This is to certify that the
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A BOAT NOISE MEASUREMENT DEVICE FOR LAW ENFORCEMENT

presented by

CASEY PATRICK MANNING

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Clark Radcliffe

Major Professor's Signature

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A BOAT NOISE MEASUREMENT DEVICE FOR LAW ENFORCEMENT

By

Casey Patrick Manning

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ABSTRACT

A BOAT NOISE MEASUREMENT DEVICE FOR LAW ENFORCEMENT

By

Casey Patrick Manning

Boat noise is a serious problem on Michigan lakes. Current Michigan boat noise laws use the scientific measurement standards SAE J1970 and SAE J2005 to qualify boat noise for law enforcement purposes. These standards are very detailed and require a skilled boat operator and precise conditions in order to be performed correctly. They also do not measure the noise level of the boat under normal operation. A new method of enforcing boat noise regulations for boats under normal operation is needed.

A boat noise measurement device was designed to study boat sound propagation and take into account all applicable errors associated with its measurements. From understanding sound propagation, this device can be used to calculate the minimum possible noise level at a specific distance from any measured distance. By taking into account all applicable errors, this device can lead to an effective law enforcement tool. The device was designed as a complement to the SAE J34 standard, which measures boat noise from boats passing by at a known distance.

The data matched the propagation model and agreed with past studies by other investigators. The results show the propagation model can yield a minimum possible noise level underpredicting the SAE J34 level. By emulating the SAE J34 standard the measurements can be made while the boat is in normal operation, as opposed to measuring the boats ability to be loud. Conservative error compensation and standard deviation correction ensures an accurate law enforcement device.

ACKNOWLEDGEMENTS

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Furthermore, special thanks to members of the Torch and Higgins Lake communities. The time spent testing loud boats on their waters was a temporary inconvenience, and their gratitude and patience was very much appreciated. And special thanks to the Antrim and Roscommon County Sheriff's Departments for their time and help in running our tests smoothly.

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KEY TO SYMBOLS AND ABBREVIATIONS

$\Delta SPL_{planar,\,doubling}$ .... Change in Planar Sound Pressure Level w/ Doubling Distance

$\Delta SPL_{spherical,\,doubling}$. Change in Spherical Sound Pressure Level w/ Doubling Distance

μ .... Value of Best-fit Logarithmic Regression Line (dBA)

ρ .... Air Density $\left(\mathrm{kg/m^3}\right)$

σ .... Sound Level Standard Deviation (dBA)

τ .... Time Constant (s)

A_n .... Normal Area $\left(\mathrm{m^2}\right)$

ANSI .... American National Standards Institute

c .... Speed of Sound (m/s)

C .... Compensation Constant, $\left(20\log_{10}\left(1-10^{-\left(\mathrm{P}_m-\mathrm{P}_b\right)/20}\right)\right)$ (dB)

ERMS .... Exponential-Root-Mean-Square

I .... Sound Pressure Wave Acoustic Intensity $\left(\mathrm{W/m^2}\right)$

ICOMIA .... International Council of Marine Industry Associations

ISO .... International Organization for Standardization

k .... Spherical Sound Propagation Constant, $\left(\sqrt{\rho c \mathcal{P}_{source}/2\pi}\right)$ (N/m)

$L_{p\tau}$ .... Exponential-Root-Mean-Square Sound Pressure Level (ANSI S1.4-1983) (Pa)

NASBLA .... National Association of State Boating Law Administrator

p .... Time-Averaged Acoustic Pressure (Pa)

$p(t)$ .... Acoustic Pressure as a Function of Time (Pa)

p_0 .... Reference Acoustic Pressure ($2\text{x}10^{-5}$ Pa)

p_b .... Background Time-Averaged Sound Pressure Level (Pa)

p_m .... Total Measured Time-Averaged Sound Pressure Level (Pa)

p_{ref} .... Reference Acoustic Pressure ($2\text{x}10^{-5}$ Pa)

p_s .... Source Time-Averaged Sound Pressure Level (Pa)

$\boldsymbol{P}_b$ .... Background Time-Averaged Sound Pressure Level (dBA)

$\boldsymbol{P}_m$ .... Total Measured Time-Averaged Sound Pressure Level (dBA)

$\boldsymbol{P}_s$ .... Source Time-Averaged Sound Pressure Level (dBA)

$\mathcal{P}_{source}$ .... Sound Pressure Wave Acoustic Power (W)

r .... Radial Distance (m)

SAE .... Society of Automotive Engineers

SPL .... Sound Pressure Level (dBA)

PROBLEM STATEMENT

Boat noise is a serious problem on Michigan lakes. The current boat noise statutes are complicated to perform and are too easily disputed to have any effect in controlling boat noise. This upsets some lakefront property owners who wish to enjoy the naturally quiet atmosphere of the lakes. Something needs to be done to alleviate this situation or else boat noise, which is unlawful, will continue to be a problem to Michigan residents.

> *"We have a cabin on Higgins Lake where we go to enjoy peace and solitude in the summer. However, in the past few years, many high powered watercraft brought to the lake have destroyed our quiet with overloud engines."*
>
> *- Higgins Lake private citizen*
> *Letter to the Governor*

Boat noise disturbs and disrupts some lakefront property owners. The state of Michigan has over 10,000 inland lakes, over 3,000 miles of shore on the Great Lakes and roughly 1 million registered boats [www.michigan.gov/dnr/]. The current Michigan boat noise standards in the Marine Safety Act (act 451 of 1994) require special test procedures and do not take into account regular in-use boat operation [Marine Safety Act, 1994]. Law enforcement officials would like a simpler test procedure standard which regulates boat noise in regular recreational use. A new method for enforcement of boat noise limits is needed. There is a clear and existing problem with boat noise in the state of Michigan, and the current solutions to that problem are ineffective.

Boat noise affects different aspects of local communities differently. Lakefront property owners are disturbed and disrupted by boat noise. Law enforcement officials would like a reasonable and enforceable standard based on the boat's noise level when in normal operation. Boat owners would prefer a standard that wasn't an inconvenience. The boating industry would like a better image in the community. Noise regulation enforcement is a continuing problem for all elements in the lakefront community. Michigan needs repeatable, reasonable and enforceable standards to regulate boat noise.

A repeatable and reasonable noise standard with method for enforcement will help all parties adversely affected by boat noise. Lakefront property owners will no longer be bothered by loud boats on their lake. Law enforcement will have an accurate and repeatable standard to measure boat noise. The boating industry will gain a better image from the public who operate quiet boats on inland lakes. A repeatable, reasonable and enforceable boat noise standard will benefit everyone.

BOAT NOISE STANDARDS

Boat noise standards exist to set a method to quantify the magnitude of sound emitted by a boat. The standards vary from static measurements of boats docked in idle to measurements taken on boats in special operation. Each standard specifically lists the terms and conditions under which the measurement must be taken to ensure a proper scientific measurement. It is extremely difficult for law enforcement officials to perform the correct procedure and conditions as stated in the standards.

Boat noise standards are prepared by scientific organizations. The five standards governing boat noise measurement were written by the Society of Automotive Engineers (SAE), the International Council of Marine Industry Associations (ICOMIA) and the International Organization for Standardization (ISO). The Michigan Marine Safety Act (act 451 of 1994) uses two of the SAE standards to measure boat noise. The maximum sound level a boat can produce is limited by the state of Michigan through these two standards [Marine Safety Act, 1994].

The Society of Automotive Engineers (SAE) was the first organization to create a standard to properly measure boat noise. "The [SAE] has more than 90,000 members - engineers, business executives, educators, and students from more than 97 countries - who share information and exchange ideas for advancing the engineering of mobility systems. SAE is [a] one-stop resource for standards development, events, and technical information and expertise used in designing, building, maintaining, and operating self-propelled vehicles for use on land or sea, in air or space." [www.sae.org/about].

Later, the International Council of Marine Industry Associations (ICOMIA) developed standards to measure boat noise. "[ICOMIA] was formed in 1965 to bring together in one global organization all the national boating federations and other bodies involved in the recreational marine industry, and to represent them at international level. [ICOMIA] supports its members in every way possible and gives recommendations and guidance on compliance with new international standards and regulations, publishes its opinions and recommendations, and formulates draft international standards and codes of practice." [www.icomia.com/about-icomia/introduction.asp].

The most recent standards regarding boat noise were created by the International Organization for Standardization (ISO). "ISO is a network of the national standards institutes of 157 countries... [ISO] identifies what International Standards are required by business, government and society, develops them in partnership with the sectors that will put them to use, adopts them by transparent procedures based on national input and delivers them to be implemented worldwide." [http://www.iso.org/iso/en/aboutiso/introduction/index.html].

The standards specify the exact characteristics required by the sound level meter for a proper measurement. Each of the standards requires that the signal be A-weighting filtered and given an explicit sampling time. Weighted filtering normalizes a given sound pressure level measurement to the human response; human ears attenuate high and low frequencies. The A-weighting filter mimics human ear response (Fig. 1). The sampling time defines the time over which sound level measurements are averaged. Slow and fast sampling times correspond to 1 and 0.125 seconds, respectively [ANSI S1.4-1983, 1983].

Further details regarding the A-weighting filter, along with the B-, C- and D-weighting filters and sampling times are provided in Appendix A.

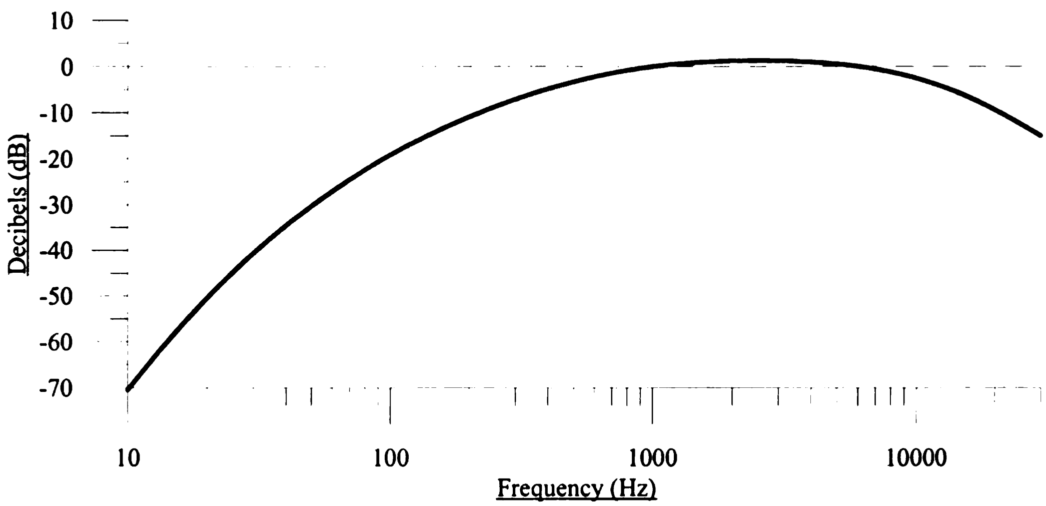

Figure 1: A-Weighting Filter Effect Over the Range of Human Hearing

The SAE J34 Standard

The SAE J34 standard, *Exterior Sound Level Measurement Procedure for Pleasure Motorboats*, was enacted in April, 1973. It was the first boat noise measurement standard. The intent of the SAE J34 was "...to provide manufacturers of marine equipment with a standard set of conditions and method of measurement of the maximum sound level of boats and motors" through a 25 meter pass-by course [SAE J34, 2001]. The method required setting a sound level meter on the shore of a body of water or a dock projecting out from the shore into the body of water to measure the sound pressure level of a passing boat. The boat follows a straight course marked by three buoys, each 50 meters apart and 25 meters from the sound level meter, forming a line perpendicular to the direction of measurement (Fig. 2).

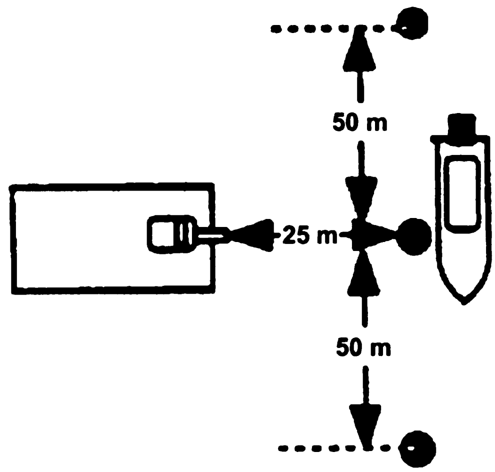

Figure 2: SAE J34 Boat Course for Pass-By Noise Measurement [copied at 150%, with labels redrawn for clarity, from SAE J34, 2001]

The SAE J34 standard specifically states the microphone of the sound level meter must to be 1.2 to 1.5 meters above the water and no less than 0.6 meters above the platform, or shore, surface. The measured motorboat sound is the highest sound level measured (dBA [App. A], fast [App. B]) during the 25 meter pass-by.

The ICOMIA 45-98 and ISO 14509 Standards

The International Council of Marine Industry Associations (ICOMIA) 45-98 boat noise standard, *Determination of Reference Boat Parameters for Sound Emissions*, was created in October, 1999 as an international standard for measurement of boat noise. The ICOMIA 45-98 standard is based on the SAE J34 standard. The SAE J34 standard states the time weighting characteristic of the sound level meter must be fast, whereas the ICOMIA 45-98 standard states the time weighting characteristic of the sound level meter must be slow. This change will eliminate any random sound pressure level impulsive noise that may occur due to waves hitting the boat hull. It will also lower the maximum sound pressure level value due to the increased sampling time. This change was made in order to "...[obtain] reproducible and comparable measurements of the pass by sound pressure level emitted by powered recreational craft..." as stated in the standards Scope [ICOMIA 45-98, 1991]. By eliminating random sound pressure level peaks, the results will become more reproducible.

The International Organization for Standardization (ISO) 14509 international boat noise standard, *Small craft - Measurement of Airborne Sound Emitted by Powered Recreational Craft*, was created in November, 2000 by the European Union as a variation of the ICOMIA 45-98 standard and a further variation of the SAE J34 standard. It keeps the same sound level meter slow time weighting characteristic as in the ICOMIA 45-98, but changes its position. In the ICOMIA 45-98 and SAE J34 standards, the sound level meter must be 1.2 meters to 1.5 meters above the surface of the water and at least 0.6 meters from the surface of the testing platform. The ISO 14509 standard states the sound level meter must be 3.5 meters (±0.5 meters) above the surface of the water and 1.2 meters from the surface of the testing platform [ISO 14509, 2004]. This places the microphone in a farther field of the sound source, where the sound reflection off the surface of the water and the surface of the testing platform will be smaller, yielding a more accurate measurement.

Pass-by measurement procedures are currently used nationally by 19 states and the U.S. Coast Guard, where 86 dBA is the maximum acceptable sound level [Lanpheer, 2000]. The Michigan Marine Safety Act currently does not include the SAE J34 standard, or any pass-by measurement methods. Instead, it specifies the use of the SAE

J1970 and J2005 standards, which are easier to perform and do not require a detailed course.

The SAE J1970 and SAE J2005 Standards

The SAE J1970 and the SAE J2005 standards, *Shoreline Sound Level Measurement Procedure* and *Stationary Sound Level Measurement Procedure for Pleasure Motorboats*, enacted in December 1991, were the second and third boat noise standards created for boat noise measurement. They were created to provide alternative field procedures for measuring sound level emitted from pleasure motorboats. Their development sought to avoid the requirement of a complicated pass-by course. The SAE J1970 and J2005 are the only two boat noise standards currently in law in the Michigan Marine Safety Act.

The SAE J1970 boat noise standard, *Shoreline Sound Level Measurement Procedure*, was enacted to be used for the measurement of sound emitted by pleasure motorboats in operation on waterways where sound level restrictions apply. The setup involves placing a sound level meter on the shore of a body of water, a dock projecting out from the shore into the body of water, or a raft/boat moored to a dock or anchored so that the sound level meter is not more than 6 meters from shore. The measurement is taken after the boat accelerates full throttle away from the measurement location for 30 seconds to emulate the Michigan Marine Safety Act's requirement for a 300 foot offshore distance to boats operating at full throttle. The sound level meter must be placed 1.2 meters to 1.5 meters above the water and no less than 0.6 meters above the platform, or shore, surface [SAE J1970, 1991]. Michigan Marine law sets a 75 dBA (slow) maximum acceptable sound level from this standard measurement procedure.

The SAE J2005, *Stationary Sound Level Measurement Procedure for Pleasure Motorboats*, boat noise standard was enacted for governmental agencies to enforce the requirement for effective muffling means in pleasure motorboats. The idea is to measure the sound level of a stationary motorboat in idle. The boat whose sound pressure level is being measured must be either be moored or lashed to a stationary object. The sound level meter needs to be placed 1.2 meters to 1.5 meters above the water and no closer than 1 meter from the vertical projection of any part of the boat in the area adjacent to the exhaust outlets [SAE J2005, 1991]. Michigan Marine law sets a 90 dBA (slow) maximum acceptable sound level from this procedure.

Table 1 compares and contrasts the existing boat noise measurement standards by their measurement type. The legal acceptable sound level limits are set by the local governing body (state).

Table 1: Comparison of Different Existing Standards

Standard	Measurement Type	Date Created	Time Weighting	Microphone Height from Platform	Microphone Height from Water
SAE J34	25m Pass-By	Apr. 73	Fast	$\geq$ 0.6m	1.2m - 1.5m
ICOMIA 45-98	25m Pass-By	Oct. 99	Slow	$\geq$ 0.6m	1.2m - 1.5m
ISO 14509	25m Pass-By	Nov. 00	Slow	1.2m	3.5m $\pm$ 0.5m
SAE J1970	Lakeshore Emulation	Dec. 91	Slow	$\geq$ 0.6m	1.2m - 1.5m
SAE J2005	Lakeshore Emulation	Dec. 91	Slow	$\geq$ 1m	1.2m - 1.5m

SPECIAL CONDITIONS OF CURRENT BOAT NOISE STANDARDS

Special conditions are required for each of the boat noise measurement standard procedures, such as the use of a dock, a large detailed course and short-distance measurement devices. The standards are excellent scientific methods for boat noise measurement; they provide repeatable measurements of the maximum boat noise level. The goal of law enforcement, however, is to place limits on boat noise during operation. None of the current standards regulate the measurement of maximum boat noise level while the boat is in normal use. Law enforcement needs a standard to measure boat noise while the boat is in normal use, as opposed to measuring boat noise under special conditions.

Boat noise measurement standards measure the subject boat's ability to be loud; they do not measure the noise level produced in normal use. They do not take into account that a boat with the ability to be loud could be quietly operated, or that a quiet boat could exceed the noise limits set in the Marine Safety Act. The situation is comparable to a car capable of traveling over 100 miles per hour. It is not illegal to purchase such a vehicle or drive it on local roads and highways. It is however, illegal to exceed the maximum speed limit. It would be legal to travel 100 miles per hour on race tracks and certain out-of-state highways, but only where designated. Cars capable of traveling over 100 miles per hour are not prohibited. Loud boats should not be prohibited. Boat operators should be able to be as loud as they like with respect to their location. The noise level produced by use should be the basis for law enforcement standards, not the boat's ability to be loud.

The standards use proper scientific measurement methods to measure the noise level of a boat. This is conflicting with law enforcement measurements which would provide a definite minimum value of the maximum sound level of the boat. This ensures all errors are accounted for and the result is error-adjusted, rather than a scientific best-estimate of the boat noise level.

SOUND PROPAGATION

Noise is produced by pressure waves which propagate through the air over distance. There are two classic models of sound propagation, spherical and planar, which model the least and most possible sound propagation over distance. Idealized planar sound propagation models sound that does not spread in the direction of travel. Idealized spherical sound propagation assumes pressure waves radiate and spread spherically from a point source over an area increasing with distance. In different situations boat noise may be best modeled with one, or a combination, of these classic propagation models.

The acoustic power of a pressure wave, $\mathcal{P}_{source}$, remains constant at its source. The magnitude of the acoustic intensity, I, (power per unit area) is given as a function of acoustic power and normal area, A_n.

$$I = \frac{\mathcal{P}_{source}}{A_n} \tag{1}$$

The magnitude of the acoustic intensity is proportional to the square of the time-averaged acoustic pressure, p, and inversely proportional to air density, ρ, and the speed of sound, c [Pierce, 1981].

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

Combining the relations (1) and (2), the local acoustic pressure is proportional to the square root of the power of the source divided by the area over which the pressure wave is traveling.

$$p = \sqrt{\frac{\rho c \mathcal{P}_{source}}{A}} \qquad (3)$$

Sound pressure level (SPL) is measured in deciBels (dB) as a function of the measured pressure, p, and reference pressure, p_{ref}, 2x10^{-5} Pascals.

$$SPL\,[dB] = 20\log_{10}\left(\frac{p}{p_{ref}}\right) \qquad (4)$$

The reference pressure, p_{ref}, is the smallest pressure wave a healthy human being can hear at 1000 hertz as measured by the American National Standards Institute (ANSI) [Pierce, 1981].

The change in sound pressure levels from two known distances, r_1 and r_2 can be rewritten as a function of the local acoustic pressures at those distances, p_1 and p_2 by (4).

$$\Delta SPL = 20\log_{10}\left(\frac{p_2}{p_1}\right) \qquad (5)$$

Planar Sound Propagation

Planar waves propagate unmitigated though the air as steady planes (Fig. 3). Planar wave fronts travel in parallel planes; their energy does not dissipate with distance because the area of the pressure wave remains constant with distance.

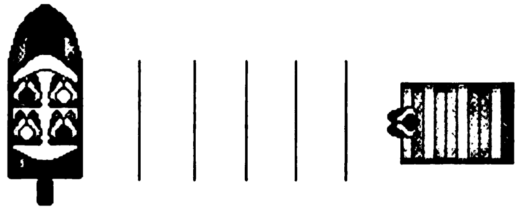

Figure 3: Planar Wave Propagation Model

This model best fits sound propagating from a large vibrating surface, like the side of a boat. Using (5) for planar waves, where the local acoustic pressure remains constant over all distances $(p_1 = p_2)$, the change in sound pressure level is zero with distance.

$$\Delta SPL_{planar,\, doubling} = 20\log_{10}\left(\frac{p_2}{p_1}\right) = 20\log_{10}(1) = 0 \qquad (6)$$

Spherical Sound Propagation

The spherical sound propagation model assumes a point sound source and sound power spreads over an increasing area as it moves away from that source. The sound pressure is spread over the increasing area of a spherical surface (Fig. 4) as a function of the radial distance from the point source, r.

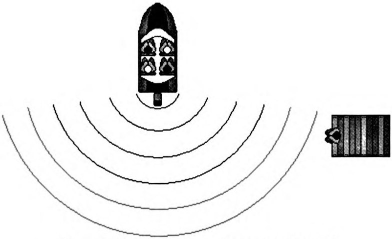

Figure 4: Spherical Wave Propagation Model

The acoustic power, $\mathcal{P}_{source}$, remains constant at the point source and the acoustic intensity is given as a function of the half-spherical area of the pressure wave, which is a function of radial distance, r.

$$I_{spherical} = \frac{\mathcal{P}_{source}}{2\pi r^2} \tag{7}$$

It can be seen the acoustic intensity decreases with the inverse square of the radial distance. This is known as the *spherical spreading law* [Pierce, 1981]. Combining the relations for acoustical intensity as a function of acoustic pressure and source power, (2) and (7), the local acoustic pressure in spherical propagation is inversely proportional to the distance from the source.

$$p_{spherical} = \frac{k}{r} \tag{8}$$

The constant, $k = \sqrt{\rho c \mathcal{P}_{source} / 2\pi}$. Substituting (8) into (5) and simplifying the result yields the change in sound pressure level as a function of distance.

$$\Delta SPL_{spherical} = 20\log_{10}\left(\frac{r_1}{r_2}\right) \tag{9}$$

This shows the change in sound pressure level between two distances in the spherical model is inversely proportional to the ratio of those two distances. The change in sound pressure level, ΔSPL, with a doubling of distance is of particular interest in noise measurements. Spherical propagation is a function of distance and for a doubling of distance, $\left({r_1}/{r_2} = 0.5\right)$, in pure spherical propagation, the sound pressure level decreases by 6.02 deciBels.

$$\Delta SPL_{spherical,\, doubling} = 20\log_{10}\left(\frac{r_1}{r_2}\right) = 20\log_{10}(0.5) = -6.02dB \tag{10}$$

The real nature of sound propagation from a boat is unknown; it is an unknown combination of planar and spherical waves. Analyzing the planar and spherical models gives the extremes of the range of the change in sound pressure with distance. Sound cannot propagate more than 0 dB/doubling, as shown by planar propagation, and cannot propagate less than -6.02 dB/doubling, as shown by spherical propagation. Real boats have a combination of both propagation models and will always have a propagation value between 0 and -6.02 deciBels with doubling of distance.

Richard Lanpheer's Sound Propagation Study

Experimental study of boat noise sound propagation was conducted by Richard Lanpheer of Mercury Marine and the National Association of State Boating Law Administrators (NASBLA) in January 1987. He used four sound level meters at four known linear distances perpendicular to the direction of pass-by (Fig. 5) [Lanpheer, 1987]. Sound level meters at 50, 100 and 200 feet distances were used to analyze sound propagation with doubling of distance. A 25 meter distance was used to analyze and compare the measured sound pressure level to the SAE J34 standard procedure.

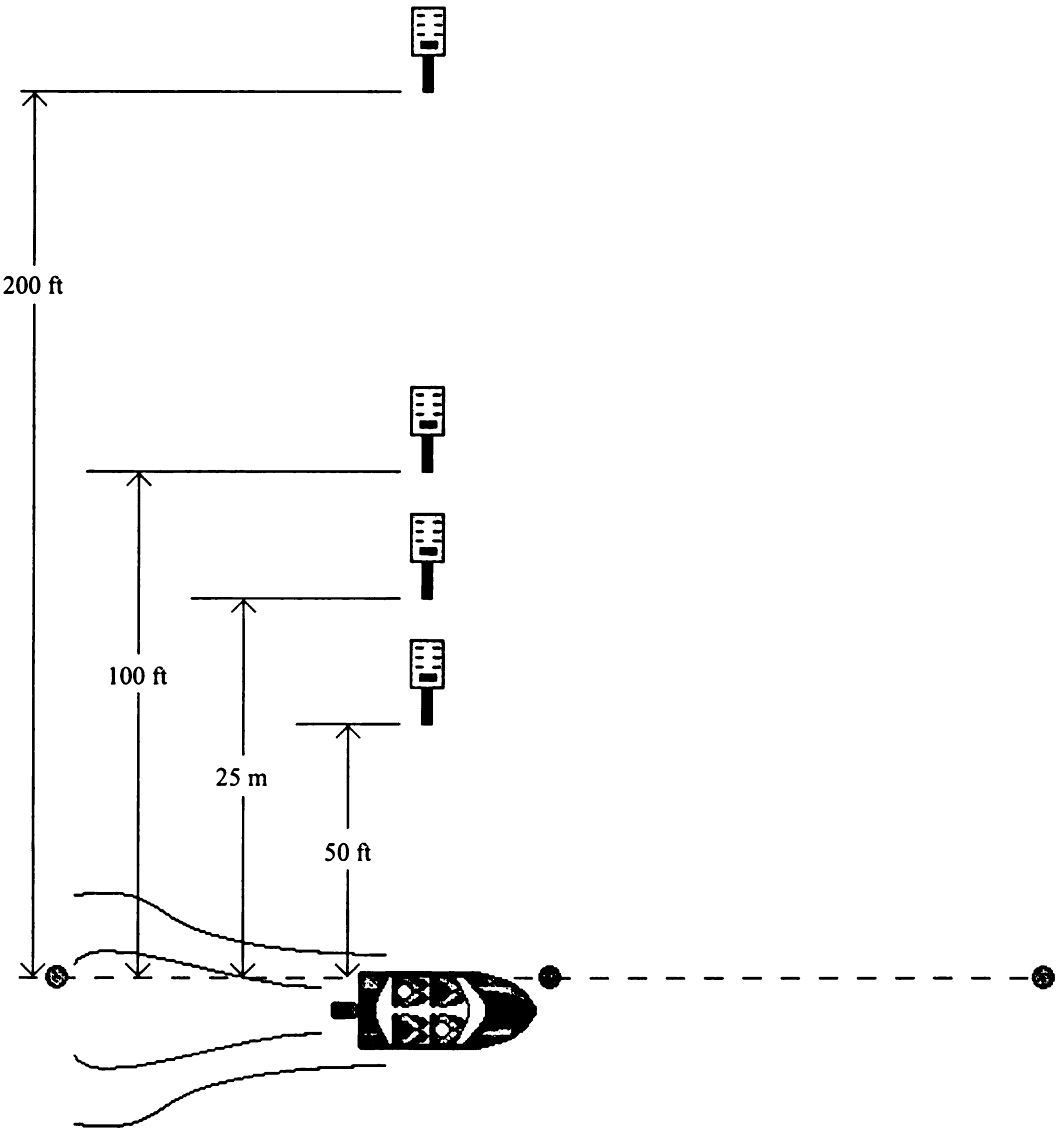

Figure 5: Boat Course for 1987 Lanpheer Pass-By Noise Measurements [reproduced from Lanpheer, 1987]

Lanpheer tested 21 boat/motor combinations "...in an effort to determine the effects of boat operational variables on sound level" [Lanpheer, 1987]. His results show that doubling the distance between a boat and a microphone reduces the measured sound level by an average of 5 dB/doubling (Fig. 6). All 21 boat/motor combination trials were within 0.5 dB/doubling of the 5 dB/doubling average value with an exception of one, in which only one of the three trial samples deviated by more than 0.5 dB/doubling [Lanpheer, 1987]. His average 5 dB/doubling lies in the range of our two extremes calculated from planar and spherical propagation, 0 and -6.02 dB/doubling, by (6) and (10).

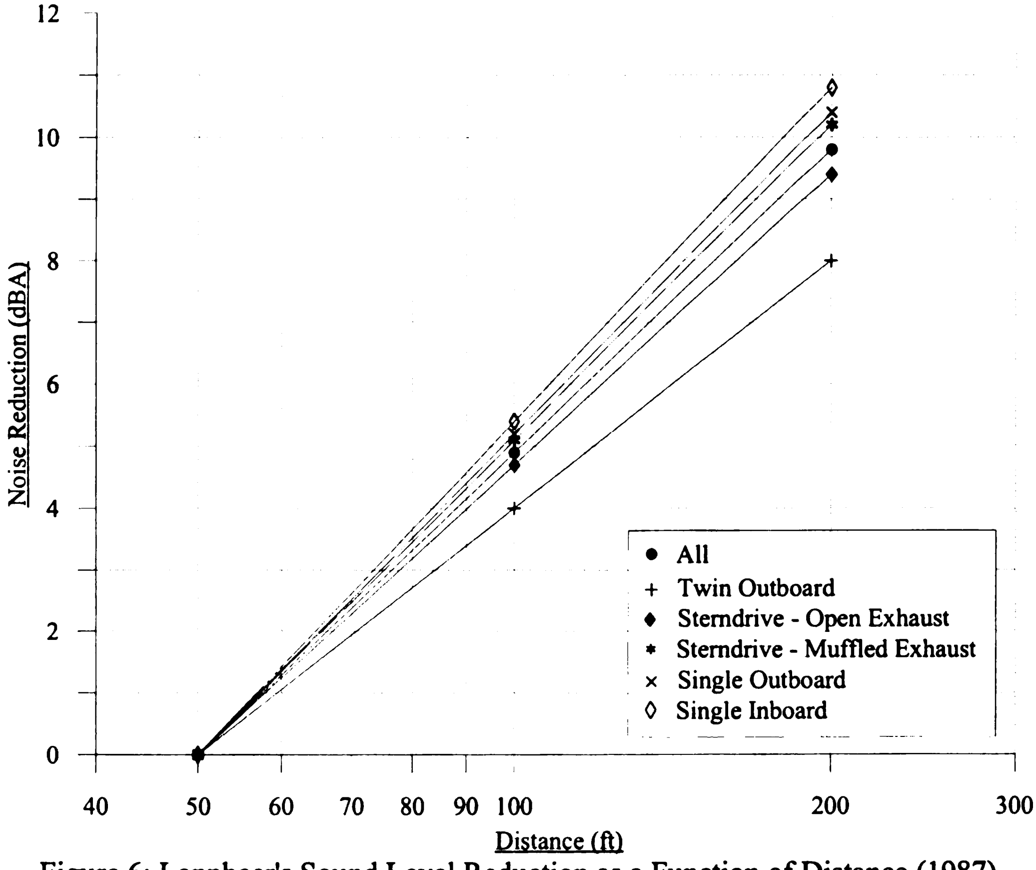

Figure 6: Lanpheer's Sound Level Reduction as a Function of Distance (1987) [reproduced from Lanpheer, 1987]

Richard Lanpheer studied noise propagation in recreational boats again in September 1992. One of the main purposes was to "...evaluate and compare existing and proposed testing methods..." [Lanpheer, 1993]. He emulated the SAE J34 pass-by standard and measured noise levels two distances, 25 meters, as stated, and 12.5 meters, to observe the increase sound pressure level with doubling. His results indicated "...that the average attenuation of sound pressure level between the two microphones was 4.9 deciBels" [Lanpheer, 1993]. This 4.9 deciBel difference between the sound pressure levels measured at 12.5 and 25 meters corresponds to an average of 4.9 dB/doubling (Fig. 7).

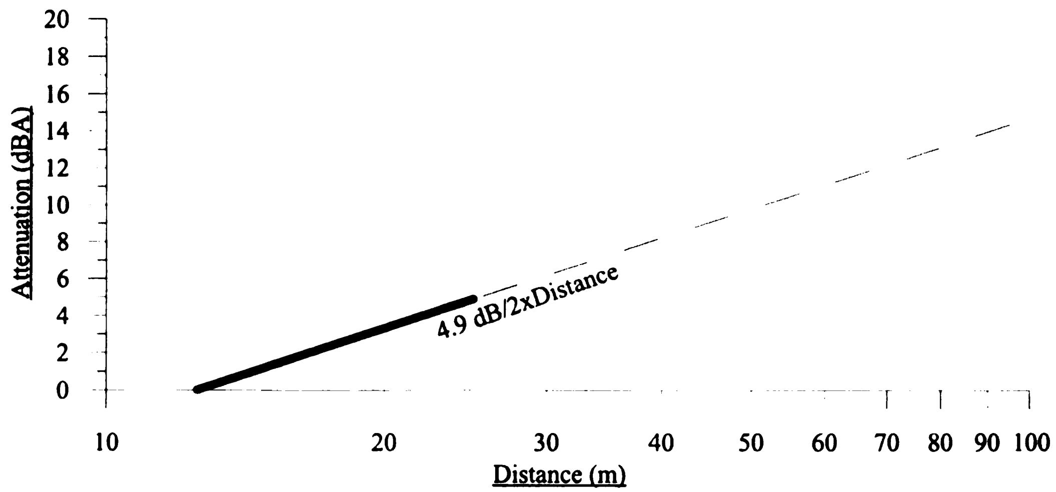

Figure 7: Lanpheer's Attenuation Measured Over Water; Outboards & Sterndrives (1993) [reproduced from Lanpheer, 1993]

These pass-by test results compare well to the 5 dB/doubling result found in the first tests. The tests themselves differ by definition. The first test is not comparable to the SAE J34 standard. The second test is, yet they show the same result (within 0.1 dB/doubling). The two tests show 5 dB/doubling is an accurate assumption for motorboat pass-by measurements. The results also indicate that, for various styles of boats, in a pass-by measurement situation, this value stays quite constant. This information and the sound propagation model can be used to calculate the sound pressure level of a boat at any arbitrary distance given the sound pressure level at a known distance.

In real world testing on a realistic lake, background sounds would interfere with any possible measurements. Background sound level measurement needs to be understood in order to strictly measure one specific sound source.

BACKGROUND SOUND LEVEL MEASUREMENT AND COMPENSATION

When a microphone measurement of a source sound level is made in the presence of background noise, the total measured sound level is greater than the actual source sound level. The oscillatory source and background sound levels combine to form a single wave of greater amplitude. Each sound pressure level can be represented by its exponential-root-mean-square (ERMS) value, which is derived and explained in detail in Appendix B. The ERMS values of multiple sound sources can be added and subtracted, regardless of phase, allowing for compensation analysis [ANSI S1.4-1983, 1983].

The actual source sound level can be calculated when the background level is known, for uncorrelated, broad-band sound levels. The total measured ERMS pressure level, p_m, is the sum of the source, p_s, and background, p_b, ERMS pressure levels.

$$p_m = p_s + p_b \tag{11}$$

Acoustic pressure levels can be rewritten in terms of deciBel units (dB) and vice versa. This is done for convenience, as sound level meters tend to measure pressure levels in units of deciBels rather than Pascals.

$$\boldsymbol{P}[dB] = 20\log_{10}\left(\frac{p}{p_{ref}}\right) \tag{12}$$

$$p = p_{ref}10^{\left(\boldsymbol{P}/20\right)} \tag{13}$$

The total measured sound, $\boldsymbol{P}_m$ in deciBels by (12), can be expressed as a function of the sum of the source and background sounds, $\boldsymbol{P}_s$ and $\boldsymbol{P}_b$, in deciBels by (11).

$$10^{\left(P_m/20\right)} = 10^{\left(P_s/20\right)} + 10^{\left(P_b/20\right)} \tag{14}$$

The sound pressure level of the source, P_s, can be calculated by (12) and (14) yielding the source sound pressure as a function of the total measured, and background sound pressure levels.

$$P_s\,[dB] = 20\log_{10}\left(10^{\left(P_m/20\right)} - 10^{\left(P_b/20\right)}\right) \tag{15}$$

(15) can be factored and simplified to collect terms and compute the compensation level in deciBels.

$$P_s\,[dB] = P_m + 20\log_{10}\left(1 - 10^{\left(P_b - P_m\right)/20}\right) \tag{16}$$

This source sound pressure level equation, (16), can now be written to compute the source sound pressure level and compensate for background noise.

$$P_s\,[dB] = P_m\,[dB] + C\,[dB] \tag{17}$$

The compensation can now be calculated as a function of the difference between the total measured and background sound pressure levels.

$$C\,[dB] = 20\log_{10}\left(1 - 10^{-\left(P_m - P_b\right)/20}\right) \tag{18}$$

Since the total measured sound pressure level will always be greater than the background source sound pressure level by itself, $P_m - P_b$ will always be positive.

Mathematically this shows the compensation exponentially approaches zero as $P_m - P_b$ increases (Fig. 8).

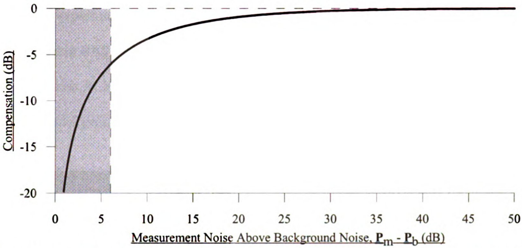

Figure 8: Sound Level Compensation for Background Noise [reproduced from Radcliffe, 2002]

As $P_m - P_b$ decreases, the sensitivity of the compensation calculation increases exponentially. This can lead to a great deal of inaccuracy in compensation calculations. The unacceptable sensitivity range (Fig. 8, shaded region) represents the range where the sensitivity is greater than 1 dB/dB. The boat noise measurement device returns an error readout for values in this range.

This analysis shows that a source's sound level can be isolated experimentally for a known background noise level. In a real world environment, background noises would contribute error to the noise level measurement of a source. It has been demonstrated that with a sole, constant background noise level measurement and a measured sound pressure level at a known distance that a noise level for any source can be found accurately, despite its distance.

FIRST BOAT NOISE MEASUREMENT DEVICE PROTOTYPE

In 2003, Sean Vidanage built a proof-of-concept boat noise measurement device (Fig. 9) to experimentally study and measure boat noise sound propagation. He used a programmable BASIC Stamp microcontroller along with external circuitry in conjunction with a Contour XLR Laser Rangefinder to measure distance and a shotgun microphone to measure sound pressure level.

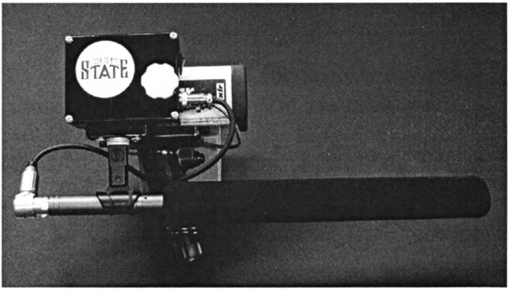

Figure 9: First Prototype of the Boat Noise Measurement Device

The purpose of this device was to demonstrate that a programmable microcontroller, laser rangefinder and directional microphone could work together to measure sound pressure levels and distances and perform calculations. The device followed a boat, measured its distance and sound pressure level repeatedly, and normalized the final sound level measurement to 25 meters. The operator could follow a boat along any designated path (Fig. 10) and measure the corresponding distance, sound level and calculate the normalized sound level at a 25 meter distance. The microcontroller would calculate the amount of error associated with distance and background noise automatically and correct the current sound pressure level to a law enforcement value at 25 meters.

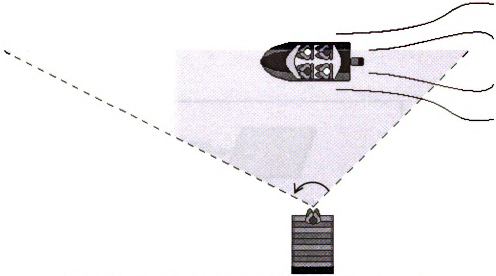

Figure 10: Pass-By Model of the First Noise Gun Prototype

The laser range finder would measure the changing distance of the boat during the trial and the shotgun microphone would measure the corresponding sound pressure levels. The device continuously corrected the measured sound levels with distance assuming Lanpheer's best estimate of boat noise sound propagation of 5 dB/doubling (±1 dB/doubling). In a pass-by situation, the highest resulting sound pressure level is the maximum noise level measured along the pass-by.

The first prototype proved that a laser rangefinder, shotgun microphone and programmable microcontroller could work together. The BASIC Stamp microcontroller could accept the readout of the laser rangefinder, it could accurately measure the shotgun microphone signal and the resulting calculations were performed correctly. It was able to function as planned and performed all the associated functions properly. A complete functionality block diagram (Fig. 11) is shown to visually explain the steps.

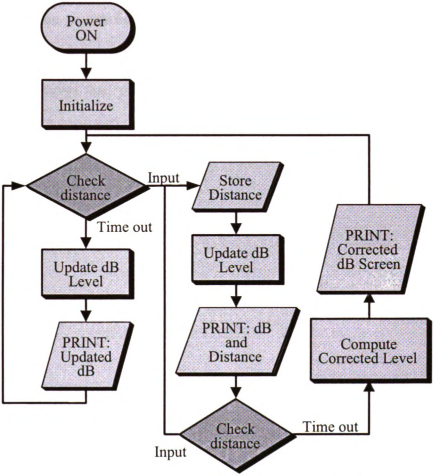

Figure 11: Second Prototype Functionality Block Diagram [copied from Vidanage, 2003]

The first prototype was not designed to follow the SAE J34 pass-by standard. The SAE J34 pass-by standard clearly states the sound level meter must be aimed perpendicular to the direction of boat travel when measuring; the shotgun microphone was aimed directly at the boat during the measurement. The first prototype was designed to follow the boat along any course and continuously calculate the resulting 25 meter corrected sound pressure level. It was designed as a proof-of-concept, an assembly of necessary components into a working model. It accurately performed distance independent noise measurements and calculations.

The microcontroller controlled all calculations and associated errors and displayed them on an attached LCD monitor. The results show that the experimental results match the mathematical model, with a reasonable error [Vidanage, 2003]. The thesis strongly shows that, with some improvement, a boat noise measurement device could be created for law enforcement purposes that follow the SAE J34 pass-by standard.

CURRENT BOAT NOISE MEASUREMENT DEVICE PROTOTYPE

Using the first prototype's circuit schematic and program code as a start, the prototype design has been improved (Fig. 12).

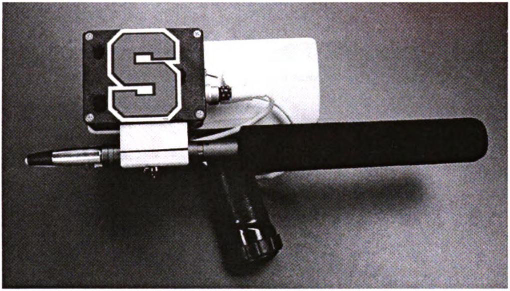

Figure 12: Second Prototype of the Boat Noise Measurement Device

LCD displays replaced the old LED displays, and a factory-produced silicon prototyping board was created to hold the circuit components to help create space and limit hand-soldering errors. An acoustic A-weighting filter, which complies with ANSI standards, was added for acoustic filtering purposes. It complies with the A-weighting filter requirement of all the existing standards.

The basic function of the second prototype differs greatly from the first prototype. The second prototype method is modeled after the SAE J34 procedure. The SAE J34 standard states the microphone must be non-directional and point away from the dock perpendicular to the course. A shotgun microphone was used to minimize background noise, which requires the device operator to follow the boat along the course, rather than place the unit stationary on the platform. The process involves following the boat with the device along its course (Fig. 13). The device does not make any calculations until the operator ends the measurement process.

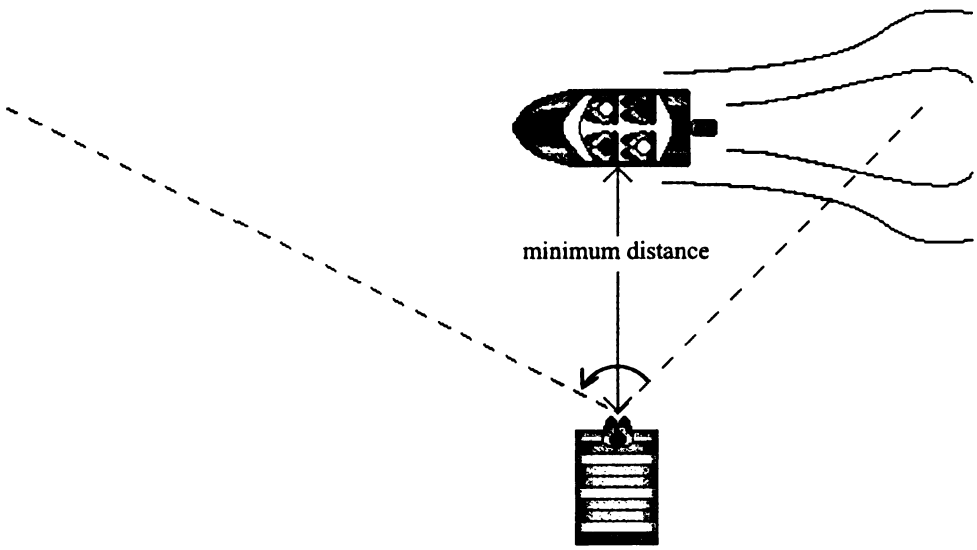

Figure 13: Pass-By Model of the Second Noise Gun Prototype with Minimum Distance Shown

In the second prototype method, distance and sound level are measured repeatedly throughout the measurement trial. When the boat completes its pass-by, the microcontroller returns the maximum sound level and the minimum distance along with the corrected and background sound levels. This new procedure does not correspond to the SAE J34 standard, but the two methods are similar and the results can be compared for accuracy. A block diagram of the functionality of the second prototype is shown in Figure 14.

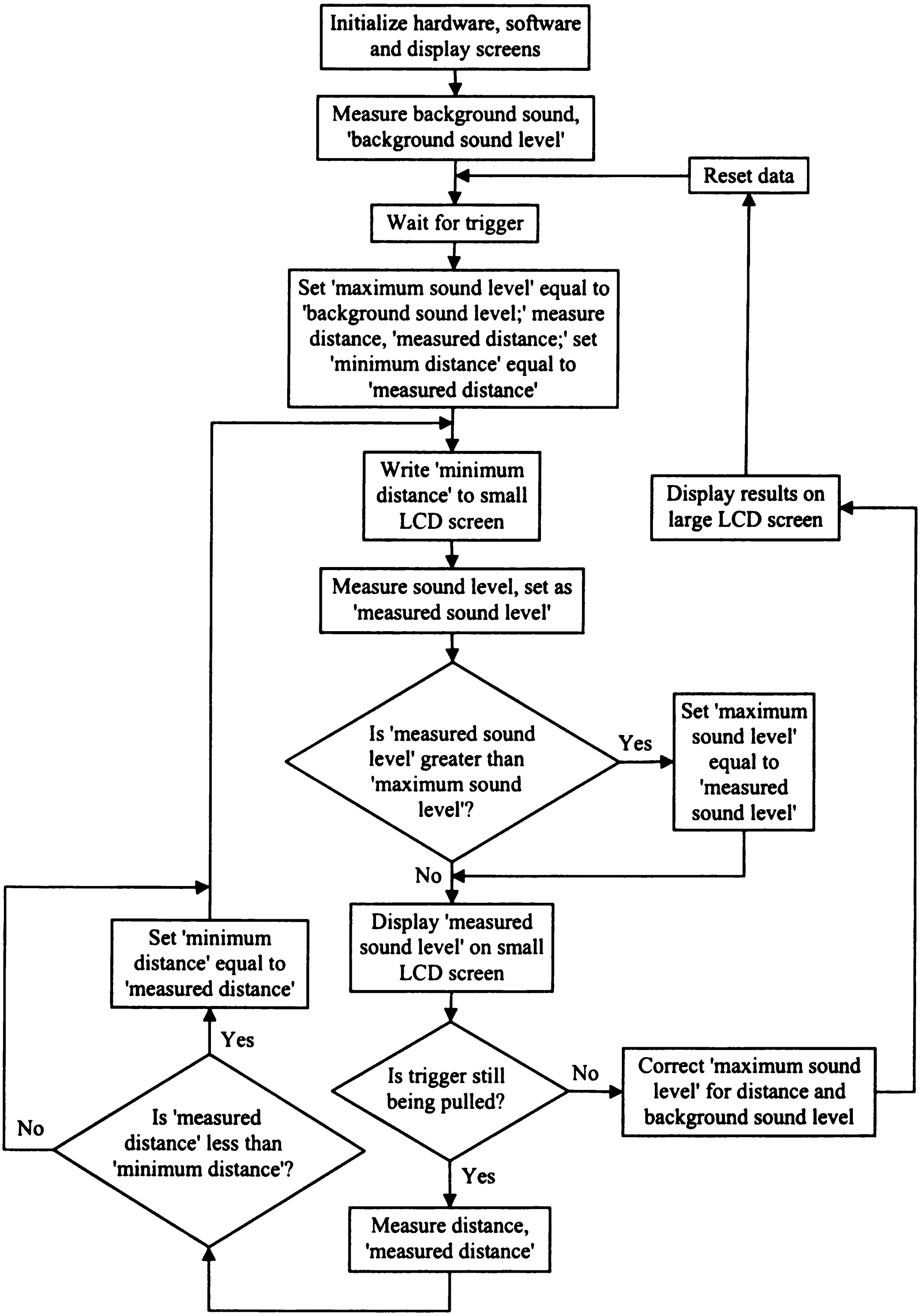

Figure 14: Second Prototype Functionality Block Diagram

The device begins with initializing the software and hardware and powering the system on. Then automatically, the device measures the background sound level of the surroundings. This is the only time the background sound level is measured. The device than waits for the user input (the trigger) and begins measuring only distance for an approaching boat.

The second prototype model is programmed to initially set the background sound level measurement to the 'maximum sound level measured,' for use as a reference in later loops. The initial distance is also recorded as the minimum distance, for comparison in later loops. From there, constant distance and sound pressure levels are made. With each measurement, the measured distance is compared to the minimum distance recorded, and the lower of the two becomes the new minimum distance recorded, for the next loop. The sound pressure level is measured and compared to the maximum sound pressure level recorded and the larger is taken.

Once the trigger is released, the distance corrections are made to normalize the result to 25 meters and the background noise corrections, following (18) are made to isolate the desired source noise. The device then displays the minimum distance, the maximum measured sound pressure level, the background noise level and the corrected noise level value.

Given that this device is designed for law enforcement purposes, all errors must go in favor of the offending boat operator. This implies all error measurements must be maximized or minimized in calculations to give the offending boat all benefits of the doubt. This separates a scientific measurement device from a law enforcement device. A scientific measurement device would like to be as close a possible to the actual values with the smallest and least amount of errors. A law enforcement device would like to be as close as possible to actual values with all the errors skewed in favor of the offender. This ensures that the resulting law enforcement measurement is the least possible value that the offender could have been; and all the associated errors are in his/her favor. Therefore any errors in measurement or correcting would only strengthen the prosecution's case. It is important to realize that a law enforcement measurement is always lower than a scientific measurement, and that this device is a law enforcement device.

The device uses a sound propagation worst case scenario to ensure a proper law enforcement measurement. In Richard Lanpheer's 1987 results (Fig. 6), he found an average of 5 dB/doubling to be an accurate model of real boat sound propagation. In the 61 samples he conducted, only one had a difference from that average greater than ±0.5 dB/doubling [Lanpheer, 1987]. Twice that difference, ±1 dB/doubling, is used in the second prototype to normalize the distance to 25 meters. Rather than use the 5 dB/doubling average value, the device skews the average within ±1 dB/doubling. That's to say that if the boat was too close, the device would subtract the loudest possible value it could have been, 6 dB/doubling. And if the boat were too far, the device would add the quietest possible it could have been, 4 dB/doubling. This ensures the normalized distance correction would be in favor of the offender, because any possible errors would only make the boat louder.

The experimental testing took place on Higgins and Torch Lakes in northern Michigan in June and September 2005 respectively. The test procedure was modeled after the SAE J34 standard. Two additional courses were added to study propagation with respect to doubling distance. A platform was erected such that a 50 meter by 100 meter area could be situated in front of it. Nine buoys marked three, three-buoy courses, each different distances from the platform; one at 25 meters, one at half that, 12.5 meters, and one at twice that, 50 meters (Fig. 15).

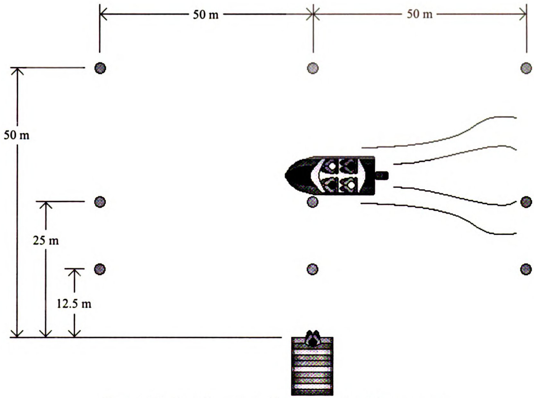

Figure 15: Boat Course for Pass-By Noise Measurement

The course is modeled after the SAE J34 course, but the procedure was not followed exactly. The platform wasn't assembled within the proper specification, the microphone was not placed accordingly, and the boats didn't pass within 1 meter of the far side of the buoys (Fig. 16). Though the course didn't follow the SAE J34 exactly, the procedure was designed to be comparable to it.

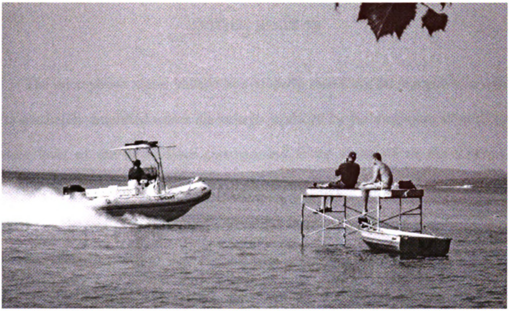

Figure 16: Torch Lake Test Run [photograph by Betsy Dole]

Assuming the acoustic power of the boat remains constant for all trials, there should be roughly 5 dB/doubling in sound propagation, as there was in Lanpheer's work. The corrected values of each of the boats should be constant as well, with slightly lower values as boats distances get smaller and larger than 25 meters. Since the distance error is a function of how far the boat is from the 25 meter distance, a larger distance would correspond to a larger error. Likewise, if the boat were very close to the 25 meter distance there would be a very little error.

The purpose of this research is to create a law enforcement device and to compare its results against Lanpheer's past sound propagation studies. The intent was to make sure the noise measurement device under-predicts the sound level meter values every time and to compare noise propagation with doubling distance to Richard Lanpheer's results. Comparing the results will help determine the accuracy and validity of the noise measurement device.

TESTING RESULTS

The microphone signal voltage was properly read from the shotgun microphone. It was accurately amplified where the voltage produced by the maximum allowed sound pressure level of the microphone corresponded to the threshold of the RMS-to-DC conversion chip input. This was done using the microphones sensitivity information, and checked experimentally with a function generator and oscilloscope repeatedly.

The amplified signal was filtered with a manufacturer-calibrated A-weighted filter. A filtering chip applied the A-weighting filter to the shotgun microphone measurement signal and showed no evidence of clipping, or distortion. The filter is designed to comply with ANSI S1.42 standard which defines the proper design response of weighting networks for acoustical measurements [Applied Dynamic Mcasurements].

The sound pressure levels versus logarithmic distance are plotted for each test for analysis, as described by (12). A typical example is shown in Figure 17 which shows Test 12's data. The shaded area represents the range of distances acceptable in the SAE J34 standard. Each measured sound pressure level data point is shown (○). From these points, a best-fit logarithmic regression line (—) is obtained to determine the best estimate of the measured sound pressure level for any given distance. This lines slope is shown for comparison to Richard Lanpheer's data.

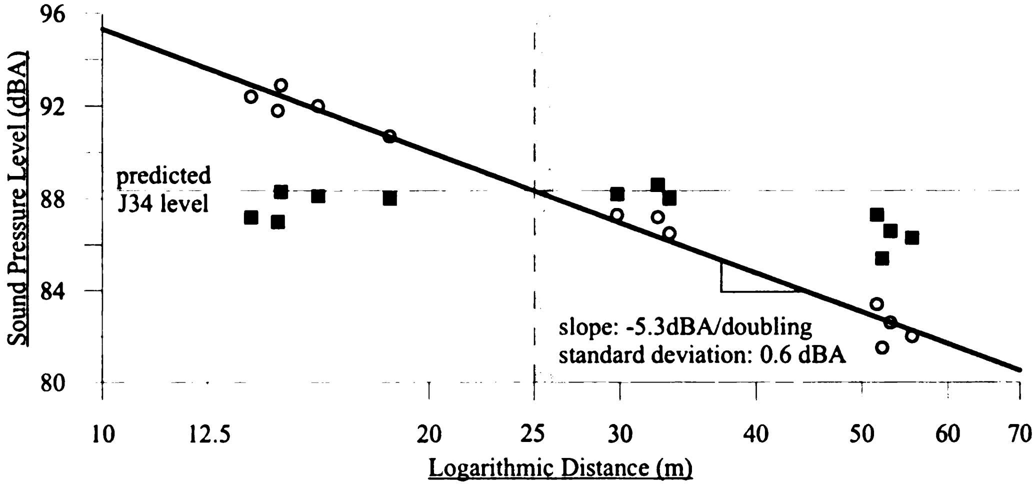

Figure 17: Test #12 Field Data, Measured SPLs (○) and Error-Compensated SPLs (■) and Predicted SAE J34 SPL (—) with Respect to the Measured SPLs Best-fit Logarithmic Regression Line (▬)

The predicted SAE J34 sound level is found by the best-fit logarithmic regression line (—). This value represents the predicted SAE J34 best scientific estimate of what the sound pressure level of the boat would be at exactly 25 meters. This line will be compared with each of the error-compensated calculated points (■), which are found by (17).

The sound level propagation over distance compared well with Richard Lanpheer's data. His experimentation led to overall boat sound propagation estimates of -4.9 dB/doubling and -5 dB/doubling [Lanpheer, 1987; Lanpheer, 1993]. The results indicated an average value of -4.86 dB/doubling, which is very close to each of his experimental results.

The range of acceptable distances for the SAE J34 standard is represented by the gray area in Figure 17. In order to properly perform the SAE J34 standard, the boat needs to be within a 25 to 26 meter distance for each pass-by. This is extremely difficult for an untrained operator. For the seven boats correctly tested, there were 26 total 25 meter pass-by measurements, of which only four (15.4%) would be acceptable by the distance requirement of the SAE J34 standard procedure [App. G]. It is unlikely the average boat operator could maneuver this course correctly by the SAE J34 standard to make a proper measurement.

In order for the device to act as a proper law enforcement device, the compensated values must be, at most, one standard deviation above the predicted SAE J34 value. The standard deviation for this measurement procedure is calculated using the same method as in the ISO 14509 standard. The ISO 14509 Standard Deviation of Reproducibility Table (Table 2) takes into consideration all sources of uncertainty which are considered to be independent of each measurement type. The International Organization for Standards (ISO) defines the total standard uncertainty as the square root of the sum of the squares of the individual standard deviations.

Table 2: Standard Deviation of Reproducibility [reproduced from ISO 14509, 2004]

Individual sources of uncertainty	Individual standard deviations of the maximum AS-weighted sound pressure level (dB)
Distance effects	0.25
Measuring equipment	1.0
Sound propagation conditions	1.5
Waves, currents and tides	1.5
Operator(s) effects	0.2
Test site variations	1.0
Operating conditions	0.5
Estimated total standard uncertainty	2.6

For the purposes of this measurement procedure, the ISO 14509 Standard Deviation of Reproducibility Table is modified to remove the 'Sound propagation conditions' uncertainty source because the device already corrects for this. With this change, the total standard uncertainty of the boat noise measurement device measurement procedure is calculated to be 2.1 dB.

Using the ISO 14509 Standard Deviation of Reproducibility method, the standard deviation of uncertainty for this measurement procedure is 2.1dB. To compare the error-compensated calculations to the SAE J34 best-estimate of the measured sound pressure level, the standard deviation, 2.1dB, is subtracted from each calculation (Fig. 18, ×). In order for this device to function as a proper law enforcement tool, the standard deviation- and distance and background noise error-corrected data points (×) must be less than the best-estimate of the predicted SAE J34 sound pressure level (—).

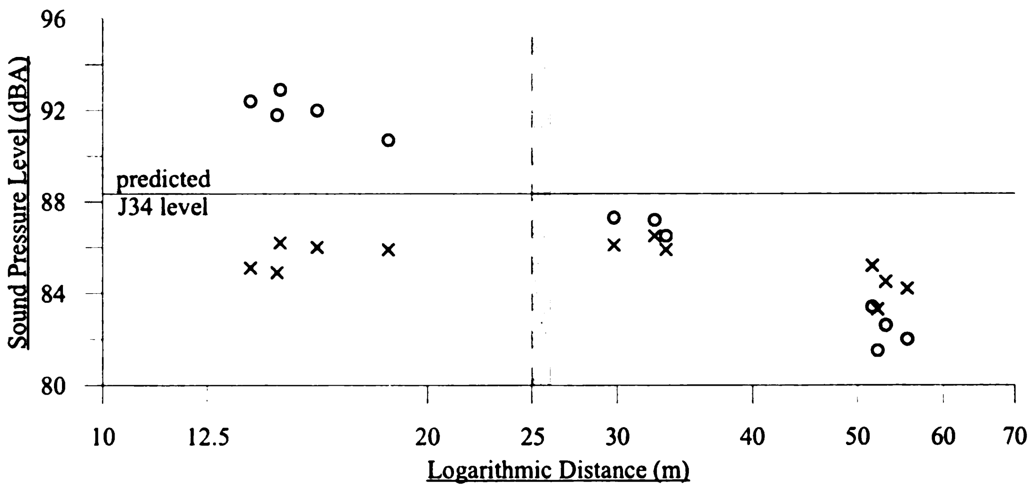

Figure 18: Test #12 Field Data, Measured SPLs (o) and Standard Deviation- and Error Compensated-Corrected (×) SPLs with Respect to the Predicted SAE J34 SPL (—)

Experimentally, the standard deviations of the seven acceptable experimental results ranged from 0.5 dBA to 2.3 dBA [App. E] with a weighted average of 1.2 dBA, by (19).

$$\sigma_{weighted-average} = \frac{\sum_{i}^{\# of\ trials}\left(\sum_{j}^{\# of\ samples}\sigma_i\right)}{\# of\ total\ samples} = 1.2dBA \tag{19}$$

The experimental weighted average standard deviation is considerably lower than the value predicted by the ISO 14509 standard deviation of reproducibility method. This shows the ISO 14509 value is a conservative value that will most likely over-predict the standard deviation produced by a boat. In all the acceptable testing that was conducted three out of 85 data points (3.5%) had standard deviation-corrections that were greater than one ISO 14509 standard deviation (2.1 dB) larger than the predicted SAE J34 sound pressure level [App. E, tests 11, 14]. All three of the values are less than 0.4 dB greater than the predicted SAE J34 sound pressure level.

The standard deviation analysis is correct assuming the data fits Gaussian distribution. Gaussian distribution implies "whenever a random experiment is replicated, the random variable that equals the average (or total) result over the replicates tends to have a normal distribution as the number of replicates becomes large" [Hubele, 2001]. An accurate way to tell if the data conforms to the Gaussian random variable normal distribution is to compare the data to the cumulative probability function (Fig. 19). This shows the percentage of the total trials covered in the entire range of normal random variables. The plot shows that 50% of the data is less than, and the other 50% is greater than, its corresponding best-fit logarithmic regression value. This makes sense assuming half the measurements would be lower than expected and the other half would be greater than expected.

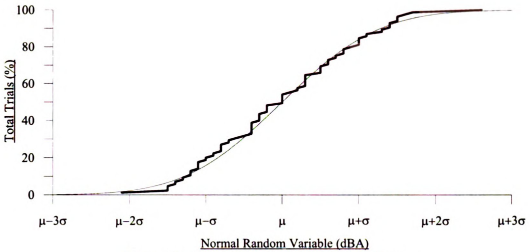

Figure 19: Cumulative Probability of the Data

The derivative of the cumulative probability function is the standard normal probability function. This represents the typical 'bell curve' that Gaussian data conforms to (Fig. 20). Data is lost in this representation due to column width definition; too thick a column and standard deviation information is lost, to thin a column, and the less likely it will appear to match the standard normal probability function.

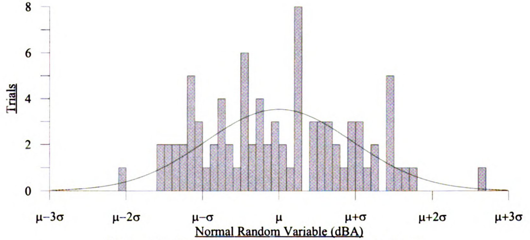

Figure 20: Standard Normal Probability of the Data

Figure 19 shows excellent data conformity to the Gaussian distribution definition, whereas it isn't as clear in Figure 20. Data conformity to Gaussian distribution shows the data is reproducible with respect to a standard deviation. Although the weighted-average standard deviation of the test data is 1.2 dB, the ISO 14509 standard deviation of uncertainty for this measurement procedure is 2.1 dB.

CONCLUSIONS

The device operated correctly as designed. It was able to accurately measure the distance to an approaching boat during pass by to find the closest point of approach. Once the closest point was determined, the device accurately measured the largest sound pressure level as the boat passed by. From the closest-point distance, the largest sound pressure level measured, and the background sound pressure level, the microcontroller was able to correct for distance to produce a best-estimate of the sound pressure level for that boat at 25 meters. The gun displayed each of these values after each run for evaluation purposes.

The laser rangefinder serial output signal was correctly read by the microcontroller; this was proved by comparing concurrent displayed measurement values from both the microcontroller, and the device. This process was done repeatedly to ensure no mistakes had been made in programming.

Based on the data analysis, the following conclusions can be made:

- Distance and sound level measurements can be made independently and correctly interpreted by the BASIC Stamp microcontroller.
- The boat noise measurement device worked properly as designed.
- The data confirms Richard Lanpheer's sound propagation model assumptions [Lanpheer, 1987; Lanpheer, 1993].
- It is possible to compensate for all errors (distance, background noise, standard deviation) to yield conservative estimates of sound level at or below the SAE J34, ICOMIA or ISO standard sound level.

- It is difficult for boats to follow the distance requirement of the SAE J34 standard; 25 to 26 meters during pass-by.
- The possible incorrect calibration of the device does not imply the device did not work correctly as designed. An incorrect calibration would effect all sound level measurements equally, meaning the measured sound levels would be off by a constant value. This would not effect sound propagation analysis or background noise compensation, by (18).

RECOMMENDATIONS FOR FUTURE WORK

- Future models of the boat noise measurement device should replace the directional shotgun microphone with an omni-directional microphone for field calibration and SAE J34, ICOMIA or ISO standard conformity. This will also allow for calibration without the use of an anechoic chamber.
- A standard pass-by test site (or many standard pass-by test sites) should be created. This will increase the ability to conduct future work. A permanent, stable platform with dimensions outlined in one of the pass-by standards will make emulating the current standards possible, and allow a safer working environment for data collection.
- The A-weighting filter should be moved into the circuit design rather than implemented by a microchip. This will ensure proper function and ANSI S1.42-2001 compliance.
- A low battery signal should be installed into the circuit model to alert the user when the voltage levels are getting low.
- The microcontroller program should be modified to subtract the standard deviation of the measurement procedure as shown in the ISO 14509 standard.
- C-weighting filtering should replace A-weighting filtering in noise measurement. Loud boats large noise levels. A-weighting is used to filter small noise levels, 25 to 55 dB, whereas C-weighting is used to filter larger noise levels, 85 to 115 dB.

Appendix A:
Weighting Filter and Sampling Time Definitions

The weighting filter and sampling time characteristics of a sound level meter can dramatically alter the results of a sound pressure level measurement. Weighting filters add frequency-dependant aspects to the gain of the measurement. The sampling time of the sound level meter defines the amount of time a signal is averaged, possibly diminishing the quality of the result. Weighting filters and sampling times are specified in all the boat noise standards discussed in this document.

Weighting Filters

Weighting filtering normalizes a given sound measurement to human response for different deciBel ranges. The human ear attenuates high and low frequencies which must be accounted for when analyzing human sound pressure level perception. Weighted filtering normalizes the given sound pressure level to the appropriate sound pressure level heard by humans. The weighted filters are designed to be the inverse of the Fletcher-Munson equal-loudness contours; the plots of the necessary gain a frequency-dependant signal requires to be of equal-loudness to a 1000 Hz reference tone [ISO 226:2003, 2003]. Since the tests were based on test subjects' opinions, Fletcher and Munson averaged their results over many test subjects to obtain reasonable averages.

There are many existing acoustic weighting filters A-, B-, C-, and D- of which, A- and C-weighing are the most popular. They happen to fall into convenient ranges where humans perceive relatively quiet and loud sounds. For low-levels of sound measurement, 25 to 55 dB, the A-weighting filter is used to scientifically normalize a signal to human sensitivity. For high-level sound measurement, 85 to 115 dB, the C-weighting filter is normally used. The B-weighting filter exists for moderately high sound levels, between the A and C ranges, which typically isn't important for acoustical measurement. The D-weighting filter is used to measure aircraft sound levels and demolitions, at 115+ dB, a range that would damage human hearing over time (Table 3).

Table 3: Weighting Filters and Their Appropriate Ranges of Use

Weighting Filter	Appropriate Range
A	25 to 55 dB
B	55 to 85 dB
C	85 to 115 dB
D	115+ dB

It is important to notice the shapes of the A- and C-weighting filters for low frequencies. The filters seem to have the same general shape for frequencies larger than 1000 Hz, with a small difference (Fig. 21). For frequencies less than 300 Hz, there is a large difference between the results. The difference between the A- and C-weighting filters at 100 Hz is 20 dB, and the difference increases as the frequency decreases. If a loud boat were to operate at a low frequency, the use of the A-weighting filter could cause huge errors in sound level measurement.

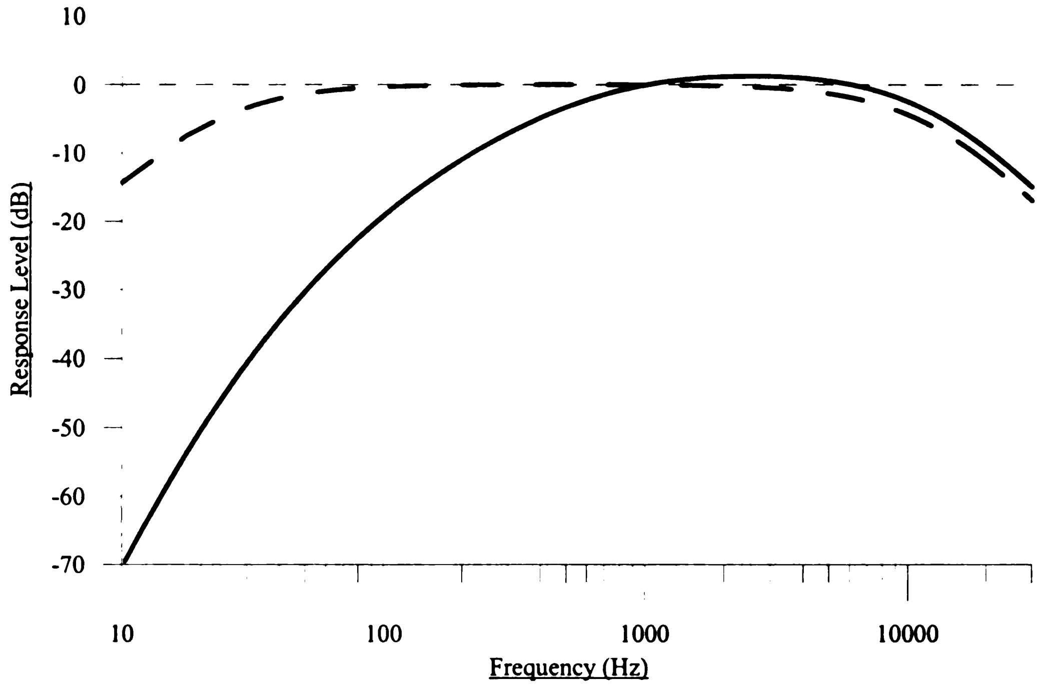

Figure 21: Relative Amplitude Response Level of the A-Weighting (———) and C-Weighting (— —) Networks to a Steady-State Sinusoid [reproduced from ANSI S1.42-2001]

Sampling Time

The sampling time defines the length of time over which sound level measurements are averaged. Infinitesimally small measurements are not possible, so a sound level wave may not be correctly measured in real time. Sampling times are the specific time intervals over which an unknown sound pressure waves is measured and averaged. Small sampling times yield large amounts of measurements, but may include unwanted random peak noise. Large sampling times yield smaller amounts of data, and tend to eliminate peak noise signals, but could eliminate wanted characteristics of the pressure wave.

Slow and fast sampling times are formal terms corresponding to 1 and 0.125 seconds respectively [ANSI S1.4-1983]. These are the common sampling times associated with boat noise measurement standards. The five standards discussed in this document use and define sampling time by these definitions (Table 2).

The sampling time involved in an unknown sound wave measurement is very important. For steady-levels with many random peaks, the slow sampling time would be preferred. This will eliminate any random peak influence for a clear steady measurement. For changing sound levels, a fast sampling time may be preferred. This will yield a clearer depiction of the wave as the sound level changes, yet may include random peak noise.

Appendix B:
The Exponential Time-Average Sound Pressure Level

The ANSI S1.4-1983 standard provides the proper specification for sound level meter measurements. As mentioned in Appendix A, sound level measurements have sampling times associated with them because infinitesimally small measurements are not possible. The standard defines the exponential-time-average sound pressure level as the appropriate method for measuring time-varying sound waves in air. The sound pressure level is given as $L_{p\tau}$ [ANSI S1.4-1983], in deciBels, where τ represents the time constant (sampling time), as defined in Appendix A and p_0 is the lowest acoustic pressure level humans can possibly hear, $2\text{x}10^{-5}\,\text{Pa}$ (defined as p_{ref} earlier).

$$L_{p\tau}(t) = 10\log\left(\frac{1}{\tau}\int_{-\infty}^{t}\frac{p^2(\xi)}{p_0^2}e^{(t-\xi)/\tau}\,d\xi\right) \tag{20}$$

The mean of any single-variable continuous function, $f(x)$, over a specific interval, $x = a$ to $x = b$, is given as the integral along that interval divided by the length of the interval.

$$f(x)_{mean} = \overline{f(x)} = \frac{1}{b-a}\int_{a}^{b} f(\xi)d\xi \tag{21}$$

The mean of an unknown pressure wave, $p(t)$, can be found by (22), where the interval length is t.

$$p(t)_{mean} = \overline{p(t)} = \frac{1}{t}\int_{0}^{t} p(\xi)d\xi \tag{22}$$

The mean-square of $p(t)$ is derived from (23) and is measured as the integral of the function squared.

$$p(t)_{mean-square} = \overline{p^2(t)} = \frac{1}{t}\int_0^t p^2(\xi)d\xi \tag{23}$$

The root-mean-square of $p(t)$, also called the *quadratic mean*, is a statistical measure of the magnitude of a varying quantity. It is given as the square root of the mean-square, from (23).

$$p(t)_{root-mean-square} = \sqrt{\overline{p^2(t)}} = \sqrt{\frac{1}{t}\int_0^t p^2(\xi)d\xi} \tag{24}$$

The exponential-root-mean-square incorporates a first-order filter, $e^{-t/\tau}$, to the root-mean-square, where the value inside the interval, $p^2(\xi)$, decreases with respect to the time constant, τ.

$$p(t)_{exp.-root-mean-square} = \sqrt{\frac{1}{t}\int_{-\infty}^{t} p^2(\xi)e^{(\xi-t)/\tau}d\xi} \tag{25}$$

The argument in the exponential filter is given as the difference between the dummy integrating factor and the current time. This changes the bounds of the integral from zero to t, to negative infinity to t to encompass the limits of the filter. The filter yields a value of zero for negative infinity and a value of one for t. Its exact value is a function of the time constant, τ, as defined in ANSI S1.4-1983 and explained in Appendix A.

The exponential-root-mean-square, in deciBels, is given as logarithmic function of the ratio between the current measured acoustic pressure and the low threshold of human hearing, p_{ref}. The logarithmic function is multiplied by 10 as a conversion from the units of bels to deciBels. The coefficient is 10 rather than 20, as shown in (4), because the argument in the integral is the squared ratio of acoustic pressure levels.

$$p(t)_{exp.-root-mean-square}[dB] = 10\log\left(\frac{1}{\tau}\int_{-\infty}^{t}\frac{p^2(\xi)}{p_{ref}^2}e^{(t-\xi)/\tau}\,d\xi\right) \tag{26}$$

The ANSI S1.4-1983 standard uses (20), which is equal to (26) with different labeling, as the basis for a mathematical model to measure sound pressure levels.

Appendix C:
Circuit Schematic and PC Board Layout

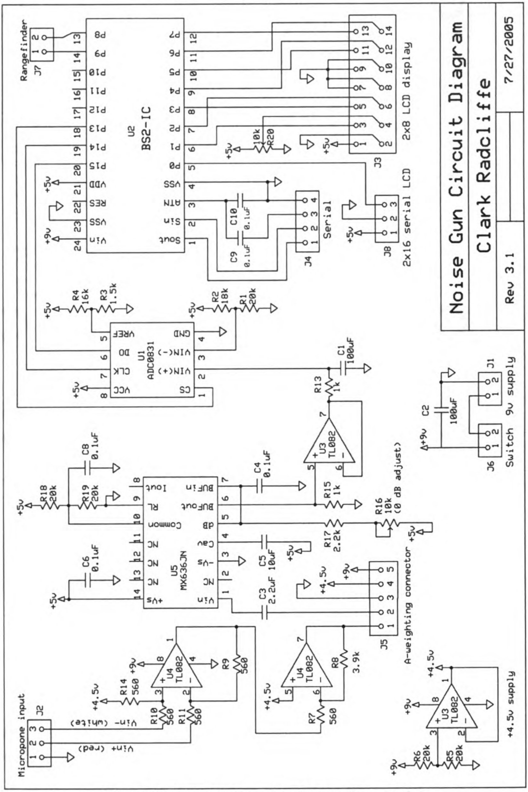

Figure 22: Circuit Schematic of Noise Gun, rev. 3.1

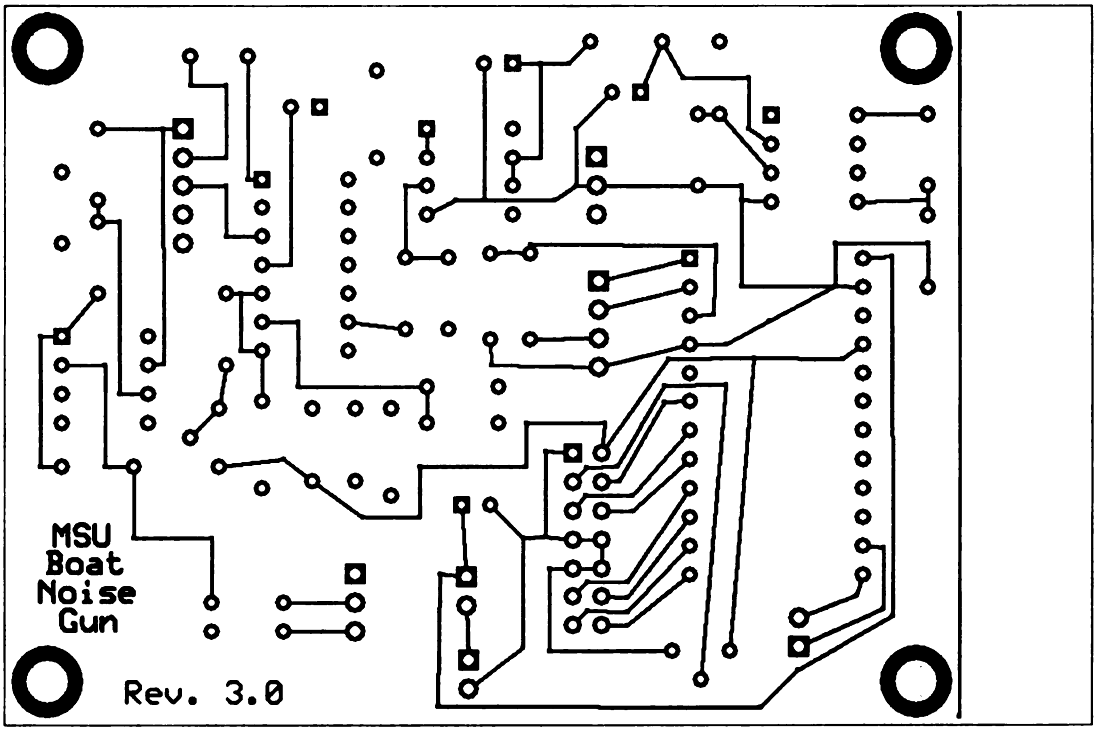

Figure 23: PC Board Layout (Top View)

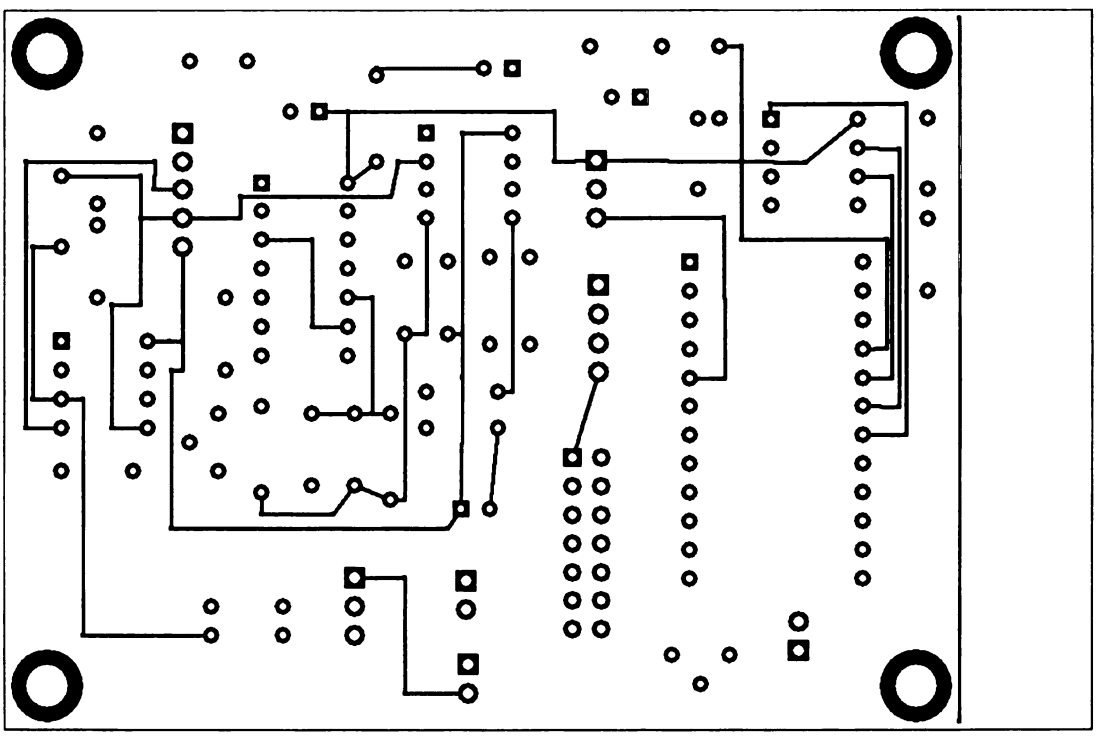

Figure 24: PC Board Layout (Bottom View)

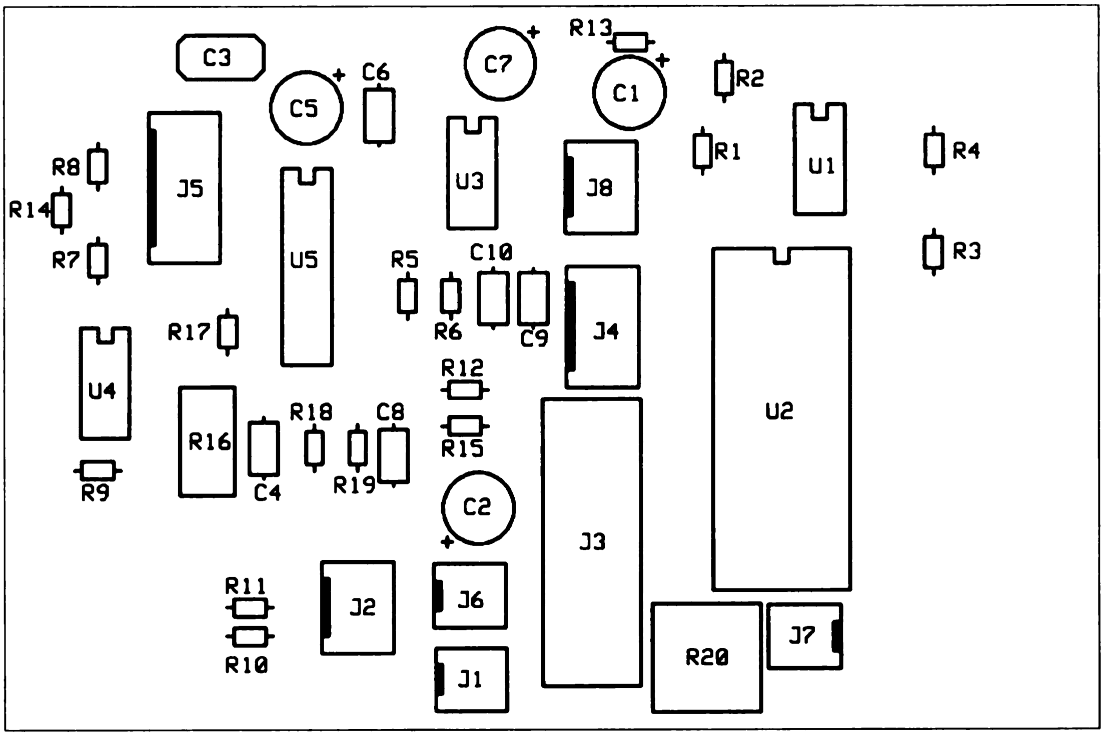

Figure 25: PC Board Layout (Component Placement View)

Appendix D:
Basic Stamp Program

```
'File: NoiseGun_CPM_1June2006.bs2
'{$STAMP BS2}   This Program is for the BS2 microprocessor
'{$PBASIC 2.5}  To be complied with PBASIC 2.5
'
'This file is based on "build4.bs2" code by Sean Vidanage, modified by
' Clark Radcliffe for the NoiseGun PCB version 3 (6-18-06),
' "NoiseGun_CJR_12July2005.bs2"


'========================================================================
'THE 2x8 PARALLEL LCD (PART DMC50448N) CONNECTIONS SHOWN BELOW
'  LCD pin  Signal  BS2 pin
'    1       0V      Vss
'    2       5V      Vdd
'    3       0-5V    ---     (Contrast control 0-5V from pot.)
'    4       RS      P1      (L = instruction, H = data)
'    5       R/W     P2      (L = write data, H = read data)
'    6       E       P3      (Enable signal)
'    7       DB0     Vss     (Data pin grounded, unused for 4 bit data)
'    8       DB1     Vss     (Data pin grounded, unused for 4 bit data)
'    9       DB2     Vss     (Data pin grounded, unused for 4 bit data)
'   10       DB3     Vss     (Data pin grounded, unused for 4 bit data)
'   11       DB4     P4      (Data bit, set by BS2 byte B)
'   12       DB5     P5      (Data bit, set by BS2 byte B)
'   13       DB6     P6      (Data bit, set by BS2 byte B)
'   14       DB7     P7      (Data bit, set by BS2 byte B)


'========================================================================
'DEFINITIONS/INITIALIZATION, BASIC STAMP PINS
'
'2x16 character serial LCD
LCD216          PIN     0               'Serial I/O pin to 2x16 display
'
'2x8 character parallel LCD
E               PIN     3               'LCD enable (1 = enabled)
RW              PIN     2               'Read/write
RS              PIN     1               'Reg select (1 = char)
LcdDirs         VAR     DIRB            'Dirs for I/O redirection
LcdBusOut       VAR     OUTB            'I/O byte B is pins P4-P7
LcdBusIn        VAR     INB
'
'Rangefinder
Rangefinder     CON     8
RangefinderL    CON     9
'
'A/D converter
AD_CS           PIN     13
AD_CLK          PIN     14
AD_D0           PIN     15
```

```
'---------------------------------------------------------------------
'DEFINITIONS/INITIALIZATION, CONSTANTS
'
'2x8 Character LCD display codes
LcdCls          CON     $01             'Clear the LCD
LcdHome         CON     $02             'Move cursor home
LcdCrsrL        CON     $10             'Move cursor left
LcdCrsrR        CON     $14             'Move cursor right
LcdDispL        CON     $18             'Shift characters left
LcdDispR        CON     $1C             'Shift characters right
LcdDDRam        CON     $80             'Display data RAM control
LcdCGRam        CON     $40             'Character generator RAM
LcdLine1        CON     $80             'DDRAM address of line 1
LcdLine2        CON     $C0             'DDRAM address of line 2
LcdScrollTm     CON     250             'LCD scroll timing (ms)
'
'2x16 Character Serial LCD
baud4800        CON     16572
baud9600        CON     16468
LCD_Baud        CON     baud9600


'---------------------------------------------------------------------
'DEFINITIONS/INITIALIZATION, COMPUTATION
'
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/L the width of catagories of
                                        ' AD_16_Times
M               CON     16384           '65536/o  for the interpolation
                                        ' formula
Std_DIST        CON     250             'Standard pass-by measurement
                                        ' distance (max10)


'---------------------------------------------------------------------
'DEFINITIONS/INITIALIZATION, VARIABLES (26 bytes = 13 Words available)
'
'Calculation/Results variables (retained always)
Ambient_dB      VAR     Word            'Ambient SPL (dBx10)
Measured_dB     VAR     Word            'Measured SPL (dBx10)
Corrected_dB    VAR     Word            'Ambient corrected SPL (dBx10)
DIST            VAR     Word            'Distance to course (metersx10)
dB_at_25m       VAR     Word            'Distance corrected SPL (dBx10)
'
'Temporary storage, used as defined below
WA              VAR     Word            'Temporary value
WB              VAR     Word            'Temporary value
WC              VAR     Word            'Temporary value
WD              VAR     Word            'Temporary value
WE              VAR     Word            'Temporary value
WF              VAR     Word            'Temporary value
WG              VAR     Word            'Temporary value
```

```
WH              VAR     Word            'Temporary value
'
'2x8 character LCD variables
addr            VAR     WH              'Address pointer
crsrPos         VAR     WG.BYTE0        'Cursor position
char            VAR     WG.BYTE1        'Character sent to LCD
idx             VAR     WF.BYTE0        'Loop counter
scan            VAR     WF.BYTE1        'Loop counter
'
'Log calculation scratch variables (only used in log calculation)
x               VAR     WA              'Word for processing the number
xf              VAR     x.BIT15         'High bit of x, note alias
x2              VAR     WB              'For squaring the number
x2f             VAR     x2.BIT15        'High bit of x2, note alias
lgx             VAR     WC              'Word will be the lg (base 2)
                                        ' of y, the mantissa
lgx0            VAR     lgx.BIT0        'Lowest bit of lgx, for bit
                                        ' addressing
lg              VAR     WD              'To hold the log base 2
lg0             VAR     lg.BYTE0        'For table lookup, array of
                                        ' bytes
k               VAR     idx.NIB0        'Loop and array index
cc              VAR     idx.NIB1        'Characteristic of the log
bitk            VAR     WE.BIT0         'Temporary bit)


'-----------------------------------------------------------------------
'DEFINITIONS/INITIALIZATION, EEPROM DATA
'
Msg1            DATA    "Startup!", 0
Msg2            DATA    " Ready! ", 0
Msg3            DATA    "Amb:", 0
Msg4            DATA    "Dst:", 0
Msg5            DATA    "dBA:", 0
Msg6            DATA    "Amb-SP ", 0
Msg7            DATA    " Error  ", 0
```

```
'=========================================================================
'PROGRAM CODE
'
'Initialization Protocol. Wait for startup fluctuations to settle.
' Then build ambient sound level. Then proceed to operation mode.
    LOW RangefinderL                    'Turn on rangefinder I/O
    GOSUB Startup_LCD28                 'Initialize the 2x8 LCD display
    GOSUB Startup_LCD216                'Write to 2x16 LCD to indicate
                                        ' machine is starting up
    PAUSE 4000                          'Pause 4 seconds for electrons
                                        ' to settle...
'Measure ambient sound pressure level SPL (dBA)
    GOSUB AD_Conversion
    Ambient_dB = Measured_dB
    Corrected_dB = Ambient_dB
    DEBUG CR, "Ambient Measured_dB: "
    DEBUG DEC Ambient_dB/10, ".", DEC1 Ambient_dB//10
    Ambient_dB = Measured_dB
    SEROUT LCD216, LCD_Baud,[254,1]     'Clear 2x16 LCD screen
    GOSUB Ambient_LCD28                 'Display ambient on 2x8 LCD
                                        ' screen
WAIT_button:                            'Wait for rangefinder button
                                        ' push
  SERIN Rangefinder,baud4800,500,WAIT_button,[WAIT(",0"),DEC WA,DEC WB]
    DIST = (WA*10 + WB)
    WA = DIST                           'Store current distance for
                                        ' output below
'At this point, we have the 1st distance, so loop and display it.
Loop_Start:
    DEBUG CR, "Current Distance=", DEC WA/10, ".", DEC WA//10
    DEBUG "   Min(distance)=", DEC DIST/10, ".", DEC DIST//10
'Write distance to line 2 of 2x8 LCD screen
'Input: DIST (word)
'Position is 2x8 LCD line #2
    char = LcdLine2                     'Get position on LCD
    GOSUB LCD28_Command                 'Set position on LCD
    addr = Msg4
    GOSUB LCD28_Put_String
    char = LcdLine2 + 4                 'Now write 4 char value to LCD
                                        ' after "DST:"  (value is in
                                        ' WA)
    GOSUB LCD28_Write_Val
GetSound:                               'Measure SPL
    GOSUB AD_Conversion                 'Get Measured_dB
'Find maxiumum(Measured_dB) and store in Corrected_dB
    IF Measured_dB > Corrected_dB THEN Corrected_dB = Measured_dB
'Display Measured_dB
    DEBUG CR,"Measured_dB:",DEC Measured_dB/10, ".",DEC Measured_dB//10
   DEBUG "  Corrected_dB:",DEC Corrected_dB/10,".",DEC Corrected_dB//10
'Write Measured_dB to line 1 of 2x8 LCD screen
'Input: Measured_dB (word)
'Position is 2x8 LCD line #1
    char = LcdLine1                     'Get position on LCD
    GOSUB LCD28_Command                 'Set position on LCD
    addr = Msg5
    GOSUB LCD28_Put_String
    WA = Measured_dB
```

```
    char = LcdLine1 + 4                    'Now write 4 char value to LCD
                                           ' after "dBA:"
    GOSUB LCD28_Write_Val
'Now get distance, use "timeout" to end loop...
   SERIN Rangefinder,baud4800,500,Correct_dB,[WAIT(",0"),DEC WA,DEC WB]
    WA =  (WA*10 + WB)
    IF WA < DIST THEN DIST = WA            'Store minimum (distance) in
                                           ' "DIST"
    GOTO Loop_Start                        'Start again
Correct_dB:                                'End of loop, correct data
    GOSUB Ambient_dB_Correction            'correct for Ambient level
    GOSUB DIST_Correction                  'Correct for distance
Display_Data_Summary:
    GOSUB LCD216_Display2                  'Print data Summary of 2x16 LCD
    PAUSE 3000                             'Wait a few seconds to make
                                           ' sure laser button is not
                                           ' pressed
    Corrected_dB = Ambient_dB              'Reset constants
    Measured_dB = 0
    GOTO Wait_Button                       'Return to wait for trigger
                                           ' press to start measurement
                                           ' again


'======================================================================
'SUBROUTINE, 2x16 LCD display
'
Startup_LCD216:
    SEROUT LCD216,baud9600,[254,1]         'Clear screen
    PAUSE 20
    SEROUT LCD216, baud9600, ["Initializing"]
    PAUSE 20
RETURN
```

```
'=======================================================================
'SUBROUTINE, 2x16 LCD display
'
'Display Data Summary on 2x16LCD
'Dst:xx.xSPL:xx.x
'Amb:xx.x25m:xx.x
LCD216_Display2:
    SEROUT LCD216, LCD_Baud,[254,1]     'Clear screen
    PAUSE 20
    SEROUT LCD216, LCD_Baud,["Dst:",DEC DIST/10,".",DEC DIST//10]
    PAUSE 20
    SEROUT LCD216, LCD_Baud,["SPL:",DEC Measured_dB/10,".",DEC
Measured_dB//10]
    PAUSE 20
    SEROUT LCD216, LCD_Baud,[$FE, $80+$40+(0)]
    PAUSE 20
    SEROUT LCD216, LCD_Baud,["Amb:",DEC Ambient_dB/10,".",DEC
Ambient_dB//10]
    PAUSE 20
    SEROUT LCD216, LCD_Baud,["Cor:",DEC Corrected_dB/10,".",DEC
Corrected_dB//10]
    PAUSE 20
RETURN


'=======================================================================
'SUBROUTINE, 2x8 LCD screen
'
'Initializes 2x8 LCD screen, writes stored (in DATA statement) zero-
' terminated string to LCD
' -- position LCD cursor
' -- point to zero-terminated string (first location in 'addr')
Startup_LCD28:
    DIRL = %11111110                    'Setup pins for LCD
    LcdBusOut = %0011                   '8-bit mode
    PULSOUT E, 3 : PAUSE 5              '3 => 3*2 usec = 6 usec & 5 = 5
                                        ' msec
    PULSOUT E, 3 : PAUSE 0
    PULSOUT E, 3 : PAUSE 0
    LcdBusOut = %0010                   '4-bit mode
    PULSOUT E, 3
    char = %00101000                    '2-line mode
    GOSUB LCD28_Command
    char = %00001100                    'On, no cursor, no blink
    GOSUB LCD28_Command
    char = %00000110                    'Increase cursor, no
                                        ' displacement shift
    GOSUB LCD28_Command
'Write "Startup" message on 2x8 LCD screen
    char=LCDcls
    GOSUB LCD28_Command
    char=LcdLine2
    GOSUB LCD28_Command
    addr=msg1
    GOSUB LCD28_Put_String
RETURN
```

```
'===========================================================================
'SUBROUTINE, 2x8 LCD screen
'
'Write ambient level on 2x8 LCD screen
'Input: Ambient_dB (word)
'Position is 2x8 LCD line #1
Ambient_LCD28:                          'Write "Amb:    " to first line
                                        ' on 2x8 LCD screen
    char = LcdLine1                     'Get position on LCD
    GOSUB LCD28_Command                 'Set position on LCD
    addr = Msg3
    GOSUB LCD28_Put_String
    WA = Ambient_dB                     'Now write 4 char value to LCD
                                        ' after "Amb:"
    char = LcdLine1 + 4
    GOSUB LCD28_Write_Val
    char = LcdLine2                     'Now write " Ready!" on 1st
                                        ' line
    GOSUB LCD28_Command
    addr = Msg2                         'Point to message
    GOSUB LCD28_Put_String              'Write it
RETURN


'===========================================================================
'SUBROUTINE, 2x8 LCD screen
'
'Write a zero-terminated string stored in EPROM DATA to 2x8 LCD at
' current cursor position
' Input: "addr" address of string
LCD28_Put_String:
    DO
         READ addr, char
         IF (char = 0) THEN EXIT
         GOSUB LCD28_Write_Char
         addr = addr + 1
    LOOP
RETURN


'===========================================================================
'SUBROUTINE, 2x8 LCD screen
'
'Send command to LCD
' -- put command byte in 'char'
LCD28_Command:                          'Write command to LCD
    LOW RS
    GOTO LCD28_Write_Char
```

```
'==========================================================================
'SUBROUTINE, 2x8 LCD screen
'
'Write character to current cursor position then increment current
' cursor position
' -- but byte to write in 'char'
LCD28_Write_Char:                         'Write character to LCD
    LcdBusOut = char.HIGHNIB              'Output high nibble
    PULSOUT E, 3                          'Strobe the enable line
    LcdBusOut = char.LOWNIB               'Output low nibble
    PULSOUT E, 3
    HIGH RS                               'Return to character mode
RETURN



'==========================================================================
'SUBROUTINE, 2x8 LCD screen
'
'Write a single character "0-9" to current cursor position
'ASCII "0" = 48
LCD28_Write_Digit:
    char = char + 48
    GOSUB LCD28_Write_Char
RETURN



'==========================================================================
'SUBROUTINE, 2x8 LCD screen
'
'Write a 4 digit value "WA" as string to EPROM starting at "char"
' char = byte address of MSB digit in 2x8 LCD screen memory
' Note: the ACSII value of the charcter "0" is 48
' 4 digit value has decimal point between 10's and 1's digit
LCD28_Write_Val:
    GOSUB LCD28_Command                   'Send address of 1st character
    char = WA/1000                        'Get 1000's digit
    IF char = 0 THEN                      'Scaled value is less than 999,
                                          ' so print as XX.X ignore
                                          ' 1000's digit
         WB = WA//1000                    'Get remander
         char = WB/100                    'Get value of 100's digit
         GOSUB LCD28_Write_Digit          'Write it to 2x8 LCD
         WB = WB//100                     'Get remainder
         char = WB/10                     'Get value of 10's digit
         GOSUB LCD28_Write_Digit          'Write it to 2x8 LCD
         char = "."                       'Decimal point
         GOSUB LCD28_Write_Char           'Write it to 2x8 LCD
         char = WB//10                    'Get value of 1's digit
         GOSUB LCD28_Write_Digit          'Write it to 2x8 LCD
    ELSE                                  'Scaled value is 1000 or more,
                                          ' print as XXX. (round 10's
                                          '  digit)
         GOSUB LCD28_Write_Digit          'Write 1000's digit to 2x8 LCD
         WB = WA//1000                    'Get remander
         char = WB/100                    'Get value of 100's digit
```

```
        GOSUB LCD28_Write_Digit         'Write it to 2x8 LCD
        WB = WB//100                    'Get remainder
        char = WB/10                    'Get value of 10's digit
        WB = WB//10                     'Get value of 1's digit
        WB = (WB + 5)/10                'Round it off
        char= char + WB                 'Add round-off to 10's digit
        GOSUB LCD28_Write_Digit         'Write it to 2x8 LCD
        char = "."                      'Decimal point
        GOSUB LCD28_Write_Char          'Write it to 2x8 LCD
    ENDIF
RETURN


'=======================================================================
'SUBROUTINE, A/D Converter with filter code
'
'Returns 10 bit value in "A"
AD_Conversion:
    WA = 0                              'Reset accumulator
    FOR idx = 1 TO 4
        GOSUB AD_GetData                'Get 8 bit data value into "B"
                                        ' (0-255)
        WA = WA + WB                    'Accumulate in "A" to yield 12
                                        ' bit value (0-1020)
    NEXT
    Measured_dB = 1020 - WA             'A/D decreases with increasing
                                        ' SPL, invert scale here
    DEBUG CLS, "Measured_dB=", DEC Measured_dB
RETURN


'=======================================================================
'SUBROUTINE, A/D Converter with filter code
'
AD_GetData:
    LOW AD_CS                           'Select A/D chip
    LOW AD_CLK                          'Initialize clock pin
    PULSOUT AD_CLK,10                   'Pulse clock to start A/D
                                        ' conversion
    SHIFTIN AD_D0,AD_CLK,MSBPOST,[WB\8] 'Get A/D data into "WB" with
                                        ' syncronous serial protocol
    HIGH AD_CS                          'Deselect A/D chip
RETURN
```

```
'=======================================================================
'SUBROUTINE, A/D Converter with filter code
'
'The ambient noise Db correction subroutine finds the appropriate
' ambient noise correction based on the difference between the
' measurement SPL (dBA) and  the ambient background SPL.  This
' correction is then used to reduce the measured SPL (dB) and compute a
' corrected SPL (dB).  The correction is approximate BUT always equals
' the exact correction for the minimum difference in each case.  The
' values can be computed with
'
'            correction = -20*log10( 1-10^(difference/20))
'
' where difference = ambient - measured (dB)
Ambient_dB_Correction:
    Measured_dB = Corrected_dB          'Store max SPL
    SELECT (Measured_dB - Ambient_dB)   'Correct max SPL for ambient
         CASE < 59                      'Measured < ambient + 6dB
              Corrected_dB = 0          'Error
              char = LcdLine1           'Print "Amb:" on 2x8 LCD line 1
              GOSUB LCD28_Command       'Set position on LCD
              addr = Msg6
              GOSUB LCD28_Put_String
              char = LcdLine2           'Print "Error" on 2x8 LCD line2
              GOSUB LCD28_Command       'Set position on LCD
              addr = Msg7
              GOSUB LCD28_Put_String
              Measured_dB = Corrected_dB'Retrieve max(Measured_dB)
              Corrected_dB = 0          'Zero Corrected_dB since there
                                        ' is an ambient error
              DEBUG CR, "Ambient Level Error"
         CASE 60 TO 79                  'Measured 6-8 dB above ambient
              Corrected_dB = Corrected_dB - 60         'Subtract 6.0 dB
         CASE 80 TO 99                  'Measured 8-9.9 dB above
                                        ' ambient
              Corrected_dB = Corrected_dB - 44         'Subtract 4.4 dB
         CASE 100 TO 120                'Measured 10-12 dB above
                                        ' ambient
              Corrected_dB = Corrected_dB - 33         'Subtract 3.3 dB
         CASE 121 TO 150                'Measured 12.1-15.0 dB above
                                        ' ambient
              Corrected_dB = Corrected_dB - 25         'Subtract 2.5 dB
         CASE 151 TO 210                'Measured 15.1-21.0 dB above
                                        ' ambient
              Corrected_dB = Corrected_dB - 17         'Subtract 1.7 dB
         CASE 211 TO 250                'Measured 21.1-25.0 dB above
                                        ' ambient
              Corrected_dB = Corrected_dB - 8          'Subtract 0.8 dB
         CASE 251 TO 293                'Measured 25.1-29.3 dB above
                                        ' ambient
              Corrected_dB = Corrected_dB - 5          'Subtract 0.5 dB
         CASE 294 TO 387                'Measured 29.4-38.7 dB above
                                        ' ambient
              Corrected_dB = Corrected_dB - 3          'Subtract 0.3 dB
         CASE 388 TO 449                'Measured 33.8-44.9 dB above
                                        ' ambient
              Corrected_dB = Corrected_dB - 1          'Subtract 0.1 dB
```

```
        CASE 450 TO 1023              'Measured more than 45.0 dB
                                      ' above ambient
             Corrected_dB = Corrected_dB            ' No Correction
    ENDSELECT
RETURN


'=======================================================================
'SUBROUTINE, A/D Converter with filter code
'
'Enter with DIST defined as measured distance to course (meters x 10
' = dm) dB_at_obs defined as measured dB at observer position
' dB_at_obs is in units of 10*dB = Bels (80.1 dB => 801 Bel)
'Correction: Add 4 dB/doubling for distances more than 250 dm subtract
' 6 dB/doubling for distances less than 250 dm
DIST_Correction:
    GOSUB Log_DIST                    'lg = log2(DIST)
'   DEBUG CR, "lg =", DEC lg          'note: Log2(250) = 7.96 => 796
                                      ' here (Log2*100)
    SELECT (DIST)
        CASE < 250                    'Measurement at less than 25 m
             WA = (796 - lg)*6/10     'Correction is negative 6
                                      ' dB/doubling
             Corrected_dB = Corrected_dB - WA      '6 dB per doubling
                                      ' subtracted
        CASE = 250
             Corrected_dB = Corrected_dB
        CASE > 250                     'Correction is positive for
                                       ' distance > 25m
             Corrected_dB = (lg - 796)*4/10 + Corrected_dB   '4 dB per
                                       ' doubling added
    ENDSELECT
RETURN
```

```
'========================================================================
'SUBROUTINE, A/D Converter with filter code
'
'Log base 2 of distance calculation.  Measurement DIST is in dm
' (decimeters).  Log calculation is for integers.  Algorithm from Sean
' Vidanage's code.
'note: log2(250) = 7.96 => 796 here  (Log2*100)
' dB_at_obs is in units of 10*dB = Bels (80.1 dB => 801 Bel)
Log_DIST:
    cc = NCD (DIST) - 1                     'Find the characteristic
    x = (DIST) << (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*100 + (lgx**2000/10)            'log2(DIST) base 2
RETURN
```

Appendix E:
Field Data

Test Number: **1**

Hull Identification: MC4728SJ

Boat Operator: (not recorded)

Date: 7-19-2005

Location: Higgins Lake, MI

Comments: This data set is NOT used in the analysis due to the different device calibration between this data set and the Torch Lake data sets.

Table 4: Test #1 Noise Gun Readout

Trial #	Boat Side	Minimum Distance Measured (m)	Maximum SPL Measured (dBA)	Measured Background Noise SPL (dBA)	Corrected SPL (dBA)
1	Port	52.6	78.1	52.7	81.8
2	Star.	53.4	75.8	52.7	79.4
3	Port	51.4	80.6	52.7	84.2
4	Star.	53.7	78.6	52.7	82.5
5	Port	26.1	82.9	52.7	82.8
6	Star.	27.0	80.5	52.7	80.7
7	Port	27.5	83.0	52.7	83.2
8	Star.	27.1	81.4	52.7	81.3
9	Port	26.5	67.6	52.7	65.4
10	Star.	27.5	81.1	52.7	81.1
11	Port	16.4	80.9	52.7	76.8
12	Star.	28.4	66.0	52.7	64.2
13	Port	15.4	83.1	52.7	78.6
14	Star.	15.1	81.6	52.7	76.8
15	Port	15.4	71.8	52.7	65.9
16	Star.	15.2	81.2	52.7	76.4
17	Port	14.9	70.7	52.7	65.7
18	Star.	14.8	70.7	52.7	65.7

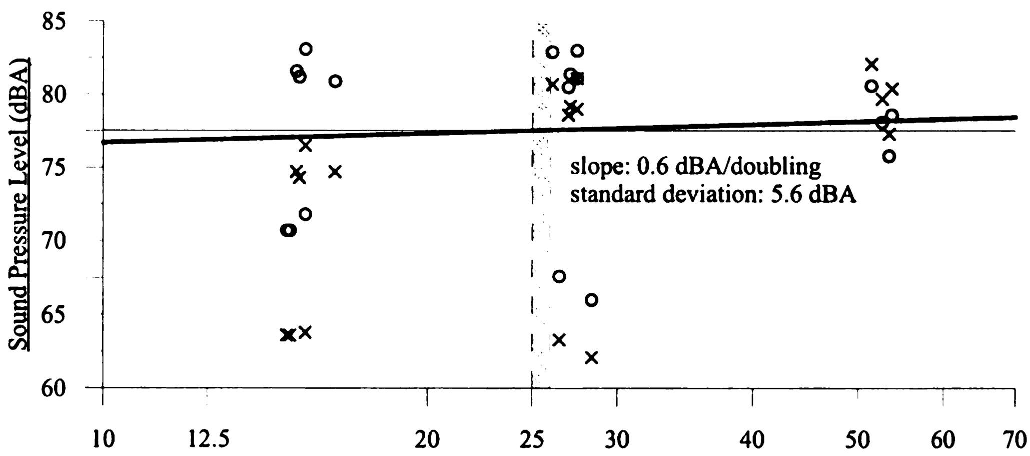

Figure 26: Test #1 Field Data, Measured SPLs (○) and Standard Deviation- and Error Compensated-Corrected (×) SPLs and Predicted SAE J34 SPL (—) with Respect to the Measured SPLs Best-fit Logarithmic Regression Line (▬)

Test Number: **2**

Hull Identification: MC8487SV

Boat Operator: (not recorded)

Date: 7-19-2005

Location: Higgins Lake, MI

Comments: This data set is **NOT** used in the analysis due to the different device calibration between this data set and the Torch Lake data sets.

Table 5: Test #2 Noise Gun Readout

Trial #	Boat Side	Minimum Distance Measured (m)	Maximum SPL Measured (dBA)	Measured Background Noise SPL (dBA)	Corrected SPL (dBA)
1	Port	30.6	67.5	51.3	66.9
2	Star.	27.6	66.6	51.3	65.4
3	Port	29.0	65.9	51.3	64.2
4	Star.	20.3	68.2	51.3	64.7
5	Port	15.7	70.2	51.3	64.5
6	Star.	15.5	70.2	51.3	64.4
7	Port	14.6	69.9	51.3	63.6
8	Star.	15.1	69.9	51.3	63.9
9	Port	50.9	61.8	51.3	62.6
10	Star.	51.8	62.0	51.3	62.9
11	Port	51.3	60.4	51.3	60.1
12	Star.	52.1	61.9	51.3	62.8
13	Port	51.7	60.1	51.3	59.9
14	Star.	51.5	62.2	51.3	63.0

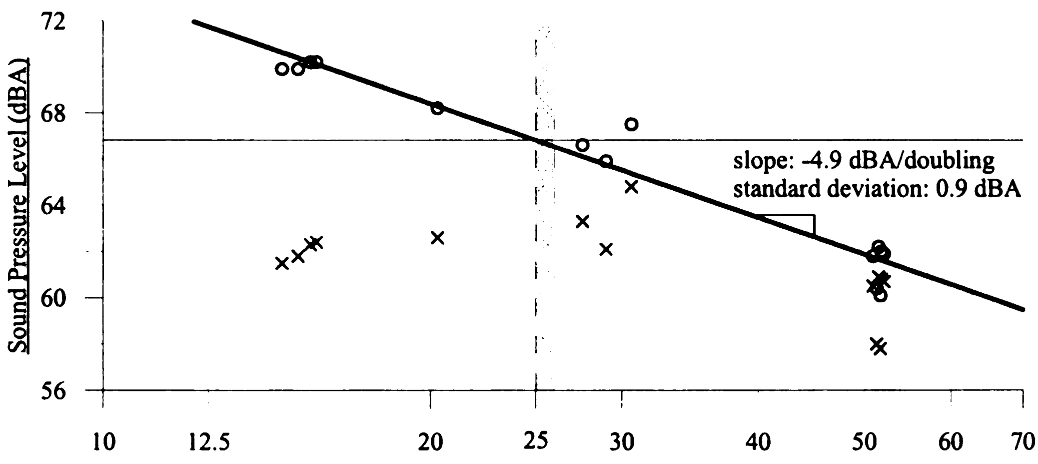

Figure 27: Test #2 Field Data, Measured SPLs (○) and Standard Deviation- and Error Compensated-Corrected (×) SPLs and Predicted SAE J34 SPL (—) with Respect to the Measured SPLs Best-fit Logarithmic Regression Line (▬)

Test Number: **3**

Hull Identification: MC4387PE

Boat Operator: (not recorded)

Date: 7-19-2005

Location: Higgins Lake, MI

Comments: **This data set is NOT used in the analysis due to the different device calibration between this data set and the Torch Lake data sets.**

Table 6: Test #3 Noise Gun Readout

Trial #	Boat Side	Minimum Distance Measured (m)	Maximum SPL Measured (dBA)	Measured Background Noise SPL (dBA)	Corrected SPL (dBA)
1	Port	50.9	58.8	51.3	56.9
2	Star.	50.3	62.5	51.3	63.2
3	Port	24.8	66.5	51.3	64.8
4	Star.	26.9	65.7	51.3	63.6
5	Port	12.9	71.2	51.3	63.8
6	Star.	12.1	71.2	51.3	63.2
7	Port	50.3	60.7	51.3	60.3
8	Star.	50.1	61.9	51.3	62.6
9	Port	25.2	67.1	51.3	65.4
10	Star.	26.8	65.5	51.3	63.4
11	Port	12.6	71.2	51.3	63.6
12	Star.	14.2	69.8	51.3	63.2

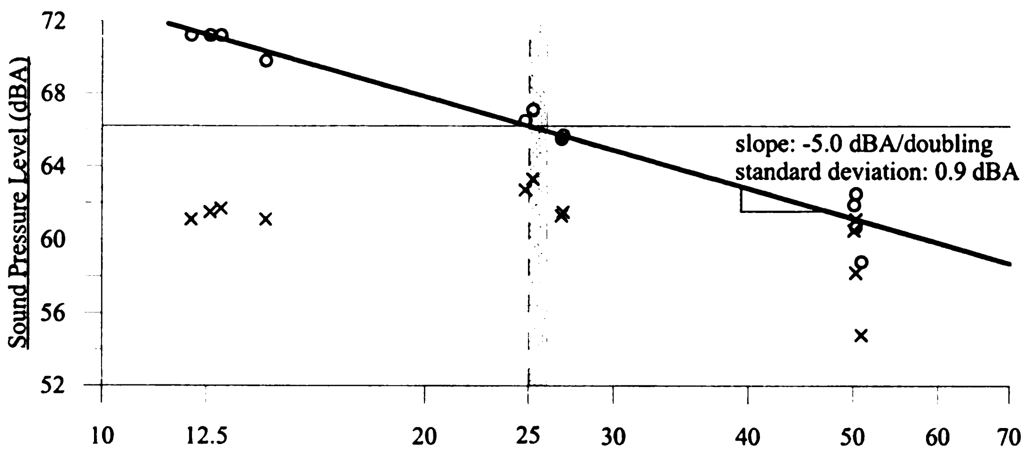

Figure 28: Test #3 Field Data, Measured SPLs (○) and Standard Deviation- and Error Compensated-Corrected (×) SPLs and Predicted SAE J34 SPL (—) with Respect to the Measured SPLs Best-fit Logarithmic Regression Line (▬)

Test Number: **4**

Hull Identification: MC3706PB

Boat Operator: Tim Tilley

Date: 9-10-2005

Location: Torch Lake, MI

Comments: Antrim County Sheriff's Department Boat; Twin 150HP Evinrude 2 stroke

Table 7: Test #4 Noise Gun Readout

Trial #	Boat Side	Minimum Distance Measured (m)	Maximum SPL Measured (dBA)	Measured Background Noise SPL (dBA)	Corrected SPL (dBA)
1	Star.	17.6	80.4	32.6	77.4
2	Port	31.4	77.5	32.6	78.7
3	Port	14.7	82.9	32.6	78.3
4	Star.	56.5	71.6	32.6	76.2
5	Port	25.7	78.0	32.6	78.1
6	Star.	12.9	81.2	32.6	75.5
7	Star.	52.7	72.1	49.4	75.6
8	Port	52.6	71.1	32.6	75.0
9	Port	13.4	81.9	49.4	76.2
10	Star.	26.5	76.0	49.4	75.8
11	Port	51.1	70.3	49.4	72.7
12	Star.	26.7	75.5	49.4	75.4

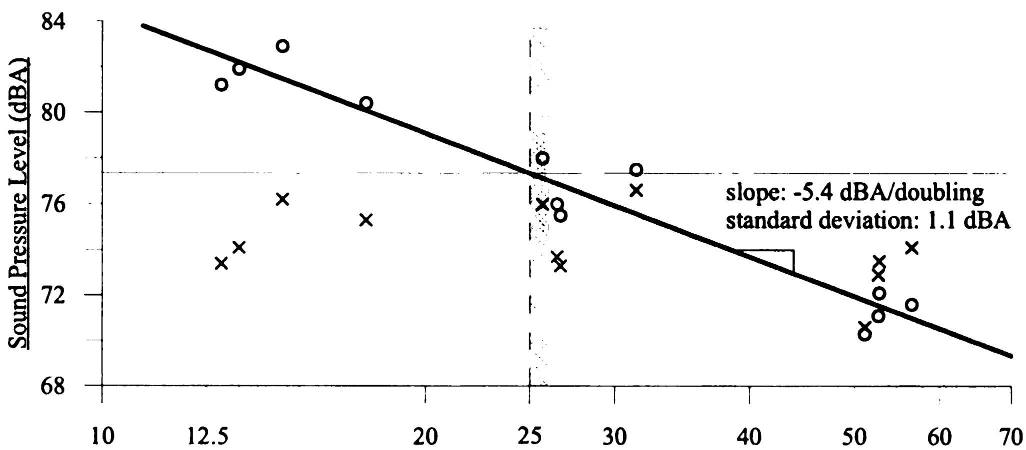

Figure 29: Test #4 Field Data, Measured SPLs (o) and Standard Deviation- and Error Compensated-Corrected (×) SPLs and Predicted SAE J34 SPL (—) with Respect to the Measured SPLs Best-fit Logarithmic Regression Line (**—**)

Test Number: **5**

Hull Identification: MC3457SN

Boat Operator: Bill Johnson

Date: 9-10-2005

Location: Torch Lake, MI

Comments: Yellow Catamaran dual hulls; 900HP, 4 stroke, V8 supercharge Teague, Gatling mufflers. This data set is **NOT** used because there weren't enough trials.

Table 8: Test #5 Noise Gun Readout

Trial #	Boat Side	Minimum Distance Measured (m)	Maximum SPL Measured (dBA)	Measured Background Noise SPL (dBA)	Corrected SPL (dBA)
1	Port	40.4	101	32.7	103
2	Port	46.5	98.0	32.7	101
3	Star.	65.3	97.4	32.7	102
4	Port	74.7	93.5	32.7	99.8
5	Star.	28.3	101	32.7	101
6	Port	44.7	92.6	32.7	95.9

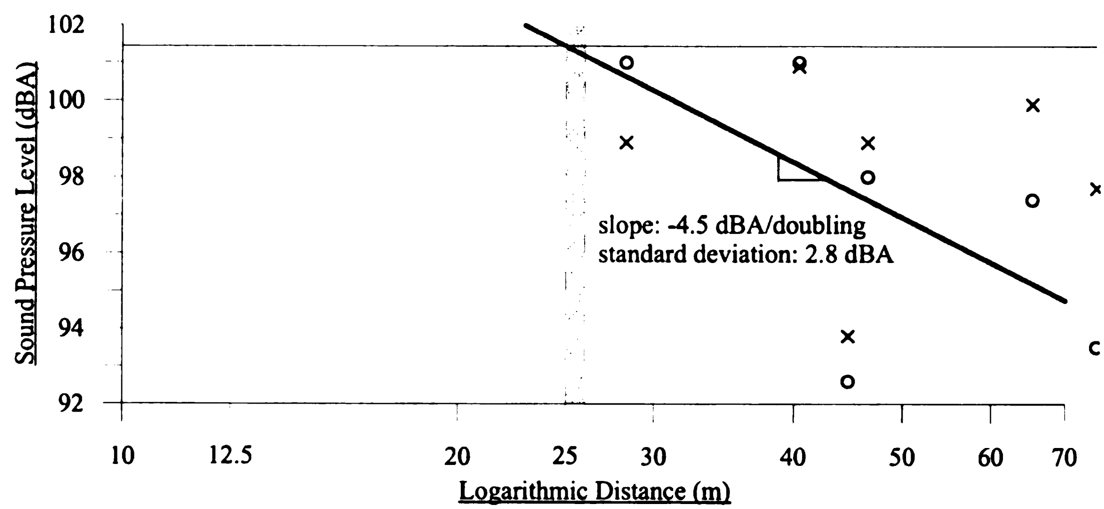

Figure 30: Test #5 Field Data, Measured SPLs (○) and Standard Deviation- and Error Compensated-Corrected (×) SPLs and Predicted SAE J34 SPL (—) with Respect to the Measured SPLs Best-fit Logarithmic Regression Line (▬)

Test Number: **6**

Hull Identification: MC3529PB

Boat Operator: Heather Wilson, sheriff's dept.

Date: 9-10-2005

Location: Torch Lake, MI

Comments: Antrim County Sheriff's Department Boat; 200 Mercury, 2 stroke, 21.5', DC Aquasport. This data set is **NOT** used because of possible wind effects.

Table 9: Test #6 Noise Gun Readout

Trial #	Boat Side	Minimum Distance Measured (m)	Maximum SPL Measured (dBA)	Measured Background Noise SPL (dBA)	Corrected SPL (dBA)
1	Port	14.6	72.8	44.2	67.7
2	Port	14.8	81.6	55.6	76.6
3	Star.	16.6	79.7	55.6	75.4
4	Port	15.5	81.6	55.6	77.0
5	Port	31.5	75.2	55.6	74.8
6	Star.	29.9	74.9	55.6	74.2
7	Star.	55.5	69.5	55.6	71.6
8	Port	53.1	67.2	55.6	68.2
9	Star.	53.0	69.4	55.6	71.2

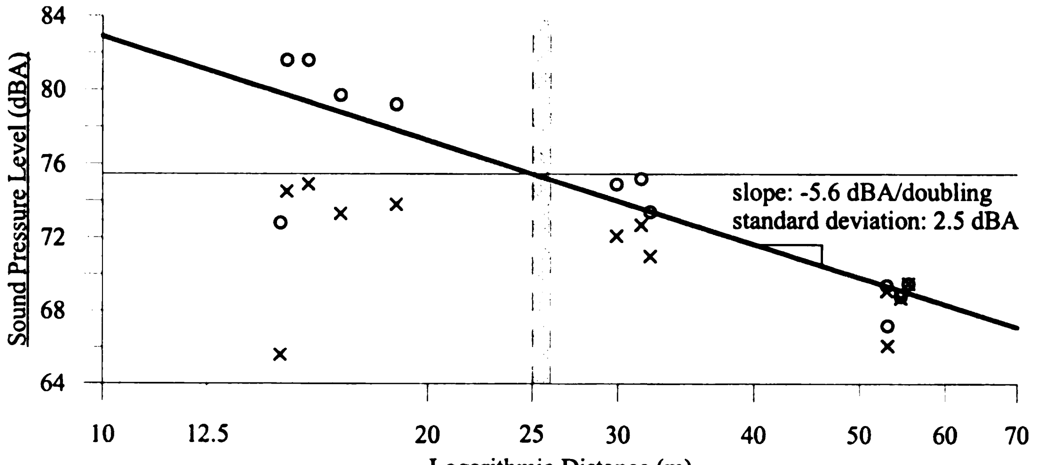

Figure 31: Test #6 Field Data, Measured SPLs (○) and Standard Deviation- and Error Compensated-Corrected (×) SPLs and Predicted SAE J34 SPL (—) with Respect to the Measured SPLs Best-fit Logarithmic Regression Line (▬)

Test Number: **7**

Hull Identification: MC3220RP

Boat Operator: Bill Johnson

Date: 9-10-2005

Location: Torch Lake, MI

Comments: 2 HB500 Birkhauser formula 350, 35.5', FASTech

Table 10: Test #7 Noise Gun Readout

Trial #	Boat Side	Minimum Distance Measured (m)	Maximum SPL Measured (dBA)	Measured Background Noise SPL (dBA)	Corrected SPL (dBA)
1	Port	13.4	88.0	42.1	82.6
2	Star.	14.3	88.2	42.1	83.4
3	Port	15.2	87.7	42.1	83.4
4	Star.	15.0	88.7	42.1	84.3
5	Port	30.1	84.7	42.1	85.6
6	Star.	29.3	84.8	42.1	85.6
7	Port	53.8	80.3	42.1	84.4
8	Star.	53.3	80.4	42.1	84.4
9	Port	53.2	81.0	42.1	85.2
10	Star.	53.8	80.8	42.1	84.9
11	Port	31.6	84.8	42.1	86.1
12	Star.	29.4	84.7	42.1	85.5

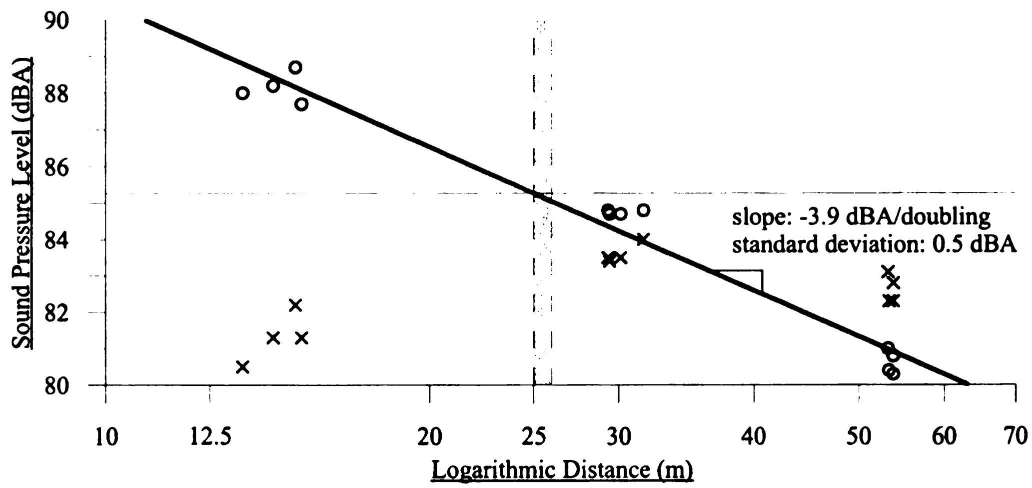

Figure 32: Test #7 Field Data, Measured SPLs (○) and Standard Deviation- and Error Compensated-Corrected (×) SPLs and Predicted SAE J34 SPL (—) with Respect to the Measured SPLs Best-fit Logarithmic Regression Line (▬)

Test Number: **8**

Hull Identification: MC1244SJ

Boat Operator: Mike Savara

Date: 9-10-2005

Location: Torch Lake, MI

Comments: 27' formula, twin 280HP, 350 cubic inch, out drive. This data set is **NOT** used because it was interrupted by a thunderstorm.

Table 11: Test #8 Noise Gun Readout

Trial #	Boat Side	Minimum Distance Measured (m)	Maximum SPL Measured (dBA)	Measured Background Noise SPL (dBA)	Corrected SPL (dBA)
1	Star.	14.9	77.4	34.4	72.8
2	Port	14.8	76.7	34.4	72.1
3	Star.	14.4	77.9	34.4	73.0
4	Port	14.4	78.2	34.4	73.3
5	Star.	27.8	73.0	34.4	73.3
6	Port	28.2	73.0	34.4	73.3

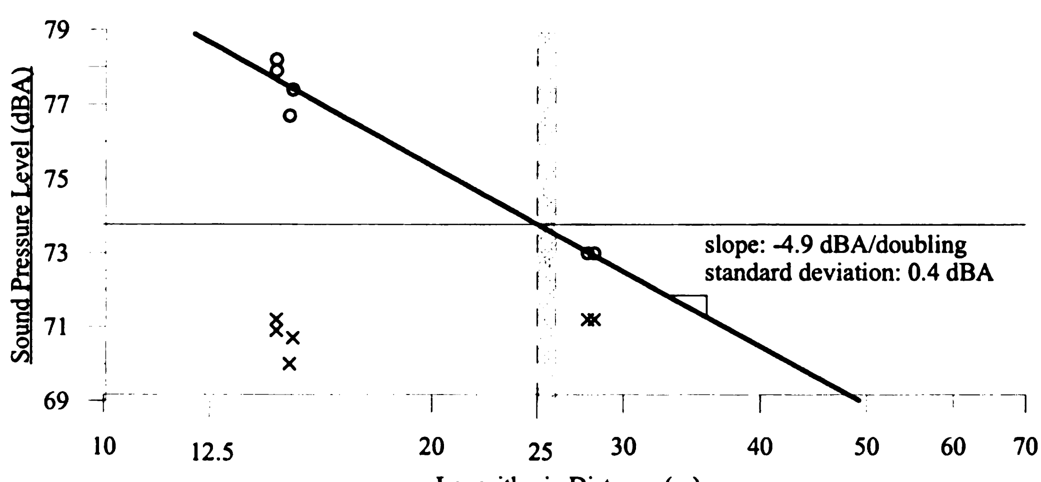

Figure 33: Test #8 Field Data, Measured SPLs (o) and Standard Deviation- and Error Compensated-Corrected (×) SPLs and Predicted SAE J34 SPL (—) with Respect to the Measured SPLs Best-fit Logarithmic Regression Line (▬)

Test Number: **9**

Hull Identification: MC6546ST

Boat Operator: Jeremy Howard

Date: 9-10-2005

Location: Torch Lake, MI

Comments: Unmodified 2005 Jetski, Yamaha VX110 Sport, 1100cc. This data set is **NOT** used because it is not considered a motorboat.

Table 12: Test #9 Noise Gun Readout

Trial #	Boat Side	Minimum Distance Measured (m)	Maximum SPL Measured (dBA)	Measured Background Noise SPL (dBA)	Corrected SPL (dBA)
1	Star.	9.9	83.6	48.6	75.3
2	Port	12.8	82.3	48.6	76.3
3	Star.	11.8	82.7	48.6	76.0
4	Port	11.1	82.8	48.6	75.5
5	Star.	24.2	77.5	48.6	76.7
6	Port	24.0	77.5	48.6	76.7
7	Star.	24.6	80.1	48.6	79.7
8	Port	24.6	77.7	48.6	77.1
9	Star.	50.8	69.6	48.6	71.9
10	Port	49.4	68.6	48.6	70.8
11	Star.	49.3	70.1	48.6	73.2
12	Port	49.1	69.3	48.6	71.4
13	Star.	11.8	82.5	48.6	75.8

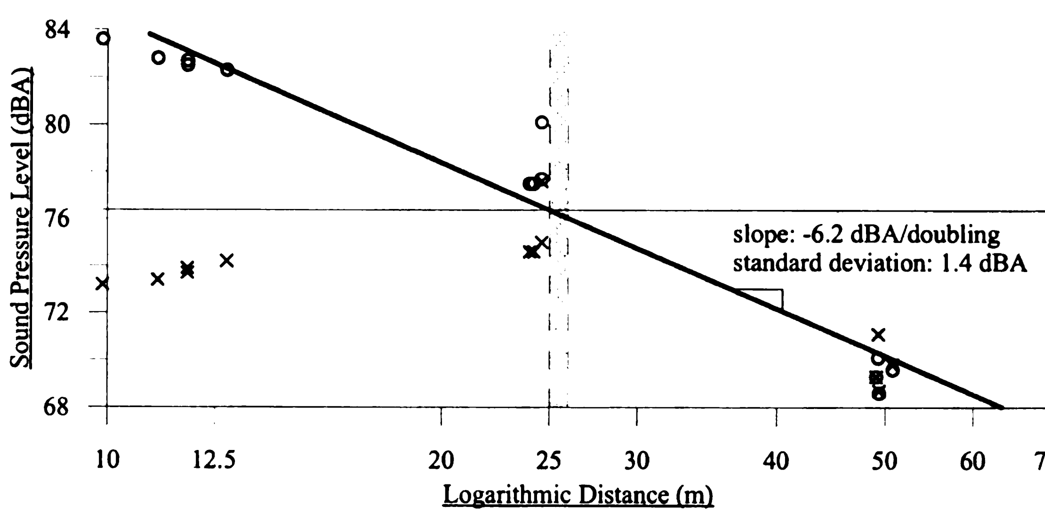

Figure 34: Test #9 Field Data, Measured SPLs (○) and Standard Deviation- and Error Compensated-Corrected (×) SPLs and Predicted SAE J34 SPL (—) with Respect to the Measured SPLs Best-fit Logarithmic Regression Line (**—**)

Test Number: **10**

Hull Identification: MC3529PB

Boat Operator: Heather Wilson, sheriff's dept.

Date: 9-10-2005

Location: Torch Lake, MI

Comments: Antrim County Sheriff's Department Boat; 200 Mercury, 2 stroke, 21.5', DC Aquasport. This data set is **NOT** used because of testing interference

Table 13: Test #10 Noise Gun Readout

Trial #	Boat Side	Minimum Distance Measured (m)	Maximum SPL Measured (dBA)	Measured Background Noise SPL (dBA)	Corrected SPL (dBA)
1	Star.	15.0	78.2	59.5	72.1
2	Port	14.4	77.7	59.5	71.2
3	Star.	14.4	77.1	59.5	70.6
4	Port	14.5	78.1	59.5	71.7
5	Star.	29.7	75.2	59.5	74.5
6	Port	28.3	72.0	59.5	70.2
7	Star.	28.5	71.8	59.5	70
8	Port	27.5	71.5	59.5	68.7
9	Star.	53.1	65.6	59.5	63.9
10	Star.	52.1	65.9	38.4	69.4
11	Port	52.6	66.8	38.4	70.5

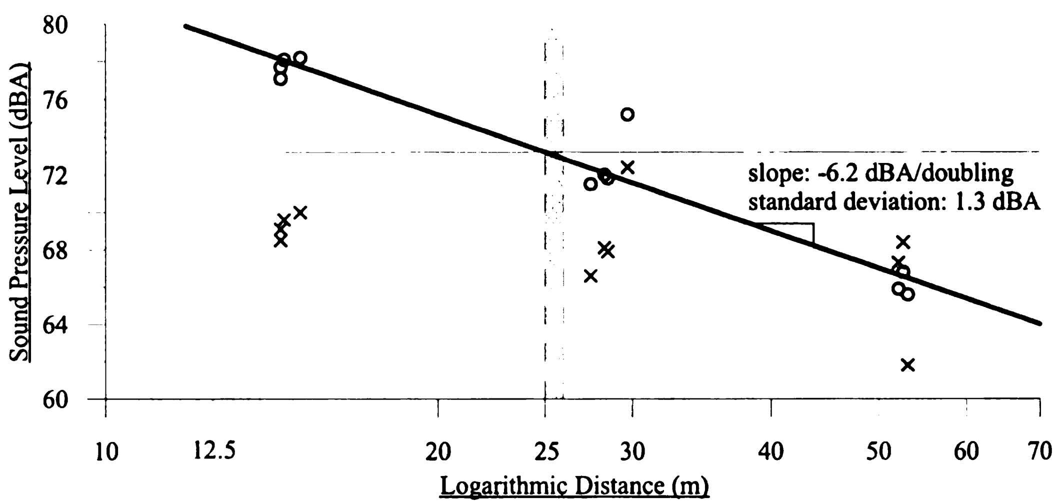

Figure 35: Test #10 Field Data, Measured SPLs (○) and Standard Deviation- and Error Compensated-Corrected (×) SPLs and Predicted SAE J34 SPL (—) with Respect to the Measured SPLs Best-fit Logarithmic Regression Line (▬)

Test Number: **11**

Hull Identification: MC2209RZ

Boat Operator: John Roberts

Date: 9-10-2005

Location: Torch Lake, MI

Comments: Powerquest 7.4 liter, all stock, 26', Legend SX

Table 14: Test #11 Noise Gun Readout

Trial #	Boat Side	Minimum Distance Measured (m)	Maximum SPL Measured (dBA)	Measured Background Noise SPL (dBA)	Corrected SPL (dBA)
1	Port	14.3	91.6	26.5	86.8
2	Star.	17.8	91.7	26.5	88.8
3	Port	13.5	91.6	26.5	86.3
4	Star.	14.1	91.5	26.5	86.6
5	Port	14.2	90.1	26.5	85.2
6	Star.	28.2	84.9	26.5	85.5
7	Port	27.7	84.9	26.5	85.5
8	Star.	53.0	80.5	26.5	84.8
9	Port	52.2	80.4	26.5	84.6
10	Star.	53.2	80.5	26.5	84.8
11	Port	52.2	81.0	26.5	85.2
12	Port	16.0	88.6	54.2	84.5
13	Port	28.2	85.0	54.2	85.3
14	Port	27.6	84.5	54.2	84.7

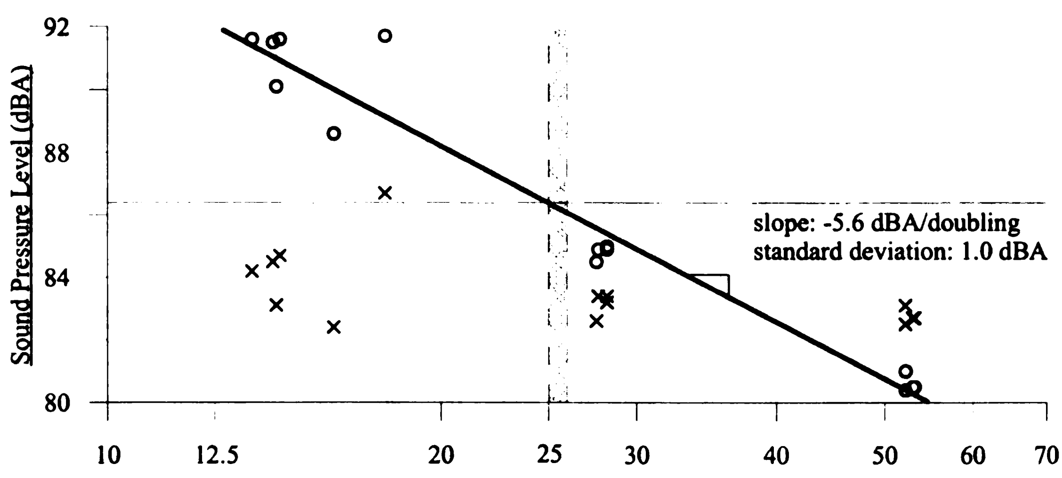

Figure 36: Test #11 Field Data, Measured SPLs (o) and Standard Deviation- and Error Compensated-Corrected (×) SPLs and Predicted SAE J34 SPL (—) with Respect to the Measured SPLs Best-fit Logarithmic Regression Line (▬)

Test Number: **12**

Hull Identification: MC7243PL

Boat Operator: Scott Kowalski

Date: 9-10-2005

Location: Torch Lake, MI

Comments: Sunsation, 24', BravoOne, 502 cubic inch, 400HP

Table 15: Test #12 Noise Gun Readout

Trial #	Boat Side	Minimum Distance Measured (m)	Maximum SPL Measured (dBA)	Measured Background Noise SPL (dBA)	Corrected SPL (dBA)
1	Star.	18.4	90.7	47.0	88
2	Port	29.8	87.3	47.0	88.2
3	Star.	32.5	87.2	47.0	88.6
4	Port	33.3	86.5	47.0	88
5	Star.	15.8	92.0	47.0	88.1
6	Port	14.5	91.8	47.0	87
7	Star.	55.6	82.0	47.0	86.3
8	Port	52.2	81.5	47.0	85.4
9	Star.	53.1	82.6	47.0	86.6
10	Port	51.6	83.4	47.0	87.3
11	Star.	14.6	92.9	47.0	88.3
12	Port	13.7	92.4	47.0	87.2

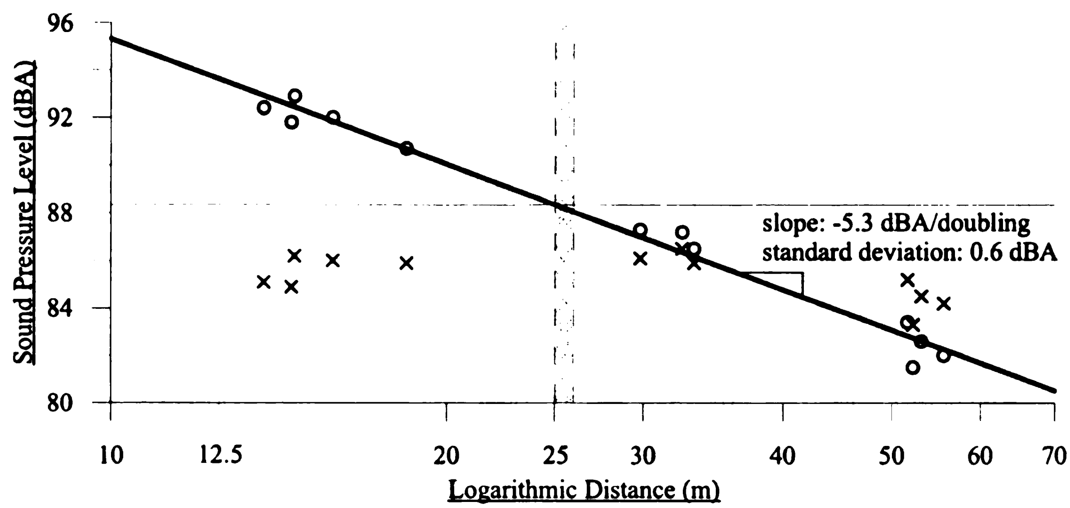

Figure 37: Test #12 Field Data, Measured SPLs (○) and Standard Deviation- and Error Compensated-Corrected (×) SPLs and Predicted SAE J34 SPL (—) with Respect to the Measured SPLs Best-fit Logarithmic Regression Line (▬)

Test Number: **13**

Hull Identification: MC7243PL

Boat Operator: Scott Kowalski

Date: 9-10-2005

Location: Torch Lake, MI

Comments: Sunsation, 24', BravoOne, 502 cubic inch, 400HP, * Captain's Choice

Table 16: Test #13 Noise Gun Readout

Trial #	Boat Side	Minimum Distance Measured (m)	Maximum SPL Measured (dBA)	Measured Background Noise SPL (dBA)	Corrected SPL (dBA)
1	Star.	15.5	78.1	39.6	73.7
2	Port	14.5	77.1	39.6	72.1
3	Star.	15.1	80.1	39.6	75.7
4	Port	29.1	72.9	39.6	73.4
5	Star.	28.4	74.6	39.6	75.0
6	Port	27.7	72.9	39.6	73.2
7	Star.	54.2	68.4	39.6	72.3
8	Port	53.1	67.6	39.6	71.4
9	Star.	51.7	68.8	39.6	72.1
10	Port	51.9	66.5	39.6	70.2
11	Port	14.3	76.5	39.6	71.4
12	Star.	27.6	75.5	39.6	75.7

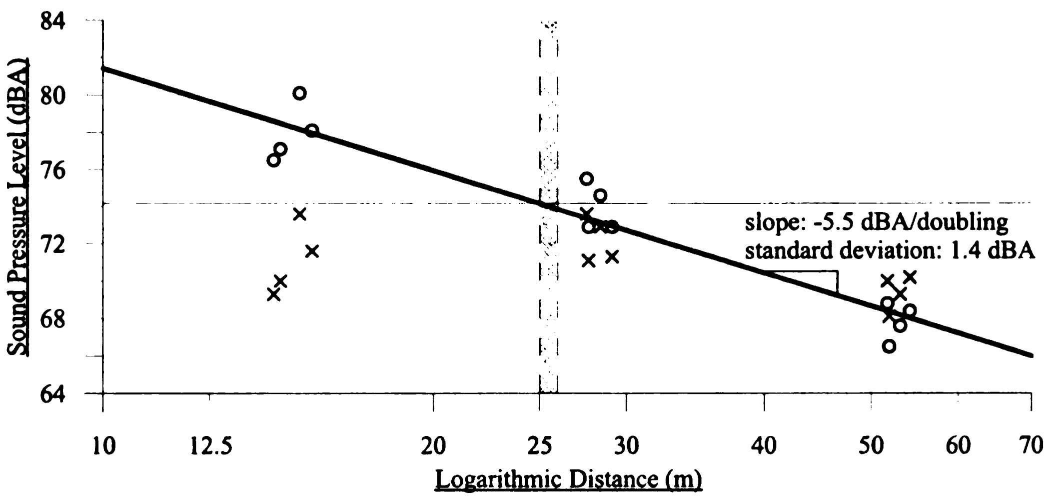

Figure 38: Test #13 Field Data, Measured SPLs (o) and Standard Deviation- and Error Compensated-Corrected (×) SPLs and Predicted SAE J34 SPL (—) with Respect to the Measured SPLs Best-fit Logarithmic Regression Line (—)

Test Number: **14**

Hull Identification: MC5326LK

Boat Operator: Rick Godden

Date: 9-10-2005

Location: Torch Lake, MI

Comments: Sea Ray, 26', 260HP, 350 cubic inch, through prop exhaust, 2 small block Chev.

Table 17: Test #14 Noise Gun Readout

Trial #	Boat Side	Minimum Distance Measured (m)	Maximum SPL Measured (dBA)	Measured Background Noise SPL (dBA)	Corrected SPL (dBA)
1	Star.	13.8	73.9	40.8	68.5
2	Port	16.1	73.5	40.8	69.5
3	Port	29.4	68.6	40.8	69.0
4	Star.	26.5	69.6	40.8	69.4
5	Port	54.9	66.7	40.8	70.7
6	Star.	54.5	66.0	40.8	70.0
7	Star.	14.5	78.9	40.8	73.9
8	Port	27.5	74.3	40.8	74.5
9	Star.	27.4	74.0	40.8	74.2
10	Port	52.4	68.6	40.8	72.3
11	Star.	52.9	70.5	40.8	74.5

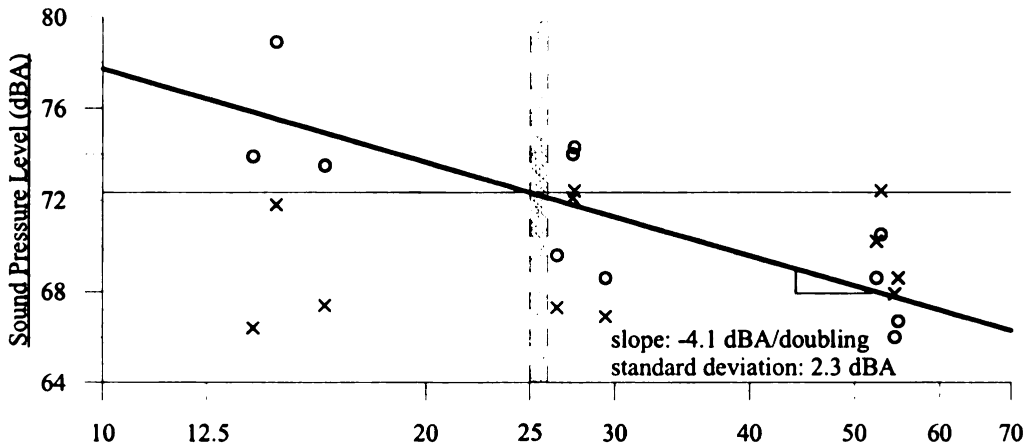

Figure 39: Test #14 Field Data, Measured SPLs (○) and Standard Deviation- and Error Compensated-Corrected (×) SPLs and Predicted SAE J34 SPL (—) with Respect to the Measured SPLs Best-fit Logarithmic Regression Line (▬)

Test Number: **15**

Hull Identification: MC2103PB

Boat Operator: Jason McCaleb

Date: 9-10-2005

Location: Torch Lake, MI

Comments: Aquasport, 21.5', 200HP Mercury outboard, 2 stroke

Table 18: Test #15 Noise Gun Readout

Trial #	Boat Side	Minimum Distance Measured (m)	Maximum SPL Measured (dBA)	Measured Background Noise SPL (dBA)	Corrected SPL (dBA)
1	Port	12.6	77.7	32.0	71.8
2	Star.	10.7	75.2	32.0	67.8
3	Port	12.4	76.8	32.0	70.7
4	Star.	25.7	69.9	32.0	69.7
5	Port	26.1	72.4	32.0	72.5
6	Star.	25.8	70.0	32.0	69.9
7	Port	25.6	72.6	32.0	72.6
8	Star.	51.5	64.0	32.0	67.8
9	Port	50.6	65.0	32.0	68.7
10	Star.	51.3	64.9	32.0	68.7
11	Port	50.4	65.0	32.0	68.7
12	Star.	11.9	74.0	32.0	67.5

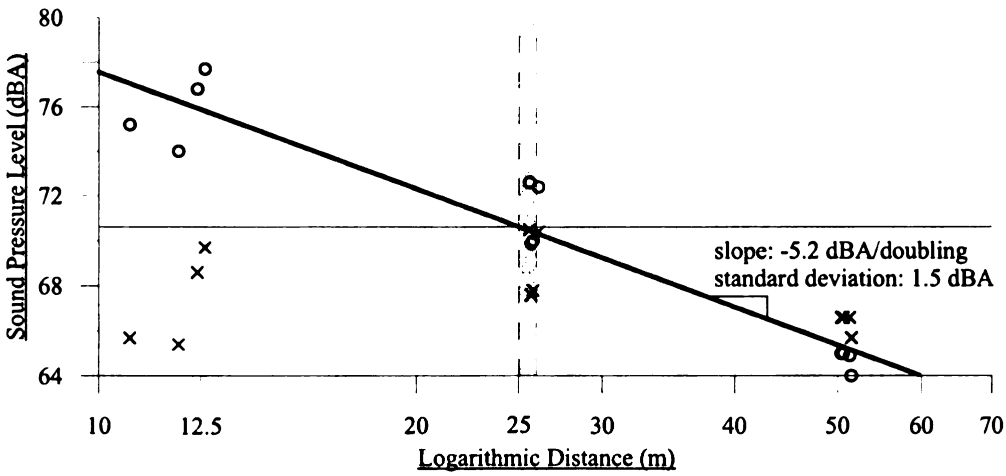

Figure 40: Test #15 Field Data, Measured SPLs (○) and Standard Deviation- and Error Compensated-Corrected (×) SPLs and Predicted SAE J34 SPL (—) with Respect to the Measured SPLs Best-fit Logarithmic Regression Line (▬)

Appendix F:
Correction Calculation Comparison

Test Number: **1**

Hull Identification: MC4728SJ

Boat Operator: (not recorded)

Date: 7-19-2005

Location: Higgins Lake, MI

Comments: This data set is **NOT** used in the analysis due to the different device calibration between this data set and the Torch Lake data sets.

Table 19: Test #1, Device Corrected SPL Approximation Compared to the Actual Decimal Calculation

Trial #	Minimum Distance Measured (m)	Maximum SPL Measured (dBA)	Measured Background Noise SPL (dBA)	Corrected SPL on Device (dBA)	Corrected SPL Calculation (dBA)	Corrected SPL Difference (dBA)
1	52.6	78.1	52.7	81.8	81.9	-0.1
2	53.4	75.8	52.7	79.4	79.5	-0.1
3	51.4	80.6	52.7	84.2	84.4	-0.2
4	53.7	78.6	52.7	82.5	82.6	-0.1
5	26.1	82.9	52.7	82.8	82.9	-0.1
6	27.0	80.5	52.7	80.7	80.6	0.1
7	27.5	83.0	52.7	83.2	83.3	-0.1
8	27.1	81.4	52.7	81.3	81.5	-0.2
9	26.5	67.6	52.7	65.4	66.2	-0.8
10	27.5	81.1	52.7	81.1	81.3	-0.2
11	16.4	80.9	52.7	76.8	76.9	-0.1
12	28.4	66.0	52.7	64.2	64.6	-0.4
13	15.4	83.1	52.7	78.6	78.6	0.0
14	15.1	81.6	52.7	76.8	76.9	-0.1
15	15.4	71.8	52.7	65.9	66.6	-0.7
16	15.2	81.2	52.7	76.4	76.6	-0.2
17	14.9	70.7	52.7	65.7	65.1	0.6
18	14.8	70.7	52.7	65.7	65.0	0.7

Test Number: **2**

Hull Identification: MC8487SV

Boat Operator: (not recorded)

Date: 7-19-2005

Location: Higgins Lake, MI

Comments: **This data set is NOT used in the analysis due to the different device calibration between this data set and the Torch Lake data sets.**

Table 20: Test #2, Device Corrected SPL Approximation Compared to the Actual Decimal Calculation

Trial #	Minimum Distance Measured (m)	Maximum SPL Measured (dBA)	Measured Background Noise SPL (dBA)	Corrected SPL on Device (dBA)	Corrected SPL Calculation (dBA)	Corrected SPL Difference (dBA)
1	30.6	67.5	51.3	66.9	67.2	-0.3
2	27.6	66.6	51.3	65.4	65.5	-0.1
3	29.0	65.9	51.3	64.2	65.0	-0.8
4	20.3	68.2	51.3	64.7	65.1	-0.4
5	15.7	70.2	51.3	64.5	65.1	-0.6
6	15.5	70.2	51.3	64.4	65.0	-0.6
7	14.6	69.9	51.3	63.6	64.2	-0.6
8	15.1	69.9	51.3	63.9	64.5	-0.6
9	50.9	61.8	51.3	62.6	62.8	-0.2
10	51.8	62.0	51.3	62.9	63.2	-0.3
11	51.3	60.4	51.3	60.1	60.8	-0.7
12	52.1	61.9	51.3	62.8	63.1	-0.3
13	51.7	60.1	51.3	59.9	60.4	-0.5
14	51.5	62.2	51.3	63.0	63.5	-0.5

Test Number: **3**

Hull Identification: MC4387PE

Boat Operator: (not recorded)

Date: 7-19-2005

Location: Higgins Lake, MI

Comments: **This data set is NOT used in the analysis due to the different device calibration between this data set and the Torch Lake data sets.**

Table 21: Test #3, Device Corrected SPL Approximation Compared to the Actual Decimal Calculation

Trial #	Minimum Distance Measured (m)	Maximum SPL Measured (dBA)	Measured Background Noise SPL (dBA)	Corrected SPL on Device (dBA)	Corrected SPL Calculation (dBA)	Corrected SPL Difference (dBA)
1	50.9	58.8	51.3	56.9	58.1	-1.2
2	50.3	62.5	51.3	63.2	63.7	-0.5
3	24.8	66.5	51.3	64.8	64.8	0.0
4	26.9	65.7	51.3	63.6	64.3	-0.7
5	12.9	71.2	51.3	63.8	64.5	-0.7
6	12.1	71.2	51.3	63.2	64.0	-0.8
7	50.3	60.7	51.3	60.3	61.1	-0.8
8	50.1	61.9	51.3	62.6	62.9	-0.3
9	25.2	67.1	51.3	65.4	65.6	-0.2
10	26.8	65.5	51.3	63.4	64.0	-0.6
11	12.6	71.2	51.3	63.6	64.3	-0.7
12	14.2	69.8	51.3	63.2	63.8	-0.6

Test Number: **4**

Hull Identification: MC3706PB

Boat Operator: Tim Tilley

Date: 9-10-2005

Location: Torch Lake, MI

Comments: Antrim County Sheriff's Department Boat; Twin 150HP Evinrude 2 stroke

Table 22: Test #4, Device Corrected SPL Approximation Compared to the Actual Decimal Calculation

Trial #	Minimum Distance Measured (m)	Maximum SPL Measured (dBA)	Measured Background Noise SPL (dBA)	Corrected SPL on Device (dBA)	Corrected SPL Calculation (dBA)	Corrected SPL Difference (dBA)
1	17.6	80.4	32.6	77.4	77.3	0.1
2	31.4	77.5	32.6	78.7	78.8	-0.1
3	14.7	82.9	32.6	78.3	78.3	0.0
4	56.5	71.6	32.6	76.2	76.2	0.0
5	25.7	78.0	32.6	78.1	78.1	0.0
6	12.9	81.2	32.6	75.5	75.4	0.1
7	52.7	72.1	49.4	75.6	75.7	-0.1
8	52.6	71.1	32.6	75.0	75.3	-0.3
9	13.4	81.9	49.4	76.2	76.3	-0.1
10	26.5	76.0	49.4	75.8	75.9	-0.1
11	51.1	70.3	49.4	72.7	73.6	-0.9
12	26.7	75.5	49.4	75.4	75.4	0.0

Test Number: **5**

Hull Identification: MC3457SN

Boat Operator: Bill Johnson

Date: 9-10-2005

Location: Torch Lake, MI

Comments: Yellow Catamaran dual hulls; 900HP, 4 stroke, V8 supercharge Teague, Gatling mufflers. This data set is **NOT** used because there weren't enough trials.

Table 23: Test #5, Device Corrected SPL Approximation Compared to the Actual Decimal Calculation

Trial #	Minimum Distance Measured (m)	Maximum SPL Measured (dBA)	Measured Background Noise SPL (dBA)	Corrected SPL on Device (dBA)	Corrected SPL Calculation (dBA)	Corrected SPL Difference (dBA)
1	40.4	101.0	32.7	103.0	103.8	-0.8
2	46.5	98.0	32.7	101.0	101.6	-0.6
3	65.3	97.4	32.7	102.0	102.9	-0.9
4	74.7	93.5	32.7	99.8	99.8	0.0
5	28.3	101.0	32.7	101.0	101.7	-0.7
6	44.7	92.6	32.7	95.9	95.9	0.0

Test Number: **6**

Hull Identification: MC3529PB

Boat Operator: Heather Wilson, sheriff's dept.

Date: 9-10-2005

Location: Torch Lake, MI

Comments: Antrim County Sheriff's Department Boat; 200 Mercury, 2 stroke, 21.5', DC Aquasport. This data set is **NOT** used because of possible wind effects.

Table 24: Test #6, Device Corrected SPL Approximation Compared to the Actual Decimal Calculation

Trial #	Minimum Distance Measured (m)	Maximum SPL Measured (dBA)	Measured Background Noise SPL (dBA)	Corrected SPL on Device (dBA)	Corrected SPL Calculation (dBA)	Corrected SPL Difference (dBA)
1	14.6	72.8	44.2	67.7	67.8	-0.1
2	18.7	79.2	55.6	75.9	76.1	-0.2
3	14.8	81.6	55.6	76.6	76.6	0.0
4	16.6	79.7	55.6	75.4	75.6	-0.2
5	15.5	81.6	55.6	77.0	77.0	0.0
6	32.1	73.4	55.6	73.1	73.6	-0.5
7	31.5	75.2	55.6	74.8	75.6	-0.8
8	29.9	74.9	55.6	74.2	74.9	-0.7
9	54.6	68.8	55.6	70.8	71.2	-0.4
10	55.5	69.5	55.6	71.6	72.1	-0.5
11	53.1	67.2	55.6	68.2	68.9	-0.7
12	53.0	69.4	55.6	71.2	71.8	-0.6

Test Number: **7**

Hull Identification: MC3220RP

Boat Operator: Bill Johnson

Date: 9-10-2005

Location: Torch Lake, MI

Comments: 2 HB500 Birkhauser formula 350, 35.5', FASTech

Table 25: Test #7, Device Corrected SPL Approximation Compared to the Actual Decimal Calculation

Trial #	Minimum Distance Measured (m)	Maximum SPL Measured (dBA)	Measured Background Noise SPL (dBA)	Corrected SPL on Device (dBA)	Corrected SPL Calculation (dBA)	Corrected SPL Difference (dBA)
1	13.4	88.0	42.1	82.6	82.6	0.0
2	14.3	88.2	42.1	83.4	83.3	0.1
3	15.2	87.7	42.1	83.4	83.3	0.1
4	15.0	88.7	42.1	84.3	84.2	0.1
5	30.1	84.7	42.1	85.6	85.7	-0.1
6	29.3	84.8	42.1	85.6	85.7	-0.1
7	53.8	80.3	42.1	84.4	84.6	-0.2
8	53.3	80.4	42.1	84.4	84.7	-0.3
9	53.2	81.0	42.1	85.2	85.3	-0.1
10	53.8	80.8	42.1	84.9	85.1	-0.2
11	31.6	84.8	42.1	86.1	86.1	0.0
12	29.4	84.7	42.1	85.5	85.6	-0.1

Test Number: **8**

Hull Identification: MC1244SJ

Boat Operator: Mike Savara

Date: 9-10-2005

Location: Torch Lake, MI

Comments: 27' formula, twin 280HP, 350 cubic inch, out drive. This data set is **NOT** used because it was interrupted by a thunderstorm.

Table 26: Test #8, Device Corrected SPL Approximation Compared to the Actual Decimal Calculation

Trial #	Minimum Distance Measured (m)	Maximum SPL Measured (dBA)	Measured Background Noise SPL (dBA)	Corrected SPL on Device (dBA)	Corrected SPL Calculation (dBA)	Corrected SPL Difference (dBA)
1	14.9	77.4	34.4	72.8	72.9	-0.1
2	14.8	76.7	34.4	72.1	72.1	0.0
3	14.4	77.9	34.4	73.0	73.1	-0.1
4	14.4	78.2	34.4	73.3	73.4	-0.1
5	27.8	73.0	34.4	73.3	73.5	-0.2
6	28.2	73.0	34.4	73.3	73.6	-0.3

Test Number: **9**

Hull Identification: MC6546ST

Boat Operator: Jeremy Howard

Date: 9-10-2005

Location: Torch Lake, MI

Comments: Unmodified 2005 Jetski, Yamaha VX110 Sport, 1100cc. This data set is **NOT** used because it is not considered a motorboat.

Table 27: Test #9, Device Corrected SPL Approximation Compared to the Actual Decimal Calculation

Trial #	Minimum Distance Measured (m)	Maximum SPL Measured (dBA)	Measured Background Noise SPL (dBA)	Corrected SPL on Device (dBA)	Corrected SPL Calculation (dBA)	Corrected SPL Difference (dBA)
1	9.9	83.6	48.6	75.3	75.4	-0.1
2	12.8	82.3	48.6	76.3	76.3	0.0
3	11.8	82.7	48.6	76.0	76.0	0.0
4	11.1	82.8	48.6	75.5	75.6	-0.1
5	24.2	77.5	48.6	76.7	76.9	-0.2
6	24.0	77.5	48.6	76.7	76.8	-0.1
7	24.6	80.1	48.6	79.7	79.7	0.0
8	24.6	77.7	48.6	77.1	77.3	-0.2
9	50.8	69.6	48.6	71.9	72.9	-1.0
10	49.4	68.6	48.6	70.8	71.6	-0.8
11	49.3	70.1	48.6	73.2	73.3	-0.1
12	49.1	69.3	48.6	71.4	72.4	-1.0
13	11.8	82.5	48.6	75.8	75.8	0.0

Test Number: **10**

Hull Identification: MC3529PB

Boat Operator: Heather Wilson, sheriff's dept.

Date: 9-10-2005

Location: Torch Lake, MI

Comments: Antrim County Sheriff's Department Boat; 200 Mercury, 2 stroke, 21.5', DC Aquasport. This data set is **NOT** used because of testing interference.

Table 28: Test #10, Device Corrected SPL Approximation Compared to the Actual Decimal Calculation

Trial #	Minimum Distance Measured (m)	Maximum SPL Measured (dBA)	Measured Background Noise SPL (dBA)	Corrected SPL on Device (dBA)	Corrected SPL Calculation (dBA)	Corrected SPL Difference (dBA)
1	15.0	78.2	59.5	72.1	72.7	-0.6
2	14.4	77.7	59.5	71.2	71.8	-0.6
3	14.4	77.1	59.5	70.6	71.1	-0.5
4	14.5	78.1	59.5	71.7	72.3	-0.6
5	29.7	75.2	59.5	74.5	74.6	-0.1
6	28.3	72.0	59.5	70.2	70.4	-0.2
7	28.5	71.8	59.5	70.0	70.1	-0.1
8	27.5	71.5	59.5	68.7	69.5	-0.8
9	53.1	65.6	59.5	63.9	64.0	-0.1
10	52.1	65.9	38.4	69.4	69.8	-0.4
11	52.6	66.8	38.4	70.5	70.8	-0.3

Test Number: **11**

Hull Identification: MC2209RZ

Boat Operator: John Roberts

Date: 9-10-2005

Location: Torch Lake, MI

Comments: Powerquest 7.4 liter, all stock, 26', Legend SX

Table 29: Test #11, Device Corrected SPL Approximation Compared to the Actual Decimal Calculation

Trial #	Minimum Distance Measured (m)	Maximum SPL Measured (dBA)	Measured Background Noise SPL (dBA)	Corrected SPL on Device (dBA)	Corrected SPL Calculation (dBA)	Corrected SPL Difference (dBA)
1	14.3	91.6	26.5	86.8	86.8	0.0
2	17.8	91.7	26.5	88.8	88.8	0.0
3	13.5	91.6	26.5	86.3	86.3	0.0
4	14.1	91.5	26.5	86.6	86.5	0.1
5	14.2	90.1	26.5	85.2	85.2	0.0
6	28.2	84.9	26.5	85.5	85.6	-0.1
7	27.7	84.9	26.5	85.5	85.5	0.0
8	53.0	80.5	26.5	84.8	84.8	0.0
9	52.2	80.4	26.5	84.6	84.6	0.0
10	53.2	80.5	26.5	84.8	84.8	0.0
11	52.2	81.0	26.5	85.2	85.2	0.0
12	16.0	88.6	54.2	84.5	84.6	-0.1
13	28.2	85.0	54.2	85.3	85.4	-0.1
14	27.6	84.5	54.2	84.7	84.8	-0.1

Test Number: **12**

Hull Identification: MC7243PL

Boat Operator: Scott Kowalski

Date: 9-10-2005

Location: Torch Lake, MI

Comments: Sunsation, 24', BravoOne, 502 cubic inch, 400HP

Table 30: Test #12, Device Corrected SPL Approximation Compared to the Actual Decimal Calculation

Trial #	Minimum Distance Measured (m)	Maximum SPL Measured (dBA)	Measured Background Noise SPL (dBA)	Corrected SPL on Device (dBA)	Corrected SPL Calculation (dBA)	Corrected SPL Difference (dBA)
1	18.4	90.7	47.0	88.0	88.0	0.0
2	29.8	87.3	47.0	88.2	88.2	0.0
3	32.5	87.2	47.0	88.6	88.6	0.0
4	33.3	86.5	47.0	88.0	88.1	-0.1
5	15.8	92.0	47.0	88.1	88.0	0.1
6	14.5	91.8	47.0	87.0	87.0	0.0
7	55.6	82.0	47.0	86.3	86.5	-0.2
8	52.2	81.5	47.0	85.4	85.6	-0.2
9	53.1	82.6	47.0	86.6	86.8	-0.2
10	51.6	83.4	47.0	87.3	87.4	-0.1
11	14.6	92.9	47.0	88.3	88.2	0.1
12	13.7	92.4	47.0	87.2	87.1	0.1

Test Number: **13**

Hull Identification: MC7243PL

Boat Operator: Scott Kowalski

Date: 9-10-2005

Location: Torch Lake, MI

Comments: Sunsation, 24', BravoOne, 502 cubic inch, 400HP, * Captain's Choice

Table 31: Test #13, Device Corrected SPL Approximation Compared to the Actual Decimal Calculation

Trial #	Minimum Distance Measured (m)	Maximum SPL Measured (dBA)	Measured Background Noise SPL (dBA)	Corrected SPL on Device (dBA)	Corrected SPL Calculation (dBA)	Corrected SPL Difference (dBA)
1	15.5	78.1	39.6	73.7	73.9	-0.2
2	14.5	77.1	39.6	72.1	72.3	-0.2
3	15.1	80.1	39.6	75.7	75.7	0.0
4	29.1	72.9	39.6	73.4	73.6	-0.2
5	28.4	74.6	39.6	75.0	75.2	-0.2
6	27.7	72.9	39.6	73.2	73.3	-0.1
7	54.2	68.4	39.6	72.3	72.5	-0.2
8	53.1	67.6	39.6	71.4	71.6	-0.2
9	51.7	68.8	39.6	72.1	72.7	-0.6
10	51.9	66.5	39.6	70.2	70.3	-0.1
11	14.3	76.5	39.6	71.4	71.5	-0.1
12	27.6	75.5	39.6	75.7	75.9	-0.2

Test Number: **14**

Hull Identification: MC5326LK

Boat Operator: Rick Godden

Date: 9-10-2005

Location: Torch Lake, MI

Comments: Sea Ray, 26', 260HP, 350 cubic inch, through prop exhaust, 2 small block Chev.

Table 32: Test #14, Device Corrected SPL Approximation Compared to the Actual Decimal Calculation

Trial #	Minimum Distance Measured (m)	Maximum SPL Measured (dBA)	Measured Background Noise SPL (dBA)	Corrected SPL on Device (dBA)	Corrected SPL Calculation (dBA)	Corrected SPL Difference (dBA)
1	13.8	73.9	40.8	68.5	68.6	-0.1
2	16.1	73.5	40.8	69.5	69.5	0.0
3	29.4	68.6	40.8	69.0	69.2	-0.2
4	26.5	69.6	40.8	69.4	69.6	-0.2
5	54.9	66.7	40.8	70.7	70.8	-0.1
6	54.5	66.0	40.8	70.0	70.0	0.0
7	14.5	78.9	40.8	73.9	74.1	-0.2
8	27.5	74.3	40.8	74.5	74.7	-0.2
9	27.4	74.0	40.8	74.2	74.3	-0.1
10	52.4	68.6	40.8	72.3	72.5	-0.2
11	52.9	70.5	40.8	74.5	74.5	0.0

Test Number: **15**

Hull Identification: MC2103PB

Boat Operator: Jason McCaleb

Date: 9-10-2005

Location: Torch Lake, MI

Comments: Aquasport, 21.5', 200HP Mercury outboard, 2 stroke

Table 33: Test #15, Device Corrected SPL Approximation Compared to the Actual Decimal Calculation

Trial #	Minimum Distance Measured (m)	Maximum SPL Measured (dBA)	Measured Background Noise SPL (dBA)	Corrected SPL on Device (dBA)	Corrected SPL Calculation (dBA)	Corrected SPL Difference (dBA)
1	12.6	77.7	32.0	71.8	71.7	0.1
2	10.7	75.2	32.0	67.8	67.8	0.0
3	12.4	76.8	32.0	70.7	70.7	0.0
4	25.7	69.9	32.0	69.7	69.9	-0.2
5	26.1	72.4	32.0	72.5	72.6	-0.1
6	25.8	70.0	32.0	69.9	70.1	-0.2
7	25.6	72.6	32.0	72.6	72.7	-0.1
8	51.5	64.0	32.0	67.8	67.9	-0.1
9	50.6	65.0	32.0	68.7	68.9	-0.2
10	51.3	64.9	32.0	68.7	68.8	-0.1
11	50.4	65.0	32.0	68.7	68.8	-0.1
12	11.9	74.0	32.0	67.5	67.5	0.0

Appendix G:
Analysis of SAE J34 Distance Acceptability

Table 34: Analysis of SAE J34 Distance Acceptability (25 - 26m) of Field Test #4

Trial #	Minimum Distance Measured (m)	Acceptable by SAE J34 Standard? (Yes/No)
2	31.4	No
5	25.7	Yes
10	26.5	No
12	26.7	No

Table 35: Analysis of SAE J34 Distance Acceptability (25 - 26m) of Field Test #7

Trial #	Minimum Distance Measured (m)	Acceptable by SAE J34 Standard? (Yes/No)
5	30.1	No
6	29.3	No
11	31.6	No

Table 36: Analysis of SAE J34 Distance Acceptability (25 - 26m) of Field Test #11

Trial #	Minimum Distance Measured (m)	Acceptable by SAE J34 Standard? (Yes/No)
6	28.2	No
7	27.7	No
13	28.2	No
14	27.6	No

Table 37: Analysis of SAE J34 Distance Acceptability (25 - 26m) of Field Test #12

Trial #	Minimum Distance Measured (m)	Acceptable by SAE J34 Standard? (Yes/No)
2	29.8	No
3	32.5	No
4	33.3	No

Table 38: Analysis of SAE J34 Distance Acceptability (25 - 26m) of Field Test #13

Trial #	Minimum Distance Measured (m)	Acceptable by SAE J34 Standard? (Yes/No)
4	29.1	No
5	28.4	No
6	27.7	No
12	27.6	No

Table 39: Analysis of SAE J34 Distance Acceptability (25 - 26m) of Field Test #14

Trial #	Minimum Distance Measured (m)	Acceptable by SAE J34 Standard? (Yes/No)
3	29.4	No
4	26.5	No
8	27.5	No
9	27.4	No

Table 40: Analysis of SAE J34 Distance Acceptability (25 - 26m) of Field Test #15

Trial #	Minimum Distance Measured (m)	Acceptable by SAE J34 Standard? (Yes/No)
4	25.7	Yes
5	26.1	No
6	25.8	Yes
7	25.6	Yes

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