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DIGITAL SOUND METER FOR MOVING VEHICLES

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Sean Nandakumar Vidanage

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Clark Radcliffe
Major Professor's Signature

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DIGITAL SOUND METER FOR MOVING VEHICLES

By

Sean Nandakumar Vidanage

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ABSTRACT

DIGITAL SOUND METER FOR MOVING VEHICLES

By

Sean Nandakumar Vidanage

Enforcement of reasonable boat noise standards is a problem for lake residents. This problem stems in large part from the complexity involved in making noise measurements in a repeatable, standardized way that can stand up to challenges in a court of law. Two specific noise measurement techniques are used by the State of Michigan: SAE J2005 and SAE J1970. The former delineates steps for testing idling boats, while the latter describes a procedure for testing lake-borne boats from the shoreline. These noise measurement procedures do not accurately reflect the maximum noise levels of operating boats, which are affected by distance and the background noise of other sources. Both standards use specific procedures with a generic background noise correction and neither uses a distance sensitive noise measurement device. These standards are more properly suited for boat manufacturer certification of boats, where background noise and distance can be controlled, and not as an enforcement standard. A new noise measurement standard specifically designed for ease of enforcement is required.

An accurate measure of normally operating boat noise is required for a useful noise measurement system. A device is needed to make a representative measure of the boat's acoustic power using measured boat sound level with integrated corrections for sensed distance to the boat and measured ambient sound level. This device needs to make this measurement process invisible, automatic, and accurate from a law enforcement point of view. This work describes the theoretical underpinnings, creation, and testing of such a device. With this device a new noise measurement system can be created which will allow law enforcement to enforce noise standards without complicated procedures and requirements.

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The author wishes to express his appreciation to Professor Radcliffe, Department of Mechanical Engineering, for his guidance in this project. Mr. Ned Wicks, of the Higgins Lake Association, deserves supreme thanks for starting this project. I hope the work contained within will help accomplish his vision. Thanks to Brad Rakerd, Professor of Audiology for his permission and assistance in using the College of Arts and Sciences anechoic chamber. Without his help this project would have been impossible. Also special thanks go out to Ms. Rebecca Sachs for editing and revision assistance for this manuscript.

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NOMENCLATURE

A	Area
c	speed of waveform (sound)
C	Background Correction (dB)
c	Speed of Sound
D	Distance Correction
I	Acoustic Intensity (W/m2)
M	Measured Sound Level
M_{corr}	Corrected Output of Boat Noise Gun
p	Acoustic Pressure
$Pref$	Reference Pressure
P_{source}	Acoustic Power
Psource	square of the acoustic pressure
$Psource$	Acoustic Power
r	radius
ρ	Air Density
rho	density of air
SPL	Sound pressure Level (dB)
x_d	dB decay per doubling of distance
yb	Mean Squared of Backround Sound
Yb	Total background sound
ym	Mean Squared of Measured Sound
Ym	Total Measured Sound
ys	Mean Squared of Source Sound
Ys	Total Source Sound

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Chapter 1

INTRODUCTION

Excessive noise levels on lakes are the source of many community problems. Given the increasing numbers of boats on lakes, shoreline residents who wish to maintain a peaceful environment have a vested interest in controlling noise pollution. An outdated Michigan statute (Act 303 of 1967) read as follows: "A person shall not operate a motorboat on the waters of this state in a manner that disturbs the peace of others." This line was omitted in future versions of the Act, and underscores the problem today.

Current standards for monitoring noise levels of boats are written in the Michigan Marine Safety Act of 1994 (Michigan 1994). The current standards, SAE J2005 (SAE 1991b) and SAE J1970 (SAE 1991a), tend to discourage the state law officials who try to apply and enforce them. The SAE J2005 standard requires that the target boat be tethered to either another boat or a dock. The engine motor is set to idle, and the measurement is taken 3 feet away. This requires extraordinary cooperation not only from the vehicle operator, but also from all other boats in the immediate environment. The SAE J1970 standard is a shoreline-based measurement of the boat noise. The measurement is taken from the shore, as long as the boat is not within 30 seconds of leaving or returning to shore. SAE J1970 can only be used when the offending boat is alone on the water and near to shore. Neither noise level standard has ever been successful in convicting a noisy boat operator in the State of Michigan.

The solution to the noise standards enforcement problem lies in the creation of a noise measurement standard, which allows the accurate measurement of the in-use noise level of a boat. The goal of the standard is to compute a value representative of the acoustic power of the boat source without requiring operator cooperation. Enforcing this standard would require a device that would compute a value representative of the noise level of a boat unaffected by distance, background noise level of other boats, and weather. In order to compute this representative value of acoustic power, a model of sound propagation is needed. With this model, and a distance measurement, the point sound pressure (dB) measurement can be related to the sound power of the boat. A measure of the background noise level is also needed so that the influence of other noise sources can be removed from the measurement. The purpose of this work is to create such a "Noise Gun." This device, coupled with redrafted statues, would finally allow law enforcement officers to enforce a reasonable noise level standard not only for boats, but for ATV's, snowmobiles, and other vehicles.

Chapter 2

BACKGROUND

The noise standards currently in effect in the State of Michigan are defined by the Marine Safety Act (Act 451 of 1994), part of which states:

> Sec. 80156. (1) Subject to subsection (2), a person shall not operate a motor boat on the waters of this state unless the motor boat is equipped and maintained with an effective muffler or underwater exhaust system that does not produce sound levels in excess of 90 dB(A) when subjected to a stationary sound level test as prescribed by SAE J2005 or a sound level in excess of 75 dB(A) when subjected to a shoreline sound level measurement procedure as described by SAE J1970.

This Act provides two sound level maximums for testing under specific conditions: the SAE J1970 and J2005 test procedure standards, written by the Society of Automotive Engineers (1991a, b). In order to understand these limits, we must look at the two standard tests in detail.

The J2005 is intended as a stationary test for motorboats. This test is designed to determine whether a boat's muffling system is adequate to reduce the sound power of the boat. The basic procedure is as follows:

- The boat must be docked or tied to another boat.
- The boat must be in a neutral gear, or at its lowest idle speed possible.
- The microphone must be placed 1.2 to 1.5 m (4 to 5 ft) above the water, and no closer than 1 m (3.3 ft) from the boat itself.
- The background noise level must be at least 10 dB lower than the level of the boat.

The J2005 test was designed mainly because stationary tests are easier to conduct than tests performed while boats are in motion. There are many problems with stationary tests, however. The process of identifying a noisy boat, chasing it down, lashing it to a police boat, and then administering the test is long and cumbersome, besides being impossible to conduct in rough water. Furthermore, newer boats have a "captain's choice" exhaust, which allows boat operators to switch between underwater exhaust and unmuffled air exhaust. Obviously, when a test is administered, a captain would switch to the quieter underwater exhaust system. The J2005 test simply does not address the problem of unreasonably noisy boats on the water.

The J1970 standard is meant to test the sound level of boats as perceived on the shoreline by riparian owners, the originators of most of the complaints. The basic procedure in this test is:

- The measurement must be taken either on shore or on a dock not more than 6 m (20 ft) from shore.

- The microphone must be placed 1.2 to 1.5 m (4 to 5 ft) above the water.
- There is no distance requirement to the target boat. The boat must not be measured 30 seconds after it launches or its last 30 seconds coming into the dock.
- The background level must be at least 10 dB lower than the level of the boat.

Theoretically, the use of a shore measurement should be enough to satisfy shoreline residents regarding boat noise. However, there are problems with this test as well. First of all, it is not easy to perform unless there is only one boat on the water, which never happens in the busy summer season. Secondly, the noisy boat can be over a mile away, but this test is impossible to conduct at such a distance. These tests, if enforcement were easy to carry out, would alleviate some of the noise problem. However, the many intricacies of measurement procedures, coupled with the variables that affect noise level which are not taken into account, produce loopholes so that citations can be challenged successfully in the court. Therefore the J1970 and J2005 standards are inadequate for enforcing a noise measurement standard for boats in-use on the water.

The SAE J34 standard (SAE 2001) is referred to in the laws of 14 states. It seeks to provide a comprehensive test to determine the maximum sound level of the boat in use. A summary of this test is as follows:

- A test site must be created as shown in Figure 1.
- The boat must pass within of 3 m (10 ft) on the outside of the buoys.

- The boat must be at +/- 100 rpm of its full throttle rpm range.
- The microphone must be placed 1.2 to 1.5 m (4 to 5 ft) above the water, and no less than 0.6 m (2 ft) above the dock surface.
- The background level must be at least 10 dB lower than the level of the boat.
- The wind speed must be below 19 km/h (13 mph).
- The peak reading as the boat completes the course shall be recorded.
- Two readings will be made for each side of the boat.

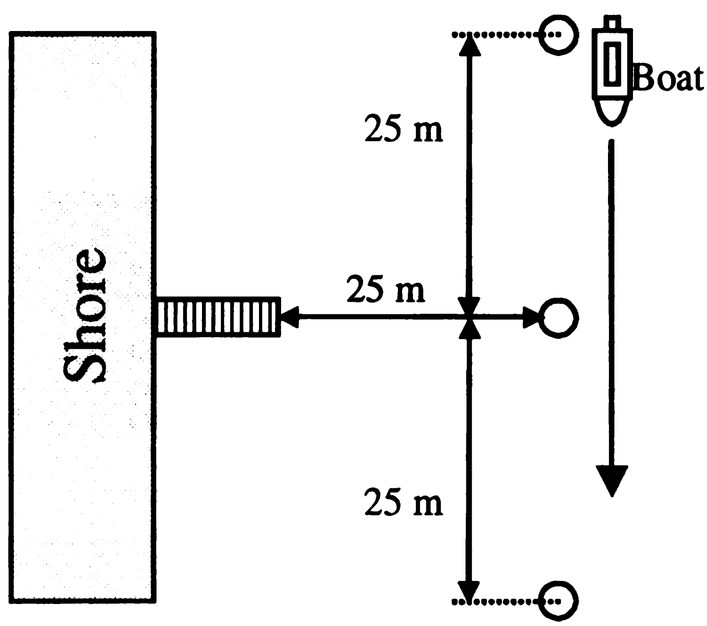

Figure 1: SAE J34 Test Layout

The J34 standard successfully measures the peak in-use noise level of the boat as it traverses the course. However, the complexity of setting up a course, and the range of variables which must be recorded, necessitate that there must be an officer in the boat as well as on the dock.

It requires skillful piloting, extremely calm conditions, and patient and qualified officers to administer the test. This standard is meant as a way for boat manufacturers to certify their boats are compliant with noise standards, rather than as an on-lake test for noisy boaters. The J34 test provides a measured value that is related to the sound power of the boat. However, the difficulty in administering this test limits its usefulness for enforcement of noise statues.

J1970, J2005, and J35 are not the only measurement standards used in the US, however, almost all states that have noise statues follow one or more of these three SAE standards. A complete listing of state standards is listed in Appendix A, and summarized in Table 1.

Table 1: Summary of State Noise Enforcement Standards

Standard	# of States
J1970	7
J2005	12
J34	14
Officer Discretion	9
Other (state standard)	11
None	6

Accurate measurement of acoustic power from a boat is difficult enough that nine states simply use officer discretion as a method of determining if a boat is overly noisy. The need for a new noise measurement standard is clear when no state has a method of easily measuring the in-use boat noise level. In Table 2, we outline the pros and cons of the three most widely used noise measurement standards, J1970, J2005, and J34. The main problem with the standards is shown in the first row. The J1970 standard is a measurement of boat noise as it is heard on shore. The J2005 standard is a measurement of boat noise as the boat is idling. The J34 standard is a measure of the peak noise level of the boat only when it completes a specific predefined course. The new enforcement standard proposed in this document would calculate a value that is representative of the maximum acoustic power of the boat at any time.

Table 2: Summary of the J1970, J2005, and J34 Standards

Standard	J1970	J2005	J34
Measurement	Measures the emission from the boat only when near shore	Measures the emission from the boat at idle	Measures peak noise level from boat
Ease of use	Boaters' 100% cooperation needed, no other boats around	Boaters' 100% cooperation needed; time consuming	Boaters' 100% cooperation needed, requires 2 officers, complex test course setup
Real World Repeatability	Never repeatable	With extreme care, repeatable	With proper procedures, repeatable
Reliability of data in a court setting	Can challenge level of the boat; not separate from other nearby boats	Distance from boat to microphone critical, can be challenged	Reliable test if complicated procedures are followed exactly

A noise measurement device that is more advanced than a standard noise meter is required by the new standard. The meter will need to output a predicted minimum sound level of the boat at a standard distance away. This will allow for measurements to be compared to other boat measurements no matter how far the meter operator is from the boat. Sound propagation and measurement techniques need to be reviewed in order to make this prediction.

The Noise Gun will need to do these predictions in an invisible manner from the operator. The corrected noise level at a standard distance away will eliminate the problems of reliability of the measurement. The integration of this procedure into a single electronic instrument will eliminate the difficulty in use that plagues the other standards. With this device, the new noise measurement standard can be used easily for law enforcement.

Chapter 3

SOUND PROPAGATION

Knowledge of how sound propagates over water is necessary for our calculations. Since our goal is to measure the sound level at the position of the observer, and convert it into what the equivalent sound level would be at a standard distance from the source, we need to have a model of how sound propagates. We will look at two ideal cases, a point source and an infinite plate source, as well as one published study of boat noise propagation. We will also look at how background noise affects a measurement of sound level.

Spherical Propagation

Spherical sound propagation is one way to idealize the acoustic propagation field produced by a boat. The point produces a level of acoustic power, which then propagates uniformly away from the point over a sphere. The acoustic power is assumed constant at any distance from the point. The energy is spread over the sphere of radius r from the sound origin. This derivation is based on standard sound propagation theory, and Radcliffe (2002a), (Appendix D).

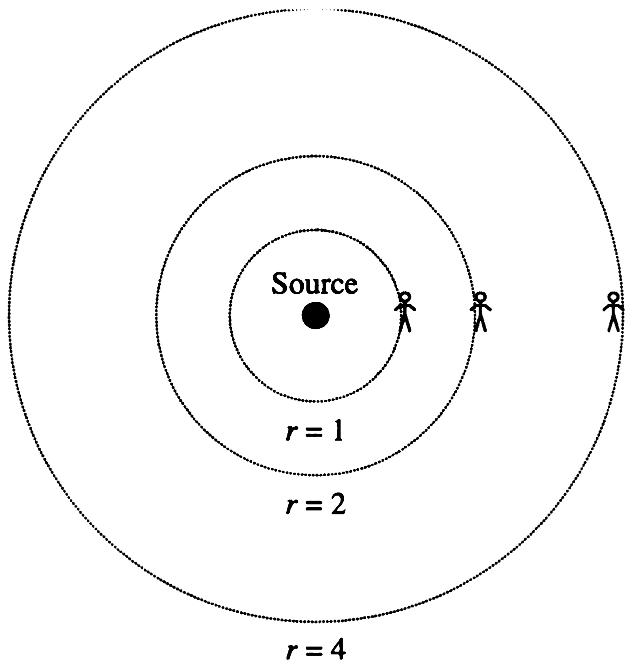

Figure 2: Sound Propagation from a Point Source

The acoustic intensity (*I*) is an energy flux (W/m^2). The acoustic power (P_{source}) is the integral of that flux over some sphere (radius *r*, surface area *A*) surrounding the source,

$$P_{source} = \int IdA = I(4\pi \ r^2) \tag{1}$$

Acoustic intensity is related to the square of the acoustic pressure (*p*), where ρ is the air density, and *c* is the speed the wave (sound),

$$I = \frac{p^2}{\rho c} \tag{2}$$

Relating the acoustic power to the acoustic pressure with (1) and (2),

$$\frac{p^2}{\rho c} = \frac{P_{source}}{4\pi r^2} \tag{3}$$

We wish to determine the relationship between the ratios of pressures to the ratio of distances

$$\frac{p_2}{p_1} = \frac{\sqrt{\rho c \left(P_{source}\right)/4\pi r_2^{\,2}}}{\sqrt{\rho c \left(P_{source}\right)/4\pi r_1^{\,2}}} = \frac{r_1}{r_2} \tag{4}$$

Sound pressure level is a function of acoustic pressure. It is specified in decibels, defined as

$$\text{SPL} = 20\log_{10}\left(\frac{p}{p_{ref}}\right) \tag{5}$$

where p_{ref} is a reference pressure $(2x10^{-5}\ \text{Pa})$,

The change in sound pressure level for two points is

$$\begin{aligned} \Delta\text{SPL} = \text{SPL}(r_2) - \text{SPL}(r_1) &= 20\log_{10}\left(\frac{p_2}{p_{ref}}\right) - 20\log_{10}\left(\frac{p_1}{p_{ref}}\right) \\ &= 20\log_{10}\left(\frac{p_2}{p_1}\right) = 20\log_{10}\left(\frac{r_1}{r_2}\right) \end{aligned} \tag{6}$$

For a doubling of distance, $r_1 = 1$ and $r_2 = 2$, the ΔSPL is -6 dB.

Infinite Plane Propagation

An infinite plane source is the other limiting case of a boat sound propagation field. This approximation can be used very close to the boat. In this case, an infinite wall radiates sound at the same intensity at every point on the wall. Since the sound wave travels linearly away from the wall and does not expand, the sound intensity from an infinitesimal patch radiates over a rectangle. The acoustic power remains constant since the area is constant, and therefore the sound level at any point away from the wall is constant.

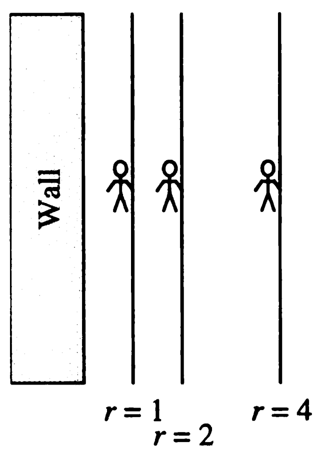

Figure 3: Sound Propagation from an Infinite Plane

The acoustic intensity (*I*) is an energy flux (W/m^2). The acoustic power (P_{source}) is the integral of that flux

$$P_{source} = \int I dA = I(A) \tag{7}$$

Acoustic intensity is related to the square of the acoustic pressure.

$$I = \frac{p^2}{\rho c} \tag{8}$$

Relating the acoustic power to the acoustic pressure with (7) and (8),

$$\frac{p^2}{\rho c} = \frac{P_{source}}{A} \tag{9}$$

We wish to determine the relationship between the ratio of pressures to the ratio of areas

$$\frac{p_2}{p_1} = \frac{\sqrt{\rho c\left(P_{source}\right)/A_2}}{\sqrt{\rho c\left(P_{source}\right)/A_1}} = \frac{A_1}{A_2} \tag{10}$$

Since the surface is infinite, the acoustic energy radiates outward into the same area at every radius from the surface. So $A_1 = A_2$, and

$$\frac{p_2}{p_1} = \frac{A}{A} = 1 \tag{11}$$

The change in sound pressure level for two points is

$$\begin{aligned} \Delta\text{SPL} = \text{SPL}(r_2) - \text{SPL}(r_1) &= 20\log_{10}\left(\frac{p_2}{p_{ref}}\right) - 20\log_{10}\left(\frac{p_1}{p_{ref}}\right) \\ &= 20\log_{10}\left(\frac{p_2}{p_1}\right) = 20\log_{10}(1) = 0 \end{aligned} \tag{12}$$

The change in sound pressure level, ΔSPL, is always 0 dB.

Motorboat Testing

The National Marine Manufactures Association (NMMA 1987) set out to measure the sound propagation field from motorboats. A boat is neither a point source nor an infinite wall

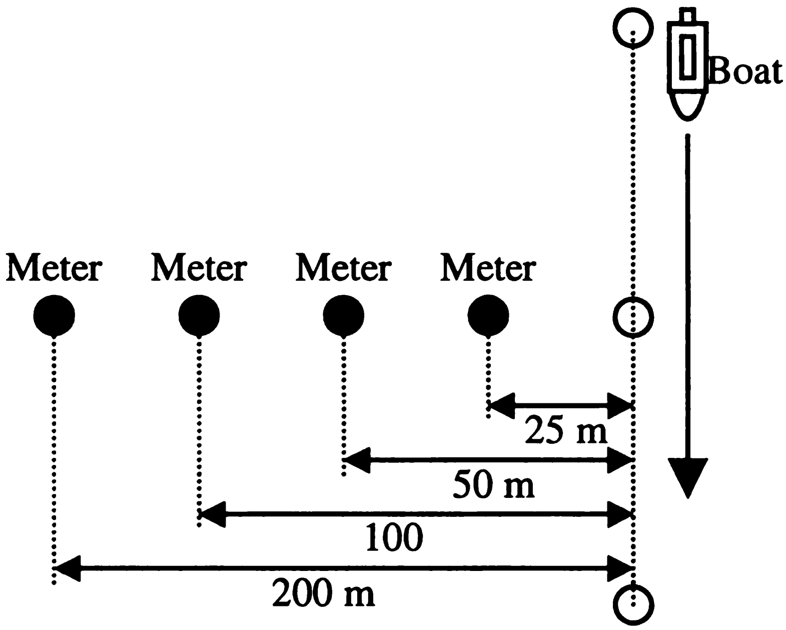

Figure 4: Sound Propagation Test Setup

source; its decay is somewhere between these two cases. These tests measured the propagation decay of a group of actual boats. Sound level meters were placed on poles at 50, 75, 100, and 200 feet away from a straight buoy course that the boat traversed. This allowed simultaneous readings of the boat noise at different distances. This test was conducted for a wide range of boats (with horsepowers from 10 to 370) in a single set of conditions. Figure 5 displays the data gathered in this experiment.

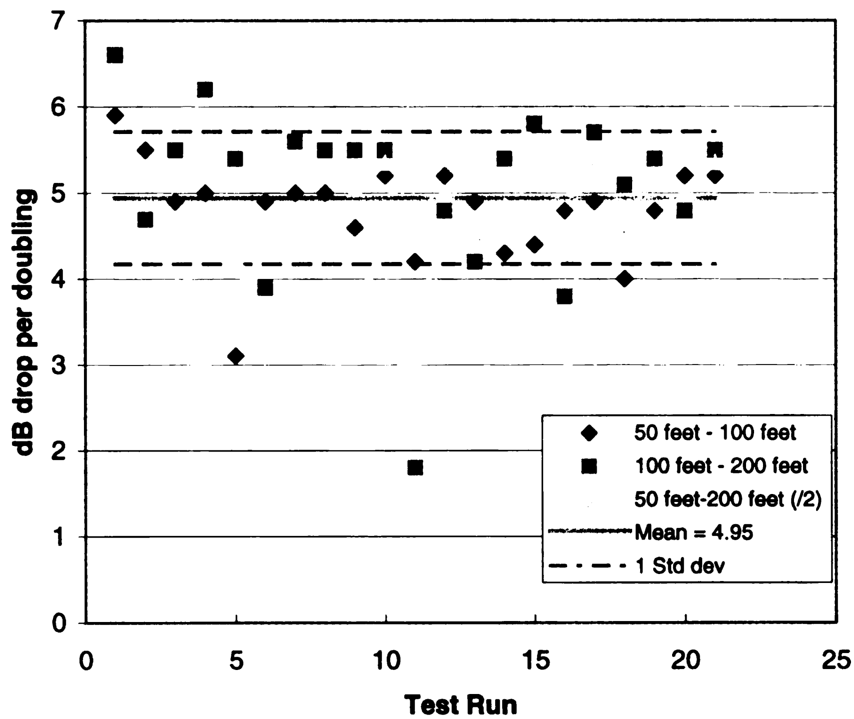

Figure 5: The National Marine Manufactures Association Test Data

The Marine Manufacturers Association study determined experimentally that on average boats had a 5 dB drop per doubling of distance. Further testing is needed to determine the average sound level decay for most watercraft, since this set of testing was not as rigorous and complete as is needed to stand up to court challenges. The data shows that most vehicles exhibited a decay value of between 4 and 6 dB per doubling of distance.

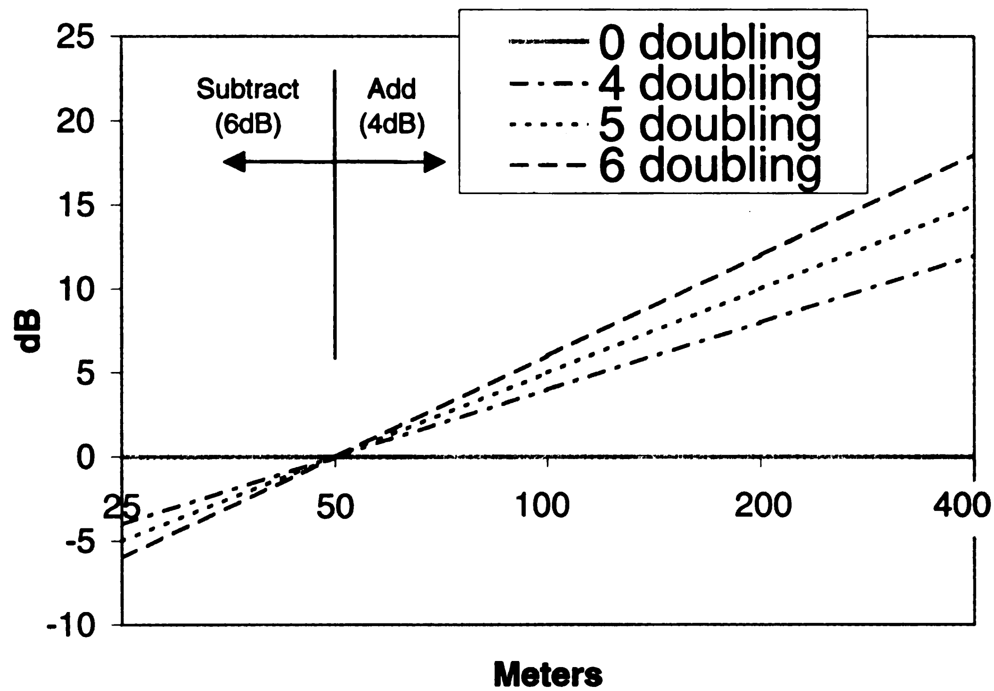

Figure 6: Sound Level Decay

Figure 6 displays the differences between various decay values. If a boat noise level is 85 dB at 200 feet, your assumption of how sound decayed with distance would affect your prediction of the sound level at 50 feet. If your assumption was that sound decayed at 4 dB per doubling of distance, you would predict that the boat would be 93 dB at 50 feet. If you assumed 6 dB, you would predict 97 dB at 50 feet. It is important to determine what this decay value is in order for the device to make an accurate prediction.

Multiple Sound Sources

Background noise is key to making a precise noise measurement. A noise source can only be measured when it is louder than the surrounding noise level. Even when the source is above the background, the reading taken from a source is a combination of the source noise and the background noise. The SAE noise standards only allow measurements when the measured source is 10 dB higher than the background. Because of this, our device must correct for the background sound level.

Since the noise reading is a linear combination of the sound intensities from the background and the source, we can subtract the background contribution (Radcliffe 2003), (Appendix E). The total mean squared measured sound y_m is the sum of the source y_s and background noise y_b, for a broadband random noise,

$$y_m = y_s + y_b \tag{13}$$

This total measured sound Y_m is expressed on a decibel (dB) scale as

$$Y_m = 20\log_{10}(y_m) = 20\log_{10}(y_s + y_b) \tag{14}$$

where the measured background level Y_b

$$Y_b(dB) = 20\log_{10}(y_b) \tag{15}$$

and the desired sound source level Y_s

$$Y_s(dB) = 20\log_{10}(y_s) \tag{16}$$

Solving for the source and background levels in (13) yields

$$y_b = 10^{(Y_b/20)} \tag{17}$$

$$y_s = 10^{(Y_s/20)} \tag{18}$$

These results can now be substituted into (16) and (13) to solve for the source pressure y_s and source level in decibels

$$\begin{aligned} Y_s(dB) &= 20\log_{10}[y_s] = 20\log_{10}[y_m - y_b] \\ &= 20\log_{10}\left[10^{(Y_m/20)} - 10^{(Y_b/20)}\right] \end{aligned} \tag{19}$$

Rearranging (19) to collect terms and compute compensation in dB,

$$\begin{aligned} Y_s(dB) &= 20\log_{10}\left[\left(10^{(Y_m/20)}\right)\left(1 - \frac{10^{(Y_b/20)}}{10^{(Y_m/20)}}\right)\right] \\ &= 20\log_{10}\left(10^{(Y_m/20)}\right) + 20\log_{10}\left(1 - 10^{((Y_b - Y_m)/20)}\right) \end{aligned} \tag{20}$$

This compensation equation (20) can now be written as

$$Y_s(dB) = Y_m + C \tag{21}$$

where the compensation $C = 20\log_{10}\left(1 - 10^{[(Y_b - Y_m)/20]}\right)$. Because the argument of the log function is always less than 1, the compensation C will always be negative.

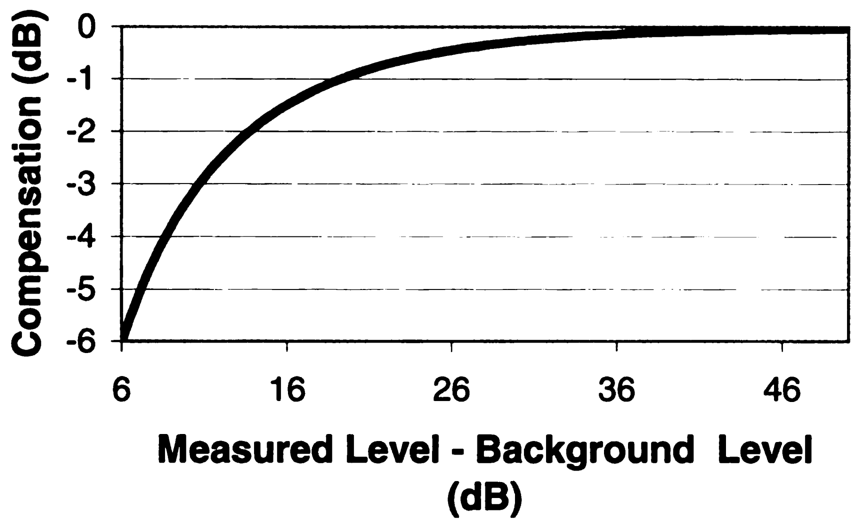

Figure 7: Sound Level Compensation C

The graph shows the required correction given the difference between the measured noise source value and the background noise. When the difference between the measurement and the background is 10 dB, the measured value is about 3.3 dB too high. Thus, if the background is 70 dB, and the measured source value is 80 dB, the real source level is about 76.7 dB. This correction is not valid when the source sound level and the background sound level are very close in value.

Targeting the Boat – Directional Measurements

Directional measurement is an important factor in the measurement of boat noise. The sound measurement must discriminate between the target object and other objects in the vicinity. There are two types of microphones that are generally used for directional pickup – a parabolic microphone or a shotgun microphone.

A parabolic microphone uses a large parabolic reflector to reflect sound waves into the microphone. This reflector only reflects wavelengths of sound less than the radius of the dish. This requirement means that for a frequency of 1000 Hz, the radius of the reflector must be at least 0.33 meters. For a frequency of 100 Hz, the microphone must have a radius of over 3.3 meters. This type of microphone provides 20-40 dB of discrimination between the target and other noise sources in the general direction of the target.

A shotgun microphone uses a long tube that reinforces the sound wave as it travels both down the tube and on the outside of the tube. The length of the tube is important to increase the directionality of the microphone. However, the length does not play a direct role in the frequency response of the microphone. This type of microphone provides 15-20 dB of directional discrimination. A response pattern for an Audiotechnica AT815b microphone is shown in figure 8.

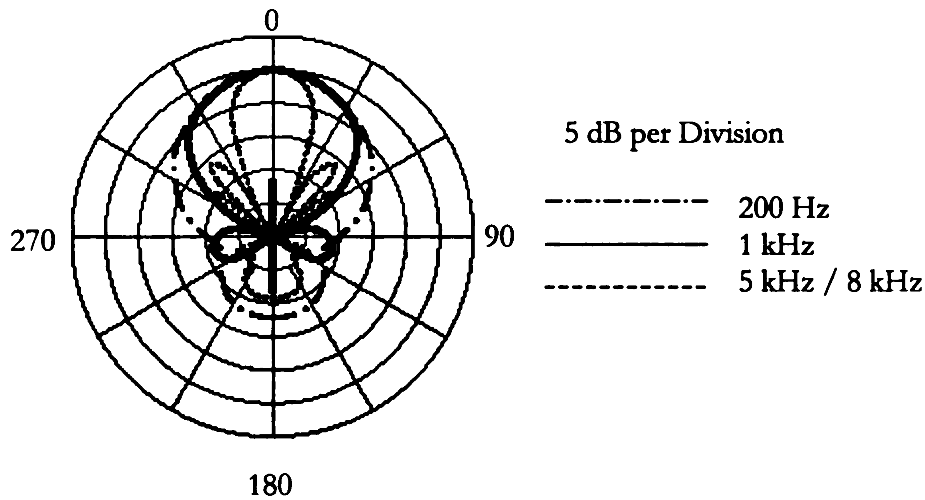

Figure 8: Polar Response Pattern of the Audio-Technica AT815b

For the directional sound measurement the shotgun microphone was chosen. The parabolic microphone offered better directionality of sound measurement, at a cost of its large cross section. The shotgun microphone offered only slightly inferior directionally of sound measurement and a much reduced cross-section. The length of the microphone can also be reduced if less directionally at low frequencies is required.

Chapter 4

THE VEHICLE SOUND LEVEL METER

Package Overview

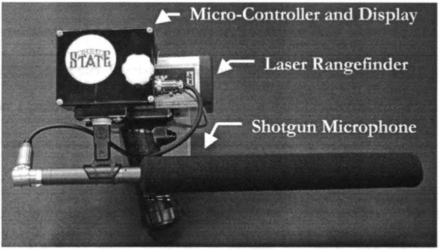

Figure 9: The Prototype Boat Noise Gun

The prototype unit shown in Figure 9 contains the electronics to make the measurements and conversions detailed in the previous section.

Input equipment details

The shotgun microphone used is an Audio Technica model AT815b. At moderate frequencies this microphone provides up to a 20 dB gain for on-axis measurements. At a level of 100 dB along the axis of the microphone, the microphone generates a voltage of

$$100\,dB\,SPL = (2\,Pa)(11.2\,mV/Pa) = 22.4\,mV \tag{22}$$

A Contour LaserRangefinder XLR[1] handles the distance measurement. The device sends out a pulsed infra-red laser and times the reflection of the beam, at a resolution of 0.1 foot. The time it takes for the beam to return, multiplied by the speed of light (approximately 983,571,056 feet per second), is twice the distance to the target. This means that for a 10 foot measurement, the device would measure a time of $2x10^{-8}$ seconds. The difference between a 10 foot measurement and a 10.1 foot measurement would be $2x10^{-10}$ seconds. The ease of use and the built-in computer interface made this device an easy choice for the prototype. However, in a production model of the Boat Noise Gun, a customized version would be designed to remove much of the bulk of the current device.

The Boat Noise Gun is run by a Basic Stamp[2] microcontroller. This device takes sound level and distance inputs, computes all relevant corrections, and controls the output displays as specified in its custom program. It is interfaced with analog circuitry that does the signal processing. The use of a microcontroller allows simple software updates to change the operation of the device.

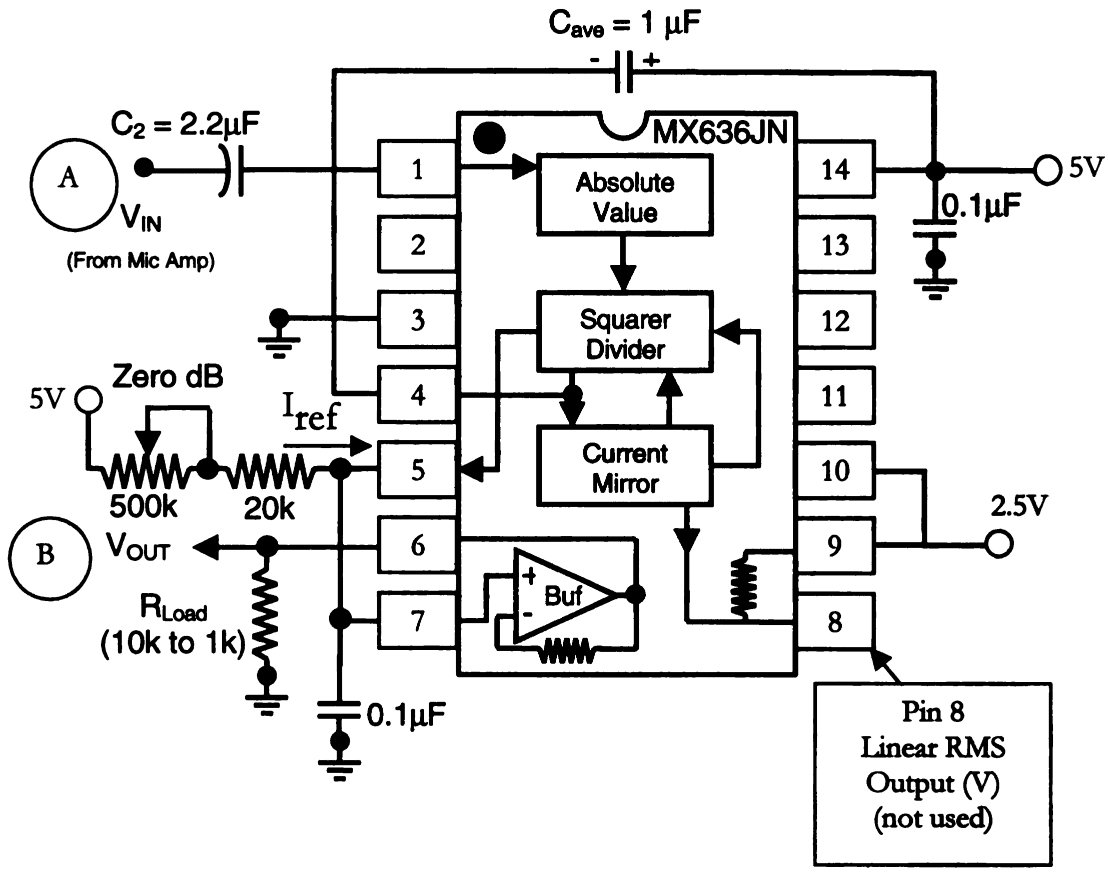

Figure 10: MX636 dB Conversion Circuit

(Maxim (1998). Figures 5 and 10)

RMS dB Chip Circuit

The signal into A in Figure 10 is from the microphone and is an AC signal. In order to measure this signal it must be rectified into a DC level. This DC level can be easily measured by a circuit that converts the analog DC voltage into a digital number. The Maxim MX636 chip takes the linear AC input from the microphone stages and converts it to a DC voltage that is proportional to the dB level of the input signal (log scale). This part of the circuit is a standard operating configuration recommended by the manufacturer, Maxim.

The input signal must first be filtered of low frequency noise. C_2 forms a high pass filter with the input resistance of 6.7 kΩ for the MX636 to remove low frequency bias. In order to be converted from an AC signal to a DC signal, the signal frequency must be above 10.8 Hz.

The time period over which the RMS value is measured is defined by the averaging capacitor, C_{ave}. $C_{ave} = 1$ µF corresponds to a settling time of 115 msec at an input voltage level of 100 mV. Smaller input voltages take longer to settle. At an input of 1 mV, the settling time is 10 times longer (about 1.1 seconds). The RMS calibration on Pin 5 is –3 mV/dB. As the input RMS level changes by 50 dB, the output voltage (Pin 5) should change by –150 mV from the 0 dB reference value set by the variable resistor on the pin.

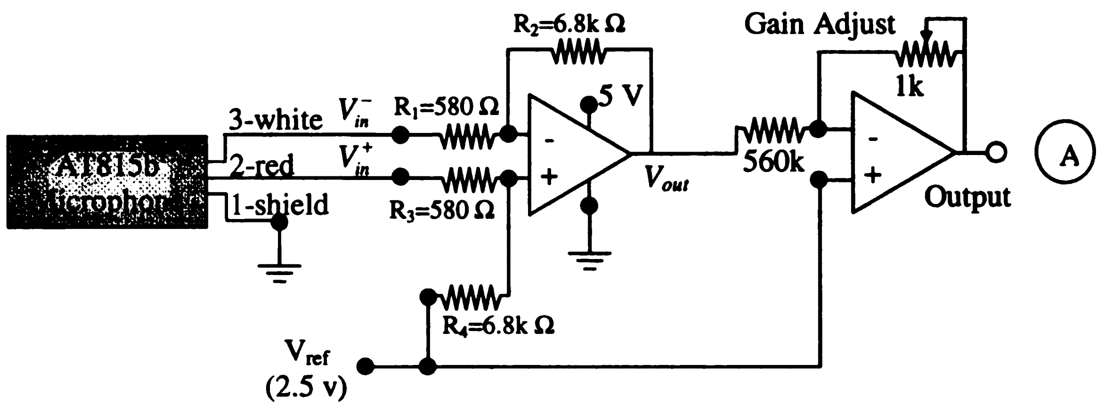

Figure 11: Microphone Amplifier Circuit.

Microphone Amplifier Circuit

The microphone amplifier circuit in Figure 11 is needed to interface the low level shotgun microphone output with the dB log measuring circuit (MX636). The input impedance of the circuit needs to match the output impedance of the microphone. The output needs to match the input requirements of the MX636 chip. This requirement is a voltage change of 0-200 mV RMS over the full range of sound inputs. The 200 mV swing must occur around a bias of 2.5V.

The direct connection to the microphone is a balanced input. The output from the microphone is sent on two wires, and difference between the voltages on the wires is the microphone signal. The ground wire is kept separate to minimize noise pickup from magnetic/electric fields. The input is impedance balanced on each wire with the output impedance of the microphone.

The first op amp is an inverting amplifier. The gain is determined as follows: First we record the fundamental laws of an op-amp $V^+ - V^- = 0$, which is a statement of the infinite gain of the amplifier, and $i_{in}^+ = i_{in}^- = 0$, which is a statement of the infinite input impedance of the op amp.

The current through R2 is

$$i_1 = \left(V_{in}^- - V_{out}\right) / \left(R_1 + R_2\right) \tag{23}$$

and into the reference source,

$$i_2 = \left(V_{in}^+ - V_{ref}\right) / \left(R_3 + R_4\right) \tag{24}$$

Using the fundamental laws of an op amp,

$$V^+ - V^- = \left[V_{in}^+ - R_3 i_2\right] - \left[V_{in}^- - R_1 i_1\right] = 0 \tag{25}$$

Substituting the equations for i_1 and i_2 into the last equation,

$$\begin{aligned} V^+ - V^- = 0 = &\left[V_{in}^+ - R_3\left(V_{in}^+ - V_{ref}\right)/\left(R_3 + R_4\right)\right] \\ &- \left[V_{in}^- - R_1\left(V_{in}^- - V_{out}\right)/\left(R_1 + R_2\right)\right] \end{aligned} \tag{26}$$

This result can be rearranged to form,

$$V_{out}\left(\frac{R_1}{R_1 + R_2}\right) - V_{ref}\left(\frac{R_3}{R_3 + R_4}\right) = V_{in}^+\left(\frac{R_4}{R_3 + R_4}\right) - V_{in}^-\left(\frac{R_2}{R_1 + R_2}\right) \tag{27}$$

If R1 = R3 and R2 = R4,

$$\left(V_{out} - V_{ref}\right) = \left(\frac{R_2}{R_1}\right)\left(V_{in}^+ - V_{in}^-\right) \tag{28}$$

Equations 27 and 28 illustrate the importance of R1, R3 and R2, R4 being matched pairs. If these resistors are not equal the gain of the amplifier is not a simple ratio. The gain would be affected differently by changes in V_{in}^+ or V_{in}^-.

Equation 28 defines the differential gain of the amplifier. Also note that this differential gain is defined about V_{ref} because when $\left(V_{in}^+ - V_{in}^-\right) = 0$, $V_{out} = V_{ref}$. V_{ref} as 2.5 V as required by the MX636 chip.

The input impedance of the circuit is the ratio between changes in each of the input voltages V_{in}^+ and V_{in}^- and associated changes in currents i_1 and i_2. Using (25),

$$V_{in}^{+} = R_3 i_2 + V_{in}^{-} - R_3 i_1 \Rightarrow dV_{in}^{+} \big/ di_1 = -R_3 \quad (29a)$$

and

$$V_{in}^{-} = R_1 i_1 + V_{in}^{+} - R_1 i_2 \Rightarrow dV_{in}^{-} \big/ di_2 = -R_1 \quad (29b)$$

The input impedance of this amplifier is strictly controlled by the two identical input resistors R_1 and R_3. If R_1 = 580 Ohms, and R_2 = 6.8k Ohms, we get the desired low microphone impedance with an amplifier gain, $(R_2/R_1) = 11.7$. With this gain, the RMS output voltage at a sound pressure level of 100 dB is (22.4 mV)*11.7 = 262.6 mV. The second op amp is also an inverting amplifier, which a variable gain. This is used to trim the output to the exact requirements of the MX636.

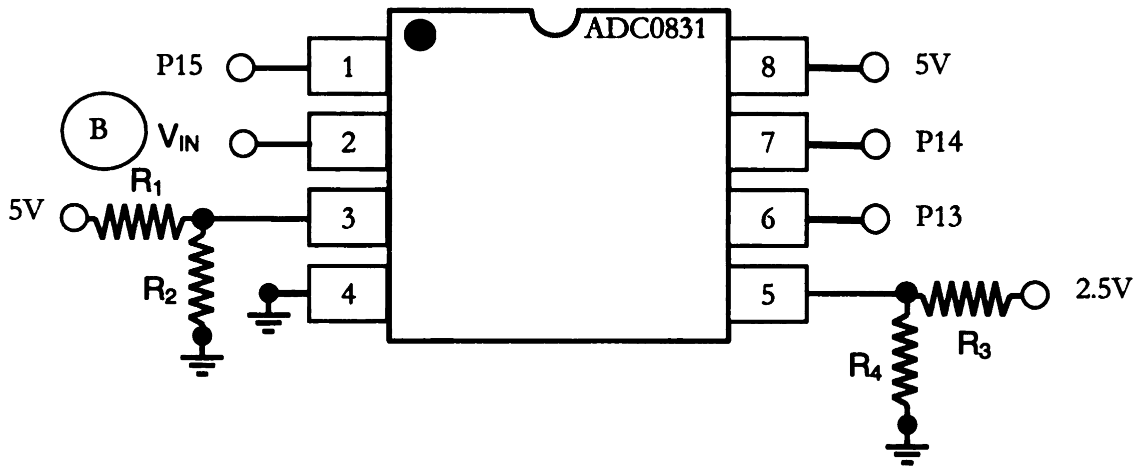

Figure 12: ADC0831 A/D Converter Circuit

A/D conversion

The A/D stages measures the analog voltage and converts it into a digital representation of the value in terms of two limiting values. This digitally represented value is an 8-bit value. This is also a standard circuit. R_1 and R_2, and similarly R_3 and R_4, are voltage dividers, which define the limiting values.

$$V_3 = \frac{R_2}{R_1}(5V), V_5 = \frac{R_4}{R_3}(2.5V) \tag{30}$$

V3 defines the bottom of the range of voltage, and V5 defines the span of voltages.

The digital output, x, is defined as

$$x = \left(\frac{V_{in} - V\min}{Vspan} \right) 255; 0 \leq x \leq 255 \tag{31}$$

The ADC0831 provides x as the output of its serial interface. This serial output is a digitally scaled (0-255) RMS microphone level in dB.

When Vin = V3, x = 0. When Vin = V3 +V5, x = 255.

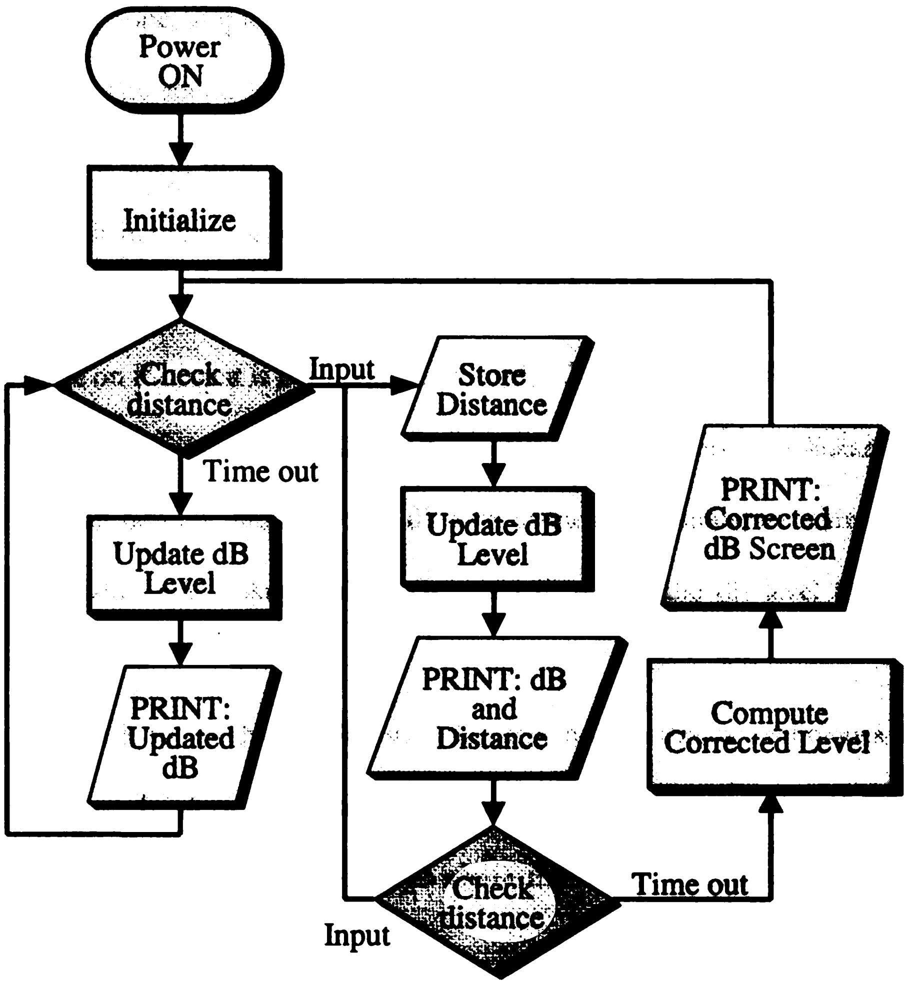

Figure 13: Noise Gun Program Flowchart.

Microcontroller Data Analysis

The microcontroller must now take the raw digital level at the Boat Noise Gun, and compute an equivalent noise level at 50 feet. It has an input from the microphone. It must compute a dB level from this number. It must then input the distance and compute a log correction to get the equivalent noise level at 50 feet. Then it takes the background noise and computes a correction for this. This process is diagramed in Figure 13.

In the Initialization block the device makes a measurement of the ambient sound level. It uses the microphone, amplifier, MX636, and A/D stages to get a digital representation of the sound level. The sound level data is inputted into the Basic Stamp as an 8-bit number, which is a representation of the decibel level at the microphone. In order to overcome any noise on this 8-bit number, an Infinite Impulse Response Filter is used. This filter is used to obtain a 12-bit number by multiple sampling of the 8-bit output of the A/D converter. As long as the noise on the input is randomly distributed, this type of filter is accurate. The 12-bit number is converted into a dB value by interpolation. Since there is a linear relationship between the 12-bit number and the actual dB level at the microphone, tests are conducted to find this relationship. A lookup table is constructed to find the dB level from the 12-bit number.

In the first loop, the Noise Gun uses the same noise sampling techniques to measure the noise value that the device is pointed at. It then gives a running display of this value and the background value. This is holding stage where the device is ready to make a calibrated measurement.

When the operator points the device at the target boat and pulls the trigger, the device moves into the 2nd loop. The device displays the distance to the target and the sound level in that direction updated continuously as long as the trigger is depressed. Upon the release of the trigger, the device begins to make the corrections for ambient noise and distance to the boat.

The ambient level correction is a logarithmic correction, and is pre-calculated for the difference between the background and the source. This log curve is then broken into linear segments, which the stamp can make an interpolation between. As shown in the Sound Propagation Section, the background correction is:

$$C = 20\log_{10}\left(1 - 10^{\left[(Y_b - Y_m)/20\right]}\right) \tag{32}$$

The distance calculation is also a log correction. The stamp must know the log of the ratio of the distances in order to find the correction. However, in this case the log is calculated on the fly in the software. As shown in the Sound Propagation Section, the SPL correction is:

$$\Delta\text{SPL} = 20\log_{10}\left(\frac{r_1}{r_2}\right)$$

Chapter 5

EXPERIMENTAL TESTS

Calibration

The Boat Noise Gun was tested in the Michigan State University anechoic chamber. Since the directional sound measurement amplifies the boat noise, a calibration must be done to equate the level the microphone records with the actual dB level at the point of the observer. This calibration is done by comparing the microphone readings with standard B&K Type 2230 Microphone readings in an environment with no reflections or other distortions of the sound propagation. This anechoic chamber has no reverberation below 30 Hz. The sound that hits the microphone is only from the source and not as reflections from any another surface. The Sound Source used was a B&K HP1001 at octave bands of 8 kHz, 4 kHz, 2 kHz, 1 kHz, 500 Hz, 250 Hz, 125 Hz, and for white noise.

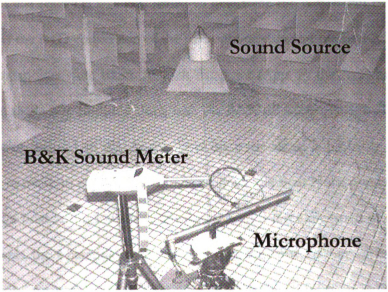

Figure 14: Anechoic Chamber Experimental Setup

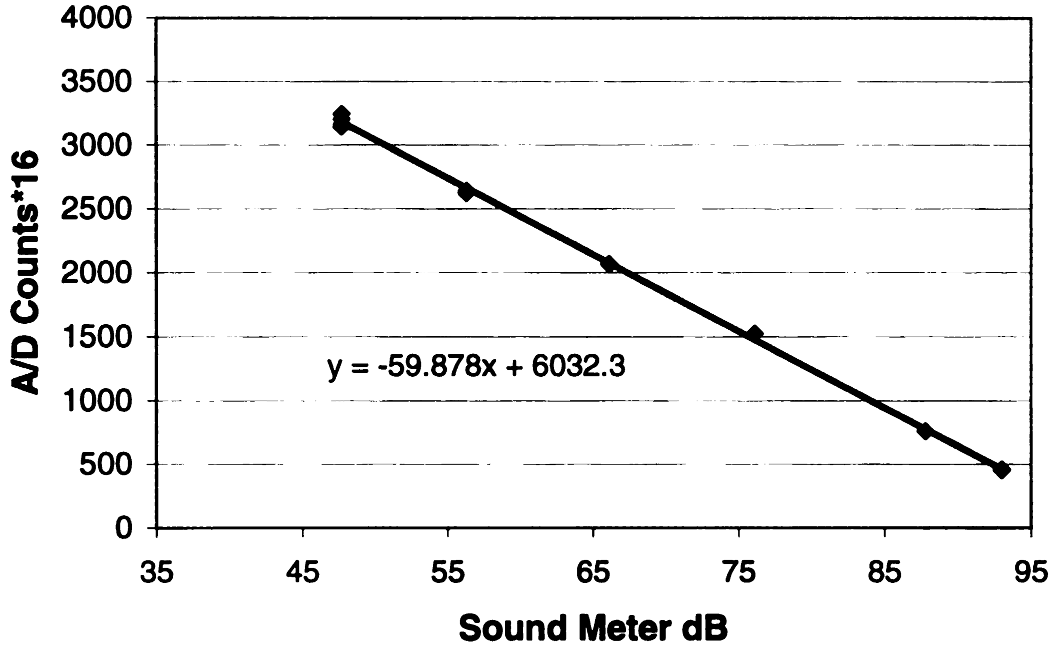

Figure 15: Data from the First Anechoic Test for White Noise

The first test (Fig. 15) was performed to determine the correlation between what the noise gun read as the A/D conversion of the microphone data and the B&K dB level. At each sound level, 4 datapoints were taken. At each datapoint (App. F) the A/D measurement the Boat Noise Gun made was recorded along with the B&K dB measurement. The data spreads at the lowest point, around 46 dB. At this level the noise signal is probably too low for the Boat Noise gun to make an accurate measurement. Since the Boat Noise gun will never make a measurement of a boat at this low level, this data spread is not anticipated to cause problems. At higher dB levels, the 4 datapoints are almost exactly the same, so they appear as one dot on the graph and not 4 separate dots. A best fit line was developed from the data collected. This line fits the data from 46 dB to 94 dB with a maximum deviation of 87 counts. From this best

fit, a lookup table was constructed for the Boat Noise Gun. With this table the Boat Noise Gun could look up the dB value for a particular A/D measurement.

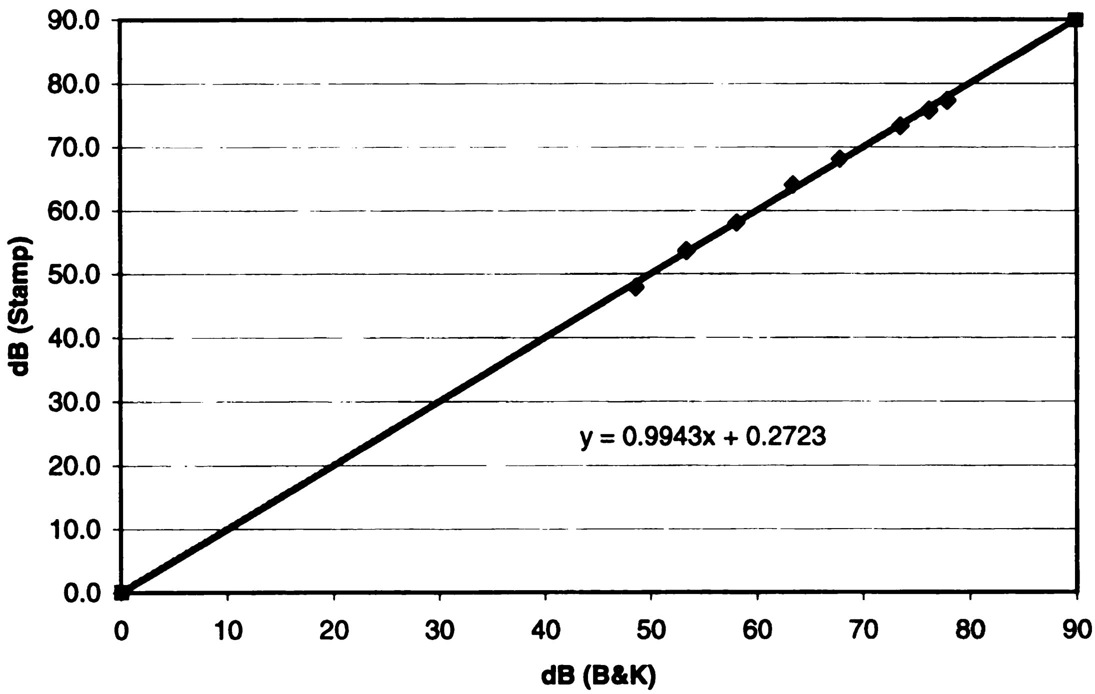

Figure 16: Data from the Second Anechoic Test for White Noise

The second set of anechoic chamber testing (Fig. 16), compared the internal dB calculation with B&K readings to confirm the accuracy to the calibrated Boat Noise Gun. At each sound level 4 datapoints were taken. Here the spread between datapoints is so small that they appear as 1 dot on the graph for a particular dB level. Ideally the line should have a slope of 1 and a intercept of 0. In this data the slope of the line is 0.99 and the intercept is 0.27. This second test proved that the lookup table between the Boat Noise Gun and the B&K meter was accurate.

Directional Tests

Tests were conducted to test the directionality of the microphone as listed in its data sheet. Tests were done in the anechoic chamber at octave bands of 8 kHz, 4 kHz, 2 kHz, 1 kHz, 500 Hz, 250 Hz, 125 Hz, and for white noise (App. F). The Sound Source was set and recorded at 78.1 dB, and the Noise Gun has a noise floor of 46dB as shown previously. The total possible directionally that could have been found was 78.1 - 46 = 32.1 dB. The manufacturer claimed the directionality of the device at 25 dB, but this test showed a value of 15 dB. Since the Boat Noise Gun can detect a gain of over 25 dB if it was present, the microphone characteristics must account for this difference. The radial shape pattern generally matches the manufacturer data.

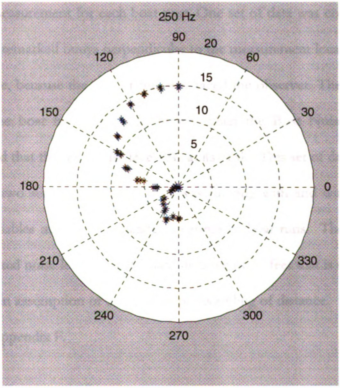

Figure 17: Polar Response of (AT815-b) at 250 Hz Octave Band

Lake Demonstration

Preliminary instrument testing was conducted at Higgin's Lake, Michigan. It should be noted that these were not strict engineering tests. Their purpose was twofold: to demonstrate of the operation of the device and to get baseline measurements for the further development of the prototype. A boat owned by a member of the Higgin's Lake Property Owners Association passed by the measurement location at approximately 40mph to provide a consistent level of boat noise at various distances. The boat had the "Captain's Choice" of operating with or without its muffler. Data recorded by the Boat Noise gun included a background noise measurement, directional raw noise measurement, distance measurement, and corrected noise measurement for each boat pass. One set of data was collected when the boat passed a line of premarked buoys perpendicular to the measurement location. This set of data is called broadside, because the side of the boat faced the observer. The 2nd set of data was recorded after the boat had passed the buoys, when the Boat Noise Gun operator subjectively determined that the boat noise level was at its peak. This set of data is called peak. Each set of data has two subsets, when the boat was running with and without its muffler turned on. These variables make four separate categories of boat runs. The data plotted in Figure 18 is the corrected noise level for a standard distance of 50 feet that is computed by the Boat Noise gun with an assumption of 5 dB decay per doubling of distance. Full data records for these tests are in Appendix F.

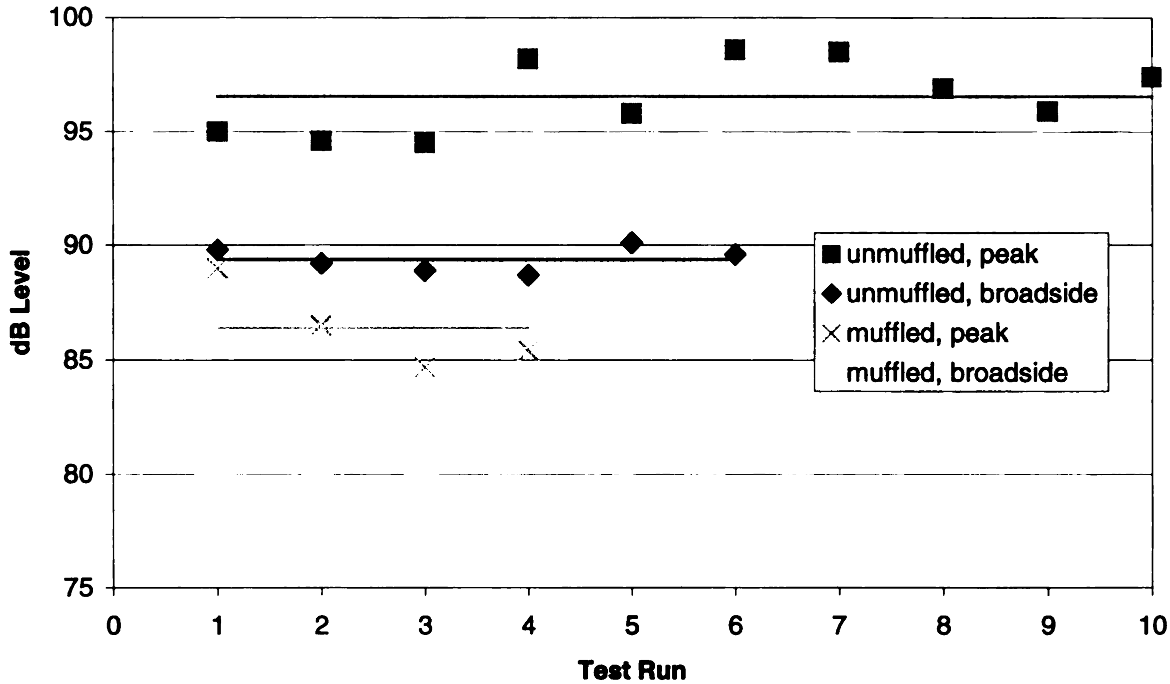

Figure 18: Summary of 27 Noise Gun Measurements, Higgin's Lake, Michigan, June 14, 2003

The Higgin's Lake tests (Fig. 18) show that the boat's orientation relative to the observer and muffler condition are important to the results. For the unmuffled peak dataset, the mean is 96.5 dB and the standard deviation is 1.6 dB. For the muffled peak dataset, the mean is 86.7 dB and the standard deviation is 2.16 dB. For the unmuffled broadside dataset, the mean is 89.4 dB and the standard deviation is 0.54 dB. For the muffled broadside dataset, the mean is 79.5 dB and the standard deviation is 2.1 dB. In spite of 10-15 mph wind noise on the microphone, the device was able to make measurements over a wide range of distances with accuracy of better than +/- 2 dB.

The dB decay for the doubling of distance x_d used by the Boat Noise Gun is 5 dB. This best estimate was derived from the NMMA study results. Since the exact optimal x_d is unknown, this parameter for the Higgin's Lake raw data was varied to determine the value of x_d yielding the lowest standard deviation in the distance corrected data for each dataset. For each dataset, x_d was varied from –3 to 9 dB and the standard deviation of each set was plotted. The lowest standard deviation for each dataset is the optimal decay rate x_d for that test case.

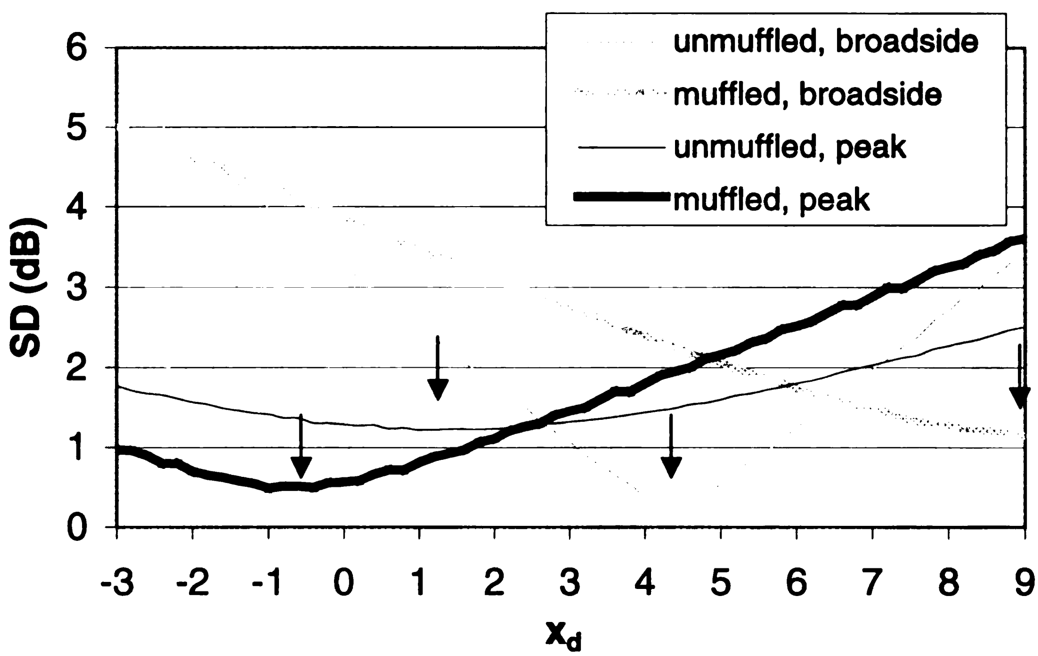

Figure 19: Lake Test data with the dB decay level altered

The best fit decay rate x_d (Figure 19) was different for each of four test cases. When the observer faced the broadside of the boat, the optimal x_d was at about 4.5 dB (unmuffled) and 9 dB (muffled). When a peak measurement was taken, and the rear of the boat was visible to the observer, the data shows that the optimal x_d was at about 1.5 dB (unmuffled), and at –0.7 dB (muffled). One hypothesis for these results is that the engine produces a plane wave coming off the back of the boat, and this wave spreads out around the corner of the boat. This would result in plane wave behavior observed from the back of the boat (peak measurement), and a spherical propagation pattern when viewing the side of the boat (broadside measurement).

The broadside vs. peak sound propagation pattern is shown by resolving the 4 cases into 2 cases. The RMS of the standard deviation of the peak cases is computed as

$$SD_{peak} = \sqrt{\frac{\left(SD_{peak,muffled}\right)^2 + \left(SD_{peak,unmuffled}\right)^2}{2}} \tag{35}$$

Similarly for the broadside cases

$$SD_{broadside} = \sqrt{\frac{\left(SD_{broadside,muffled}\right)^2 + \left(SD_{broadside,unmuffled}\right)^2}{2}} \tag{36}$$

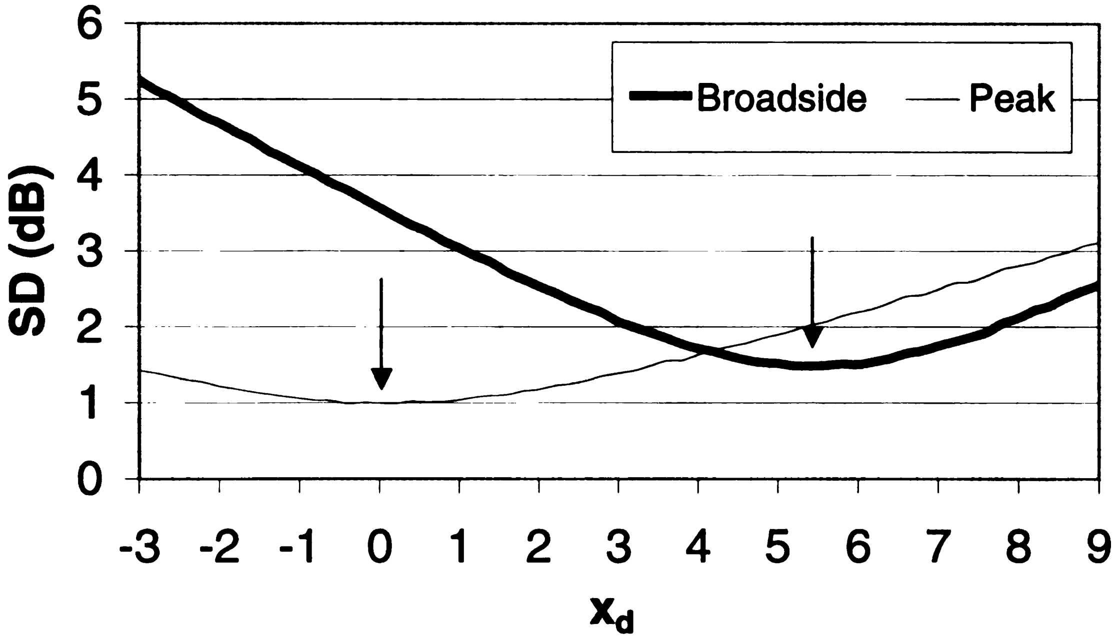

Figure 20: dB decay level altered for 2 cases

Figure 19 confirms that the two cases are separate. For the Peak dataset, the ideal x_d is very close to 0 dB. This correlates with plane waves. The Broadside dataset has an ideal x_d of about 5.5 dB. This correlates well with the 6 dB of spherical propagation. More data needs to be taken to determine if there are only 2 cases or if the propagation pattern varies radially around the boat.

Chapter 6

CONCLUSION

This project has created the Boat Noise Gun to meet the requirements of a directionally dependent noise measurement that is distance independent. The challenges of background and distance compensation have been solved, and these corrections have been implemented in a way that allows changes to be made easily. Functionally, the device makes a background noise measurement, a directional noise measurement, and a distance measurement. From these three pieces of data it constructs an estimate of the loudness of the boat at a standard distance of 50 feet away.

Knowledge of the sound propagation pattern for boats is critical to the future development of the device. The sound propagation pattern affects the distance correction. In this research we have had initial indications that this decay value is dependent on the vantage point of the observer relative to the boat. Determining this propagation pattern is crucial.

This propagation affect greatly changes the design parameters of the Boat Noise Gun. If x_d depends on orientation of the observer to the boat, then that information would also have to be sensed for a distance correction to be made. If this difference can be resolved to a simple change between peak and broadside measurements, then a switch could be incorporated into the device to change the operational mode (x_d of 0 or 6 dB). If the propagation pattern changes radially around the boat a measurement of the angle of the observer to the boat would have to be made.

The Boat Noise gun was successful in conducting directionally dependent distance independent noise measurements. In the process of this work questions about the propagation pattern of boats were raised. The Boat Noise gun, with its combination of a distance measurement and a sound measurement, provides the tool to make the tests necessary to measure the propagation pattern of boats. These tests are not possible without the simultaneous distance and sound level measurement capability of the MSU Boat Noise Gun. These tests will facilitate the further development of the Boat Noise gun as a complete law enforcement tool for use on lakes and beyond.

APPENDICES

APPENDIX A

Table 3: State Noise Enforcement Standards

State	Allowable dBA	Testing Procedures	Cutouts	Type of Violation	Fines & Penalties
Alabama	86	50 ft. from vessel	Prohibited	Misdemeanor	Minimum of $50
Alaska**					
Arizona	86	SAE-J34	Allowed if Std. are met	Misdemeanor	$500 Max
Arkansas	N/A	Not Measured	Prohibited	Misdemeanor	$150 Max
California	86-Mfg. Before 1/76	SAE-J34	Not Specified Illegal	Infraction	$135 & Proof Correct
	84-Mfg. After 1/76				
	82-Mfg. After 1/78				
Colorado	86	SAE-J34	Allowed if Stds are met	Petty Offense-Class 2	Maximum $ 25.00
Connecticut	86-Mfg. Before Jan-76	SAE-J34	Allowed if Stds. are met	Violation	$100-$500
	84-Mfg. 1/76-12/81				
Delaware*					
D.C.	N/A	Officer Discretion	Allowed if Stds are met	Violation	Verbal-$50
Florida	90-State Standard	50ft. from vessel	Prohibited	Misdemeanor	$500 and/or 60days
	80-Broward Cty.				

Table 3 (cont'd)

State	Allowable dBA	Testing Procedures	Cutouts	Type of Violation	Fines & Penalties
Georgia	84	SAE-J34	Prohibited	Misdemeanor	$1,000 or 1 yr.
Hawaii*					
Idaho	75-Lakes-Reser.	SAE-J1970	Prohibited	Misdemeanor	$ 300 and/or 30 days
	90-Mfg Before 1/95	SAE-J2005			
	88-Mfg After 1/95	SAE-J2005			
Illinois	90-Stationary	SAE-J2005	Not Specified Illegal	Misdemeanor	$100-plus
	75-Operating	SAE-J1970			
Indiana	Not Specified	Officer Discretion	Prohibited	Infraction	$1-$500
Iowa	86	SAE-J34	Allowed if Stds are met	Misdemeanor	$10-$100
Kansas*					
Kentucky	Not Specified	Officer Discretion	Permitted	Violation	$15-$100 Plus
Louisiana	Not Specified	Officer Discretion	No dry straight pipes w/o baffles. Class 1	Violation	$50-$150
Maine	Not Specified	Officer Discretion	Prohibited (except racing)	Violation	$100-$500
Maryland	90-Mfg. Before 1/93	SAE-J1970	Not Specified Illegal	Misdemeanor	$500-$1000/30 days

Table 3 (cont'd)

State	Allowable dBA	Testing Procedures	Cutouts	Type of Violation	Fines & Penalties
Massachusetts	Not Specified	Not Measured	Prohibited	Misdemeanor	Less than-$100
Michigan	90-Stationary	SAE-J2005	Prohibited	Misdemeanor	90-days/$100-$500
	75-Shoreline	SAE-1970			
Minnesota	84 Mfg. Before 1/82	Pass-By	Prohibited	Misdemeanor	$100-$700 90 days
	82-Mfg. After1/82 at idle (decibel adjusted)				
Mississippi	86	SAE-J34	Allowed if Stds. are met	Misdemeanor	$50-$100
Missouri	86-Mfg. Before 1/96	SAE-J34	Allowed if Stds. are met	Infraction	$100/$200/$300
	90-Mfg. Before 1/96	SAE-J2005			
Montana	90-Statewide	SAE-J2005	Prohibited	Misdemeanor	$500
	75-Shoreline	SAE-1970			
Nebraska	Not Specified	Not Measured	Prohibited	Misdemeanor	$100
Nevada	86	W/B&K 50ft. SAE-J34	Prohibited	Misdemeanor	$1000&6Mo. ($50)+$25/Court Cost
New Hampshire	82-Mfg. Before 77	SAE-J34	Prohibited	Violation then Misd.	$100
	84-Mfg. 1/78-12/81	(Dir. of Safe may use)			
	82-Mfg. After 12/81	SAE-J2005			

Table 3 (cont'd)

State	Allowable dBA	Testing Procedures	Cutouts	Type of Violation	Fines & Penalties
New Jersey	90	SAE-J2005	Prohibited	Disorderly Operation	$100/$300/$500
New Mexico	Not Specified	Not Measured	Prohibited	Misdemeanor	$500 or 30/days
New York	90 Stationary	SAE-J2005	Prohibited	Violation	$50-$250
	75 Shoreline	SAE-J1970			
North Carolina	County's Discretion	Officer Discretion	Prohibited	Misdemeanor	$200/plus
North Dakota*					
Ohio	Municipalities Only	Varies	Not Specified Illegal	Minor Misdemeanor	$100/plus
Oklahoma	86	Officer Discretion	Prohibited	Misdemeanor	$100
Oregon	90-Mfg. Before 1/93	SAE-J2005	Prohibited	Class B Infraction	Court App.-$350/Max Bail-$99
Pennsylvani a	90-Mfg. Before 1/93	SAE-J2005		Summary Off./3rd Deg.	Moor Vessel-$25
	88-Mfg. After 1/93	SAE-J34	Prohibited		
	82-Using SAE-J34	SAE-J34			
Rhode Island	Not Specified	Not Measured	Prohibited	Violation	$100
South Carolina***	Not Specified	Officer Discretion	Not Specified Illegal	Misdemeanor	$50/$100/$200
South Dakota	Not Specified	Officer Discretion	Prohibited	Class 2 Misdemeanor	$200-Max
Tennessee	86	SAE-J34	Prohibited	Misdemeanor	$50-$100

Table 3 (cont'd)

State	Allowable dBA	Testing Procedures	Cutouts	Type of Violation	Fines & Penalties
Texas	Not Specified	Not Measured	Not Specified Illegal	Class C Misdemeanor	$25-$500
Utah	90-Mfg. Before 1/93	SAE-J2005	Prohibited	Class B Misdemeanor	$1000 and/or 6-mon.
	88-Mfg After1/93	SAE-J2005			
	75-Shoreline	SAE-J1970			
Vermont	82	SAE-J34	Prohibited	Civil Violation	$300
Virginia	Not Specified	Not Measured	Prohibited	Misdemeanor	$250-Max
State	**Allowable dBA**	**Testing Procedures**	**Cutouts**	**Type of Violation**	**Fines & Penalties**
Washington	90-Mfg. Before 1/94	SAE-J2005	Not Specified Illegal	Infrac. then Misdem.	$100/day Oper/Mfg.
	88-Mfg. After 1/94	SAE-J2005			
	75-Idle	SAE-			
West Virginia	Not Specified	Not Measured	Prohibited	Not Specified	None
Wisconsin	86	SAE-J34	Prohibited	Violation	$141
Wyoming	Not Specified	Not Measured	Prohibited	Misdemeanor	$200-Max

APPENDIX B

Digital Sound Meter Circuit Diagram

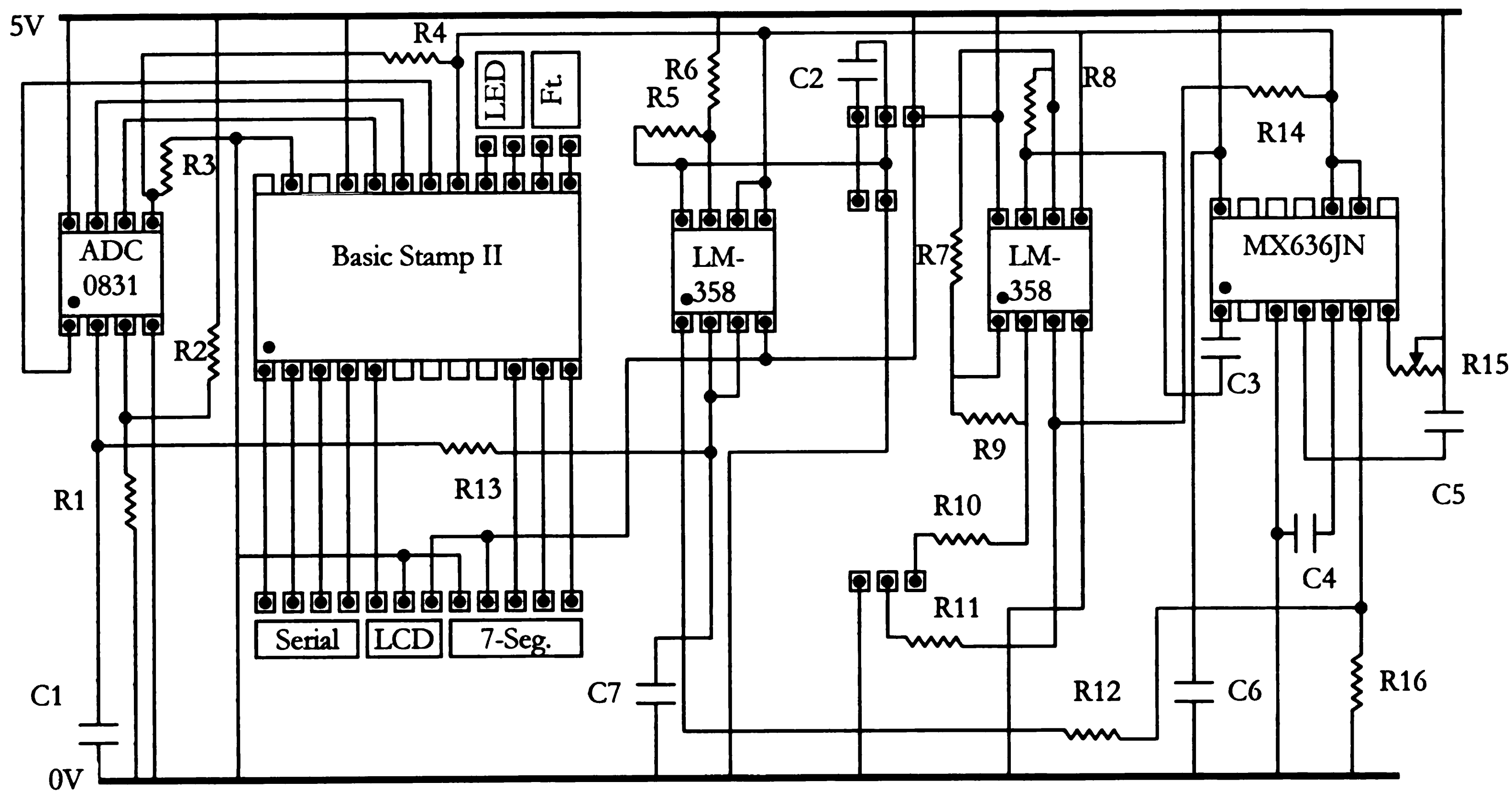

Figure 21: Circuit Schematic Diagram

Table 4: Discrete Component Values for Overall Circuit

R 1 =	~10KΩ	C 1 =	1uF
R 2 =	~10KΩ	C 2 =	100uF
R 3 =	10KΩ	C 3 =	2.2 uF
R 4 =	~800Ω	C 4 =	0.1uF
R 5 =	10KΩ	C 5 =	1uF
R 6 =	10KΩ	C 6 =	0.1uF
R 7 =	560Ω	C 7 =	1uF
R 8 =	2.178KΩ		
R 9 =	6.8KΩ		
R 10 =	580Ω		
R 11 =	580Ω		
R 12 =	1KΩ		
R 13 =	1KΩ		
R 14 =	6.8KΩ		
R 15 =	500KΩ		
R 16 =	1KΩ		

APPENDIX C

Basic Stamp Code

```
'=================================================================
'=================================================================
'=================================================================
'=================================================================
' Start Program
'=================================================================
'=================================================================
'=================================================================
'=================================================================

'Variable Defininitions/Initialization
'Digital Sound Meter Code
'{$STAMP BS2} 'This Program is for the BS2 microprocessor


'-----------------------------------------
'Stamp Pins
'-----------------------------------------
'7 segment LED
Dpin            CON 7 'data pin (MAX7219.1)
Clock           CON 5 'clock pin (MAX7219.13)
Load            CON 6 'load pin (MAX7219.12)
'-----------------------------------------
'Status LED
LEDHIGH         CON 11
LEDLOW          con 10
'-----------------------------------------
'Character LCD
LCD             CON 0
'-----------------------------------------
'A/D Converter
CS              con 13
CLK             con 14
D0              con 15
'-----------------------------------------
Rangefinder     con 8
RangefinderL    con 9
'-----------------------------------------
'Variables & Constants
'-----------------------------------------
'LED Constants
Decode  CON $09         ' bcd decode register
Brite   CON $0A         ' intensity register
Scan    CON $0B         ' scan limit register
ShutDn  CON $0C         ' shutdown register (1 = on)
Test    CON $0F         ' display test mode
DecPnt  CON %10000000
Blank   CON %1111       ' blank a digit
Yes     CON 1
ON      CON 1
No      CON 0
OFF     CON 0
'-----------------------------------------
'Calculation/Results Variables
AD_Number       VAR     byte    'Number recorded from AD Converter
Contour_Data    VAR     word    'Distance before decimal
```

```
Contour_DataB   VAR     nib     'Distance after decimal
dB_at_obs       VAR     word    'dB level at the observer
sign            var     dB_at_obs.bit15
dB_at_50ft      VAR     word    'Calculated dB level at 50 feet
AD_16_Times     VAR     word    '16 AD Conversions Added up
Ambient_dB      VAR     word    'Ambient level dB stored here
baud4800 con 16572
baud9600 con 16468
'---------------------------------------
'7 segment LED scratch variables
digit           VAR Nib         ' display digit
d7219           VAR Byte        ' data for MAX7219
index           VAR Nib         ' loop counter
idxOdd          VAR index.Bit0  ' is index odd? (1 = yes)
odd             VAR index.bit0  ' Lsb of index.
Seven_Segment   VAR bit
'---------------------------------------
'Log calculation scratch variables
x       var word        ' for processing the number
xf      var x.bit15     ' high bit of x, note alias
x2      var word        ' for squaring the number
x2f     var x2.bit15    ' high bit of x2, note alias
lgx     var word        ' will be the lg (base 2) of y, the mantissa
lgx0    var lgx.bit0    ' lowest bit of lgx, for bit addressing
bitk    var bit         ' temporary bit
k       var nib         ' loop and array index
cc      var nib         ' characteristic of the lg
lg      var word        ' to hold the log base 2
lg0     var lg.byte0    ' for table lookup, array of bytes
log     var word        ' to hold the log base 10
'---------------------------------------
Z  con 500      ' the maximum value of dB_Difference,  0<= AD_16_Times
<Z
' make this an exact power of 2.
L  con 125      ' the number of intervals in the table
o  con 4     ' Z/Lthe width of catagories of AD_16_Times
M  con 16384    ' 65536/o  for the interpolation formula
'---------------------------------------
'Ambient Correction Data
table   data    word    44444
                data    word    26934
                data    word    21111
                data    word    17786
                data    word    15482
                data    word    13737
                data    word    12344
                data    word    11196
                data    word    10224
                data    word    9388
                data    word    8658
                data    word    8015
                data    word    7441
                data    word    6927
                data    word    6463
                data    word    6041
                data    word    5657
                data    word    5305
                data    word    4982
                data    word    4685
                data    word    4410
                data    word    4155
                data    word    3918
                data    word    3698
```

```
data    word    3493
data    word    3302
data    word    3123
data    word    2955
data    word    2798
data    word    2651
data    word    2513
data    word    2382
data    word    2260
data    word    2144
data    word    2036
data    word    1933
data    word    1836
data    word    1745
data    word    1658
data    word    1576
data    word    1499
data    word    1425
data    word    1356
data    word    1290
data    word    1228
data    word    1169
data    word    1113
data    word    1059
data    word    1009
data    word    961
data    word    915
data    word    872
data    word    831
data    word    792
data    word    754
data    word    719
data    word    685
data    word    653
data    word    623
data    word    594
data    word    566
data    word    540
data    word    515
data    word    491
data    word    468
data    word    447
data    word    426
data    word    406
data    word    388
data    word    370
data    word    353
data    word    337
data    word    321
data    word    307
data    word    292
data    word    279
data    word    266
data    word    254
data    word    243
data    word    232
data    word    221
data    word    211
data    word    201
data    word    192
data    word    183
data    word    175
data    word    167
```

```
                data    word    160
                data    word    152
                data    word    145
                data    word    139
                data    word    132
                data    word    126
                data    word    121
                data    word    115
                data    word    110
                data    word    105
                data    word    100
                data    word    96
                data    word    91
                data    word    87
                data    word    83
                data    word    80
                data    word    76
                data    word    73
                data    word    69
                data    word    66
                data    word    63
                data    word    60
                data    word    58
                data    word    55
                data    word    52
                data    word    50
                data    word    48
                data    word    46
                data    word    44
                data    word    42
                data    word    40
                data    word    38
                data    word    36
                data    word    35
                data    word    33
                data    word    32
                data    word    30
                data    word    29
                data    word    28


                Low RangefinderL

'=====================================================================
'Initialize
'=====================================================================
'Initialization Protocal. Wait for startup fluctuations to settle.
'Then build ambient sound level. Then proceed to operation mode.

pause 1000              'Inital Pause until LCD screen is ready for data
gosub Startup_LCD       'Write to LCD to indicate machine is starting up
pause 4000              'Pause for fluctuations to settle.
gosub Build_Ambient_Sound_Level
gosub Ambient_LCD       'Tell LCD to display Ambient Screen

'=====================================================================
'Speed Update Loop - Loop 1
'=====================================================================
'Initial loop. Continue to update the Sound Level number through the
infinite impulse filter
'while waiting for serial data from the laser rangefinder.
```

```
First_Loop_Startup:

gosub Ambient_LCD


First_Loop:

if in8=1 then Continous_Dist_Update_Loop_Start
                'If there is LCD data incoming, drop into 2nd loop
gosub AD_Conversion             'Update Sound level
gosub Ambient_LCD_Update        'Update LCD Screen

goto First_Loop
'==================================================================
'Distance Update Loop - Loop 2
'==================================================================

Continous_Dist_Update_Loop_Start:
gosub Distance_LCD_Start
gosub loop_startup
Continous_Distance_Update_Loop:
SERIN Rangefinder, baud4800,200,Sound_Computation,[WAIT(",0"),DEC
dB_at_50ft, DEC Contour_DataB]
'Recieve the Serial Data from the Rangefinder. If there is a timeout,
then the trigger has been
'let go and it is time to proceed to calcuating a corrected value
Contour_Data = dB_at_50ft*10 + Contour_DataB


gosub AD_Conversion     'Update Sound level
gosub AD_Conversion
gosub AD_Conversion
gosub AD_Conversion
gosub AD_Conversion
gosub AD_Conversion
gosub AD_Conversion


gosub Distance_AND_dB_Update_Screen     'Update Screen with Sound and
Distance

goto Continous_Distance_Update_Loop

'==================================================================
'Compute Corrected Sound Level
'==================================================================

Sound_Computation:


Compute_Corrected_Level:


gosub Loudness_Test
Passed:


gosub Ambient_dB_Correction
goto Doubling_Test


continue:
```

```
gosub Display_Corrected_Level
gosub Ambient_LCD
goto First_Loop_Startup:

'==================================================================
'==================================================================
'==================================================================
'==================================================================
'End Main Program
'==================================================================
'==================================================================
'==================================================================
'==================================================================




'==================================================================
'==================================================================
'Subroutines
'==================================================================
'==================================================================
Doubling_Test:
if Contour_Data>500 then log_code_1
pause 5
if Contour_Data<500 then log_code_2
pause 5
if Contour_Data=500 then log_code_3
'---------------------------------------------------------------------
----------------
Loudness_Test:
'Decide whether Source is loud enough
if (dB_at_obs-Ambient_dB)>60 AND dB_at_obs>Ambient_dB Then Passed:
gosub Sound_Too_Low
goto First_Loop_Startup
'---------------------------------------------------------------------
----------------
Startup_LCD:
serout LCD,baud9600,[254,1]     ' Clear Screen
pause 20
serout LCD,baud9600,["Initializing"]
pause 20
return
'---------------------------------------------------------------------
----------------

Build_Ambient_Sound_Level:
for x = 1 TO 350
gosub AD_Conversion
next
Ambient_dB = dB_at_obs
return
'---------------------------------------------------------------------
----------------
Ambient_LCD:

serout LCD,baud9600,[254,1] ' Clear Screen
SEROUT LCD,baud9600,[$FE, 0]
serout LCD,baud9600,["Ambient: "]

serout LCD,baud9600,[DEC Ambient_dB/10, ".",DEC Ambient_dB//10]

return
```

```
'-----------------------------------------------------------------------
----------------
Ambient_LCD_Update:
SEROUT LCD,baud9600,[$FE, $80+$40+(0)]
serout LCD,baud9600,["Current: "]
SEROUT LCD,baud9600,[DEC dB_at_obs/10, ".", DEC dB_at_obs//10]
Activate_LED_Display:

return
'-----------------------------------------------------------------------
----------------

Distance_AND_dB_Update_Screen:
SEROUT LCD,baud9600,[$FE, $80+$40+(0)]
SEROUT LCD,baud9600,[DEC dB_at_obs/10, ".", DEC dB_at_obs//10, "-"]
SEROUT LCD,baud9600,[DEC Contour_Data/10, ".", DEC Contour_Data//10,
"F"]
gosub Write_LED_Disp



return
'-----------------------------------------------------------------------
----------------
Distance_LCD_Start:
serout LCD,baud9600,[254,1] ' Clear Screen
SEROUT LCD,baud9600,[$FE, 0]
serout LCD,baud9600,["Ambient: "]
serout LCD,baud9600,[DEC Ambient_dB/10, ".",DEC Ambient_dB//10]
SEROUT LCD,baud9600,[$FE, $80+$40+(0)]
SEROUT LCD,baud9600,[DEC dB_at_obs/10, ".", DEC dB_at_obs//10, "-"]
SEROUT LCD,baud9600,[DEC Contour_Data/10, ".", DEC Contour_Data//10,
"F"]

return


'-----------------------------------------------------------------------
----------------
AD_Conversion:
high CS
low CS
low CLK
pulsout CLK,210
shiftin D0,CLK,msbpost,[AD_Number\8]
'Infinite_Impulse_Response:
lgx = 16*AD_Number
lg = 15*AD_16_Times
AD_16_Times = lgx + lg / 16
'Interpolate:
d7219= (AD_16_Times) /4096          ' choose the catagory within the
table
lgx= (AD_16_Times)  //4096          ' remainder
dB_at_obs=323-1007
dB_at_obs= -sign^(abs dB_at_obs**(16*lgx))+sign +1007 ' can handle both
+ and -
return


        '---------------------------------------------------------------
-----------------------
```

```
Display_Corrected_Level:
serout LCD,baud9600,[254,1] ' Clear Screen
pause 5
serout LCD,baud9600,["D:"]
pause 5
serout LCD,baud9600,[DEC Contour_Data/10,".",DEC Contour_Data//10, " "]
pause 5
serout LCD,baud9600,["A:"]
pause 5
serout LCD,baud9600,[DEC Ambient_dB/10,".",DEC Ambient_dB//10]
pause 5
SEROUT LCD,baud9600,[$FE, $80+$40+(0)]
PAUSE 5
serout LCD,baud9600,[DEC dB_at_obs/10,".",DEC dB_at_obs//10, " , "]
PAUSE 5
serout LCD,baud9600,[DEC dB_at_50ft/10,".",DEC dB_at_50ft//10]



gosub Write_LED_Disp2



check:
if in8=1 then pass_Check
goto check
pass_Check:


Shutdown_7_Segmenta:

DirL = %11100000 ' data, clock and load as outs

FOR index = 0 TO 7
LOOKUP index,[Scan,3,Brite,0,Decode,$0F,ShutDn,0],d7219
SHIFTOUT Dpin,Clock,MSBFirst,[d7219]
IF idxOdd = No THEN NoLoada
PULSOUT Load,3 ' load parameter
NoLoada:
NEXT            'Shutdown display

return
'------------------------------------------------------------------------
----------------

Sound_Too_Low:

Shutdown_7_Segment5:
DirL = %11100000 ' data, clock and load as outs

FOR index = 0 TO 7
LOOKUP index,[Scan,3,Brite,0,Decode,$0F,ShutDn,0],d7219
SHIFTOUT Dpin,Clock,MSBFirst,[d7219]
IF idxOdd = No THEN NoLoad5
PULSOUT Load,3 ' load parameter
NoLoad5:
NEXT            'Shutdown display

serout LCD,baud9600,[254,1] ' Clear Screen
SEROUT LCD,baud9600,[$FE, 0]
serout LCD,baud9600,["Sound Level Low"]
```

```
check2:
if in8=1 then pass_Check2
goto check2
pass_Check2:

pause 1000
gosub Ambient_LCD

return

'-----------------------------------------------------------------------
----------------
log_code_1:
'Log of Distance Ratio Calculation
cc=ncd (Contour_Data) - 1          ' find the characteristic
x=(Contour_Data) << (15-cc)        ' adjust for a denominator of 32768
                     ' optionally, show the decompostion
lgx=0                  ' initialize accumulator
for k=14 to 0          ' 15 steps of precision
x2=x**x              ' high byte of x squared
lgx0(k)=x2f          ' high bit of x squared is this bit of log.
bitk=~x2f            ' complement of that bit
x=x2<<bitk+(bitk&xf)' adjust x
next                 ' repeat
' combine it into one 16 bit word (but lose one digit!):
lg=cc*1000+(lgx**20000/10)
' convert it to log base 10:
log=lg**19728

dB_at_50ft = dB_at_obs+(((((log-2699)*2*5)/6))/10)


goto continue
'-------------------------------------------------------------------
log_code_2:
'Log of Distance Ratio Calculation
cc=ncd (Contour_Data) - 1          ' find the characteristic
x=(Contour_Data) << (15-cc)        ' adjust for a denominator of 32768
lgx=0                  ' initialize accumulator
for k=14 to 0          ' 15 steps of precision
x2=x**x              ' high byte of x squared
lgx0(k)=x2f          ' high bit of x squared is this bit of log.
bitk=~x2f            ' complement of that bit
x=x2<<bitk+(bitk&xf)' adjust x
next                 ' repeat
' combine it into one 16 bit word (but lose one digit!):
lg=cc*1000+(lgx**20000/10)
' convert it to log base 10:
log=lg**19728


dB_at_50ft = dB_at_obs-(((((2699-log)*2)))/10)

goto continue
'-------------------------------------------------------------------
log_code_3:
dB_at_50ft = dB_at_obs
goto continue

'-------------------------------------------------------------------
loop_startup:
```

```
Initialize_7_Segment2:
DirL = %11100000 ' data, clock and load as outs
FOR index = 0 TO 7                              'Write to 7 Segment LED
LOOKUP index,[Scan,3,Brite,0,Decode,$0F,ShutDn,1],d7219
SHIFTOUT Dpin,Clock,MSBFirst,[d7219]
IF idxOdd = No THEN NoLoad3
PULSOUT Load,3 ' load parameter
NoLoad3:
NEXT
return


'-------------------------------------------------------------------
Write_LED_Disp:
FOR index = 4 TO 1
d7219 = Blank
IF (index = 4) AND (dB_at_obs < 1000) THEN PutDigit
d7219 = dB_at_obs DIG (index - 1)
IF (index <> 2) THEN PutDigit
d7219 = d7219 | DecPnt ' decimal point on DIGIT 3



PutDigit:
IF (index =1 ) THEN putdigit1
putdigita:
SHIFTOUT Dpin,Clock,MSBFirst,[index,d7219]
PULSOUT Load,3
NEXT
return
putdigit1:
d7219 = Blank
goto putdigita

'-------------------------------------------------------------------
Write_LED_Disp2:
FOR index = 4 TO 1
d7219 = Blank
IF (index = 4) AND (dB_at_50ft < 1000) THEN PutDigitz
d7219 = dB_at_50ft DIG (index - 1)
IF (index <> 2) THEN PutDigitz
d7219 = d7219 | DecPnt ' decimal point on DIGIT 3




PutDigitz:

putdigitc:
SHIFTOUT Dpin,Clock,MSBFirst,[index,d7219]
PULSOUT Load,3
NEXT
return
'-------------------------------------------------------------------
Ambient_dB_Correction:


d7219= (dB_at_obs-Ambient_dB) /o           ' choose the catagory within
the table
lgx= (dB_at_obs-Ambient_dB)  //o          ' remainder
for cc=0 to 3   ' read values that bracket the category.
read d7219*2+cc+table,lg0(cc)  '  lg and log are contiguous 4 bytes
next
```

```
if lgx = 1 then change_o1
if lgx = 3 then change_o2
if lgx = 2 then finish

change_o1:
lgx = 3
goto finish
change_o2:
lgx = 1
goto finish
finish:
'dB_at_obs =dB_at_obs-( lg-log*lgx  /o+log   ) ' simple interpolation,
works only when log -Q and F are small.

dB_at_obs  =dB_at_obs - ((( lg-log )**(M*lgx  ) +log )/100) ' better
alternative
'dB_at_obs =dB_at_obs-((lg-log)**(lgx  <<(17-NCD o))+log) ' another
alternative, using fast shifts


return
```

APPENDIX D

SOUND PROPAGATION AND MEASUREMENT IN AN OPEN SPACE ENVIRONMENT

By
Clark J Radcliffe, Ph.D.
Professor of Mechanical Engineering
Michigan State University
East Lansing, MI 48824-1226
(517) 355-5198
radcliffe@me.msu.edu

Spherical Sound Propagation

Sound Propagation over an open ground surface can be idealized as propagation over a semi-infinite plane. This model ignores the effect of surface variations but captures the general, non-reflective, character of sound propagation over water and open ground. Consider the model below

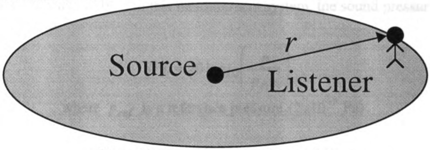

Figure 22: Spherical Sound Propagation

The sound propagates as a spherical wave in an unbounded fluid medium. The source is considered to be centered at the origin and to have spherical symmetry insofar as the excitation of sound is concerned. The symmetry of the excitation and the environment requires that the time averaged acoustic intensity I only has a radial component and that its amplitude be dependent only on the distance r from the source center. To determine the radial dependence, one applies the acoustic energy conservation principle where the average acoustic power $\mathbf{P}_{source}$ is constant at any distance and the acoustic intensity (power/unit area) becomes

$$I = \frac{\mathbf{P}_{source}}{4\pi r^2} \tag{37}$$

This acoustic propagation model, intensity decreases with the inverse square of the radial distance, is known as the *spherical spreading law.*

Acoustic Intensity I at any point is proportional to the square of the time averaged acoustic pressure.

$$I = \frac{p^2}{\rho c} \tag{38}$$

Combining the above relations (37) and (38) shows that *local, point, acoustic pressure is inversely proportional to distance from the source.*

$$\frac{p^2}{\rho c} = \frac{P_{source}}{4\pi r^2} \Rightarrow p = \sqrt{\frac{\rho c P_{source}}{4\pi r^2}} = \frac{A}{r} \tag{39}$$

where $A = \sqrt{\rho c \mathbf{P}_{source}/4\pi}$ is a constant

The implication of this result is that a simple point measurement of local acoustic pressure decreases dramatically with distance. Typical acoustic pressure measurements are expressed in decibels (dB). In this measurement system, the sound pressure level, SPL is computed as

$$SPL = 20\log_{10}\left(\frac{p}{p_{ref}}\right) \tag{40}$$

where p_{ref} is a reference pressure ($2x10^{-5}$ Pa).

Using this relationship, the change in SPL between any two point measurement locations for the same sound source becomes

$$\begin{aligned} \Delta SPL = SPL(r_2) - SPL(r_1) &= 20\log_{10}\left(\frac{p_2}{p_{ref}}\right) - 20\log_{10}\left(\frac{p_1}{p_{ref}}\right) \\ &= 20\log_{10}\left(\frac{p_2}{p_1}\right) = 20\log_{10}\left(\frac{A/r_2}{A/r_1}\right) = 20\log_{10}\left(\frac{r_1}{r_2}\right) \end{aligned} \tag{41}$$

For a sound measured to be 90 dBA at a 3 foot distance form the source, the resulting point SPL measurements at other distances are shown in Table 5.

Table 5: Predicted Point SPL Measurements Versus Distance

Distance (ft)	*SPL* (dBA)
3	90
6	84
10	79.5
30	70
50	65.6
100	59.5
150	56
200	53.5
250	51.6
300	50

Sound measurements where the sound to be measured is comparable to the ambient sound can not be made as simple, point, SPL measurements. In this case, sound pressure beyond 30 feet from the source must be physically amplified as a pressure before it is presented to the measurement microphone in order to raise it above a 70 dB ambient sound pressure level. Physical amplification must be directionally dependent so that sound in the direction of the source is amplified above sound from sources in other directions. There are two devices available that directionally amplify incoming sound: the parabolic microphone and the shotgun microphone.

The parabolic measurement microphone uses a parabolic surface to selectively reflect local sound to a measurement microphone and directionally discriminate between sound sources. The physics of the reflecting surface is very similar to that of a parabolic mirror with one exception. The reflection only occurs when the wavelength of the sound is nearly as same as the dimension of the reflector. A sound with a frequency of 1000 Hz. has a wavelength of about 16 inches and can be reflected by surfaces of at least 16 inches in dimension. A sound with a frequency of 100 Hz. has a wavelength of about 13 feet and requires a reflector dimension of about 13 feet for effective reflection - clearly impractical for common use. Parabolic microphones can provide 20 - 40 dB discrimination within their effective frequency range and allow measurement of distant sources.

The shotgun microphone is more effective at low frequencies because it is not so closely dependent on wavelength for effectiveness. The shotgun microphone uses a long perforated tube whose internal propagating pressure is augmented by an acoustic wave that propagates along the outside of the tube at the same speed. An 18 inch shotgun microphone can generate significant directional response for sounds with frequencies down to 30 Hz., far below the low frequency directionality of a parabolic microphone.

The tradeoff is a reduction in the directionality of the high frequency response in this design.

The sound of an operating vehicle is dominated by the tonal quality of its exhaust. For a 4 stroke engine with C cylinders operating at N rpm, the fundamental exhaust tone is at frequency

$$f_4 = CN/120\,\text{Hz}.$$

while for a 2 stroke engine with C cylinders operating at N rpm, the fundamental exhaust tone occurs at frequency

$$f_2 = CN/60\,\text{Hz}.$$

Typical 4 stroke engines operate from 600-6000 rpm while typical 2 stroke engines operate from 900-9000 rpm. For a 4 stroke engine with 8 cylinders, the fundamental exhaust tone range is 40– 400 Hz while for a 2 stroke engine with 2 cylinders, the fundamental exhaust tone range is 30-300 Hz. In both cases, any engine noise acoustic measurement must have good directionality from 30 to 400 Hz. This requirement dictates the choice of a shotgun microphone for our measurement system. The appearance and directionality of an Audio-Technica AT815B are shown in Figure 2

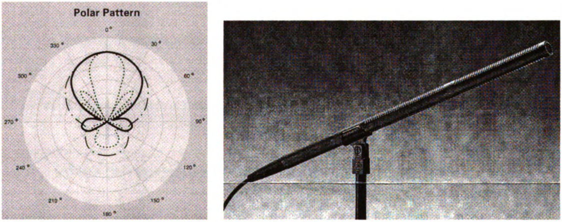

Figure 23: The Audio-Technical AT815b Shotgun Microphone

Measurement

The design and calibration procedure to allow discrimination of noise sources in a verifiable way is a principle issue facing the development of the instrument proposed. In this case, assume we make a measurement of voltage v (volts) from the microphone at distance $r_2 = 100$(ft) and wish to compute the equivalent SPL at a distance r_1=3 (ft). The microphone has a calibration sensitivity $S = 12.5$ mV/Pa and the standard SPL pressure reference, $p_{ref} = 2\text{x}10^{-5}$ Pa is used. In this case, the measured pressure,

$$p = v/S$$

and the SPL at distance r_2 (ft) is

$$\begin{aligned} SPL(r_2) &= 20\log(p/p_{ref}) = 20\log(p) - 20\log(p_{ref}) = 20\log(v/S) - 20\log(p_{ref}) \\ &= 20\log(v) - 20\log(S) - 20\log(p_{ref}) \\ &= 20\log(v) - 20\log(0.0125) - 20\log(2x10^{-5}) \\ &= 20\log(v) + 38.62 + 93.98 \\ &= 20\log(v) + 132.04 \end{aligned}$$

applying the distance correction

$$\begin{aligned} SPL(r_1) &= SPL(r_2) + \Delta SPL(r_2/r_1) = SPL(r_2) + 20\log(r_2/r_1) \\ &= SPL(r_2) + 20\log(100/3) = 20\log(v) + 132.04 + 30.46 \\ &= 20\log(v) + 162.50\, dB \end{aligned}$$

APPENDIX E

BACKGROUND NOISE COMPENSATION

Clark Radcliffe

When a microphone measurement of a source is made in the presence of background noise, the measured source level is greater than the actual source level. This difference can be compensated for when the background level is known.

The total measured sound y_m is the sum of the source y_s and background noise y_b,

$$y_m = y_s + y_b \tag{42}$$

This total measured sound is expressed on a decibel (dB) scale as

$$Y_m = 20\log_{10}(y_m) = 20\log_{10}(y_s + y_b) \tag{43}$$

where the measured background level

$$Y_b(dB) = 20\log_{10}(y_b) \tag{44}$$

and the desired sound source level

$$Y_s(dB) = 20\log_{10}(y_s) \tag{45}$$

Solving (44) and (45) for the source and background levels in (40) yields,

$$y_b = 10^{(Y_b/20)} \tag{46a}$$

$$y_s = 10^{(Y_s/20)} \tag{46b}$$

These results can now be substituted into (42) and (45) to solve for the source pressure y_s and source level in decibels

$$\begin{aligned} Y_s(dB) &= 20\log_{10}[y_s] = 20\log_{10}[y_m - y_b] \\ &= 20\log_{10}\left[10^{(Y_m/20)} - 10^{(Y_b/20)}\right] \end{aligned} \tag{47}$$

Rearranging (47) to collect terms and compute compensation in dB,

$$Y_s(dB) = 20\log_{10}\left[\left(10^{(Y_m/20)}\right)\left(1 - \frac{10^{(Y_b/20)}}{10^{(Y_m/20)}}\right)\right]$$
$$= 20\log_{10}\left(10^{(Y_m/20)}\right) + 20\log_{10}\left(1 - 10^{((Y_b - Y_m)/20)}\right) \quad (48)$$

This compensation equation (45) can now be written as

$$Y_s(dB) = Y_m + C \quad (49)$$

where the compensation $C = 20\log_{10}\left(1 - 10^{[(Y_b - Y_m)/20]}\right)$. Because the argument of the log function is always less than one, the compensation C (Fig. 23) will always be negative.

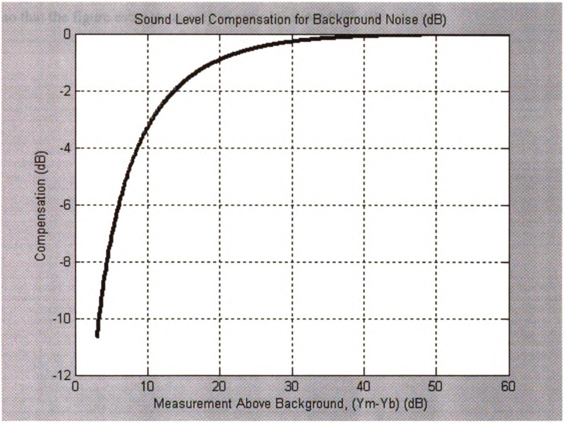

Figure 24: Compensation C with Known Background Level Y_b

Example:

Assume that the background level is measured to be $Y_b = 56$ dB and a noise measurement of $Y_m = 70$ dB is made. The actual source level is found by entering the figure for

$$(Ym\text{-}Yb) = (70\text{-}56)\,dB = 14\ dB\,.$$

The result read from the figure is approximately $C = -2$ dB and the actual source level is

$$Y_s(dB) = Y_m + C = 70\,dB + (-\,2\,dB) = 68\,dB$$

Analytically, the background compensation

$$C = 20\log_{10}\left(1 - 10^{[(Y_b - Y_m)/20]}\right) = \text{-}1.9331$$

so that the figure estimate is only in error by about 0.07 dB.

APPENDIX F

Anechoic and Lake Test Data

Table 6: 1st Anechoic Test

	White Noise				8 Khz				4 Khz				2 Khz			
ambient	39.2	3549	211	42.2	39.9	3571	227	41.8	39.8	3508	221	42.9	37.7	3567	228	41.8
	39.2	3437	216	44.2	39.9	3606	232	41.1	39.8	3628	230	40.7	37.7	3726	234	39
	39.2	3584	227	41.5	39.9	3667	229	40	39.8	3543	210	42.3	37.7	3654	229	40.3
	39.2	3554	227	40.3	39.9	3685	236	39.7	39.8	3587	220	41.5	37.7	3566	223	41.8
50	41.3	3440	213	44.1	41	3634	226	40.6	41.2	3650	230	40.3	39.4	3311	214	46.4
	41.3	3433	218	44.2	41	3611	225	41	41.2	3516	225	42.7	39.4	3652	230	40.3
	41.3	3355	211	45.6	41	3559	223	42	41.2	3694	231	39.6	39.4	3629	235	40.7
	41.3	3592	230	44.4	41	3597	231	41	41.2	3677	233	39.9	39.4	3573	224	41.7
60	47.7	3245	205	47.6	41.3	3429	217	44.3	41.6	3562	226	41.9	43.4	3426	218	44.4
	47.7	3142	200	49.4	41.3	3488	223	43.2	41.6	3495	219	43.1	43.4	3409	217	44.7
	47.7	3166	196	49	41.3	3459	220	43.8	41.6	3514	223	42.8	43.4	3337	211	46
	47.7	3205	203	48.3	41.3	3339	208	45.9	41.6	3570	224	41.8	43.4	3428	218	44.3
70	56.3	2637	165	58.5	45	3401	214	44.8	48.1	3156	198	49.2	51.5	2872	180	54.3
	56.3	2627	164	58.7	45	3376	213	45.3	48.1	3129	197	49.7	51.5	2865	179	54.4
	56.3	2641	165	58.4	45	3380	214	45.2	48.1	3123	196	49.8	51.5	2876	180	54.2
	56.3	2621	164	58.8	45	3348	211	45.8	48.1	3087	194	50.4	51.5	2877	180	54.2
80	66.1	2067	128	68.7	53.6	2716	169	57.1	57.9	2468	154	61.8	61.4	2277	144	64.9
	66.1	2067	129	68.7	53.6	2707	170	57.2	57.9	2474	154	61.4	61.4	2291	144	64.7
	66.1	2067	129	68.7	53.6	2708	170	57.3	57.9	2465	154	61.6	61.4	2282	143	64.9
90	76.1	1525	96	78.4	63.4	2028	125	69.4	67.7	1897	118	71.8	71.4	1742	108	74.5
	76.1	1521	95	78.5	63.4	2044	127	69.1	67.7	1890	118	71.9	71.4	1750	110	74.4
	76.1	1520	95	78.5	63.4	2039	128	69.2	67.7	1900	119	71.7	71.4	1731	108	74.7
	76.1	1522	96	78.5	63.4	2027	127	69.4	67.7	1889	118	71.9	71.4	1737	109	74.6
ambient	36.4	3608	229	41	36.4	3608	229	41	36.4	3608	229	41	36.4	3608	229	41
	36.4	3582	227	41.5	36.4	3582	227	41.5	36.4	3582	227	41.5	36.4	3582	227	41.5
	36.4	3686	229	39.6	36.4	3686	229	39.6	36.4	3686	229	39.6	36.4	3686	229	39.6
	36.4	3515	223	42.7	36.4	3515	223	42.7	36.4	3515	223	42.7	36.4	3515	223	42.7
Closer Sound Source	87.8	760	47	92.1	76.2	1152	72	85.1	81.2	1032	65	87.2	84.9	912	57	89.4
	87.8	758	47	92.1	76.2	1146	72	85.2	81.2	1051	65	86.9	84.9	930	58	89
	87.8	761	48	92.1	76.2	1142	71	85.2	81.2	1035	65	87.2	84.9	919	59	89.2
	87.8	760	48	92.1	76.2	1145	71	85.2	81.2	1047	66	86.9	84.9	919	56	89.2

Table 6 (cont'd)

ambient	37	3716	230	39.1	37	3716	230	39.1	37	3716	230	39.1	37	3716	230	39.1
	37	3614	228	40.9	37	3614	228	40.9	37	3614	228	40.9	37	3614	228	40.9
	37	3648	229	40.3	37	3648	229	40.3	37	3648	229	40.3	37	3648	229	40.3
	37	3621	229	40.8	37	3621	229	40.8	37	3621	229	40.8	37	3621	229	40.8
ambient	38	3648	226	40.3	38	3648	226	40.3	38	3648	226	40.3	38	3648	226	40.3
	38	3468	221	43.6	38	3468	221	43.6	38	3468	221	43.6	38	3468	221	43.6
	38	3606	231	41.1	38	3606	231	41.1	38	3606	231	41.1	38	3606	231	41.1
	38	3607	227	41.1	38	3607	227	41.1	38	3607	227	41.1	38	3607	227	41.1
Sideways Sound	93	460	28	97.5	90.1	569	35	95.5	94	355	23	99.3	94.2	412	26	98.3
	93	459	28	97.5	90.1	576	36	95.4	94	355	22	99.3	94.2	409	25	98.4
	93	454	28	97.6	90.1	570	36	95.5	94	355	22	99.3	94.2	402	25	98.5
	93	455	28	97.5	90.1	575	36	95.4	94	360	23	99.2	94.2	416	27	98.2
	1 Khz				500 hz				250 hz				125 hz			
ambient	35.5	3366	223	45.4	36	3622	238	40.8	36.3	3624	224	40.8	37.1	3458	217	43.8
	35.5	3570	224	41.8	36	3643	227	40.5	36.3	3583	235	41.5	37.1	3664	241	40.1
	35.5	3676	227	39.9	36	3546	226	42.2	36.3	3633	223	40.6	37.1	3676	232	39.8
	35.5	3572	226	41.7	36	3673	234	39.9	36.3	3711	227	39.2	37.1	3627	242	40.8
50	36.9	3657	234	40.2	38.4	3619	231	40.4	37.6	3686	236	39.7	38.8	3683	234	39.8
	36.9	3670	231	40	38.4	3685	238	39.7	37.6	3673	234	39.9	38.8	3680	223	39.8
	36.9	3630	234	40.7	38.4	3692	235	39.8	37.6	3652	231	40.3	38.8	3713	227	39.2
	36.9	3691	238	39.6	38.4	3675	233	39.9	37.6	3692	226	39.6	38.8	3693	231	39.6
60	40.7	3614	230	41	41.9	3411	218	44.6	40.1	3647	227	40.4	39.5	3633	228	40.6
	40.7	3585	227	41.5	41.9	3523	224	42.6	40.1	3603	224	41.2	39.5	3613	231	41
	40.7	3654	232	40.3	41.9	3516	224	42.7	40.1	3625	230	40.8	39.5	3647	230	40.4
	40.7	3577	226	41.7	41.9	3521	223	42.7	40.1	3576	224	41.2	39.5	3572	222	41.7
70	48.9	3077	193	50.6	50.5	2970	107	52.5	47.5	3125	195	49.8	46.6	3413	214	44.6
	48.9	3059	191	50.9	50.5	2991	187	52	47.5	3160	198	49.1	46.6	3411	214	44.6
	48.9	3090	194	50.4	50.5	3017	189	51.7	47.5	3118	197	49.9	46.6	3433	216	44.2
	48.9	3091	194	50.4	50.5	3026	189	51.5	47.5	3137	197	49.5	46.6	3395	211	44.9
80	58.5	2486	157	61.2	60.1	2421	152	62.4	57.1	2556	159	59.9	55.5	2824	177	55.1
	58.5	2485	154	61.2	60.1	2447	154	61.9	57.1	2535	157	60.3	55.5	2795	176	55.7
	58.5	2469	154	61.5	60.1	2434	152	62.1	57.1	2557	158	59.9	55.5	2840	177	54.9
	58.5	2471	155	61.5	60.1	2423	151	62.3	57.1	2539	158	60.3	55.5	2828	178	55.1
90	68.6	1929	121	71.2	70.5	1870	117	72.2	66.8	1982	124	70.2	65.3	2332	144	64
	68.6	1923	119	71.3	70.5	1864	116	72.3	66.8	1991	124	70.1	65.3	2332	145	64
	68.6	1925	121	71.3	70.5	1859	117	72.4	66.8	1995	124	70	65.3	2346	146	63.7
	68.6	1909	119	71.5	70.5	1891	117	71.9	66.8	2005	128	69.8	65.3	2275	142	65
ambient	36.4	3608	229	41	36.4	3608	229	41	36.4	3608	229	41	36.4	3608	229	41
	36.4	3582	227	41.5	36.4	3582	227	41.5	36.4	3582	227	41.5	36.4	3582	227	41.5
	36.4	3686	229	39.6	36.4	3686	229	39.6	36.4	3686	229	39.6	36.4	3686	229	39.6
	36.4	3515	223	42.7	36.4	3515	223	42.7	36.4	3515	223	42.7	36.4	3515	223	42.7
Closer Sound Source	82.1	1102	70	86	82.8	1117	70	85.7	79.9	1231	78	83.6	78.4	1475	90	79.3
	82.1	1106	70	85.9	82.8	1093	69	86.1	79.9	1230	76	83.7	78.4	1421	91	80.2
	82.1	1119	70	85.6	82.8	1104	68	85.9	79.9	1227	76	83.7	78.4	1430	88	80.1
	82.1	1099	71	86	82.8	1097	69	86	79.9	1249	79	83.3	78.4	1424	90	80.2

Table 6 (cont'd)

ambient	37	3716	230	39.1	37	3716	230	39.1	37	3716	230	39.1	37	3716	230	39.1
	37	3614	228	40.9	37	3614	228	40.9	37	3614	228	40.9	37	3614	228	40.9
	37	3648	229	40.3	37	3648	229	40.3	37	3648	229	40.3	37	3648	229	40.3
	37	3621	229	40.8	37	3621	229	40.8	37	3621	229	40.8	37	3621	229	40.8
ambient	38	3648	226	40.3	38	3648	226	40.3	38	3648	226	40.3	38	3648	226	40.3
	38	3468	221	43.6	38	3468	221	43.6	38	3468	221	43.6	38	3468	221	43.6
	38	3606	231	41.1	38	3606	231	41.1	38	3606	231	41.1	38	3606	231	41.1
	38	3607	227	41.1	38	3607	227	41.1	38	3607	227	41.1	38	3607	227	41.1
Sideways Sound	**90.6**	**665**	**41**	93.8	**89.9**	**710**	**45**	93	**86.1**	**874**	**54**	90	**83.9**	**1120**	**70**	85.6
	90.6	**661**	**42**	93.9	89.9	**723**	**45**	92.7	86.1	**891**	**54**	89.7	83.9	**1170**	**73**	84.7
	90.6	**668**	**42**	93.7	89.9	**737**	**45**	92.5	86.1	**872**	**52**	90.1	83.9	**1134**	**71**	85.4
	90.6	**663**	**41**	93.8	89.9	**719**	**45**	92.8	86.1	**885**	**52**	89.8	83.9	**1170**	**71**	84.7

Table 7: 1st Anechoic Test, Angular Data

					Stamp	Post
Angle	Frequency	B&K dB	A/D Count*16	A/D Count	Computed dB	Computed dB
0	125	66.8	2247	141	65	65.4
0	125	66.8	2199	139	66	66.3
0	125	66.8	2177	136	67	66.7
0	125	66.8	2181	137	67	66.6
0	250	68.4	1943	122	71	70.9
0	250	68.4	1909	122	72	71.5
0	250	68.4	1924	121	71	71.2
0	250	68.4	1937	121	71	71
0	500	71.9	1802	111	74	73.4
0	500	71.9	1802	113	74	73.4
0	500	71.9	1799	113	74	73.5
0	500	71.9	1793	110	74	73.6
0	1000	70.4	1825	115	73	73
0	1000	70.4	1830	114	73	72.9
0	1000	70.4	1837	115	73	72.8
0	1000	70.4	1820	114	73	73.1
0	2000	73.2	1636	102	76	76.4
0	2000	73.2	1628	102	77	76.5
0	2000	73.2	1644	102	76	76.2
0	2000	73.2	1645	103	77	76.2

Table 7 (cont'd)

					Stamp	Post
Angle	Frequency	B&K dB	A/D Count*16	A/D Count	Computed dB	Computed dB
0	4000	69.3	1794	112	74	73.6
0	4000	69.3	1789	112	74	73.6
0	4000	69.3	1786	112	74	73.7
0	4000	69.3	1789	113	74	73.6
0	8000	65.1	1944	122	71	70.9
0	8000	65.1	1945	122	71	70.8
0	8000	65.1	1943	121	71	70.9
0	8000	65.1	1947	122	71	70.8
0	9999	76.5	1479	93	79	79.2
0	9999	76.5	1480	94	79	79.2
0	9999	76.5	1474	93	79	79.3
0	9999	76.5	1482	92	79	79.1
30	125	66.7	2226	140	66	65.8
30	125	66.7	2232	142	66	65.7
30	125	66.7	2274	143	65	65
30	125	66.7	2293	142	65	64.6
30	250	68.2	1985	124	70	70.1
30	250	68.2	1995	125	70	69.9
30	250	68.2	1975	125	70	70.3
30	250	68.2	1989	123	70	70.1
30	500	71.9	1864	117	72	72.3
30	500	71.9	1869	116	72	72.2
30	500	71.9	1863	115	72	72.3
30	500	71.9	1849	115	73	72.6
30	1000	70.3	1900	119	72	71.7
30	1000	70.3	1923	120	71	71.2
30	1000	70.3	1930	122	71	71.1
30	1000	70.3	1928	121	71	71.2
30	2000	73.1	1717	108	76	74.9
30	2000	73.1	1731	108	75	74.7
30	2000	73.1	1726	108	75	74.8
30	2000	73.1	1737	109	75	74.6
30	4000	69.3	1930	121	71	71.1
30	4000	69.3	1930	120	71	71.1
30	4000	69.3	1934	121	71	71
30	4000	69.3	1935	121	71	71
30	8000	64.5	2269	142	65	65
30	8000	64.5	2282	142	65	64.8
30	8000	64.5	2280	143	65	64.8
30	8000	64.5	2276	142	65	64.9

Table 7 (cont'd)

					Stamp	Post
Angle	Frequency	B&K dB	A/D Count*16	A/D Count	Computed dB	Computed dB
30	9999	76.5	1587	99	77	77.3
30	9999	76.5	1588	100	77	77.2
30	9999	76.5	1595	100	77	77.1
30	9999	76.5	1587	99	77	77.3
60	125	66.5	2476	153	61	61.3
60	125	66.5	2453	154	62	61.7
60	125	66.5	2495	152	62	61
60	125	66.5	2472	153	62	61.4
60	250	68.4	2189	136	67	66.5
60	250	68.4	2209	137	66	66.1
60	250	68.4	2174	136	67	66.7
60	250	68.4	2209	140	66	66.1
60	500	71.9	2107	132	68	67.9
60	500	71.9	2078	130	69	68.5
60	500	71.9	2099	130	68	68.1
60	500	71.9	2085	130	68	68.3
60	1000	70.8	2254	141	65	65.3
60	1000	70.8	2290	144	65	64.7
60	1000	70.8	2275	142	65	64.9
60	1000	70.8	2274	142	65	65
60	2000	73.1	2317	146	64	64.2
60	2000	73.1	2321	145	65	64.1
60	2000	73.1	2322	144	64	64.1
60	2000	73.1	2315	145	64	64.2
60	4000	69.4	2304	144	65	64.4
60	4000	69.4	2310	145	64	64.3
60	4000	69.4	2303	143	65	64.4
60	4000	69.4	2302	144	65	64.4
60	8000	65.2	2434	153	0	62.1
60	8000	65.2	2436	152	62	62
60	8000	65.2	2426	152	62	62.2
60	8000	65.2	2436	152	62	62
60	9999	76.6	1920	120	71	71.3
60	9999	76.6	1921	120	71	71.3
60	9999	76.6	1923	120	71	71.2
60	9999	76.6	1928	121	71	71.2
90	125	66.9	2836	176	0	54.9
90	125	66.9	2909	182	0	53.6
90	125	66.9	2896	181	0	53.8
90	125	66.9	2838	178	0	54.8

Table 7 (cont'd)

					Stamp	Post
Angle	Frequency	B&K dB	A/D Count*16	A/D Count	Computed dB	Computed dB
90	250	68.4	2493	156	0	61
90	250	68.4	2553	159	0	60
90	250	68.4	2499	154	0	60.9
90	250	68.4	2524	157	0	60.5
90	500	71.7	2455	154	0	61.7
90	500	71.7	2484	156	0	61.2
90	500	71.7	2454	154	0	61.7
90	500	71.7	2469	155	0	61.5
90	1000	70.5	2593	161	0	59.2
90	1000	70.5	2595	162	0	59.2
90	1000	70.5	2594	161	0	59.2
90	1000	70.5	2577	162	0	59.5
90	2000	73.1	2227	140	0	65.8
90	2000	73.1	2235	140	0	65.6
90	2000	73.1	2244	140	0	65.5
90	2000	73.1	2229	140	0	65.8
90	4000	69.3	2383	149	0	63
90	4000	69.3	2376	149	0	63.1
90	4000	69.3	2382	149	0	63
90	4000	69.3	2389	150	0	62.9
90	8000	65	2627	164	0	58.6
90	8000	65	2639	164	0	58.4
90	8000	65	2635	164	0	58.5
90	8000	65	2649	166	0	58.2
90	9999	76.5	2114	132	0	67.8
90	9999	76.5	2112	133	0	67.9
90	9999	76.5	2117	132	0	67.8
90	9999	76.5	2118	132	0	67.7
120	125	66.5	3197	204	0	48.4
120	125	66.5	3275	206	0	47
120	125	66.5	3271	207	0	47.1
120	125	66.5	3218	201	0	48
120	250	68.9	2790	176	0	55.7
120	250	68.9	2771	173	0	56
120	250	68.9	2772	173	0	56
120	250	68.9	2755	172	0	56.3
120	500	71.5	2408	152	0	62.5
120	500	71.5	2386	149	0	62.9
120	500	71.5	2370	148	0	63.2
120	500	71.5	2386	149	0	62.9

Table 7 (cont'd)

					Stamp	Post
Angle	Frequency	B&K dB	A/D Count*16	A/D Count	Computed dB	Computed dB
120	1000	70.2	2548	159	0	60
120	1000	70.2	2554	159	0	59.9
120	1000	70.2	2532	159	0	60.3
120	1000	70.2	2536	158	0	60.3
120	2000	73.1	2274	142	0	65
120	2000	73.1	2264	142	0	65.1
120	2000	73.1	2275	143	0	64.9
120	2000	73.1	2290	142	0	64.7
120	4000	69.3	2437	152	0	62
120	4000	69.3	2449	153	0	61.8
120	4000	69.3	2450	153	0	61.8
120	4000	69.3	2454	153	0	61.7
120	8000	64.7	2830	177	0	55
120	8000	64.7	2824	177	0	55.1
120	8000	64.7	2843	177	0	54.8
120	8000	64.7	2826	177	0	55.1
120	9999	76.3	2165	136	0	66.9
120	9999	76.3	2155	134	0	67.1
120	9999	76.3	2158	135	0	67
120	9999	76.3	2150	134	0	67.2
150	125	66.2	2819	172	0	55.2
150	125	66.2	2801	175	0	55.5
150	125	66.2	2804	176	0	55.5
150	125	66.2	2849	177	0	54.6
150	250	69.6	2509	156	0	60.7
150	250	69.6	2533	157	0	60.3
150	250	69.6	2514	158	0	60.6
150	250	69.6	2578	161	0	59.5
150	500	71.2	2481	155	0	61.2
150	500	71.2	2494	155	0	61
150	500	71.2	2511	156	0	60.7
150	500	71.2	2466	156	0	61.5
150	1000	70.9	2768	173	0	56.1
150	1000	70.9	2764	172	0	56.2
150	1000	70.9	2755	172	0	56.3
150	1000	70.9	2751	172	0	56.4
150	2000	73.3	2328	146	0	64
150	2000	73.3	2327	145	0	64
150	2000	73.3	2333	146	0	63.9
150	2000	73.3	2346	145	0	63.7

Table 7 (cont'd)

					Stamp	Post
Angle	Frequency	B&K dB	A/D Count*16	A/D Count	Computed dB	Computed dB
150	4000	69.4	2352	146	0	63.6
150	4000	69.4	2351	147	0	63.6
150	4000	69.4	2341	146	0	63.7
150	4000	69.4	2338	147	0	63.8
150	8000	64.8	2559	160	0	59.8
150	8000	64.8	2564	161	0	59.8
150	8000	64.8	2565	159	0	59.7
150	8000	64.8	2551	160	0	60
150	9999	76.4	2159	134	0	67
150	9999	76.4	2167	135	0	66.9
150	9999	76.4	2157	134	0	67
150	9999	76.4	2164	135	0	66.9
180	125	66.6	2843	179	0	54.8
180	125	66.6	2771	174	0	56
180	125	66.6	2767	173	0	56.1
180	125	66.6	2733	173	0	56.7
180	250	68.9	2523	168	0	60.5
180	250	68.9	2581	156	0	59.4
180	250	68.9	2481	156	0	61.2
180	250	68.9	2507	157	0	60.8
180	500	71.7	2499	156	0	60.9
180	500	71.7	2532	158	0	60.3
180	500	71.7	2535	159	0	60.3
180	500	71.7	2521	157	0	60.5
180	1000	70.1	2765	173	0	56.2
180	1000	70.1	2715	170	0	57
180	1000	70.1	2801	174	0	55.5
180	1000	70.1	2762	172	0	56.2
180	2000	73.2	2534	159	0	60.3
180	2000	73.2	2508	158	0	60.8
180	2000	73.2	2500	156	0	60.9
180	2000	73.2	2525	158	0	60.5
180	4000	69.5	2585	161	0	59.4
180	4000	69.5	2558	160	0	59.9
180	4000	69.5	2573	160	0	59.6
180	4000	69.5	2573	161	0	59.6
180	8000	64.9	2794	174	0	55.6
180	8000	64.9	2826	176	0	55.1
180	8000	64.9	2883	175	0	54
180	8000	64.9	2817	176	0	55.2

Table 7 (cont'd)

					Stamp	Post
Angle	Frequency	B&K dB	A/D Count*16	A/D Count	Computed dB	Computed dB
180	9999	76.3	2267	142	0	65.1
180	9999	76.3	2268	143	0	65.1
180	9999	76.3	2268	142	0	65.1
180	9999	76.3	2280	141	0	64.8
270	125	0	2703	167	0	57.3
270	125	0	2774	171	0	56
270	125	0	2701	168	0	57.3
270	125	0	2725	172	0	56.9
270	250	0	2623	164	0	58.7
270	250	0	2573	161	0	59.6
270	250	0	2599	163	0	59.1
270	250	0	2561	159	0	59.8
270	500	0	2600	163	0	59.1
270	500	0	2602	162	0	59.1
270	500	0	2545	159	0	60.1
270	500	0	2596	162	0	59.2
270	1000	0	2500	156	0	60.9
270	1000	0	2527	158	0	60.4
270	1000	0	2537	159	0	60.2
270	1000	0	2522	158	0	60.5
270	2000	0	2253	141	0	65.3
270	2000	0	2246	141	0	65.5
270	2000	0	2257	141	0	65.3
270	2000	0	2249	140	0	65.4
270	4000	0	2359	148	0	63.4
270	4000	0	2344	147	0	63.7
270	4000	0	2339	147	0	63.8
270	4000	0	2337	147	0	63.8
270	8000	0	2503	157	0	60.8
270	8000	0	2511	157	0	60.7
270	8000	0	2529	158	0	60.4
270	8000	0	2533	159	0	60.3
270	9999	0	2123	132	0	67.7
270	9999	0	2116	132	0	67.8
270	9999	0	2124	133	0	67.6
270	9999	0	2114	132	0	67.8
0	250	68.2	1916	119	0	71.4
0	250	68.2	1922	122	0	71.3
0	250	68.2	1907	122	0	71.5
0	250	68.2	1952	123	0	70.7

Table 7 (cont'd)

					Stamp	Post
Angle	Frequency	B&K dB	A/D Count*16	A/D Count	Computed dB	Computed dB
115	250	68.5	2847	178	0	54.7
115	250	68.5	2844	178	0	54.7
115	250	68.5	2847	179	0	54.7
115	250	68.5	2838	175	0	54.8
115	125	66.6	3330	212	0	46
115	125	66.6	3392	212	0	44.9
115	125	66.6	3261	204	0	47.3
115	125	66.6	3353	210	0	45.6
115	500	71.6	2399	149	0	62.7
115	500	71.6	2363	148	0	63.4
115	500	71.6	2387	150	0	62.9
115	500	71.6	2379	149	0	63.1
115	1000	70.6	2511	157	0	60.7
115	1000	70.6	2532	159	0	60.3
115	1000	70.6	2498	156	0	60.9
115	1000	70.6	2509	156	0	60.7
115	9999	76.3	2159	135	0	67
115	9999	76.3	2159	136	0	67
115	9999	76.3	2152	135	0	67.1
115	9999	76.3	2148	135	0	67.2

Table 8: 2nd Anechoic Test

	sideways source				sideways source				upright source				upright source			
	White Noise				250 hz				White Noise				250 hz			
ambient	35.6	38.6	3721	230	35	38.9	3707	231	38	39.2	3686	236	71	70.3	1826	113
	35.6	41.3	3562	228	35	38.7	3713	233	38	39.4	3626	229	71	71.2	1770	112
	35.6	38.6	3720	232	35	38.1	3554	239	38	39.6	3663	231	71	70.3	1822	115
	35.6	38.5	3730	239	35	40.2	3627	226	38	39.1	3694	220	71	70.8	1794	112
	36.9	36.2	3867	244	39	38	3756	233	40	38.9	3704	231	69	68.2	1949	122
	36.9	35.9	3881	245	39	38.6	3721	230	40	37.9	3765	237	69	67.9	1965	123
	36.9	36	3876	246	39	38.3	3741	236	40	38	3857	236	69	68.1	1955	122
	36.9	36.7	3835	242	39	38.1	3749	231	40	38.1	3751	234	69	68.3	1944	122
	40.2	38.6	3722	234	45	43	3460	216	43	40.6	3599	226	62	61.8	2334	146
	40.2	38.6	3720	234	45	43.5	3431	214	43	40.6	3603	227	62	61.5	2350	148
	40.2	38.8	3712	234	45	43.4	3432	215	43	40.5	3610	226	62	61.2	2369	148
	40.2	39.6	3664	231	45	43.9	3407	213	43	40.4	3614	227	62	61.4	2354	148
	45.5	44.4	3375	211	49	49.1	3095	193	47	45	3339	205	55	55.1	2732	170
	45.5	44.4	3375	211	49	49.1	3095	193	47	44.9	3346	210	55	56	2677	168
	45.5	44.6	3364	211	49	49.3	3078	192	47	45	3338	208	55	55	2738	169
	45.5	44.6	3362	210	49	49.4	3077	190	47	45.1	3332	208	55	55.5	2709	169
	48.2	48.3	3128	196	54	54.5	2767	176	49	48	3156	196	48	48	3161	198
	48.2	48.3	3140	196	54	54.5	2771	173	49	47.8	3170	198	48	47.4	3192	200
	48.2	48.4	3135	196	54	54.4	2774	174	49	48	3158	198	48	47.7	3174	198
	48.2	48.4	3136	195	54	54.3	2780	173	49	47.9	3166	197	48	47.3	3199	199
	51.9	53.2	2848	178	59	60.1	2432	152	53	53.6	2821	175	45	43.1	3452	216
	51.9	53.3	2841	178	59	60.4	2416	152	53	53.5	2829	176	45	43.7	3414	215
	51.9	53.2	2849	178	59	59.3	2482	156	53	53.7	1819	176	45	43.7	3417	217
	51.9	53.2	2847	179	59	59.9	2449	152	53	53.5	2830	177	45	42.7	3476	216
	55.7	57.8	2574	160	63	63.6	2226	141	58	58.1	2556	160	39	38.3	3737	235
	55.7	57.6	2581	160	63	62.6	2283	141	58	58	2559	159	39	38.8	3712	233
	55.7	57.7	2575	161	63	62.9	2264	141	58	58	2561	160	39	37.4	3796	235
	55.7	57.7	2576	161	63	62.8	2270	142	58	58	2561	160	39	37.3	3799	240
	58.5	60.5	2400	150	68	68.1	1956	124	63	64	2200	138				
	58.5	60.7	2399	150	68	67.9	1970	123	63	64	2203	138				
	58.5	60.7	2401	150	68	67.8	1971	121	63	64.1	2197	138				
	58.5	60.6	2406	151	68	68.2	1949	121	63	64.1	2192	137				
	60.1	62.3	2303	144	73	72.5	1694	105	68	68.2	1951	122				
	60.1	62.3	2300	144	73	72.2	1708	103	68	68.1	1958	122				
	60.1	62.3	2301	143	73	72.5	1694	109	68	68.1	1958	122				
	60.1	62.4	2295	144	73	72.4	1697	107	68	68.1	1957	123				
	62.3	64.4	2176	136	77	75.4	1517	95	74	73.2	1648	102				
	62.3	64.4	2176	136	77	76.1	1475	95	74	73.4	1637	102				
	62.3	64.4	2175	138	77	76	1482	92	74	73.4	1637	102				
	62.3	64.5	2173	136	77	75.8	1497	96	74	73.4	1635	102				

Table 8 (cont'd)

sideways source				sideways source				upright source			
White Noise				250 hz				White Noise			
65.6	67.7	1980	124					76.2	75.7	1503	93
65.6	67.6	1984	124					76.2	75.9	1486	93
65.6	67.7	1978	123					76.2	75.7	1503	93
65.6	67.6	1986	124					77.9	77.2	1410	88
68.9	70.5	1809	113					77.9	77.3	1403	88
68.9	70.6	1807	113					77.9	77.4	1401	88
68.9	70.6	1808	113					77.9	77.3	1405	88
68.9	70.7	1802	113								
71.3	72.8	1674	105								
71.3	72.7	1678	105								
71.3	72.8	1672	105								
71.3	72.8	1676	104								
73.4	74.8	1552	97								
73.4	74.8	1553	97								
73.4	74.7	1558	98								
73.4	74.8	1554	97								
75.6	76.7	1439	90								
75.6	76.8	1437	90								
75.6	76.7	1441	89								
75.6	76.7	1441	90								
78.2	79.1	1294	80								
78.2	79.1	1295	81								
78.2	79.1	1296	81								
78.2	79.1	1296	81								
80.3	81	1185	75								
80.3	81	1180	75								
80.3	80.9	1186	74								
80.3	80.9	1191	75								
83.9	84.3	984	61								
83.9	84.3	980	61								
83.9	84.2	989	62								
83.9	84.2	989	61								
85.3	85.5	912	57								
85.3	85.4	917	58								
85.3	85.5	913	57								
85.3	85.5	914	57								
86.1	86.2	870	54								
86.1	86.1	875	55								

Table 9: 2nd Anechoic Test, Angular Data

Stamp

Angle	Frequency	B&K dB	Computed dB	A/D Count*16	A/D Count
0	0	36	38.7	3716	226
0	0	36	37.6	3783	230
0	0	36	39.4	3674	230
0	0	36	36.8	3767	234
0	250	78.1	76.6	1448	88
0	250	78.1	76.6	1445	89
0	250	78.1	76.1	1479	91
0	250	78.1	76.1	1478	95
10	250	78.1	76.1	1476	91
10	250	78.1	76.7	1430	90
10	250	78.1	76.4	1458	92
10	250	78.1	76.4	1459	93
20	250	78.1	76.1	1479	93
20	250	78.1	76.2	1471	92
20	250	78.1	76.1	1475	93
20	250	78.1	76	1481	92
30	250	78.1	75.5	1510	94
30	250	78.1	75.7	1500	93
30	250	78.1	75.4	1516	92
30	250	78.1	75.6	1508	92
40	250	77.9	74	1599	99
40	250	77.9	74.6	1567	97
40	250	77.9	74.6	1566	99
40	250	77.9	74.2	1592	97
50	250	78	73	1660	103
50	250	78	73.2	1652	103
50	250	78	73.3	1645	103
50	250	78	73.4	1640	104
60	250	78.1	71.2	1767	109
60	250	78.1	71.4	1759	108
60	250	78.1	72	1722	108
60	250	78.1	71.8	1733	106
70	250	78	69.7	1862	117
70	250	78	69.5	1870	116
70	250	78	69.9	1868	116
70	250	78	69.3	1885	118
80	250	77.1	67.7	1982	125
80	250	77.1	67.6	1988	125
80	250	77.1	67.2	2009	125
80	250	77.1	66.6	2043	127
90	250	76.8	64.6	2162	135
90	250	76.8	65	2140	136
90	250	76.8	64.7	2156	132
90	250	76.8	65.2	2128	133

Table 9 (cont'd)

Angle	Frequency	B&K dB	Stamp Computed dB	A/D Count*16	A/D Count
100	**250**	**77.1**	**62.2**	**2309**	**143**
100	250	77.1	61.8	2331	144
100	250	77.1	62.2	2309	145
100	250	77.1	62.1	2316	146
110	**250**	**77.0**	**61.6**	**2346**	**147**
110	250	77.0	61.5	2349	148
110	250	77.0	61.6	2345	147
110	250	77.0	61.7	2338	147
120	**250**	**76.8**	**62.4**	**2298**	**142**
120	250	76.8	62.6	2284	142
120	250	76.8	62.3	2301	142
120	250	76.8	62.8	2274	144
130	**250**	**76.8**	**64.2**	**2189**	**140**
130	250	76.8	64.1	2194	136
130	250	76.8	64.5	2171	136
130	250	76.8	64.5	2160	136
140	**250**	**76.3**	**65.0**	**2139**	**136**
140	250	76.3	64.9	2149	133
140	250	76.3	64.8	2151	135
140	250	76.3	65.0	2143	135
150	**250**	**76.4**	**65.5**	**2111**	**132**
150	250	76.4	65.4	2118	133
150	250	76.4	65.2	2127	131
150	250	76.4	65.8	2093	130
160	**250**	**76.6**	**66.6**	**2044**	**127**
160	250	76.6	66.5	2151	128
160	250	76.6	66.5	2053	127
160	250	76.6	66.9	2025	125
170	**250**	**76.4**	**66.1**	**2072**	**130**
170	250	76.4	66.1	2077	128
170	250	76.4	65.8	2095	130
170	250	76.4	66.1	2076	129
180	**250**	**76.7**	**66.2**	**2071**	**130**
180	250	76.7	66.2	2066	132
180	250	76.7	66.3	2062	129
180	250	76.7	66.0	2078	130
0	**white**	**80.3**	**80.9**	**1186**	**74**

Table 9 (cont'd)

			Stamp		
Angle	Frequency	B&K dB	Computed dB	A/D Count*16	A/D Count
0	white	80.3	81.0	1185	74
0	white	80.3	81.0	1184	74
0	white	80.3	80.9	1186	74
10	**white**	**80.3**	80.7	1200	75
10	white	80.3	80.9	1190	74
10	white	80.3	80.9	1189	74
10	white	80.3	80.8	1195	74
20	**white**	**80.4**	80.4	1218	76
20	white	80.4	80.4	1220	77
20	white	80.4	80.4	1218	76
20	white	80.4	80.4	1217	76
30	**white**	**80.3**	78.2	1351	84
30	white	80.3	78.3	1347	84
30	white	80.3	78.2	1348	85
30	white	80.3	78.2	1349	85
40	**white**	**80.5**	75.4	1517	95
40	white	80.5	75.3	1524	96
40	white	80.5	75.3	1526	95
40	white	80.5	75.2	1529	96
50	**white**	**80.3**	74.0	1600	99
50	white	80.3	74.1	1595	100
50	white	80.3	74.0	1599	100
50	white	80.3	74.1	1596	100
60	**white**	**80.5**	72.4	1698	106
60	white	80.5	72.3	1701	107
60	white	80.5	72.4	1697	106
60	white	80.5	72.4	1697	106
70	**white**	**80.5**	71.4	1759	109
70	white	80.5	71.5	1751	110
70	white	80.5	71.0	1746	109
70	white	80.5	71.6	1746	109
80	**white**	**80.6**	70.4	1818	114
80	white	80.6	70.4	1816	113
80	white	80.6	70.4	1820	113
80	white	80.6	70.4	1817	114
90	**white**	**80.5**	70.5	1811	113
90	white	80.5	70.4	1815	113
90	white	80.5	70.5	1811	114
90	white	80.5	70.4	1815	114
100	**white**	**80.5**	69.0	1903	118
100	white	80.5	68.9	1909	119
100	white	80.5	69.2	1891	119

Table 9 (cont'd)

Angle	Frequency	B&K dB	Stamp Computed dB	A/D Count*16	A/D Count
100	white	80.5	69.0	1904	119
110	**white**	**80.5**	69.8	1856	116
110	white	80.5	69.7	1858	116
110	white	80.5	69.8	1854	116
110	white	80.5	69.7	1860	116
120	**white**	**80.4**	69.1	1893	118
120	white	80.4	69.3	1885	118
120	white	80.4	69.2	1891	118
120	white	80.4	69.3	1184	118
130	**white**	**80.3**	69.6	1866	116
130	white	80.3	69.3	1882	117
130	white	80.3	69.5	1869	117
130	white	80.3	69.3	1882	117
140	**white**	**80.8**	70.3	1825	114
140	white	80.8	70.3	1826	114
140	white	80.8	70.3	1826	114
140	white	80.8	70.3	1826	114
150	**white**	**80.9**	70.3	1822	114
150	white	80.9	70.2	1830	115
150	white	80.9	70.3	1823	115
150	white	80.9	70.3	1825	114
160	**white**	**80.8**	69.4	1876	118
160	white	80.8	69.4	1875	118
160	white	80.8	69.4	1878	117
160	white	80.8	69.5	1874	118
170	**white**	**80.8**	67.9	1966	123
170	white	80.8	67.9	1966	123
170	white	80.8	68.2	1952	122
170	white	80.8	68.4	1940	122
180	**white**	**80.9**	66.6	2045	128
180	white	80.9	66.7	2039	128
180	white	80.9	66.8	2033	127
180	white	80.9	66.6	2045	128

Table 10: Lake Testing

	Date:		6/14/2003					
	Time		11:00 AM					
	Temp:		~75 F					
	Wind		5-10 mph					
	Ambient:		67.8 dB	(device)				
	Boat:		Baja					
	Conditions:		Bow Pass, 40 mph, 3500 rpm, open exhaust and muffled,					
						B&K		
Run	Exhaust	Location	Dist (ft)	Raw	Corr.	RMS - slow	comments	
	-		-	-	-	~ 68		
1	open	broadside	112.7	84.0	89.8	86.0	Bow Pass, direct cross of bouy	
2	open	broadside	72.7	86.5	89.2	88.0	Bow Pass, direct cross of bouy	
3	open	broadside	59.0	87.8	88.9	97.0	Bow Pass, direct cross of bouy	
4	open	broadside	80.6	85.3	88.7	87.0	Bow Pass, direct cross of bouy	
5	muffled	broadside	64.3	81.5	83.3	86.1	Bow Pass, direct cross of bouy	
6	muffled	broadside	104.6	72.2	77.5	78.3	Bow Pass, direct cross of bouy	
7	muffled	broadside	70.2	77.5	79.9	82.9	Bow Pass, direct cross of bouy	
	-	-	-	-	-	76.0	Peak ~45 off stern	
8	open	Max	233.0	84.8	95.9	94.6	Peak ~45 off stern	
9	open	Max	210.0	88.3	98.6	96.3	Peak ~45 off stern	
10	open	Max	224.0	86.1	96.9	93.8	Peak ~45 off stern	
11	open	Max	172.0	89.3	98.2	95.2	Peak ~45 off stern	
12	muffled	Max	256.0	77.2	89.0	84.0	Peak ~45 off stern	
13	muffled	Max	174.0	77.5	86.5	84.7	Peak ~45 off stern	
14	muffled	Max	157.9	76.4	84.7	82.5	Peak ~45 off stern	
15	open	Max	235.0	86.2	97.4	93.0	15 deg stern - left - right pass	
16	open	broadside	210.0	79.8	90.1	84.6	90 deg stern – left - right pass	
17	open	Max	216.0	87.9	98.5	91.0	15 deg stern - left - right pass	
18	open	broadside	180.0	80.4	89.6	84.5	90 deg stern - left - right pass	
19	muffled	Max	300.0	70.8	85.4	78.7	45 off	
20	muffled	Max	296.0	69.7	82.5	79.0	45 off	
21	muffled	broadside	271.0	68.2	80.4	76.0	90 off front	
22	open	broadside	114.7	73.2	79.2	92.3	direct pass bow past bouy	
23	open	broadside	112.3	85.3	91.1	88.0	direct pass bow past bouy	
24	muffled	broadside	121.0	71.6	77.9	80.3	direct pass bow past bouy	
25	muffled	broadside	150.0	75.0	81.0	80.1	direct pass bow past bouy	
26	muffled	broadside	110.0	73.5	79.2	79.8	direct pass bow past bouy	
27	muffled	broadside	116.1	72.9	78.9	80.6	direct pass bow past bouy	
28	open	Max	143.4	87	94.6	95.5	45 off stern	
29	open	Max	185	86.4	95.8	94.1	45 off stern	

Table 10 (cont'd)

						B&K	
Run	Exhaust	Location	Dist (ft)	Raw	Corr.	RMS - slow	comments
30	open	Max	143	87.4	95	93.3	45 off stern
31	open	Max	153	86.4	94.5	93.8	45 off stern
32	muffled	Max	123	74	80.5	82.1	45 off stern
33	muffled	broadside	123.8	76.1	82.6	-	sheriff conducting tests
34	muffled	broadside	129.7	73.4	80.2	-	sheriff conducting tests
35	muffled	broadside	134.8	76.4	83.5	-	sheriff conducting tests
36	open	broadside	204.3	82.1	92.2	-	sheriff conducting tests - straight on
37	open	broadside	213.4	83.1	93.6	-	sheriff conducting tests - straight on
38	open	Max	264	85.7	97.7	-	sheriff conducting tests - 15 off stern
39	open	Max	233.4	86.4	97.5	-	sheriff conducting tests - 15 off stern
40	open	Max	366	84.7	99.1	-	sheriff conducting tests - 15 off stern
41	open	Max	333	82.9	96.6	-	sheriff conducting tests - 15 off stern
42	open	Max	275	82.7	95.1	-	sheriff conducting tests - buoy
43	open	Max	293.1	82.5	95.2	-	sheriff conducting tests - buoy

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