127
Sample 21	0.986	1.018	1.100	0.913	1.123	1.132	1.098	0.423	1.005	0.962
Sample 22	1.002	1.013	0.910	1.079	0.933	1.093	1.096	1.087	1.159	1.117
Sample 23	1.012	1.005	1.085	1.070	1.108	0.949	1.096	1.233	1.178	1.135
Sample 24	1.017	1.022	1.073	1.043	1.096	0.956	0.914	1.046	0.990	0.981
Sample 25	1.005	0.998	1.100	0.885	1.123	0.959	1.101	1.072	1.135	1.093
Sample 26	1.019	1.039	1.100	1.052	1.123	0.966	1.105	1.211	1.142	1.134
Sample 27	0.992	1.032	1.070	1.077	1.093	1.127	0.925	1.223	1.142	1.099
Sample 28	1.040	1.020	1.068	1.079	1.091	1.139	1.064	0.906	1.105	1.096
Sample 29	1.014	1.008	1.056	1.055	1.079	0.949	1.058	1.252	1.009	0.966

As in previous experiment, for every 10-degree movement of the SONAR Beacon, 100 distance sample data were recorded. Figure 8-6 is the graph plotted using the sample data when SONAR Beacon is positioned at 10 degrees. The measurements lie between 0.9 metres and 1.25 metres. For every 10-degree increment, a distance measurement has been charted this way and can be found in Appendix B.

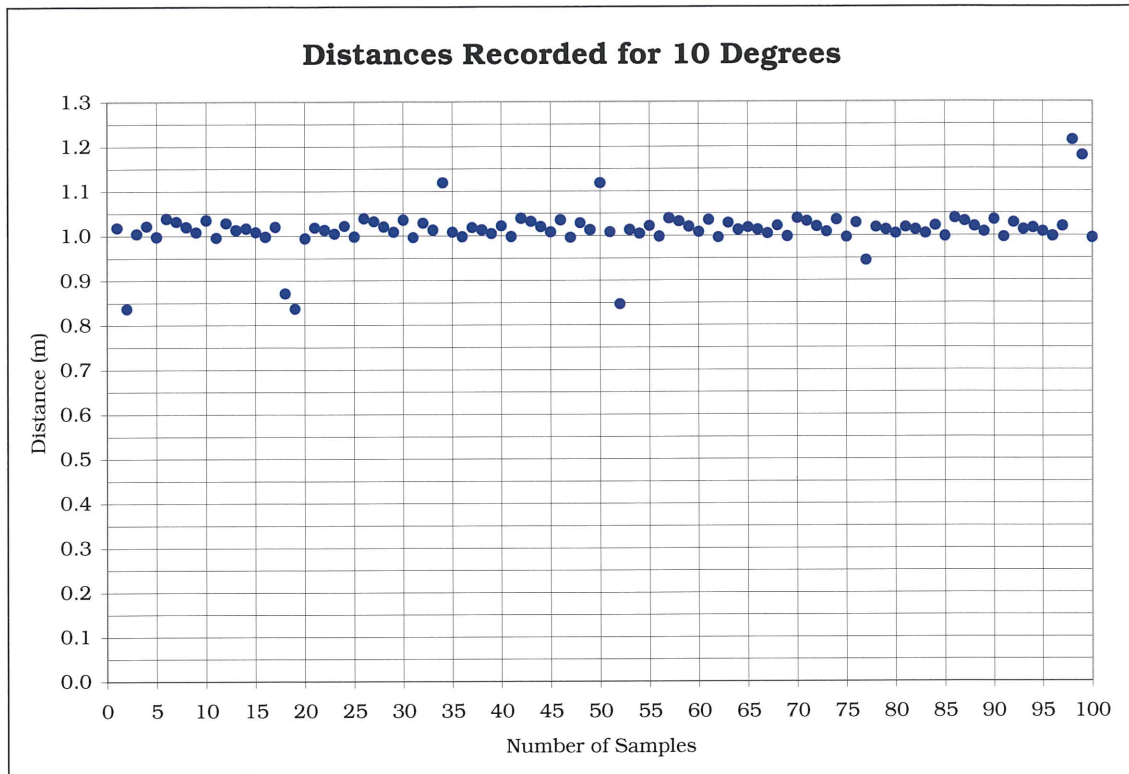
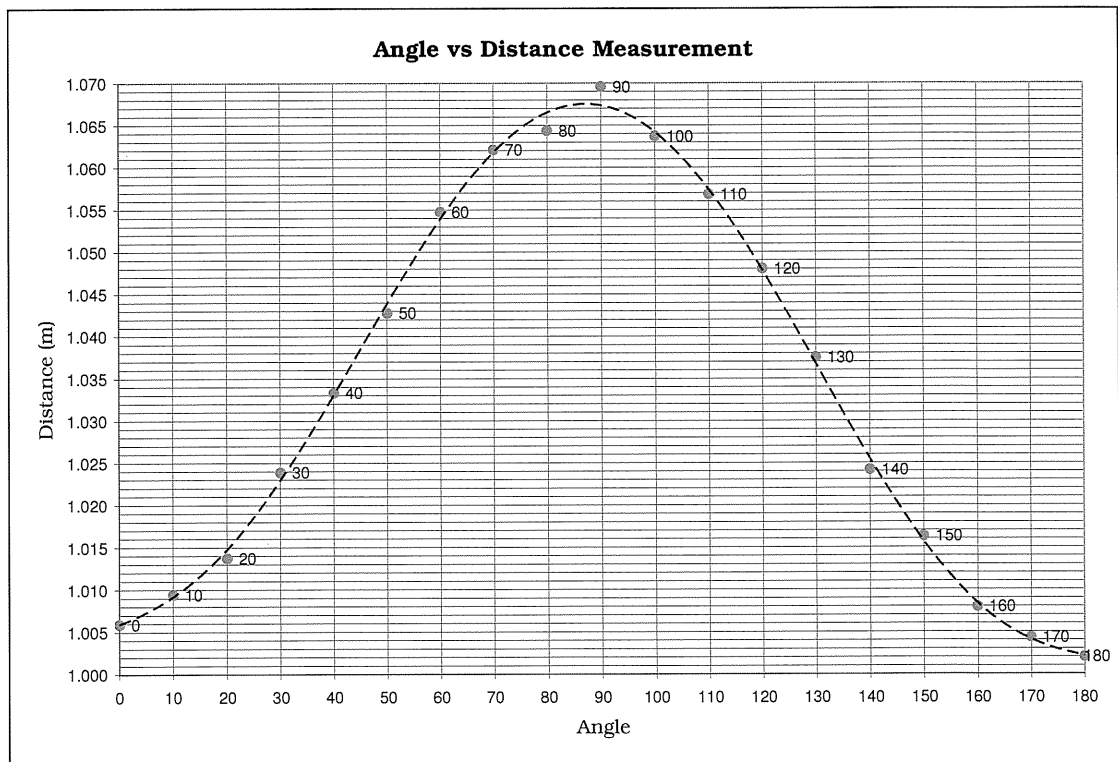


Figure 8-6 Distance measurements for a 10 degrees

The distances obtained from Experiment 2 are averaged and tabulated in Table 8-8. Included in the table are the variances and error percentage. The variance is the difference between the radial distance of 1m and the averaged distances. The averaged distances are plotted and shown in Figure 8-7. Using Microsoft Excel 2003 a trend-line is applied to the averaged distances. The results from Experiment 2 show the largest error in distance measurement is when the SONAR Beacon's microphone becomes perpendicular to the SONAR Transmitter's speaker. The results indicate that when the SONAR beacon is tangential to the SONAR Transmitter and within 40 degrees of the Sonar Transmitter speaker the accuracy of the system is $\pm 2\%$ (see Figure 8-8). The Figure has been extrapolated to encompass 360 degrees. The results also indicate that, if the SONAR Beacon is outside the 40 degree angle (indicated by the red zones in the Figure), the system will yield erroneous distance measurements. The error is due to the angle of projection of the sound wave emitted from the speaker, which is attributed to the physical dimensions of the speaker cone. It is interesting to note the affect on accuracy when the SONAR Transmitter's speaker is not facing the SONAR Beacon's microphone as the measurements are askew when angled at 0 degrees.

Table 8-8 Experiment 2 Averaged distance measurements

Angle	Averaged Distance (m)	Variance	Error %
0	1.006	0.006	0.6
10	1.009	0.009	0.9
20	1.010	0.010	1.0
30	1.024	0.024	2.4
40	1.014	0.014	1.4
50	1.043	0.043	4.3
60	1.055	0.055	5.5
70	1.062	0.062	6.2
80	1.083	0.083	8.3
90	1.070	0.070	7.0
100	1.064	0.064	6.4
110	1.057	0.057	5.7
120	1.048	0.048	4.8
130	1.037	0.037	3.7
140	1.024	0.024	2.4
150	1.016	0.016	1.6
160	1.008	0.008	0.8
170	1.004	0.004	0.4
180	1.002	0.002	0.2

**Figure 8-7 Averaged Times vs. Distance**

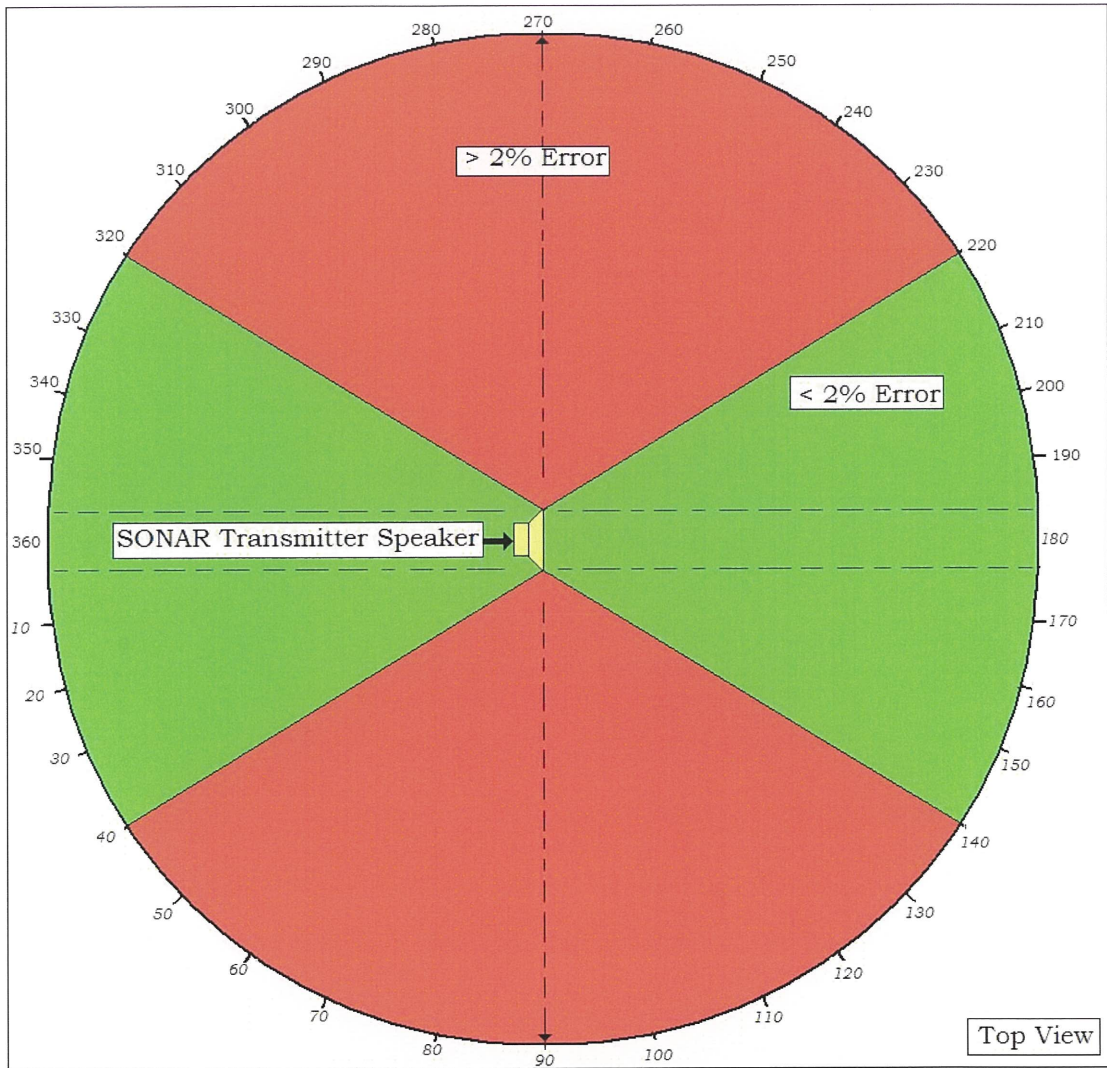


Figure 8-8 Sound Wave Propagation in Relation to Accuracy

8.4 Experiment 3 - Test on Elevation Change

Aim: Analyse the accuracy of the distance measurement made by keeping the SONAR Transmitter in one place and elevating the SONAR Beacon to different heights.

Hypothesis: The distance measurements will not be accurate when the SONAR Beacon is not level with the SONAR Transmitter.

Figure 8-9 is the setup of Experiment 3, where the SONAR Beacon was elevated at a height increment of 0.5 metre.

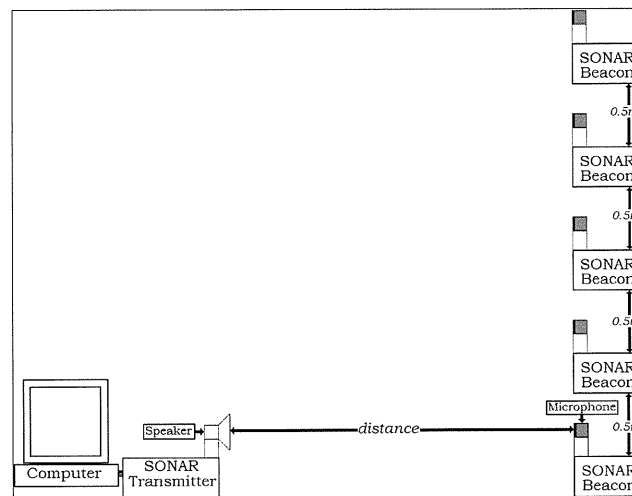


Figure 8-9 Experiment 3 Apparatus Setup

Procedure and Data collection:

1. Connect SONAR Transmitter to computer using LabVIEW Interface.
2. Place SONAR Beacon 2 metres away from the SONAR Transmitter ensuring the microphone and speaker are in line with each other.
3. Record the distance using the LabVIEW interface and take 100 samples.
4. Keep the horizontal distance constant at 2 metres, and vertically elevate the SONAR Beacon 0.5 metres as shown in Figure 8-9 and record the distance using the LabVIEW interface and take 100 samples.
5. Elevate the SONAR Beacon by another 0.5 metres vertically, record the distance using the LabVIEW interface and take 100 samples.
6. Repeat step 5 until the data for a 3-metre elevation is recorded.

8.4.1 Experiment 3 - Results and Data Analysis

Part of the raw data collected in Experiment 3 is shown in Table 8-9. The complete raw data set can be found in Appendix B. The table consists of the physical count attained from the timing microcontroller.

Table 8-9 Raw Data from Experiment3

HEIGHT	0	0.5	1	1.5	2	2.5	3
1	2729	2778	2844	2743	3020	2987	3042
2	2633	2774	2757	3007	3166	3257	3387
3	2657	2743	2836	3017	3182	3284	3417
4	2654	2737	2850	3004	3195	3293	3428
5	2637	2748	2857	3002	3171	3280	3412
6	2645	2775	2853	2909	3184	3237	3358
7	2658	2787	2852	3017	3187	3287	3416
8	2653	2794	2844	3017	3179	3280	3408
9	2660	2735	2855	3011	3178	3281	3413
10	2563	2782	2836	3011	3198	3328	3478
11	2645	2777	2857	3024	3186	3297	3430
12	2659	2792	2751	3004	3194	3265	3393
13	2560	2775	2842	3010	3197	3330	3481
14	2566	2774	2837	2938	3168	3267	3404
15	2561	2773	2850	3021	3190	3331	3482
16	2636	2777	2850	3027	3087	3221	3336
17	2649	2784	2750	2922	3201	3234	3358
18	2643	2774	2843	3007	3180	3282	3412
19	2661	2781	2853	3024	3197	3298	3429
20	2664	2779	2850	3028	3176	3281	3409
21	2724	2774	2840	2739	3016	2983	3038
22	2628	2770	2753	3003	3162	3254	3384
23	2652	2739	2832	3013	3178	3281	3413
24	2649	2733	2846	3000	3191	3289	3424
25	2632	2744	2853	2998	3167	3276	3408
26	2640	2771	2849	2905	3180	3233	3355
27	2653	2783	2848	3013	3183	3283	3412
28	2648	2790	2840	3013	3175	3276	3404
29	2655	2731	2851	3007	3174	3278	3409
30	2558	2778	2832	3007	3194	3324	3474
31	2640	2773	2853	3020	3182	3293	3426
32	2654	2788	2747	3000	3190	3261	3389
33	2555	2771	2838	3006	3193	3326	3477
34	2561	2770	2833	2934	3164	3263	3400
35	2556	2769	2846	3017	3186	3327	3478
36	2631	2773	2846	3023	3083	3217	3333
37	2644	2780	2746	2918	3197	3230	3355
38	2638	2770	2839	3003	3176	3278	3409
39	2656	2777	2849	3020	3193	3294	3426
40	2659	2775	2846	3024	3172	3278	3405
41	2734	2784	2850	2749	3026	2993	3048
42	2638	2780	2763	3013	3172	3264	3394
43	2662	2749	2842	3023	3188	3291	3423
44	2659	2743	2856	3010	3201	3299	3434
45	2642	2754	2863	3008	3177	3286	3418

All of the raw data collected in Experiment 3 is converted into a distance measurement using Equation 8.7. Only part of the converted data is tabulated in Table 8-10. The complete table of the converted raw data collected in Experiment 3 can be found in Appendix B.

Table 8-10 Experiment 3 - Sample of RAW data converted in a distance measurement

Elevation	0	0.5	1	1.5	2	2.5	3
Sample 1	2.175	2.021	2.270	2.582	2.539	2.767	3.039
Sample 2	2.011	2.014	2.121	2.564	2.789	3.230	3.630
Sample 3	2.052	1.961	2.256	2.112	2.816	3.276	3.681
Sample 4	2.047	1.951	2.280	2.559	2.839	3.291	3.700
Sample 5	2.017	1.970	2.292	2.556	2.798	3.268	3.673
Sample 6	2.031	2.016	2.285	2.397	2.820	3.195	3.581
Sample 7	2.053	2.037	2.283	2.582	2.825	3.280	3.679
Sample 8	2.045	2.049	2.270	2.582	2.811	3.269	3.665
Sample 9	2.057	1.948	2.289	2.571	2.809	3.271	3.674
Sample 10	1.891	2.028	2.256	2.571	2.844	3.351	3.786
Sample 11	2.031	2.020	2.292	2.594	2.823	3.297	3.703
Sample 12	2.055	2.045	2.110	2.559	2.837	3.242	3.640
Sample 13	1.886	2.016	2.266	2.570	2.842	3.354	3.791
Sample 14	1.896	2.014	2.258	2.446	2.792	3.247	3.659
Sample 15	1.887	2.013	2.280	2.588	2.830	3.356	3.792
Sample 16	2.016	2.020	2.280	2.599	2.654	3.168	3.543
Sample 17	2.038	2.032	2.109	2.419	2.849	3.190	3.581
Sample 18	2.028	2.014	2.268	2.564	2.813	3.271	3.674
Sample 19	2.059	2.026	2.285	2.594	2.842	3.299	3.703
Sample 20	2.064	2.023	2.280	2.600	2.806	3.271	3.667
Sample 21	2.167	2.014	2.263	2.705	2.532	2.760	3.033
Sample 22	2.002	2.008	2.114	2.558	2.782	3.223	3.624
Sample 23	2.044	1.954	2.249	2.575	2.809	3.270	3.675
Sample 24	2.038	1.944	2.273	2.552	2.832	3.284	3.694
Sample 25	2.009	1.963	2.285	2.549	2.791	3.262	3.667
Sample 26	2.023	2.009	2.278	2.390	2.813	3.189	3.575
Sample 27	2.045	2.030	2.277	2.575	2.818	3.274	3.673
Sample 28	2.037	2.042	2.263	2.575	2.804	3.262	3.659
Sample 29	2.049	1.941	2.282	2.564	2.803	3.265	3.668

Shown in Figure 8-10 are the 100 linear distances recorded when the SONAR Beacon was elevated to a height of 1.5 metres. The measurements lie between 2.3 metres and 2.7 metres. For each height a distance measurement has been charted this way and can be found in Appendix B.

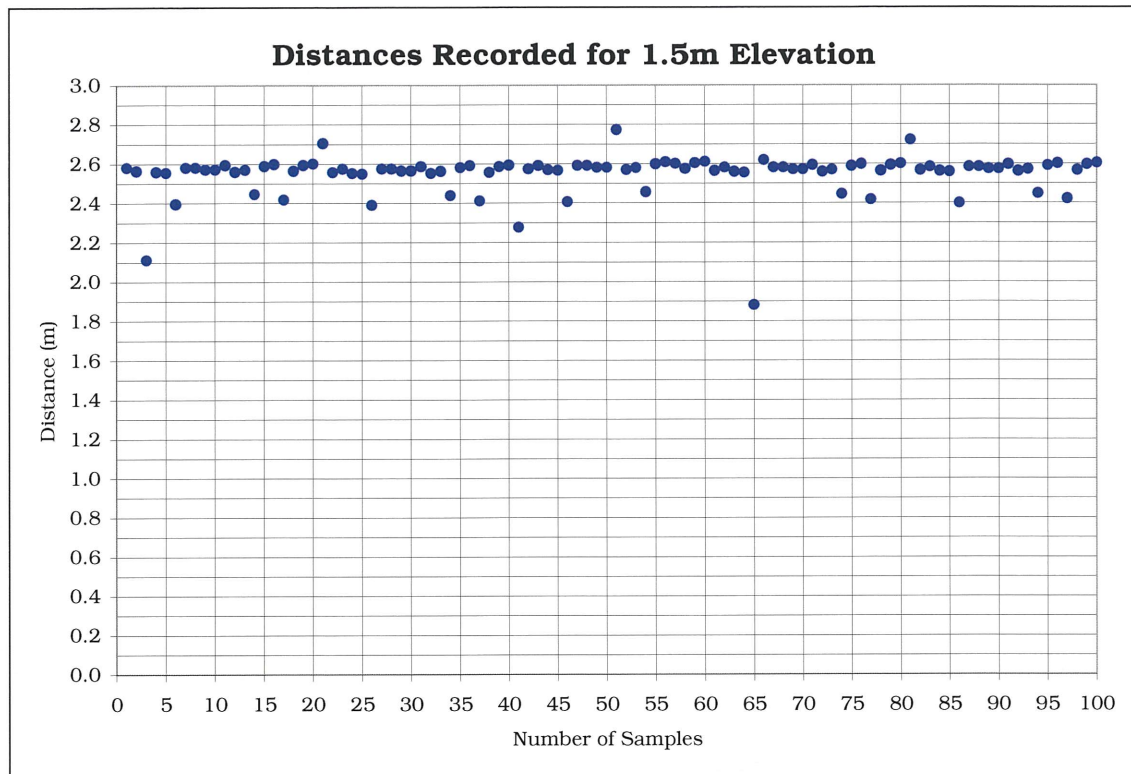


Figure 8-10 Distance measurements for an Elevation of 1.5m

The converted distance data collected in Experiment 3 is averaged and tabulated in Table 8-11. Included in the table are the variances and error percentage. The variance is the difference between the linear distance of 2m and the averaged distances. The averaged data is plotted in Figure 8-12. Using Microsoft Excel 2003 a trend-line is applied to the averaged distances.

Table 8-11 Experiment 3 Averaged distance measurements

Distance (m)	Average Distance (m)	Variance (m)	Error %
0.0	2.017	0.017	0.9
0.5	2.012	0.012	0.6
1.0	2.253	0.253	12.6
1.5	2.549	0.549	27.4
2.0	2.800	0.800	40.0
2.5	3.246	1.246	62.3
3.0	3.645	1.645	82.3

The tabulated data suggest that the error associated with the horizontal distance measurement increases exponentially as the SONAR Beacon is elevated to a distance of 3 metres (see Figure 8-11).

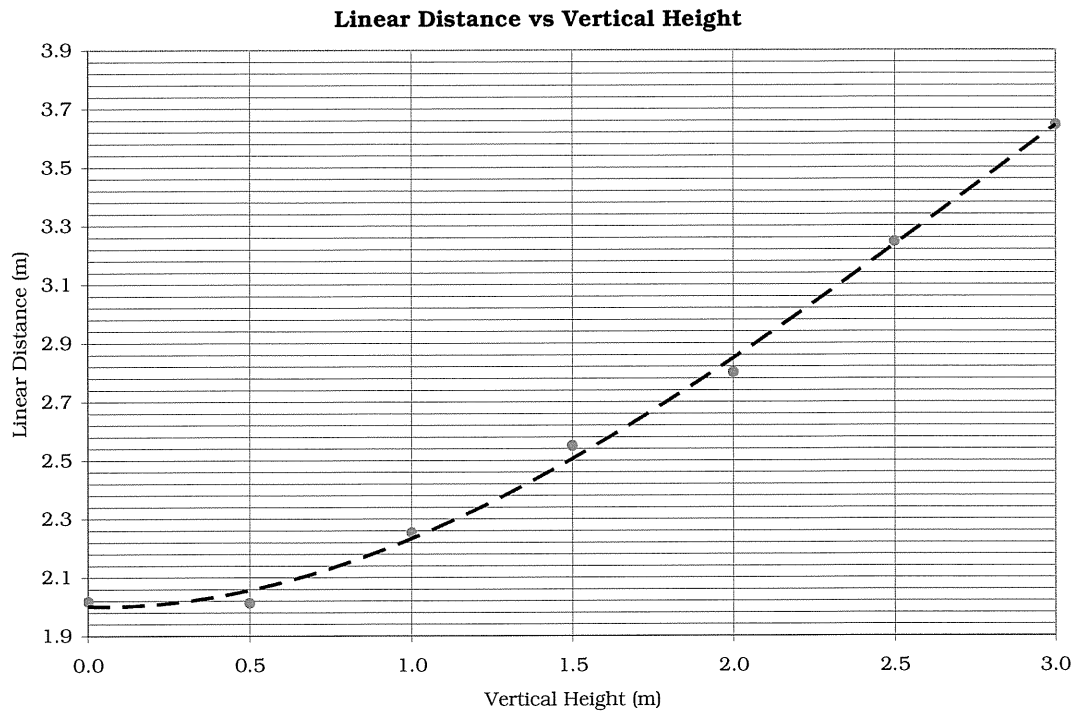


Figure 8-11 Linear Distance vs. Averaged Vertical Height

The measured distance recorded is the distance from the cone of the speaker to the microphone and not the linear distance between the SONAR Beacon and Transmitter. Shown in Figure 8-12 is an example of a right angle triangle. By employing Pythagoras' Theorem, the lengths of the hypotenuse are calculated for the different elevations used in Experiment 3 and tabulated in Table 8-12.

The difference between the calculated length of the hypotenuse and the measured distances are within 1% of each other. It is important to note that the results are consistent and that the SONAR system could be calibrated when the SONAR Beacon is fixed at a set height. Therefore it can be concluded that the SONAR System accuracy is not affected by the height or elevation when measuring the direct distance from SONAR Beacon microphone to the SONAR system speaker.

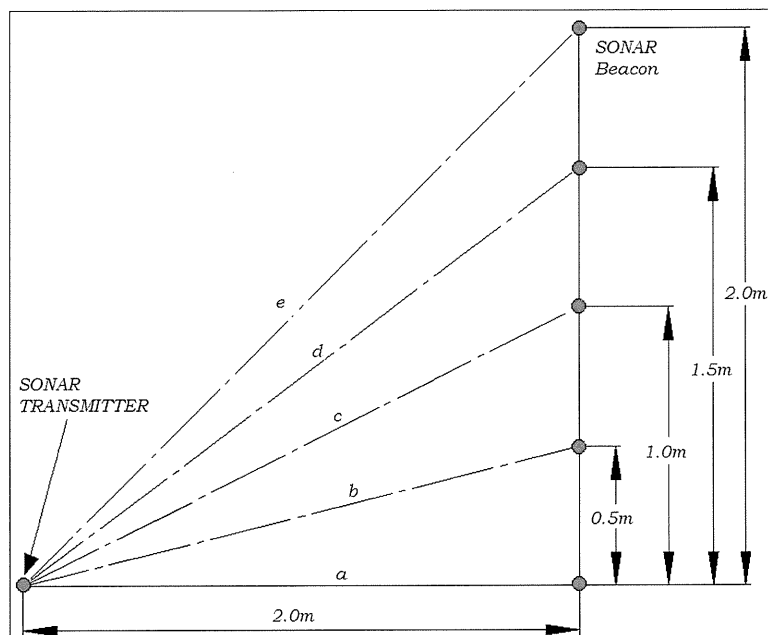


Figure 8-12 Right angled triangle

Table 8-12 Calculated hypotenuse and Measured Distances

Height (m)	Hypotenuse	AVERAGE Distance (m)	Variance (m)	Error %
0.0	2.000	2.017	0.017	0.86
0.5	2.062	2.012	-0.049	-2.39
1.0	2.236	2.253	0.017	0.75
1.5	2.500	2.549	0.049	1.95
2.0	2.828	2.800	-0.028	-1.00
2.5	3.202	3.246	0.045	1.40
3.0	3.606	3.645	0.040	1.10

9 Conclusions and Recommendations

The aim of the proposed research is to design and develop a SONAR System that could overcome the limitations of current range finding techniques used for indoor mobile robotic navigation. This is achieved by amalgamating current SONAR and RF-Beacon methodologies. The outcomes of the experiments are encouraging. However, there are areas that require further improvement.

9.1 Comparisons with Reviewed Range Finding Systems

A review into current systems on the market used for range finding for mobile robots revealed some key limitations such as environmental limitations and applications, line of sight, high processing requirement and cost. The development of the hybrid system in this research aimed to improve the situation and provide some contribution towards overcoming the limitations. The ranging finding system proposed in this research can be used for indoor mobile robot localisation.

GPS, SONAR, and LIDAR technologies for mobile robotic localisation were reviewed in Chapter 2. All the three systems employ TOF techniques for range finding and have certain limitations. Conclusively, the SONAR system developed in this research provides a solution for the line-of-sight issues normally addressed with TOF techniques employed by current ultrasonic SONAR systems; however at the cost of accuracy. The SONAR System is developed for an indoor area no larger than 10m by 10m, where the average ultrasonic pair costs under \$100 NZD and has an operational distance of 3 metres as seen in Table 9-1.

The SONAR Beacon orientation does affect the system's outcome. When the SONAR Beacon is orientated at an angle greater than 40 degrees to the SONAR Transmitter, the average error of the outcome is about +/-8%. The angle at which the SONAR Beacon can be positioned is greater than most of the ultrasonic transmitter receiver pairs available on the market and does not impact on the measurement as much. Table 9-1

lists some features of navigation systems. Each has its own advantages. For a similar task, a few systems can be used. The difference is the cost and accuracy.

Table 9-1 Comparison Table

	GPS Receiver	Ultrasonic Range Sensor	LIDAR	Thesis SONAR System
Typical Cost	\$80 ¹⁹	\$60 ²⁰	\$1000	\$100
Indoor Operation	NO	YES	NO	YES
Average Accuracy	+/- 10m	+/- 1cm	+/- 1m	+/- 5cm
Required Line-of-Sight Operation	NO	YES	YES	NO

A key objective for this research was to design a system suitable for indoor applications. Unlike GPS systems which are limited to outdoor applications, the SONAR Beacon can be placed at key locations within an indoor environment and calibrated for different elevations. The data acquired from Experiment 3 shows that elevation had no effect of the direct distance measurement between the SONAR Transmitter speaker and SONAR Beacon microphone.

With a complete development cost of \$100 NZD for a single SONAR Transmitter and Beacon pair, \$50 NZD would be required for another Beacon to be added to the system. As discussed in Chapter 3, a minimum of 3 Beacons is required for a complete Cartesian coordinate trilateration system, thus bringing the theoretical cost for a complete system to \$200 NZD. The system can output raw binary information and therefore can be incorporated into any existing mobile robotic project. With an average accuracy of +/- 2% the system can be used as a trilateration system to find the approximated location of a mobile vehicle.

The hybrid SONAR system must be fused with other sensor technology to create a complete autonomous mobile robot. This is true for all the systems reviewed in this research. The cost, accuracy and potential of the system developed in this research can make it an attractive option for mobile robotic developers. The system can also be

¹⁹ Does not include software or microcontroller/computer to interpret information from the GPS receiver

²⁰ Does not include software or microcontroller/computer to interpret information from the ultrasonic range sensor

developed to work with audible sounds already used in industrial robotics where some mobile robots emit an audible beep to alert people to the whereabouts of the robot.

9.2 Future Development Considerations

The system developed in this research requires further research to create a commercially viable product. An attempt to miniaturise the SONAR system components would be the first development approach. At the moment the system consists of several individual modules wired together. Design of a single circuit board that encompasses all the circuit boards would make the system compact and easy to be implemented. Further research into the use of different audio frequencies will provide information on frequencies that are more suitable for everyday use. The pitch of the 2 kHz target frequency is obviously a bit sharp and may cause irritation to people around the robot.

The SONAR Beacon draws a large amount of current due to the power requirement of the radio modules. To improve power consumption, the system can activate the radio transmitters only when a distance measurement is required. This would require taking advantage of the PIC18F1111 transceivers capability of radio transmission and reception.

A review on the effect of an omni-direction microphone and speaker on the distance measurement should also be conducted. The addition of a parabolic dish to the microphone could increase the sensitivity of the SONAR Beacon. Increased sensitivity may result in improved distance resolution. Finally, the PICAXE-08M microcontroller is limited by a slow clock speed and functionality. Therefore, a microcontroller that has more functionality with a faster clock speed should be explored. Furthermore, the PICAXE-08M has no timeout operations. A microcontroller with timeout functionality would allow the system to reset when no information is received and could provide faster and more reliable information for radio transmission.

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Appendix A

Chapter 5

Foot Note 5 - ZW3102 Receive Code and ZW3100 Send Code

Foot Note 8 - PICHRT111 Send and Receive Code

Chapter 6

Foot Note 9 - BASIC pulsio Code

Foot Note 11 - LabVIEW Code

Foot Note 12 - BASIC communication Code

Chapter 7

Foot Note 13 - TFG Microcontroller BASIC Code

Foot Note 14 - RTDA Microcontroller BASIC Code

Foot Note 15 - RAC microcontroller BASIC code

Foot Note 16 - LabVIEW Interface

CHAPTER 5**ZW3001**

'---TRANSMITTING PICAXE---

setfreq m8

main:

if pin3 = 1 then

serout 0,N4800_8,(\$D,\$D,\$D)

else

goto main

endif

goto main

ZW3002

'---RECIEVING PICAXE---

setfreq m8

main:

low 1

serin 2, n4800_8,(\$D)

high 1

pause 1000

goto main

PICVRT111 Send and Receive Code

```

*****Receive*****
'V+ - N/A
'0V - N/A
'0V - N/A
'0 - ENABLE - Set HIGH to ENABLE CHIP // LOW to DISABLE CHIPRTX
'1 - CONFIG - Set HIGH for CONFIG MODE // LOW to NORMAL MODE
'2 - Data input from PICAXE - NOT CONNECTED TO ANYTHING ATM
'3 - Wired to Ground
'4 - DTX - Data output to PICAXE
'V+ - VCC - 5V
'0V - Wired to 3

init:          setfreq m8
                HIGH 0
                LOW 1

SerialIn:      low 2
                serin 3, N2400, ($D)
                high 2
                pause 10
                goto SerialIn

*****Transmitter*****
'V+ - VCC - 5V
'0V - DTX - Data output to PICAXE
'0V - GND - GROUND
'0 - RTX - Data input from PICAXE
'1 - CONFIG - Set HIGH for CONFIG MODE // LOW to NORMAL MODE
'2 - ENABLE - Set HIGH to ENABLE CHIP // LOW to DISABLE CHIP
'3 - N/A
'4 - N/A
'V+ - N/A
'0V - N/A

init:          setfreq m8
                HIGH 2
                LOW 1

SerialOut:     if pin3 = 1 then
                serout 0, T4800_8, ($8)
                LOW 0
                goto SerialOut
                Endif
                goto SerialOut

```

CHAPTER 6

Pulsin CODE

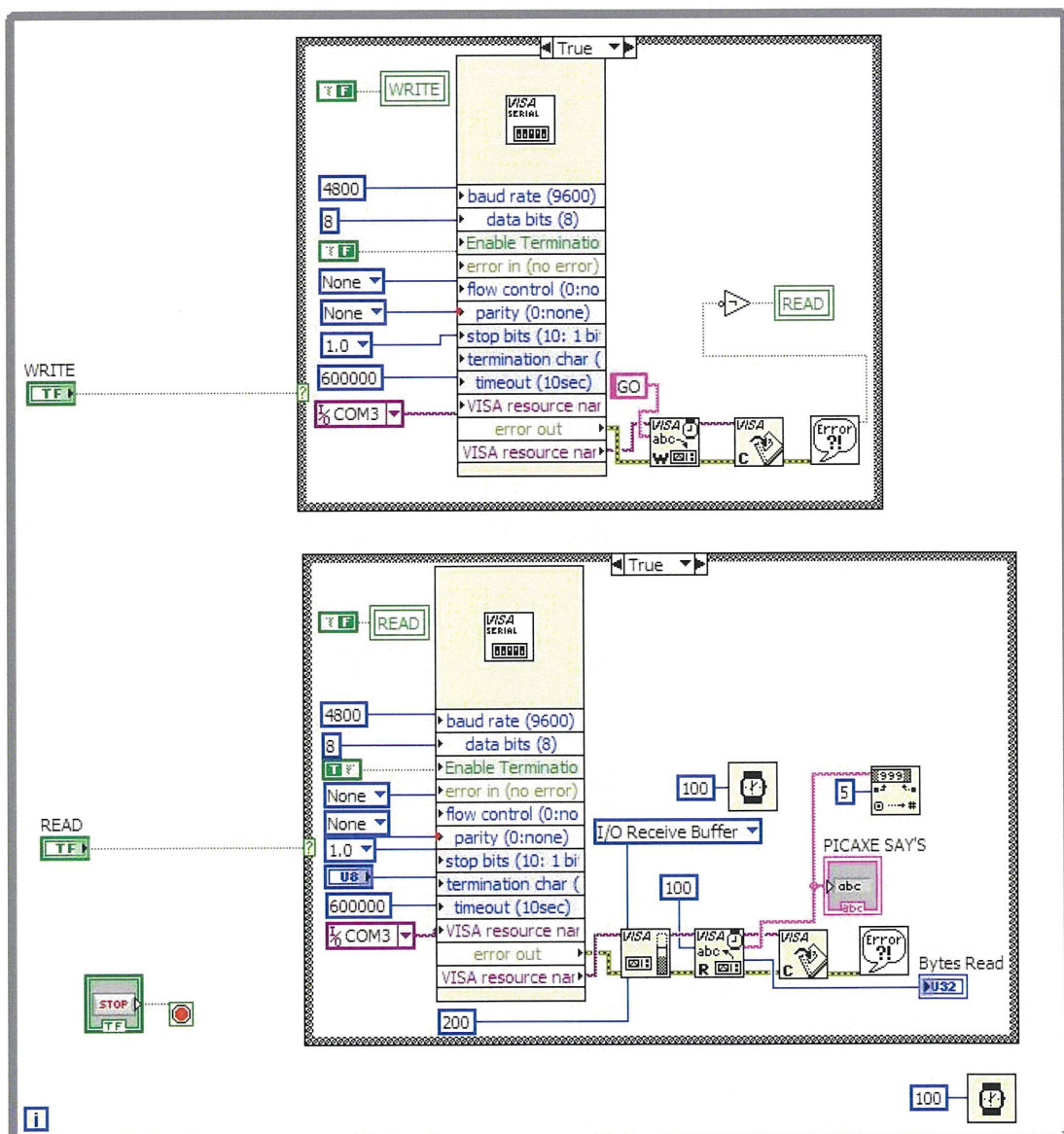
```
setfreq m8
```

```
main:
```

```
    pulsin 3, 1, w0
    sertxd (#w0," ")
    pause 2000
```

```
goto main
```

LabVIEW Code



Communication Code

```
'---Communication CODE-----
Init:
Setfreq m8           ' set clock to 8Mhz
Symbol PulseCount = w1 ' Assigning a name to variable w1
Input 1,2           ' make pin 1 & 2 an input
Output 0            ' set outputs to low

'-----

CompIn:
serin 1,N4800_8,("GO") 'Waits for signal on PIN1
pulsin 2,1,PulseCount 'Records Pulse width in number of counts
                        'at 0.5us per count on PIN2
pause 500             'Wait 500ms before outputting data
serout 0,N4800_8, ("The count is ",#PulseCount,$D) 'Outputs the number of
                                                    Counts via PIN0
LOW 1                 'Make PIN1 Low
goto CompIn
```

CHAPTER 7

TFG Code

```
'SPEAKER ON'-----
INTI:
setfreq m8           'Clock set to 8MHz
input 1              'Pin 3 set to input
output 2             'Pins 1,2 set to output
HIGH 2              'Insure all Outputs are set LOW to begin
                    with.

CompIn:
serin 1,N4800_8,("GO") 'Waits for Serial Communication from
                        Computer Via LabVIEW pause 10

LOW 2
PAUSE 100
HIGH 2
goto CompIn         'Make Beep. When complete will loop
                    back to waiting condition.
```

RTDA Code

```

'---TIMING CODE-----
Init:
Setfreq m8                ' set clock to 8Mhz
Symbol PulseCount = w1    ' Assigning a name to variable w1
Input 1,2                 ' make pin 1 & 2 an input
Output 0                  ' set outputs to low

'-----

CompIn:
  serin 1,N4800_8,("GO")   'Waits for signal on PIN1
  pause 19                 'Makes PIN1 High
  pulsln 2,1,PulseCount    'Records Pulse width in number of counts
                           at 0.5us per count on PIN2

  serin 1,N4800_8,(b0,$D)
  if b0 = 1 then
    serout 0,N4800_8, ("The count is ",#PulseCount,$D)  'Outputs the number of
                                                         Counts via PIN0
  else
    serout 0,N4800_8, ("The count is FALSE", $D)
  end if
  LOW 1
                                                         'Make PIN1 Low

goto CompIn

```

RAC Code

```

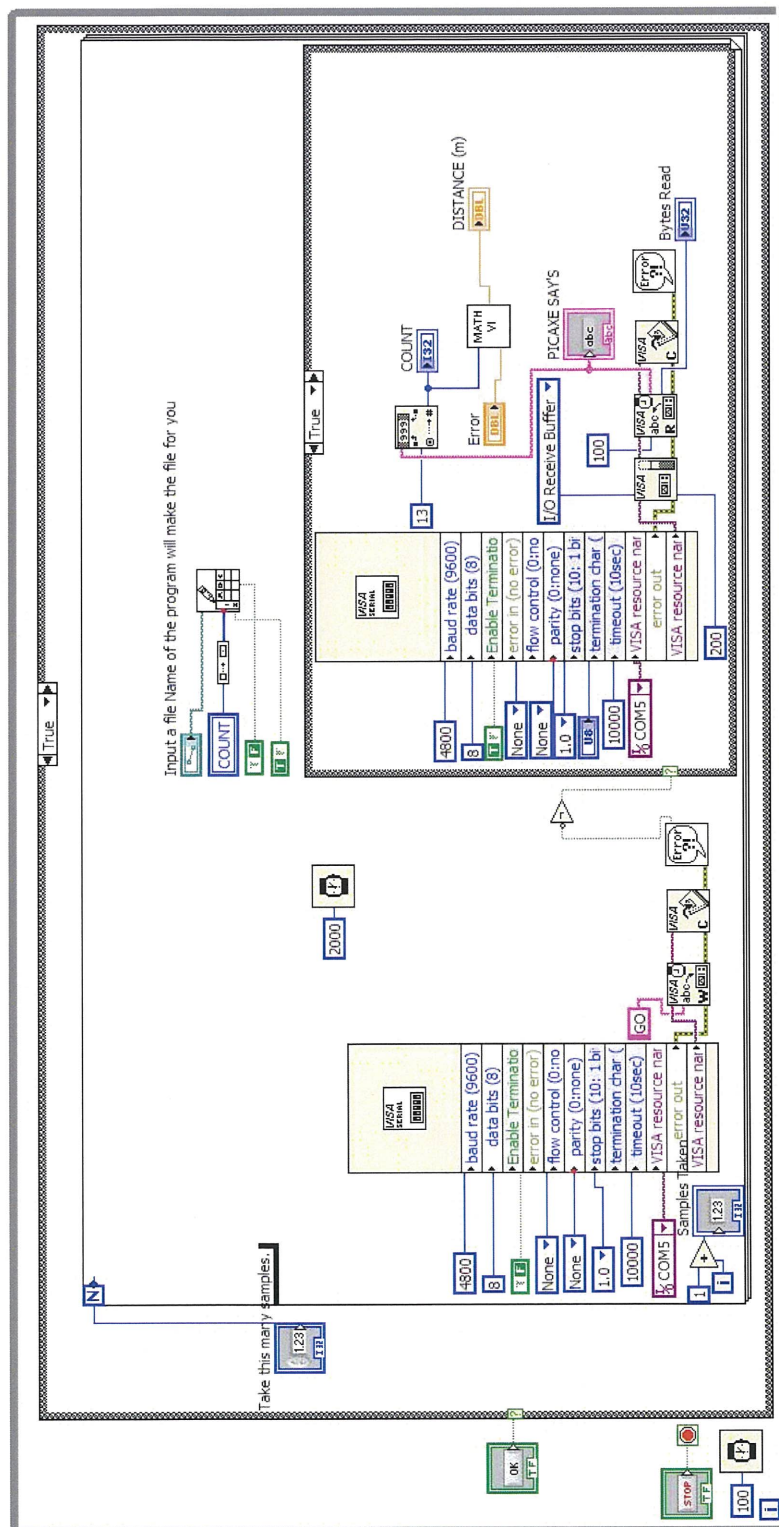
'---TRANSMITTER PICAXE---
setfreq m8                'set system clock to 8MHz
setint %00001000,%00001000 'set interrupt
input 2,3                 'set PIN3 to an input
output 0                  'set PIN1 & PIN2 to Serial OUT

main:
goto main

interrupt:
  serout 0,N4800_8,($D)
  setint %00001000,%00001000
return

```

LabVIEW Interface



Appendix B

Experiment 1 RAW data

Experiment 1 Time data

Experiment 1 Count to Time Charts

Experiment 1 Distance data

Experiment 2 RAW data

Experiment 2 Distance data

Experiment 3 Count to Distance Charts

Experiment 3 RAW data

Experiment 3 Distance data

Experiment 3 Count to Distance Charts

EXPERIMENT 1 RAW Data

DISTANCE	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5	7	7.5	8	8.5	9	9.5	10
1	1700	2177	2491	2875	3063	3514	3856	4251	4387	5425	4811	5916	5579	5867	5433	6471	7569	7151	7494	7368
2	1622	2237	2403	2588	3091	3243	3518	3846	4253	4382	4818	5106	5510	5569	5879	6154	6563	6919	7037	7496
3	1844	2012	2496	2689	2895	3242	3517	3838	4253	4380	4812	4266	4568	4847	5976	6258	6459	6934	7041	7480
4	1836	2232	2275	2691	3092	3038	3517	3851	4247	4377	4807	5113	5508	5578	5870	6258	6555	6934	7460	7487
5	1714	2034	2406	1946	2876	3360	3496	3848	4247	5425	4829	5105	5511	5589	5876	6168	6572	6003	7147	6777
6	1827	2031	2182	2701	2896	3242	3518	3850	4245	5427	4819	5090	5313	5577	5148	6257	6566	7774	7037	7490
7	1613	1106	2403	2591	3091	3036	3528	3848	4262	4386	4821	5094	5315	5594	5146	6261	6573	7170	6337	7263
8	1841	2139	2404	2691	3090	1875	3530	3847	4241	4379	4799	5101	5915	5568	5871	6158	6571	7672	7037	7383
9	1621	2012	2494	2688	3078	3244	3511	3858	4263	4378	4806	5105	5512	5576	5138	6266	5725	7033	7146	7487
10	1840	2018	2180	2686	2897	3266	3530	3860	4249	4371	4825	4258	5323	5580	5976	5416	6566	7667	6332	7265
11	1727	2139	2171	2692	2899	3040	3530	3857	4264	4400	4816	5092	5317	5571	5139	6263	5733	6108	7128	7380
12	1611	2014	2182	2699	3094	2538	3532	3857	4256	4386	4815	5113	5315	5580	5130	6156	6568	7780	6305	7488
13	1608	2141	2176	2687	3091	3041	3508	3853	4245	4392	4826	5089	4576	5570	5884	5427	6567	7037	6921	7383
14	1838	2140	2402	2682	3093	3035	3531	3858	4268	4376	4826	5105	5507	5590	5872	5437	5744	6000	7044	7492
15	1620	2144	2383	2592	2893	3250	3526	3837	4263	4376	4808	4282	5320	5593	5860	6165	5727	7668	7041	6750
16	1612	2034	2500	2690	3092	3242	3508	3851	4256	4387	4811	5113	5320	5595	5880	6165	6471	7035	7455	7485
17	1839	2041	2500	2684	3092	3253	3512	3848	4240	4388	4820	5099	5313	5581	5873	6143	6559	6003	7261	7263
18	1616	2234	2494	2699	3100	3038	3526	3866	4255	4385	4813	5108	5324	5594	5129	6261	6464	7166	7459	7483
19	1826	2016	2180	2687	2875	3041	3508	3854	4247	4398	3966	5088	4566	5587	5875	6164	6466	5006	7461	7489
20	1823	2017	2400	2596	2895	3262	3506	3865	4251	4394	4810	5103	5512	5689	5139	6161	6474	5995	7150	7497
21	1837	2012	2178	2592	3096	3036	2816	3864	4253	4379	4825	5098	5323	5582	5140	6152	6476	7169	7463	7493
22	1843	2237	2276	2694	2897	3260	3521	3866	4240	4385	4808	4005	5315	5569	5881	6165	6569	6135	7047	7490
23	1607	2038	2172	2674	2899	3260	3508	3839	1272	4397	4811	4279	5917	5569	5870	6266	5732	7033	7149	7386
24	1825	2141	2496	2684	3079	3242	3517	3851	4247	4394	4820	5114	5515	5584	5873	6264	6566	6128	7042	6777
25	1415	2022	2179	2698	3087	3265	3517	3850	4258	4378	4829	5100	5325	5587	5139	6165	6569	7779	6541	7388
26	1610	2037	2169	2589	3096	3243	3514	3852	4247	4377	4818	5090	5313	5598	5977	5442	6569	6004	7460	7266
27	1612	2240	2173	2591	3093	3040	3516	3862	4268	4375	4825	5105	5323	5589	5862	6153	5733	7028	7143	7266
28	1611	2037	2171	2595	3089	3040	3624	3849	4257	4377	4819	5089	5314	5579	5882	6262	6465	7773	6438	7264
29	1938	2237	2401	2700	2875	3037	3515	3863	4264	4373	4808	5111	5508	4855	5977	6168	6471	7781	2940	7486
30	1714	2016	2173	2590	2892	3247	3516	3861	4269	4384	4824	5110	5325	4865	5873	6169	5731	7776	6127	7490
31	1624	2235	2174	2589	2897	3033	3510	3852	4255	4384	4826	4286	5914	4849	5873	6170	6574	7868	7143	7483
32	1836	2017	2497	2702	3083	3264	3528	3850	4062	4375	4808	5099	5507	5578	5876	6266	6465	7778	7472	7484
33	1618	2015	2404	2590	2894	3254	3523	3847	4255	4371	4821	5106	5917	5586	5864	6155	6465	7025	7259	6781
34	1616	2122	2499	2591	2899	3243	3524	3846	4267	4396	3972	5111	5317	5585	5134	6170	6464	7033	7257	7482
35	1823	2232	2177	2691	2895	3044	3520	3841	4249	4384	4816	5095	5319	5586	5140	6164	6568	7775	6291	6646
36	1619	2013	2169	2691	2901	3263	3507	3844	4238	4396	4806	5113	5507	5595	5869	6163	6468	7774	1096	7488
37	1606	2039	2496	2586	3092	3038	3506	3859	4251	4374	4808	5098	5511	5588	5146	5421	6571	7566	7042	7490
38	1838	2012	2171	2593	3085	3268	3516	3841	4255	4375	4827	5090	5515	5585	5880	6163	6564	7667	7147	7261
39	1608	2016	2401	2686	3099	3045	3520	3121	4247	4371	4815	5114	5513	5573	5880	6261	6466	7568	7455	7483
40	1845	2019	2181	2584	3082	3039	3518	3843	4256	4400	4826	5086	5320	5594	5873	6167	6575	7031	7149	7380
41	1836	2017	2170	2698	2846	3358	3529	3851	4247	4387	4805	5094	5507	5569	5864	6153	6568	7572	7043	7266
42	1609	2040	2403	2691	2877	3259	3507	3843	4252	4375	4803	5100	5325	5574	5884	6265	5745	6002	7264	7370
43	1608	2239	2398	2691	2892	3245	3521	3851	4255	4375	4822	5096	5327	5584	5132	6262	6563	7035	6296	7365
44	1932	2016	2183	2677	3087	3036	3533	3849	4248	4378	4812	5098	5324	5593	5885	6167	6562	7027	7273	7485
45	1824	2031	2275	2696	2901	3358	3503	3860	4261	4377	4819	5093	5327	5584	5869	5422	5732	7025	6304	7481
46	1445	2017	2174	2692	2903	3039	3503	3844	4250	4378	4819	5097	5509	5597	5867	6169	6461	7777	7041	7484
47	1617	2018	2169	2594	2901	3264	3505	3849	4262	4387	4824	4013	4559	5580	5862	6266	6467	7018	3997	7382
48	1844	2031	2177	2698	3094	3265	3531	3845	4254	5422	4807	5114	5318	4839	5883	6165	6564	7033	7273	6681
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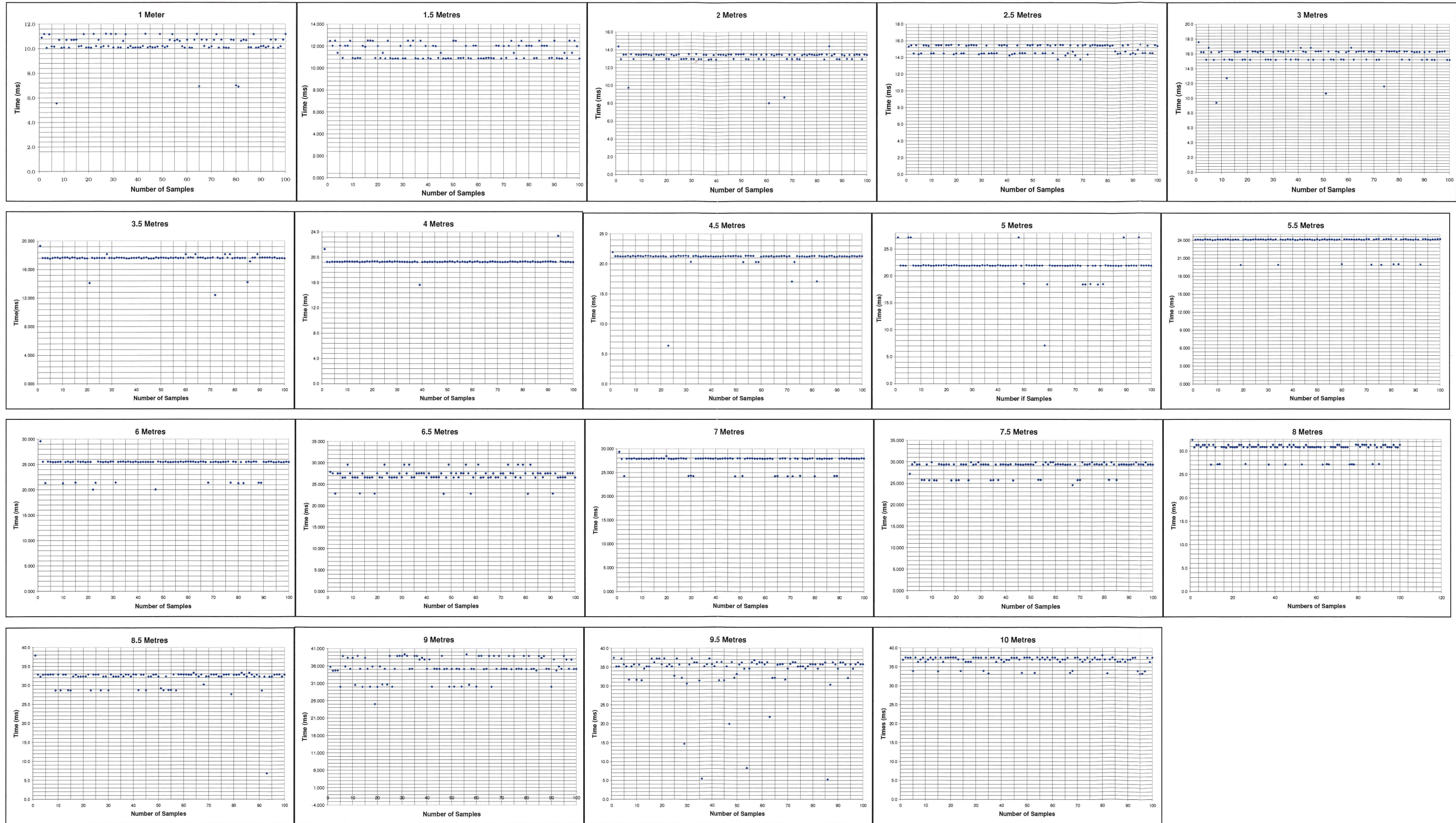
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51	1838	2019	2495	2702	2900	2123	3524	3866	4252	4394	4803	5111	5314	4853	5865	6162	5842	6010	7146	7489
52	1831	2034	2181	2591	3086	3261	3518	3857	4252	4383	4819	5089	5511	5574	5974	6157	5741	7038	7258	7381
53	1712	2139	2180	2588	3094	3045	3510	3839	4058	4378	4829	5088	5322	5597	5156	5425	6466	7023	6921	6676
54	1844	2233	2184	2694	2896	3038	3525	3866	4267	4386	4811	5093	5514	5596	5150	6153	5750	6010	1657	7496
55	1837	2127	2401	2686	2899	3263	3517	3840	4266	4383	4821	5100	5511	5592	5867	6261	5750	7019	6924	7385
56	1845	2143	2181	2692	3096	3244	3528	3857	4261	4377	4821	5091	5915	5581	5976	6168	6569	7868	7262	7488
57	1617	2121	2172	2593	3080	3045	3512	3848	4260	4381	4810	5109	5511	5576	5876	6159	5726	6106	7371	7385
58	1840	2036	2406	2687	2901	3038	3521	3840	4057	1411	4809	5093	4563	5589	5975	6168	6571	7027	7169	7496
59	1605	2013	2406	2588	3094	3241	3515	3865	4059	3684	4817	5109	5319	5576	5979	6159	6574	7022	7268	7367
60	1834	2140	2175	2690	2754	3265	3622	3841	4238	4389	3997	5110	5512	5570	5870	6164	6566	6010	7258	7495
61	1827	2013	2175	1599	3097	3358	3527	3855	4250	4378	4824	5108	5918	5580	5884	6171	6570	7777	7145	7485
62	1848	2011	2174	2690	3097	3039	3531	3866	4254	4373	4822	5109	5310	5587	5874	6158	6557	7781	7262	7384
63	1838	2142	2183	2673	2845	3249	3524	3841	4248	4378	4820	5095	5321	5572	5882	5418	6560	7020	4364	7264
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66	1938	2144	2177	2685	2941	3261	3528	3838	4250	4374	4814	5109	5325	5580	5874	5424	6467	5999	7128	7480
67	1622	2040	2406	1727	2846	3040	3526	3860	4252	4373	4823	5090	5508	5592	4910	6165	6569	7778	7149	6682
68	1729	2142	2404	2594	3086	3256	3506	3864	4258	4381	4807	4282	5320	5591	5874	6169	6044	7030	7162	6782
69	1609	2014	2175	2688	2751	3261	3518	3851	4263	4389	4810	5095	5323	4836	5141	6155	6469	7773	6338	7486
70	1828	2034	2400	2593	3084	3245	3519	3847	4243	4380	4831	5094	5508	5571	5145	6266	6473	7031	6919	7496
71	1842	2139	2183	2689	3100	3035	3530	3847	4257	4389	4826	5106	5507	4840	5974	6260	6573	7037	7169	7382
72	1937	2233	2403	2594	2871	3038	2479	3841	3410	4376	3976	5090	5316	5591	5872	6161	6568	7031	7261	7265
73	1842	2013	2495	2588	3077	3269	3526	3847	4059	3684	4813	5089	5915	5575	5868	6155	6575	7776	7258	7367
74	1843	2144	2275	2680	3097	2312	3507	3845	4259	3684	4829	5102	5517	4859	5887	6158	6468	7019	7027	7486
75	1846	2019	2172	2698	3098	3264	3516	3865	4247	4379	4831	5099	5511	5592	5975	6156	6467	7774	7046	7264
76	1838	2012	2405	2679	3086	3260	3622	3857	4254	3695	3971	5113	5327	5577	5873	5425	6563	7034	7043	7380
77	1831	2011	2494	2702	3088	3262	3524	3855	4245	4379	4818	4282	5918	5572	5884	5432	6572	7038	6921	7485
78	1847	2144	2176	2691	3087	3267	3621	3844	4240	4380	4831	5110	5313	5586	5865	5421	6572	7026	7045	7383
79	1614	2138	2403	2684	3097	3246	3510	3860	4248	3683	4827	5099	5917	5595	5877	6271	5532	7775	7151	7382
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81	1616	1379	2402	2695	3082	3040	3524	3865	4263	3695	3991	5092	4561	5578	5877	6170	6558	7773	7143	7378
82	1610	2125	2178	2699	3095	3259	3512	3851	3417	4400	4828	4264	5916	5585	5151	6267	6568	7025	6921	6648
83	1840	2143	2182	2584	2954	3263	3518	3845	4264	4389	3993	5098	5507	5570	5975	6261	6668	7035	7150	7379
84	1844	2135	2497	2695	2891	3038	3517	3866	4252	4385	4813	5110	5316	5589	5873	6264	6567	6934	7149	7489
85	1604	2019	2405	2879	2899	3258	2838	3847	4244	4385	4826	5095	5516	5582	5142	6152	6466	7775	7257	7368
86	1618	2018	2404	2674	3086	3240	3420	3846	4241	4385	4833	5112	5510	5579	5869	6261	6665	7672	1052	7266
87	1615	2234	2404	2702	2941	3246	3523	3844	4264	4373	4812	5107	5326	5586	5876	5437	6569	7768	6077	7267
88	1845	2013	2180	2592	3094	3246	3526	3854	4267	4378	4815	4280	5508	4856	5877	6259	6467	7036	7260	7387
89	1844	2017	2185	2589	2873	3036	3624	3861	4238	5428	4810	4278	5512	4858	5867	6153	6561	7029	7148	7265
90	1836	2036	2499	2688	2900	3243	3525	3863	4238	4380	4827	5103	5513	5580	5869	5440	6472	6003	6921	7371
91	1618	2039	2180	2675	2874	3041	3529	3864	4257	4377	4814	5095	4567	5598	5870	6160	5728	7573	7260	7383
92	1610	2016	2172	2595	2976	3255	3528	3851	4249	4384	3986	5113	5510	5578	5884	6258	6460	6934	7253	7482
93	1337	2033	2171	2686	3099	3037	3528	3848	4252	4380	4830	5114	5314	5598	5977	6260	1365	7168	7142	7494
94	1605	2143	2276	2593	2898	3035	3529	4670	4246	4374	4833	5086	5325	5585	5881	6165	6457	7038	6427	6782
95	1831	2012	2180	2684	2902	3246	3518	3864	4240	5428	4816	5086	5326	5583	5881	6164	6469	7779	7151	6640
96	1845	2142	2499	2696	3080	3256	3531	3850	4260	4380	4810	5104	5324	5583	5869	6157	6562	7571	6921	6644
97	1619	2011	2276	2688	2902	3258	3510	3847	4257	4377	4824	5087	5514	5584	5977	6260	6571	7037	7149	6771
98	1838	2036	2498	2590	2899	3267	3512	3854	4245	4384	4821	5089	5514	5575	5870	6161	6572	7568	7256	7489
99	1619	2144	2398	2694	3096	3035	3515	3843	4258	4380	4831	5107	5514	5597	5879	6151	6465	7026	7148	7262
100	1823	2236	2173	2686	3075	3032	3509	3843	4254	4374	4833	5092	5320	5586	5866	6263	6563	7028	7157	7489

EXPERIMENT 1 Time Data

DISTANCE	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5	7	7.5	8	8.5	9	9.5	10
1	8.500	10.885	12.455	14.375	15.315	17.570	19.280	21.255	21.935	27.125	24.055	29.580	27.895	29.335	27.165	32.355	37.845	35.755	37.470	36.840
2	8.110	11.185	12.015	12.940	15.455	16.215	17.590	19.230	21.265	21.910	24.090	25.530	27.550	27.845	29.395	30.770	32.815	34.595	35.185	37.480
3	9.220	10.060	12.480	13.445	14.475	16.210	17.585	19.190	21.265	21.900	24.060	21.330	22.840	24.235	29.880	31.290	32.295	34.670	35.205	37.400
4	9.180	11.160	11.375	13.455	15.460	15.190	17.585	19.255	21.235	21.885	24.035	25.565	27.540	27.890	29.350	31.290	32.775	34.670	37.300	37.435
5	8.570	10.170	12.030	9.730	14.380	16.800	17.480	19.240	21.235	27.125	24.145	25.525	27.555	27.945	29.380	30.840	32.860	30.015	35.735	33.885
6	9.135	10.155	10.910	13.505	14.480	16.210	17.590	19.250	21.225	27.135	24.095	25.450	26.565	27.885	25.740	31.285	32.830	38.870	35.185	37.450
7	8.065	5.530	12.015	12.955	15.455	15.180	17.640	19.240	21.310	21.930	24.105	25.470	26.575	27.970	25.730	31.305	32.865	35.850	31.685	36.315
8	9.205	10.695	12.020	13.455	15.450	9.375	17.650	19.235	21.205	21.895	23.995	25.505	29.575	27.840	29.355	30.790	32.855	38.360	35.185	36.915
9	8.105	10.060	12.470	13.440	15.390	16.220	17.555	19.290	21.315	21.890	24.030	25.525	27.560	27.880	25.690	31.330	28.625	35.165	35.730	37.435
10	9.200	10.090	10.900	13.430	14.485	16.330	17.650	19.300	21.245	21.855	24.125	21.290	26.615	27.900	29.880	27.080	32.830	38.335	31.660	36.325
11	8.635	10.695	10.855	13.460	14.495	15.200	17.650	19.285	21.320	22.000	24.080	25.460	26.585	27.855	25.695	31.315	28.665	30.540	35.640	36.900
12	8.055	10.070	10.910	13.495	15.470	12.690	17.660	19.285	21.280	21.930	24.075	25.565	26.575	27.900	25.650	30.780	32.840	38.900	31.525	37.440
13	8.040	10.705	10.880	13.435	15.455	15.205	17.540	19.265	21.225	21.960	24.130	25.445	22.880	27.850	29.420	27.135	32.835	35.185	34.605	36.915
14	9.190	10.700	12.010	13.410	15.465	15.175	17.655	19.290	21.340	21.880	24.130	25.525	27.535	27.950	29.360	27.185	28.720	30.000	35.220	37.460
15	8.100	10.720	11.915	12.960	14.465	16.250	17.630	19.185	21.315	21.880	24.040	21.410	26.600	27.965	29.300	30.825	28.635	38.340	35.205	33.750
16	8.060	10.170	12.500	13.450	15.460	16.210	17.540	19.255	21.280	21.935	24.055	25.565	26.600	27.975	29.400	30.825	32.355	35.175	37.275	37.425
17	9.195	10.205	12.500	13.420	15.460	16.265	17.560	19.240	21.200	21.940	24.100	25.495	26.565	27.905	29.365	30.715	32.795	30.015	36.305	36.315
18	8.080	11.170	12.470	13.495	15.500	15.190	17.630	19.330	21.275	21.925	24.065	25.540	26.620	27.970	25.645	31.305	32.320	35.830	37.295	37.415
19	9.130	10.080	10.900	13.435	14.375	15.205	17.540	19.270	21.235	21.990	19.830	25.440	22.830	27.935	29.375	30.820	32.330	25.030	37.305	37.445
20	9.115	10.085	12.000	12.980	14.475	16.310	17.530	19.325	21.255	21.970	24.050	25.515	27.560	28.445	25.695	30.805	32.370	29.975	35.750	37.485
21	9.185	10.060	10.890	12.960	15.480	15.180	14.080	19.320	21.265	21.895	24.125	25.490	26.615	27.910	25.700	30.760	32.380	35.845	37.315	37.465
22	9.215	11.185	11.380	13.470	14.485	16.300	17.605	19.330	21.200	21.925	24.040	20.025	26.575	27.845	29.405	30.825	32.845	30.675	35.235	37.450
23	8.035	10.190	10.860	13.370	14.495	16.300	17.540	19.195	6.360	21.985	24.055	21.395	29.585	27.845	29.350	31.330	28.660	35.165	35.745	36.930
24	9.125	10.705	12.480	13.420	15.395	16.210	17.585	19.255	21.235	21.970	24.100	25.570	27.575	27.920	29.365	31.320	32.830	30.640	35.210	33.885
25	7.075	10.110	10.895	13.490	15.435	16.325	17.585	19.250	21.290	21.890	24.145	25.500	26.625	27.935	25.695	30.825	32.845	38.895	32.705	36.940
26	8.050	10.185	10.845	12.945	15.480	16.215	17.570	19.260	21.235	21.885	24.090	25.450	26.565	27.990	29.885	27.210	32.845	30.020	37.300	36.330
27	8.060	11.200	10.865	12.955	15.465	15.200	17.580	19.310	21.340	21.875	24.125	25.525	26.615	27.945	29.310	30.765	28.665	35.140	35.715	36.330
28	8.055	10.185	10.855	12.975	15.445	15.200	18.120	19.245	21.285	21.885	24.095	25.445	26.570	27.895	29.410	31.310	32.325	38.865	32.190	36.320
29	9.690	11.185	12.005	13.500	14.375	15.185	17.575	19.315	21.320	21.865	24.040	25.555	27.540	24.275	29.885	30.840	32.355	38.905	14.700	37.430
30	8.570	10.080	10.865	12.950	14.460	16.235	17.580	19.305	21.345	21.920	24.120	25.550	26.625	24.325	29.365	30.845	28.655	38.880	30.635	37.450
31	8.120	11.175	10.870	12.945	14.485	15.165	17.550	19.260	21.275	21.920	24.130	21.430	29.570	24.245	29.365	30.850	32.870	39.340	35.715	37.415
32	9.180	10.085	12.485	13.510	15.415	16.320	17.640	19.250	20.310	21.875	24.040	25.495	27.535	27.890	29.380	31.330	32.325	38.890	37.360	37.420
33	8.090	10.075	12.020	12.950	14.470	16.270	17.615	19.235	21.275	21.855	24.105	25.530	29.585	27.930	29.320	30.775	32.325	35.125	36.295	33.905
34	8.080	10.610	12.495	12.955	14.495	16.215	17.620	19.230	21.335	21.980	19.860	25.555	26.585	27.925	25.670	30.850	32.320	35.165	36.285	37.410
35	9.115	11.160	10.885	13.455	14.475	15.220	17.600	19.205	21.245	21.920	24.080	25.475	26.595	27.930	25.700	30.820	32.840	38.875	31.455	33.230
36	8.095	10.065	10.845	13.455	14.505	16.315	17.535	19.220	21.190	21.980	24.030	25.565	27.535	27.975	29.345	30.815	32.340	38.870	5.480	37.440
37	8.030	10.195	12.480	12.930	15.460	15.190	17.530	19.295	21.255	21.870	24.040	25.490	27.555	27.940	25.730	27.105	32.855	37.830	35.210	37.450
38	9.190	10.060	10.855	12.965	15.425	16.340	17.580	19.205	21.275	21.875	24.135	25.450	27.575	27.925	29.400	30.815	32.820	38.335	35.735	36.305
39	8.040	10.080	12.005	13.430	15.495	15.225	17.600	15.605	21.235	21.855	24.075	25.570	27.565	27.865	29.400	31.305	32.330	37.840	37.275	37.415
40	9.225	10.095	10.905	12.920	15.410	15.195	17.590	19.215	21.280	22.000	24.130	25.430	26.600	27.970	29.365	30.835	32.875	35.155	35.745	36.900
41	9.180	10.085	10.850	13.490	14.230	16.790	17.645	19.255	21.235	21.935	24.025	25.470	27.535	27.845	29.320	30.765	32.840	37.860	35.215	36.330
42	8.045	10.200	12.015	13.455	14.385	16.295	17.535	19.215	21.260	21.875	24.015	25.500	26.625	27.870	29.420	31.325	28.725	30.010	36.320	36.850
43	8.040	11.195	11.990	13.455	14.460	16.225	17.605	19.255	21.275	21.875	24.110	25.480	26.635	27.920	25.660	31.310	32.815	35.175	31.480	36.825
44	9.660	10.080	10.915	13.385	15.435	15.180	17.665	19.245	21.240	21.890	24.060	25.490	26.620	27.965	29.425	30.835	32.810	35.135	36.365	37.425
45	9.120	10.155	11.375	13.480	14.505	16.790	17.515	19.300	21.305	21.885	24.095	25.465	26.635	27.920	29.345	27.110	28.660	35.125	31.520	37.405
46	7.225	10.085	10.870	13.460	14.515	15.195	17.515	19.220	21.250	21.890	24.095	25.485	27.545	27.985	29.335	30.845	32.305	38.885	35.205	37.420
47	8.085	10.090	10.845	12.970	14.505	16.320	17.525	19.245	21.310	21.935	24.120	20.065	22.795	27.900	29.310	31.330	32.335	35.090	19.985	36.910
48	9.220	10.155	10.885	13.490	15.470	16.325	17.655	19.225	21.270	27.110	24.035	25.570	26.590	24.195	29.415	30.825	32.820	35.165	36.365	33.405
49	8.570	11.175	10.865	13.475	15.425	16.340	17.575	19.290	21.290	21.870	24.020	25.495	29.580	27.975	29.390	31.305	32.865	30.035	32.190	37.425

50	8.060	10.195	12.495	13.485	15.490	15.185	17.635	19.245	21.325	18.525	24.150	25.450	27.575	27.965	29.405	30.850	32.335	35.125	33.220	37.475
51	9.190	10.095	12.475	13.510	14.500	10.615	17.620	19.330	21.260	21.970	24.015	25.555	26.570	24.265	29.325	30.810	29.210	30.050	35.730	37.445
52	9.155	10.170	10.905	12.955	15.430	16.305	17.590	19.285	21.260	21.915	24.095	25.445	27.555	27.870	29.870	30.785	28.705	35.190	36.290	36.905
53	8.560	10.695	10.900	12.940	15.470	15.225	17.550	19.195	20.290	21.890	24.145	25.440	26.610	27.985	25.780	27.125	32.330	35.115	34.605	33.380
54	9.220	11.165	10.920	13.470	14.480	15.190	17.625	19.330	21.335	21.930	24.055	25.465	27.570	27.980	25.750	30.765	28.750	30.050	8.285	37.480
55	9.185	10.635	12.005	13.430	14.495	16.315	17.585	19.200	21.330	21.915	24.105	25.500	27.555	27.960	29.335	31.305	28.750	35.095	34.620	36.925
56	9.225	10.715	10.905	13.460	15.480	16.220	17.640	19.285	21.305	21.885	24.105	25.455	29.575	27.905	29.880	30.840	32.845	39.340	36.310	37.440
57	8.085	10.605	10.860	12.965	15.400	15.225	17.560	19.240	21.300	21.905	24.050	25.545	27.555	27.880	29.380	30.795	28.630	30.530	36.855	36.925
58	9.200	10.180	12.030	13.435	14.505	15.190	17.605	19.200	20.285	7.055	24.045	25.465	22.815	27.945	29.875	30.840	32.855	35.135	35.845	37.480
59	8.025	10.065	12.030	12.940	15.470	16.205	17.575	19.325	20.295	18.420	24.085	25.545	26.595	27.880	29.895	30.795	32.870	35.110	36.340	36.835
60	9.170	10.700	10.875	13.450	13.770	16.325	18.110	19.205	21.190	21.945	19.985	25.550	27.560	27.850	29.350	30.820	32.830	30.050	36.290	37.475
61	9.135	10.065	10.875	7.995	15.485	16.790	17.635	19.275	21.250	21.890	24.120	25.540	29.590	27.900	29.420	30.855	32.850	38.885	35.725	37.425
62	9.240	10.055	10.870	13.450	15.485	15.195	17.655	19.330	21.270	21.865	24.110	25.545	26.550	27.935	29.370	30.790	32.785	38.905	36.310	36.920
63	9.190	10.710	10.915	13.365	14.225	16.245	17.620	19.205	21.240	21.890	24.100	25.475	26.605	27.860	29.410	27.090	32.800	35.100	21.820	36.320
64	8.020	11.180	10.920	13.455	14.505	16.310	18.115	19.215	21.295	21.895	24.095	25.455	27.555	24.215	29.310	30.805	33.325	35.165	32.135	36.920
65	8.075	6.920	10.905	13.475	15.435	16.310	17.635	19.245	21.185	21.895	24.065	25.565	26.555	24.275	29.345	27.180	32.825	38.885	32.185	36.920
66	9.690	10.720	10.885	13.425	14.705	16.305	17.640	19.190	21.250	21.870	24.070	25.545	26.625	27.900	29.370	27.120	32.335	29.995	35.640	37.400
67	8.110	10.200	12.030	8.635	14.230	15.200	17.630	19.300	21.260	21.865	24.115	25.450	27.540	27.960	24.550	30.825	32.845	38.890	35.745	33.410
68	8.645	10.710	12.020	12.970	15.430	16.280	17.530	19.320	21.290	21.905	24.035	21.410	26.600	27.955	29.370	30.845	30.220	35.150	35.810	33.910
69	8.045	10.070	10.875	13.440	13.755	16.305	17.590	19.255	21.315	21.945	24.050	25.475	26.615	24.180	25.705	30.775	32.345	38.865	31.690	37.430
70	9.140	10.170	12.000	12.965	15.420	16.225	17.595	19.235	21.215	21.900	24.155	25.470	27.540	27.855	25.725	31.330	32.365	35.155	34.595	37.480
71	9.210	10.695	10.915	13.445	15.500	15.175	17.650	19.235	21.285	21.945	24.130	25.530	27.535	24.200	29.870	31.300	32.865	35.185	35.845	36.910
72	9.685	11.165	12.015	12.970	14.355	15.190	12.395	19.205	17.050	21.880	19.880	25.450	26.580	27.955	29.360	30.805	32.840	35.155	36.305	36.325
73	9.210	10.065	12.475	12.940	15.385	16.345	17.630	19.235	20.295	18.420	24.065	25.445	29.575	27.875	29.340	30.775	32.875	38.880	36.290	36.835
74	9.215	10.720	11.375	13.400	15.485	11.560	17.535	19.225	21.295	18.420	24.145	25.510	27.585	24.295	29.435	30.790	32.340	35.095	35.135	37.430
75	9.230	10.095	10.860	13.490	15.490	16.320	17.580	19.325	21.235	21.895	24.155	25.495	27.555	27.960	29.875	30.780	32.335	38.870	35.230	36.320
76	9.190	10.060	12.025	13.395	15.430	16.300	18.110	19.285	21.270	18.475	19.855	25.565	26.635	27.885	29.365	27.125	32.815	35.170	35.215	36.900
77	9.155	10.055	12.470	13.510	15.440	16.310	17.620	19.275	21.225	21.895	24.090	21.410	29.590	27.860	29.420	27.160	32.860	35.190	34.605	37.425
78	9.235	10.720	10.880	13.455	15.435	16.335	18.105	19.220	21.200	21.900	24.155	25.550	26.565	27.930	29.325	27.105	32.860	35.130	35.225	36.915
79	8.070	10.690	12.015	13.420	15.485	16.230	17.550	19.300	21.240	18.415	24.135	25.495	29.585	27.975	29.385	31.355	27.660	38.875	35.755	36.910
80	9.135	6.995	12.020	13.420	15.520	16.335	17.580	19.290	21.300	21.890	24.110	21.300	27.560	24.215	29.885	31.295	32.800	35.115	35.755	37.995
81	8.080	6.895	12.010	13.475	15.410	15.200	17.620	19.325	21.315	18.475	19.955	25.460	22.805	27.890	29.385	30.850	32.790	38.865	35.715	36.890
82	8.050	10.625	10.890	13.495	15.475	16.295	17.560	19.255	17.085	22.000	24.140	21.320	29.580	27.925	25.755	31.335	32.840	35.125	34.605	33.240
83	9.200	10.715	10.910	12.920	14.770	16.315	17.590	19.225	21.320	21.945	19.965	25.490	27.535	27.850	29.875	31.305	33.340	35.175	35.750	36.895
84	9.220	10.675	12.485	13.475	14.455	15.190	17.585	19.330	21.260	21.925	24.065	25.550	26.580	27.945	29.365	31.320	32.835	34.670	35.745	37.445
85	8.020	10.095	12.025	14.395	14.495	16.290	14.190	19.235	21.220	21.925	24.130	25.475	27.580	27.910	25.710	30.760	32.330	38.875	36.285	36.840
86	8.090	10.090	12.020	13.370	15.430	16.200	17.100	19.230	21.205	21.925	24.165	25.560	27.550	27.895	29.345	31.305	33.325	38.360	5.260	36.330
87	8.075	11.170	12.020	13.510	14.705	16.230	17.615	19.220	21.320	21.865	24.060	25.535	26.630	27.930	29.380	27.185	32.845	38.840	30.385	36.335
88	9.225	10.065	10.900	12.960	15.470	16.230	17.630	19.270	21.335	21.890	24.075	21.400	27.540	24.280	29.385	31.295	32.335	35.180	36.300	36.935
89	9.220	10.085	10.925	12.945	14.365	15.180	18.120	19.305	21.190	27.140	24.050	21.390	27.560	24.290	29.335	30.765	32.805	35.145	35.740	36.325
90	9.180	10.180	12.495	13.440	14.500	16.215	17.625	19.315	21.190	21.900	24.135	25.515	27.565	27.900	29.345	27.200	32.360	30.015	34.605	36.855
91	8.090	10.195	10.900	13.375	14.370	15.205	17.645	19.320	21.285	21.885	24.070	25.475	22.835	27.990	29.350	30.800	28.640	37.865	36.300	36.915
92	8.050	10.080	10.860	12.975	14.880	16.275	17.640	19.255	21.245	21.920	19.930	25.565	27.550	27.890	29.420	31.290	32.300	34.670	36.265	37.410
93	6.685	10.165	10.855	13.430	15.495	15.185	17.640	19.240	21.260	21.900	24.150	25.570	26.570	27.990	29.885	31.300	6.825	35.840	35.710	37.470
94	8.025	10.715	11.380	12.965	14.490	15.175	17.645	23.350	21.230	21.870	24.165	25.430	26.625	27.925	29.405	30.825	32.285	35.190	32.135	33.910
95	9.155	10.060	10.900	13.420	14.510	16.230	17.590	19.320	21.200	27.140	24.080	25.430	26.630	27.915	29.405	30.820	32.345	38.895	35.755	33.200
96	9.225	10.710	12.495	13.480	15.400	16.280	17.655	19.250	21.300	21.900	24.050	25.520	26.620	27.915	29.345	30.785	32.810	37.855	34.605	33.220
97	8.095	10.055	11.380	13.440	14.510	16.290	17.550	19.235	21.285	21.885	24.120	25.435	27.570	27.920	29.885	31.300	32.855	35.185	35.745	33.855
98	9.190	10.180	12.490	12.950	14.495	16.335	17.560	19.270	21.225	21.920	24.105	25.445	27.570	27.875	29.350	30.805	32.860	37.840	36.280	37.445
99	8.095	10.720	11.990	13.470	15.480	15.175	17.575	19.215	21.290	21.900	24.155	25.535	27.570	27.985	29.395	30.755	32.325	35.130	35.740	36.310
100	9.115	11.180	10.865	13.430	15.375	15.160	17.545	19.215	21.270	21.870	24.165	25.460	26.600	27.930	29.330	31.315	32.815	35.140	35.785	37.445
AVERAGE	8.660	10.284	11.505	13.181	14.988	15.722	17.516	19.284	20.991	21.831	23.756	24.979	27.039	27.424	28.675	30.424	31.799	35.485	33.805	36.586

EXPERIMENT 1 Count to Time Charts



EXPERIMENT 1 Distance Data

DISTANCE	0.5	1	1.5	2	2.5	3	3.5	4	4.5	5	5.5	6	6.5	7	7.5	8	8.5	9	9.5	10
1	0.385	1.202	1.740	2.398	2.720	3.493	4.079	4.756	4.989	6.768	5.715	7.609	7.031	7.525	6.781	8.560	10.441	9.725	10.313	10.097
2	0.251	1.305	1.590	1.907	2.768	3.029	3.500	4.062	4.759	4.980	5.727	6.221	6.913	7.014	7.545	8.017	8.717	9.327	9.530	10.316
3	0.632	0.920	1.749	2.080	2.433	3.027	3.498	4.048	4.759	4.977	5.717	4.782	5.299	5.777	7.712	8.195	8.539	9.353	9.536	10.289
4	0.618	1.297	1.370	2.083	2.770	2.678	3.498	4.071	4.749	4.972	5.709	6.233	6.910	7.030	7.530	8.195	8.704	9.353	10.254	10.301
5	0.409	0.957	1.595	0.806	2.400	3.229	3.462	4.065	4.749	6.768	5.746	6.219	6.915	7.049	7.540	8.041	8.733	7.758	9.718	9.084
6	0.603	0.952	1.211	2.100	2.434	3.027	3.500	4.069	4.746	6.771	5.729	6.194	6.576	7.028	6.293	8.193	8.723	10.792	9.530	10.306
7	0.236	-0.633	1.590	1.912	2.768	2.674	3.517	4.065	4.775	4.987	5.733	6.200	6.579	7.057	6.290	8.200	8.735	9.758	8.330	9.917
8	0.627	1.137	1.591	2.083	2.767	0.685	3.521	4.064	4.739	4.975	5.695	6.212	7.607	7.013	7.532	8.024	8.731	10.618	9.530	10.122
9	0.250	0.920	1.745	2.078	2.746	3.031	3.488	4.083	4.777	4.974	5.707	6.219	6.917	7.026	6.276	8.209	7.282	9.523	9.716	10.301
10	0.625	0.930	1.207	2.074	2.436	3.068	3.521	4.086	4.753	4.962	5.739	4.768	6.593	7.033	7.712	6.752	8.723	10.609	8.322	9.920
11	0.431	1.137	1.192	2.085	2.439	2.681	3.521	4.081	4.778	5.011	5.724	6.197	6.583	7.018	6.278	8.203	7.295	7.938	9.686	10.117
12	0.232	0.923	1.211	2.097	2.774	1.821	3.524	4.081	4.765	4.987	5.722	6.233	6.579	7.033	6.262	8.020	8.726	10.803	8.275	10.302
13	0.227	1.141	1.201	2.076	2.768	2.683	3.483	4.074	4.746	4.998	5.741	6.192	5.313	7.016	7.554	6.771	8.724	9.530	9.331	10.122
14	0.621	1.139	1.588	2.068	2.772	2.672	3.522	4.083	4.785	4.970	5.741	6.219	6.908	7.050	7.533	6.788	7.314	7.753	9.542	10.309
15	0.248	1.146	1.555	1.913	2.429	3.041	3.514	4.047	4.777	4.970	5.710	4.809	6.588	7.055	7.513	8.036	7.285	10.611	9.536	9.038
16	0.234	0.957	1.756	2.081	2.770	3.027	3.483	4.071	4.765	4.989	5.715	6.233	6.588	7.059	7.547	8.036	8.560	9.526	10.246	10.297
17	0.623	0.969	1.756	2.071	2.770	3.046	3.490	4.065	4.737	4.991	5.731	6.209	6.576	7.035	7.535	7.998	8.711	7.758	9.913	9.917
18	0.241	1.300	1.745	2.097	2.784	2.678	3.514	4.096	4.763	4.986	5.719	6.224	6.594	7.057	6.260	8.200	8.548	9.751	10.253	10.294
19	0.601	0.926	1.207	2.076	2.398	2.683	3.483	4.076	4.749	5.008	4.268	6.190	5.296	7.045	7.539	8.034	8.551	6.050	10.256	10.304
20	0.596	0.928	1.584	1.920	2.433	3.061	3.479	4.095	4.756	5.001	5.714	6.216	6.917	7.220	6.278	8.029	8.565	7.744	9.723	10.318
21	0.620	0.920	1.204	1.913	2.777	2.674	2.297	4.093	4.759	4.975	5.739	6.207	6.593	7.037	6.279	8.013	8.568	9.756	10.260	10.311
22	0.630	1.305	1.372	2.088	2.436	3.058	3.505	4.096	4.737	4.986	5.710	4.334	6.579	7.014	7.549	8.036	8.728	7.984	9.547	10.306
23	0.226	0.964	1.194	2.054	2.439	3.058	3.483	4.050	-0.348	5.006	5.715	4.804	7.611	7.014	7.530	8.209	7.294	9.523	9.722	10.128
24	0.599	1.141	1.749	2.071	2.748	3.027	3.498	4.071	4.749	5.001	5.731	6.235	6.922	7.040	7.535	8.205	8.723	7.972	9.538	9.084
25	-0.103	0.937	1.206	2.095	2.762	3.067	3.498	4.069	4.768	4.974	5.746	6.211	6.596	7.045	6.278	8.036	8.728	10.801	8.680	10.131
26	0.231	0.962	1.189	1.908	2.777	3.029	3.493	4.072	4.749	4.972	5.727	6.194	6.576	7.064	7.713	6.797	8.728	7.760	10.254	9.922
27	0.234	1.310	1.195	1.912	2.772	2.681	3.497	4.089	4.785	4.968	5.739	6.219	6.593	7.049	7.516	8.015	7.295	9.514	9.711	9.922
28	0.232	0.962	1.192	1.919	2.765	2.681	3.682	4.067	4.766	4.972	5.729	6.192	6.577	7.031	7.551	8.202	8.550	10.791	8.503	9.919
29	0.793	1.305	1.586	2.098	2.398	2.676	3.495	4.091	4.778	4.965	5.710	6.230	6.910	5.791	7.713	8.041	8.560	10.804	2.510	10.299
30	0.409	0.926	1.195	1.910	2.427	3.036	3.497	4.088	4.787	4.984	5.738	6.228	6.596	5.808	7.535	8.042	7.292	10.796	7.970	10.306
31	0.255	1.302	1.197	1.908	2.436	2.669	3.486	4.072	4.763	4.984	5.741	4.816	7.605	5.781	7.535	8.044	8.736	10.953	9.711	10.294
32	0.618	0.928	1.751	2.102	2.755	3.065	3.517	4.069	4.432	4.968	5.710	6.209	6.908	7.030	7.540	8.209	8.550	10.799	10.275	10.296
33	0.244	0.925	1.591	1.910	2.431	3.048	3.509	4.064	4.763	4.962	5.733	6.221	7.611	7.043	7.520	8.018	8.550	9.509	9.910	9.091
34	0.241	1.108	1.754	1.912	2.439	3.029	3.510	4.062	4.783	5.004	4.278	6.230	6.583	7.042	6.269	8.044	8.548	9.523	9.907	10.292
35	0.596	1.297	1.202	2.083	2.433	2.688	3.503	4.053	4.753	4.984	5.724	6.202	6.586	7.043	6.279	8.034	8.726	10.794	8.251	8.860
36	0.246	0.921	1.189	2.083	2.443	3.063	3.481	4.059	4.734	5.004	5.707	6.233	6.908	7.059	7.528	8.032	8.555	10.792	-0.650	10.302
37	0.224	0.966	1.749	1.903	2.770	2.678	3.479	4.084	4.756	4.967	5.710	6.207	6.915	7.047	6.290	6.761	8.731	10.436	9.538	10.306
38	0.621	0.920	1.192	1.915	2.758	3.072	3.497	4.053	4.763	4.968	5.743	6.194	6.922	7.042	7.547	8.032	8.719	10.609	9.718	9.913
39	0.227	0.926	1.586	2.074	2.782	2.690	3.503	2.820	4.749	4.962	5.722	6.235	6.918	7.021	7.547	8.200	8.551	10.439	10.246	10.294
40	0.633	0.932	1.209	1.900	2.753	2.679	3.500	4.057	4.765	5.011	5.741	6.187	6.588	7.057	7.535	8.039	8.738	9.519	9.722	10.117
41	0.618	0.928	1.190	2.095	2.349	3.226	3.519	4.071	4.749	4.989	5.705	6.200	6.908	7.014	7.520	8.015	8.726	10.446	9.540	9.922
42	0.229	0.968	1.590	2.083	2.402	3.056	3.481	4.057	4.758	4.968	5.702	6.211	6.596	7.023	7.554	8.207	7.316	7.756	9.919	10.100
43	0.227	1.309	1.581	2.083	2.427	3.032	3.505	4.071	4.763	4.968	5.734	6.204	6.600	7.040	6.266	8.202	8.717	9.526	8.260	10.092
44	0.782	0.926	1.213	2.059	2.762	2.674	3.526	4.067	4.751	4.974	5.717	6.207	6.594	7.055	7.556	8.039	8.716	9.512	9.934	10.297
45	0.597	0.952	1.370	2.092	2.443	3.226	3.474	4.086	4.773	4.972	5.729	6.199	6.600	7.040	7.528	6.762	7.294	9.509	8.274	10.290
46	-0.052	0.928	1.197	2.085	2.446	2.679	3.474	4.059	4.754	4.974	5.729	6.206	6.911	7.062	7.525	8.042	8.543	10.798	9.536	10.296
47	0.243	0.930	1.189	1.917	2.443	3.065	3.478	4.067	4.775	4.989	5.738	4.348	5.284	7.033	7.516	8.209	8.553	9.497	4.321	10.121
48	0.632	0.952	1.202	2.095	2.774	3.067	3.522	4.060	4.761	6.762	5.709	6.235	6.584	5.763	7.552	8.036	8.719	9.523	9.934	8.920
49	0.409	1.302	1.195	2.090	2.758	3.072	3.495	4.083	4.768	4.967	5.704	6.209	7.609	7.059	7.544	8.200	8.735	7.765	8.503	10.297

50	0.234193	0.965834	1.754018	2.09328	2.780371	2.675851	3.515438	4.067167	4.77996	3.820431	5.748055	6.193551	6.921764	7.055413	7.548885	8.04407	8.552963	9.509064	8.856242	10.31438
51	0.621432	0.931565	1.747164	2.101847	2.441109	1.109763	3.510298	4.096296	4.757685	5.000994	5.701792	6.229533	6.577362	5.787464	7.521469	8.030362	7.48206	7.769919	9.716391	10.3041
52	0.609438	0.957267	1.209143	1.911655	2.759809	3.059662	3.500017	4.080875	4.757685	4.982146	5.729207	6.191837	6.91491	7.022857	7.708235	8.021795	7.309002	9.531339	9.908296	10.11905
53	0.405538	1.137178	1.207429	1.906515	2.773517	2.689558	3.48631	4.050033	4.425277	4.973579	5.746342	6.190124	6.59107	7.062267	6.306638	6.767554	8.551249	9.505637	9.330866	8.911072
54	0.631712	1.298242	1.214283	2.08814	2.434255	2.677564	3.512011	4.096296	4.783386	4.987286	5.7155	6.198691	6.920051	7.060553	6.296357	8.014941	7.324423	7.769919	0.311298	10.3161
55	0.619718	1.116617	1.586101	2.074432	2.439395	3.063089	3.498304	4.051746	4.781673	4.982146	5.732634	6.210685	6.91491	7.053699	7.524896	8.199993	7.324423	9.498783	9.336006	10.1259
56	0.633426	1.144032	1.209143	2.084713	2.776944	3.030534	3.517152	4.080875	4.773106	4.971865	5.732634	6.195264	7.607142	7.034851	7.711662	8.040643	8.727734	10.9535	9.91515	10.30239
57	0.242761	1.106336	1.193722	1.915082	2.749529	2.689558	3.489736	4.065454	4.771392	4.978719	5.713786	6.226106	6.91491	7.026284	7.540317	8.025222	7.283301	7.934409	10.10192	10.1259
58	0.624859	0.960694	1.594668	2.076145	2.442822	2.677564	3.505157	4.051746	4.423563	-0.110209	5.712073	6.198691	5.290566	7.048559	7.709948	8.040643	8.731161	9.512491	9.7558	10.3161
59	0.222199	0.921284	1.594668	1.906515	2.773517	3.025393	3.494877	4.094582	4.42699	3.784449	5.72578	6.226106	6.585929	7.026284	7.716802	8.025222	8.736301	9.503924	9.925431	10.09506
60	0.614578	1.138892	1.198862	2.081286	2.190946	3.066516	3.678215	4.053459	4.733697	4.992427	4.320757	6.227819	6.916624	7.016004	7.530037	8.033789	8.722593	7.769919	9.908296	10.31438
61	0.602584	0.921284	1.198862	0.211919	2.778657	3.225866	3.515438	4.077448	4.754258	4.973579	5.737775	6.224393	7.612282	7.033138	7.554025	8.045783	8.729447	10.79757	9.714677	10.29725
62	0.638566	0.917858	1.197149	2.081286	2.778657	2.679278	3.522292	4.096296	4.761112	4.965011	5.734348	6.226106	6.570508	7.045132	7.53689	8.023508	8.707172	10.80443	9.91515	10.12419
63	0.621432	1.142319	1.21257	2.052157	2.34687	3.039101	3.510298	4.053459	4.750831	4.973579	5.730921	6.202118	6.589356	7.01943	7.550598	6.75556	8.712313	9.500497	4.94959	9.918577
64	0.220486	1.303382	1.214283	2.082999	2.442822	3.061376	3.679929	4.056886	4.769679	4.975292	5.729207	6.195264	6.91491	5.77033	7.516329	8.028649	8.892224	9.522772	8.484425	10.12419
65	0.239334	-0.156472	1.209143	2.089853	2.761523	3.061376	3.515438	4.067167	4.731983	4.975292	5.718927	6.23296	6.572222	5.790891	7.528323	6.786402	8.72088	10.79757	8.501559	10.12419
66	0.792776	1.145746	1.202289	2.072719	2.51136	3.059662	3.517152	4.048319	4.754258	4.966725	5.72064	6.226106	6.59621	7.033138	7.53689	6.765841	8.552963	7.751071	9.685549	10.28868
67	0.251328	0.967547	1.594668	0.43124	2.348583	2.680991	3.513725	4.086015	4.757685	4.965011	5.736061	6.193551	6.90977	7.053699	5.885131	8.035503	8.727734	10.79929	9.721531	8.921353
68	0.434666	1.142319	1.591241	1.916795	2.759809	3.051095	3.479456	4.092869	4.767965	4.978719	5.708646	4.809088	6.587643	7.051986	7.53689	8.042356	7.828176	9.517631	9.743806	9.092697
69	0.229053	0.922998	1.198862	2.077859	2.185806	3.059662	3.500017	4.070594	4.776533	4.992427	5.713786	6.202118	6.592783	5.758336	6.280936	8.018368	8.556389	10.79072	8.331928	10.29896
70	0.604297	0.957267	1.584387	1.915082	2.756383	3.032247	3.501731	4.06374	4.742264	4.977006	5.749769	6.200404	6.90977	7.017717	6.28779	8.20856	8.563243	9.519345	9.327439	10.3161
71	0.628286	1.137178	1.21257	2.079572	2.783798	2.672424	3.520578	4.06374	4.766252	4.992427	5.741201	6.220966	6.908057	5.76519	7.708235	8.19828	8.734588	9.529625	9.7558	10.12076
72	0.791063	1.298242	1.589527	1.916795	2.391419	2.677564	1.719749	4.053459	3.314965	4.970152	4.284774	6.193551	6.580789	7.051986	7.533464	8.028649	8.72602	9.519345	9.913437	9.920291
73	0.628286	0.921284	1.747164	1.906515	2.744388	3.07337	3.513725	4.06374	4.42699	3.784449	5.718927	6.191837	7.607142	7.024571	7.52661	8.018368	8.738014	10.79586	9.908296	10.09506
74	0.629999	1.145746	1.370207	2.064151	2.778657	1.433604	3.481169	4.060313	4.769679	3.784449	5.746342	6.214112	6.925191	5.797745	7.559165	8.023508	8.554676	9.498783	9.512491	10.29896
75	0.635139	0.931565	1.193722	2.094993	2.780371	3.064802	3.49659	4.094582	4.749118	4.975292	5.749769	6.208972	6.91491	7.053699	7.709948	8.020082	8.552963	10.79243	9.545046	9.918577
76	0.621432	0.919571	1.592954	2.062438	2.759809	3.057949	3.678215	4.080875	4.761112	3.803297	4.276207	6.23296	6.599637	7.027998	7.535177	6.767554	8.717453	9.524485	9.539906	10.11734
77	0.609438	0.917858	1.745451	2.101847	2.763236	3.061376	3.510298	4.077448	4.745691	4.975292	5.727494	4.809088	7.612282	7.01943	7.554025	6.779548	8.732874	9.531339	9.330866	10.29725
78	0.636853	1.145746	1.200576	2.082999	2.761523	3.069943	3.676502	4.0586	4.737123	4.977006	5.749769	6.227819	6.575649	7.043419	7.521469	6.7607	8.732874	9.510778	9.543333	10.12248
79	0.23762	1.135465	1.589527	2.071005	2.778657	3.03396	3.48631	4.086015	4.750831	3.782735	5.742915	6.208972	7.610569	7.05884	7.542031	8.217128	6.950893	10.79415	9.724958	10.12076
80	0.602584	-0.13077	1.591241	2.071005	2.790651	3.069943	3.49659	4.082588	4.771392	4.973579	5.734348	4.771392	6.916624	5.77033	7.713375	8.196566	8.712313	9.505637	9.724958	10.49258
81	0.241047	-0.165039	1.587814	2.089853	2.752956	2.680991	3.510298	4.094582	4.776533	3.803297	4.310476	6.196977	5.287139	7.029711	7.542031	8.04407	8.708886	10.79072	9.71125	10.11391
82	0.230767	1.11319	1.204003	2.096707	2.77523	3.056235	3.489736	4.070594	3.326959	5.011274	5.744628	4.778246	7.608855	7.041705	6.298071	8.210274	8.72602	9.509064	9.330866	8.863096
83	0.624859	1.144032	1.210856	1.899661	2.533635	3.063089	3.500017	4.060313	4.778246	4.992427	4.313903	6.207258	6.908057	7.016004	7.709948	8.199993	8.897365	9.526199	9.723245	10.11562
84	0.631712	1.130325	1.750591	2.089853	2.425688	2.677564	3.498304	4.096296	4.757685	4.985573	5.718927	6.227819	6.580789	7.048559	7.535177	8.205133	8.724307	9.353141	9.721531	10.3041
85	0.220486	0.931565	1.592954	2.405127	2.439395	3.054522	2.334875	4.06374	4.743977	4.985573	5.741201	6.202118	6.923478	7.036565	6.28265	8.013228	8.551249	10.79415	9.906583	10.09678
86	0.244474	0.929852	1.591241	2.053871	2.759809	3.02368	3.3321	4.062027	4.738837	4.985573	5.753196	6.231246	6.913197	7.031425	7.528323	8.199993	8.892224	10.61766	-0.725335	9.922004
87	0.239334	1.299955	1.591241	2.101847	2.51136	3.03396	3.508584	4.0586	4.778246	4.965011	5.717213	6.222679	6.597923	7.043419	7.540317	6.788116	8.727734	10.78215	7.88472	9.923717
88	0.633426	0.921284	1.207429	1.913368	2.773517	3.03396	3.513725	4.075734	4.783386	4.973579	5.722354	4.805661	6.90977	5.792605	7.542031	8.196566	8.552963	9.527912	9.911723	10.12933
89	0.631712	0.928138	1.215997	1.908228	2.394846	2.674137	3.681642	4.087728	4.733697	6.772695	5.713786	4.802234	6.916624	5.796032	7.524896	8.014941	8.714026	9.515918	9.719818	9.920291
90	0.618005	0.960694	1.754018	2.077859	2.441109	3.02882	3.512011	4.091155	4.733697	4.977006	5.742915	6.215825	6.918337	7.033138	7.528323	6.793256	8.56153	7.757925	9.330866	10.10192
91	0.244474	0.965834	1.207429	2.055584	2.396559	2.682704	3.518865	4.092869	4.766252	4.971865	5.72064	6.202118	5.29742	7.06398	7.530037	8.026935	7.286728	10.44803	9.911723	10.12248
92	0.230767	0.926425	1.193722	1.918509	2.571331	3.049381	3.517152	4.070594	4.752544	4.983859	4.301909	6.23296	6.913197	7.029711	7.554025	8.194853	8.540968	9.353141	9.899729	10.29211
93	-0.237004	0.955553	1.192008	2.074432	2.782084	2.675851	3.517152	4.065454	4.757685	4.977006	5.748055	6.234673	6.577362	7.06398	7.713375	8.19828	-0.189027	9.754087	9.709537	10.31267
94	0.222199	1.144032	1.37192	1.915082	2.437682	2.672424	3.518865	5.473904	4.747404	4.966725	5.753196	6.186697	6.59621	7.041705	7.548885	8.035503	8.535828	9.531339	8.484425	9.092697
95	0.609438	0.919571	1.207429	2.071005	2.444536	3.03396	3.500017	4.092869	4.737123	6.772695	5.724067	6.186697	6.							

EXPERIMENT 2 RAW Data

Degrees	0	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180
1	2051	2070	2118	2008	2131	2048	2018	2091	2052	1937	2043	2125	1950	2094	2022	2132	2064	2058	2093
2	2060	1964	2108	2105	2020	2133	2101	2094	2142	2128	1946	2108	2138	2014	2102	2012	2073	2059	2001
3	2066	2062	2109	2100	2122	2140	2098	2092	2153	2039	2174	2105	2142	2100	2097	2114	2068	2065	2095
4	2069	2072	2102	2084	2115	2136	2096	1722	2063	2122	2162	2103	2138	2031	2081	2107	2078	2068	2102
5	2062	2058	2118	1992	2131	2113	2095	2110	2128	2132	2147	2102	2115	2113	1989	2123	2064	2061	2107
6	2070	2082	2118	2089	2131	2029	2023	2195	2152	2137	2138	2030	2031	2122	2086	2123	1988	2069	2094
7	2054	2078	2100	2104	2113	2033	2103	2186	2132	2117	2053	2025	2035	2119	2101	2105	2084	2053	2107
8	2082	2071	2099	2105	2112	2035	2116	2101	2130	2115	2053	2108	2037	2113	2102	2104	2077	2081	2110
9	2067	2064	2092	2091	2105	2039	2115	2182	2054	2039	2134	2105	2041	2014	2088	2097	2070	2066	2008
10	2057	2080	2119	2084	2132	2133	2115	2089	2137	2122	2141	2103	2135	2021	2081	2124	2086	2056	2102
11	2069	2057	2110	2016	2123	2140	2009	2004	2147	2132	2156	2016	2142	2103	2013	2115	2063	2068	2000
12	2060	2076	2098	2092	2111	2029	2118	2006	2152	2137	2158	2125	2031	2111	2089	2103	2082	2059	1691
13	2059	2067	2021	2004	2034	2030	2120	2007	2148	2133	2159	2127	2032	2103	2001	2026	2073	2058	2216
14	2064	2069	1411	2088	1424	2039	2018	2002	2052	2037	2154	2022	2041	2015	2085	1416	2075	2063	2088
15	2075	2064	2114	2110	2127	2123	2101	2093	2049	2034	2145	2103	2125	2025	2107	2119	2070	2074	2114
16	2077	2058	2098	2105	2111	2120	2098	2016	2146	2131	2158	2100	2122	2122	2102	2103	2064	2076	2093
17	1984	2071	2012	2094	2025	2139	2096	2187	2150	2135	2139	2123	2141	2100	2091	2017	2077	1983	2002
18	2060	1984	2101	2089	2114	2048	2095	2091	2059	2044	2155	2106	2140	2017	2086	2106	1990	2059	2002
19	2053	1964	2112	2095	2125	2133	2023	2094	2158	2043	2132	2121	2126	2030	2092	2117	1970	2052	2080
20	2062	2056	2097	2084	2110	2140	2103	2092	2148	2133	2059	2100	2119	2125	2081	2102	2062	2061	2106
21	2051	2070	2118	2008	2131	2136	2116	1722	2062	2037	2043	2025	2050	2090	2005	2123	2076	2050	2093
22	2060	2067	2007	2105	2020	2113	2115	2110	2152	2127	2046	2108	2135	2014	2102	2012	1965	2059	2001
23	2066	2062	2109	2100	2122	2029	2115	2195	2163	2138	2144	2105	2142	2100	2097	2114	2068	2065	2095
24	2069	2072	2102	2084	2115	2033	2009	2086	2053	2048	1674	2103	2138	2031	2081	2107	2078	2068	2102
25	2062	2058	2118	1992	2131	2035	2118	2101	2138	2113	2062	2102	2115	2113	1989	2123	2064	2061	2107
26	2070	2082	2118	2089	2131	2039	2120	2182	2142	2137	2147	2030	2031	2122	2086	2123	2088	2069	2094
27	2054	2078	2100	2104	2113	2133	2015	2189	2142	2117	2138	2110	2035	2119	2101	2105	2084	2053	2107
28	2082	2071	2099	2105	2112	2140	2096	2004	2120	2115	2053	2123	2037	2113	2102	2104	2077	2081	2110
29	2067	2064	2092	2091	2105	2029	2093	2206	2064	2039	2134	2122	2041	2110	2088	2097	2070	2066	2008
30	2057	2080	2119	2084	2132	2030	2116	2017	2127	2122	2141	2122	2135	2021	2081	2124	2086	2056	2102
31	2069	2057	2110	2016	2123	2039	2099	2012	2057	2132	2156	2016	2142	2103	2013	2115	2063	2068	2000
32	2060	2076	2098	2092	2111	2123	2114	2193	2142	2137	2158	2125	2031	2111	2089	2103	2082	2059	1691
33	2059	2067	2021	2004	2034	2120	2093	2006	2158	2133	2159	2127	2032	2103	2001	2026	2073	2058	2216
34	2064	2129	1411	2088	1424	2139	2115	2187	2142	2037	2154	2022	2041	2015	2085	1416	1975	2063	2088
35	2075	2064	2114	2110	2127	2138	2009	2003	2059	2034	2145	2103	2125	2025	2107	2119	2070	2074	2114
36	2077	2058	2098	2105	2111	2124	2118	2180	2036	2131	2158	2100	2122	2122	2102	2103	2064	2076	2093
37	2051	2070	2118	2008	2131	2117	2120	2107	2160	2037	2043	2025	2050	2090	2005	2123	2076	2050	2093
38	2060	2067	2007	2105	2020	2039	2015	2189	2049	2127	2046	2108	2135	2014	2102	2012	2073	2059	2001
39	2066	2062	2109	2100	2122	2133	2096	2204	2068	2138	2144	2105	2142	2100	2097	2114	2068	2065	2095
40	2069	2072	2102	2084	2115	2140	2093	2026	2038	2048	1674	2103	2138	2031	2081	2107	2078	2068	2102
41	2062	2058	2118	1992	2131	2029	2116	2027	2052	2113	2062	2102	2115	2113	1989	2123	2064	2061	2107
42	2070	2082	2118	2089	2131	2030	2099	2012	2162	2137	2147	2030	2031	2122	2086	2123	2088	2069	2094
43	2054	2078	2100	2104	2113	2039	2114	2193	2133	2117	2138	2110	2035	2119	2101	2105	1984	2053	2107
44	2082	2071	2099	2105	2112	2123	2093	2006	2083	2115	2053	2123	2037	2113	2102	2104	2077	2081	2110
45	2067	2064	2092	2091	2105	2120	2115	2187	2108	2039	2134	2122	2041	2110	2088	2097	2070	2066	2008
46	2057	2080	2119	2084	2132	2139	2115	2003	2072	2122	2141	2122	2135	2021	2081	2124	2086	2056	2102
47	2069	2057	2110	2016	2123	2138	2009	2180	2102	2132	2156	2016	2142	2103	2013	2115	2063	2068	2000
48	2060	2076	2098	2092	2111	2124	2118	2107	2150	2137	2158	2125	2031	2111	2089	2103	2082	2059	1691

49	2059	2066.65	2020.56	2004	2034	2117	2120	2182	2034	2133	2159	2127	2032	2103	2001	2026	1973	2058	2216
50	2064	2128	1410.56	2088	1424	2029	2015	2189	2157	2037	2154	2022	2041	2015	2085	1416	2075	2063	2088
51	2075	2063.65	2113.56	2110	2127	2030	2096	2004	2127	2034	2145	2103	2125	2025	2107	2119	2070	2074	2114
52	2051	1969.65	2117.56	2008	2131	2029	2093	2006	2172	2037	2043	2025	2050	2090	2005	2123	2076	2050	2093
53	2060	2066.65	2006.56	2105	2020	2030	2116	2107	2128	2127	2046	2108	2135	2014	2102	2012	2073	2059	2001
54	2066	2061.65	2108.56	2100	2122	2039	2099	2002	2052	2138	2144	2105	2142	2100	2097	2114	2068	2065	2095
55	2069	2071.65	2101.56	2084	2115	2123	2018	2193	2029	2048	1674	2103	2138	2031	2081	2107	2078	2068	2102
56	2062	2057.65	2117.56	1992	2131	2120	2101	2106	2096	2113	2062	2102	2115	2113	2089	2123	2064	2061	2107
57	2070	2081.65	2117.56	2089	2131	2139	2098	2087	2050	2137	2147	2030	2031	2122	2086	2123	2088	2069	2094
58	2054	2077.65	2099.56	2104	2113	2138	2096	2203	2059	2117	2138	2110	2035	2119	2101	2105	2084	2053	2107
59	2082	2070.65	2098.56	2105	2112	2124	2095	2180	2058	2115	2053	2123	2037	2113	2102	2104	2077	2081	2110
60	2067	2063.65	2091.56	2091	2105	2117	2023	2107	2148	2039	2134	2122	2041	2110	2088	2097	1870	2066	2008
61	2057	2079.65	2118.56	2084	2132	2029	2103	2122	2052	2122	2141	2122	2135	2021	2081	2124	2086	2056	2102
62	2069	2056.65	2109.56	2016	2123	2030	2116	2119	2142	2132	2156	2016	2142	2103	2013	2115	2063	2068	2000
63	2060	2075.65	2097.56	2092	2111	2039	2115	2104	2153	2137	2158	2125	2031	2111	2089	2103	2082	2059	1691
64	2059	2066.65	2020.56	2004	2034	2123	2115	2106	2063	2133	2159	2127	2032	2103	2001	2026	2073	2058	2216
65	2051	2069.65	2117.56	2008	2131	2120	2009	2091	2028	2037	2043	2025	2050	2090	2005	2123	2076	2050	2093
66	2060	2066.65	2106.56	2105	2020	2139	2118	2094	2052	2127	2046	2108	2135	2014	2102	2012	2073	2059	2001
67	2066	2061.65	2108.56	2100	2122	2138	2120	2112	2132	2138	2144	2105	2142	2100	2097	2114	2068	2065	2095
68	2069	2071.65	2101.56	2084	2115	2124	2015	1722	2130	2048	1674	2103	2138	2031	2081	2107	2078	2068	2102
69	2062	2057.65	2117.56	1992	2131	2029	2096	2110	2054	2113	2062	2102	2115	2113	2189	2123	2064	2061	2107
70	2070	2081.65	2117.56	2089	2131	2030	2093	2195	2037	2137	2147	2030	2031	2122	2086	2123	2088	2069	2094
71	2054	2077.65	2099.56	2104	2113	2029	2116	2186	2147	2117	2138	2110	2035	2119	2101	2105	2084	2053	2107
72	2082	2070.65	2098.56	2105	2112	2029	2099	2001	2152	2115	2053	2123	2037	2113	2102	2104	2077	2081	2110
73	2067	2063.65	2091.56	2091	2105	2030	2114	2082	2148	2039	2134	2122	2041	2110	2088	2097	2070	2066	2008
74	2057	2079.65	2118.56	2084	2132	2029	2093	2089	2052	2122	2141	2122	2135	2021	2081	2124	2086	2056	2102
75	2069	2056.65	2109.56	2016	2123	2030	2096	2204	2049	2132	2156	2016	2142	2103	2013	2115	2063	2068	2000
76	2060	2075.65	2097.56	2092	2111	2039	2093	2206	2046	2137	2158	2125	2031	2111	2089	2103	2082	2059	1691
77	2059	2026.65	2020.56	2004	2034	2123	2116	2207	2150	2133	2159	2127	2032	2103	2001	2026	2073	2058	2216
78	2051	2069.65	2117.56	2008	2131	2120	2099	2102	2059	2037	2043	2025	2050	2090	2005	2123	2076	2050	2093
79	2060	2066.65	2006.56	2105	2020	2139	2114	2093	2058	2127	2046	2108	2135	2014	2102	2012	2073	2059	2001
80	2066	2061.65	2108.56	2100	2122	2138	2093	2056	2048	2138	2144	2105	2142	2100	2097	2114	2068	2065	2095
81	2051	2069.65	2117.56	2008	2131	2029	2015	2187	2052	2037	2043	2025	2050	2090	2005	2123	2076	2050	2093
82	2060	2066.65	2006.56	2105	2020	2030	2096	2203	2142	2127	2046	2108	2135	2014	2102	2012	2073	2059	2001
83	2066	2061.65	2108.56	2100	2122	2029	2093	2180	2153	2138	2144	2105	2142	2100	2097	2114	2068	2065	2095
84	2069	2071.65	2101.56	2084	2115	2030	2116	2107	2063	2048	1674	2103	2138	2031	2081	2107	2078	2068	2102
85	2062	2057.65	2117.56	1992	2131	2039	2099	2162	2083	2113	2062	2102	2115	2113	1989	2123	2064	2061	2107
86	2070	2081.65	2117.56	2089	2131	2123	2114	2159	2108	2137	2147	2030	2031	2122	2086	2123	2088	2069	2094
87	2054	2077.65	2099.56	2104	2113	2120	2093	2014	2072	2117	2138	2110	2035	2119	2101	2105	2084	2053	2107
88	2082	2070.65	2098.56	2105	2112	2139	2099	2006	2152	2115	2053	2123	2037	2113	2102	2104	2077	2081	2110
89	2067	2063.65	2091.56	2091	2105	2138	2114	2007	2049	2039	2134	2122	2041	2110	2088	2097	2070	2066	2008
90	2057	2079.65	2118.56	2084	2132	2124	2093	2002	2068	2122	2141	2122	2135	2021	2081	2124	2086	2056	2102
91	2069	2056.65	2109.56	2016	2123	2117	2099	2193	2038	2132	2156	2016	2142	2103	2013	2115	2063	2068	2000
92	2060	2075.65	2097.56	2092	2111	2029	2114	2016	2052	2137	2158	2125	2031	2111	2089	2103	2082	2059	1691
93	2059	2066.65	2020.56	2004	2034	2030	2093	2187	2148	2133	2159	2127	2032	2103	2001	2026	2073	2058	2216
94	2064	2068.65	1410.56	2088	1424	2039	2093	2003	2052	2037	2154	2022	2041	2015	2085	1416	2075	2063	2088
95	2075	2063.65	2113.56	2110	2127	2030	2116	2180	2049	2034	2145	2103	2125	2025	2107	2119	2070	2074	2114
96	2077	2057.65	2097.56	2105	2111	2030	2099	2087	2036	2131	2158	2100	2122	2122	2102	2103	2064	2076	2093
97	1984	2070.65	2011.56	2094	2025	2039	2114	2003	2060	2135	2139	2123	2141	2100	2091	2017	2077	1983	2002
98	2060	2183.65	2100.56	2089	2114	2123	2093	2180	2039	2044	2155	2106	2140	2017	2086	2106	1990	2059	2002
99	2053	2163.65	2111.56	2095	2125	2120	2114	2107	2048	2043	2132	2121	2126	2030	2092	1917	1970	2052	2080
100	2062	2055.65	2096.56	2084	2110	2139	2093	2080	2038	2133	2059	2100	2119	2125	2081	2102	2062	2061	2106
Average	2062.38	2067.204	2066.954	2072.88	2078.38	2083.9	2090.88	2095.18	2096.5	2099.54	2096.12	2092.1	2086.96	2080.82	2073.05	2068.47	2063.59	2061.46	2060.12

EXPERIMENT 2 Distance Data

Degrees	0	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180
1	0.986395	1.018351	1.100442	0.912717	1.123471	0.981255	0.929852	1.054933	0.988109	0.791063	0.972688	1.11319	0.813337	1.060073	0.936705	1.125184	1.00867	0.998389	1.05836
2	1.001816	0.836726	1.084062	1.078921	0.933279	1.126898	1.072067	1.060073	1.142319	1.11833	0.806484	1.084062	1.135465	0.922998	1.073781	0.919571	1.024091	1.000103	0.900723
3	1.012097	1.004643	1.085021	1.070354	1.10805	1.138892	1.066927	1.056646	1.161167	0.965834	1.197149	1.078921	1.142319	1.070354	1.065214	1.094342	1.015524	1.010383	1.061787
4	1.017237	1.021778	1.073027	1.042939	1.096056	1.132038	1.0635	0.422672	1.006957	1.10805	1.176588	1.075494	1.135465	0.952126	1.037799	1.082348	1.032658	1.015524	1.073781
5	1.005243	0.99779	1.100442	0.885302	1.123471	1.092629	1.061787	1.087488	1.11833	1.125184	1.150886	1.073781	1.096056	1.092629	0.880162	1.109763	1.00867	1.00353	1.082348
6	1.018951	1.038912	1.100442	1.051506	1.123471	0.948699	0.938419	1.233131	1.159453	1.133751	1.135465	0.950413	0.952126	1.10805	1.046366	1.109763	0.878448	1.017237	1.060073
7	0.991536	1.032059	1.0696	1.077208	1.092629	0.955553	1.075494	1.21771	1.125184	1.099483	0.989822	0.941846	0.95898	1.102909	1.072067	1.078921	1.042939	0.989822	1.082348
8	1.039512	1.020064	1.067887	1.078921	1.090915	0.95898	1.097769	1.072067	1.121757	1.096056	0.989822	1.084062	0.962407	1.092629	1.073781	1.077208	1.030945	1.037799	1.087488
9	1.01381	1.00807	1.055893	1.054933	1.078921	0.965834	1.096056	1.210856	0.991536	0.965834	1.128611	1.078921	0.969261	0.922998	1.049793	1.065214	1.018951	1.012097	0.912717
10	0.996676	1.035485	1.102156	1.042939	1.125184	1.126898	1.096056	1.051506	1.133751	1.10805	1.140605	1.075494	1.130325	0.934992	1.037799	1.111477	1.046366	0.994962	1.073781
11	1.017237	0.996076	1.086735	0.926425	1.109763	1.138892	0.914431	0.905863	1.150886	1.125184	1.166307	0.926425	1.142319	1.075494	0.921284	1.096056	1.006957	1.015524	0.89901
12	1.001816	1.028632	1.066173	1.056646	1.089202	0.948699	1.101196	0.90929	1.159453	1.133751	1.169734	1.11319	0.952126	1.089202	1.051506	1.075494	1.039512	1.000103	0.369556
13	1.000103	1.013211	0.934238	0.905863	0.957267	0.950413	1.104623	0.911004	1.152599	1.126898	1.171447	1.116617	0.95384	1.075494	0.900723	0.943559	1.024091	0.998389	1.269113
14	1.00867	1.016638	-0.110963	1.049793	-0.087934	0.965834	0.929852	0.902437	0.988109	0.962407	1.16288	0.936705	0.969261	0.924711	1.044652	-0.101641	1.027518	1.006957	1.049793
15	1.027518	1.00807	1.093588	1.087488	1.116617	1.109763	1.072067	1.05836	0.982968	0.957267	1.147459	1.075494	1.11319	0.941846	1.082348	1.102909	1.018951	1.025804	1.094342
16	1.030945	0.99779	1.066173	1.078921	1.089202	1.104623	1.066927	0.926425	1.149172	1.123471	1.169734	1.070354	1.10805	1.10805	1.073781	1.075494	1.00867	1.029231	1.05836
17	0.871595	1.020064	0.918817	1.060073	0.941846	1.137178	1.0635	1.219424	1.156026	1.130325	1.137178	1.109763	1.140605	1.070354	1.054933	0.928138	1.030945	0.869881	0.902437
18	1.001816	0.870995	1.071314	1.051506	1.094342	0.981255	1.061787	1.054933	1.000103	0.974401	1.164593	1.080635	1.138892	0.928138	1.046366	1.080635	0.881875	1.000103	0.902437
19	0.989822	0.836726	1.090161	1.061787	1.11319	1.126898	0.938419	1.060073	1.169734	0.972688	1.125184	1.106336	1.114904	0.950413	1.056646	1.099483	0.847606	0.988109	1.036085
20	1.005243	0.994363	1.06446	1.042939	1.087488	1.138892	1.075494	1.056646	1.152599	1.126898	1.000103	1.070354	1.102909	1.11319	1.037799	1.073781	1.005243	1.00353	1.080635
21	0.986395	1.018351	1.100442	0.912717	1.123471	1.132038	1.097769	0.422672	1.005243	0.962407	0.972688	0.941846	0.984682	1.05322	0.907577	1.109763	1.029231	0.984682	1.05836
22	1.001816	1.013211	0.91025	1.078921	0.933279	1.092629	1.096056	1.087488	1.159453	1.116617	0.977828	1.084062	1.130325	0.922998	1.073781	0.919571	0.839039	1.000103	0.900723
23	1.012097	1.004643	1.085021	1.070354	1.10805	0.948699	1.096056	1.233131	1.178301	1.135465	1.145746	1.078921	1.142319	1.070354	1.065214	1.094342	1.015524	1.010383	1.061787
24	1.017237	1.021778	1.073027	1.042939	1.096056	0.955553	0.914431	1.046366	0.989822	0.981255	0.340427	1.075494	1.135465	0.952126	1.037799	1.082348	1.032658	1.015524	1.073781
25	1.005243	0.99779	1.100442	0.885302	1.123471	0.95898	1.101196	1.072067	1.135465	1.092629	1.005243	1.073781	1.096056	1.092629	0.880162	1.109763	1.00867	1.00353	1.082348
26	1.018951	1.038912	1.100442	1.051506	1.123471	0.965834	1.104623	1.210856	1.142319	1.133751	1.150886	0.950413	0.952126	1.10805	1.046366	1.109763	1.049793	1.017237	1.060073
27	0.991536	1.032059	1.0696	1.077208	1.092629	1.126898	0.924711	1.22285	1.142319	1.099483	1.135465	1.087488	0.95898	1.102909	1.072067	1.078921	1.042939	0.989822	1.082348
28	1.039512	1.020064	1.067887	1.078921	1.090915	1.138892	1.0635	0.905863	1.104623	1.096056	0.989822	1.109763	0.962407	1.092629	1.073781	1.077208	1.030945	1.037799	1.087488
29	1.01381	1.00807	1.055893	1.054933	1.078921	0.965834	1.096056	1.210856	1.251979	1.00867	0.965834	1.128611	1.10805	0.969261	1.087488	1.049793	1.065214	1.018951	1.012097
30	0.996676	1.035485	1.102156	1.042939	1.125184	1.126898	1.097769	0.928138	1.116617	1.10805	1.140605	1.10805	1.130325	0.934992	1.037799	1.111477	1.046366	0.994962	1.073781
31	1.017237	0.996076	1.086735	0.926425	1.109763	1.138892	1.068641	0.919571	0.996676	1.125184	1.166307	0.926425	1.142319	1.075494	0.921284	1.096056	1.006957	1.015524	0.89901
32	1.001816	1.028632	1.066173	1.056646	1.089202	1.109763	1.094342	1.229704	1.142319	1.133751	1.169734	1.11319	0.952126	1.089202	1.051506	1.075494	1.039512	1.000103	0.369556
33	1.000103	1.013211	0.934238	0.905863	0.957267	1.104623	1.05836	0.90929	1.169734	1.126898	1.171447	1.116617	0.95384	1.075494	0.900723	0.943559	1.024091	0.998389	1.269113
34	1.00867	1.119444	-0.110963	1.049793	-0.087934	1.137178	1.096056	1.219424	1.142319	0.962407	1.16288	0.936705	0.969261	0.924711	1.044652	-0.101641	0.856174	1.006957	1.049793
35	1.027518	1.00807	1.093588	1.087488	1.116617	1.135465	0.914431	0.90415	1.000103	0.957267	1.147459	1.075494	1.11319	0.941846	1.082348	1.102909	1.018951	1.025804	1.094342
36	1.030945	0.99779	1.066173	1.078921	1.089202	1.111477	1.101196	1.207429	0.960694	1.123471	1.169734	1.070354	1.10805	1.10805	1.073781	1.075494	1.00867	1.029231	1.05836
37	0.986395	1.018351	1.100442	0.912717	1.123471	1.099483	1.104623	1.082348	1.173161	0.962407	0.972688	0.941846	0.984682	1.05322	0.907577	1.109763	1.029231	0.984682	1.05836
38	1.001816	1.013211	0.91025	1.078921	0.933279	0.965834	0.924711	1.22285	0.982968	1.116617	0.977828	1.084062	1.130325	0.922998	1.073781	0.919571	1.024091	1.000103	0.900723
39	1.012097	1.004643	1.085021	1.070354	1.10805	1.126898	1.0635	1.248552	1.015524	1.135465	1.145746	1.078921	1.142319	1.070354	1.065214	1.094342	1.015524	1.010383	1.061787
40	1.017237	1.021778	1.073027	1.042939	1.096056	1.138892	1.05836	0.943559	0.96412	0.981255	0.340427	1.075494	1.135465	0.952126	1.037799	1.082348	1.032658	1.015524	1.073781
41	1.005243	0.99779	1.100442	0.885302	1.123471	0.948699	1.097769	0.945273	0.988109	1.092629	1.005243	1.073781	1.096056	1.092629	0.880162	1.109763	1.00867	1.00353	1.082348
42	1.018951	1.038912	1.100442	1.051506	1.123471	0.950413	1.068641	0.919571	1.176588	1.133751	1.150886	0.950413	0.952126	1.10805	1.046366	1.109763	1.049793	1.017237	1.060073
43	0.991536	1.032059	1.0696	1.077208	1.092629	0.965834	1.094342	1.229704	1.126898	1.099483	1.135465	1.087488	0.95898	1.102909	1.072067	1.078921	0.871595	0.989822	1.082348
44	1.039512	1.020064	1.067887	1.078921	1.090915	1.109763	1.05836	0.90929	1.041225	1.096056	0.989822	1.109763	0.962407	1.092629	1.073781	1.077208	1.030945	1.037799	1.087488
45	1.01381	1.00807	1.055893	1.054933	1.078921	1.104623	1.096056	1.219424	1.084062	0.965834	1.128611	1.10805	0.969261	1.087488	1.049793	1.065214	1.018951	1.012097	0.912717
46	0.996676	1.035485	1.102156	1.042939	1.125184	1.137178	1.096056	0.90415	1.022378	1.10805	1.140605	1.10805	1.130325	0.934992	1.037799	1.111477	1.046366	0.994962	1.073781
47	1.017237	0.996076	1.086735	0.926425	1.109763	1.135465	0.914431	1.207429	1.073781	1.125184	1.166307	0.926425	1.142319	1.075494	0.921284	1.096056	1.006957	1.015524	0.89901
48	1.001816	1.0286																	

50	1.00867	1.11833	-0.110963	1.049793	-0.087934	0.948699	0.924711	1.22285	1.16802	0.962407	1.16288	0.936705	0.969261	0.924711	1.044652	-0.101641	1.027518	1.006957	1.049793	
51	1.027518	1.00807	1.093588	1.087488	1.116617	0.950413	1.0635	0.905863	1.116617	0.957267	1.147459	1.075494	1.11319	0.941846	1.082348	1.102909	1.018951	1.025804	1.094342	
52	0.986395	0.847007	1.100442	0.912717	1.123471	0.948699	1.05836	0.90929	1.193722	0.962407	0.972688	0.941846	0.984682	1.05322	0.907577	1.109763	1.029231	0.984682	1.05836	
53	1.001816	1.013211	0.91025	1.078921	0.933279	0.950413	1.097769	1.082348	1.11833	1.116617	0.977828	1.084062	1.130325	0.922998	1.073781	0.919571	1.024091	1.000103	0.900723	
54	1.012097	1.004643	1.085021	1.070354	1.10805	0.965834	1.068641	0.902437	0.988109	1.135465	1.145746	1.078921	1.142319	1.070354	1.065214	1.094342	1.015524	1.010383	1.061787	
55	1.017237	1.021778	1.073027	1.042939	1.096056	1.109763	0.929852	1.229704	0.948699	0.981255	0.340427	1.075494	1.135465	0.952126	1.037799	1.082348	1.032658	1.015524	1.073781	
56	1.005243	0.99779	1.100442	0.885302	1.123471	1.104623	1.072067	1.080635	1.0635	1.092629	1.005243	1.073781	1.096056	1.092629	1.051506	1.109763	1.00867	1.00353	1.082348	
57	1.018951	1.038912	1.100442	1.051506	1.123471	1.137178	1.066927	1.048079	0.984682	1.133751	1.150886	0.950413	0.952126	1.10805	1.046366	1.109763	1.049793	1.017237	1.060073	
58	0.991536	1.032059	1.0696	1.077208	1.092629	1.135465	1.0635	1.246839	1.000103	1.099483	1.135465	1.087488	0.95898	1.102909	1.072067	1.078921	1.042939	0.989822	1.082348	
59	1.039512	1.020064	1.067887	1.078921	1.090915	1.111477	1.061787	1.207429	0.998389	1.096056	0.989822	1.109763	0.962407	1.092629	1.073781	1.077208	1.030945	1.037799	1.087488	
60	1.01381	1.00807	1.055893	1.054933	1.078921	1.099483	0.938419	1.082348	1.152599	0.965834	1.128611	1.10805	0.969261	1.087488	1.049793	1.065214	0.676262	1.012097	0.912717	
61	0.996676	1.035485	1.102156	1.042939	1.125184	0.948699	1.075494	1.10805	0.988109	1.10805	1.140605	1.10805	1.130325	0.934992	1.037799	1.111477	1.046366	0.994962	1.073781	
62	1.017237	0.996076	1.086735	0.926425	1.109763	0.950413	1.097769	1.102909	1.142319	1.125184	1.166307	0.926425	1.142319	1.075494	0.921284	1.096056	1.006957	1.015524	0.89901	
63	1.001816	1.028632	1.066173	1.056646	1.089202	0.965834	1.096056	1.077208	1.161167	1.133751	1.169734	1.11319	0.952126	1.089202	1.051506	1.075494	1.039512	1.000103	0.369556	
64	1.000103	1.013211	0.934238	0.905863	0.957267	1.109763	1.096056	1.080635	1.006957	1.126898	1.171447	1.116617	0.95384	1.075494	0.900723	0.943559	1.024091	0.998389	1.269113	
65	0.986395	1.018351	1.100442	0.912717	1.123471	1.104623	0.914431	1.054933	0.946986	0.962407	0.972688	0.941846	0.984682	1.05322	0.907577	1.109763	1.029231	0.984682	1.05836	
66	1.001816	1.013211	1.081594	1.078921	0.933279	1.137178	1.101196	1.060073	0.988109	1.116617	0.977828	1.084062	1.130325	0.922998	1.073781	0.919571	1.024091	1.000103	0.900723	
67	1.012097	1.004643	1.085021	1.070354	1.10805	1.135465	1.104623	1.090915	1.125184	1.135465	1.145746	1.078921	1.142319	1.070354	1.065214	1.094342	1.015524	1.010383	1.061787	
68	1.017237	1.021778	1.073027	1.042939	1.096056	1.111477	0.924711	0.422672	1.121757	0.981255	0.340427	1.075494	1.135465	0.952126	1.037799	1.082348	1.032658	1.015524	1.073781	
69	1.005243	0.99779	1.100442	0.885302	1.123471	0.948699	1.0635	1.087488	0.991536	1.092629	1.005243	1.073781	1.096056	1.092629	1.22285	1.109763	1.00867	1.00353	1.082348	
70	1.018951	1.038912	1.100442	1.051506	1.123471	0.950413	1.05836	1.233131	0.962407	1.133751	1.150886	0.950413	0.952126	1.10805	1.046366	1.109763	1.049793	1.017237	1.060073	
71	0.991536	1.032059	1.0696	1.077208	1.092629	0.948699	1.097769	1.21771	1.150886	1.099483	1.135465	1.087488	0.95898	1.102909	1.072067	1.078921	1.042939	0.989822	1.082348	
72	1.039512	1.020064	1.067887	1.078921	1.090915	0.948699	1.068641	0.900723	1.159453	1.096056	0.989822	1.109763	0.962407	1.092629	1.073781	1.077208	1.030945	1.037799	1.087488	
73	1.01381	1.00807	1.055893	1.054933	1.078921	0.950413	1.094342	1.039512	1.152599	0.965834	1.128611	1.10805	0.969261	1.087488	1.049793	1.065214	1.018951	1.012097	0.912717	
74	0.996676	1.035485	1.102156	1.042939	1.125184	0.948699	1.05836	1.051506	0.988109	1.10805	1.140605	1.10805	1.130325	0.934992	1.037799	1.111477	1.046366	0.994962	1.073781	
75	1.017237	0.996076	1.086735	0.926425	1.109763	0.950413	1.0635	1.248552	0.982968	1.125184	1.166307	0.926425	1.142319	1.075494	0.921284	1.096056	1.006957	1.015524	0.89901	
76	1.001816	1.028632	1.066173	1.056646	1.089202	0.965834	1.05836	1.251979	0.977828	1.133751	1.169734	1.11319	0.952126	1.089202	1.051506	1.075494	1.039512	1.000103	0.369556	
77	1.000103	0.944673	0.934238	0.905863	0.957267	1.109763	1.097769	1.253692	1.156026	1.126898	1.171447	1.116617	0.95384	1.075494	0.900723	0.943559	1.024091	0.998389	1.269113	
78	0.986395	1.018351	1.100442	0.912717	1.123471	1.104623	1.068641	1.073781	1.000103	0.962407	0.972688	0.941846	0.984682	1.05322	0.907577	1.109763	1.029231	0.984682	1.05836	
79	1.001816	1.013211	0.91025	1.078921	0.933279	1.137178	1.094342	1.05836	0.998389	1.116617	0.977828	1.084062	1.130325	0.922998	1.073781	0.919571	1.024091	1.000103	0.900723	
80	1.012097	1.004643	1.085021	1.070354	1.10805	1.135465	1.05836	0.994962	0.981255	1.135465	1.145746	1.078921	1.142319	1.070354	1.065214	1.094342	1.015524	1.010383	1.061787	
81	0.986395	1.018351	1.100442	0.912717	1.123471	0.948699	0.924711	1.219424	0.988109	0.962407	0.972688	0.941846	0.984682	1.05322	0.907577	1.109763	1.029231	0.984682	1.05836	
82	1.001816	1.013211	0.91025	1.078921	0.933279	0.950413	1.0635	1.246839	1.142319	1.116617	0.977828	1.084062	1.130325	0.922998	1.073781	0.919571	1.024091	1.000103	0.900723	
83	1.012097	1.004643	1.085021	1.070354	1.10805	0.948699	1.05836	1.207429	1.161167	1.135465	1.145746	1.078921	1.142319	1.070354	1.065214	1.094342	1.015524	1.010383	1.061787	
84	1.017237	1.021778	1.073027	1.042939	1.096056	0.950413	1.097769	1.082348	1.006957	0.981255	0.340427	1.075494	1.135465	0.952126	1.037799	1.082348	1.032658	1.015524	1.073781	
85	1.005243	0.99779	1.100442	0.885302	1.123471	0.965834	1.068641	1.176588	1.041225	1.092629	1.005243	1.073781	1.096056	1.092629	0.880162	1.109763	1.00867	1.00353	1.082348	
86	1.018951	1.038912	1.100442	1.051506	1.123471	1.109763	1.094342	1.171447	1.084062	1.133751	1.150886	0.950413	0.952126	1.10805	1.046366	1.109763	1.049793	1.017237	1.060073	
87	0.991536	1.032059	1.0696	1.077208	1.092629	1.104623	1.05836	0.922998	1.022378	1.099483	1.135465	1.087488	0.95898	1.102909	1.072067	1.078921	1.042939	0.989822	1.082348	
88	1.039512	1.020064	1.067887	1.078921	1.090915	1.137178	1.068641	0.90929	1.159453	1.096056	0.989822	1.109763	0.962407	1.092629	1.073781	1.077208	1.030945	1.037799	1.087488	
89	1.01381	1.00807	1.055893	1.054933	1.078921	1.135465	1.094342	0.911004	0.982968	0.965834	1.128611	1.10805	0.969261	1.087488	1.049793	1.065214	1.018951	1.012097	0.912717	
90	0.996676	1.035485	1.102156	1.042939	1.125184	1.111477	1.05836	0.902437	1.015524	1.10805	1.140605	1.10805	1.130325	0.934992	1.037799	1.111477	1.046366	0.994962	1.073781	
91	1.017237	0.996076	1.086735	0.926425	1.109763	0.950413	1.099483	1.068641	1.229704	0.96412	1.125184	1.166307	0.926425	1.142319	1.075494	0.921284	1.096056	1.006957	1.015524	0.89901
92	1.001816	1.028632	1.066173	1.056646	1.089202	0.948699	1.094342	0.926425	0.988109	1.133751	1.169734	1.11319	0.952126	1.089202	1.051506	1.075494	1.039512	1.000103	0.369556	
93	1.000103	1.013211	0.934238	0.905863	0.957267	0.950413	1.05836	1.219424	1.152599	1.126898	1.171447	1.116617	0.95384	1.075494	0.900723	0.943559	1.024091	0.998389	1.269113	
94	1.00867	1.016638	-0.110963	1.049793	-0.087934	0.965834	1.05836	0.90415	0.988109	0.962407	1.16288	0.936705	0.969261	0.924711	1.044652	-0.101641	1.027518	1.006957	1.049793	
95	1.027518	1.00807	1.093588	1.087488	1.116617	0.950413	1.097769	1.207429	0.982968	0.957267	1.147459	1.075494	1.11319	0.941846	1.082348	1.102909	1.018951	1.025804	1.094342	
96	1.030945	0.99779	1.066173	1.078921	1.089202	0.950413	1.068641	1.048079	0.960694	1.123471	1.169734	1.070354	1.10805	1.10805	1.073781	1.075494	1.00867	1.029231	1.05836	
97	0.871595	1.020064	0.918817	1.060073	0.941846	0.965834	1.094342	0.90415	1.001816	1.130325	1.137178	1.109763	1.140605	1.070354	1.054933	0.928138	1.030945	0.		

EXPERIMENT 2 Count to Distance Charts



EXPERIMENT 3 RAW Data

HEIGHT	0.0	0.5	1.0	1.5	2.0	2.5	3.0
1	2745	2655	2800	2982	2957	3090	3249
2	2649	2651	2713	2972	3103	3360	3594
3	2673	2620	2792	2708	3119	3387	3624
4	2670	2614	2806	2969	3132	3396	3635
5	2653	2625	2813	2967	3108	3383	3619
6	2661	2652	2809	2874	3121	3340	3565
7	2674	2664	2808	2982	3124	3390	3623
8	2669	2671	2800	2982	3116	3383	3615
9	2676	2612	2811	2976	3115	3384	3620
10	2579	2659	2792	2976	3135	3431	3685
11	2661	2654	2813	2989	3123	3400	3637
12	2675	2669	2707	2969	3131	3368	3600
13	2576	2652	2798	2975	3134	3433	3688
14	2582	2651	2793	2903	3105	3370	3611
15	2577	2650	2806	2986	3127	3434	3689
16	2652	2654	2806	2992	3024	3324	3543
17	2665	2661	2706	2887	3138	3337	3565
18	2659	2651	2799	2972	3117	3385	3619
19	2677	2658	2809	2989	3134	3401	3636
20	2680	2656	2806	2993	3113	3384	3616
21	2740	2651	2796	3054	2953	3086	3245
22	2644	2647	2709	2968	3099	3357	3591
23	2668	2616	2788	2978	3115	3384	3620
24	2665	2610	2802	2965	3128	3392	3631
25	2648	2621	2809	2963	3104	3379	3615
26	2656	2648	2805	2870	3117	3336	3562
27	2669	2660	2804	2978	3120	3386	3619
28	2664	2667	2796	2978	3112	3379	3611
29	2671	2608	2807	2972	3111	3381	3616
30	2574	2655	2788	2972	3131	3427	3681
31	2656	2650	2809	2985	3119	3396	3633
32	2670	2665	2703	2965	3127	3364	3596
33	2571	2648	2794	2971	3130	3429	3684
34	2577	2647	2789	2899	3101	3366	3607
35	2572	2646	2802	2982	3123	3430	3685
36	2647	2650	2802	2988	3020	3320	3540
37	2660	2657	2702	2883	3134	3333	3562
38	2654	2647	2795	2968	3113	3381	3616
39	2672	2654	2805	2985	3130	3397	3633
40	2675	2652	2802	2989	3109	3381	3612
41	2750	2661	2806	2805	2963	3096	3255
42	2654	2657	2719	2978	3109	3367	3601
43	2678	2626	2798	2988	3125	3394	3630
44	2675	2620	2812	2975	3138	3402	3641
45	2658	2631	2819	2973	3114	3389	3625
46	2666	2658	2815	2880	3127	3346	3572
47	2679	2670	2814	2988	3130	3396	3629
48	2674	2677	2806	2988	3122	3389	3621
49	2681	2618	2817	2982	3121	3391	3626
50	2584	2665	2798	2982	3141	3437	3691
51	2666	2660	2819	3094	3129	3406	3643

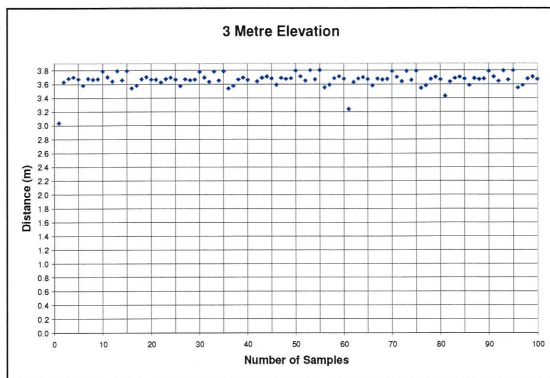
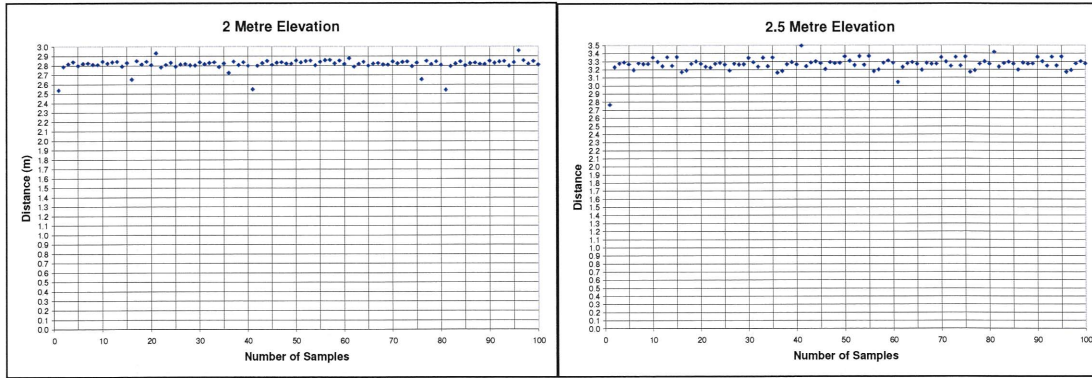
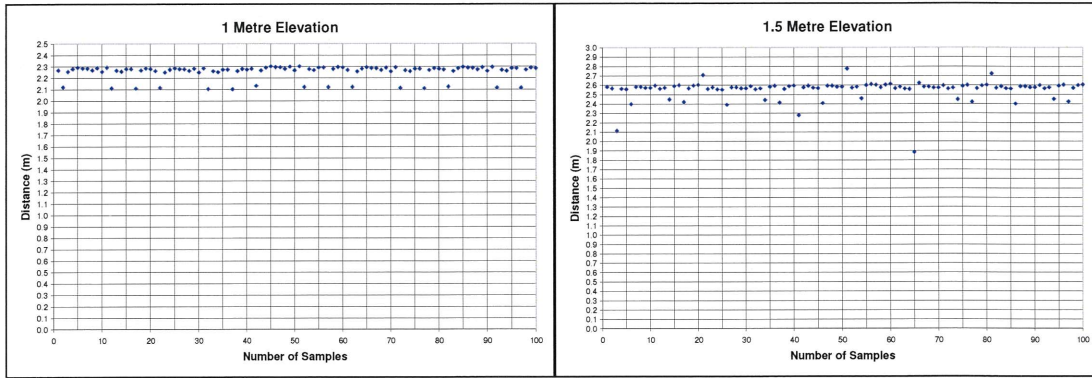
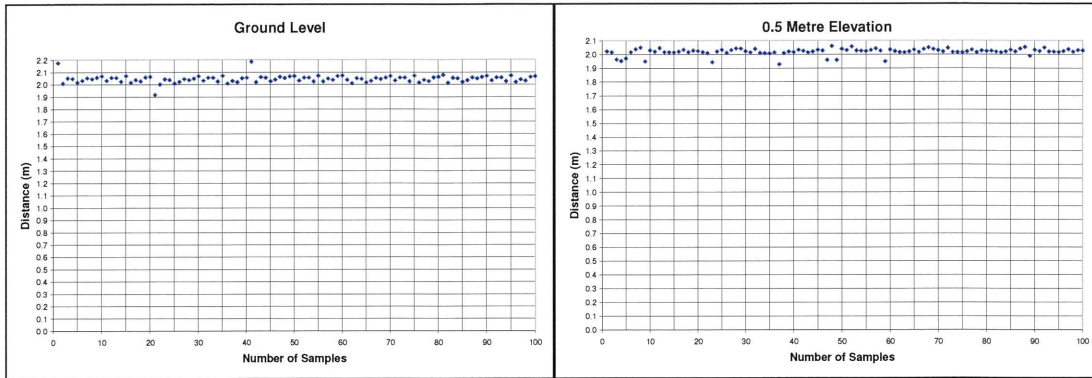
52	2680	2675	2713	2975	3137	3374	3606
53	2581	2658	2804	2981	3140	3439	3694
54	2587	2657	2799	2909	3111	3376	3617
55	2582	2656	2812	2992	3133	3440	3695
56	2657	2660	2812	2998	3030	3330	3550
57	2670	2667	2712	2993	3144	3343	3572
58	2664	2657	2805	2978	3123	3391	3626
59	2682	2664	2815	2995	3140	3407	3643
60	2685	2662	2812	2999	3119	3391	3622
61	2744	2655	2800	2972	2957	3090	3249
62	2648	2651	2713	2982	3103	3361	3595
63	2672	2620	2792	2969	3119	3388	3624
64	2669	2614	2806	2967	3132	3396	3635
65	2652	2625	2813	2574	3108	3383	3619
66	2660	2652	2809	3004	3121	3340	3566
67	2673	2664	2808	2982	3124	3390	3623
68	2668	2671	2800	2982	3116	3383	3615
69	2675	2612	2811	2976	3115	3385	3620
70	2578	2659	2792	2976	3135	3431	3685
71	2660	2654	2813	2989	3123	3400	3637
72	2674	2669	2707	2969	3131	3368	3600
73	2575	2652	2798	2975	3134	3433	3688
74	2581	2651	2793	2903	3105	3370	3611
75	2576	2650	2806	2986	3127	3434	3689
76	2651	2654	2806	2992	3024	3324	3544
77	2664	2661	2706	2887	3138	3337	3566
78	2658	2651	2799	2972	3117	3385	3620
79	2676	2658	2809	2989	3134	3401	3637
80	2679	2656	2806	2993	3113	3385	3616
81	2746	2657	2802	3064	2959	3092	3251
82	2650	2653	2715	2974	3105	3363	3597
83	2674	2622	2794	2984	3121	3390	3626
84	2671	2616	2808	2971	3134	3398	3637
85	2654	2627	2815	2969	3110	3385	3621
86	2662	2654	2811	2876	3123	3342	3568
87	2675	2666	2810	2984	3126	3392	3625
88	2670	2673	2802	2984	3118	3385	3617
89	2677	2614	2813	2978	3117	3387	3622
90	2580	2661	2794	2978	3137	3433	3687
91	2662	2656	2815	2991	3125	3402	3639
92	2676	2671	2709	2971	3133	3370	3602
93	2577	2654	2800	2977	3136	3435	3690
94	2583	2653	2795	2905	3107	3372	3613
95	2578	2652	2808	2988	3129	3436	3691
96	2653	2656	2808	2994	3026	3326	3546
97	2666	2663	2708	2889	3140	3339	3568
98	2660	2653	2801	2974	3119	3387	3622
99	2678	2660	2811	2991	3136	3403	3639
100	2681	2658	2808	2995	3115	3387	3618
AVERAGE	2653	2650	2790	2963	3110	3370	3603

EXPERIMENT 3 Distance Data

HEIGHT	0.0	0.5	1.0	1.5	2.0	2.5	3.0
1	2.175	2.021	2.270	2.582	2.539	2.767	3.039
2	2.011	2.014	2.121	2.564	2.789	3.230	3.630
3	2.052	1.961	2.256	2.112	2.816	3.276	3.681
4	2.047	1.951	2.280	2.559	2.839	3.291	3.700
5	2.017	1.970	2.292	2.556	2.798	3.268	3.673
6	2.031	2.016	2.285	2.397	2.820	3.195	3.581
7	2.053	2.037	2.283	2.582	2.825	3.280	3.679
8	2.045	2.049	2.270	2.582	2.811	3.269	3.665
9	2.057	1.948	2.289	2.571	2.809	3.271	3.674
10	1.891	2.028	2.256	2.571	2.844	3.351	3.786
11	2.031	2.020	2.292	2.594	2.823	3.297	3.703
12	2.055	2.045	2.110	2.559	2.837	3.242	3.640
13	1.886	2.016	2.266	2.570	2.842	3.354	3.791
14	1.896	2.014	2.258	2.446	2.792	3.247	3.659
15	1.887	2.013	2.280	2.588	2.830	3.356	3.792
16	2.016	2.020	2.280	2.599	2.654	3.168	3.543
17	2.038	2.032	2.109	2.419	2.849	3.190	3.581
18	2.028	2.014	2.268	2.564	2.813	3.271	3.674
19	2.059	2.026	2.285	2.594	2.842	3.299	3.703
20	2.064	2.023	2.280	2.600	2.806	3.271	3.667
21	2.167	2.014	2.263	2.705	2.532	2.760	3.033
22	2.002	2.008	2.114	2.558	2.782	3.223	3.624
23	2.044	1.954	2.249	2.575	2.809	3.270	3.675
24	2.038	1.944	2.273	2.552	2.832	3.284	3.694
25	2.009	1.963	2.285	2.549	2.791	3.262	3.667
26	2.023	2.009	2.278	2.390	2.813	3.189	3.575
27	2.045	2.030	2.277	2.575	2.818	3.274	3.673
28	2.037	2.042	2.263	2.575	2.804	3.262	3.659
29	2.049	1.941	2.282	2.564	2.803	3.265	3.668
30	1.883	2.021	2.249	2.564	2.837	3.344	3.780
31	2.023	2.013	2.285	2.587	2.816	3.291	3.697
32	2.047	2.038	2.104	2.552	2.830	3.236	3.634
33	1.877	2.009	2.259	2.563	2.835	3.347	3.784
34	1.888	2.008	2.251	2.439	2.786	3.240	3.653
35	1.879	2.006	2.273	2.582	2.823	3.350	3.786
36	2.008	2.013	2.273	2.592	2.647	3.161	3.537
37	2.030	2.025	2.102	2.412	2.842	3.183	3.575
38	2.020	2.008	2.261	2.558	2.806	3.265	3.668
39	2.050	2.020	2.278	2.587	2.835	3.293	3.697
40	2.056	2.016	2.273	2.594	2.799	3.265	3.661
41	2.184	2.032	2.280	2.278	2.549	2.777	3.050
42	2.020	2.025	2.131	2.575	2.799	3.240	3.642
43	2.061	1.972	2.266	2.592	2.827	3.287	3.692
44	2.056	1.961	2.290	2.570	2.849	3.301	3.711
45	2.026	1.980	2.302	2.566	2.808	3.279	3.684
46	2.040	2.026	2.295	2.407	2.830	3.206	3.592
47	2.062	2.047	2.294	2.592	2.835	3.291	3.690
48	2.054	2.059	2.280	2.592	2.821	3.279	3.677
49	2.066	1.958	2.299	2.582	2.820	3.282	3.685
50	1.900	2.038	2.266	2.582	2.854	3.361	3.797
51	2.040	2.030	2.302	2.774	2.833	3.308	3.714

52	2.06	2.06	2.12	2.57	2.85	3.25	3.65
53	1.89	2.03	2.28	2.58	2.85	3.36	3.80
54	1.90	2.02	2.27	2.46	2.80	3.26	3.67
55	1.90	2.02	2.29	2.60	2.84	3.37	3.80
56	2.02	2.03	2.29	2.61	2.66	3.18	3.55
57	2.05	2.04	2.12	2.60	2.86	3.20	3.59
58	2.04	2.02	2.28	2.57	2.82	3.28	3.68
59	2.07	2.04	2.30	2.60	2.85	3.31	3.71
60	2.07	2.03	2.29	2.61	2.82	3.28	3.68
61	2.17	2.02	2.27	2.56	2.54	2.77	3.04
62	2.01	2.01	2.12	2.58	2.79	3.23	3.63
63	2.05	1.96	2.26	2.56	2.82	3.28	3.68
64	2.05	1.95	2.28	2.56	2.84	3.29	3.70
65	2.02	1.97	2.29	1.88	2.80	3.27	3.67
66	2.03	2.02	2.29	2.62	2.82	3.20	3.58
67	2.05	2.04	2.28	2.58	2.82	3.28	3.68
68	2.04	2.05	2.27	2.58	2.81	3.27	3.67
69	2.06	1.95	2.29	2.57	2.81	3.27	3.68
70	1.89	2.03	2.26	2.57	2.84	3.35	3.79
71	2.03	2.02	2.29	2.59	2.82	3.30	3.70
72	2.05	2.05	2.11	2.56	2.84	3.24	3.64
73	1.88	2.02	2.27	2.57	2.84	3.35	3.79
74	1.89	2.01	2.26	2.45	2.79	3.25	3.66
75	1.89	2.01	2.28	2.59	2.83	3.36	3.79
76	2.01	2.02	2.28	2.60	2.65	3.17	3.54
77	2.04	2.03	2.11	2.42	2.85	3.19	3.58
78	2.03	2.01	2.27	2.56	2.81	3.27	3.67
79	2.06	2.03	2.29	2.59	2.84	3.30	3.70
80	2.06	2.02	2.28	2.60	2.81	3.27	3.67
81	2.18	2.02	2.27	2.72	2.54	2.77	3.04
82	2.01	2.02	2.12	2.57	2.79	3.23	3.63
83	2.05	1.96	2.26	2.59	2.82	3.28	3.69
84	2.05	1.95	2.28	2.56	2.84	3.29	3.70
85	2.02	1.97	2.30	2.56	2.80	3.27	3.68
86	2.03	2.02	2.29	2.40	2.82	3.20	3.59
87	2.06	2.04	2.29	2.59	2.83	3.28	3.68
88	2.05	2.05	2.27	2.59	2.81	3.27	3.67
89	2.06	1.95	2.29	2.57	2.81	3.28	3.68
90	1.89	2.03	2.26	2.57	2.85	3.35	3.79
91	2.03	2.02	2.30	2.60	2.83	3.30	3.71
92	2.06	2.05	2.11	2.56	2.84	3.25	3.64
93	1.89	2.02	2.27	2.57	2.85	3.36	3.79
94	1.90	2.02	2.26	2.45	2.80	3.25	3.66
95	1.89	2.02	2.28	2.59	2.83	3.36	3.80
96	2.02	2.02	2.28	2.60	2.66	3.17	3.55
97	2.04	2.04	2.11	2.42	2.85	3.19	3.59
98	2.03	2.02	2.27	2.57	2.82	3.28	3.68
99	2.06	2.03	2.29	2.60	2.85	3.30	3.71
100	2.07	2.03	2.28	2.60	2.81	3.28	3.67
AVERAGE	2.02	2.01	2.25	2.55	2.80	3.25	3.65

EXPERIMENT 3 Count to Distance Charts



Appendix C

Chapter 4

LM386 Datasheet

TL064CN Datasheet

SS2167 Datasheet

Foot Note 1 - NE597 Datasheet

Chapter 5

ZW3100 Datasheet

Chapter 7

LM317T Datasheet

Foot Note 17 - LM78L05 Datasheet

Foot Note 18 - MAX680 Datasheet

LM386

Low Voltage Audio Power Amplifier

General Description

The LM386 is a power amplifier designed for use in low voltage consumer applications. The gain is internally set to 20 to keep external part count low, but the addition of an external resistor and capacitor between pins 1 and 8 will increase the gain to any value from 20 to 200.

The inputs are ground referenced while the output automatically biases to one-half the supply voltage. The quiescent power drain is only 24 milliwatts when operating from a 6 volt supply, making the LM386 ideal for battery operation.

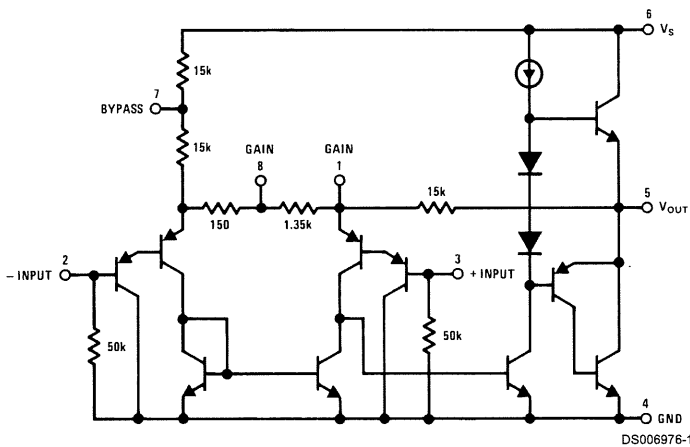
Features

- Battery operation
- Minimum external parts
- Wide supply voltage range: 4V–12V or 5V–18V
- Low quiescent current drain: 4mA
- Voltage gains from 20 to 200
- Ground referenced input
- Self-centering output quiescent voltage
- Low distortion: 0.2% ($A_V = 20$, $V_S = 6V$, $R_L = 8\Omega$, $P_O = 125mW$, $f = 1kHz$)
- Available in 8 pin MSOP package

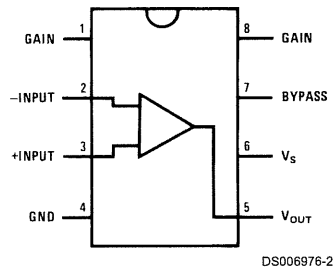
Applications

- AM-FM radio amplifiers
- Portable tape player amplifiers
- Intercoms
- TV sound systems
- Line drivers
- Ultrasonic drivers
- Small servo drivers
- Power converters

Equivalent Schematic and Connection Diagrams



Small Outline,
Molded Mini Small Outline,
and Dual-In-Line Packages



Top View
Order Number LM386M-1,
LM386MM-1, LM386N-1,
LM386N-3 or LM386N-4
See NS Package Number
M08A, MUA08A or N08E

Absolute Maximum Ratings (Note 2)

If Military/Aerospace specified devices are required, please contact the National Semiconductor Sales Office/ Distributors for availability and specifications.

Supply Voltage (LM386N-1, -3, LM386M-1)	15V	Dual-In-Line Package Soldering (10 sec)	+260°C
Supply Voltage (LM386N-4)	22V	Small Outline Package (SOIC and MSOP)	
Package Dissipation (Note 3) (LM386N)	1.25W	Vapor Phase (60 sec)	+215°C
(LM386M)	0.73W	Infrared (15 sec)	+220°C
(LM386MM-1)	0.595W	See AN-450 "Surface Mounting Methods and Their Effect on Product Reliability" for other methods of soldering surface mount devices.	
Input Voltage	±0.4V	Thermal Resistance	
Storage Temperature	-65°C to +150°C	θ_{JC} (DIP)	37°C/W
Operating Temperature	0°C to +70°C	θ_{JA} (DIP)	107°C/W
Junction Temperature	+150°C	θ_{JC} (SO Package)	35°C/W
Soldering Information		θ_{JA} (SO Package)	172°C/W
		θ_{JA} (MSOP)	210°C/W
		θ_{JC} (MSOP)	56°C/W

Electrical Characteristics (Notes 1, 2)

$T_A = 25^\circ\text{C}$

Parameter	Conditions	Min	Typ	Max	Units
Operating Supply Voltage (V_S) LM386N-1, -3, LM386M-1, LM386MM-1 LM386N-4		4 5		12 18	V V
Quiescent Current (I_Q)	$V_S = 6V, V_{IN} = 0$		4	8	mA
Output Power (P_{OUT}) LM386N-1, LM386M-1, LM386MM-1 LM386N-3 LM386N-4	$V_S = 6V, R_L = 8\Omega, THD = 10\%$ $V_S = 9V, R_L = 8\Omega, THD = 10\%$ $V_S = 16V, R_L = 32\Omega, THD = 10\%$	250 500 700	325 700 1000		mW mW mW
Voltage Gain (A_V)	$V_S = 6V, f = 1\text{ kHz}$ 10 μF from Pin 1 to 8		26 46		dB dB
Bandwidth (BW)	$V_S = 6V, \text{Pins 1 and 8 Open}$		300		kHz
Total Harmonic Distortion (THD)	$V_S = 6V, R_L = 8\Omega, P_{OUT} = 125\text{ mW}$ $f = 1\text{ kHz, Pins 1 and 8 Open}$		0.2		%
Power Supply Rejection Ratio (PSRR)	$V_S = 6V, f = 1\text{ kHz, } C_{BYPASS} = 10\ \mu\text{F}$ Pins 1 and 8 Open, Referred to Output		50		dB
Input Resistance (R_{IN})			50		k Ω
Input Bias Current (I_{BIAS})	$V_S = 6V, \text{Pins 2 and 3 Open}$		250		nA

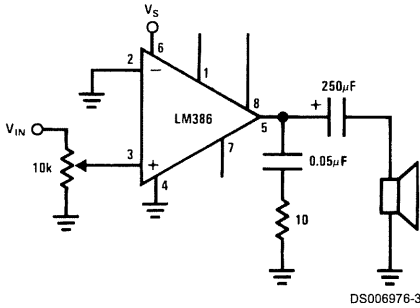
Note 1: All voltages are measured with respect to the ground pin, unless otherwise specified.

Note 2: Absolute Maximum Ratings indicate limits beyond which damage to the device may occur. Operating Ratings indicate conditions for which the device is functional, but do not guarantee specific performance limits. Electrical Characteristics state DC and AC electrical specifications under particular test conditions which guarantee specific performance limits. This assumes that the device is within the Operating Ratings. Specifications are not guaranteed for parameters where no limit is given, however, the typical value is a good indication of device performance.

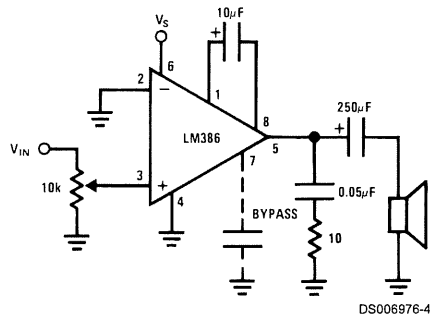
Note 3: For operation in ambient temperatures above 25°C, the device must be derated based on a 150°C maximum junction temperature and 1) a thermal resistance of 107°C/W junction to ambient for the dual-in-line package and 2) a thermal resistance of 170°C/W for the small outline package.

Typical Applications

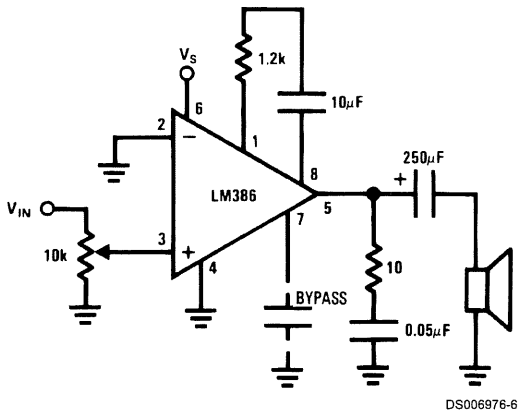
**Amplifier with Gain = 20
Minimum Parts**



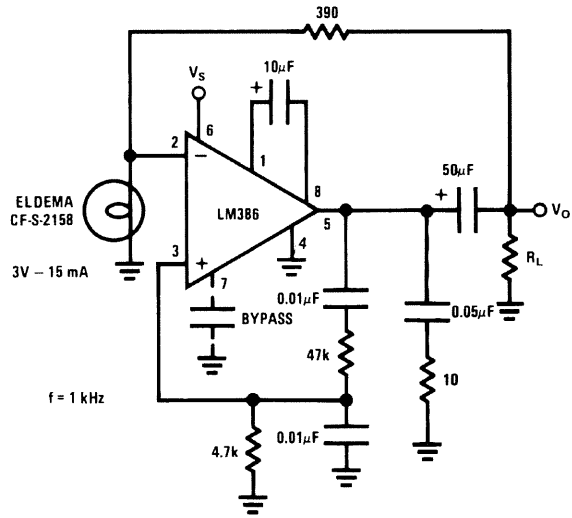
Amplifier with Gain = 200



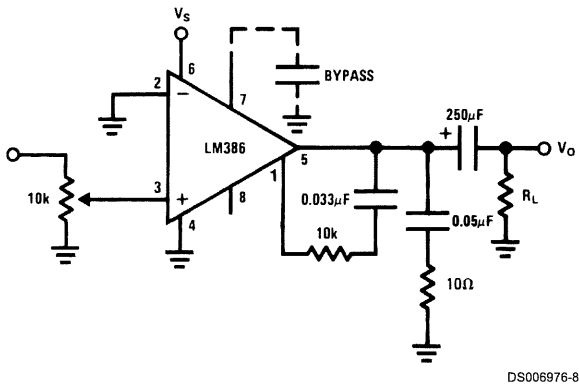
Amplifier with Gain = 50



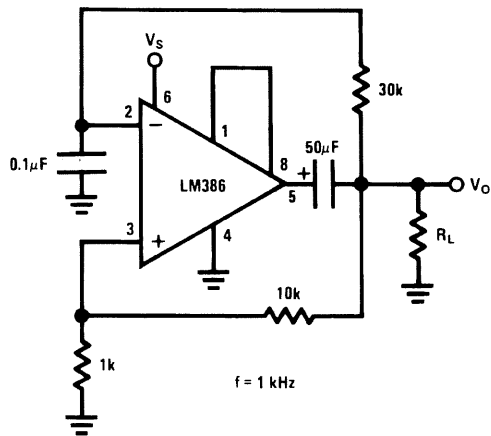
Low Distortion Power Wienbridge Oscillator



Amplifier with Bass Boost

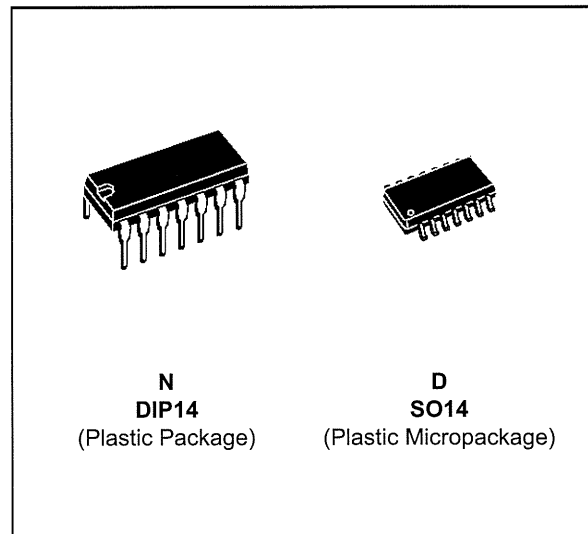


Square Wave Oscillator



LOW POWER J-FET QUAD OPERATIONAL AMPLIFIERS

- VERY LOW POWER CONSUMPTION : 200 μ A
- WIDE COMMON-MODE (UP TO V_{CC}^+) AND DIFFERENTIAL VOLTAGE RANGES
- LOW INPUT BIAS AND OFFSET CURRENTS
- OUTPUT SHORT-CIRCUIT PROTECTION
- HIGH INPUT IMPEDANCE J-FET INPUT STAGE
- INTERNAL FREQUENCY COMPENSATION
- LATCH UP FREE OPERATION
- HIGH SLEW RATE : 3.5V/ μ s



DESCRIPTION

The TL064, TL064A and TL064B are high speed J-FET input quad operational amplifiers. Each of these J-FET input operational amplifiers incorporates well matched, high voltage J-FET and bipolar transistors in a monolithic integrated circuit.

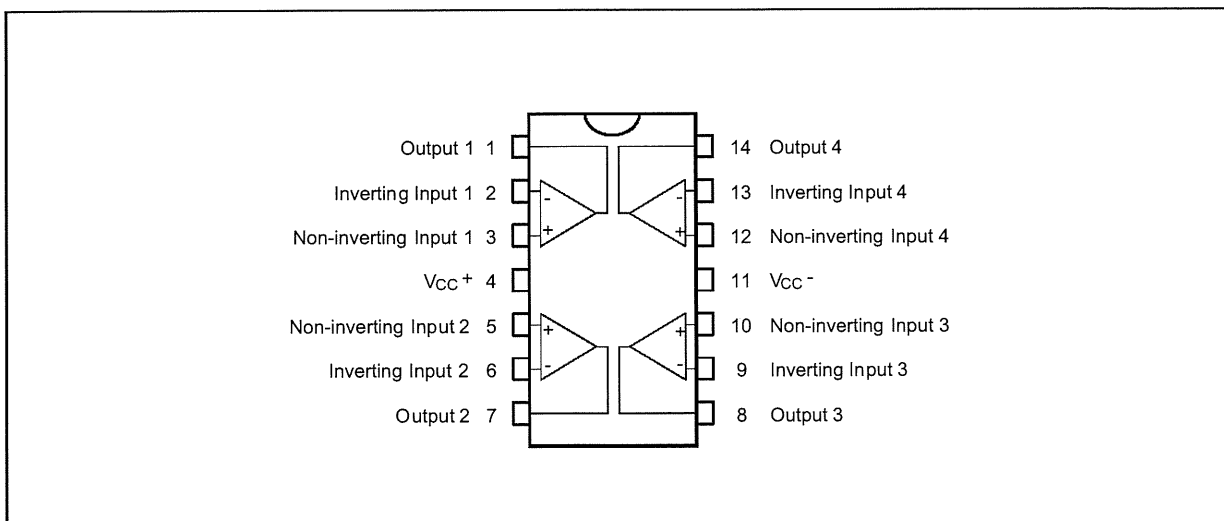
The device features high slew rate, low input bias and offset currents, and low offset voltage temperature coefficient.

ORDER CODES

Part Number	Temperature Range	Package	
		N	D
TL064M/AM/BM	-55°C, +125°C	•	•
TL064I/AI/BI	-40°C, +105°C	•	•
TL064C/AC/BC	0°C, +70°C	•	•

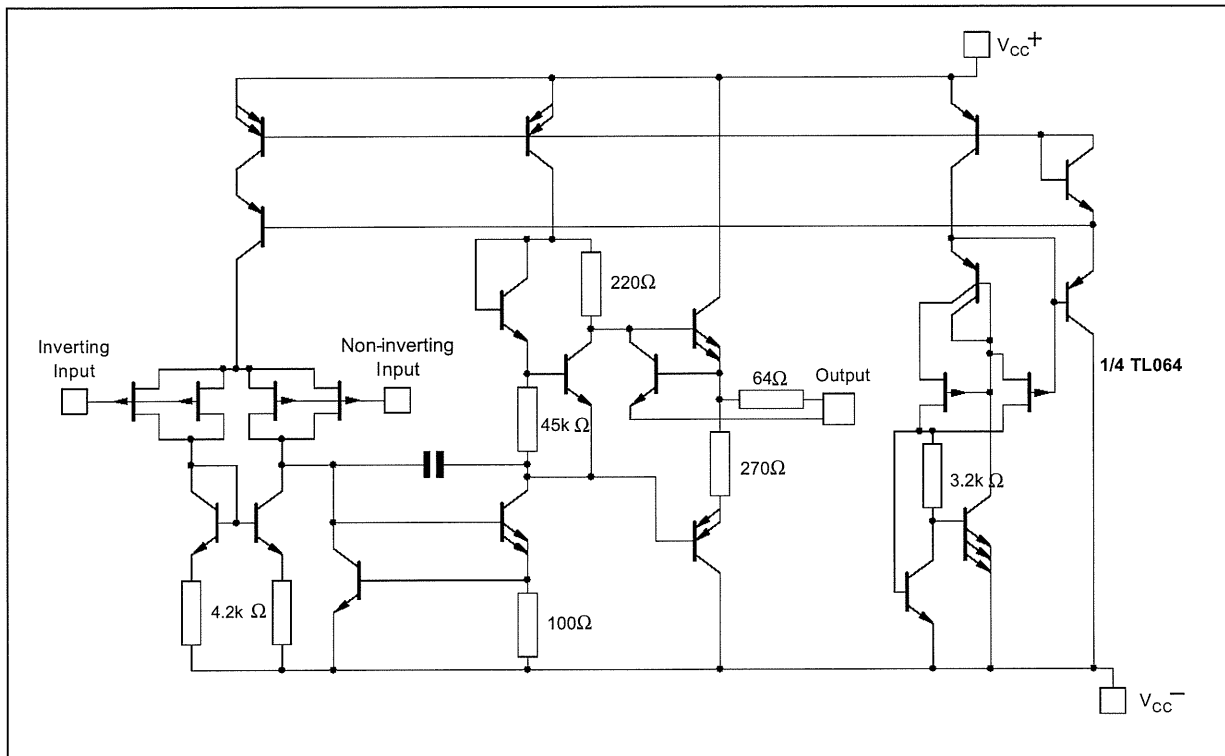
Example : TL064IN

PIN CONNECTIONS (top view)



TL064 - TL064A - TL064B

SCHEMATIC DIAGRAM



MAXIMUM RATINGS

Symbol	Parameter	TL064M,AM,BM	TL064I,AI,BI	TL064C,AC,BC	Unit
V_{CC}	Supply Voltage - (note 1)	± 18	± 18	± 18	V
V_i	Input Voltage - (note 3)	± 15	± 15	± 15	V
V_{id}	Differential Input Voltage - (note 2)	± 30	± 30	± 30	V
P_{tot}	Power Dissipation	680	680	680	mW
	Output Short-Circuit Duration (Note 4)	Infinite	Infinite	Infinite	
T_{oper}	Operating Free-Air Temperature Range	-55 to +125	-40 to +105	0 to +70	$^{\circ}C$
T_{stg}	Storage Temperature Range	-65 to +150	-65 to +150	-65 to +150	$^{\circ}C$

- Notes :**
1. All voltage values, except differential voltage, are with respect to the zero reference level (ground) of the supply voltages where the zero reference level is the midpoint between V_{CC}^+ and V_{CC}^- .
 2. Differential voltages are the non-inverting input terminal with respect to the inverting input terminal.
 3. The magnitude of the input voltage must never exceed the magnitude of the supply voltage or 15 volts, whichever is less.
 4. The output may be shorted to ground or to either supply. Temperature and/or supply voltages must be limited to ensure that the dissipation rating is not exceeded.

ELECTRICAL CHARACTERISTICS

$V_{CC} = \pm 15V$, $T_{amb} = 25^{\circ}C$ (unless otherwise specified)

Symbol	Parameter	TL064M			TL064I			TL064C			Unit
		Min.	Typ.	Max.	Min.	Typ.	Max.	Min.	Typ.	Max.	
V_{io}	Input Offset Voltage ($R_s = 50\Omega$) $T_{amb} = 25^{\circ}C$ $T_{min.} \leq T_{amb} \leq T_{max.}$		3	6 15		3	6 9		3	15 20	mV
DV_{io}	Temperature Coefficient of Input Offset Voltage ($R_s = 50\Omega$)		10			10			10		$\mu V/^{\circ}C$
I_{io}	Input Offset Current * $T_{amb} = 25^{\circ}C$ $T_{min.} \leq T_{amb} \leq T_{max.}$		5	100 20		5	100 10		5	200 5	pA nA
I_{ib}	Input Bias Current * $T_{amb} = 25^{\circ}C$ $T_{min.} \leq T_{amb} \leq T_{max.}$		30	200 50		30	200 20		30	400 10	pA nA
V_{icm}	Input Common Mode Voltage Range	± 11.5	+15 -12		± 11.5	+15 -12		± 11	+15 -12		V
V_{OPP}	Output Voltage Swing ($R_L = 10k\Omega$) $T_{amb} = 25^{\circ}C$ $T_{min.} \leq T_{amb} \leq T_{max.}$	20 20	27		20 20	27		20 20	27		V
A_{vd}	Large Signal Voltage Gain ($R_L = 10k\Omega$, $V_o = \pm 10V$) $T_{amb} = 25^{\circ}C$ $T_{min.} \leq T_{amb} \leq T_{max.}$	4 4	6		4 4	6		3 3	6		V/mV
GBP	Gain Bandwidth Product ($T_{amb} = 25^{\circ}C$, $R_L = 10k\Omega$ $C_L = 100pF$)		1			1			1		MHz
R_i	Input Resistance		10^{12}			10^{12}			10^{12}		Ω
CMR	Common Mode Rejection Ratio ($R_s = 50\Omega$)	80	86		80	86		70	76		dB
SVR	Supply Voltage Rejection Ratio ($R_s = 50\Omega$)	80	95		80	95		70	95		dB
I_{cc}	Supply Current (Per Amplifier) ($T_{amb} = 25^{\circ}C$, no load, no signal)		200	250		200	250		200	250	μA
V_{O1}/V_{O2}	Channel Separation ($A_v = 100$, $T_{amb} = 25^{\circ}C$)		120			120			120		dB
P_D	Total Power Consumption ($T_{amb} = 25^{\circ}C$, no load, no signal)		6	7.5		6	7.5		6	7.5	mW

* The input bias currents of a FET-input operational amplifier are normal junction reverse currents, which are temperature sensitive. Pulse techniques must be used that will maintain the junction temperature as close to the ambient temperature as possible.

ELECTRICAL CHARACTERISTICS (continued)

$V_{CC} = \pm 15V$, $T_{amb} = 25^{\circ}C$

Symbol	Parameter	TL064C,I,M			Unit
		Min.	Typ.	Max.	
SR	Slew Rate ($V_i = 10V$, $R_L = 10k\Omega$, $C_L = 100pF$, $A_v = 1$)	1.5	3.5		V/ μs
t_r	Rise Time ($V_i = 20mV$, $R_L = 10k\Omega$, $C_L = 100pF$, $A_v = 1$) (see Figure 1)		0.2		μs
K_{ov}	Overshoot Factor ($V_i = 20mV$, $R_L = 10k\Omega$, $C_L = 100pF$, $A_v = 1$) (see figure 1)		10		%
e_n	Equivalent Input Noise Voltage ($R_s = 100\Omega$, $f = 1KHz$)		42		$\frac{nV}{\sqrt{Hz}}$

TL064 - TL064A - TL064B

ELECTRICAL CHARACTERISTICS (continued)

$V_{CC} = \pm 15V$, $T_{amb} = 25^{\circ}C$ (unless otherwise specified)

Symbol	Parameter	TL064AC,AI,AM			TL064BC,BI,BM			Unit
		Min.	Typ.	Max.	Min.	Typ.	Max.	
V_{io}	Input Offset Voltage ($R_s = 50\Omega$) $T_{amb} = 25^{\circ}C$ $T_{min.} \leq T_{amb} \leq T_{max.}$		3	6 7.5		2	3 5	mV
DV_{io}	Temperature Coefficient of Input Offset Voltage ($R_s = 50\Omega$)		10			10		$\mu V/^{\circ}C$
I_{io}	Input Offset Current * $T_{amb} = 25^{\circ}C$ $T_{min.} \leq T_{amb} \leq T_{max.}$		5	100 3		5	100 3	pA nA
I_{ib}	Input Bias Current * $T_{amb} = 25^{\circ}C$ $T_{min.} \leq T_{amb} \leq T_{max.}$		30	200 7		30	200 7	pA nA
V_{icm}	Input Common Mode Voltage Range	± 11.5	+15 -12		± 11.5	+15 -12		V
V_{OPP}	Output Voltage Swing ($R_L = 10k\Omega$) $T_{amb} = 25^{\circ}C$ $T_{min.} \leq T_{amb} \leq T_{max.}$	20 20	27		20 20	27		V
A_{vd}	Large Signal Voltage Gain ($R_L = 10k\Omega$, $V_o = \pm 10V$) $T_{amb} = 25^{\circ}C$ $T_{min.} \leq T_{amb} \leq T_{max.}$	4 4	6		4 4	6		V/mV
GBP	Gain Bandwidth Product ($T_{amb} = 25^{\circ}C$, $R_L = 10k\Omega$, $C_L = 100pF$)		1			1		MHz
R_i	Input Resistance		10^{12}			10^{12}		Ω
CMR	Common Mode Rejection Ratio ($R_s = 50\Omega$)	80	86		80	86		dB
SVR	Supply Voltage Rejection Ratio ($R_s = 50\Omega$)	80	95		80	95		dB
I_{cc}	Supply Current (Per Amplifier) ($T_{amb} = 25^{\circ}C$, no load, no signal)		200	250		200	250	μA
V_{O1}/V_{O2}	Channel Separation ($A_v = 100$, $T_{amb} = 25^{\circ}C$)		120			120		dB
P_D	Total Power Consumption (Each Amplifier) ($T_{amb} = 25^{\circ}C$, no load, no signal)		6	7.5		6	7.5	mW
SR	Slew Rate ($V_i = 10V$, $R_L = 10k\Omega$, $C_L = 100pF$, $A_v = 1$)	1.5	3.5		1.5	3.5		V/ μs
t_r	Rise Time ($V_i = 20mV$, $R_L = 10k\Omega$, $C_L = 100pF$, $A_v = 1$)		0.2			0.2		μs
K_{OV}	Overshoot Factor ($V_i = 20mV$, $R_L = 10k\Omega$, $C_L = 100pF$, $A_v = 1$) - (see figure 1)		10			10		%
e_n	Equivalent Input Noise Voltage ($R_s = 100\Omega$, $f = 1kHz$)		42			42		$\frac{nV}{\sqrt{Hz}}$

* The input bias currents of a FET-input operational amplifier are normal junction reverse currents, which are temperature sensitive. Pulse techniques must be used that will maintain the junction temperature as close to the ambient temperature as possible.

PARAMETER MEASUREMENT INFORMATION

Figure 1 : Voltage follower

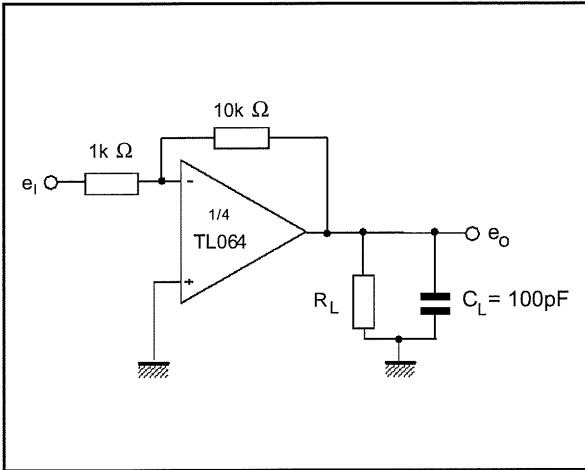
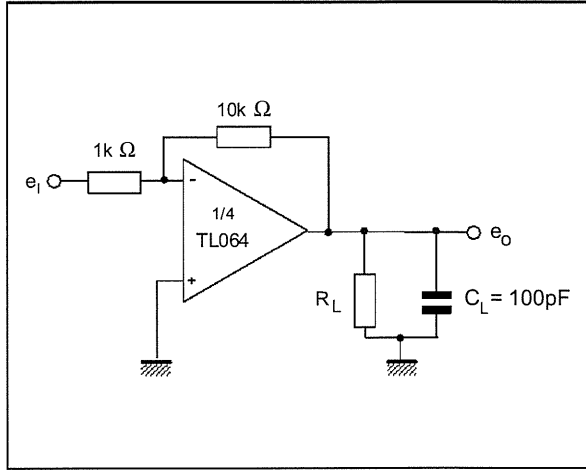
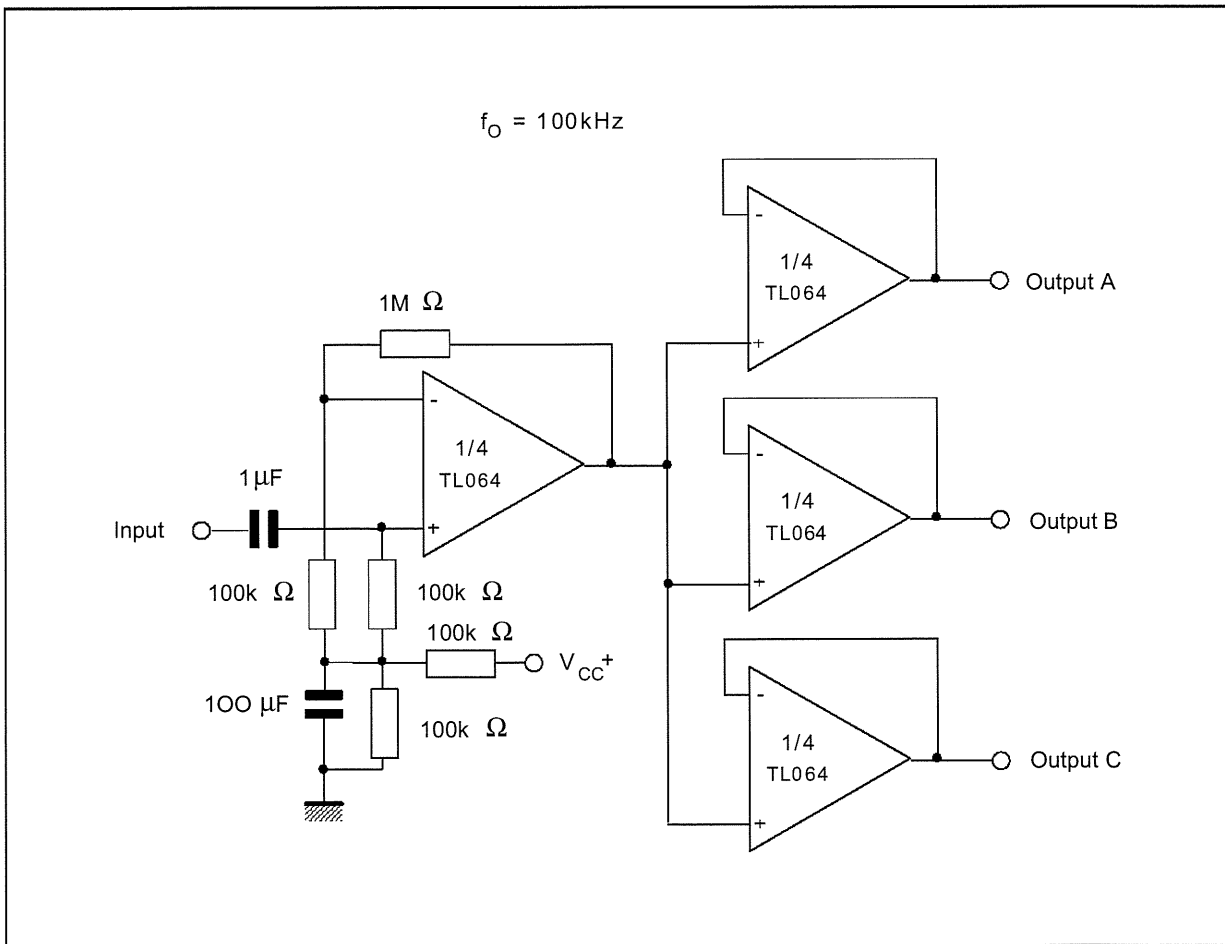


Figure 2 : Gain-of-10 inverting amplifier



TYPICAL APPLICATION

AUDIO DISTRIBUTION AMPLIFIER



Using the SSM2167 Evaluation Board

By Shawn Scarlett

SSM2167 EVALUATION BOARD

The evaluation board is a convenient means to evaluate and understand the operation of the SSM2167. This documentation provides a basic explanation of how the board is set up and how to use it to evaluate the SSM2167. This document is only a supplement and makes several references to figures contained in the product data sheet. The current data sheet is available on-line at www.analog.com.

This document also contains the schematics and layout for the evaluation board to allow easy modification and experimentation. Applications support is available from Analog Devices, Inc. on-line or in the United States at 1(800) ANALOG D or 1(800) 262-5643.

Basic Connections and Setup

The board features simple, easy-to-use connections that allow for a broad range of experimentation. The evaluation board is available only with the SSM2167-1.

Power and Ground

The SSM2167 is optimized for operation at 3 V; however, it can operate from a wide range of supplies. Please refer to the product data sheet for the maximum limits. The SSM2167 board can be connected to a bench power supply or two AA batteries. Power leads will need to be soldered into place at JP3. Alternatively, a header jack can be soldered to the board to allow easy disconnection. The power and ground connections are critical to the performance of the board, so care should be taken to ensure proper connection.

Shutdown Connection

Located at JP3, along with the power and ground, is the low current shutdown connection. The board has a pull-up resistor installed so that if no connection is made at that point, the part will operate in active mode. To enable the shutdown feature, simply connect the SHUTDOWN pin on JP3 to ground. If an in-depth analysis is to be done on the shutdown current, the pull-up resistor R5 may be removed. The shutdown pin should not be left floating. If R5 is removed, be sure to connect the SHUTDOWN pin directly to the supply or ground.

Signal Connections, Input, and Output

Signal sources can be connected to the evaluation board with standard 3.5 mm jacks or leads which can be soldered directly to the board at JP2 and JP3. The board uses 3.5 mm stereo sockets with the signal on the tip and the sleeve connected to the board ground; the ring is left floating. At both jumper connections, a ground point is available to prevent noise.

The input jack is configured for maximum versatility. By default, it is designed for use with an electret microphone or input source. It can be changed easily to accommodate dynamic microphones.

Electret Microphones

The evaluation board is configured with a 2.2 k Ω resistor (R4) to the supply for use as a biasing resistor. It is connected directly to the signal path so that both the jack and the jumper (JP2) can be used as input connections. Standard computer electret microphones can be used without modification because the ring and tip are connected internally in the microphone. The input jack and JP2 are decoupled from the input pin via a 0.1 μ F capacitor (C1).

Dynamic Microphones

If the board is to be used with a dynamic or self-powered microphone, R4 should be removed.

Output Signal

The output jack is decoupled from the circuit via a 10 μ F capacitor (C2). The connection can be made at either JP1 or the standard 3.5 mm jack, with the signal connection to the tip of the plug. For listening tests, the output signal can be connected directly from the 3.5 mm jack to an RCA input on a normal audio amplifier using a standard stereo adapter cable. In this case, use the left (white or black) RCA connection because it corresponds with the tip of the 3.5 mm jack. The output of the SSM2167 is not sufficient to drive headphones or other output transducers without external amplification.

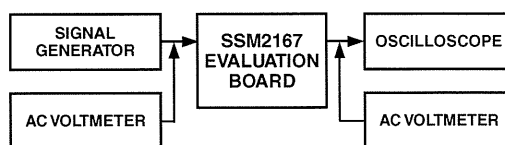


Figure 1. Test Equipment Setup

Test Equipment Setup

The recommended equipment and configuration is shown in Figure 1. A low noise audio generator with a smooth output adjustment range of 50 μ V to 50 mV is a suitable signal source. A 40 dB pad is useful to reduce the level of most generators by 100' to simulate microphone levels. The input voltmeter can be connected before the pad and need only go down to 10 mV. The output voltmeter should go up to 2 V. The oscilloscope is used to verify that the output is sinusoidal, that no clipping is occurring in the buffer, and that the noise-gating threshold is set.

STEP 1. Connections

Connect power, ground, input, and output as discussed above.

STEP 2. Test Setup

To confirm the operation of the board and test setup, first put JP4 in the 1:1 position and JP5 in the -55 dB position. With power on, adjust the generator for an input level of 15 mV, 1 kHz. The output meter should indicate approximately 100 mV. If it does not, check the setup. Substituting the SSM2167-2 will give an output of approximately 40 mV.

STEP 3. Listening

Connect a microphone to the SSM2167 and listen to the results. Be sure to include the proper power for the microphone as discussed above. Experiment with the settings to hear how the results change. Compression ratio will keep the output steady over a range of source-to-microphone distances, and the noise gate will keep the background sounds subdued.

STEP 4. Setting the Noise-Gate Threshold

The evaluation board provides three different preset values of noise-gate threshold. Experiment with these values by varying the gate. The board also provides landing pads for a custom value that can be extrapolated from the table given in the data sheet, or TPC 1 in the Typical Performance Characteristics section of the data sheet. Using above 5 k Ω is not recommended because extremely low noise-gate thresholds may approach the noise floor of the system.

The highest setting (-48 dB) is recommended to start an evaluation. If the input signal is not sufficient to surpass the threshold, lower the setting. In most applications, the input signal will easily overcome this setting. If the gate is set too low, the background noise will be amplified well into the audible range. By examining the function (Figure 1) in the data sheet, the maximum gain of the part can be determined when the input signal is at the noise-gate threshold. The dashed line on the transfer function represents unity gain; the distance between the dashed line and the solid line represents the VCA gain.

STEP 5. Adjusting the Compression Ratio

The evaluation board provides three different settings for the compression ratio in the same manner as the noise-gate threshold. Experiment with different compression ratios to determine what will sound best in a given system; starting with a 2:1 ratio is recommended. High compression ratios will exaggerate the effect of the noise gate because compression ratio determines the gain at the noise gate, as shown in Figure 4 of the data sheet. Compression of 10:1 should be used only in systems where the noise floor is well below the noise gate. Most systems require between 2:1 and 5:1 compression for best results.

Listening Test

The final step in evaluating the SSM2167 should be a listening test. The improvement in vocal clarity can be heard by recording the SSM2167 output or listening to it live. Ideally, the evaluation board should be connected to an existing system. The impact of the compression is demonstrated by shorting out RCOMP (R9 through R12). When the RCOMP resistor is shorted, the VCA will revert to the audible 1:1 compression setting. This will not affect the noise-gate or limiting settings. The effect of turning off the compression will be most noticeable when the input signal is between -50 dBV and -40 dBV. Evaluating the SSM2167 within the end application will also give the best indication of how high the noise-gate threshold should be set. The noise level of the system will be greatly influenced by the design of the system, including cooling fans, hard drives, handling, and other sources of acoustic noise.

Listening tests are the most critical part of an evaluation. Since test equipment and signal generators do not represent audio signals well, listening is the best way to evaluate the benefits of the SSM2167. The evaluation board makes it easy to implement the SSM2167 and to pick appropriate application settings. The end result is a noticeable improvement in signal clarity and a system that is easy for customers to use.

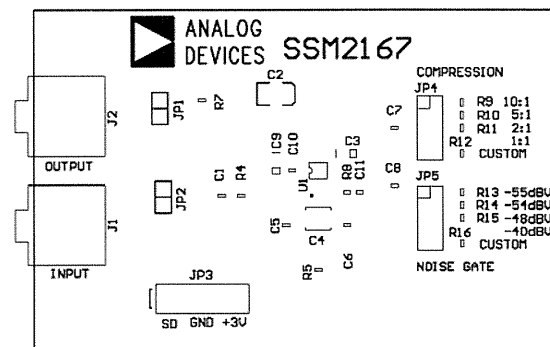


Figure 2. SSM2167 Evaluation Board; Top Layer Including Component Identification and Placement

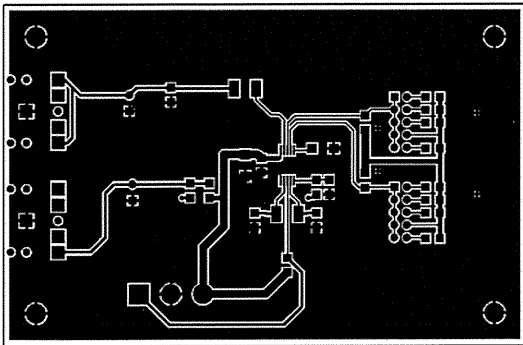


Figure 3. SSM2167 Evaluation Board; Top Layer

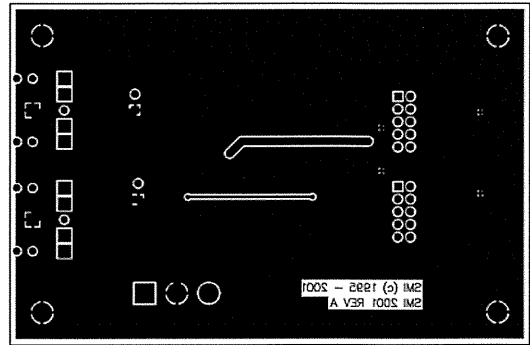


Figure 4. SSM2167 Evaluation Board; Bottom Layer

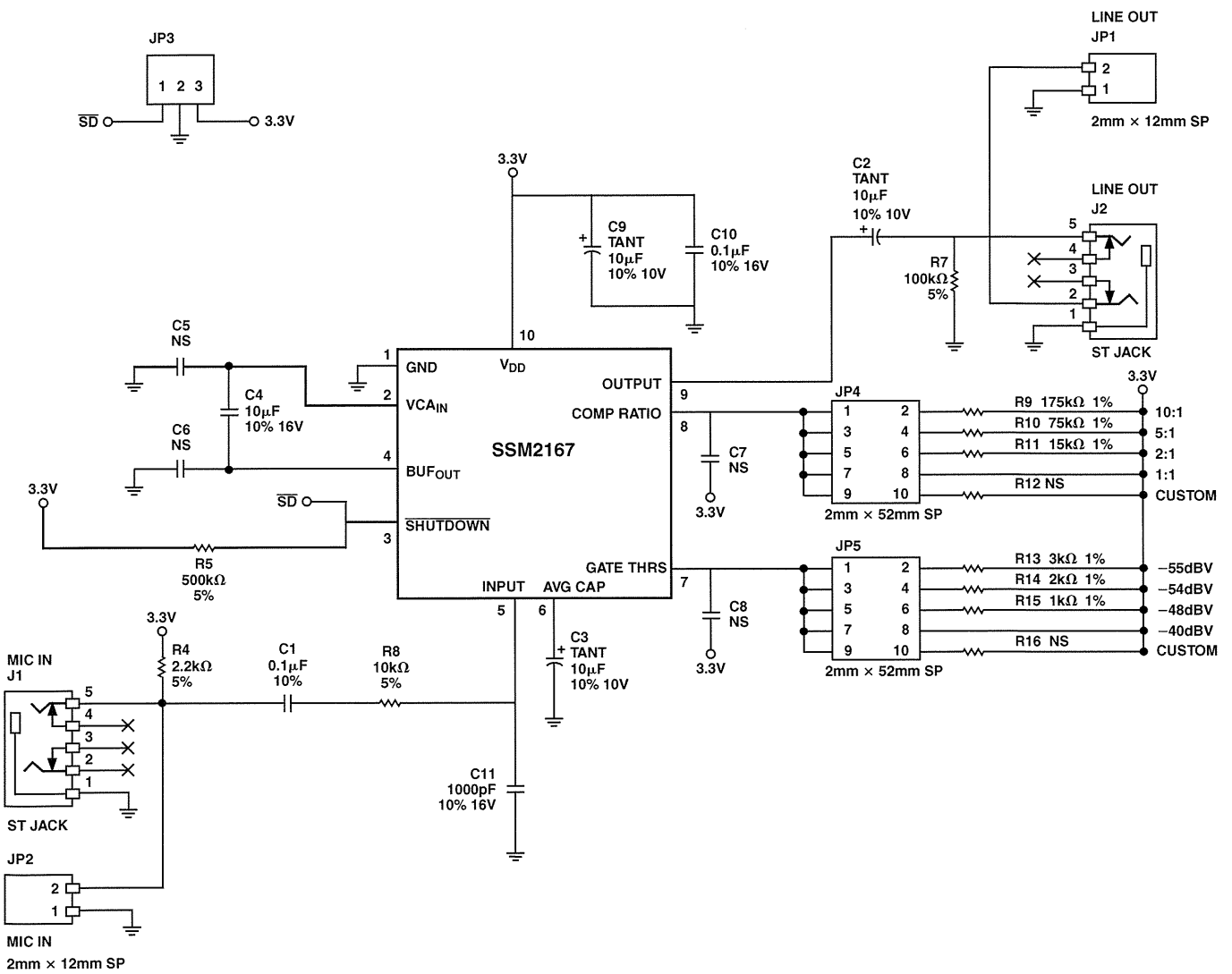


Figure 5. SSM2167 Evaluation Board Circuit Schematic

Table I. Part List for SSM2167 Evaluation Board

Reference	Part	PCB Footprint	Value	Tolerance
U1	IC	10-Lead MSOP	SSM2167	
C1, C10	CAP	805	0.1 μ F (X7R)	10%
C2, C3, C9	CAP	CASE – A	10 μ F (TANT)	10%
C4	CAP NP	1206	10 μ F (X5R)	10%
J1, J2	ST JACK	T.H.	ST JACK	
JP4, JP5	HEADER	T.H.	2 mm \times 52 mm SP	
R5	RES	805	499 k Ω	1%
R8	RES	805	10 k Ω	5%
R4	RES	805	2.2 k Ω	5%
R7	RES	805	100 k Ω	5%
R9	RES	805	175 k Ω	5%
R10	RES	805	75 k Ω	5%
R11	RES	805	15 k Ω	5%
R13	RES	805	3 k Ω	5%
R14	RES	805	2 k Ω	5%
R15	RES	805	1 k Ω	5%
JP4 (7-8), JP5 (7-8)	JUMPER		2 mm SHUNT	
R12, R16	RES	805	NS	
C5, C6, C7, C8	CAP	805	NS	
C11	CAP	805	NS	
JP1, JP2	HEADER	2 mm \times 12 mm SP	NS	
JP3	HEADER	3 mm \times 10.2 in SP	NS	

NS = Not Stuffed

DATA SHEET

NE567/SE567

Tone decoder/phase-locked loop

Product data
Supersedes data of 1992 Apr 15

2002 Sep 25

Tone decoder/phase-locked loop

NE567/SE567

AVAILABLE OUTPUTS (Figure 18)

The primary output is the uncommitted output transistor collector, Pin 8. When an in-band input signal is present, this transistor saturates; its collector voltage being less than 1.0 volt (typically 0.6V) at full output current (100mA). The voltage at Pin 2 is the phase detector output which is a linear function of frequency over the range of 0.95 to $1.05 f_O$ with a slope of about 20mV per percent of frequency deviation. The average voltage at Pin 1 is, during lock, a function of the in-band input amplitude in accordance with the transfer characteristic given. Pin 5 is the controlled oscillator square wave output of magnitude $(+V - 2V_{BE}) \cong (+V - 1.4V)$ having a DC average of $+V/2$. A $1k\Omega$ load may be driven from pin 5. Pin 6 is an exponential triangle of $1V_{P-P}$ with an average DC level of $+V/2$. Only high impedance loads may be connected to pin 6 without affecting the CCO duty cycle or temperature stability.

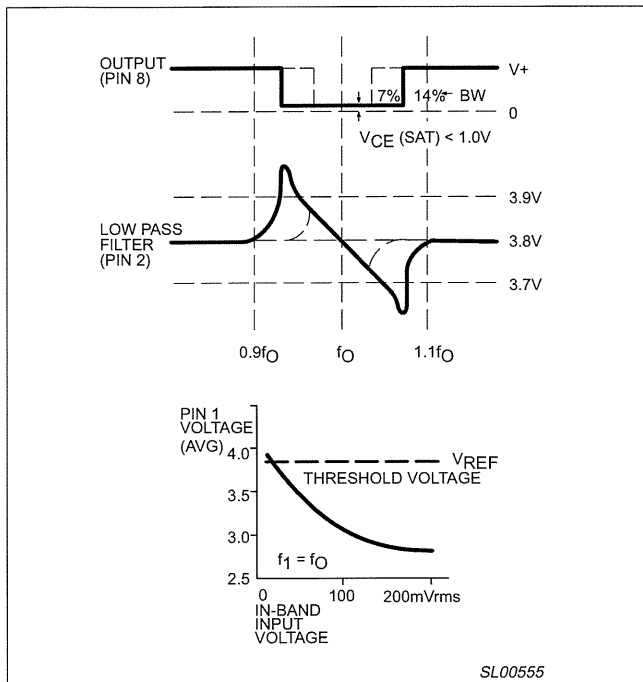


Figure 18. Available outputs

OPERATING PRECAUTIONS

A brief review of the following precautions will help the user achieve the high level of performance of which the 567 is capable.

1. Operation in the high input level mode (above 200 mV) will free the user from bandwidth variations due to changes in the in-band signal amplitude. The input stage is now limiting, however, so that out-band signals or high noise levels can cause an apparent bandwidth reduction as the inband signal is suppressed. Also, the limiting action will create in-band components from sub-harmonic signals, so the 567 becomes sensitive to signals at $f_O/3$, $f_O/5$, etc.
2. The 567 will lock onto signals near $(2n+1) f_O$, and will give an output for signals near $(4n+1) f_O$ where $n = 0, 1, 2$, etc. Thus, signals at $5f_O$ and $9f_O$ can cause an unwanted output. If such signals are anticipated, they should be attenuated before reaching the 567 input.
3. Maximum immunity from noise and out-band signals is afforded in the low input level (below 200 mV_{RMS}) and reduced bandwidth operating mode. However, decreased loop damping causes the worst-case lock-up time to increase, as shown by the Greatest Number of Cycles Before Output vs Bandwidth graph.
4. Due to the high switching speeds (20 ns) associated with 567 operation, care should be taken in lead routing. Lead lengths should be kept to a minimum. The power supply should be adequately bypassed close to the 567 with a $0.01\mu F$ or greater capacitor; grounding paths should be carefully chosen to avoid ground loops and unwanted voltage variations. Another factor which must be considered is the effect of load energization on the power supply. For example, an incandescent lamp typically draws 10 times rated current at turn-on. This can cause supply voltage fluctuations which could, for example, shift the detection band of narrow-band systems sufficiently to cause momentary loss of lock. The result is a low-frequency oscillation into and out of lock. Such effects can be prevented by supplying heavy load currents from a separate supply or increasing the supply filter capacitor.

Tone decoder/phase-locked loop

NE567/SE567

SPEED OF OPERATION

Minimum lock-up time is related to the natural frequency of the loop. The lower it is, the longer becomes the turn-on transient. Thus, maximum operating speed is obtained when C_2 is at a minimum. When the signal is first applied, the phase may be such as to initially drive the controlled oscillator away from the incoming frequency rather than toward it. Under this condition, which is of course unpredictable, the lock-up transient is at its worst and the theoretical minimum lock-up time is not achievable. We must simply wait for the transient to die out.

The following expressions give the values of C_2 and C_3 which allow highest operating speeds for various band center frequencies. The minimum rate at which digital information may be detected without information loss due to the turn-on transient or output chatter is about 10 cycles per bit, corresponding to an information transfer rate of $f_0/10$ baud.

$$C_2 = \frac{130}{f_0} \mu\text{F}$$

$$C_3 = \frac{260}{f_0} \mu\text{F}$$

In cases where turn-off time can be sacrificed to achieve fast turn-on, the optional sensitivity adjustment circuit can be used to move the quiescent C_3 voltage lower (closer to the threshold voltage). However, sensitivity to beat frequencies, noise and extraneous signals will be increased.

OPTIONAL CONTROLS (Figure 19)

The 567 has been designed so that, for most applications, no external adjustments are required. Certain applications, however, will be greatly facilitated if full advantage is taken of the added control possibilities available through the use of additional external components. In the diagrams given, typical values are suggested where applicable. For best results the resistors used, except where noted, should have the same temperature coefficient. Ideally, silicon diodes would be low-resistivity types, such as forward-biased transistor base-emitter junctions. However, ordinary low-voltage diodes should be adequate for most applications.

SENSITIVITY ADJUSTMENT (Figure 19)

When operated as a very narrow-band detector (less than 8%), both C_2 and C_3 are made quite large in order to improve noise and out-band signal rejection. This will inevitably slow the response time. If, however, the output stage is biased closer to the threshold level, the turn-on time can be improved. This is accomplished by drawing additional current to terminal 1. Under this condition, the 567 will also give an output for lower-level signals (10 mV or lower).

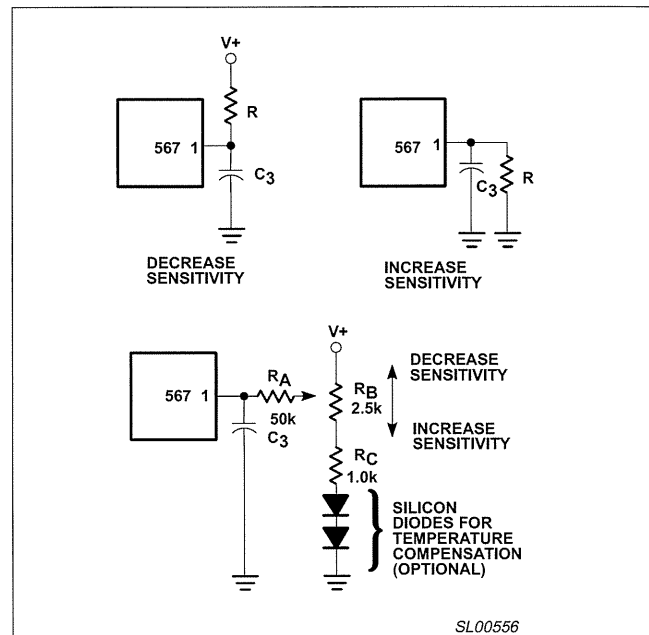


Figure 19. Sensitivity adjustment

By adding current to terminal 1, the output stage is biased further away from the threshold voltage. This is most useful when, to obtain maximum operating speed, C_2 and C_3 are made very small. Normally, frequencies just outside the detection band could cause false outputs under this condition. By desensitizing the output stage, the out-band beat notes do not feed through to the output stage. Since the input level must be somewhat greater when the output stage is made less sensitive, rejection of third harmonics or in-band harmonics (of lower frequency signals) is also improved.

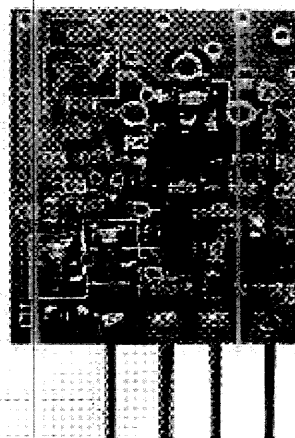
◎Ideal for 315/433.92MHz Remote Keyless-Entry Transmitter.

◎SAW RESONATOR

◎ASK Design

The TXC1 is an ASK transmitter module .The result is excellent performance in a simple-to-use .The TXC1 is designed specifically for remote-control , wireless mouse and car alarm system operating at 315/433.92 Mhz in the USA under FCC Part 15 regulation.

315/433.92MHZ
Hybrid
Transmitter



Absolute Maximum Ratings

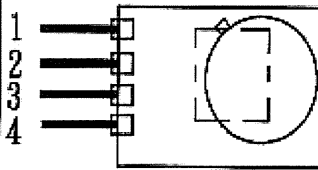
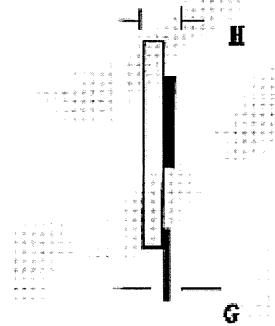
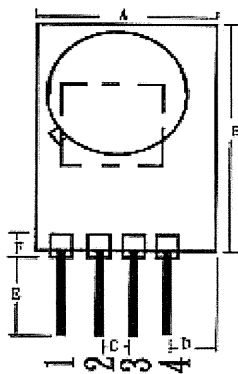
Parameter	Value	Units
Power Supply and/or Modulation Input Voltage	3	V
Operating temperature	-20 to +80	°C

Transmitter Characteristics

Parameter	Symbol	Condition	Value		Unit
			min.	typ. max.	
Output power		Vcc=3.0V,TA-27°C, 50Ω load	315MHz	3	dBm
			433.92MHz	3	dBm
Supply current	Icc			10	mA
Supply voltage Range	Vcc			3	V
Data Rate			300		10K bps

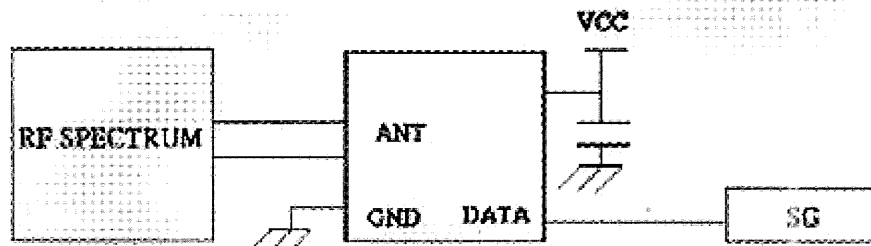
Pin assignment

PIN	Connections
1	GND
2	DATA
3	VCC
4	ANT

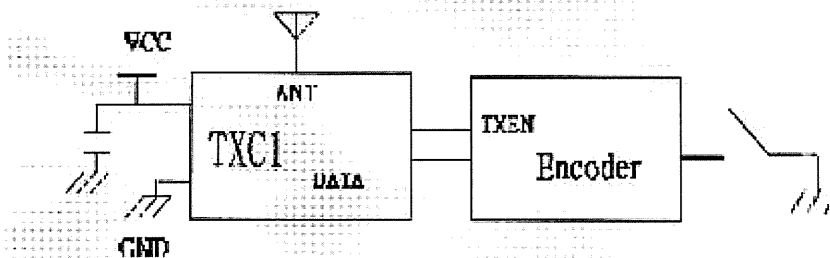



Dimensions	Millimeters	Dimensions	Millimeters
A	14.5 +/-0.25mm	E	5.9 +/-0.1mm
B	18.5 +/-0.25mm	F	0.1 +/-0.05mm
C	2.54 (MAX)	G	0.3 +/-0.01mm
D	5.0 +/-0.1mm	H	4 +/-0.25mm

Typing Test Circuit



Typical transmitter Application



Notes:

1. Encoder : HT12D/F , PTC (2262)
 2. Antenna : Length = 22.6cm for 315MHz ; Length = 17.2 cm for 433.92MHz.
-

LM117/LM317A/LM317

3-Terminal Adjustable Regulator

General Description

The LM117 series of adjustable 3-terminal positive voltage regulators is capable of supplying in excess of 1.5A over a 1.2V to 37V output range. They are exceptionally easy to use and require only two external resistors to set the output voltage. Further, both line and load regulation are better than standard fixed regulators. Also, the LM117 is packaged in standard transistor packages which are easily mounted and handled.

In addition to higher performance than fixed regulators, the LM117 series offers full overload protection available only in IC's. Included on the chip are current limit, thermal overload protection and safe area protection. All overload protection circuitry remains fully functional even if the adjustment terminal is disconnected.

Normally, no capacitors are needed unless the device is situated more than 6 inches from the input filter capacitors in which case an input bypass is needed. An optional output capacitor can be added to improve transient response. The adjustment terminal can be bypassed to achieve very high ripple rejection ratios which are difficult to achieve with standard 3-terminal regulators.

Besides replacing fixed regulators, the LM117 is useful in a wide variety of other applications. Since the regulator is "floating" and sees only the input-to-output differential voltage, supplies of several hundred volts can be regulated as long as

the maximum input to output differential is not exceeded, i.e., avoid short-circuiting the output.

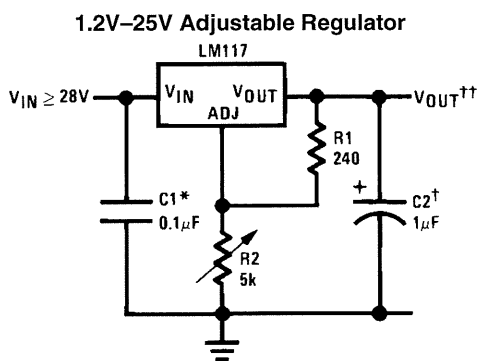
Also, it makes an especially simple adjustable switching regulator, a programmable output regulator, or by connecting a fixed resistor between the adjustment pin and output, the LM117 can be used as a precision current regulator. Supplies with electronic shutdown can be achieved by clamping the adjustment terminal to ground which programs the output to 1.2V where most loads draw little current.

For applications requiring greater output current, see LM150 series (3A) and LM138 series (5A) data sheets. For the negative complement, see LM137 series data sheet.

Features

- Guaranteed 1% output voltage tolerance (LM317A)
- Guaranteed max. 0.01%/V line regulation (LM317A)
- Guaranteed max. 0.3% load regulation (LM117)
- Guaranteed 1.5A output current
- Adjustable output down to 1.2V
- Current limit constant with temperature
- P+ Product Enhancement tested
- 80 dB ripple rejection
- Output is short-circuit protected

Typical Applications



906301

Full output current not available at high input-output voltages

*Needed if device is more than 6 inches from filter capacitors.

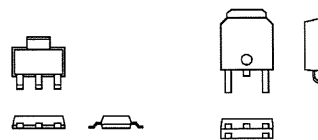
†Optional—improves transient response. Output capacitors in the range of 1μF to 1000μF of aluminum or tantalum electrolytic are commonly used to provide improved output impedance and rejection of transients.

$$\dagger\dagger V_{OUT} = 1.25V \left(1 + \frac{R_2}{R_1} \right) + I_{ADJ}(R_2)$$

LM117/LM317A/LM317 Package Options

Part Number	Suffix	Package	Output Current
LM117, LM317	K	TO-3	1.5A
LM317A, LM317	T	TO-220	1.5A
LM317	S	TO-263	1.5A
LM317A, LM317	EMP	SOT-223	1.0A
LM117, LM317A, LM317	H	TO-39	0.5A
LM117	E	LCC	0.5A
LM317A, LM317	MDT	TO-252	0.5A

SOT-223 vs. TO-252 (D-Pak) Packages



SOT-223

TO-252

906354

Scale 1:1

Absolute Maximum Ratings (Note 1)

If Military/Aerospace specified devices are required, please contact the National Semiconductor Sales Office/Distributors for availability and specifications.

Power Dissipation	Internally Limited
Input-Output Voltage Differential	+40V, -0.3V
Storage Temperature	-65°C to +150°C
Lead Temperature	
Metal Package (Soldering, 10 seconds)	300°C
Plastic Package (Soldering, 4 seconds)	260°C
ESD Tolerance (Note 5)	3 kV

Operating Temperature Range

LM117	$-55^{\circ}\text{C} \leq T_J \leq +150^{\circ}\text{C}$
LM317A	$-40^{\circ}\text{C} \leq T_J \leq +125^{\circ}\text{C}$
LM317	$0^{\circ}\text{C} \leq T_J \leq +125^{\circ}\text{C}$

Preconditioning

Thermal Limit Burn-In	All Devices 100%
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LM117 Electrical Characteristics (Note 3)

Specifications with standard type face are for $T_J = 25^{\circ}\text{C}$, and those with **boldface type** apply over full Operating Temperature Range. Unless otherwise specified, $V_{IN} - V_{OUT} = 5\text{V}$, and $I_{OUT} = 10\text{mA}$.

Parameter	Conditions	LM117 (Note 2)			
		Min	Typ	Max	Units
Reference Voltage	$3\text{V} \leq (V_{IN} - V_{OUT}) \leq 40\text{V}$, $10\text{mA} \leq I_{OUT} \leq I_{MAX}$	1.20	1.25	1.30	V
Line Regulation	$3\text{V} \leq (V_{IN} - V_{OUT}) \leq 40\text{V}$ (Note 4)		0.01 0.02	0.02 0.05	%/V
Load Regulation	$10\text{mA} \leq I_{OUT} \leq I_{MAX}$ (Note 4)		0.1 0.3	0.3 1	%
Thermal Regulation	20 ms Pulse		0.03	0.07	%/W
Adjustment Pin Current			50	100	μA
Adjustment Pin Current Change	$10\text{mA} \leq I_{OUT} \leq I_{MAX}$ $3\text{V} \leq (V_{IN} - V_{OUT}) \leq 40\text{V}$		0.2	5	μA
Temperature Stability	$T_{MIN} \leq T_J \leq T_{MAX}$		1		%
Minimum Load Current	$(V_{IN} - V_{OUT}) = 40\text{V}$		3.5	5	mA
Current Limit	$(V_{IN} - V_{OUT}) \leq 15\text{V}$ K Package	1.5	2.2	3.4	A
	H, E Package	0.5	0.8	1.8	
	$(V_{IN} - V_{OUT}) = 40\text{V}$ K Package	0.3	0.4		A
	H, E Package	0.15	0.20		
RMS Output Noise, % of V_{OUT}	$10\text{Hz} \leq f \leq 10\text{kHz}$		0.003		%
Ripple Rejection Ratio	$V_{OUT} = 10\text{V}$, $f = 120\text{Hz}$, $C_{ADJ} = 0\mu\text{F}$		65		dB
	$V_{OUT} = 10\text{V}$, $f = 120\text{Hz}$, $C_{ADJ} = 10\mu\text{F}$	66	80		dB
Long-Term Stability	$T_J = 125^{\circ}\text{C}$, 1000 hrs		0.3	1	%
Thermal Resistance, θ_{JC} Junction-to-Case	K (TO-3) Package		2		$^{\circ}\text{C/W}$
	H (TO-39) Package		21		
	E (LCC) Package		12		
Thermal Resistance, θ_{JA} Junction-to-Ambient (No Heat Sink)	K (TO-3) Package		39		$^{\circ}\text{C/W}$
	H (TO-39) Package		186		
	E (LCC) Package		88		

LM317A and LM317 Electrical Characteristics (Note 3)

Specifications with standard type face are for $T_J = 25^\circ\text{C}$, and those with **boldface type** apply over **full Operating Temperature Range**. Unless otherwise specified, $V_{IN} - V_{OUT} = 5\text{V}$, and $I_{OUT} = 10\text{ mA}$.

Parameter	Conditions	LM317A			LM317			Units
		Min	Typ	Max	Min	Typ	Max	
Reference Voltage		1.238	1.250	1.262	-	1.25	-	V
	$3\text{V} \leq (V_{IN} - V_{OUT}) \leq 40\text{V}$, $10\text{ mA} \leq I_{OUT} \leq I_{MAX}$	1.225	1.250	1.270	1.20	1.25	1.30	V
Line Regulation	$3\text{V} \leq (V_{IN} - V_{OUT}) \leq 40\text{V}$ (Note 4)		0.005 0.01	0.01 0.02		0.01 0.02	0.04 0.07	%/V
Load Regulation	$10\text{ mA} \leq I_{OUT} \leq I_{MAX}$ (Note 4)		0.1 0.3	0.5 1		0.1 0.3	0.5 1.5	%
Thermal Regulation	20 ms Pulse		0.04	0.07		0.04	0.07	%/W
Adjustment Pin Current			50	100		50	100	μA
Adjustment Pin Current Change	$10\text{ mA} \leq I_{OUT} \leq I_{MAX}$ $3\text{V} \leq (V_{IN} - V_{OUT}) \leq 40\text{V}$		0.2	5		0.2	5	μA
Temperature Stability	$T_{MIN} \leq T_J \leq T_{MAX}$		1			1		%
Minimum Load Current	$(V_{IN} - V_{OUT}) = 40\text{V}$		3.5	10		3.5	10	mA
Current Limit	$(V_{IN} - V_{OUT}) \leq 15\text{V}$ K, T, S Packages	-	-	-	1.5	2.2	3.4	A
	EMP Package	1.5	2.2	3.4	1.5	2.2	3.4	
	H, MDT Packages	0.5	0.8	1.8	0.5	0.8	1.8	
	$(V_{IN} - V_{OUT}) = 40\text{V}$ K, T, S Packages	-	-		0.15	0.40		A
EMP Package	0.112	0.30		0.112	0.30			
H, MDT Packages	0.075	0.20		0.075	0.20			
RMS Output Noise, % of V_{OUT}	$10\text{ Hz} \leq f \leq 10\text{ kHz}$		0.003			0.003		%
Ripple Rejection Ratio	$V_{OUT} = 10\text{V}$, $f = 120\text{ Hz}$, $C_{ADJ} = 0\text{ }\mu\text{F}$		65			65		dB
	$V_{OUT} = 10\text{V}$, $f = 120\text{ Hz}$, $C_{ADJ} = 10\text{ }\mu\text{F}$	66	80		66	80		dB
Long-Term Stability	$T_J = 125^\circ\text{C}$, 1000 hrs		0.3	1		0.3	1	%
Thermal Resistance, θ_{JC} Junction-to-Case	K (TO-3) Package		-			2		$^\circ\text{C/W}$
	T (TO-220) Package		-			4		
	S (TO-263) Package		-			4		
	EMP (SOT-223) Package		23.5			23.5		
	H (TO-39) Package		21			21		
	MDT (TO-252) Package		12			12		
Thermal Resistance, θ_{JA} Junction-to-Ambient (No Heat Sink)	K (TO-3) Package		-			39		$^\circ\text{C/W}$
	T (TO-220) Package		-			50		
	S (TO-263) Package (Note 6)		-			50		
	EMP (SOT-223) Package (Note 6)		140			140		
	H (TO-39) Package		186			186		
	MDT (TO-252) Package (Note 6)		103			103		

Note 1: Absolute Maximum Ratings indicate limits beyond which damage to the device may occur. Operating Ratings indicate conditions for which the device is intended to be functional, but do not guarantee specific performance limits. For guaranteed specifications and test conditions, see the Electrical Characteristics. The guaranteed specifications apply only for the test conditions listed.

Note 2: Refer to RETS117H drawing for the LM117H, or the RETS117K for the LM117K military specifications.

Note 3: $I_{MAX} = 1.5\text{A}$ for the K (TO-3), T (TO-220), and S (TO-263) packages. $I_{MAX} = 1.0\text{A}$ for the EMP (SOT-223) package. $I_{MAX} = 0.5\text{A}$ for the H (TO-39), MDT (TO-252), and E (LCC) packages. Device power dissipation (P_D) is limited by ambient temperature (T_A), device maximum junction temperature (T_J), and package thermal resistance (θ_{JA}). The maximum allowable power dissipation at any temperature is: $P_{D(MAX)} = ((T_{J(MAX)} - T_A)/\theta_{JA})$. All Min. and Max. limits are guaranteed to National's Average Outgoing Quality Level (AOQL).

Note 4: Regulation is measured at a constant junction temperature, using pulse testing with a low duty cycle. Changes in output voltage due to heating effects are covered under the specifications for thermal regulation.

Note 5: Human body model, 100 pF discharged through a 1.5 k Ω resistor.

Note 6: When surface mount packages are used (TO-263, SOT-223, TO-252), the junction to ambient thermal resistance can be reduced by increasing the PC board copper area that is thermally connected to the package. See the Applications Hints section for heatsink techniques.

Application Hints

In operation, the LM117 develops a nominal 1.25V reference voltage, V_{REF} , between the output and adjustment terminal. The reference voltage is impressed across program resistor $R1$ and, since the voltage is constant, a constant current I_1 then flows through the output set resistor $R2$, giving an output voltage of

$$V_{OUT} = V_{REF} \left(1 + \frac{R2}{R1} \right) + I_{ADJ}R2 \quad (1)$$

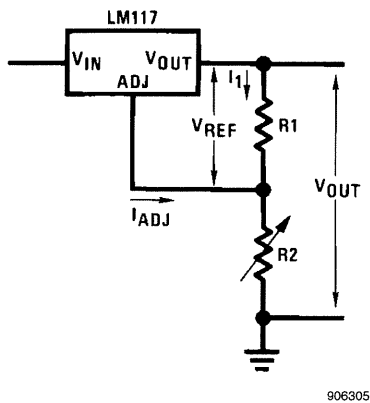


FIGURE 1.

Since the 100 μ A current from the adjustment terminal represents an error term, the LM117 was designed to minimize I_{ADJ} and make it very constant with line and load changes. To do this, all quiescent operating current is returned to the output establishing a minimum load current requirement. If there is insufficient load on the output, the output will rise.

EXTERNAL CAPACITORS

An input bypass capacitor is recommended. A 0.1 μ F disc or 1 μ F solid tantalum on the input is suitable input bypassing for almost all applications. The device is more sensitive to the absence of input bypassing when adjustment or output capacitors are used but the above values will eliminate the possibility of problems.

The adjustment terminal can be bypassed to ground on the LM117 to improve ripple rejection. This bypass capacitor prevents ripple from being amplified as the output voltage is increased. With a 10 μ F bypass capacitor 80dB ripple rejection is obtainable at any output level. Increases over 10 μ F do not appreciably improve the ripple rejection at frequencies above 120Hz. If the bypass capacitor is used, it is sometimes necessary to include protection diodes to prevent the capacitor from discharging through internal low current paths and damaging the device.

In general, the best type of capacitors to use is solid tantalum. Solid tantalum capacitors have low impedance even at high frequencies. Depending upon capacitor construction, it takes about 25 μ F in aluminum electrolytic to equal 1 μ F solid tantalum at high frequencies. Ceramic capacitors are also good at high frequencies; but some types have a large decrease in capacitance at frequencies around 0.5 MHz. For this reason, 0.01 μ F disc may seem to work better than a 0.1 μ F disc as a bypass.

Although the LM117 is stable with no output capacitors, like any feedback circuit, certain values of external capacitance can cause excessive ringing. This occurs with values between 500 pF and 5000 pF. A 1 μ F solid tantalum (or 25 μ F

aluminum electrolytic) on the output swamps this effect and insures stability. Any increase of the load capacitance larger than 10 μ F will merely improve the loop stability and output impedance.

LOAD REGULATION

The LM117 is capable of providing extremely good load regulation but a few precautions are needed to obtain maximum performance. The current set resistor connected between the adjustment terminal and the output terminal (usually 240 Ω) should be tied directly to the output (case) of the regulator rather than near the load. This eliminates line drops from appearing effectively in series with the reference and degrading regulation. For example, a 15V regulator with 0.05 Ω resistance between the regulator and load will have a load regulation due to line resistance of $0.05\Omega \times I_L$. If the set resistor is connected near the load the effective line resistance will be $0.05\Omega (1 + R2/R1)$ or in this case, 11.5 times worse.

Figure 2 shows the effect of resistance between the regulator and 240 Ω set resistor.

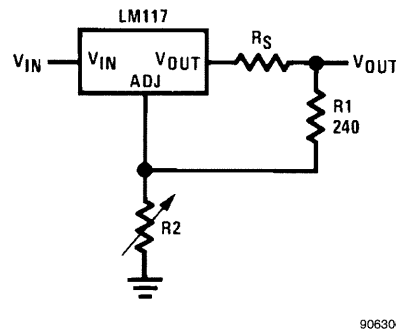


FIGURE 2. Regulator with Line Resistance in Output Lead

With the TO-3 package, it is easy to minimize the resistance from the case to the set resistor, by using two separate leads to the case. However, with the TO-39 package, care should be taken to minimize the wire length of the output lead. The ground of $R2$ can be returned near the ground of the load to provide remote ground sensing and improve load regulation.

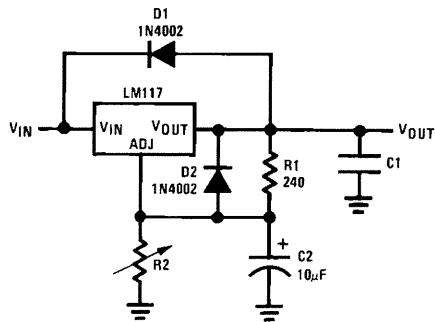
PROTECTION DIODES

When external capacitors are used with any IC regulator it is sometimes necessary to add protection diodes to prevent the capacitors from discharging through low current points into the regulator. Most 10 μ F capacitors have low enough internal series resistance to deliver 20A spikes when shorted. Although the surge is short, there is enough energy to damage parts of the IC.

When an output capacitor is connected to a regulator and the input is shorted, the output capacitor will discharge into the output of the regulator. The discharge current depends on the value of the capacitor, the output voltage of the regulator, and the rate of decrease of V_{IN} . In the LM117, this discharge path is through a large junction that is able to sustain 15A surge with no problem. This is not true of other types of positive regulators. For output capacitors of 25 μ F or less, there is no need to use diodes.

The bypass capacitor on the adjustment terminal can discharge through a low current junction. Discharge occurs when either the input, or the output, is shorted. Internal to the LM117 is a 50 Ω resistor which limits the peak discharge current. No protection is needed for output voltages of 25V or less and 10 μ F capacitance. Figure 3 shows an LM117 with protection

diodes included for use with outputs greater than 25V and high values of output capacitance.



$$V_{OUT} = 1.25V \left(1 + \frac{R_2}{R_1} \right) + I_{ADJ}R_2 \quad (2)$$

D1 protects against C1
D2 protects against C2

FIGURE 3. Regulator with Protection Diodes

HEATSINK REQUIREMENTS

The LM317 regulators have internal thermal shutdown to protect the device from over-heating. Under all operating conditions, the junction temperature of the LM317 should not exceed the rated maximum junction temperature (T_J) of 150°C for the LM117, or 125°C for the LM317A and LM317. A heatsink may be required depending on the maximum device power dissipation and the maximum ambient temperature of the application. To determine if a heatsink is needed, the power dissipated by the regulator, P_D , must be calculated:

$$P_D = ((V_{IN} - V_{OUT}) \times I_L) + (V_{IN} \times I_G) \quad (3)$$

Figure 4 shows the voltage and currents which are present in the circuit.

The next parameter which must be calculated is the maximum allowable temperature rise, $T_{R(MAX)}$:

$$T_{R(MAX)} = T_{J(MAX)} - T_{A(MAX)} \quad (4)$$

where $T_{J(MAX)}$ is the maximum allowable junction temperature (150°C for the LM117, or 125°C for the LM317A/LM317), and $T_{A(MAX)}$ is the maximum ambient temperature which will be encountered in the application.

Using the calculated values for $T_{R(MAX)}$ and P_D , the maximum allowable value for the junction-to-ambient thermal resistance (θ_{JA}) can be calculated:

$$\theta_{JA} = (T_{R(MAX)} / P_D) \quad (5)$$

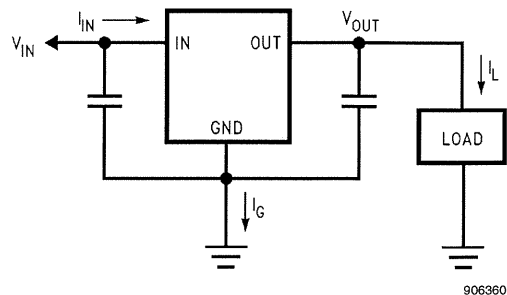


FIGURE 4. Power Dissipation Diagram

If the calculated maximum allowable thermal resistance is higher than the actual package rating, then no additional work is needed. If the calculated maximum allowable thermal resistance is lower than the actual package rating either the power dissipation (P_D) needs to be reduced, the maximum ambient temperature $T_{A(MAX)}$ needs to be reduced, the thermal resistance (θ_{JA}) must be lowered by adding a heatsink, or some combination of these.

If a heatsink is needed, the value can be calculated from the formula:

$$\theta_{HA} \leq (\theta_{JA} - (\theta_{CH} + \theta_{JC})) \quad (6)$$

where θ_{CH} is the thermal resistance of the contact area between the device case and the heatsink surface, and θ_{JC} is thermal resistance from the junction of the die to surface of the package case.

When a value for $\theta_{(H-A)}$ is found using the equation shown, a heatsink must be selected that has a value that is less than, or equal to, this number.

The $\theta_{(H-A)}$ rating is specified numerically by the heatsink manufacturer in the catalog, or shown in a curve that plots temperature rise vs power dissipation for the heatsink.

HEATSINKING SURFACE MOUNT PACKAGES

The TO-263 (S), SOT-223 (EMP) and TO-252 (MDT) packages use a copper plane on the PCB and the PCB itself as a heatsink. To optimize the heat sinking ability of the plane and PCB, solder the tab of the package to the plane.

HEATSINKING THE SOT-223 PACKAGE

Figure 5 and Figure 6 show the information for the SOT-223 package. Figure 6 assumes a $\theta_{(J-A)}$ of 74°C/W for 1 ounce copper and 51°C/W for 2 ounce copper and a maximum junction temperature of 125°C. Please see AN-1028 for thermal enhancement techniques to be used with SOT-223 and TO-252 packages.

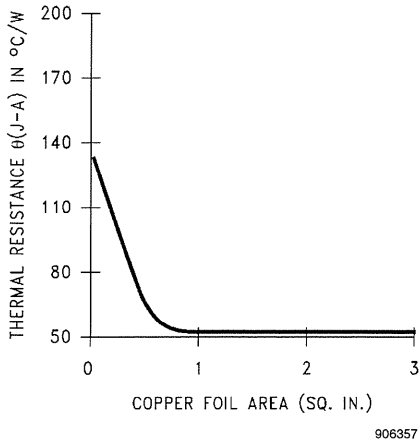


FIGURE 5. $\theta_{(J-A)}$ vs Copper (2 ounce) Area for the SOT-223 Package

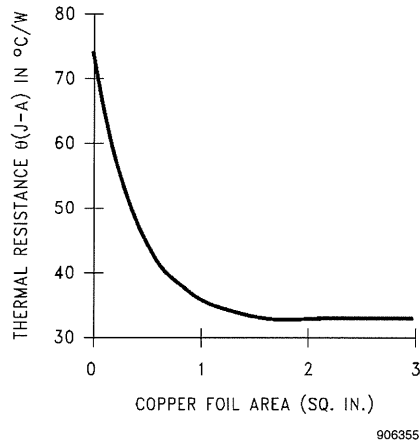


FIGURE 7. $\theta_{(J-A)}$ vs Copper (1 ounce) Area for the TO-263 Package

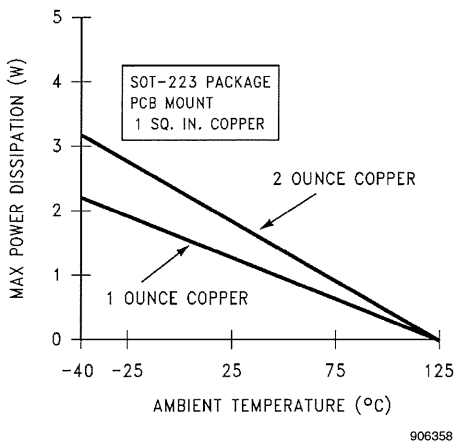


FIGURE 6. Maximum Power Dissipation vs T_{AMB} for the SOT-223 Package

As a design aid, *Figure 8* shows the maximum allowable power dissipation compared to ambient temperature for the TO-263 device (assuming $\theta_{(J-A)}$ is 35°C/W and the maximum junction temperature is 125°C).

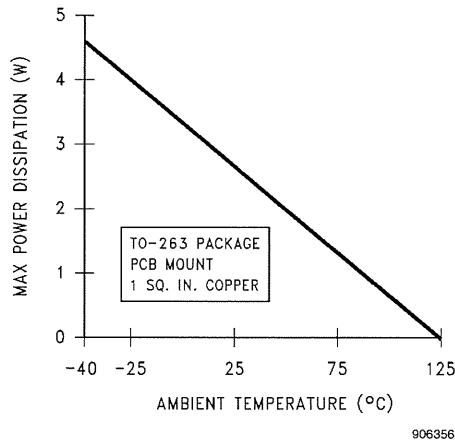


FIGURE 8. Maximum Power Dissipation vs T_{AMB} for the TO-263 Package

HEATSINKING THE TO-263 PACKAGE

Figure 7 shows for the TO-263 the measured values of $\theta_{(J-A)}$ for different copper area sizes using a typical PCB with 1 ounce copper and no solder mask over the copper area used for heatsinking.

As shown in *Figure 7*, increasing the copper area beyond 1 square inch produces very little improvement. It should also be observed that the minimum value of $\theta_{(J-A)}$ for the TO-263 package mounted to a PCB is 32°C/W .

HEATSINKING THE TO-252 PACKAGE

If the maximum allowable value for θ_{JA} is found to be $\geq 103^{\circ}\text{C/W}$ (Typical Rated Value) for TO-252 package, no heatsink is needed since the package alone will dissipate enough heat to satisfy these requirements. If the calculated value for θ_{JA} falls below these limits, a heatsink is required.

As a design aid, *Table 1* shows the value of the θ_{JA} of TO-252 for different heatsink area. The copper patterns that we used to measure these θ_{JA} s are shown at the end of the Application Notes Section. *Figure 9* reflects the same test results as what are in *Table 1*.

Figure 10 shows the maximum allowable power dissipation vs. ambient temperature for the TO-252 device. *Figure 11* shows the maximum allowable power dissipation vs. copper area (in^2) for the TO-252 device. Please see AN-1028 for thermal enhancement techniques to be used with SOT-223 and TO-252 packages.

LM78LXX Series 3-Terminal Positive Regulators

General Description

The LM78LXX series of three terminal positive regulators is available with several fixed output voltages making them useful in a wide range of applications. When used as a zener diode/resistor combination replacement, the LM78LXX usually results in an effective output impedance improvement of two orders of magnitude, and lower quiescent current. These regulators can provide local on card regulation, eliminating the distribution problems associated with single point regulation. The voltages available allow the LM78LXX to be used in logic systems, instrumentation, HiFi, and other solid state electronic equipment.

The LM78LXX is available in the plastic TO-92 (Z) package, the plastic SO-8 (M) package and a chip sized package (8-Bump micro SMD) using National's micro SMD package technology. With adequate heat sinking the regulator can deliver 100mA output current. Current limiting is included to limit the peak output current to a safe value. Safe area protection for the output transistors is provided to limit inter-

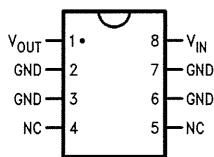
nal power dissipation. If internal power dissipation becomes too high for the heat sinking provided, the thermal shutdown circuit takes over preventing the IC from overheating.

Features

- LM78L05 in micro SMD package
- Output voltage tolerances of $\pm 5\%$ over the temperature range
- Output current of 100mA
- Internal thermal overload protection
- Output transistor safe area protection
- Internal short circuit current limit
- Available in plastic TO-92 and plastic SO-8 low profile packages
- No external components
- Output voltages of 5.0V, 6.2V, 8.2V, 9.0V, 12V, 15V
- See AN-1112 for micro SMD considerations

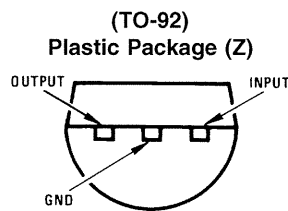
Connection Diagrams

SO-8 Plastic (M)
(Narrow Body)



00774402

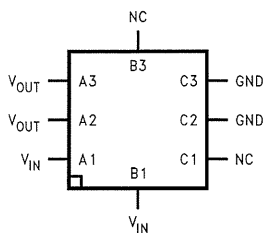
Top View



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Bottom View

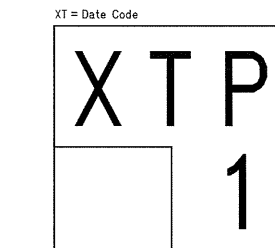
8-Bump micro SMD



00774424

Top View
(Bump Side Down)

micro SMD Marking Orientation



Pin A1 Corner
Pin A1 is identified by lower left corner with respect to the text.

00774433

Top View

Absolute Maximum Ratings (Note 1)

If Military/Aerospace specified devices are required, please contact the National Semiconductor Sales Office/Distributors for availability and specifications.

Power Dissipation (Note 5)	Internally Limited
Input Voltage	35V
Storage Temperature	-65°C to +150°C
ESD Susceptibility (Note 2)	1kV

Operating Junction Temperature

SO-8, TO-92	0°C to 125°C
micro SMD	-40°C to 85°C

Soldering Information

Infrared or Convection (20 sec.)	235°C
Wave Soldering (10 sec.)	260°C (lead time)

LM78LXX Electrical Characteristics

Limits in standard typeface are for $T_j = 25^\circ\text{C}$, **Bold typeface applies over 0°C to 125°C for SO-8 and TO-92 packages, and -40°C to 85°C for micro SMD package.** Limits are guaranteed by production testing or correlation techniques using standard Statistical Quality Control (SQC) methods. Unless otherwise specified: $I_O = 40\text{mA}$, $C_1 = 0.33\mu\text{F}$, $C_O = 0.1\mu\text{F}$.

LM78L05Unless otherwise specified, $V_{IN} = 10\text{V}$

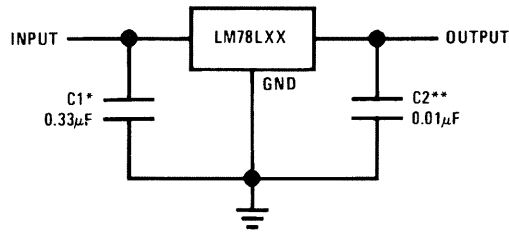
Symbol	Parameter	Conditions	Min	Typ	Max	Units
V_O	Output Voltage		4.8	5	5.2	V
		$7\text{V} \leq V_{IN} \leq 20\text{V}$ $1\text{mA} \leq I_O \leq 40\text{mA}$ (Note 3)	4.75		5.25	
		$1\text{mA} \leq I_O \leq 70\text{mA}$ (Note 3)	4.75		5.25	
ΔV_O	Line Regulation	$7\text{V} \leq V_{IN} \leq 20\text{V}$		18	75	mV
		$8\text{V} \leq V_{IN} \leq 20\text{V}$		10	54	
ΔV_O	Load Regulation	$1\text{mA} \leq I_O \leq 100\text{mA}$		20	60	mV
		$1\text{mA} \leq I_O \leq 40\text{mA}$		5	30	
I_Q	Quiescent Current			3	5	mA
ΔI_Q	Quiescent Current Change	$8\text{V} \leq V_{IN} \leq 20\text{V}$ $1\text{mA} \leq I_O \leq 40\text{mA}$			1.0 0.1	
V_n	Output Noise Voltage	$f = 10\text{ Hz to } 100\text{ kHz}$ (Note 4)		40		μV
$\frac{\Delta V_{IN}}{\Delta V_{OUT}}$	Ripple Rejection	$f = 120\text{ Hz}$ $8\text{V} \leq V_{IN} \leq 16\text{V}$	47	62		dB
I_{PK}	Peak Output Current			140		mA
$\frac{\Delta V_O}{\Delta T}$	Average Output Voltage Tempco	$I_O = 5\text{mA}$		-0.65		$\text{mV}/^\circ\text{C}$
$V_{IN}(\text{Min})$	Minimum Value of Input Voltage Required to Maintain Line Regulation			6.7	7	V
θ_{JA}	Thermal Resistance (8-Bump micro SMD)			230.9		$^\circ\text{C}/\text{W}$

LM78L62ACUnless otherwise specified, $V_{IN} = 12\text{V}$

Symbol	Parameter	Conditions	Min	Typ	Max	Units
V_O	Output Voltage		5.95	6.2	6.45	V
		$8.5\text{V} \leq V_{IN} \leq 20\text{V}$ $1\text{mA} \leq I_O \leq 40\text{mA}$ (Note 3)	5.9		6.5	
		$1\text{mA} \leq I_O \leq 70\text{mA}$ (Note 3)	5.9		6.5	

Typical Applications

Fixed Output Regulator

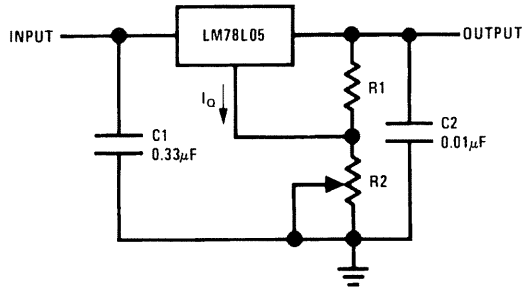


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*Required if the regulator is located more than 3" from the power supply filter.

**See (Note 4) in the electrical characteristics table.

Adjustable Output Regulator

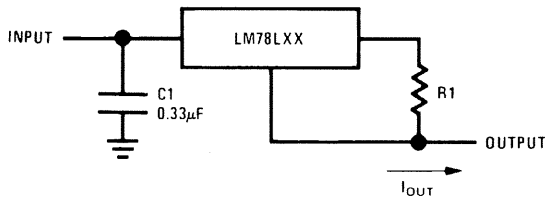


00774409

$$V_{OUT} = 5V + (5V/R1 + I_Q) R2$$

$$5V/R1 > 3 I_Q, \text{ load regulation } (L_r) \approx [(R1 + R2)/R1] (L_r \text{ of LM78L05})$$

Current Regulator

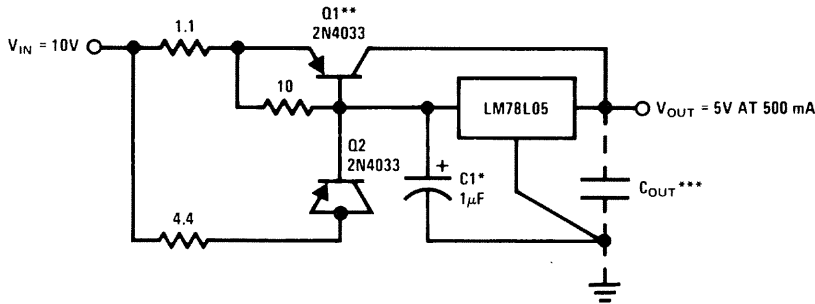


00774410

$$I_{OUT} = (V_{OUT}/R1) + I_Q$$

$$>I_Q = 1.5\text{mA over line and load changes}$$

5V, 500mA Regulator with Short Circuit Protection



00774411

*Solid tantalum.

**Heat sink Q1.

***Optional: Improves ripple rejection and transient response.

Load Regulation: $0.6\% \leq I_L \leq 250\text{mA}$ pulsed with $t_{ON} = 50\text{ms}$.



+5V to ±10V Voltage Converters

MAX680/MAX681

General Description

The MAX680/MAX681 are monolithic, CMOS, dual charge-pump voltage converters that provide ±10V outputs from a +5V input voltage. The MAX680/MAX681 provide both a positive step-up charge pump to develop +10V from +5V input and an inverting charge pump to generate the -10V output. Both parts have an on-chip, 8kHz oscillator. The MAX681 has the capacitors internal to the package, and the MAX680 requires four external capacitors to produce both positive and negative voltages from a single supply.

The output source impedances are typically 150Ω, providing useful output currents up to 10mA. The low quiescent current and high efficiency make this device suitable for a variety of applications that need both positive and negative voltages generated from a single supply.

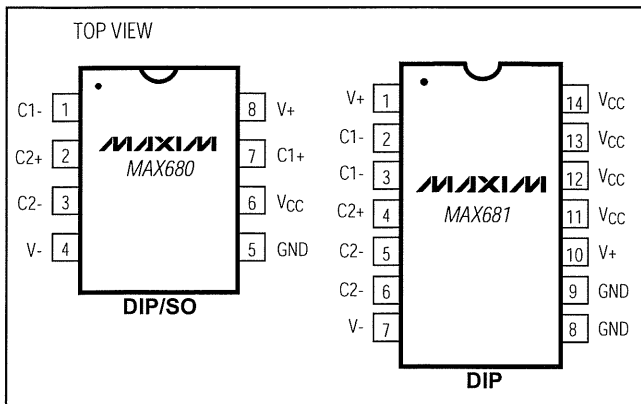
The MAX864/MAX865 are also recommended for new designs. The MAX864 operates at up to 200kHz and uses smaller capacitors. The MAX865 comes in the smaller μMAX package.

Applications

The MAX680/MAX681 can be used wherever a single positive supply is available and where positive and negative voltages are required. Common applications include generating ±6V from a 3V battery and generating ±10V from the standard +5V logic supply (for use with analog circuitry). Typical applications include:

- ±6V from 3V Lithium Cell
- Hand-Held Instruments
- Data-Acquisition Systems
- Panel Meters
- ±10V from +5V Logic Supply
- Battery-Operated Equipment
- Operational Amplifier Power Supplies

Pin Configurations



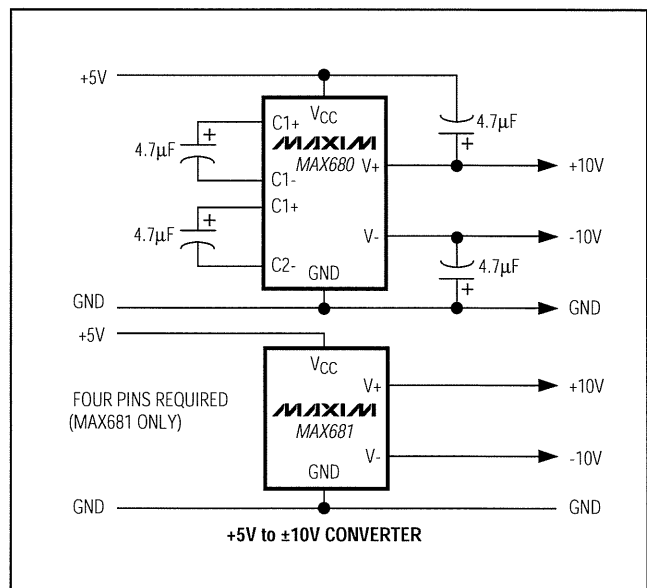
Features

- ◆ 95% Voltage-Conversion Efficiency
- ◆ 85% Power-Conversion Efficiency
- ◆ +2V to +6V Voltage Range
- ◆ Only Four External Capacitors Required (MAX680)
- ◆ No Capacitors Required (MAX681)
- ◆ 500μA Supply Current
- ◆ Monolithic CMOS Design

Ordering Information

PART	TEMP. RANGE	PIN-PACKAGE
MAX680CPA	0°C to +70°C	8 Plastic DIP
MAX680CSA	0°C to +70°C	8 Narrow SO
MAX680C/D	0°C to +70°C	Dice
MAX680EPA	-40°C to +85°C	8 Plastic DIP
MAX680ESA	-40°C to +85°C	8 Narrow SO
MAX680MJA	-55°C to +125°C	8 CERDIP
MAX681CPD	0°C to +70°C	14 Plastic DIP
MAX681EPD	-40°C to +85°C	14 Plastic DIP

Typical Operating Circuits



+5V to ±10V Voltage Converters

ABSOLUTE MAXIMUM RATINGS

V _{CC}	+6.2V	Continuous Power Dissipation (T _A = +70°C)
V ₊	+12V	8-Pin Plastic DIP (derate 9.09mW/°C above +70°C)
V ₋	-12V	8-Pin Narrow SO (derate 5.88mW/°C above +70°C)
V- Short-Circuit Duration	Continuous	8-Pin CERDIP (derate 8.00mW/°C above +70°C)
V ₊ Current	75mA	14-Pin Plastic DIP (derate 10.00mW/°C above +70°C)
V _{CC} ΔV/ΔT	1V/μs	Storage Temperature Range
		Lead Temperature (soldering, 10sec)

Stresses beyond those listed under "Absolute Maximum Ratings" may cause permanent damage to the device. These are stress ratings only, and functional operation of the device at these or any other conditions beyond those indicated in the operational sections of the specifications is not implied. Exposure to absolute maximum rating conditions for extended periods may affect device reliability.

ELECTRICAL CHARACTERISTICS

(V_{CC} = +5V, test circuit Figure 1, T_A = +25°C, unless otherwise noted.)

PARAMETER	CONDITIONS	MIN	TYP	MAX	UNITS	
Supply Current	V _{CC} = 3V, T _A = +25°C, R _L = ∞		0.5	1	mA	
	V _{CC} = 5V, T _A = +25°C, R _L = ∞		1	2		
	V _{CC} = 5V, 0°C ≤ T _A ≤ +70°C, R _L = ∞			2.5		
	V _{CC} = 5V, -40°C ≤ T _A ≤ +85°C, R _L = ∞			3		
	V _{CC} = 5V, -55°C ≤ T _A ≤ +125°C, R _L = ∞			3		
Supply-Voltage Range	MIN ≤ T _A ≤ MAX, R _L = 10kΩ	2.0	1.5 to 6.0	6.0	V	
Positive Charge-Pump Output Source Resistance	I _{L+} = 10mA, I _{L-} = 0mA, V _{CC} = 5V, T _A = +25°C		150	250	Ω	
	I _{L+} = 5mA, I _{L-} = 0mA, V _{CC} = 2.8V, T _A = +25°C		180	300		
	I _{L+} = 10mA, I _{L-} = 0mA, V _{CC} = 5V	0°C ≤ T _A ≤ +70°C				325
		-40°C ≤ T _A ≤ +85°C				350
	-55°C ≤ T _A ≤ +125°C			400		
Negative Charge-Pump Output Source Resistance	I _{L-} = 10mA, I _{L+} = 0mA, V ₊ = 10V, T _A = +25°C		90	150	Ω	
	I _{L-} = 5mA, I _{L+} = 0mA, V ₊ = 5.6V, T _A = +25°C		110	175		
	I _{L-} = 10mA, I _{L+} = 0mA, V ₊ = 10V	0°C ≤ T _A ≤ +70°C				200
		-40°C ≤ T _A ≤ +85°C				200
	-55°C ≤ T _A ≤ +125°C			250		
Oscillator Frequency		4	8		kHz	
Power Efficiency	R _L = 10kΩ		85		%	
Voltage-Conversion Efficiency	V ₊ , R _L = ∞	95	99		%	
	V ₋ , R _L = ∞	90	97			

+5V to ±10V Voltage Converters

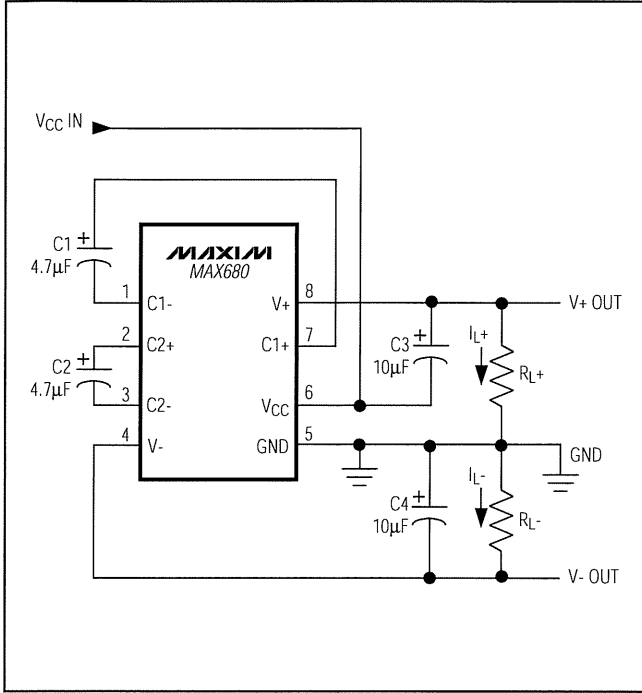


Figure 1. Test Circuit

Detailed Description

The MAX681 contains all circuitry needed to implement a dual charge pump. The MAX680 needs only four capacitors. These may be inexpensive electrolytic capacitors with values in the $1\mu\text{F}$ to $100\mu\text{F}$ range. The MAX681 contains two $1.5\mu\text{F}$ capacitors as C1 and C2, and two $2.2\mu\text{F}$ capacitors as C3 and C4. See *Typical Operating Characteristics*.

Figure 2a shows the idealized operation of the positive voltage converter. The on-chip oscillator generates a 50% duty-cycle clock signal. During the first half of the cycle, switches S2 and S4 are open, S1 and S3 are closed, and capacitor C1 is charged to the input voltage V_{CC} . During the second half-cycle, S1 and S3 are open, S2 and S4 are closed, and C1 is translated upward by V_{CC} volts. Assuming ideal switches and no load on C3, charge is transferred onto C3 from C1 such that the voltage on C3 will be $2V_{CC}$, generating the positive supply.

Figure 2b shows the negative converter. The switches of the negative converter are out of phase from the positive converter. During the second half of the clock cycle, S6 and S8 are open and S5 and S7 are closed, charging C2 from V_+ (pumped up to $2V_{CC}$ by the positive charge pump) to GND. In the first half of the clock

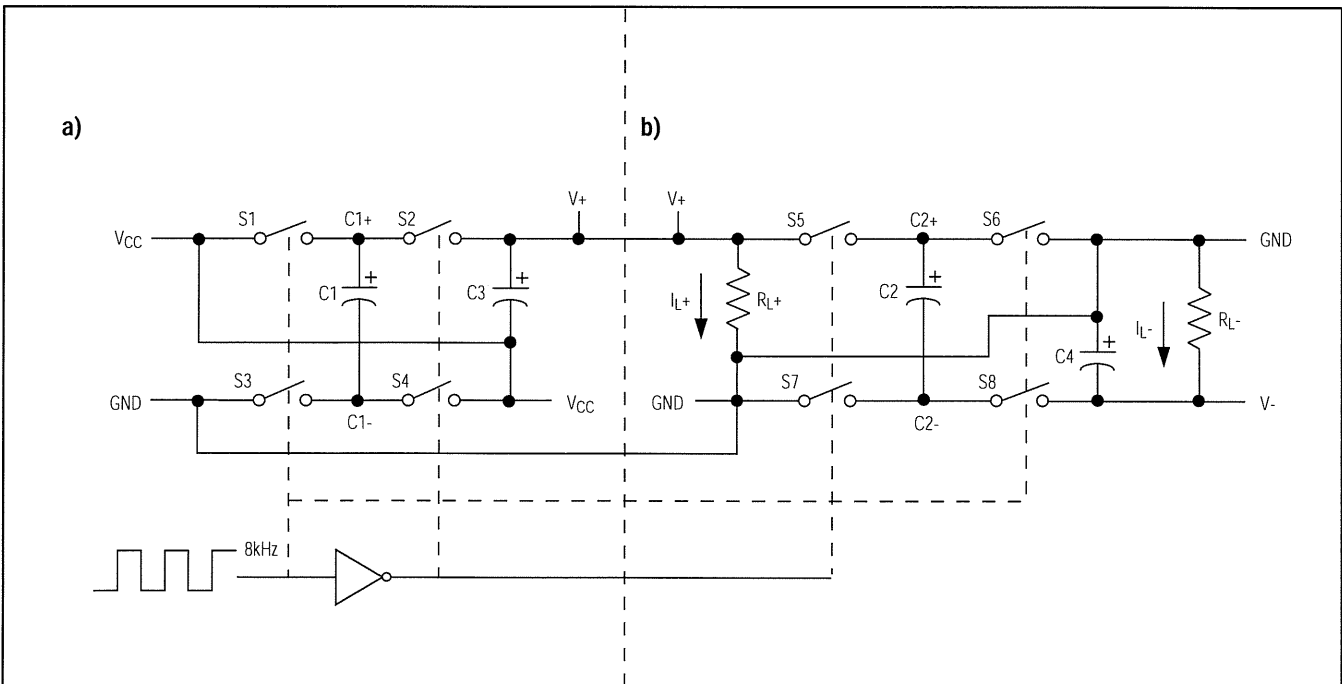


Figure 2. Idealized Voltage Quadrupler: a) Positive Charge Pump; b) Negative Charge Pump

+5V to ±10V Voltage Converters

cycle, S5 and S7 are open, S6 and S8 are closed, and the charge on C2 is transferred to C4, generating the negative supply. The eight switches are CMOS power MOSFETs. S1, S2, S4, and S5 are P-channel switches, while S3, S6, S7, and S8 are N-channel switches.

Efficiency Considerations

Theoretically, a charge-pump voltage multiplier can approach 100% efficiency under the following conditions:

- The charge-pump switches have virtually no offset and extremely low on-resistance
- Minimal power is consumed by the drive circuitry
- The impedances of the reservoir and pump capacitors are negligible

For the MAX680/MAX681, the energy loss per clock cycle is the sum of the energy loss in the positive and negative converters as below:

$$\begin{aligned} \text{LOSS}_{\text{TOT}} &= \text{LOSS}_{\text{POS}} + \text{LOSS}_{\text{NEG}} \\ &= \frac{1}{2} C_1 [(V_+)^2 - (V_+)(V_{CC})] + \\ &\quad \frac{1}{2} C_2 [(V_+)^2 - (V_-)^2] \end{aligned}$$

There will be a substantial voltage difference between $(V_+ - V_{CC})$ and V_{CC} for the positive pump, and between V_+ and V_- , if the impedances of pump capacitors C1 and C2 are high relative to their respective output loads.

Larger C3 and C4 reservoir capacitor values reduce output ripple. Larger values of both pump and reservoir capacitors improve efficiency.

Maximum Operating Limits

The MAX680/MAX681 have on-chip zener diodes that clamp V_{CC} to approximately 6.2V, V_+ to 12.4V, and V_- to -12.4V. Never exceed the maximum supply voltage: excessive current may be shunted by these diodes, potentially damaging the chip. The MAX680/MAX681 operate over the entire operating temperature range with an input voltage of +2V to +6V.

Applications

Positive and Negative Converter

The most common application of the MAX680/MAX681 is as a dual charge-pump voltage converter that provides positive and negative outputs of two times a positive input voltage. For applications where PC board space is at a premium, the MAX681, with its capacitors internal to the package, offers the smallest footprint. The simple circuit shown in Figure 3 performs the same function using the MAX680 with external capacitors C1 and C3 for the positive pump and C2 and C4 for the negative pump. In most applications, all four capacitors are low-cost, 10 μ F or 22 μ F polarized electrolytics. When using the MAX680 for low-current applications, 1 μ F can be used for C1 and C2 charge-pump capacitors, and 4.7 μ F for C3 and C4 reservoir capacitors. C1 and C3 must be rated at 6V or greater, and C2 and C4 must be rated at 12V or greater.

MAX680/MAX681

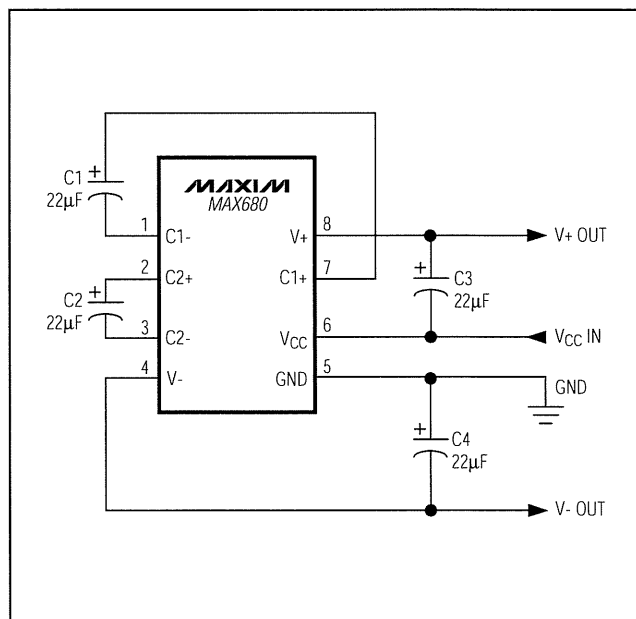


Figure 3. Positive and Negative Converter