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Exxon SYU Sound Propagation Study

November 1995

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Submitted to: Exxon Exploration Company
222 Benmar
Houston, Texas 77060

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Acoustic Technologies Division
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Summary

On November 9th and 10th, 1995, BBN conducted an acoustic propagation test in the vicinity of the Santa Ynez Unit (SYU) off the coast of Santa Barbara, California. Calibrated measurements were made of the airgun source array (powered up to its maximum operating level) of the GECO seismic vessel M/VMintrop, to be used in the Exxon SYU 3D seismic survey. An additional ship, the M/VCavalier, was used as a stationary receiver platform from which hydrophones were deployed.

Objectives

The objective of the tests was to determine the ranges from the source at which the average pulse pressure level is reduced to 190, 180 and 160 dB re µPa (microPascal). This is measured over a bandwidth from 5 Hz to 20 kHz, and estimated for the higher level of the airgun source array at broadside. The average pulse pressure measure is what was used to correlate with marine mammal noise avoidance behavior in studies performed by Malme et al. (1984).

Two phases of tests were conducted in the SYU unit and adjacent waters to adequately characterize propagation in this region of sloping bathymetry. The first phase measured acoustic propagation up-slope from the SYU toward the shore. The second phase measured source array output with a close pass of the source ship to the receiver array and acoustic propagation along the shelf within the SYU unit.

Conclusions

The ranges to the 190 and 180 dB re µPa average pulse pressure level were estimated for the broadside aspect to the airgun array. The range to the 190 and 180 dB re µPa average pulse levels were estimated using linear regression analysis of data obtained from a close pass of the source ship to the receiver array in Phase II. During this run, acoustic levels were measured at ranges as close as 157 meters which were used to estimate the nearfield average pulse pressure levels. The resulting distances to the 190 and 180 dB re µPa isopleths are summarized below:

Range to 190 dB re µPa Average pulse pressure Level	77 meters
Range to 180 dB re µPa Average pulse pressure Level	316 meters

The long range acoustic propagation in this environment makes determination of the range to the 160 dB re μPa average pulse pressure level more complicated. The received levels were observed to be dependent on receiver depth and direction of propagation. Levels did not consistently decrease with range for the shallow water receiver. Measurements of up-slope propagation and cross slope propagation are different due to the interaction with the sloping bottom. Representative results using linear regression analysis are presented below for received levels for up-slope propagation to receivers in 53, 75, 153, 179 and 201 meters of water depth, and for cross-slope propagation in 258 meters of water depth in the SYU area:

Propagation direction and water depth	Range to 160 dB re μPa average pressure level-meter
Up-slope to 53 meter water depth	No expected levels higher than 160 dB from source within the SYU
Up-slope to 75 meter water depth	1523 meters
Up-slope to 125 meter water depth	1988 meters
Up-slope to 179 meter water depth	2511 meters
Up-slope to 201 meter water depth	3204 meters
Cross-slope in 258 meter water depth	3739 meters

1. Introduction

Field verification tests were required as part of the Incidental Harassment Authorization permit for the 1995 geophysical operations in the Santa Ynez Unit (SYU) of offshore California. BBN, Inc. was utilized as the independent contractor for the tests. Charles R. Greene and Don A. Chalfant of Greeneridge Sciences Inc., were also present in the role of independent observers. Dr. Greene was aboard the receiver vessel, and Mr. Chalfant was aboard the Source Vessel. In addition, MMS personnel were aboard both vessels to observe the operations. Jack McCarthy of the MMS was aboard the receiver vessel.

1.1 Description of Field Data Acquisition

The experiments were conducted between approximately 4:23 PM on November 9th and 5:56 PM on November 10th, 1995, within and in the immediate vicinity of the Exxon's Santa Ynez Unit (SYU) in Federal waters offshore of Santa Barbara, California. The SYU is roughly rectangular in shape and is characterized by shoaling bathymetry along its northern boundary, which roughly follows the California state waters line.

The purpose of the acoustic propagation experiments was to determine how received acoustic levels decreased as a function of range from the seismic airgun source array operated within the SYU. In environments with a sloping bathymetry, acoustic propagation varies in different directions and at different locations. In order to characterize acoustic propagation in the vicinity of the SYU area, two phases of experiments were conducted to look at both propagation up-slope toward shore and propagation parallel to shore.

The purpose of the Phase I experiments was to determine the sensitivity of the propagation to the placement of the receiver, since it is known that propagation up-slope can be highly variable. The first phase in the Exxon experimental protocol, consisted of a series of 5 up-slope propagation tests using a receiving array anchored in state waters at various depths and offsets from the northern boundary of the SYU. The source ship was restricted from entering state waters and performed tracks in federal waters across the SYU area. The receiving hydrophone array was deployed from a moored vessel at five locations spaced at distances of approximately 1080 meters. apart at water depths from 53 to 201 meters. The first receiver location was approximately 2 km off-shore, while the last was 6 km offshore, within 1 km of the northern boundary of the SYU. The seismic vessel M/V Mintrop followed tracks that resembled a square wave pattern with sides of about 1 km, south of the receiver ship in the SYU (Figure 1). These tracks were designed to expose the receiver to all aspects angles of the airgun array to determine its directivity pattern and to make direct measurements of the array pulses at different ranges broadside to the source array. In actuality six runs were made in Phase I. A second run was performed with the receiver ship at the first position, because the first run was incomplete.

Phase II in the Exxon experiment protocol was a nearfield source level measurement and a cross-slope propagation experiment. The receiving array was moored at the northern edge of the SYU boundary as the source array was towed east, parallel to the SYU northern border, past the receiver array and out to a range of 9 km (Figure 2). The purpose of this experiment was to determine how sound propagated in the cross slope or approximate constant water depth geometries consistent with the interior of the SYU itself and to determine array source levels and directivity with nearfield measurements. The Mintrop started the run to the west of the receiver array and made a close approach of the source vessel and performed a circular track near the receiver in order to allow nearfield measurements. It then proceeded directly away from the receiver to the east out to a range of 9.6 km. Two dog-legs were executed by the source ship at the 5 and 9.6 km marks to allow comparison of endfire and broadside source levels for both sides of the array.

1.2 Source Ship

The source ship was the M/V Mintrop, a trawler which was converted into a seismic exploration vessel by GECO-Prakla. This ship deployed an eighteen element airgun array with a total displacement of 3959 cu. in.. The array was deployed at a depth of 6 meters, and had a physical aperture of 18 x18 m, defined by three subarrays of 18 m length containing 6 guns of different sizes at 3 meter spacing, with each subarray deployed 9 meters athwartships from its neighbor. The forward-most starboard airgun was held in reserve in the event of a gun failure during operations. The instantaneous peak source level of the airgun array reduced to a reference distance of 1 meter was estimated by Exxon before the experiment to be 23.7 Bar-m at broadside to the array horizontally, and 106 Bar-m in the main lobe directed vertically. In engineering units familiar to underwater acousticians, these instantaneous peak pressures correspond to

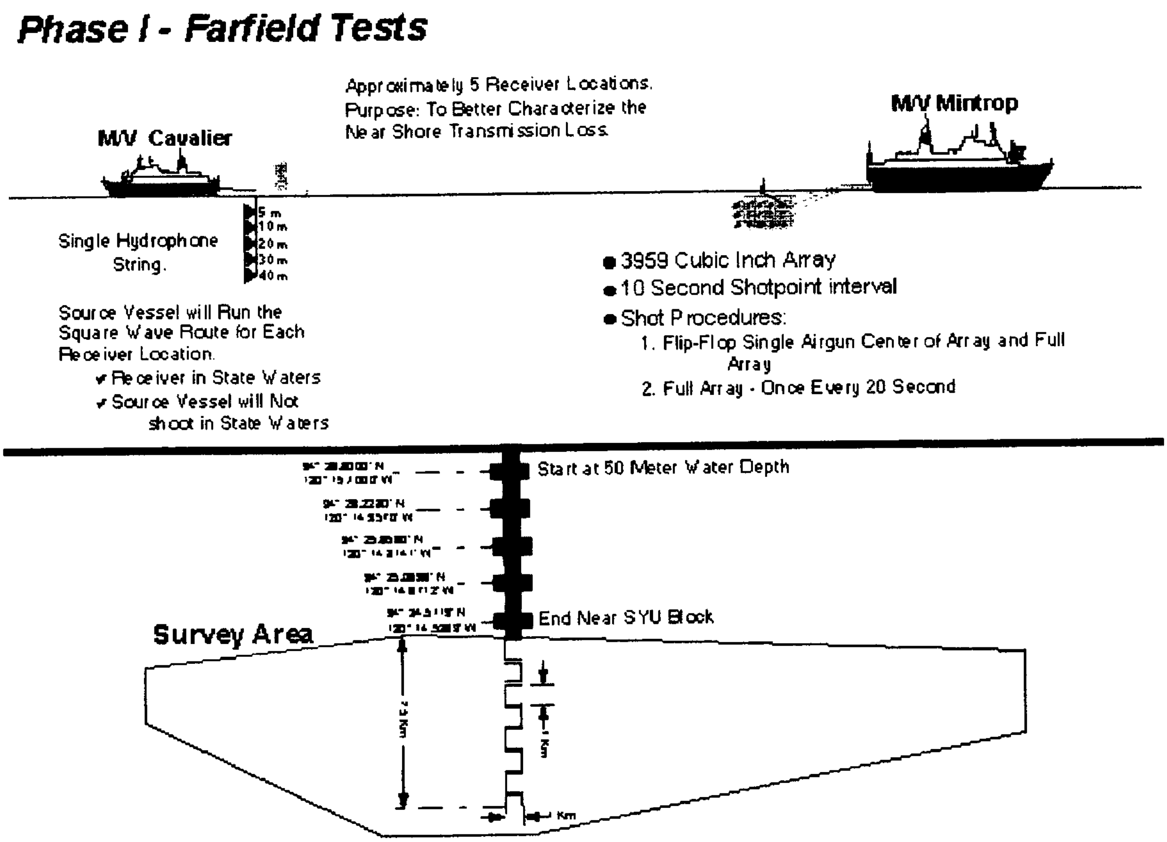

Figure 1. Phase I experimental geometry. The receiver was placed in shallow water north of the SYU and the source was towed along a square wave pattern in order to expose the receiver to broadside and endfire aspect as a function of range. As the received signal characteristics depend both upon the source and the receiver location in up-slope (shoaling) bathymetry, a total of five experiments were conducted at water depths between 53 and 201 meters, at locations between 2 and 6 km from shore.

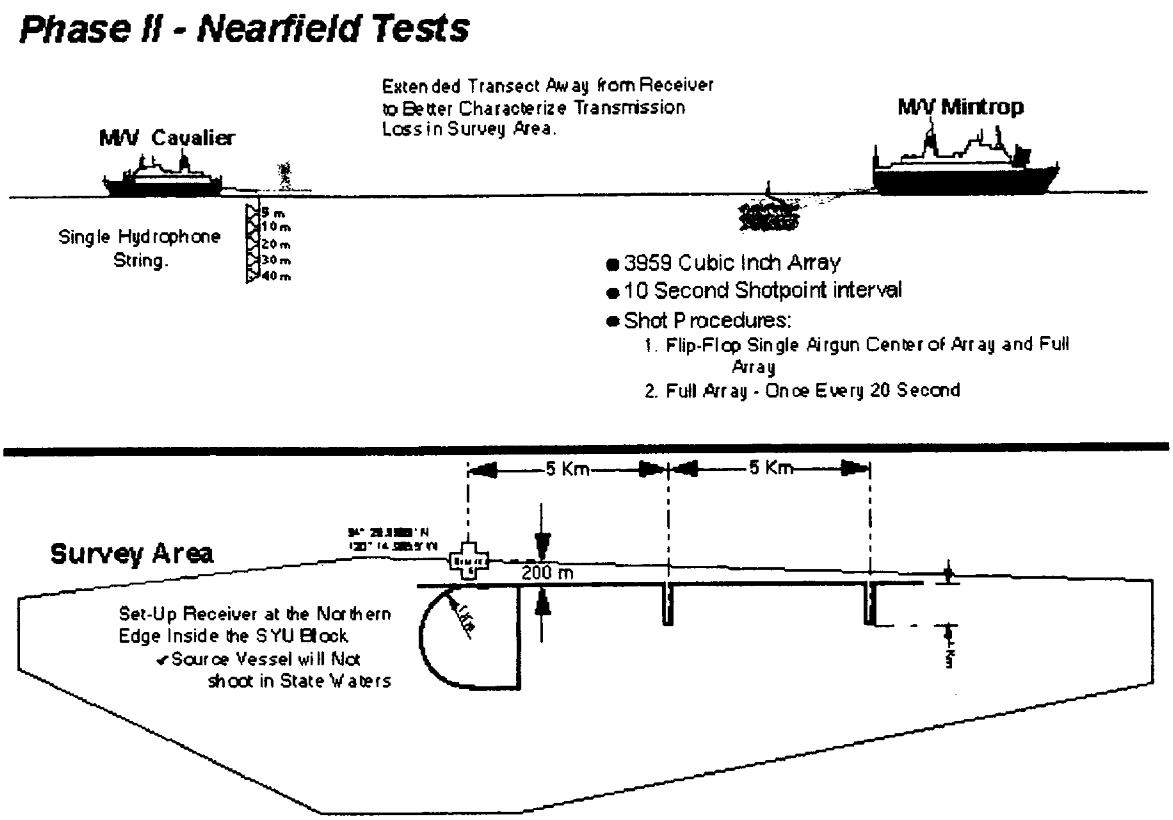

Figure 2. Phase II experimental geometry. The receiver was placed in deep water at the northern end of the SYU and the source was towed close by the receiver in a 2 km diameter loop and then towed east along the northern end of the block, executing two beam aspect legs at 5 and 9.6 km. The purpose of this experiment was to determine the 190, 180 and 160 dB re μPa isopleths for operations within the SYU.

247.5 dB re μPa-m at broadside, and 260.5 dB re 1 μPa-m in the vertical direction. The source array firing interval was designed to emulate the interval used for seismic recording operations. A single airgun shot was alternated with the full source array at 10 second intervals.

1.3 Receiver Ship and Receiving Array Geometry

The receiving vessel was the M/V Cavalier, a supply boat leased by Exxon. The receiving array was deployed off a special arrangement of buoys, which floated approximately 30 meters from the stern of the ship. The receiving array had a physical aperture of 35 meters, with hydrophone elements deployed at 5, 10, 20 and 40 meter depth and was held in a vertical position by a 30 kg depressor.. The aperture of the array was dictated by the shallow 50 meter water depth of the first location. The array was decoupled from the motion of the waves by a train of buoys to make the assembly neutrally buoyant. A diagram of the assembly is shown in Figure 3. The buoy train was connected at a distance of about 7 meters to a large marker buoy which held a GPS antenna on a short mast. The marker buoy itself was connected to the Cavalier with a 1 inch nylon hawser strength member, to which the hydrophone cable and GPS antenna cable were loosely tied and floated using Norwegian buoys. The hawser was tied to bollard posts on the aft deck. The array typically streamed out about 30 meters from the vessel. Under some wind and current conditions, the array drifted up against the vessel, and had to be manually held off to prevent tangling on the props or rudder. The array was tended for the full duration of the test.

1.4 Data Acquisition and Recording System

The hydrophones were manufactured by High Tech, Inc. and consisted of 4 HTI-194 and 1 HTI-215. These are cylindrical piezo-electric element phones with built-in current-mode preamplifiers for 2 wire low noise operation and minimal response variation when driving cables. The hydrophones were mounted on an hair-faired Kevlar cable and deployed with the assistance of a pneumatic winch.

The hydrophones deployed on the array cable had the depths, sensitivities and channel numbers outlined in Table 1. The HTI-194 hydrophone/preamp units (the hydrophones had built-in preamps) were calibrated by High Tech Inc. over the range of 200 to 1.5 kHz. The variation over this range was less than +- 0.5 dB.

Table 1. Vertical hydrophone array specifications

Channel #	Depth (m)	Sensitivity dB re V /µPa	Roll off (kHz)	Serial #
0	40	- 213.8	20	2006
1	30	- 195.29	>20	101001
2	20	- 195.22	>20	101002
3	10	- 195.27	>20	101003
4	5	- 195.25	>20	101004

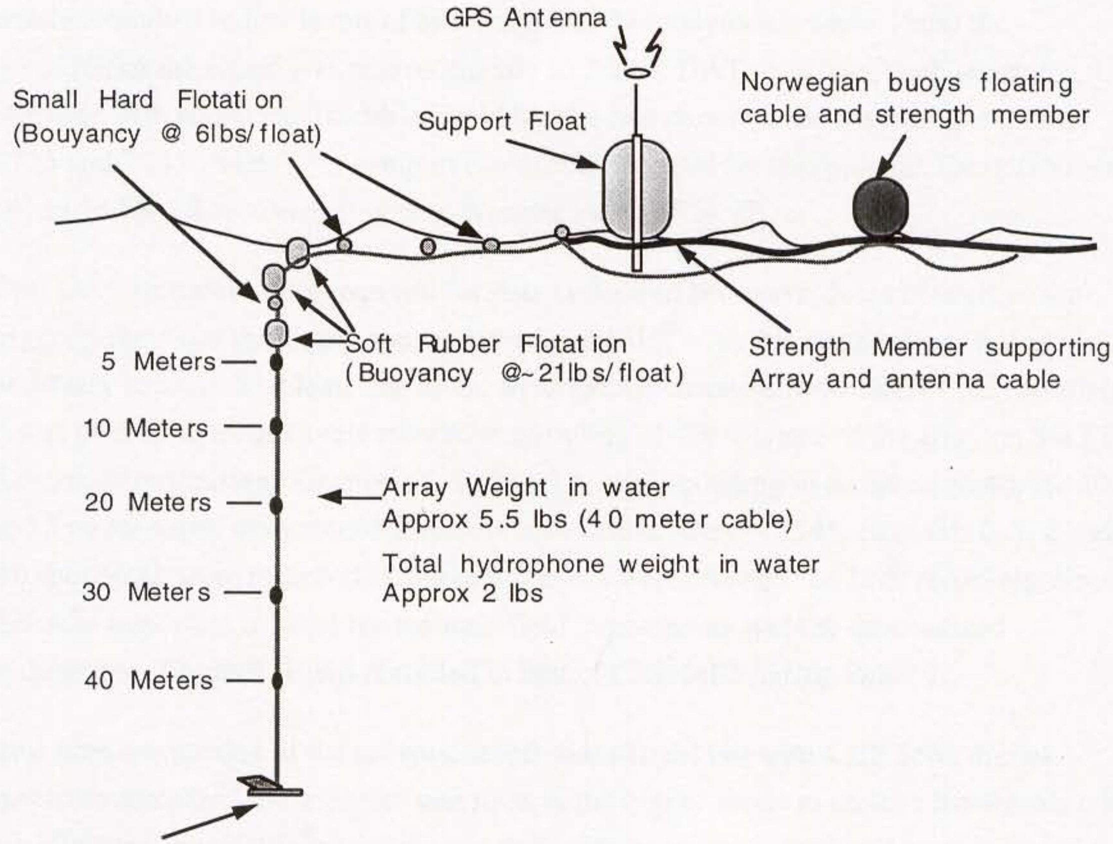

Figure 3. Receiving array deployment arrangement. Hydrodynamic and mechanical noise was reduced by deploying the array in a neutrally buoyant configuration off a train of small floats. The float train was connected to a larger sea buoy to which the navigation antenna was affixed. The entire arrangement was deployed approximately 30 meters from the stern of the M/V Cavalier.

The preamps were calibrated separately over the range of 2 Hz to 30 kHz and varied less than 0.2 dB from 10 Hz to 30 kHz. Hydrophone crystals of the same type used in these units have been previously calibrated and have constant sensitivity from 10 Hz to 2 kHz and are 1 to 2 dB less sensitive from 4 kHz to 20 kHz. They are omnidirectional in the horizontal plane to over 15 kHz and are +- 2 dB in the vertical plane. A calibration for the particular desensitized hydrophone was not available, and the manufacturers sensitivity was used.

The dry end of the hydrophone cable was lead to a low noise preamplifier with 20 dB of gain per channel. No additional filtering was used since the array suspension and calm weather resulted in low levels of low frequency hydrodynamic noise. From the preamplifier the signal was passed directly to 2 Teac DAT recorders, each recording 4 channels with signal bandwidth of 20 kHz. The two data recorders were Teac models T135 and T145 which were setup to run at double speed for this project. These DAT units utilize 14 bit A/D converters with a dynamic range of 78 dB.

Two DAT recorders were required for data collection because 5 data channels plus a trigger pulse from the airgun source were recorded. With this arrangement it was necessary to exclude at least one of the hydrophone channels from each of the recorders. It was desired to record a representative sampling of the aperture of the array on the T135 for ease of processing. Channels 0, 2, 3 and 4, corresponding to receivers at 40, 20, 10, and 5 meter depth were recorded on this instrument. On the T145, channels 0, 1, 2 and the shot break were recorded. Channels 0 and 2 were recorded on both recorders, since the most important channel for the near-field experiments was the desensitized hydrophone. Channel 1 was recorded in lieu of Channel 3 during Phase I.

Real time monitoring of the acoustic levels was carried out with a HP 3561 digital spectrum analyzer. The analyzer was used in the trigger mode to capture the signals from the 30 meter phone. The instantaneous peak voltages were logged and were converted to dB re μPa with the system/hydrophone gain of -175 dB re V / μPa.

1.5 Post-processing System

The post processing system was comprised of a Teac DAT interface card, QuickVu™ software and a 100 MHz Pentium based PC with 44 MBytes of RAM and 2 GBytes of hard disk space. Time series data was downloaded to the PC by selecting time windows containing the airgun pulses. All post analysis was then performed with the data loaded into the MATLAB™ environment. Scripts were written which read the binary files produced by QuickVu™ and converted the time series into microPascals. All subsequent processing was performed in the engineering units of microPascals.

1.6 Navigation

Navigation was supplied by Racal, a navigation contractor familiar with geophysical and marine positioning. Navigation information from the M/V Mintrop was combined with differential GPS positions for the receiver array to provide relative positions of the source and receiver and the bearing to the receiver from the array. It was originally planned that the M/V Mintrop would collect the M/V Cavaliers position via a radio link, but the communication equipment failed. However, because the receiver ship was anchored, it was possible to transfer sufficiently precise navigation data from the receiving vessel every 5 minutes via radio communications to the M/V Mintrop. On the M/V Mintrop, the position of the source array was determined relative to the ships navigation by a laser range-finder. Navigation data was processed the day after the experiment by Geco-Prakla and Energy Innovations to provide an ASCII file containing shot, date, time, ship XY, Gun XY Receiver XY, distance between airgun array and receiver, bearing to receiver, shot heading, and water depth. This data was used directly for determining the range and aspect angle of the array to the receiver required by our processing. The ship tracks for the five Phase I experiments are illustrated in Figures 4a, 4b and 4c. The ship track for the Phase II experiment is illustrated in Figure 5. On all of these figures, the relative bearing of the receiving vessel is indicated by the green vectors, which point vertically when the receiving vessel was directly ahead of the array, vertically down when the receiving vessel lay astern of the source array, and to the right when the receiving vessel lay to starboard of the source array.

1.7 Weather

Weather was favorable throughout the two phases and during deployment and recovery of the acoustic array. The wind was less than 15 knots, with sea states of 0 to 1. Wind directions ranged from south to west. At each receiver ship position there was a westward current which affected the streaming of the array.

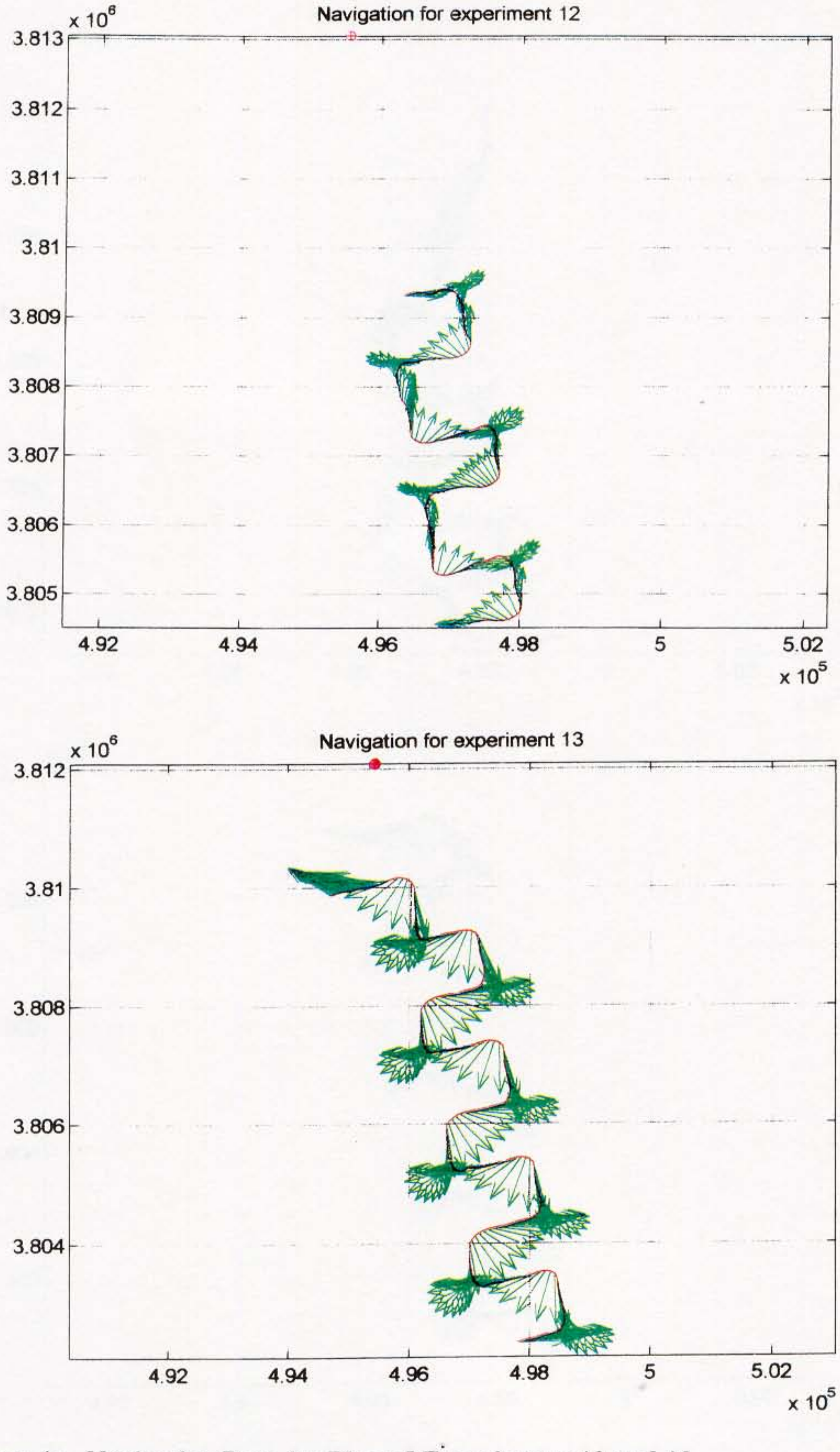

Figure 4a. Navigation Data for Phase I Experiments 12 and 13.

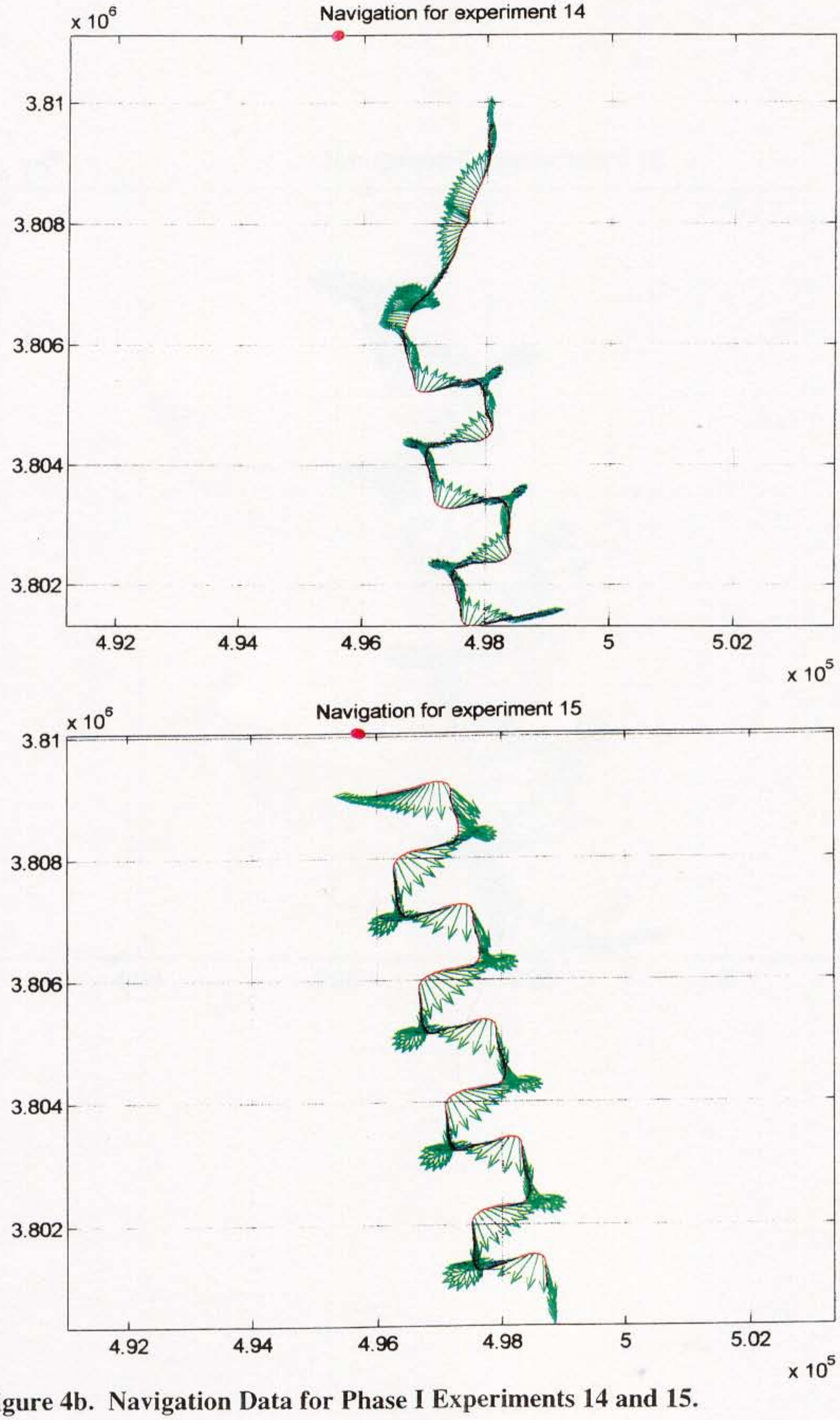

Figure 4b. Navigation Data for Phase I Experiments 14 and 15.

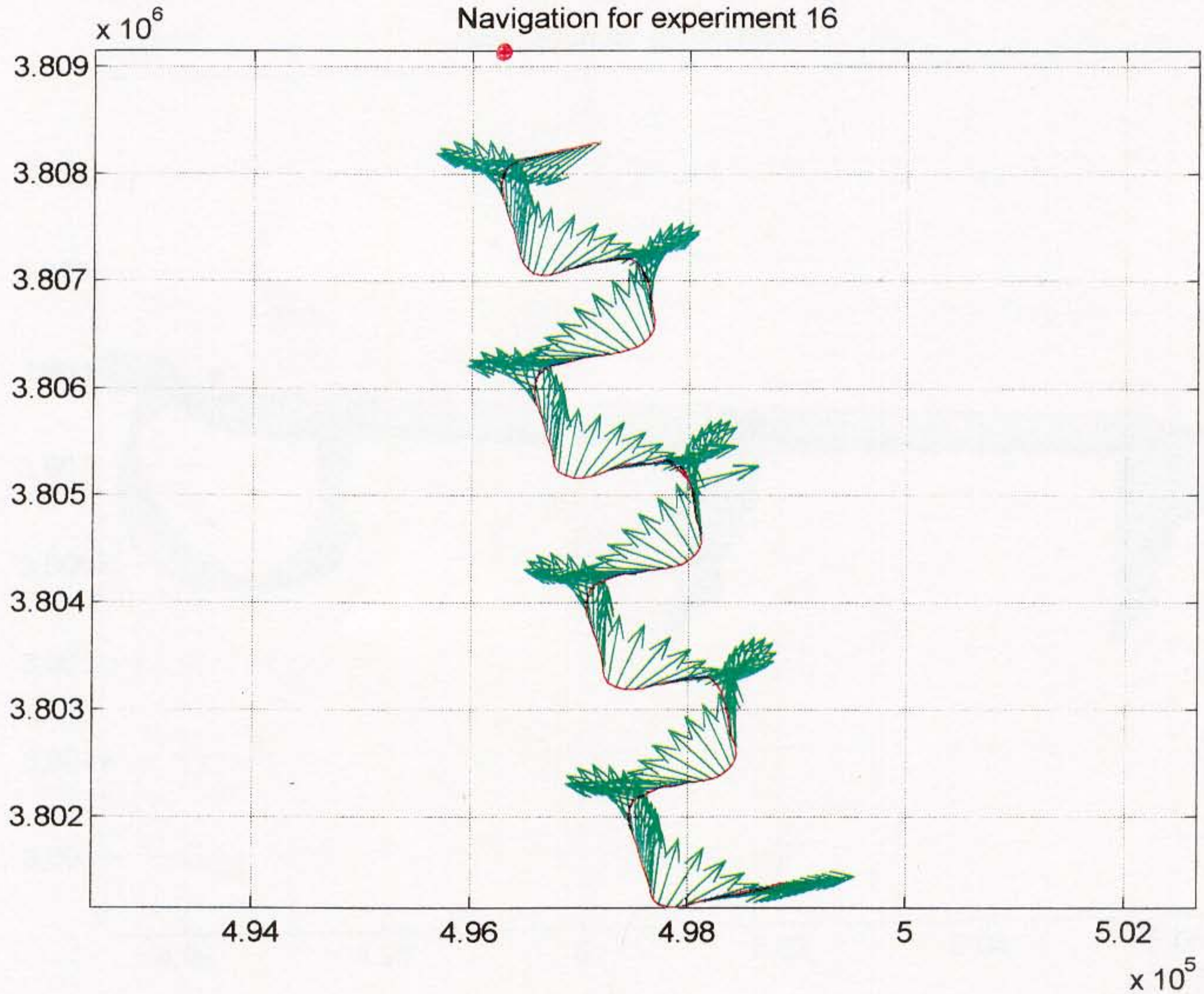

Figure 4c. Navigation Data for Phase I Experiment 16.

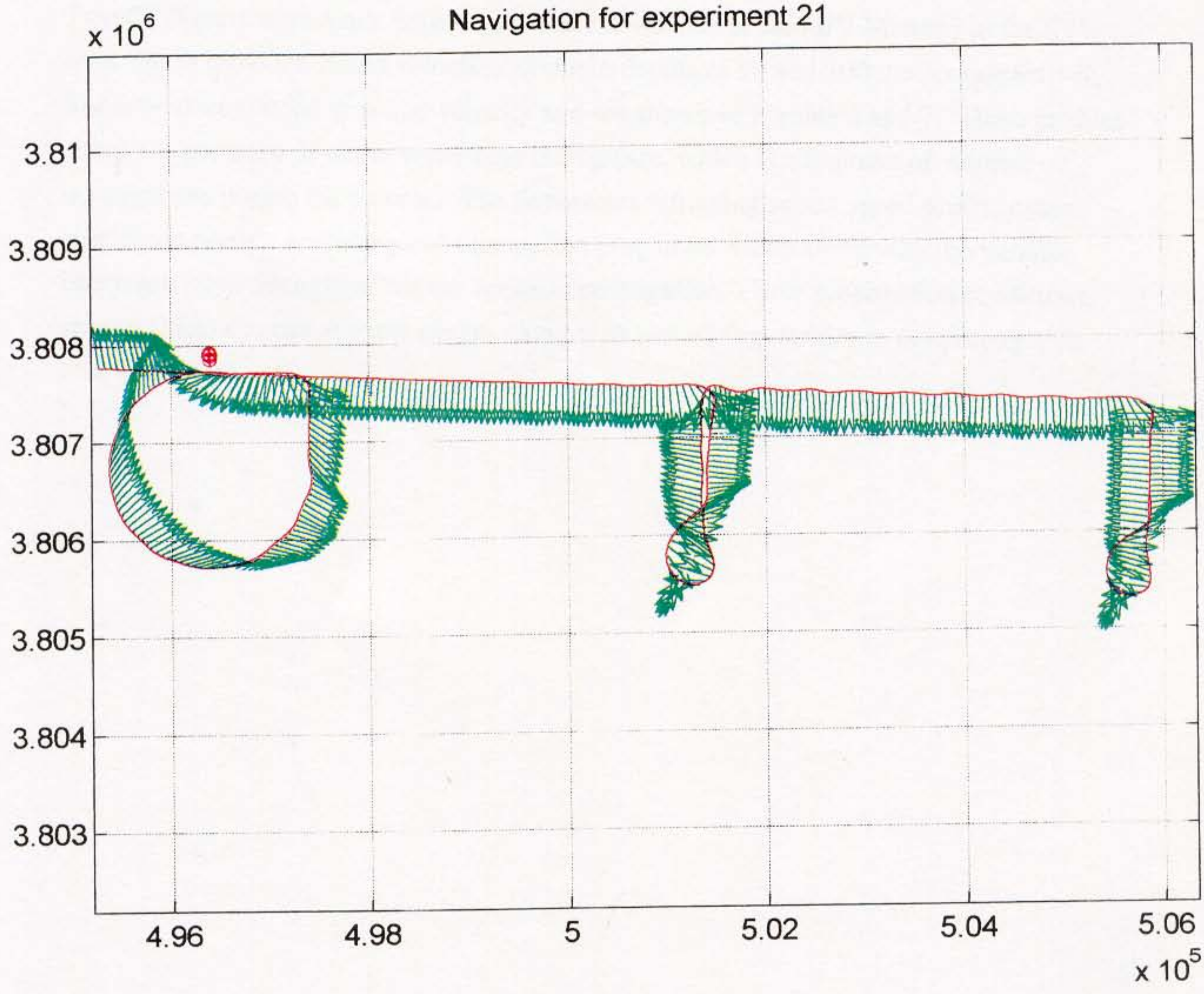

Figure 5. Navigation Data for Phase II Experiment 21

1.8 Sound speed

Two CTD casts were made before and after the tests from the M/V Mintrop in the SYU area. These provided sound velocities down to depths of 80 and 100 meters respectively. These were converted to sound velocity and are shown in Figures 6 and 7. These profiles show the presence of warm water near the surface, which is a remnant of warmer temperatures during the summer. The downward refracting sound speed profile causes significant bottom scattering and attenuation properties which along with the variable bathymetry can strongly affect the acoustic propagation. These propagation conditions caused shadow zones at some ranges along with some irregularities in the propagation loss with range.

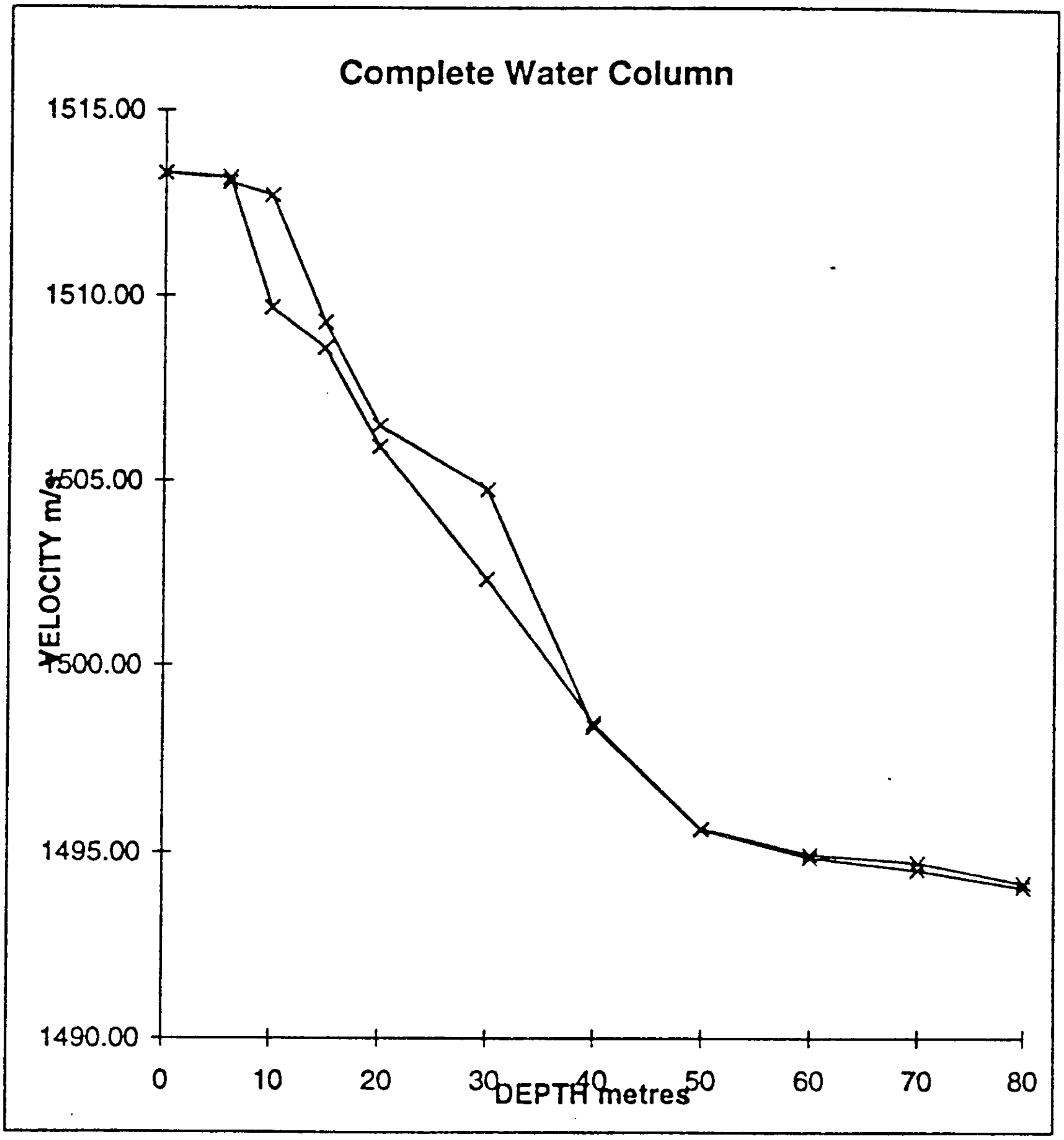

Figure 6. **CTD cast to 80 meters from a position approximately half way along the square wave ship track of the M/V Mintrop from the Phase I experiments. This profile is strongly downward refracting, indicating strong bottom interaction and the possibility of acoustic shadow zones at shallow receiver depths.**

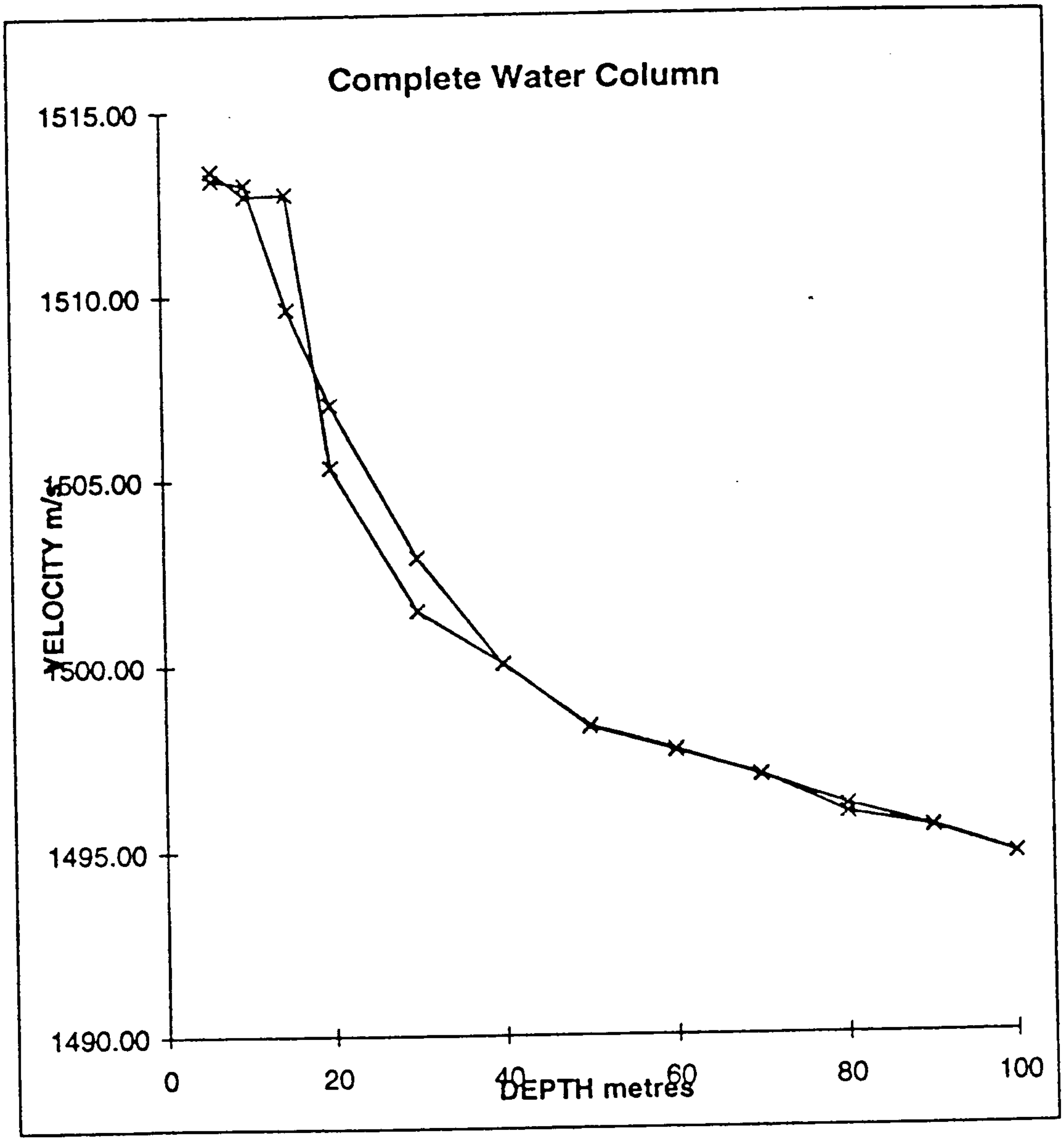

Figure 7. CTD cast from a location near the close pass from the Phase II experiment. This sound speed profile is quantitatively similar to the first measurement illustrated in Figure 6, and causes significant bottom interaction of long range acoustic transmissions as well as the creation of shadow zones for receivers in shallow water when the source is in deep water.

2. Data Processing and Results

2.1 Acoustic Data Processing

The continuously recorded time series were first windowed to capture the arrival from the airgun array and downloaded to the PC for analysis. One airgun array shot every minute was selected, which typically provides spatial sampling of acoustic levels every 125 meters of range. Over some portions of the Phase I runs, no arrival was discernible above the broadband noise floor. This noise floor was set by noise from the M/V Cavaliers' generator which could not be turned off for the tests. The rms noise floor was approximately 145 dB re μPa.

The windowed time series for all the received signals at all hydrophone depths were input to MATLAB™ for processing. The acoustic time series were first filtered to remove very low frequency noise due to motions of the array caused by wave action transmitted through the cable and strumming effects of the current. The filter used was a 4th order high pass Butterworth filter at 5 Hz. The hydrophone and system sensitivities were then used to change the voltages from the DAT to acoustic levels in microPascals. The filtered data were then processed to measure the average pulse pressure. This was computed by summing the square of the pressure over the pulse duration, multiplying by the sample interval and then dividing by the pulse duration. The pulse duration was defined to be the interval between which 10 to 90% of the energy in the time series accumulated. The average pulse pressure is the acoustic exposure metric used in investigations of the effects of underwater noise on migrating gray whales in California (C.I. Malme, P.R. Miles, C.W. Clark, P. Tyack and J.E. Bird, "*Investigations of the potential effects of underwater noise from petroleum industry activities on migrating gray whale behavior/ Phase II: January 1984 migration,*" BBN Report 5586, for US Minerals Manage. Serv, Anchorage, Al). "Malme et all expressed the average pulse pressure as the effective peak pressure of an equivalent constant-amplitude sine wave with the same pulse duration. This convention has been followed in this report.

Additional acoustic measures were logged, including peak amplitudes, energy, and energy spectral density (ESD). A set of recorded time series and spectra for the peak amplitude collected during the Phase II experiment are shown in Figures 8a and 8b. In Figure 9, time series from later in the Phase II experiment are also shown, where the

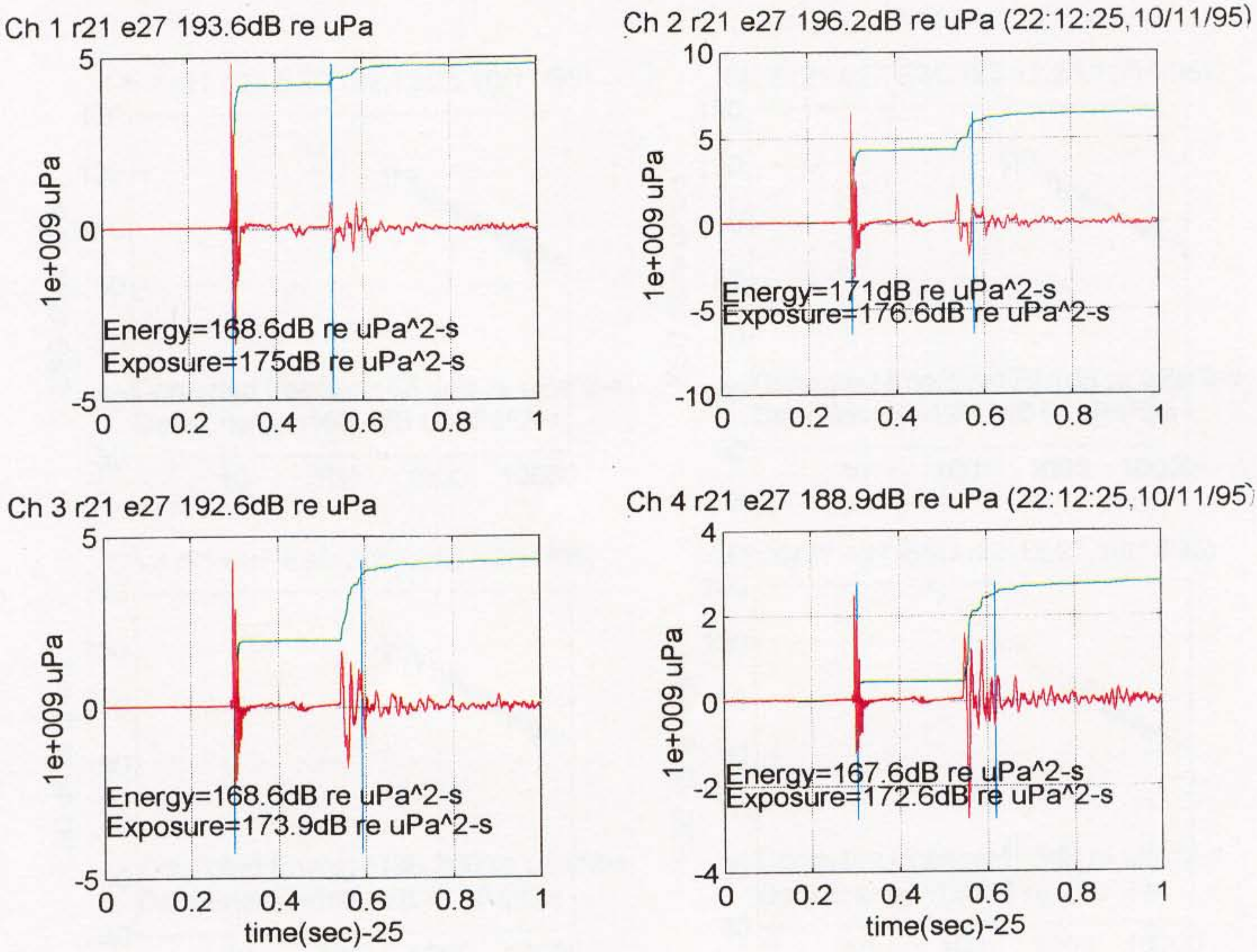

Figure 8a. Time series received across the hydrophone array at a range near 180 meters offset during the Phase II experiment. The black traces are the unfiltered time series, and the red traces are after the 5 Hz high pass filter has been applied and the green trace is the integrated energy normalized to fit on the same scale. The caption contains the peak pressure amplitude in dB re μPa, which is in general about 15 dB greater than the average pulse pressure amplitude, which is an average measure over the signal duration. The cyan cursors indicate the time duration over which the pressure amplitude was averaged to obtain the average pulse pressure. Small cursor spacings typically imply that the energy arrival was compact in time, and that the average pulse pressure amplitude was therefore higher.

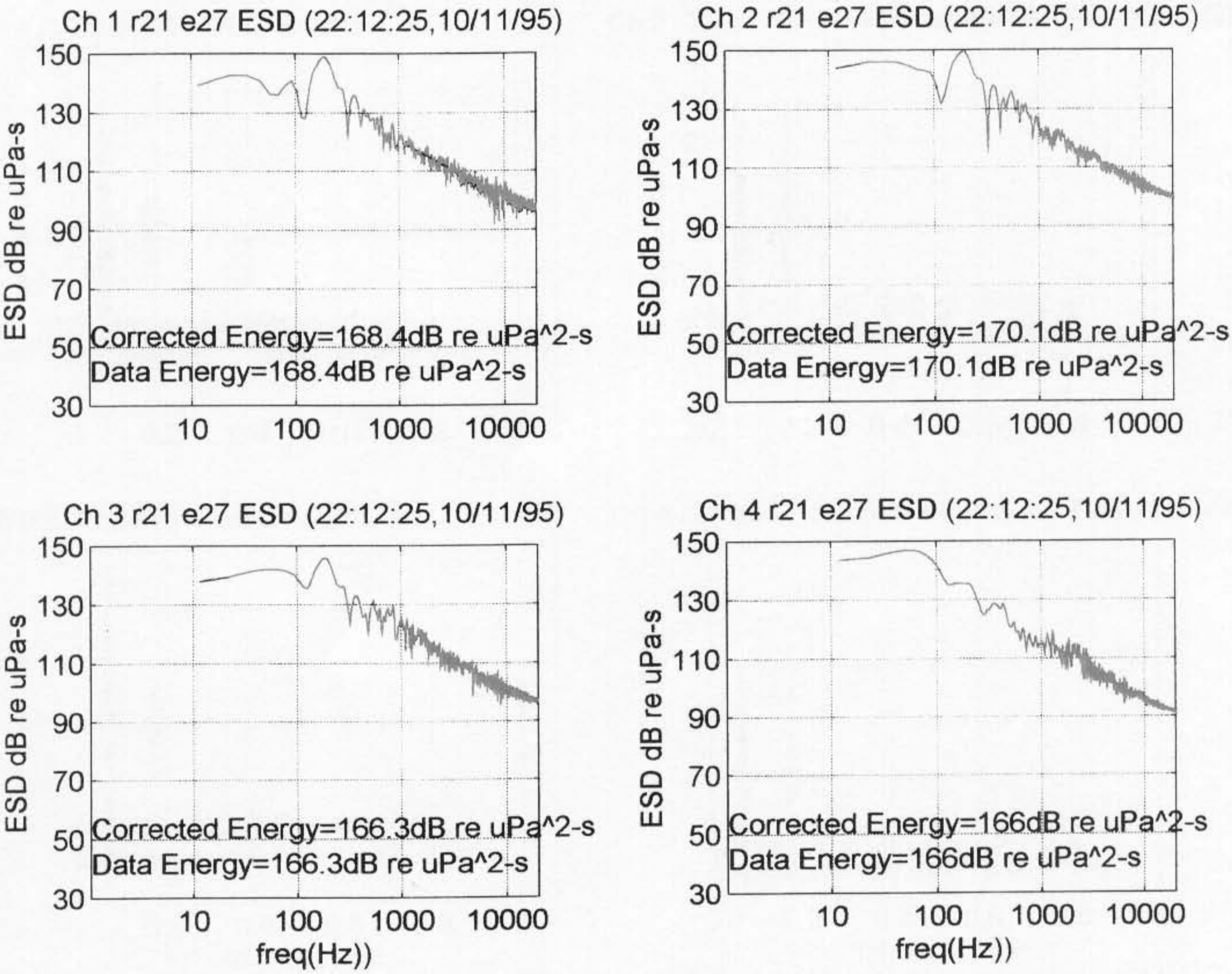

Figure 8b. Energy spectral density of the source signature measured at a range of 180 meters as a function of receiver depth. The upper left figure is for the 40 meter hydrophone, the upper right figure is for the 20 meter hydrophone, the lower left figure is for the 10 meter phone and the lower right figure is for the 5 meter phone. The energies are plotted in density form, which means that the energy in a 1 Hz bin can be directly read off the figure. For instance, the energy in the received signal at 1000 Hz is approximately 120 dB re μPa^2-s across all the hydrophones.

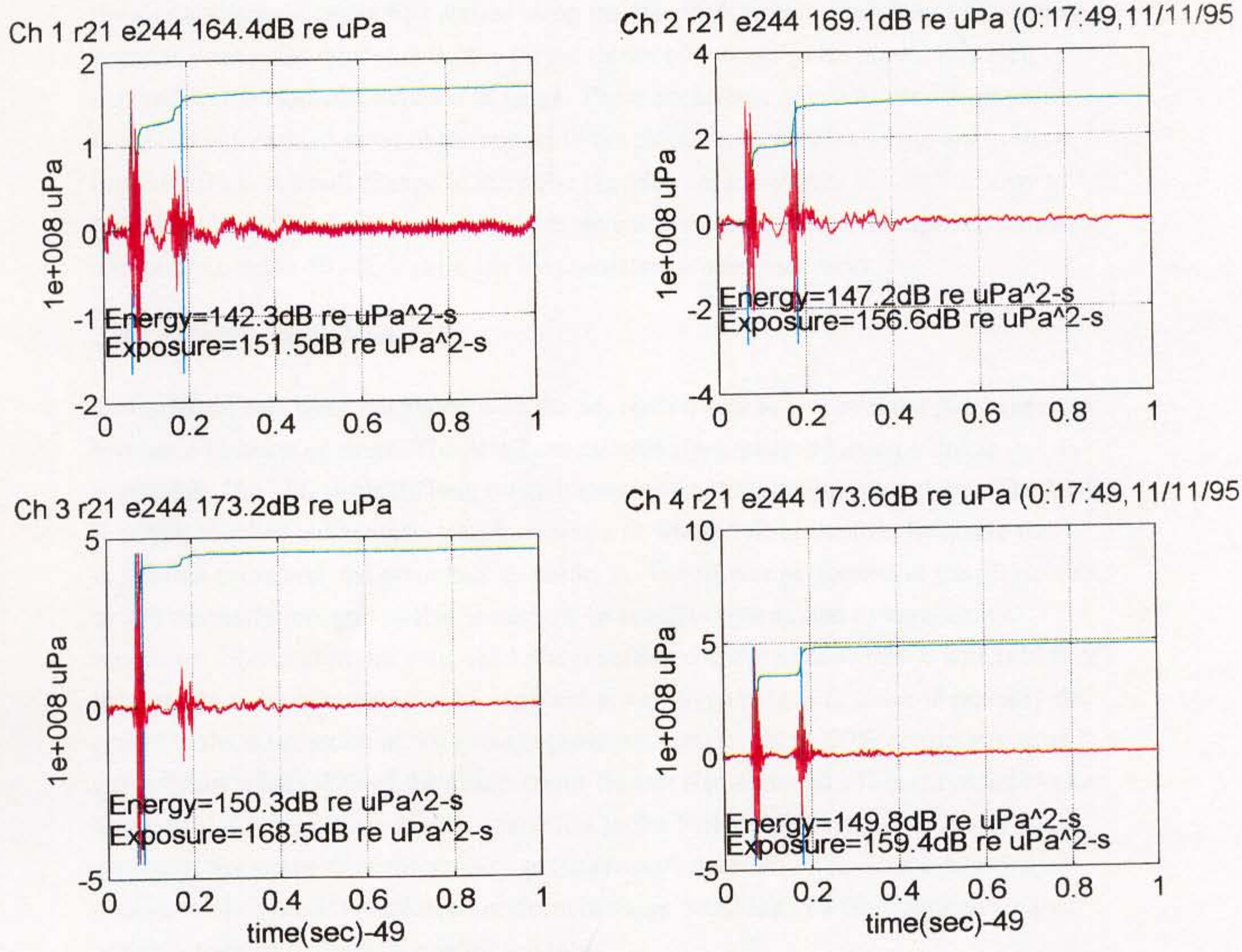

Figure 9. Time series for Phase II experiment at a range of 5 km at broadside aspect. Note that the 10 meter hydrophone (lower left hand panel) has all of its energy in a single arrival. This leads to a very short pulse duration of 16 msec and a correspondingly high average pulse pressure of 168.5 dB re μPa.

pulse duration for the lower left hand plot is seen to be very short due to the fact that all the signal energy is in the first arrival using the 10 - 90% metric. This result was shown because short pulse durations lead to larger values of average pulse pressure, which in turn moves the isopleths outward in range. These occasional jumps to very short pulse duration contribute to some of the spread in the plotted measurements, and are in some sense artifacts. A small change in the pulse duration criterion from 10 - 90% energy to 5 - 95% would have made all pulse lengths more uniform, and reduced this spread. However, we maintained the 10 - 90% criterion for consistency with prior work.

2.2 Regression Analysis

The acoustic data were integrated with the navigation data to plot average pulse pressure level as a function of range. The data from all tests were analyzed using a linear regression, "L1" fit, to obtain long range transmission characteristics up-slope. The L1 fit is a least absolute value norm, which returns a fit where half of the data lie above the regression curve and the other half lie below it. The fit was performed in the dB domain, as it is generally recognized that sensitivity to sound is best related to logarithmic measures. Obtained in this way, the L1 regression provides a curve below which 50% of the average pulse pressures can be expected at any given range. In order to quantify the spread in the distribution of the average pulse pressure levels, a "90% confidence limit " curve below which 90% of the observations lie was also obtained. This curve always lies above the L1 regression, which is equivalent to the 50% confidence limit. In our approach, the statistics of the average pulse pressure distribution about the 50% confidence line are assumed to be uniform in range, resulting in a 90% confidence limit which is parallel to the 50% confidence limit.

Because of the way the whale avoidance statistics were calculated in the original studies by Malme et. al., the L1 regression, 50% curve which parameterizes the average exposure at a given range, is the proper measure with which to calculate the isopleths to the 190, 180 and 160 dB re μPa average pulse pressure levels. The 90% confidence intervals are reported in the interest of quantifying the spread of the observed average pulse pressure distributions, but are not appropriate for determination of isopleths as they are not consistent with the statistical methodology used by Malme et. al. to determine that 160 dB re μPa average pulse pressure caused 10% avoidance by gray whales.

2.3 Summary of Phase I Results

Figure 10 shows received average pulse pressure level for Phase I Experiment 12, where the receiver array was deployed from the M/V Cavalier in 53 meters of water depth, upslope and toward shore from the Exxon SYU. Hydrophones data from depths of 5, 10, and 20 and 40 meters were analyzed. Data from the 40 meter phone was found to be anomalously low in level and was excluded from the final transmission loss parameterization. These data may be available in the future pending checkout and re recalibration of the 40 m phone. Modeling results and observations indicated that the directivity of the airgun array resulted in approximately 8.5 dB greater output to broadside compared to endfire. For this reason all the received levels were compensated for the source array directivity using the angles in the navigation data in order to obtain an effective exposure level as if all measurements were made at broadside, the direction of maximum exposure.

The results of Phase I Experiment 12 indicated that for the seismic source array operating within the SYU, average pulse pressure levels greater than 160 dB re μPa were extremely unlikely to occur in shallow water. The expected range to the 160 dB re μPa isopleth was determined to be 479 meters, a range which would require the source vessel to be far north of the SYU boundary. The spread between the L1 fit and the 90% confidence interval was found to be 7 dB. Sound transmission is very poor up-slope into shallow water from the deep water due to mode stripping and bottom attenuation, and the data exhibited significant scatter. This scatter is mainly due to the highly variable transmission characteristics of the upslope environment into extremely shallow water. The data were observed to obey a 15.4 log R power law.

For Phase I Experiment 13, where the receiver was 2.8 km from shore in 75 meter water depth, the average pulse pressures illustrated in Figure 11 were obtained. I
the endfire data have been corrected by 8.5 dB to account for source direct
Although the receiver has only moved 1.08 km towards the SYU into sligl Down slope
water, a significant number of average pulse pressure amplitudes exceedi
μPa were recorded at short ranges. This illustrates the highly variable nature of up slope propagation. The L1 fit to the data yields a range to the 160 dB re μPa isopleth of 1523 meters, and the spread between the L1 fit and the 90% confidence interval was 7.5 dB. The data were observed to obey a 24.8 log R power law.

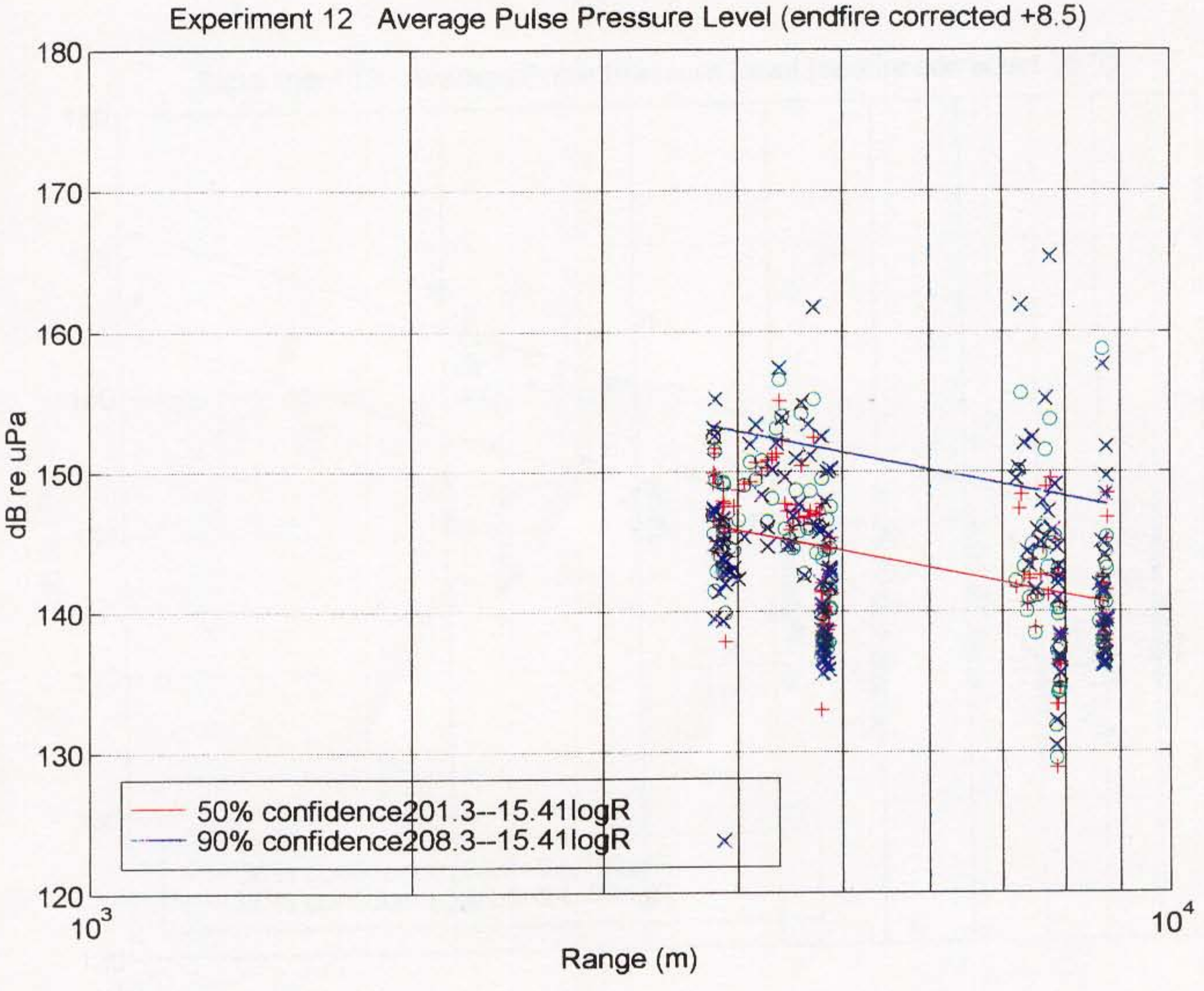

Figure 10. **The average pulse pressure level for the shallow water Phase I Experiment 12, where the receiver was placed in 53 meters of water. For this receiver location the average pulse pressure level is not expected to exceed 160 dB re μPa for source positions within the SYU. The 'x' symbols represent data from the 5 meter phone, the 'o' symbol data from the 10 meter phone, and the '+' symbol data from the 20 meter phone. Note that the results show a shadow zone between the source ranges of 5 to 7 km, a result caused by the shoaling bathymetry and the downward refracting sound speed profile. At a ranges beyond 7 km, the source ship executed a broadside aspect run, and the receiver picked up stronger signals, probably due to a bottom arrival being picked up at the receiver depth for this range. Such anomalous propagation effects are sensitive to details in the sound speed structure and the experimental geometry, and may not persist from season to season.**

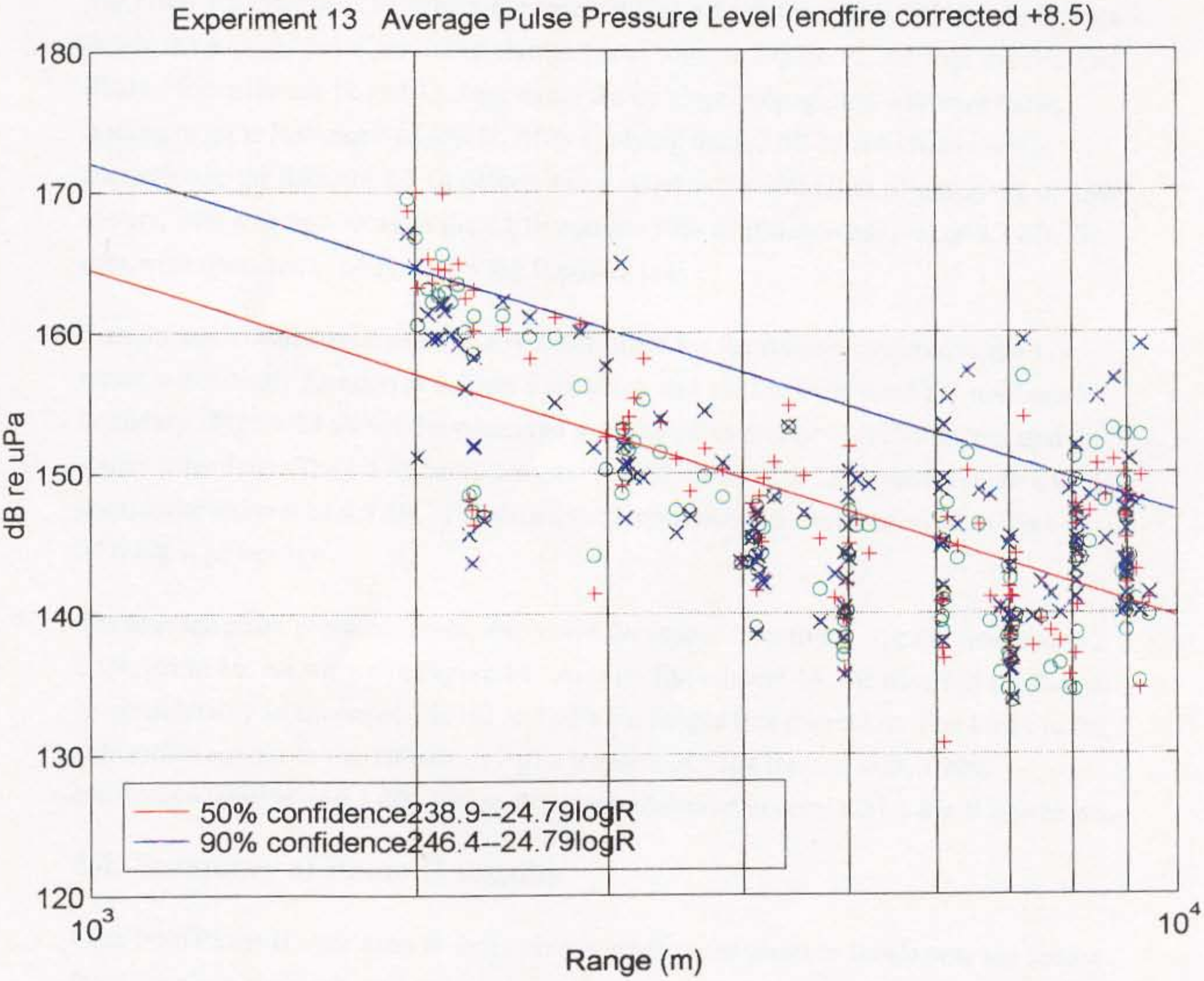

Figure 11. **The average pulse pressure level for Phase I Experiment 13. As with Experiment 12, signals received at intermediate range (4 - 5 km) were lower than those received at long range. In this case average pulse pressure levels at a range of 2 - 3 km exceed 160 dB re 1 μPa. An L1 fit to the data yields a range to the 160 dB isopleth of 1523 meters, with a 7.5 dB 90% confidence interval. The endfire data have been corrected by 8.5 dB.**

For Phase I Experiment 14, where the receiver was 3.6 km from shore in 153 meter water depth, the average pulse pressures obtained are shown in Figure 12. As with the first two Phase I Experiments 12 and 13, here again the up slope propagation was very harsh, leading to quite low received levels. After applying the 8.5 dB broadside to endfire correction to the data, the L1 fit determines a range to the 160 dB re µPa isopleth of 1988 meters, with a spread between the L1 fit and the 90% confidence interval of 8.3 dB. The data were observed to obey a 27.6 log R power law.

Transmission characteristics were also determined for the receiver moored at the 179 meter water depth location at 4.2 km from shore and 1.8 km from the SYU northern boundary. Figure 13 shows the measured average pulse pressure level compensated for source directivity. The L1 fit curve crosses the 160 dB level at 2511 meters, with a 90% confidence interval of 4.5 dB. The data from Experiment 15 were observed to obey a 34.6 log R power law.

The average pulse pressure levels, corrected for source directivity, for the final Phase I Experiment 16, are shown in Figure 14. As with Experiment 15, the received levels can be considerably in excess of 160 dB re 1 µPa for ranges less than 5 km. The L1 fit to the data yields a range to the 160 dB re 1 µPa isopleth of 3204 meters, with a 90% confidence interval of 6.1 dB. These data were observed to obey a 21.1 log R power law.

2.4 Summary of Phase II Results

Data from Phase II were used to determine average pulse pressure levels near the source from the close approach and transmission characteristics for the cross slope propagation. To determine long range transmission characteristics, average pulse pressure levels for all selected shots were compensated for directivity and plotted as a function of range. As with the Phase I experiment, the directivity effects of the source array were compensated using an 8.5 dB broad-side to end-fire ratio. Three hydrophones are plotted together in Figure 15 for ranges from 500 meters to 10 km along with a L1 parameterization of the data obtained by fitting data between the ranges of 500 and 10000 meters. The results show that the 160 dB re µPa isopleth occurs at a range of 3739 meters, with a 90% confidence interval of 4.4 dB. The long range, cross slope data were observed to obey a 20.9 log R power law.

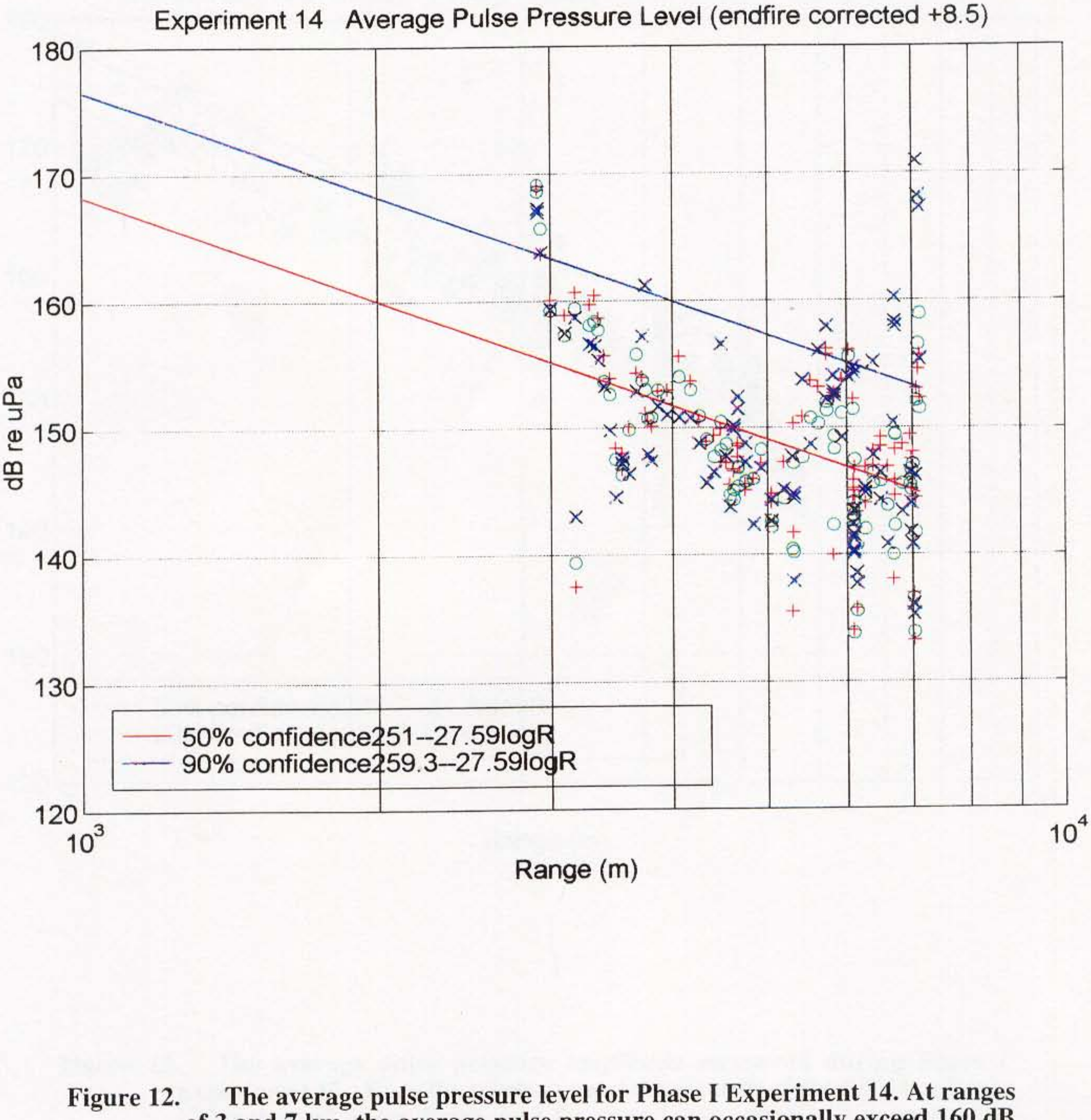

Figure 12. The average pulse pressure level for Phase I Experiment 14. At ranges of 3 and 7 km, the average pulse pressure can occasionally exceed 160 dB re 1 μPa, however the depression of the received levels at intermediate ranges yields an L1 fit which predicts that the 160 dB isopleth is 1988 meters, with a 8.3 dB 90% confidence interval. Throughout this report, an 8.5 dB broadside to endfire correction has been applied to the data.

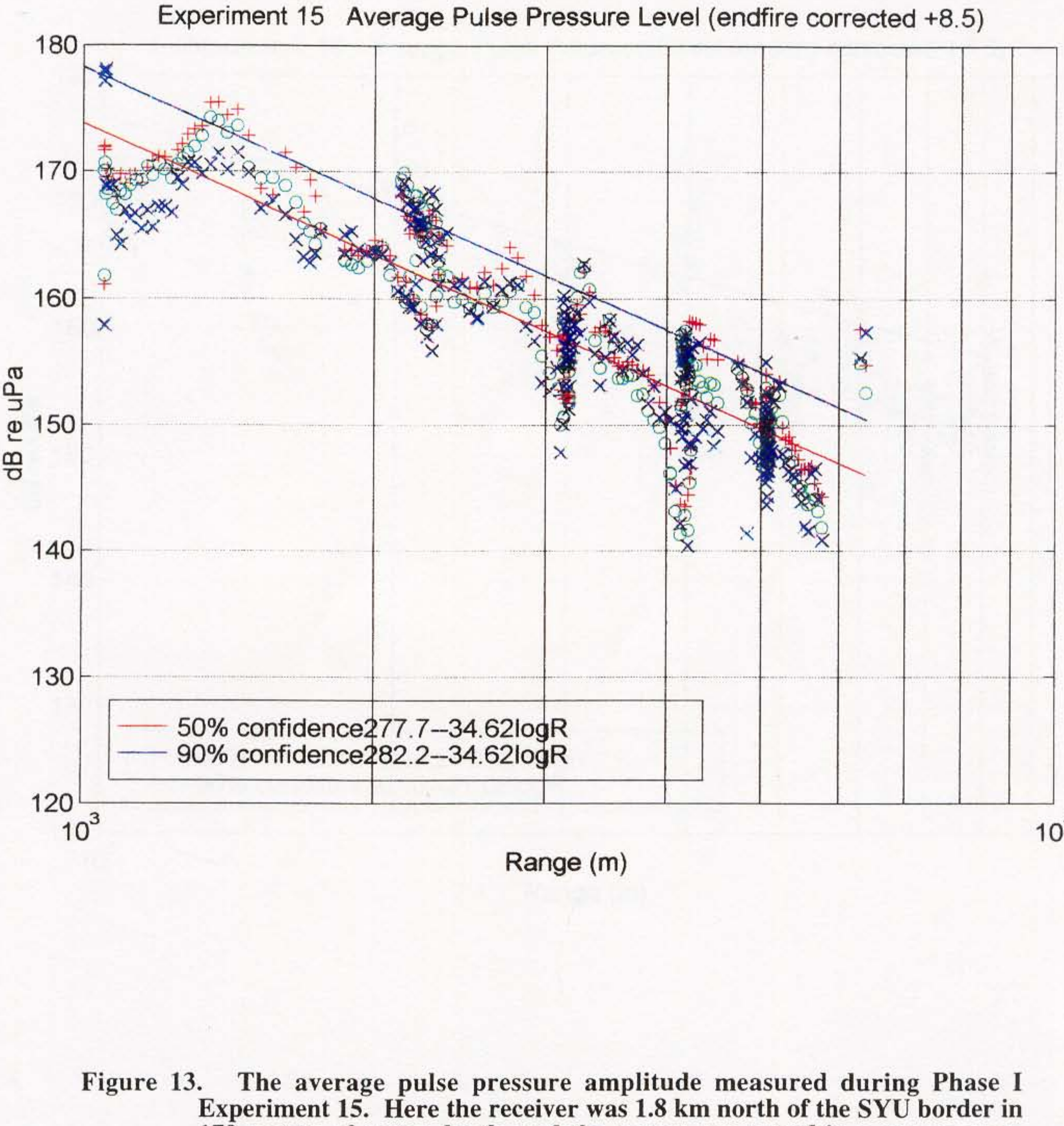

Figure 13. The average pulse pressure amplitude measured during Phase I Experiment 15. Here the receiver was 1.8 km north of the SYU border in 179 meters of water depth, and the source was towed in a square wave pattern up to the northern boundary of the SYU. A L1 fit to the data yields a range to the 160 dB re μPa isopleth of 2511 meters, with a 4.5 dB 90% confidence interval. Note that the endfire aspect data have been corrected by an 8.5 dB endfire to broadside directivity function. Endfire aspect data, thus corrected, fall more nearly into line with the broadside data, which were recorded at constant ranges of 2.2, 3.2, 4.2 and 5 km.

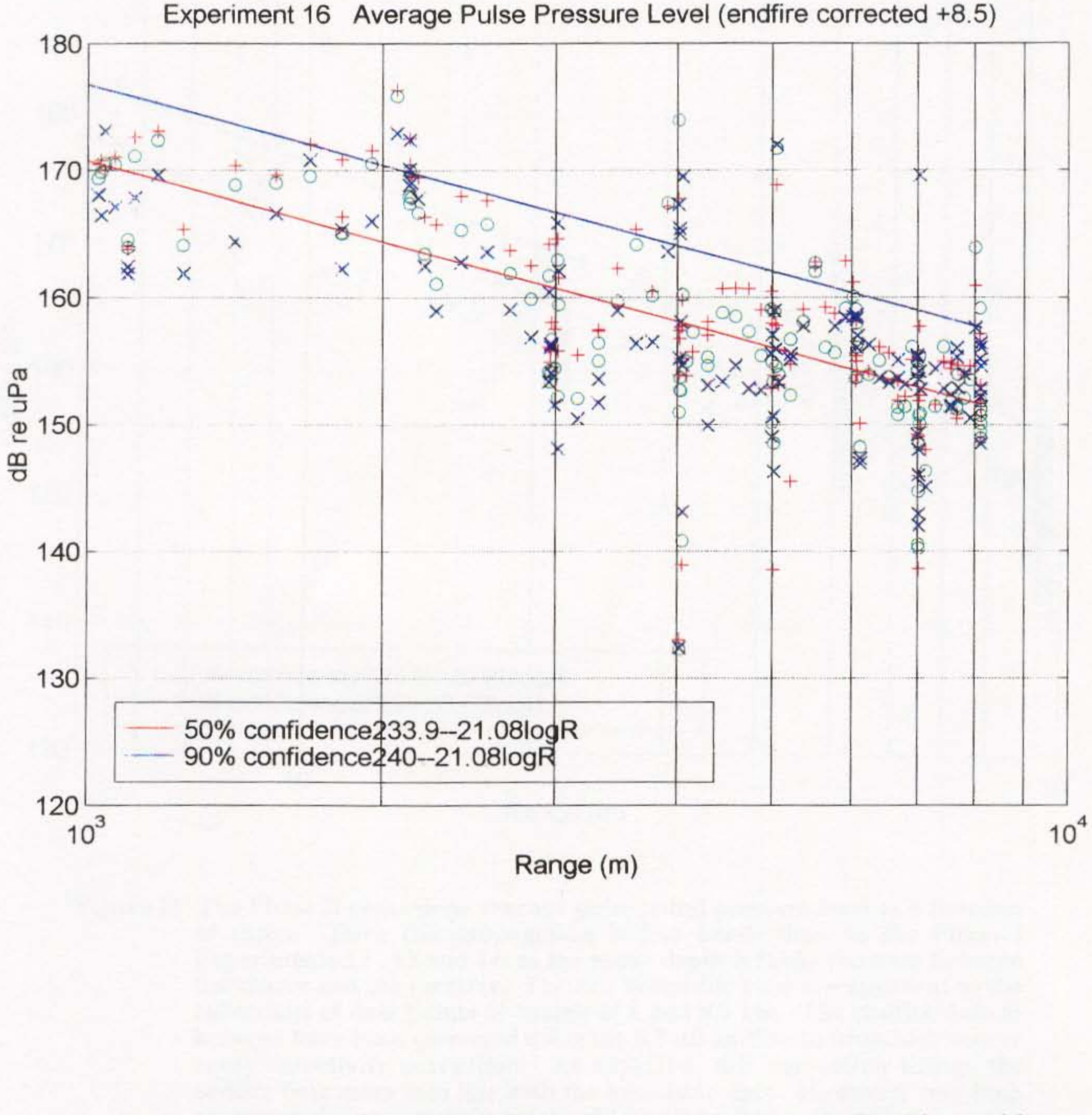

Figure 14. The average pulse pressure amplitude for Phase I Experiment 16, where the receiver was 1 km north of the SYU in 201 meters of water depth. At this water depth, the propagation is more range independent, and the received levels are correspondingly higher. A L1 fit to the data yields a range of 3204 meters to the 160 dB re μPa isopleth, with a 6.1 dB 90% confidence interval. Endfire data points have been corrected by 8.5 dB.

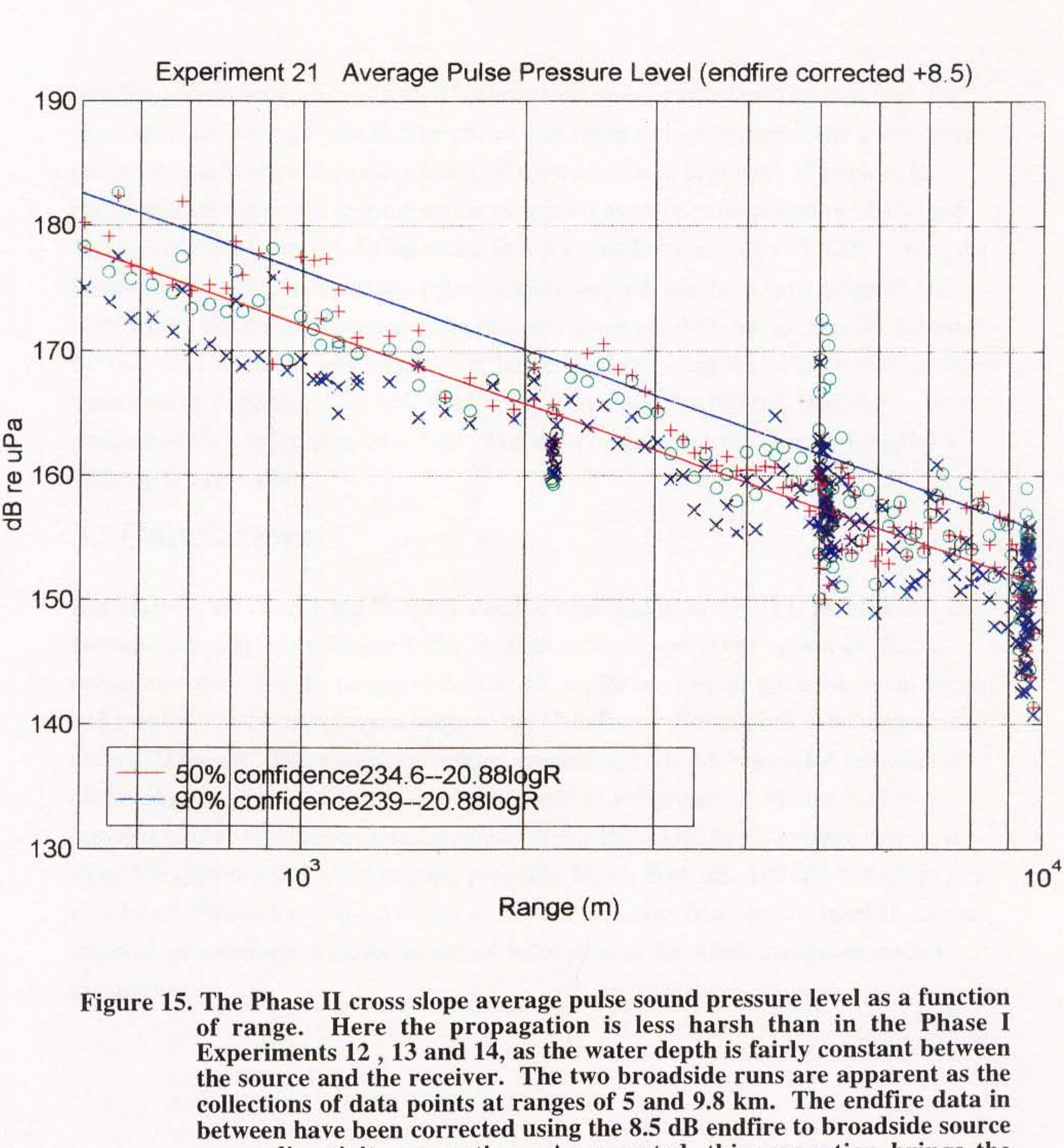

Figure 15. The Phase II cross slope average pulse sound pressure level as a function of range. Here the propagation is less harsh than in the Phase I Experiments 12 , 13 and 14, as the water depth is fairly constant between the source and the receiver. The two broadside runs are apparent as the collections of data points at ranges of 5 and 9.8 km. The endfire data in between have been corrected using the 8.5 dB endfire to broadside source array directivity correction. As expected, this correction brings the endfire data more into line with the broadside data. However, very high average pulse pressures in excess of 160 dB 1 μPa are in evidence on the 10 meter hydrophone at a range of 5 km. As Figure 9 illustrates, these high values correspond to a single large coherent arrival structure, and the 160 dB re μPa isopleth is moved correspondingly outward to account for this effect. An L1 fit to the data points between 500 meters and 10 km yields a range to the 160 dB re 1 μPa isopleth of 3739 meters, with a 4.4 dB 90% confidence interval.

Nearfield levels were also estimated for broadside and corrected endfire data from the close approach during Phase II. The source ship made a close approach and a loop near the receiver ship allowing measurement of source levels at broadside. The close in measurements were used to estimate the ranges for average pulse pressures of 180 and 190 dB re µPa (Figure 16). Using an L1 fit to the data between 100 and 2000 meters, the broadside 180 dB re µPa average pulse pressure isopleth was found at a range of 316 meters from the source. Average pulse pressure levels of 190 were not measured during the test. The 190 dB re µPa isopleth can be extrapolated using the L1 fit to data to obtain a distance of 77 meters. The 90% confidence interval on the 190 and 180 dB measurements was found to be 4.7 dB. The short range data were observed to obey a 16.3 log R power law.

3. Conclusions

Results from the Phase I and Phase II acoustic experiments in the SYU indicate that the average ranges to the 160 dB re 1 µPa isopleth are not expected to exceed 4 km. Our results also show that the ranges to the 180 dB re µPa isopleth are not expected to exceed 316 meters, and that the average range to the 190 dB re 1 µPa isopleth is not expected to exceed 77 meters. These results are based on placing L1 linear regression through the observed average pulse pressure levels, this method being used by Malme et al. in previous marine mammal avoidance studies. Since the isopleths are average results, it should be expected that average pulse pressures higher than 160, 180 and 190 dB re µPa may be received at the isopleth ranges in 50% of the cases, however the isopleth ranges reported are consistent with the statistical foundation of the whale avoidance studies themselves.

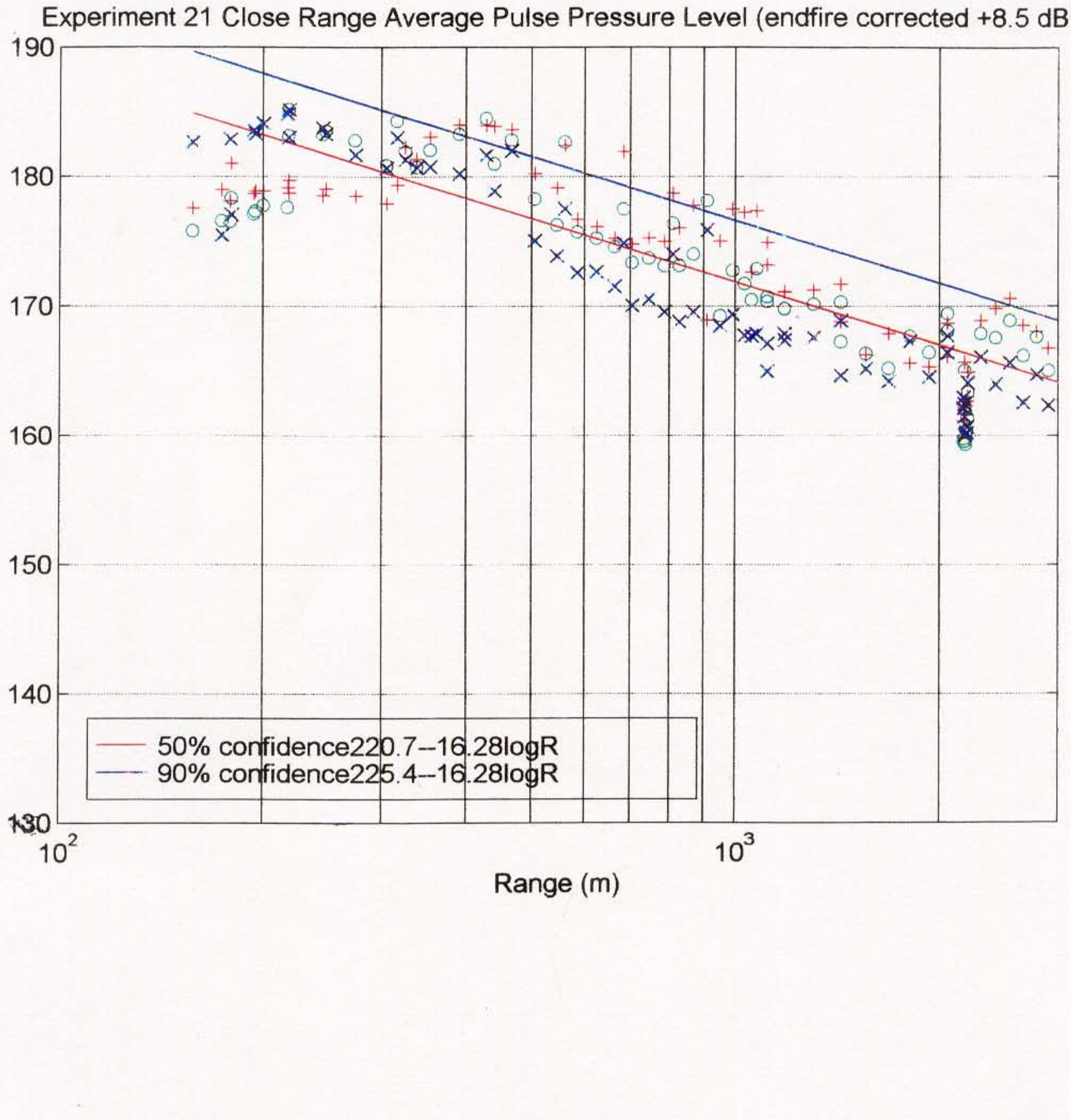

Figure 16. **For the close pass part of the Phase II Experiment, 8.5 dB endfire to broadside corrected data yields ranges to the 190 dB re 1 μPa isopleth of 77 meters, and to the 180 dB re 1 μPa isopleth of 316 meters. Data was fit with an L1 regression for data between the ranges of 100 and 2000 meters. The 90% confidence interval is 4.7 dB.**