# Acoustic Energy Attenuation of 3DVSP Airgun Arrays Operating in Long Beach Harbor

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***Abstract* – Increased awareness of the disruptive impact high-power sonars and airguns potentially have on marine mammal populations has resulted in the adoption of flexible survey protocols, which account for movements of these animals through the region. To effectively modulate source transmissions and maintain adequate standoff distances, accurate estimates of range-dependent sound pressure levels (SPLs) are required. To determine safe ranges of airgun operation during a three dimensional vertical seismic profile survey (3DVSP) in Long Beach Harbor, stationary hydrophones were deployed to measure SPLs received from 160 in$^3$, 320 in$^3$ and 560 in$^3$ airgun arrays fired along a 5 km track. Recordings from bow and stern source boat aspects are analyzed for pulse energy, pulse duration, peak instantaneous pressure, and rms pressure over the pulse duration. For each airgun array and aspect combination, range-limited linear regression curve fits are carried out to characterize transmission loss. Distances at which the SPL drops below 190 dB, 180 dB, and 160 dB rms re: 1μPa are determined, where operation of airguns at distances from marine mammals greater than the 160 dB range is mandated by the National Marine Fisheries Service (NMFS). For the 160 in$^3$ array, the bow aspect 160 dB level is estimated at 1279 m. For the 320 in$^3$ array, the bow and stern aspect 160 dB levels are estimated at 1712 m and 1916 m respectively. For the 560 in$^3$ array, the bow and stern aspect 160 dB levels are estimated at 2057 m and 2672 m respectively. The data collection and analysis techniques described in this paper rapidly and inexpensively determine NMFS compliant airgun operating procedures.***

## I. INTRODUCTION

Airguns release high-pressure air into the water to create large amplitude pressure waves. These high-intensity impulsive transmissions are used for identifying and mapping marine hydrocarbon deposits. Airgun sounds may be sufficiently intense to affect the physical constitution and/or behavior of marine mammals inhabiting the immediate vicinity [1]. Marine mammals are protected under the Marine Mammal Protection Act (MMPA), and some species are further protected under the Endangered Species Act. To determine MMPA compliant ranges of airgun operation during a three dimensional vertical seismic profile (3DVSP) survey planned for Long Beach Harbor, an Acoustic Energy Attenuation Test (AEAT) was carried out by measuring received sound pressure level (SPL) vs. source range.

The AEAT was conducted from January 29-31, 2002. During this test, stationary hydrophones were used to measure sound pressure levels received from an airgun array fired approximately every 45 m (pulse repetition rate of 20 sec) along a 5 km survey track. The survey track ran NW-SE across Long Beach Harbor, approximately parallel to the shoreline in water depth 10-15 m. The receiving phones were deployed from a boat at the SE end of the track: 33$^o$ 43.55' N, 118$^o$ 07.59' W. Runs were measured for three separate airguns: 160 in$^3$, 320 in$^3$, and 560 in$^3$.

Each airgun array consisted of eight elements, which measured approximately 4 m long, 1 m wide, 1.5 m deep, and was towed approximately 30 m behind the source boat. The bottom of the array was at a depth of 3m. The impulsive sources generated sound primarily in the frequency band 5-300 Hz, with root-mean-square (rms) sound pressure levels (SPL) of 236.8 dB and 238.9 dB (re: 1 μPa at 1 m) for the 320 in$^3$ and 560 in$^3$ airguns respectively.

For each of the five array/aspect combinations, four quantities were examined vs. range: peak sound pressure level (peak SPL), pulse duration, energy flux density (EFD), and rms sound pressure level (rms SPL) [2]. Distances at which the rms SPL drop below 190 dB, 180 dB, and 160 dB rms re: 1μPa were determined, where operation of airguns at distances from marine mammals greater than the 160 dB range is mandated by the National Marine Fisheries Service (NMFS).

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In section II, the recording and analysis methods are described. Section III presents the measured acoustic propagation data for each of the three airguns. Measurements for peak SPL, pulse duration, and pulse EFD are described, and rms SPL measurements are discussed in detail and plotted versus range to the airgun source. A linear regression model is used to fit the rms SPL data vs. log(range), and estimates of the regression coefficients are presented. Section IV summarizes the rms SPL results and states estimates of NMFS compliant marine mammal standoff distances.

## II. MATERIALS AND METHODS

Two tug boats were used for the test. The 75 ft source boat *M/V Deanna Lee* towed the airgun arrays and the 65 ft *M/V Redondo* was used as the receiver ship. *Redondo*'s radar provided distance measures to the source boat for near real-time analysis of SPL vs. range. During post-processing, ranges to the source were calculated using airgun array navigation files provided by the *Deanna Lee* and GPS coordinates measured at the *Redondo*.

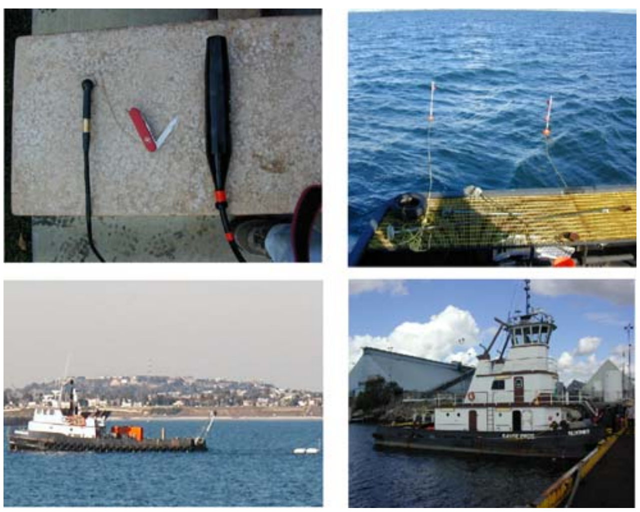

Fig. 1. AEAT Deployment. Clockwise from upper left corner: Reson TC4033 (low sensitivity) and ITC6050c (high sensitivity) hydrophones; Hydrophones deployment off *M/V Redondo* fantail; Receiver ship *M/V Redondo*; Source ship *M/V Deanna Lee* towing airgun array

Two calibrated hydrophones were suspended at a depth of 4.5 m in 12 m of water depth. A hairy fairing was attached to the submerged portion of each hydrophone cable to minimize cable strumming, and a windsock was wrapped about each sensor to minimize flow and current noise. Spar buoys were used to decouple the hydrophones from the motion of the boat and partially decouple them from wave motion. The remaining effects of wave motion were minimal, at low frequencies, and easily removed with a digital filter implemented in software during post-processing. Photographs of the hydrophones, spar buoy deployment, and source and receive boats are displayed in Fig. 1.

The simplified AEAT system schematic is illustrated in Fig. 2. Each hydrophone was connected to a separate amplifier channel. The outputs of the amplifier went into a pair of low-pass filters to suppress aliasing of sound energy at frequencies above the band of interest back into the pass band after digitization. The outputs of the anti-aliasing filters were fed in parallel to two independent stereo amplifiers: one with a continuously adjustable gain to provide the operators with an audio channel, and the other with a fixed gain to feed an analog to digital converter (A/D).

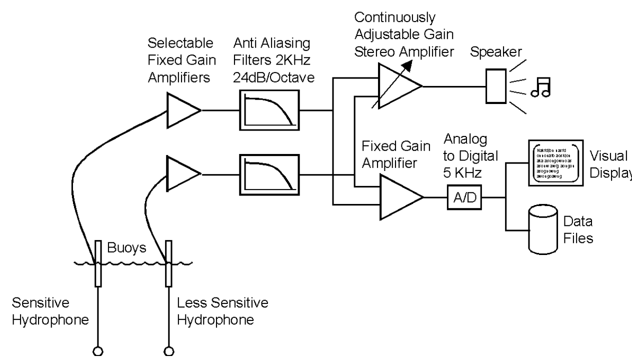


Fig. 2. AEAT Data Acquisition System

The hydrophones used were an ITC 6050C with a sensitivity of –157 dB re: 1 V/μPa and a Reson TC4033 with a sensitivity of –203.6 dB re: 1 V/μPa. Each hydrophone's amplifier channel had five independently selectable discrete gain settings separated by 6 dB. The two-phone system was capable of measuring waterborne acoustic signals with intensities spanning a range of 120 dB.

The anti-aliasing filters were 4-pole filters with a Bessel characteristic, which provided a 24 dB per octave suppression above 2 kHz. Each sound channel was sampled and digitized at a rate of 5 kHz. Digitization with 12-bit resolution was accomplished with a National Instruments DAQCard-AI-16E-4 multi-function data acquisition card in a laptop computer. The digitized data were stored in standard .WAV files that could be conveniently accessed for analysis.

The Integrated System for Holistic Multi-channel Acoustic Exploration and Localization (ISHMAEL) software package, developed by the NMFS Marine Mammal Lab, was used to control digitization and file storage of the data. It also provided a real-time display of the acoustic signals in both the time and frequency domains. This enabled the operator to visually assess signal levels, and select amplifier gains to keep at least one of the signal levels within the dynamic range of the A/D.

The experimental and analytical methodologies used in this study were adapted from [1] and [3]. The measured signal parameters for each airgun shot included peak SPL (in dB re: 1 μPa), pulse duration (the time over which the pulse energy accumulates from 5% to 95% of the total value), the energy flux density (in dB re: the energy of a 1 μPa signal of one second duration), and the rms SPL over the pulse duration (in dB re: 1 μPa).

A summary of the data runs is presented in Table 1. Signals received from bow and stern source boat aspects were recorded. For the bow aspect, the source boat approached the receiving station, and was between the airgun array and the receivers. For the stern aspect, the source boat transited away from the receiving station, and was on the far side of the airgun array. Bow and stern aspects for the 320 $in^3$ and 560 $in^3$ arrays were recorded. Only the bow aspect was recorded for the 160 $in^3$ array. Each of the five array/aspect combinations was given a 5-digit designation based on which airgun was used and which aspect was presented. The second digit represents the aspect (1=bow, 0=stern); and the last three digits designate the airgun used (160, 320, or 560 for each airgun size, respectively).

Table 1. Survey Track Information

| Source | Aspect | Run Id | Date | Start Time | End Time |
|---|---|---|---|---|---|
| 160 $in^3$ | Bow | 11160 | 1/30 | 10:04 | 10:32 |
| 320 $in^3$ | Stern | 10320 | 1/29 | 23:09 | 23:50 |
| 320 $in^3$ | Bow | 11320 | 1/30 | 00:14 | 00:55 |
| 560 $in^3$ | Stern | 10560 | 1/31 | 13:23 | 14:18 |
| 560 $in^3$ | Bow | 11560 | 1/31 | 14:28 | 15:08 |

Fig. 3 shows an example of the near real-time post-processing display produced during measurements. The data depicted is from one shot during run 11320, (bow aspect, 320 $in^3$ airgun), at time Jan. 30, 00:31, and at range 3720m.

Data approximately five times the pulse duration is selected and extracted from the overall time series with an automatic peak picking system (Fig. 3, top panel). The cumulative energy from this selected data is computed (Fig. 3, bottom panel) and used to determine a window function from 5%-95% of cumulative energy (red vertical dashed lines in Fig. 3). The data points within this windowed region are used to compute the received signal's rms SPL, peak SPL, total EFD, and pulse duration.

Examination of the energy density spectrum of this and other received signals reveals that received signal energy is concentrated in the 70 Hz – 160 Hz band. The majority of energy below 70 Hz evidently is transmitted into the sediment.

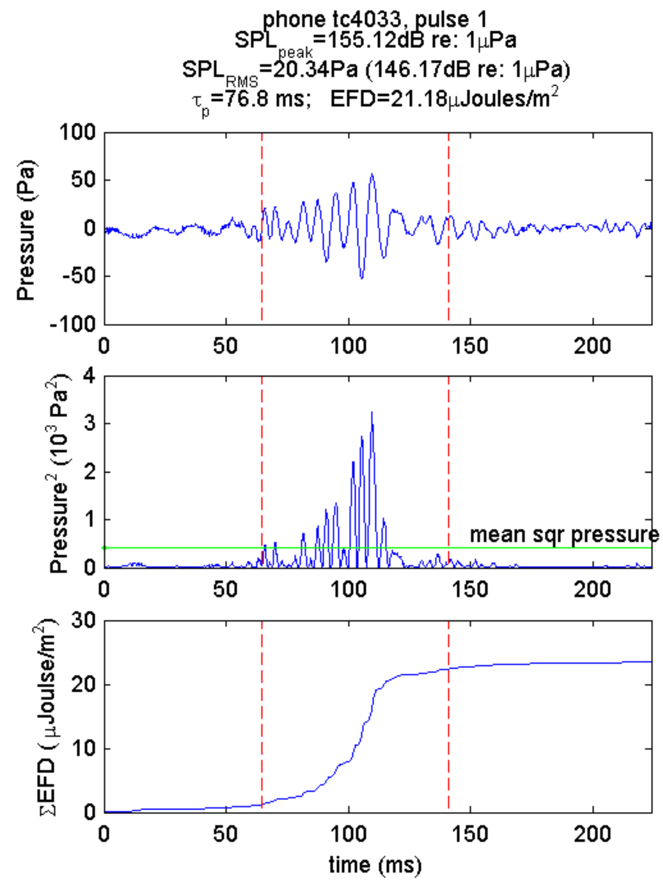


Fig. 3. Near real-time AEAT display (Run 11320, Jan. 30, 00:31, range 3720m). The vertical red lines show the 5%-95% EFD gates used for computing the SPL.

In all runs, except 10320, the receive vessel's engine and generator were shut down, and all electronic equipment was powered using batteries. Ambient noise levels were measured at 130 dB – 150 dB, and were most likely dependent on shipping patterns (engine and wake noise), seismic disturbances, and the position of the source boat (engine noise and residual source reverberation). In the frequencies of interest, noise from the receive ship generator, when operated during run 10320, did not contribute significantly to the recorded ambient noise. During this experiment and in post processing, the effects of noise are minimized by first filtering the raw time series with a 5 Hz high-pass digital filter, then subtracting estimates for noise energy flux density and rms SPL computed for each run/hydrophone combination from the values computed for the respective airgun signals.

## III. DATA ANALYSIS

This section presents the analysis of sound attenuation associated with use of the 160 $in^3$, 320 $in^3$, and 560 $in^3$ VSP airgun arrays, concentrating on measures of rms SPL.

In the near field, pulse durations are on the order of 10 ms, whereas at ranges of several kilometers, pulse duration increases by an order of magnitude ( to ~100 ms). Pulse duration increases linearly with log(range), and is likely due to summation of the signal through multiple surface and bottom reflected acoustic travel paths. Measures of pulse EFD represent integrated sound intensity over the duration of the pulse. Measured EFD dropped off rapidly with distance when ranges exceeded 1100m. This nonlinearity was due largely to the increased pulse durations described above.

The rms SPL, or time-averaged pressure over the width of the pulse, is the measure used to determine safe operating distances in the presence of marine mammal populations. Fig. 4 shows plots of rms SPL vs. log(range) for each of the five runs. In general, rms SPL (and peak SPL) decayed linearly with log (Range) between ranges 300 m – 3000 m, while exhibiting a somewhat more rapid drop in SPL at ranges greater than 1100m in runs 10320, 11320, and 10560. At distances exceeding 3-4 km, the relationship between rms SPL and log (Range) appears to be nonlinear in the Long Beach Harbor shallow water environment.

For regression analysis, we chose range intervals 300 m – 3000 m for the 160 $in^3$ and 320 $in^3$ arrays, and 300 m – 4000 m for the 560 $in^3$ array. The corresponding best-fit linear regression lines are plotted in Fig. 4.

For the appropriate ranges, the slope (*m*) and intercepts (*b*), corresponding to the lines presented in Fig. 4A-E, can be used to estimate rms SPL (in dB re: 1 μPa) given distance from the source by:

$$SPL\_dB = m \times \log_{10}(Range) + b.$$

The slope and intercept for each of the five array/aspect combinations are provided in Table 2, along with the valid range intervals ($R_{min}$ and $R_{max}$), the number of samples used in the linear regression fit (N~100 each), and the respective standard errors and coefficients of determination. Note the slopes range from –25 to –35, where a slope of –20 would indicate spherical spreading. The steeper negative slopes measured indicate that a significant amount of acoustic energy is being redirected into the harbor sediment.

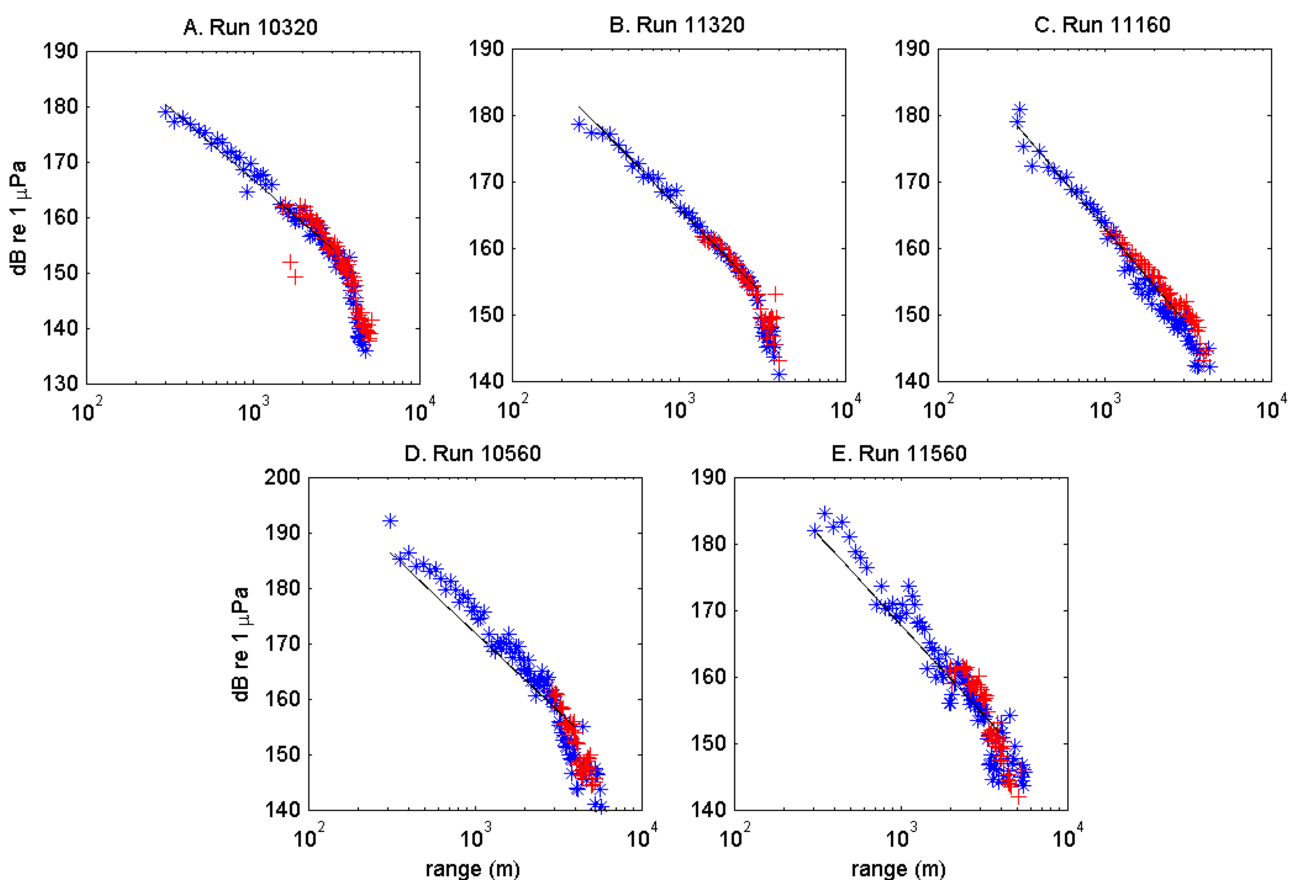


Fig. 4. Rms SPL vs. $\log_{10}$(range) for airgun arrays: (*, blue) symbols represent measurements from the TC4033 hydrophone, and (+, red) symbols represent measurements from the ITC6053c hydrophone.

Table 2. Linear regression fits for AEAT rms SPL data

| Source | Aspect | intercept | slope | $R_{min}$ (m) | $R_{max}$ (m) | N | std error (dB) | coef. of det. |
|---|---|---|---|---|---|---|---|---|
| 160 $in^3$ | bow | 250.7 | -29.2 | 298 | 2917 | 99 | 16.4 | 0.95 |
| 320 $in^3$ | stern | 245.1 | -25.9 | 301 | 2987 | 80 | 16.2 | 0.93 |
| 320 $in^3$ | bow | 243.3 | -25.8 | 255 | 2987 | 89 | 7.2 | 0.99 |
| 560 $in^3$ | stern | 280.8 | -35.2 | 310 | 3968 | 101 | 24.3 | 0.94 |
| 560 $in^3$ | bow | 268.6 | -32.8 | 304 | 3961 | 121 | 29.4 | 0.91 |

## IV. SUMMARY AND DISCUSSION

For each airgun array and aspect combination used in the THUMS Long Beach survey, ranges corresponding to 190 dB, 180 dB, and 160 dB rms received pressure levels (re: 1 μPa) were estimated and are summarized in Table 3. The 190 dB rms SPLs were rarely measured; therefore, these values are estimated using the regression formulas presented in Table 2. Note that higher SPL levels were consistently measured at stern source boat aspects. This may be due to array directionality, or scattering of signal energy by the source ship hull and wake when the vessel is located within the sound path.

Table 3. Results Summary

| Source | Aspect | 160dB range (m) | 180dB range (m) | 190dB range (m) |
|---|---|---|---|---|
| 160 $in^3$ | Bow | 1279 | 264 | 120 |
| 320 $in^3$ | Stern | 1916 | 325 | 134 |
| 320 $in^3$ | Bow | 1712 | 287 | 117 |
| 560 $in^3$ | Stern | 2672 | 723 | 376 |
| 560 $in^3$ | Bow | 2057 | 505 | 250 |

Operation of airguns at distances from marine mammals greater than the 160 dB rms SPL range is mandated by the National Marine Fisheries Service. For the 160 $in^3$ array, the bow aspect 160 dB level is estimated at 1279 m. For the 320 $in^3$ array, the bow and stern aspect 160 dB levels are estimated at 1712 m and 1916 m respectively. For the 560 $in^3$ array, the bow and stern aspect 160 dB levels are estimated at 2057 m and 2672 m respectively.

The data collection and analysis techniques described in this paper rapidly and inexpensively determine NMFS compliant airgun operating procedures. Furthermore, the data described in this report was used to prototype a method of rapidly estimating local geoacoustic properties [2,4]. These properties were used to generate solutions to a range dependent propagation model, providing sound propagation characteristics for the general Long Beach Harbor area. This follow-on work demonstrates the utility of employing a single-line Acoustic Energy Attenuation Test for determining sound propagation characteristics in a general region of operation.

## REFERENCES


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