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Restoration Project Final Report

Ex-situ target strength measurements of Pacific herring *Clupea pallasi* and Pacific sand lance *Ammodytes hexapterus*

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Final Report

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Ex-situ* target strength measurements of Pacific herring *Clupea pallasi* and Pacific sand lance *Ammodytes hexapterus

Abstract

Near-dorsal aspect target strengths (TS) of individual, live, juvenile and adult Pacific herring *Clupea pallasi* and juvenile Pacific sand lance *Ammodytes hexapterus* were measured *ex-situ* with 120 kHz dual beam acoustics. An experimental frame was designed to support a transducer, fish cage, standard calibration target and two video cameras. Herring were measured at a variety of depths while they swam freely in an acoustically transparent mesh cylinder secured 3 m below the transducer. Sand lance were measured while tethered at 4-m depth. The TS of individual herring declined as they were lowered in the water column. The decline was in accordance with that expected from Boyle's Law. We examined the impact of depth and show that the result at 40-m depth is equivalent to that from the equation of Thorne (1977a), which is commonly used for Pacific herring, and at 150 m is equivalent to the relationship recommended by Foote (1987) for Atlantic herring. Both results are reasonable for the respective vertical distributions of the two species. Thus, we explain the apparent discrepancy in published algorithms for Atlantic and Pacific herring TS by their different nighttime overwintering depth preferences and Boyle's Law. Since the vertical distribution of herring varies, we recommend that TS estimates be referenced to the depth of measurement. This suggestion may be applicable to all fish with swimbladders. The measurements on the juvenile Pacific sand lance, which lack swimbladders, yielded a TS= 20logL(cm)-80.0. This is appreciably higher than the algorithm published for Atlantic sandeel of the same genus, TS= 20logL(cm)-93.7, but is in reasonable accord with other information about fish without swimbladders.

Key words: herring, sand lance, target strength, Boyle's Law

Introduction

Acoustical methods to estimate fish density and distribution have widespread use in fisheries science today (Thomas 1992; Thomas and Kirsch 2000). The density of fish is estimated from the equation $D = v^2 / k\sigma_{bs}$, where v^2 is the average volume backscatter from a population of fish, k is the electroacoustic calibration constant (determined from calibration), and σ_{bs} is the average backscattering cross-section. This is often re-written in terms of absolute biomass density in kg/m^3 by multiplying the numerical density by average fish weight in kg, and separating the terms, $B = D_w = (v^2 /k)(w/\sigma_{bs})$ (Thorne 1983a). The backscattering coefficient is often expressed in terms of target strength (TS) where $TS = 10\log(\sigma_{bs})$.

The average volume backscatter of fish (v^2) is measured in the field by echointegration (Thorne 1983b; Foote 1987; MacLennan and Simmonds 1992; Rose 1992). The conversion of v^2 to density requires knowledge of the target strength, which is a function of many factors, including species and length (Thorne 1983a,b). Where fisheries scientists can classify the acoustic fish targets on a survey to species and size, they can use TS information to estimate sample volumes and fish densities (Foote 1987; MacLennan and Simmonds 1992; Kieser and Ehrenberg 1990). However, the use of TS algorithms is the largest source of non-survey error in acoustic abundance estimates (Rose 1992).

TS Estimation

Many physical and biological variables affect target strength including: size of the fish, depth of the fish, tilt angle distribution of the fish, frequency of the transducer, and physiology and morphology of the fish (Thorne 1983a,b; Foote 1987; Rose and Leggett 1988; Thorne and Thomas 1990; MacLennan and Simmonds 1992; Misund et al. 1995; Misund 1997). Early experiments showed TS varied significantly by aspect, so comparisons have been limited to near-dorsal (Love 1977). The dependence of TS on fish tilt is also non-linear, and is due to the non-spherical shape of swimbladders and fish. The maximum TS is not necessarily at level orientation and mean tilt is usually not level (Huse and Ona 1996).

Early TS experiments used tethering devises to suspend dead fish at known aspects in the beam (Love 1977). These experiments were generally not successful at measuring the TS of fishes with swimbladders. Subsequently, *ex-situ* measurements were conducted with groups of live, active animals in cages or on tethers (Edwards and Armstrong 1983; Edwards et al. 1984). The initial *ex-situ* TS experiments that were conducted on Atlantic herring measured the backscatter of net-cages that held a large number of fish. Other researchers derived early estimates of TS from comparison procedures between the near-synoptic measures of backscatter to average catches from nets (Thorne 1983b; Misund and Ovredal 1988; McClatchie and Thorne 2000). With the availability of multibeam transducers in the 1980's, it became popular to measure *in-situ* TS with dual-beam or split beam techniques. However, this technique has limited utility with schooling fishes such as herring because of target coincidence (Traynor and Ehrenberg 1979; MacLennan and Simmonds 1992).

Several *ex-situ* experiments have documented the importance of the swimbladder. Mukai and Iida (1996) show that the TS of individual kokanee (*Oncorhynchus nerka*) declined in accordance to Boyle's Law when lowered in the water column. Other observations have shown that the swimbladder volume and cross-sectional area decline inversely with pressure, but that this is not a linear change (Blaxter et al. 1979; Ona 1990). Mukai and Iida suggested that depth adjustment of the TS in accordance with Boyle's law might be applied to all physostomatous fish. Rose and Porter (1996) showed that nighttime TS in Atlantic cod (*Gadus morhua*), a physoclistous species, was 1.5 dB higher than daytime, which was consistent with cod being neutrally buoyant and off-the-bottom at night and negatively buoyant and near-the-bottom in the day. Fishes without swimbladders have been consistently shown to have lower target strengths (Edwards et al. 1984, Armstrong 1986).

Herring and Sand Lance

Herring stocks have been surveyed for decades using acoustic methods in the North Pacific and North Atlantic Oceans. Pacific herring stocks from Alaska to California have been assessed with acoustic techniques for management purposes since the mid 1970's, (Thorne 1977a,b; Trumble et al. 1982; Thorne et al. 1983; Thorne and Thomas 1990). There have been several studies published on Atlantic and Pacific herring TS. The most commonly used TS for Pacific herring (TS=26.5logL-76.4@120 kHz; Thorne 1977a) was determined by comparison with independent data. The most commonly used TS for Atlantic herring (TS=20logL-72.3@70 kHz; Misund and Ovredal 1988) was also determined by comparison with independent data, but is virtually identical to the *in-situ* measurements of Foote (1987) using split-beam. There is a discrepancy between these estimates of Atlantic and Pacific herring that amounts to about 4 dB. Thus an acoustic estimate of herring biomass could differ by a factor of about 2.5 depending on which herring TS algorithm was applied.

The Pacific sand lance and Atlantic sandeel, *Ammodytes spps* are known to be important forage fish, especially for seabirds (Furness and Tasker 2000; Piatt and Anderson 1996). Acoustic surveys in Alaskan waters have attempted to monitor Pacific sand lance distribution and abundance. Armstrong (1986) used cage experiments on groups of fish to estimate a TS relationship for Atlantic sandeel. The result, TS=20logL-93.7, suggests a smaller target strength than typically observed for fish without swimbladders (Foote 1980) and may not be applicable to the ongoing acoustic assessment in Alaska.

In this paper, we present results of TS studies on both Pacific herring and Pacific sand lance. We assess the near-dorsal aspect of TS using *ex-situ* experiments at 120kHz. We present regression models that predict TS of sand lance based upon length and of herring based upon both length and depth. Finally, we compare our results to determine if we can resolve the differences in the published values of TS, and examine the impacts on current assessment procedures.

Methods

Data Acquisition

A total of three *ex-situ* experiments were conducted: (1) on Pacific herring in the fall of 1998 to measure "good-condition" fish after the summer feeding season, (2) on Pacific herring in the spring of 1999 to measure "starved-condition" fish after overwinter aestivation, and (3) on Pacific sand lance during July-August, 1999. For herring, the measurements were conducted on single, live, juveniles and adults held in a net-cage at a range of depths from 4 to 43 meters. For sand lance the measurements were conducted on live, tethered juvenile sand lance held at 4 meters depth.

A BioSonics DT5000 echo sounder with a 120 kHz dual beam (6^0 -13^0) transducer was used in experiments 1 and 3. A BioSonics 101 echo sounder with a preamp 120kHz dual beam transducer (6^0 –16^0) was used in experiment 2. Calibration of both systems was made synoptically with all fish measurements using a 33-mm tungsten carbide calibration sphere (Foote et al. 1987; MacLennan and Armstrong 1984). This sphere has a theoretical TS of -40.6 dB@120 kHz, and water temperature of 8^0 and salinity of 30 ppt.

The experimental technique for the herring measurements was modified from Edwards and Armstrong (1983). All measurements used a rigid, aluminum frame to deploy the transducer and fish cage at a fixed range and orientation (Figure 1). The aluminum calibration frame was designed so that none of its parts would be in the main or side lobes of the 6° circular transducers. We made the diameter of the rings so that they would be located in the second null outside the first side lobe. A cylindrical fish cage 0.5-m diameter by 0.5 m height was suspended with its center 3 m from the transducer. The fish cage was constructed from fine nylon mesh. One fish at a time was placed in the cage for measurement. The caged fish were continuously monitored with an underwater video system. Video signals were observed during the experiments on a TV monitor. Measurements of fish that exhibited unusual behavior were discarded. Video signals were acquired with a frame grabber and the images stored to hard disk. Video signals were analyzed for orientation of the fish within the experimental cage.

Experiment 1

Experiment 1 was conducted in November 1998 from a purse seine vessel moored in Zaikof Bay, Prince William Sound. Herring were captured by purse seine and held in floating net pens where they acclimated to 0-4 m for 24 hours prior to measurement. Only fish in excellent condition were kept. Adult herring are spring spawners and showed little gonad development at this time. One fish was placed in the cage for each series of measurements by raising the frame enough to bring the net cage to the surface. The fish swam freely in the cage while being measured and their movements were observed and recorded on video. Each fish was given 15 minutes to acclimate to depth (4-43 meters) before measuring its TS. TS data were collected for 10 minutes, or about 1,200 pings. Biological information was collected from the fish after measuring TS. Measurements at 4 m depth were completed on 19 fish, ranging in size from 11.3 to 26.6 cm. Multiple depth measurements were completed on 8 of the fish, ranging in size from 11.3 to 25.7 cm.

Experiment 2

Experiment 2 was conducted April 1999 from a purse seine vessel at the dock in Cordova Harbor. Herring were captured by purse seine, transported to Cordova Harbor and held in floating pens where they acclimated to 0-4 meters for a minimum of 24 hrs. Experiment 1 procedures were followed. TS data were collected for 20 minutes, or about 18,000 pings. Measurements were completed on 15 adults, ranging in size from 21.1 to 26.8 cm.

Experiment 3

Experiment 3 was conducted July/August 1999. Juvenile sand lance were captured using a fine-mesh experimental seine, transported to Cordova harbor and held in an aquarium with gravel substrate. The TS measurements were made from the R/V *Orca Challenger* at the dock in Cordova harbor. Using 2-pound monofilament fishing line and a small sewing needle, we tethered the sand lance by starting at the head, pushing the needle up through the maxilla then running it just under the skin along the back. The fish was held in place by tying a loop knot around the caudal peduncle. All tethering and transfer of fish were done underwater, as we observed a tendency of the fish to gulp air when out of water. All fish were allowed to acclimate for at least fifteen minutes before data were collected. Measurements were completed on 51 fish, ranging in size from 6.2 to 9.8 cm.

Processing and Analysis Methods

Dual-beam techniques were used to calculate TS (Traynor and Ehrenberg 1979; Iida et al. 1991). For both experiments 1and 3, the DT data files were processed using BioSonics Visual Analyzer software, Version 3.1.1, where the objective was to acquire valid fish and calibration sphere targets. Visual Analyzer was configured as follows: the target threshold was –90, correlation factor was 0.90, and maximum pulse width factor was 2.5. All subsequent data editing and validation tasks were performed using IDL programs and procedures on the UNIX (Sun) workstation, or in other software on the PC. The signals from experiment 2 were analyzed with a BioSonics Model 281 Echo Signal Processor (ESP). ESP View was used to convert ESP files to text, which were transferred to the Sun workstation for subsequent data editing and validation tasks. Target acceptance was limited to targets within the -3 dB angle of the directivity pattern. The TS to length regressions were calculated using both standard models of the TS-length relationship: (1) TS = m log [length (cm)] + b, following Love (1977) and Foote (1987), and (2) TS = 20 log [length (cm)] + b, following MacLennan and Simmonds (1992). The latter form facilitates direct comparisons among TS relationships.

Results and Discussion

Experimental Frame Performance

Measurements were made on an empty cage or tether placed in the experimental frame for all three experiments to determine background reverberation. Reverberation was very low except for echoes between –60 and –45 dB from the bottom of the cage at 3.4 m range. This cage reverberation was removed by rejecting all targets beyond 3.3 m range. The monofilament tether used in experiment #3 caused reverberation below –70 dB, which had little or no effect on the TS measurements of the sand lance.

Ex situ Herring TS Versus Length

The target strength of herring clearly increased with length. The relationship for all observations combined was TS = 26.2L-72.5, or equivalently, TS = 20L-64.3 (Figure 2).

There was insufficient range in length to accurately determine a TS-length relationship for the spring herring. However, the TS measured for herring in the spring was higher than that for comparable size fish in the fall. Removing the spring observations changes the equation to TS = 20L-66.1, a 1.8 db lower TS when the spring observations are excluded. This result is consistent other observations. Seasonal changes in herring TS have been noted previously (Kautsky and Lemberg 1990; Ona et al. 2000). Potential explanations include changes in lipid content, gonad development and stomach content, all of which may affect swimbladder volume. Larger swimbladder volumes have been reported for fish with low fat content and also for spent fish (Kaustky and Lemberg 1990). Rottingen et al. (1994) reported an overwinter increase in body density as lipid stores are consumed for energy and during gonad development. These factors were variable in our samples: four were immature, two were ripe, one was spawning and eight were spent. However, the low lipid content and the large percentage of spent fish would be expected to result in higher target strengths.

Changes In TS With Depth

The herring showed a substantial decrease in TS below 4 m (Figure 3). The reduction was similar to that observed by Mukai and Iida (1996) and in accord with that expected from the effects of Boyle's Law (Figure 4).

If we apply the correction factor for Boyle's law to the TS relationship that was determined at 4 m in this study and compare the result to the equation of Thorne (1977a), we see that the two equations produce identical estimates at a depth of 40 m (Figure 5). A similar comparison with the equation of Foote (1987) for the Atlantic herring produces an identical estimate at 150 m. Herring in Prince William Sound typically distribute in 10 to 60 m depths. Huse and Ona (1996) and Nottestad (1999) show the nighttime depths of Norwegian herring range from 50 to 400 meters. Thus most of the discrepancy between the Pacific and Atlantic herring TS relationships can be attributed to the differences in their vertical distributions.

This result suggests that TS measures of swimbladder fishes should always be referenced to the depth of the fish. Boyle's law predicts that the volume of a sphere will decrease with depth, so that in a fish, the bladder volume is inversely proportional to pressure. Since backscattering cross-section is linearly related to surface area of the scatterer, this predicts $\Delta TS = -6.67P+3.17$ (Mukai and Iida, 1996). Deviation from this theory may occur because the swimbladder is not a perfect sphere, there may be some time for the swimbladder to adapt to the new pressure, and fish may control the swimbladder size for buoyancy control. In addition, as noted above, swimbladder size may be affected by gonad development, lipid concentrations and stomach fullness. Additional complexity is associated with gas bubble release by herring during vertical migrations (Thorne and Thomas 1990; Nottestad 1998) and potential changes in aspect associated with different behaviors or ambient conditions. Thus, it may be unrealistic to assume a target strength without an understanding of these factors and of the condition and behavior of the fish at the time of the survey.

***Ex-situ* Sand Lance TS Versus Length**

The TS of 51 juvenile sand lance increased with length, TS=24.5logL-84.1, or equivalently TS = 20logL-80.0 (Figure 6). The algorithm is not expected to vary by depth because of the absence of a swimbladder. The result indicates a target strength that is 14 db lower than that for the fall herring at 4 m. The sand lance target strength would be equivalent to that from a herring of the same length at about 600 m, where the swimbladder would be reduced to about 1/150 of its volume at 4 m. The estimated target strengths are considerably higher than would be estimated by the equation of TS = 20logL-93.7 from Armstrong (1986) for *Ammodytes sp.* at 38 kHz. The reason for the large difference is unclear. One possibility is the difference in the experimental approach. Armstrong (1986) measured a group of fish in a cage. Our fish tended to burrow into the gravel in the aquarium and were seldom off bottom. The tether procedure was necessary to make a measurement that simulated a pelagic behavior. The difference in frequency of the measurements is another possibility. We would expect a small fish without a swimbladder to have less reflection at the lower frequency (38 kHz). Edwards et al. (1984) estimated TS = 20logL-86.9 for mackerel (*Scomber scombrus*) at 120 kHz, which also lacks a swimbladder. This value is closer to ours, but still lower. A size/frequency interaction may explain some of the difference, as the mackerel were about 3 times longer. Unfortunately, there are very limited observations on fish without swim bladders. Our result for sand lance is very similar to the value for squid (*Loligo opalescens*) of the same size at 120 kHz (TS=20logL-79.9; Jefferts et al. 1987). In addition, Foote (1980) estimated that the swimbladder of cod, a physoclistous species, accounts for 90-95% of the acoustic backscatter. On that basis, our observed reduction of about –14 dB compared to herring at 4 m seems more reasonable than the 28 dB difference reported for the Atlantic sandeel.

Another factor that may affect the comparisons is the difference in *ex-situ* experimental procedures. Armstrong (1986) and Edwards et al. (1984) used cages that extended outside of the main lobe of the transducer and derived TS indirectly from echointegration measurements. In contrast, we directly measured TS, but limited our measurements to within the –3 dB angles to optimize signal to noise conditions. Our approach limits the aspect angles over which the measurements are made. However, the directivity pattern also strongly weights against returns from more peripheral locations in the beam. It would take a considerable difference in target strengths from relatively minor aspect changes to cause an appreciable difference, and that seems unlikely.

Conclusions

The target strength of herring is depth dependent. This dependence explains much of the discrepancies reported between target strength equations for Atlantic and Pacific herring. The impact of depth on herring target strength is substantial. It is clear that estimates of target strength and biomass must account for depth differences not only between the two species, but also over the range of depth distributions associated with various surveys for both species. For example, at least part of the diel differences in herring biomass estimates (Thorne 1977a,b; Thorne et al. 1983) can be attributed to depth differences.

Other factors affect the target strength of herring, such as seasonal differences. While the magnitudes of these impacts are smaller, they still need to be considered in order to more accurately measure processes such as seasonal mortality. Improved understanding of the impact of several of these factors is still needed.

Information on the target strengths of fish without swimbladders is still meager. There is a substantial and largely unexplained difference between our measurements of Pacific sand lance and the reported values of the Atlantic sandeel of the same genus. Estimates of sand lance from acoustic surveys should be treated cautiously until this difference is resolved. In the interim, we recommend that acoustic surveys of Pacific sand lance use the estimates from this study as both more specific and more conservative.

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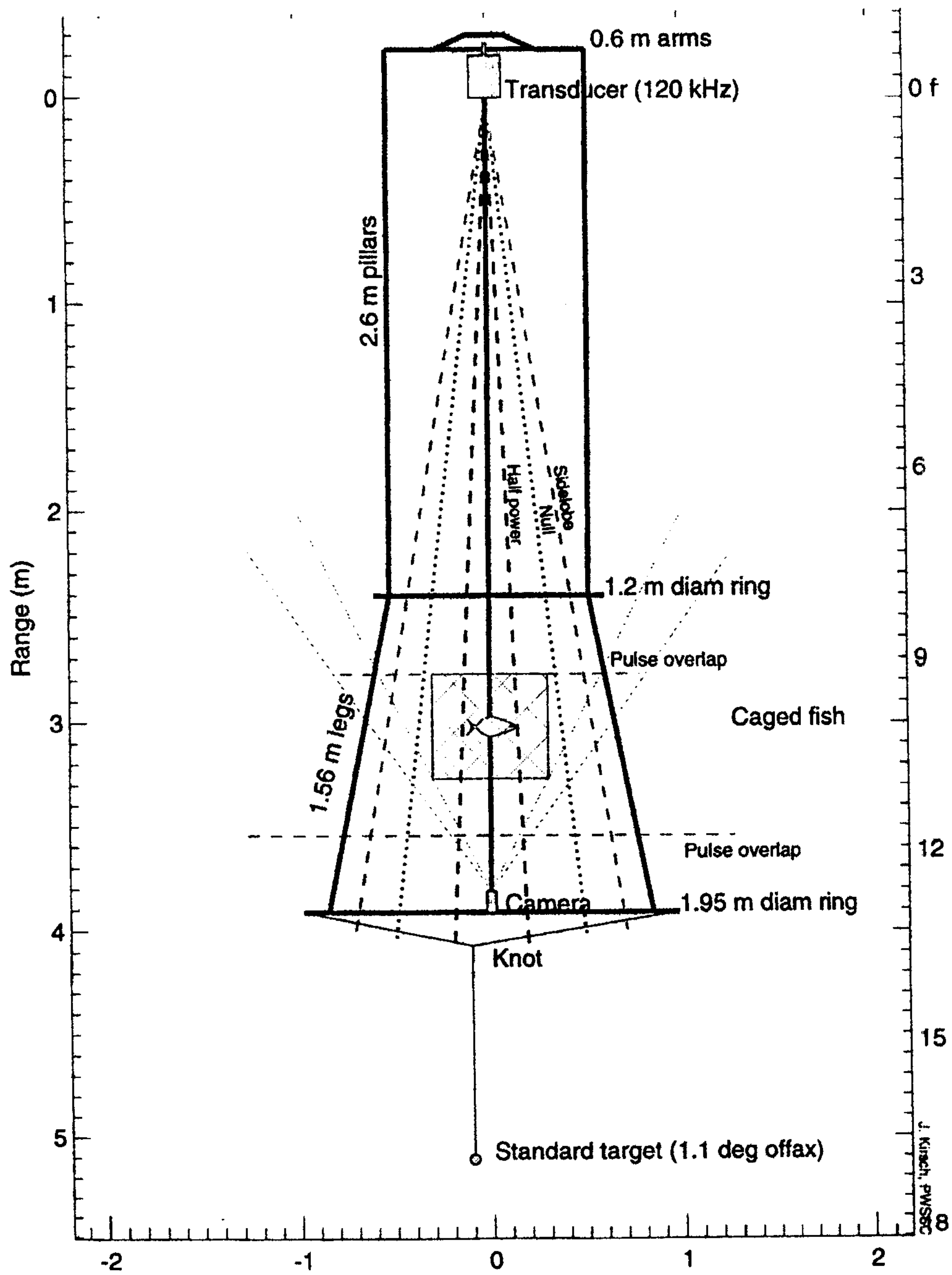

Figure 1. Side view of experimental frame used for target strength measurements showing locations of transducer, fish, camera and standard target.

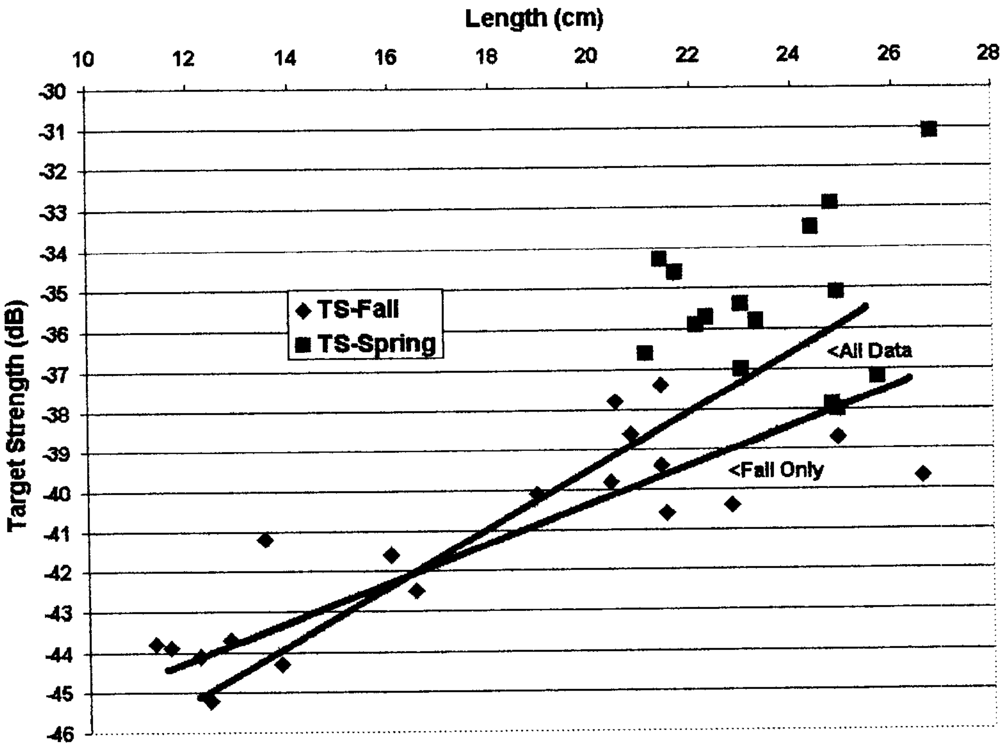

Figure 2. Observed target strength (dB) to length relationship of Pacific herring.

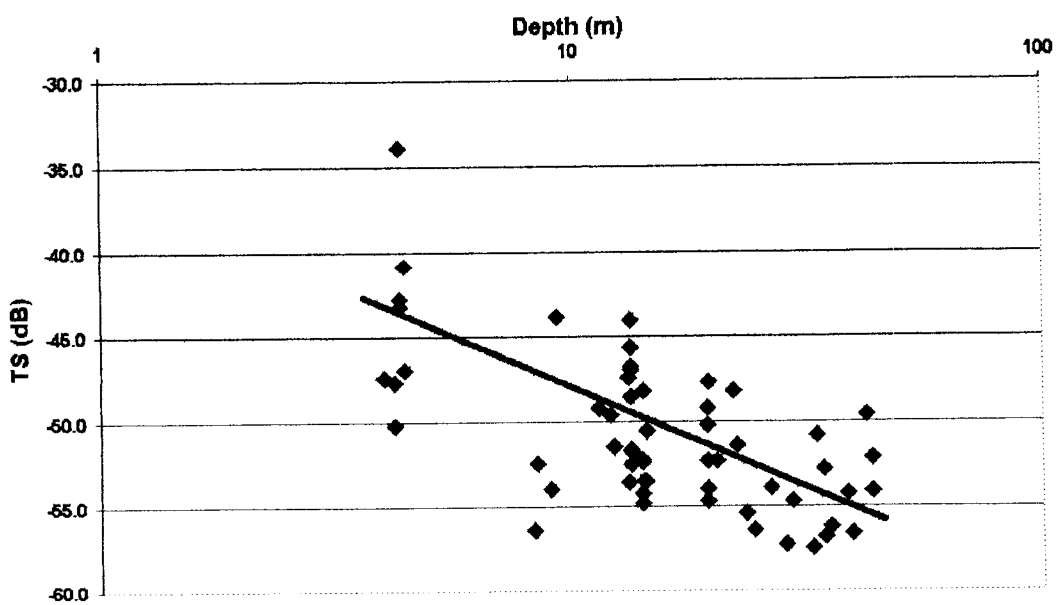

Figure 3. Scatter plot of Pacific herring target strengths at various depths.

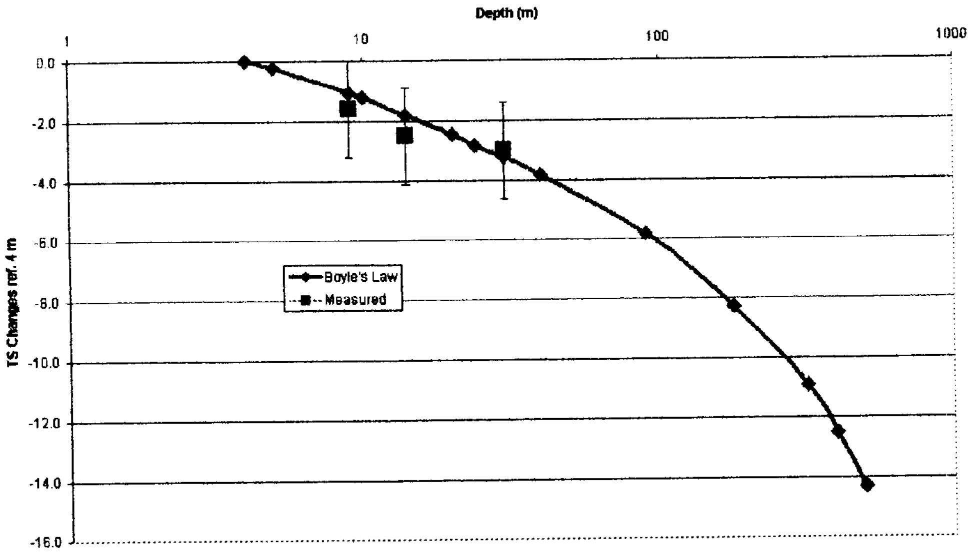

Figure 4. Comparison of observed changes in target strength with those predicted from Boyles law, i.e. ΔTS=-6.7P+3.17 (Mukai and Iida 1996).

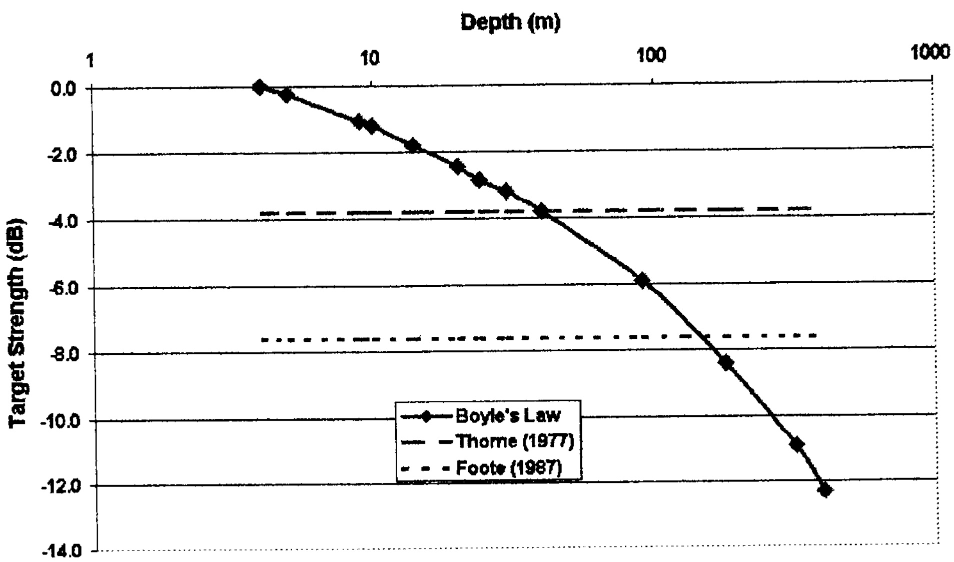

Figure 5. Depth dependent changes in TS compared to depth independent equations of Thorne (1977a) and Foote (1987). The depth dependent function is the target strength measured at 4 m in this study as modified by Boyle's law.

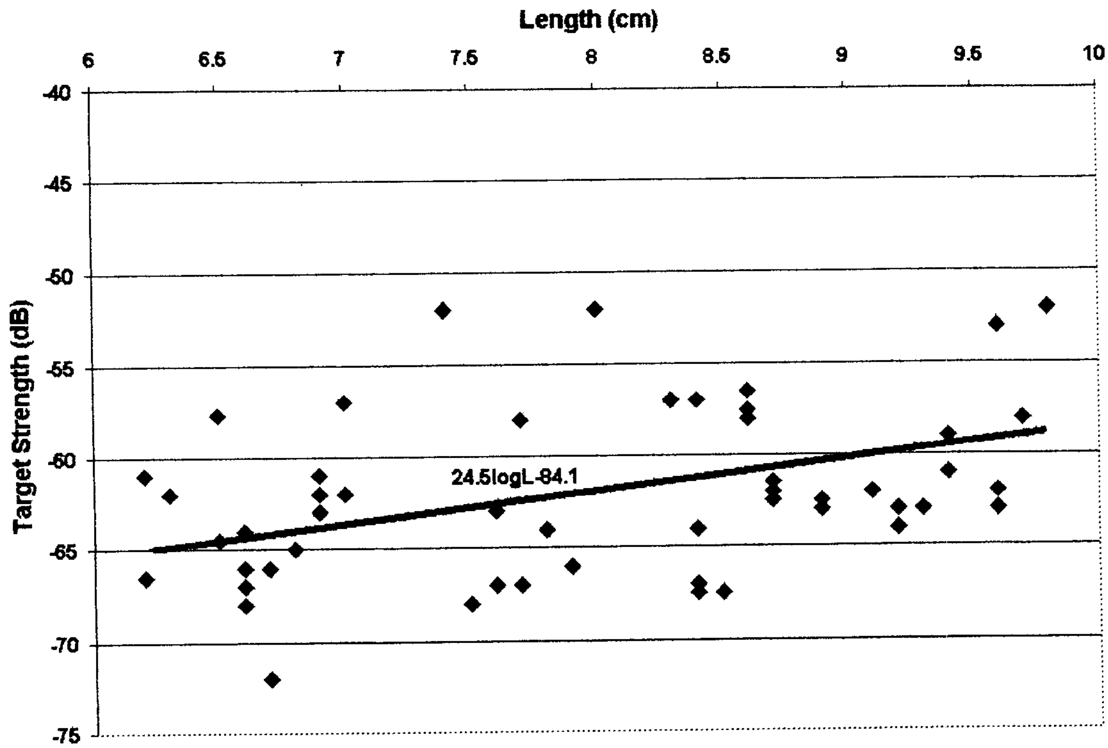

Figure 6. Observed target strength to length relationship for Pacific sand lance.