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G. L. Thomas , Jay Kirsch & Richard E. Thorne

To cite this article: G. L. Thomas , Jay Kirsch & Richard E. Thorne (2002) Ex Situ Target Strength Measurements of Pacific Herring and Pacific Sand Lance, North American Journal of Fisheries Management, 22:4, 1136-1145, DOI: [10.1577/1548-8675\(2002\)022<1136:ESTSMO>2.0.CO;2](https://doi.org/10.1577/1548-8675(2002)022<1136:ESTSMO>2.0.CO;2)

To link to this article: [http://dx.doi.org/10.1577/1548-8675\(2002\)022<1136:ESTSMO>2.0.CO;2](http://dx.doi.org/10.1577/1548-8675(2002)022<1136:ESTSMO>2.0.CO;2)



Published online: 08 Jan 2011.



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## Ex Situ Target Strength Measurements of Pacific Herring and Pacific Sand Lance

G. L. THOMAS

Prince William Sound Science Center,  
Post Office Box 705, Cordova, Alaska 99547, USA

JAY KIRSCH

Harman Music Group,  
8760 South Sandy Parkway, Sandy, Utah 84070, USA

RICHARD E. THORNE\*

Prince William Sound Science Center,  
Post Office Box 705, Cordova, Alaska 99547, USA

**Abstract.**—Near-dorsal aspect target strengths (TS) of individual live juvenile and adult Pacific herring *Clupea pallasii* 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. Pacific herring were measured at a variety of depths while they swam freely in an acoustically transparent cylinder that was secured 3 m below the transducer. Pacific sand lance were measured while tethered at a 4-m depth. We found that both depth and season affected the target strength of Pacific herring. The TS of individual Pacific herring declined as they were lowered in the water column. The decline was in accord with that expected from the effects of Boyle's Law on the swim bladder volume. This impact of depth may explain the apparent discrepancy in published target strength algorithms for Atlantic herring *C. harengus* and Pacific herring. The depth distribution of Atlantic herring is typically deeper. The results suggest that the depth of measurement needs to be considered in both target strength measurements and acoustic surveys of herring. We also found higher target strengths of Pacific herring during spring than in fall. Larger swim bladder volumes may be associated with spent fish or reduced lipid content during spring. The measurements on the juvenile Pacific sand lance, which lack swim bladders, yielded a much lower target strength than Pacific herring of equivalent size. However, the observed values were appreciably higher than the TS algorithm published for sand lance *Ammodytes* spp. in the Atlantic Ocean.

Acoustical methods to estimate fish density and distribution have widespread use in fisheries science today (MacLennan and Simmonds 1992; Thomas 1992; Simmonds and MacLennan 1996; Thomas and Kirsch 2000; Thomas and Thorne 2001). Knowledge about the acoustic backscattering characteristics of fish targets is central to the estimation process (Thorne 1983a, 1993b; Kieser and Ehrenberg 1990; Rose 1992; Misund 1997). The common measure of that characteristic is the backscattering cross section,  $\sigma_{bs}$ . The backscattering cross section is often expressed in terms of target strength (TS) where  $TS = 10 \cdot \log_{10}(\sigma_{bs})$ .

Stocks of Pacific herring *Clupea pallasii* from Alaska to California have been assessed with acoustic techniques for management purposes since the early 1970s (Thorne 1977a, 1977b;

Trumble et al. 1982; Thorne et al. 1983; Thorne and Thomas 1990; Thomas and Thorne 2001). In 1993, the Prince William Sound Science Center and the Alaska Department of Fish and Game began a series of acoustic surveys of the Pacific herring stock within Prince William Sound. The objective was to monitor the recovery of the stock in the aftermath of the *Exxon Valdez* oil spill (Rice et al. 1993). The estimation of Pacific herring biomass from these surveys was based on a target strength–length relationship for Pacific herring of  $TS = 26.5 \log_{10} L - 76.4$ , where  $L$  is length (cm). This equation evolved from many different sources including in situ measurements of individual herring, comparisons with catches, and comparisons with independent measures of abundance (Thorne 1977a; Trumble et al. 1982).

While adopting this TS assumption for our survey effort, we realized that TS characteristics are complex. Previous investigation on Pacific herring had suggested both depth and fat content could

\* Corresponding author: thorne@pwssc.gen.ak.us

Received February 20, 2001; accepted January 23, 2002

affect TS (Kautsky et al. 1991). Further, the TS values for Atlantic herring *C. harengus* that are tabled in MacLennan and Simmonds (1992) were considerably different than the equation we were applying to Pacific herring. These differences were far greater than could be explained by anatomical differences or differences in the acoustic frequencies.

In addition to our concern about the target strength values for Pacific herring, we encountered appreciable abundance of Pacific sand lance *Ammodytes hexapterus* on our surveys. Sand lance species are known to be important forage fish, especially for seabirds (Piatt and Anderson 1996; Furness and Tasker 2000). A swim bladder is absent in sand lance, and we had little information upon which to estimate abundance from our acoustic surveys. Consequently, we developed an experimental procedure to directly measure TS values for Pacific herring and Pacific sand lance to improve our understanding of this critical metric.

### Target Strength Estimation

A wide variety of experiments and measurements have been conducted on fish TS because of its importance to acoustic surveys. Early TS experiments used tethering devices to suspend dead fish at known aspects in the beam (Love 1977). Although these experiments successfully documented many factors affecting target strength, such as length and aspect, there was concern that the results might not be representative of the characteristics of live fish. 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). Many of these ex situ experiments measured the backscatter from large numbers of fish that were held in net cages. Other researchers derived early estimates of target strength 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 1980s, measures of in situ TS with dual-beam or split-beam techniques became popular. However, this technique has limited utility with schooling fishes, such as Pacific herring, because of target coincidence and species uncertainty (Traynor and Ehrenberg 1979; MacLennan and Simmonds 1992).

Several ex situ experiments have documented the importance of the swim bladder. Mukai and Iida (1996) show that 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 swim bladder volume and cross sectional area decline inversely with pressure, but not linearly (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 physostomatus fish. Rose and Porter (1996) showed that nighttime TS in Atlantic cod *Gadus morhua*, a physoclistous species, was 1.5 dB higher than in daytime and suggested the difference was consistent with Atlantic cod being neutrally buoyant and off the bottom at night and negatively buoyant and near the bottom in the day.

Fishes without swim bladders have been consistently shown to have lower target strengths (Foote 1980; Edwards et al. 1984). Armstrong (1986) used cage experiments on groups of fish to estimate a TS relationship for sand lance *Ammodytes* spp. in the Atlantic Ocean. However, the result,  $TS = 20 \cdot \log_{10} L - 93.7$ , is considerably smaller than the TS typically observed for fish without swim bladders.

We chose to use ex situ experimental techniques but to measure fish individually. We felt that the ex situ approach provided the best combination of controlled direct observation and natural conditions. Using individual fish, we could make direct measurements, rather than inferring individual values indirectly from multiple target returns. We investigated the impact of depth and season on Pacific herring and measured Pacific sand lance to determine a TS value for this species and to provide insight into the role of the swim bladder in affecting TS. We limited our observations to a single frequency, 120 kHz, because this was the primary frequency used in our acoustic surveys.

### Methods

**Data acquisition.**—Two ex situ experiments were conducted on Pacific herring, the first in the fall of 1998 and the second in the spring of 1999. Fall and spring are the two periods when acoustic surveys have been conducted in Prince William Sound, and these two periods represent substantial differences in fat content and gonad development. A third experiment was conducted on Pacific sand lance during July and August 1999.

For Pacific herring, the measurements were conducted on single, live juveniles and adults held in a net-cage at a range of depths of 4–43 m. For Pacific sand lance the measurements were con-

ducted on live, tethered juvenile sand lance held at a 4-m depth.

A BioSonics DT5000 echo sounder and a 120-kHz dual-beam ( $6^\circ/13^\circ$ ) transducer were used in experiments 1 and 3. A BioSonics 101 echo sounder and a preamp 120-kHz dual-beam transducer ( $6^\circ/16^\circ$ ) were used in experiment 2. Calibration of both systems was made synoptically for all fish measurements by using a 33-mm tungsten carbide calibration sphere (MacLennan and Armstrong 1984; Foote et al. 1987). The TS value of the sphere was adjusted according to water temperature and salinity conditions at the time of the experiments.

The experimental technique for the Pacific herring measurements was modified from Edwards and Armstrong (1983). All measurements used a rigid, aluminum frame to deploy the fish cage at a fixed range and orientation from the transducer (Figure 1). The aluminum calibration frame was designed so that none of its parts would be in the main or side lobes of the  $6^\circ$  circular transducers. We chose 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, 0.5 m high) 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 was continuously monitored with an underwater video system. The video signals were observed during the experiments on a monitor and were also acquired with a frame grabber and stored to hard disk. These video signals were analyzed for the fish's orientation within the experimental cage. Acoustic measurements were limited to fish with normal, near-horizontal swimming behavior.

*Experiment 1.*—Experiment 1 was conducted in November 1998 from a purse seine vessel moored in Simpson Bay in Prince William Sound, Alaska. Pacific herring were captured by purse seine and held in floating net-pens where they acclimated to the 0–4-m depth for 24 h preceding 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 its movements were observed and recorded on video. Target strength measurements in some cases were made over periods of several hours. Both behavior and TS typically stabilized within 15 min of a depth change. We col-

lected data until over 1,000 measurements were taken on each fish at each depth. Biological information was collected from the fish after measuring TS. Measurements at the 4-m depth were completed on 19 fish, ranging in size from 11.3 to 26.6 cm; additional depth measurements were completed on 8 of the fish (11.3–25.7 cm). Each of these fish was typically measured at seven additional depths down to 43 m, the limit of our experimental capability.

*Experiment 2.*—Experiment 2 was conducted April 1999 from a purse seine vessel at the dock in Cordova Harbor, Alaska. Pacific herring were captured by purse seine, transported to Cordova Harbor, and held in floating pens where they acclimated to a 0–4-m depth for a minimum of 24 h. Experiment 1 procedures were followed. Measurements were completed on 15 adult herring (21.1–26.8 cm).

*Experiment 3.*—Experiment 3 was conducted July and August 1999. Juvenile Pacific sand lance were captured using a fine-mesh experimental seine, transported to Cordova Harbor and held in an aquarium containing a gravel substrate. The TS measurements were made from the R/V *Orca Challenger* at the dock in Cordova Harbor. Using 0.9-kg 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 because we observed a tendency of the fish to gulp air when out of water. All fish were allowed to acclimate for at least 15 min before data were collected. Data collection procedures were similar to experiment 1, and we made about 1,000 measurements per fish. Measurements were completed on 56 fish, (6.2–9.8 cm).

*Processing and analysis methods.*—Dual-beam techniques were used to calculate TS (Traynor and Ehrenberg 1979). For experiments 1 and 3, the data files from the BioSonics DT (digital transducer) were processed using BioSonics Visual Analyzer software, version 3.1.1. The objective was to acquire valid fish and calibration sphere targets. The Visual Analyzer was configured as follows: the target threshold was  $-90$  dB, correlation factor was 0.90, and maximum pulse width factor was 2.5. Subsequent data editing and validation tasks were performed using custom Interactive Data Language programs and procedures on a UNIX (Sun) workstation. The signals from experiment 2

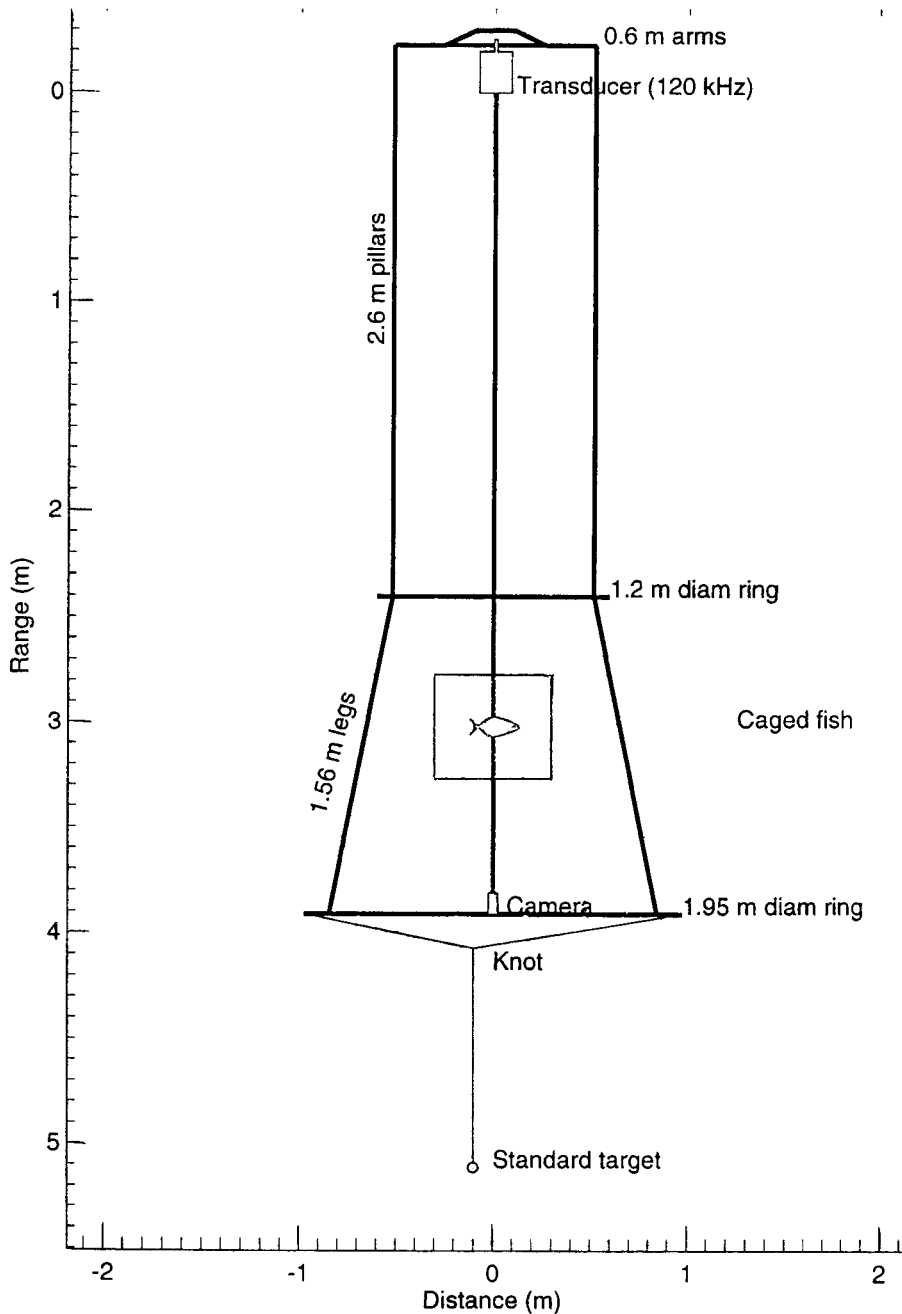


FIGURE 1.—Side view of the experimental frame used for target strength measurements of Pacific herring and Pacific sand lance showing locations of the transducer, fish, camera, and standard target.

were analyzed with a BioSonics model 281 Echo Signal Processor (ESP). The ESP View was used to convert ESP files to text, which were transferred to the Sun workstation for subsequent data editing and validation tasks. The first criterion for target acceptance was the level of natural behavior that

was inferred from the video records. The second was a requirement for targets to be within the  $-3$ -dB angle of the directivity pattern. The mean back-scattering cross section and its standard error were calculated for each fish. The TS to length regressions were calculated using both standard models

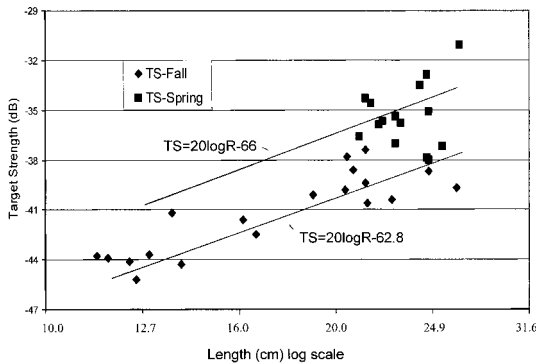


FIGURE 2.—Observed relationship of target strength (TS; decibels) to length for Pacific herring from experiment 1 (fall) and experiment 2 (spring).

of the TS–length (in cm) relationship: (1)  $TS = m \cdot \log_{10}(\text{length}) + b$ , following Love (1977) and Foote (1987), and (2)  $TS = 20 \cdot \log_{10}(\text{length}) + b$ , following MacLennan and Simmonds (1992). The latter form facilitates direct comparisons among TS relationships.

## Results and Discussion

### Experimental Frame Performance

To determine background reverberation, in all three experiments we measured an empty cage or tether placed in the experimental frame. Reverberation was generally below  $-90$  dB. Exceptions were echoes between  $-60$  and  $-45$  dB from the bottom of the cage at a 3.4-m range and minor reverberation ( $\leq 70$  dB) from the monofilament tether used in experiment 3. The former was removed by rejecting all targets beyond 3.3 m range. The latter was too low to have any effect on the TS measurements of the Pacific sand lance.

The cameras documented several behaviors that allowed editing of aberrant conditions. Fish often showed an initial nose-up orientation until they became adjusted to the conditions. In a few cases after prolonged measurements, fish moved toward the bottom of the cage and turned on their sides, which was usually followed by death of the specimen. The most interesting behavior was frantic escape actions when large walleye pollock *Theragra chalcogramma*, a known predator, approached the cage.

### Ex situ Pacific Herring Target Strength Versus Length

The TS of Pacific herring increased with length (Figure 2). The relationship for all observations combined was  $TS = 26.2 \cdot \log_{10}L - 72.5$ . The range

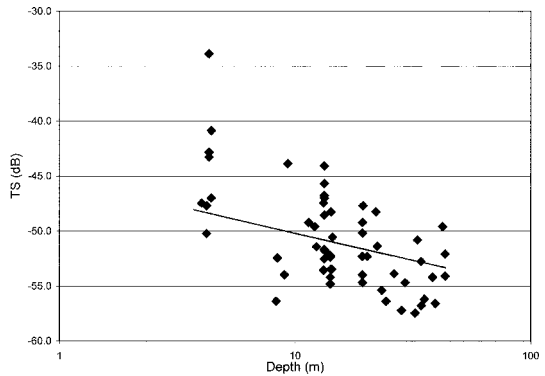


FIGURE 3.—Scatter plot of Pacific herring target strengths (TS) at various depths. Regression line is fit of Boyle's Law to the observations.

of lengths measured for the spring herring was relatively narrow. However, the TS of the herring during spring were clearly higher. We compared the two seasons by using the alternative form of the TS–length equation, which forces the slope to 20. The resulting equation for fall herring is  $TS = 20 \cdot \log_{10}L - 66$  and for spring herring is  $TS = 20 \cdot \log_{10}L - 62.8$ . The results suggest a 3.2-dB difference in TS between the two seasons.

This result is consistent with other observations. Seasonal changes in herring TS have been noted previously (Kautsky et al. 1991; Ona et al. 2001). Potential explanations include changes in lipid content, gonad development, and stomach content, all of which may affect swim bladder volume. Larger swim bladder volumes have been reported for fish with low fat content and also for spent fish (Kautsky et al. 1991). 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 TSs.

Our observed increase of 3.2 dB compares to a 6–9-dB increase in TS for Pacific herring during spring reported by Kautsky et al. (1991). However, their comparison was indirect (i.e., an in situ measurement during spring compared with equations that had been developed primarily from fall herring observations). Their observations also included a high ratio of spent fish.

### Changes in Target Strength with Depth

The TS of Pacific herring decreased with depth (Figure 3). The data were variable even though

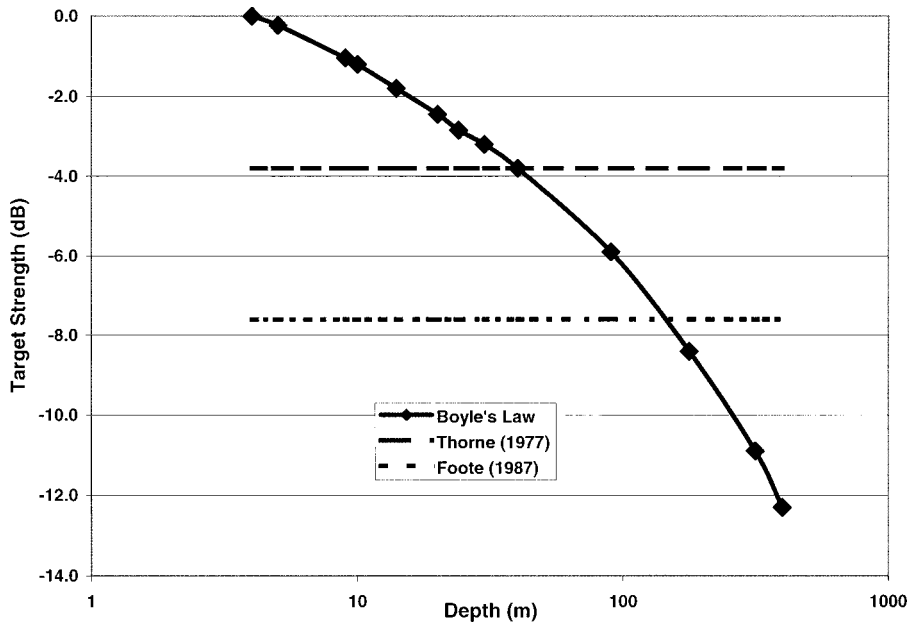


FIGURE 4.—Depth-dependent changes in target strength compared with depth-independent equations of Thorne (1977a) and Foote (1987). The depth-dependent function is the target strength measured in this study for Pacific herring at 4 m, as modified by Boyle's law.

standard errors around individual fish were typically less than  $\pm 1$  dB. Some of the variability resulted from effects of differing lengths. Fish lengths in the experiment varied slightly more than two-fold. The sample size was too small to segregate these two confounding sources of variability. Despite this complication, the decrease in the TS with depth was obvious.

The herring swim bladder is physostomatous. Previous research has shown that herring swim bladders lack capability of gas secretion (Blaxter and Hunter 1982; Thorne and Thomas 1990). Under these circumstances, we would expect swim bladder volume to compress with depth in response to the effects of Boyle's law, which states that an enclosed volume of a gas will decrease in inverse proportion to pressure. Because backscattering cross section is linearly related to surface area of the scatterer, the change in TS is as follows:  $\Delta TS = -6.67P + 3.17$  for a spherical volume, where  $P$  is pressure in atmospheres.

There is insufficient precision or range of depth measurements in our data to conclusively determine correspondence with the theoretical effects of Boyle's law. Our observations indicate a slightly steeper decline in TS than is theoretical, but the difference is not significant. Deviation from the theoretical effects of Boyle's law may occur for

several reasons (Blaxter et al. 1979; Ona 1990): the swim bladder is not a perfect sphere, other components of the fish contribute to the backscatter, and changes in aspect associated with different behaviors.

Additional uncertainties may be associated with the effects of depth on Pacific herring target strengths during surveys because of gas bubble release by herring species during vertical migrations (Thorne and Thomas 1990; Nottestad 1998) and gulping of air at the surface after vertical migrations (Thomas and Thorne 2001).

The effect of Boyle's law may explain some of the large differences between TS equations for Pacific and Atlantic herring as reported in MacLennan and Simmonds (1992). If we apply the depth correction factor for Boyle's law from Mukai and Iida (1996) to the TS relationship that was determined at 4 m and compare that result with the depth-independent equation of Thorne (1977a), we see that the two equations produce identical estimates at a depth of 40 m (Figure 4). A similar comparison with the depth independent equation of Foote (1987) as cited in MacLennan and Simmonds (1992) for Atlantic herring produces an identical estimate at 150 m. Adult Pacific herring in Prince William Sound typically distribute in 10–50-m depths at night and 60–100-m depths during



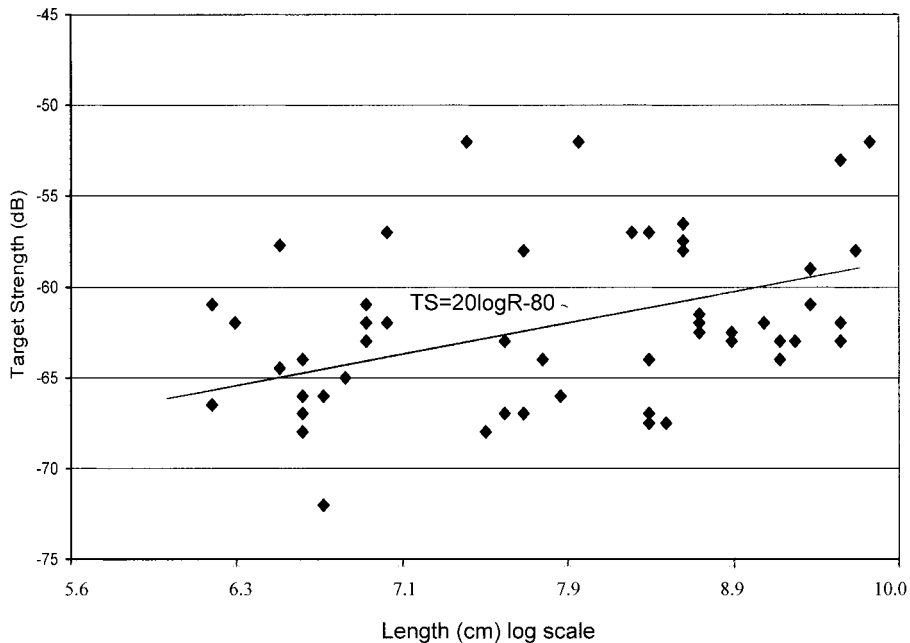


FIGURE 5.—Observed target strength–length relationship for Pacific sand lance.

day. Huse and Ona (1996) and Nottestad (1998) show the nighttime depths of Atlantic herring range from 50 to 400 m. Nottestad and Axelsen (1999) report a daytime depth range of 150–350 m for Atlantic herring during spring, but some are distributed at less than 100 m. Based on the predicted effects of Boyle's law, these differences in vertical distributions are sufficient to account for the differences between the reported Pacific and Atlantic herring TS relationships.

#### *Ex Situ Pacific Sand Lance Target Strength Versus Length*

The TS of 56 juvenile Pacific sand lance increased with length:  $TS = 24.5 \log_{10} L - 84.1$ , or  $TS = 20 \log_{10} L - 80.0$  (Figure 5). The TS relation is not expected to vary by depth because of the absence of a swim bladder. Consequently, the TS is 14 dB lower than that of Pacific herring at 4 m in the fall. The estimated target strengths are considerably higher than would be estimated by the equation  $TS = 20 \log_{10} L - 93.7$  from Armstrong (1986) for sand lance of the Atlantic Ocean 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 their pelagic behavior. The difference in frequency of the measurements, 38 kHz versus 120 kHz, is another possibility. We would expect a small fish without a swim bladder to have less reflection at the lower frequency (Medwin and Clay 1998). Edwards et al. (1984) estimated  $TS = 20 \log_{10} L - 86.9$  for Atlantic mackerel *Scomber scombrus* at 120 kHz, which also lacks a swim bladder. This value is closer to ours but still lower. A size-frequency interaction may explain some of the difference, as the mackerel were about three times longer. Unfortunately, there are very limited observations on fish without swim bladders. Our result for Pacific sand lance is very similar to the value for the California market squid *Loligo opalescens* of the same size at 120 kHz:  $TS = 20 \log_{10} L - 79.9$  (Jefferts et al. 1987). In addition, Foote (1980) estimated that the swim bladder of Atlantic cod, a physoclistous species, accounts for 90–95% of the acoustic backscatter. On that basis, our observed reduction of 14 dB compared with Pacific herring at 4 m seems more reasonable than the 28 dB difference reported for the Atlantic sand lance species.

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 echo-integration measurements. In contrast, we directly measured TS but limited our measurements to within the  $-3$  dB angles needed to optimize signal-to-noise conditions. Our approach limits the aspect angles to near the acoustic axis. Because echoes further from the acoustic axis are greatly reduced in size by the directivity pattern, it would take a considerable difference in target strengths from relatively minor aspect changes to cause an appreciable difference between the two approaches, and that seems unlikely.

### Conclusions

Several factors affect the TS of fish. Presence or absence of a swim bladder is a major factor as seen in the 14-dB difference that we observed between sand lance and fall herring of the same size at 4 m depth. Although many studies have addressed the TS-length relationship, this study indicates that both depth and season are potentially greater sources of variability. Fish length has a major effect on individual fish TS. However, the effect on biomass assessment is relatively small. Thorne (1983a) showed that a two-fold difference in length changes the scaling factor for estimates of biomass by less than 2 dB. In contrast, we observed a 3.2-dB difference in the TS of Pacific herring between spring and fall. The effect of depth is also substantial. A relatively minor change in depth from 10 to 30 m results in a TS change of 2 dB for Pacific herring.

Several previous studies of Pacific herring have reported differences between estimates obtained during day versus night surveys (Thorne 1977a,b; Thorne et al. 1983). At least some of these differences are probably attributable to depth differences associated with diel vertical migrations. Consequently, acoustic estimates of Pacific herring biomass need to take into account the depth distributions associated with various surveys. A similar depth dependence probably exists for Atlantic herring, which would explain much of the discrepancies reported between TS equations for the two herring species. Further research is needed to determine if TS varies with depth for other physostomatus fishes.

The change in TS for Pacific herring associated with season is probably also related to changes in the swim bladder volume, but effects of factors such as lipid content and gonad development are not clearly differentiated and need further research. The use of acoustic estimates to investigate population metrics, such as recruitment or seasonal

mortality, will require accurate understanding of seasonal changes in TS.

Information on the target strengths of fish without swim bladders is still limited. There is a substantial and largely unexplained difference between our measurements of Pacific sand lance and the reported values of the Atlantic sand lance species 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 our estimates reported here because they both more specific and more conservative.

The ex situ experimental technique used in this study was very effective. Signal-to-noise characteristics were favorable for individual fish measurement. Although the size of the cage was small, the fish had room to swim naturally, and cameras allowed detailed synoptic evaluation of behaviors. The capability to lower the entire assemblage to different depths facilitated the measurements and eliminated potential errors from changes in geometry. The attached calibration sphere allowed continual monitoring of the acoustic system, including potential changes in transducer performance with depth. The 43-m maximum depth in this study could be eliminated with longer cables.

### Acknowledgments

This project would not have been possible without the following people: Loren Tuttle, Greg Carpenter, and Jackie Popp assisted with data collection. Liz Seneor, Shelton Gay, and John Williams helped with field preparation. Brian King, John Herschlieb, George Covell, and Bob Sanford assisted with boats. Herb Jensen, Jack Babic, Lee Hulbert, John Thedinga captured live samples. David Marino assisted in the data analysis. This work was supported by the *Exxon Valdez* Oil Spill Trustee Council as project 99468 and by the Oil Spill Recovery Institute as contract 00-10-03.

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