**In situ measures of target-strength variability of individual fish**

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Much recent target-strength research has addressed variability in echo amplitude that can be attributed to transducer directivity or fish behavior. Several workers have documented considerable variations in target-strength estimates obtained from consecutive ensonifications of individual fish; a periodic pattern of variation has often been observed. The principal sources of variation appear to be associated with the behavior of the fish and the complex nature of the backscattering process. Acoustic frequency and individual fish size also influence backscattering cross-section and associated variation. We present several examples of data obtained from sequences of consecutive ensonifications of individual fish and discuss possible causes and implications of the variability observed.


**Introduction**

The success of hydroacoustic survey techniques in providing a quantitative measure of fish size or density almost always depends on what is known about the target-strength (TS) distribution of the fish being surveyed. Much of the early target-strength research focused on establishing a relationship between fish length or weight and TS. Variations due to position in the beam and fish behavior were removed by immobilizing a specimen on the acoustic axis (Nakken and Olsen, 1977; Love, 1971; Buerkle and Sreedharan, 1981; Dahl and Mathisen, 1981). The TS length regressions that came from these studies were used during fish-abundance estimation factor calculations. Nakken and Olsen (1977) observed that the maximum dorsal aspect TS from their experiments on cod was 8–9 dB higher than the corresponding average TS value that would be expected from field observations, and this was where wide tilt-angle distribution occurred. Welsby (1975), however, attributed differences of this magnitude to the ability of a live fish "to impress on the echo amplitude another kind of modulation, which is a function of its body movement. This modulation rate is not directly linked to the size of the object in wavelengths". Since dorsal-aspect measurements on immobilized fish do not incorporate the effect of behavior, two approaches for considering behavior were developed.

As the tilt angle of a fish is generally considered to be the primary cause of target-strength variation, the first technique involved measuring TS as a function of tilt angle. The distribution of *in situ* tilt angles was then modelled or measured, and the TS distribution and the tilt-angle distribution were combined to calculate the effective mean TS (Nakken and Olsen, 1977; Nakken, 1977; Foote, 1980; Buerkle and Sreedharan, 1981).

Other controlled experiments involved measuring echo amplitudes of fish in cages located on or near the acoustic axis (Carlson, 1978; Edwards et al., 1984; Goddard and Welsby, 1986). With this technique, investigators attempted to remove directivity effects; it was assumed that behavioral patterns were similar to those occurring in the wild. However, Dunn (1978) noted that the acclimation time for caged gadoids to adjust to an enforced pressure increase (typical of cage experiments) was in units of days rather than hours. Røttingen (1976) indicated that the TS of fish in a cage changed with packing density. Edwards et al. (1984) reported a diel pattern in tilt angles and unnatural cage behavior for mackerel, and summarized the validity of estimating the "natural state" TS as follows: "Caged fish experiments place a small population of fish in an alien environment. They are constrained to swim within a relatively small volume of water at fixed depth. These conditions cannot be considered natural and whether the fish ever adopt truly natural behavior patterns within a small experimental cage is a debatable point".

Another category of experiments to measure TS involved *in situ* studies. The primary advantage here was that the behavioral source of variation was accurately contained in the echo amplitudes. Difficulties with *in situ* experiments involved successful removal of the transducer directivity effects, and unbiased capture of samples from the ensonified population. Several indi-
rect techniques were proposed for removing the directivity. These techniques all assumed that the scatterers were uniformly distributed in the acoustically sampled volume. An innovative non-parametric technique developed by Craig and Forbes (1969) was designed to remove directivity effects geometrically, although the recursive nature allowed errors to compound. High sample sizes were needed to minimize the number of TS cells with negative counts. However, Lindem (1982) and others have reported successes with this technique. Ehrenberg (1972), Lozow (1982), and Robinson (1982) have developed more general mathematical formulations and solutions to the problem originally addressed by Craig and Forbes. Ehrenberg (1983) concluded that “all of these techniques for indirectly estimating the target strength or backscattering cross section density function are susceptible to numerical and statistical error. They do not work well in many cases of interest”. Other proposed indirect techniques assumed that the backscattering cross-section had a particular functional form (Peterson et al., 1976; Ehrenberg et al., 1981; Clay, 1983). The task was then to estimate the parameters of that assumed distribution. Although these parametric modes are “better behaved”, their accuracy is only as good as the validity of the assumed underlying distribution.

Measurements of behavioral effects other than tilt angle on TS have begun to appear in the literature. Nakken and Olsen (1977) presented a cyclic pattern of dorsal-aspect TS fluctuation from a “swimming” cod (Gadus morhua) constrained in a harness, and indicated a periodic relationship between TS and tail beat (Fig. 1). However, Foote (1985) hypothesized that the observed pattern may have resulted from the attempt of the upside-down fish to right itself, and concluded from his modelling study that “traditional” swimming movement would have an inconsequential effect on TS. Goddard and Welsby (1986) used the variation in echo amplitude (Fig. 2) to classify “normal” behavior of their caged fish. Several examples of long-term variation (hours or days) in TS have also been published (Edwards et al., 1984; Dunn, 1978; Edwards and Armstrong, 1981).

The development of dual and split-beam techniques (Ehrenberg, 1974, 1983) has given scientists a powerful tool for analyzing target strength in situ. Since the techniques directly remove the transducer directivity from each individually resolved echo, the backscattering cross-section for each echo can be calculated. The resulting distribution of echo amplitudes can then be used...
to calculate the effective mean backscattering cross-section of a fish population, which is used when converting integrated echo density to fish density. In addition, variations in TS for individual, free-swimming fish under various environmental factors can be measured.

Drew (1980) was the first to present data on ping-to-ping variations in the target strength of an individual free-swimming fish in Lake Washington, near Seattle, using dual-beam *in situ* techniques (Fig. 3). These dorsal-aspect data are from a fish assumed to be an adult salmon (*Oncorhynchus nerka*) 50–60 cm in length. The fish was detected with a 105 kHz system at night at a depth below 10 m. Swimming motion was offered as the cause of the cyclic pattern. Drew and others hypothesized that a species signature might exist in the pattern of TS variation for some fish. The mean TS is almost 5 dB lower than the maximum TS. Our own work considers TS estimation as a three-dimensional process: echo amplitudes containing variation from fish morphology, position in the beam, and fish behavior/fish directivity interactions. The measurements were made in riverine and lacustrine environments, and the implications of the observed variations on fish-abundance estimation and fish sizing are discussed.

### Materials and methods

All *in situ* measurements of target strength were made with a 420 kHz dual-beam BioSonics echo sounder transmitting a 0.4–0.5 ms signal through a 6° (at the −3 dB points) element and receiving through 6° and 15° elements. Analogue signals were recorded through a Sony Pulse Code Modulation Digitizer on a Beta video recorder. Signals were played back in the laboratory into a BioSonics dual-beam processor with a 15 kHz sampling rate. The processor measured depth and peak amplitude on both channels for each target. Echoes whose −6 and −18 dB pulsewidths were within predicted limits were classified as single targets.

All measurements were made from stationary transducers, either mounted on a float or a boat and aimed downwards, or mounted on a structure on the bottom and aimed horizontally. The TS of a table-tennis ball was measured (Fig. 4) to demonstrate any variability due to the measurement process on a non-directive target. The low variation combined with a calibration accuracy of 0.5 dB indicates that the potential inaccuracies are 1 dB or less.

Groups of echoes from a single fish were isolated with a target-tracking program. The mean target-strength values presented in the text and in Figures 2–3 and 11 are used to show variability (by looking at the standard deviation) because TS is approximately normally distributed. Presentation of mean backscattering cross-section would not be as intuitive a measure of variability because the distribution is skewed. However, the mean backscattering cross-section should be used for all other instances when averaging is required.

### Results

An example of short-term variation in target strength is given in Figure 5. These night-time dorsal-aspect measurements, made in the Hudson River in New York, are presumably of a striped bass (*Morone saxatilis*). The angular position in the 6° beam angle is also plotted. The calculated angular position of the fish in the beam shows high variability, possibly due to close detection range (6.5 m) and large fish size relative to beam diameter. This variability would carry over into the TS estimated for each ping if it were due to the fish’s not acting as a point scatterer. However, when the fish is near axis, short-term variations are in the range of 10 dB. Although variations are not periodic, the observed pattern is believed to be a function of the swimming motion of the fish in the slow nearshore currents. The standard deviation about the mean TS is similar to that observed by Drew (1980) for the salmon in Lake Washington.

Dual-beam measurements were made from an anchored boat during January 1987, in Lake Mead, Ne-
vada. The population being surveyed consisted primarily of a dispersed layer of threadfin shad (*Dorosoma petenense*), with a few predatory striped bass present. All target strengths were dorsal aspect, measured at night. Figure 6 shows the pattern of TS variation for a threadfin shad. The shad length is over 10 times the acoustic wavelength (0.35 cm). The observed high variability, possibly atypical since this example was chosen at random, may be related to feeding or predator-avoidance behavior. The total change in target depth of 0.3 m during the observation period may indicate a rather substantial change in tilt angle. Figure 7 illustrates the ping-to-ping variation for a striped bass in Lake Mead. This fish, probably about 20–25 cm long, shows less ping-to-ping variation than the shad example and less than the swimming fish in the Hudson River.

On the Klamath River in northern California, adult chinook salmon (*Oncorhynchus tshawytscha*) were counted by a horizontally aimed dual-beam system as they migrated upstream. The pattern of variation in the side-aspect target strength is shown in Figure 8. The target disappeared for about four seconds, either by momentarily passing out of the beam, or because its echoes did not meet the single-target detection criteria during that time. The mean side-aspect TS for this fish was 10 dB lower than the maximum value. The standard deviation of the side-aspect TS was higher than for the other examples of large fish. The 10–15 dB changes in TS observed between pings (0.2 seconds) are not surprising for a side-aspect observation of a fish swimming up a river, because of the side-aspect directivity pattern and the continually changing body shape produced by swimming. The observed variability was similar to that of the much smaller threadfin shad (Fig. 6).

**Discussion**

The patterns of ping-to-ping variability are dependent on the interaction of fish directivity and behavior. It is apparent that fish behavior affects the mean backscattering cross-section. If the mean backscattering cross-section of fish exhibiting a certain behavior is applied to a population exhibiting different behavioral characteristics, a bias may be introduced in fish-abundance estimates. This concern has been documented by modelling studies where two behavioral conditions were examined ("schooling" and "aggregating"). This work indicated that the abundance can be underestimated by up to 50% or overestimated by up to 90% (Foote, 1979) if the wrong tilt-angle distribution is used when calculating mean backscattering cross-section. If a reasonable number of targets can be resolved as single echoes, and if these single targets represent the population accurately, simultaneous echo integration and dual/split-beam measurements will provide the best estimate of density. There still exists the problem of schools in
Figure 5. Night-time dorsal-aspect target-strength observations of a free-swimming fish, probably a striped bass (*Morone saxatilis*), in the Hudson River, 29 February 1984. Depth of fish 6.6 m. Lower plot indicates the angular position in the beam with time.

Figure 6. Observations of night-time dorsal-aspect target strength for a free-swimming small fish, probably a threadfin shad (*Dorosoma petenense*), in Lake Mead, 21 January 1987. Frequency 420 kHz. Lower plot indicates angular position in the beam with time.
which it is impossible to measure \textit{in situ} TS, and where inconsistent patterns of schooling behavior occur.

When the TS distribution of a fish population is compared with the length-frequency distribution from the catch, the acoustic distribution is broader than the distribution of lengths. This is primarily due to the interaction between the behavior and the directivity of an individual fish, but also to the complex nature of the backscattering process of a living, dynamic object. Figure 9 examines the acoustic size "distribution" for a single fish. Based on the data from the fish in Figure 7, Figure 9 shows a distribution of acoustic sizes for a single length observation. Since many populations in nature have multi-modal length distributions, the broadening of the acoustic distribution often causes TS modes to overlap to such a degree that they cannot be resolved. When dual-beam or split-beam techniques are used, the variability caused by ping-to-ping changes can often be reduced by averaging several TS values from an individual fish. This is not possible with indirect techniques, since the transducer directivity cannot be removed from a selected echo, but must be removed from a larger population of echoes. To examine the effects of averaging many echoes from each fish (target tracking), Ehrenberg (1984) modelled the results of echo averaging using a Monte Carlo simulation. The fish population was made bimodal by randomly drawing echo-level samples from two Rayleigh distributions with means differing by 6 dB. He included the effects of (Gaussian distributed) noise, assumed narrow and wide beam widths of 6° and 15° respectively, and observed that the modes were more clearly separated with increasing numbers of echoes per fish averaged (Fig. 10).

The target-tracking process was applied to the Lake Mead survey data for empirical examination of its effect on the TS distribution. The survey data were analyzed with and without target tracking, although the size modes were considerably more than 6 dB apart. The results compare the TS distribution based on all echoes as independent samples (Fig. 11A) with the distribution from all fish that were ensonified at least five times (Fig. 11B). Note that target tracking separates the TS modes while reducing the total number of echoes used. The high ratio of small (prey) to large (predator) targets is not unusual.

\textbf{Conclusion}

The use of dual- and split-beam technology has provided opportunities for scientists to collect \textit{in situ} target-
Figure 8. Observations of night-time side-aspect target strength of a chinook salmon (*Oncorhynchus tshawytscha*) migrating up the Klamath River in California, 30 August 1986. Frequency 420 kHz. Lower plot indicates angular position in the beam with time.

Target-tracking analysis of dual-beam TS measurements offers a practical means of observing ping-to-ping variation caused by fish behavior and directivity. Target-tracking analysis may often require collecting a segment of data at a slower boat speed, unless targets are deep enough to be detected many times as the beam passes over them. Such target tracking offers significant improvements in resolving different modes from overlapping target-strength distributions. The conversion factor from integrated echo intensity to fish density must, however, be based on the average backscattering cross-section of the total distribution.

As the target strength is highly dependent on fish
behavior, it is beneficial to use continuous *in situ* measurements of the backscattering cross-section during abundance estimation in non-schooling species. Concerns about using a mean backscattering cross-section from lower density peripheral areas to represent the mean in high-density situations are valid.

The advent of multi-beam acoustic technology offers fishery science the possibility of investigating the effect of behavior on the target strength of individual fish. The ping-to-ping variation in TS could be correlated with simultaneous observations of behavior. If an unobtrusive direct-observation technique could be developed,
this class of experiments would further our knowledge of the interaction between fish size and species, acoustic frequency, and behavioral effects.

References


