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# Application of dual-beam and split-beam target tracking in fisheries acoustics

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Dual-beam and split-beam acoustical techniques were originally developed to provide direct *in situ* measurements of the target strength of individual fish and plankton. The amount of information that can be extracted from these acoustic systems can be significantly increased when the techniques are used in conjunction with ping-to-ping target tracking. For example, target tracking can be used to isolate multiple target-strength measurements from an individual fish or plankton. These measurements can then be averaged to provide a lower variance estimate of the target strength. The measurement of the angular location of the target provided by split-beam systems further enhances the usefulness of tracking. The angular data measured on subsequent pings can be used to resolve returns from single and multiple targets and estimate the direction and speed of the fish as they pass through the beam. Information on fish speed and direction is particularly useful for fixed location acoustic studies. This paper uses a combination of actual data, simulation results, and analysis to describe the various applications and expected performance of acoustic systems that combine dual-beam and split-beam techniques with target tracking.

Key words: dual-beam, split-beam, target-strength measurement, target tracking.

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## Introduction

Single fish traces on echograms can be distinguished from background noise because of the distinctive marks that are generated by multiple ensonifications of the fish. This same ping-to-ping consistency of the returns from individual scatterers can be exploited by automatic processing techniques. In its simplest form, target tracking can be applied to the output of an ordinary single-beam acoustic system. Single-beam target tracking can be used to automatically sort out target returns from background noise. The usefulness of target tracking is significantly enhanced when tracking is used in conjunction with dual-beam and split-beam acoustic systems (Brede *et al.*, 1990). The commonly used dual-beam and split-beam multi-beam techniques were initially used to remove the effect of the beam pattern factor from an acoustic echo, thereby providing a direct measure of the reflectivity of the scatterer as measured by the back-scattering cross-section, $\sigma_{bs}$, or target strength, $TS = 10\log[\sigma_{bs}]$ (Ehrenberg, 1989). By tracking and averaging the measured backscattering cross-section of individual scatterers from ping to ping, lower variance estimates of the "acoustic size" of the individual scatterers are obtained. The angular location data provided with split-beam systems can also be used in conjunction with the tracking data for fixed location acoustic systems to provide estimates of fish swimming speed, location in the water column, and direction of travel. Target tracking can also be used to separate the returns from a single scatterer from the returns of multiple scatterers at the same range.

The process of obtaining target tracks from acoustic data is a two-step process. The first step is identical to the single-echo isolation techniques used for target-strength estimation. The shape of the received echoes on the full beam of a split-beam system or on the narrow beam of a dual-beam system is measured and compared with the expected shape for a single echo. If the pulse shape criteria are satisfied, the measured parameters (such as echo intensity, angular location in the beam, beam pattern, and range) are saved. The second step of the tracking process uses the single-target data collected for a number of transmitted pulses to form target tracks. The tracks are formed sequentially: the parameters for target track j at ping n are used to estimate the expected values of the parameters at ping $n+1$. If the measured parameters for a detected single echo on ping $n+1$ fall

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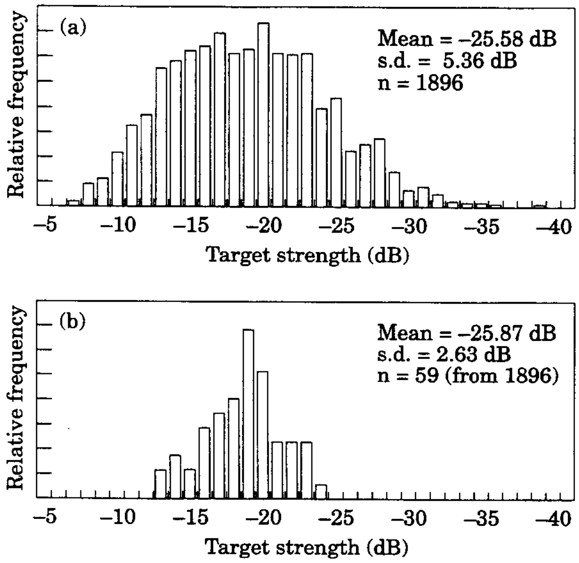

Figure 1. Measured target strength histograms for untracked (a) and tracked (b) fish. Data collected using a fixed location, side-looking, split-beam system on the Kenai River in 1994.

within the range expected for track j, the new echo is added to track j. If a detected target's parameters do not meet the criteria for any of the existing tracks, a new track is started. The purpose of the paper is to discuss the benefits of target tracking, rather than the details of the implementation of tracking algorithms.

## Single-target average target-strength measurement

Extensive measurements have been made to determine the relationship between target strength and length of fish for various orientations and species of fish. Some of the most extensive measurements of this type have been made by Love (1977). The target-strength measurement results are usually expressed in terms of a regression relationship that provides a means of using fish length to estimate average target strength. These regression relationships can also be used to convert the *in situ* measurements of target strengths into estimates of fish size. However, this conversion is complicated by the ping-to-ping variability in the *in situ* measurements of target strength. Target tracking can be used to isolate the target-strength estimates from individual single fish, which can then be averaged to produce a single, lower variance estimate of the average target strength for each tracked fish target.

The effectiveness of target tracking for reducing the variance in the measured average target strength is illustrated by the untracked and tracked target-strength histograms shown in Figure 1. The data were collected using a fixed-location, side-looking 200 kHz split-beam acoustic system operating on the Kenai River in Alaska during the 1994 summer chinook salmon migration. Note that target tracking and averaging reduced the target-strength standard deviation from 5.36 dB for no tracking to 2.63 dB for tracked fish.

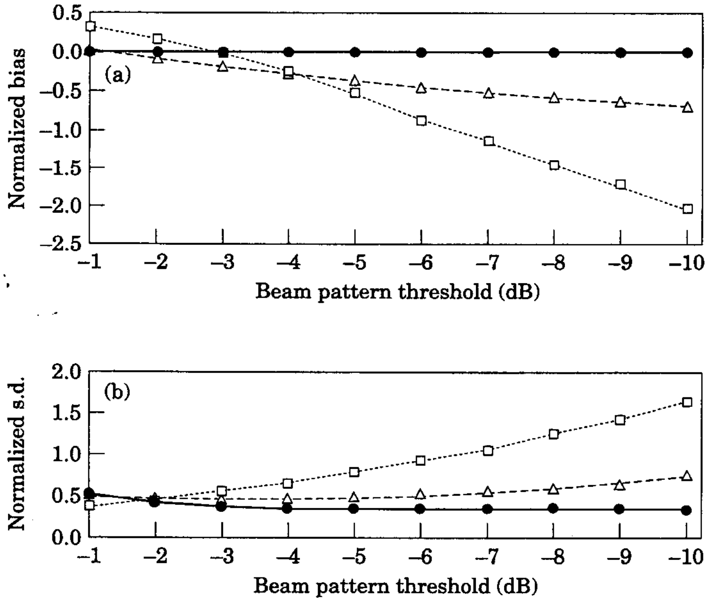

Figure 2. Simulation results showing the effects of signal-to-noise and beam pattern threshold on the normalized bias (a) and standard deviation (b) for dual-beam and split-beam techniques. ● = 60 dB SNR, dual and split beam; □ = 15 dB SNR, dual beam; △ = 15 dB SNR, split beam.

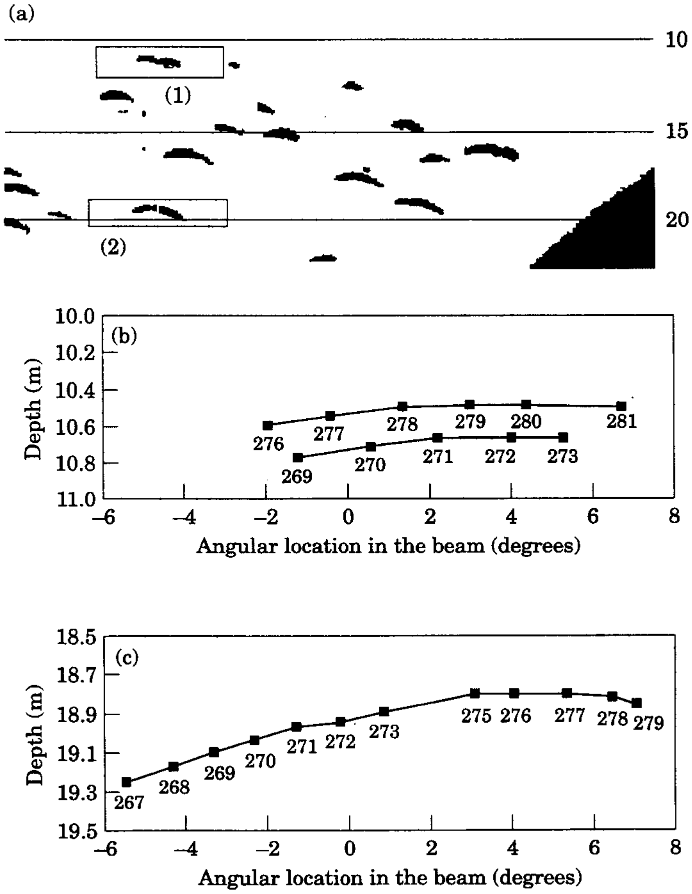

Figure 3. Echogram (a) and corresponding angle versus depth plots for trace 1 (b) and trace 2 (c). Numbers along the curve correspond to ping number. Data collected with a split-beam system in a North American lake in 1994.

The number of times a fish is detected as it passes through the beam can be maximized by accepting target echoes for a wide range of beam angles. However, accepting targets over too large a beam angle can induce a bias in the average target-strength estimate, since small fish targets are less likely to be detected as they move further off axis. This effect has been quantified using a Monte Carlo simulation of the techniques for estimating the target strength of tracked fish. The details of the simulation are described in Appendix A. Figures 2a and 2b show the normalized bias and normalized standard deviation in the average backscattering cross-section estimate as a function of the beam pattern threshold and signal-to-noise ratio for the dual-beam and split-beam techniques. Note that at high signal-to-noise, nearly all targets are well above the noise threshold and there is essentially no bias for either dual-beam or split-beam techniques. As the signal-to-noise decreases, the additive noise affects the bias in a number of ways. First, smaller fish near the edge of the beam will often result in echo levels that are comparable to the noise level. These noisy echoes will often neither satisfy the noise threshold nor the single-echo shape criteria. This discrimination against small fish echoes produces an estimate that is too large (negative bias). Secondly, additive noise increases the average level in the full beam outputs for the dual-beam or split-beam techniques. This increased signal level also produces an estimate that is too large.

Finally, the additive noise affects the estimates of the beam pattern for the dual-beam and split-beam techniques. The bias plots in Figure 2a indicate that the adverse effects of noise can be minimized by only accepting targets with relatively large estimated beam pattern factors (targets near the acoustic axis of the beam). The plots also show that the split-beam technique has a significantly smaller bias than the dual-beam method. This is consistent with earlier analysis and measurements of dual-beam and split-beam systems (Ehrenberg, 1979; Traynor and Ehrenberg, 1990).

At high signal-to-noise ratios, the standard deviations in the dual-beam and split-beam estimates are due almost entirely to the randomness in the backscattering cross-section, $\sigma_{bs}$. When this is the case, the standard deviation shown in Figure 2b decreases with increased

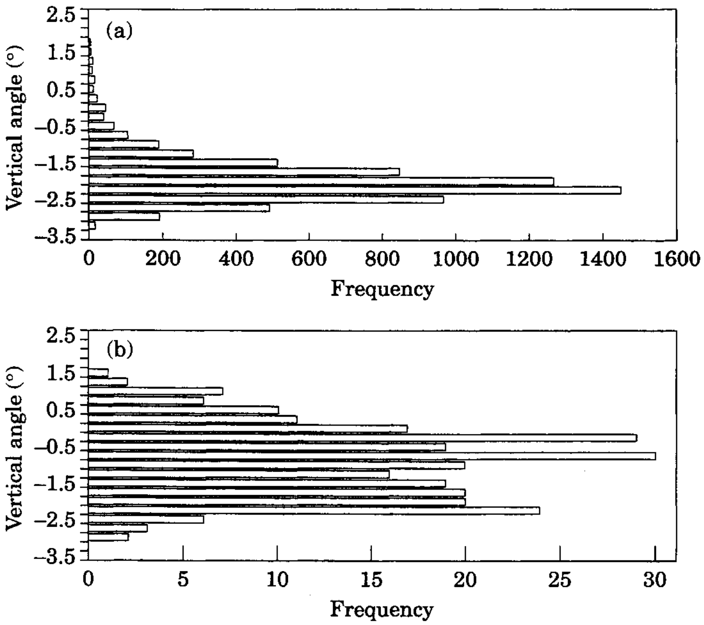

Figure 4. Upstream (a) and downstream (b) vertical distribution of salmon in the Chandalar River in Alaska in 1994 measured using a fixed location, side-looking, split-beam system. In (a), n=6513, mean= −2.12 degrees, s.d.=0.63. In (b), n=262, mean= −0.99 degrees, s.d.=1.06.

effective beam width (lower beam pattern threshold), since the average number of detections per fish increases with beam width. However, at lower values of signal-to-noise, the additive noise significantly contributes to the variability in the estimates of $\sigma_{bs}$. The additive noise has the greatest effect on the variability of targets near the edge of the beam. Consequently, the normalized standard deviation in the estimate is also minimized by restricting the range of angles or beam pattern factors for which targets are accepted for processing. Note that additive noise has a smaller effect on the split-beam techniques.

## Split-beam tracking

The angular location estimates provided by split-beam techniques significantly enhance the tracking performance and usefulness of the data compared to what can be obtained with single-beam or dual-beam tracking techniques. The angular estimates obtained with split-beam systems are relatively insensitive to the effects of additive noise. Appendix B contains a derivation of the rms error in a split-beam estimate of the angular location as a function of signal-to-noise ratio. It is shown that the angular rms error is only about a tenth of a beam width for a signal-to-noise ratio as low as 10 dB.

The angular location data provided by the split-beam technique can be used to sort out returns from single and multiple scatterers at approximately the same range. This is illustrated by the echogram and associated angular location plots shown in Figure 3. These data were collected during a mobile survey in a North American lake. The echogram display of received signal intensity versus range shows two traces, labelled 1 and 2, that appear to be from single fish passing through the beam. However, the plot of angular location versus depth giving the ping number for individual data points clearly shows that echo trace 1 actually corresponds to two fish. Trace 1 is produced by two fish. One enters the left side (negative beam angle) of the beam at ping no. 276 and exits the right side at ping no. 281. The second fish enters the left side of the beam at ping no. 269 and exits the right at ping no. 273. Trace 2 could be interpreted as being produced by two fish. However, the smooth progression of the fish's angular locations clearly shows that this trace is produced by a single fish.

Split-beam echosounders and target tracking have enabled acoustic techniques to be used effectively at a fixed location for monitoring fish passage in rivers. Rivers can be complex acoustic environments and the signals out of echosounding systems can be due to downstream travelling fish and debris, as well as upstream migrants. Furthermore, there can often be a considerable amount of reverberation present in the received signals. Split-beam ping-to-ping tracking is used to isolate the acoustic returns of upstream fish from those of downstream debris and fish, providing the data needed to determine the speed of the targets as they pass a monitoring site, and providing an effective way to discriminate random reverberation from signals produced by fish as they pass through the beam. Figure 4 illustrates the type of data that can be obtained when a split-beam system is used with target tracking. This figure shows the distribution of vertical beam angles of upstream and downstream fish (primarily chinook salmon) as they pass through a side-looking beam on the Chandalar River in Alaska. The upstream data in Figure 4a show that the fish are deeper in the water column where the water velocity is slower (presumably in an effort to conserve energy). About 17% of the tracked targets are travelling downstream. Figure 4b shows that the downstream targets are more widely distributed in the water column and their average depth is higher than that for upstream fish.

Split-beam Chandalar River data are routinely processed to determine the swimming speed of the upstream and downstream fish. The speed is determined by first using the angular estimates to determine the three-dimensional coordinates where the fish enters and exits the beam, then by dividing the distance travelled by the time in the beam.

## Discussion

The amount of information that can be extracted from acoustic data is maximized when the outputs of split-beam and dual-beam systems are combined with target-tracking techniques. The use of target tracking provides a lower variance estimate of the target strength of the scatterer. Split-beam techniques are particularly useful for target-strength estimation, because they are less affected by additive noise than dual-beam techniques, and because they provide angular location in addition to the target-strength estimates and range data. The ping-to-ping angular location data can be used to sort out returns from single and multiple fish and determine the direction, speed, and angular trajectory of the scatterer as it passes through the beam.

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## Appendix A: Simulation of target-tracking technique

Monte Carlo simulations provide a good means for analyzing the effects of noise and parameter selection on complex processing techniques such as the target-tracking methods discussed in this paper. The simulation results presented here used 10 000 independent Monte Carlo runs to estimate the normalized bias and standard deviations for the backscattering cross-section estimates where

$$\text{Normalized bias} = \frac{\bar{\sigma}_{bs} - \hat{\sigma}_{bs}}{\bar{\sigma}_{bs}} \tag{A1}$$

$$\text{Normalized standard deviation} = \frac{\sqrt{\mathrm{var}[\hat{\sigma}_{bs}]}}{\bar{\sigma}_{bs}} \tag{A2}$$

where $\bar{\sigma}_{bs}$ and $\hat{\sigma} \times_{bs}$ are the average and estimated values of the backscattering cross-section, respectively. The randomness in the backscattering was modelled using a Rayleigh probability distribution for the square root of the backscattering cross-section. Ehrenberg *et al.* (1981) and Clay and Heist (1985) have shown that this is an accurate statistical model when the scatterer is large relative to an acoustic wave. The simulated target followed a straight line as it traversed the beam. The starting location and angular direction of the fish paths were selected randomly. The target position along the track was used to calculate the angular location of the target in the beam and the relative phase shifts in the signals received at the transducers. The full, wide, and half beam pattern factors were then calculated and used in conjunction with the value of random backscattering cross-section to determine the amplitude of the signal received on the full, wide, and half beam transducers. The proper noise levels were then added to the full and partial beam output signals. The additive noise was Gaussian-distributed with a zero mean and a variance that was dependent on the directivity of the beam pattern being simulated. The signal-to-noise ratio was specified as the ratio of the power in the signal due to an average size target on the acoustic axis of the beam relative to the power in the noise. Targets signals that satisified a noise and beam width or beam pattern threshold were used to calculate an average value for the target backscattering cross-section. The noise threshold was set to twice the standard deviation of the noise. The beam pattern threshold specified the minimum estimated beam pattern factor for which an echo was accepted. The beam pattern estimate was calculated from the estimated beam locations for the split-beam method and was measured directly for the dual-beam technique. For an accurate comparison of the dual-beam and split-beam methods, the full transducer beam widths for the two techniques were set equal. The width of the wide-beam transducer used in the dual-beam simulation was 2.5 times the width of the narrow beam.

## Appendix B: The effects of noise of split-beam angle estimate

Split-beam techniques provide angular location estimates by measuring the electrical phase difference between the signal received on the transducer half-beam pairs. If the effective separation between the transducer half beams is d, then the correspondence between angular location $\theta$, and electrical phase difference, $\Delta\theta_e$, is:

$$\theta=\sin^{-1}\left[\frac{\Delta\theta_e}{2\pi d/\lambda}\right] \tag{B1}$$

where $\lambda$ is the acoustic wave length (Ehrenberg, 1989). In most cases of interest, the transducers have a narrow beam width and the small angle approximation for the sine function can be used. In this case:

$$\theta\approx\frac{\Delta\theta_e}{2\pi d/\lambda} \tag{B2}$$

A standard analysis used for the analysis of phase modulation in communication systems can be used to determine the effect of noise on phase angle measurements (Carlson, 1975). This analysis shows that additive Gaussian noise results in a phase measurement that is an unbiased, Gaussian distributed random variable with a variance (measured in radians squared) given by:

$$\mathrm{var}[\theta_e]=\frac{1}{P_s/P_n} \tag{B3}$$

where $P_s$ and $P_n$ are the signal and noise power, respectively. Using the fact that the split-beam technique uses the difference between the phases measured on the two half beams, the fact that each half beam has a signal-to-noise ratio that is half that of the full beam, and the fact that the variance of the difference of two independent random variables is the sum of the variances, it follows that:

$$\mathrm{var}[\Delta\theta_e]=\frac{1}{\mathrm{SNR}} \tag{B4}$$

where SNR is the full beam signal-to-noise ratio. The rms error in the angular location estimate, $\theta_{rms}$, follows from Equations B2 and B4.

$$\theta_{rms}=\sqrt{\mathrm{var}[\theta]}=\frac{1}{2\pi\sqrt{\mathrm{SNR}}d/\lambda} \tag{B5}$$

For example, a rectangular transducer with a 4 degree beamwidth ($d/\lambda=6.36$) has a rms angular error of 0.008 radians or 0.45 degrees for a SNR of 10 dB.