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Observations of controlled moving targets with split-beam sonar and implications for detection of migrating adult salmon in rivers

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Abstract

When measuring the flux of migrating salmon in rivers there are often multiple fish in the beam simultaneously. To obtain accurate measurements of flux, an understanding of the effects of multiple targets is required. Multiple targets in various configurations were passed through a horizontally-oriented 4° × 10° beam from a split-beam echo sounder. The effects on target strength, detection probability, spatial and temporal patterns of echoes, and measurement of target position are presented. When multiple targets were in the beam at the same range, the target strength was positively biased, whereas, when they were in-line at different ranges, the target strength and detection probability were negatively biased for the shadowed targets. Targets at the same range, but separated in the vertical or horizontal direction, produced characteristic patterns in the X vs. ping and Y vs. X plots. Similar patterns were found in routine observations of migrating salmon, allowing the identification of some multiple-target events. Identification of these events can aid in the correct interpretation of migrating fish data for flux measurement. © 2002 Ifremer/CNRS/Inra/Cemagref/Éditions scientifiques et médicales Elsevier SAS. All rights reserved.

Résumé

Observations de cibles contrôlées mobiles avec un sondeur à faisceau scindé et implications pour la détection en rivière de saumons migrateurs adultes. Lorsque l'on mesure le flux de saumons migrateurs en rivière, il y a souvent de nombreux poissons détectés simultanément par le sondeur. Afin d'obtenir des mesures plus précises du flux, il est nécessaire de comprendre l'effet de cibles multiples. Des cibles multiples, sous diverses configurations, ont été placées dans le faisceau d'un sondeur à faisceau scindé, transducteur 4° × 10°, orienté horizontalement. Les effets sur l'indice de réflexion, la probabilité de détection, le type de dispersion des échos dans l'espace et dans le temps, et la mesure de la position de la cible sont présentés. Lorsque des cibles multiples apparaissent dans le sondeur à une même portée (distance), l'indice de réflexion est biaisé positivement; si elles sont alignées à différentes portées, l'indice de réflexion et la probabilité de détection sont biaisés négativement pour les cibles cachées. Des cibles à la même portée, mais séparées dans la direction verticale ou horizontale, produisent des dispersions caractéristiques des échos dans les projections des X par rapport au signal, et des Y par rapport aux X. Des schémas identiques de dispersion des échos ont été trouvés lors d'observations de routine chez le saumon en migration, permettant l'identification de cibles multiples. L'identification de ces cibles peut aider à l'interprétation exacte du nombre de poissons migrateurs pour des mesures de flux migratoire. © 2002 Ifremer/CNRS/Inra/Cemagref/Éditions scientifiques et médicales Elsevier SAS. Tous droits réservés.

Keywords: Hydroacoustic; Split-beam; Multiple targets; Detection probability; Target strength

1. Introduction

Measurements from a split-beam echo sounder provide three-dimensional target location in the beam as a function of time and hence allow target strength estimation (Traynor, 1986; Traynor and Ehrenberg, 1990) and tracking of individual fish in four dimensions (Carlson and Jackson, 1980). These properties allow the split-beam sonar to provide estimates of fish movement and flux in addition to the traditional fish density measurements (Ehrenberg and Torkelson, 1996). For example, we use split-beam sonar to

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estimate the number of salmon migrating in the Fraser River. Often for migrating adult sockeye salmon (*Oncorhynchus nerka*) there are multiple fish in the beam, which can cause detection problems. We have seen what we suspected were the results of interference between multiple-fish targets in our riverine data. We wanted to understand these effects by measuring the echoes from multiple, moving targets with known properties in a controlled environment that was similar to the riverine environment. We hoped to measure the effects of various target configurations on target strength, target position measurement, probability of detection, and the spatial and temporal pattern of resolved echoes, and to provide qualitative explanations in terms of target proximity, secondary scattering and absorption. These experimental results enabled us to relate to fish data collected in a river, allowing improved interpretation of single- and multiple-fish events in those data.

2. Materials and methods

2.1. Study area

The experiment was performed at Cultus Lake, 90 km east of the city of Vancouver, in the province of British Columbia, Canada. We chose the lake outlet as it had a rectangular wharf, which allowed the easy deployment of the split-beam system and targets. There was sufficient water depth to operate a fixed-location elliptical transducer aimed in a side-looking configuration with a range of approximately 20 m. We operated the acoustic system in a manner similar to the configuration used for riverine applications, where the attainable range is limited by the return signal from the water surface and/or the bottom substrate. The site allowed us to control the target motion, the target position within the beam and the target speed. This level of control is not easily achieved in moving water.

2.2. Acoustic data collection

We used a Hydroacoustic Technology Inc. (HTI) Model 243 Digital Split-Beam Hydroacoustic System (HTI 1998) for the experiment. This system included a 200 kHz Model 243 Digital Echo Sounder, a Digital Echo Processor, a Digital Chart Recorder, a 4° × 10° elliptical transducer with a 75 m transducer cable, an oscilloscope, a DAT to record the raw, unthresholded digital samples for both phase and amplitude and an MS Windows 95-based desktop PC. The computer contained HTI's software TS/INTEGRATION/TRACKER for real-time three-dimensional target tracking and the Pacific Salmon Commission's (PSC) FishTrack software (Xie, 1999, Xie, 2000) for off-line tracking and editing of data files produced by the acoustic system. The transducer was mounted on a Remote Oceans System dual-axis underwater rotator connected to a shore-based rotator controller. The electronic components were housed in a mobile van and powered by a 2 kW gasoline generator.

The echo sounder was operated at 20 dB re 1W transmit power with a –18 dB total receiver gain. The source level was 214.45 dB and the receive sensitivity was –169.50 dB. To provide target strength data, the acoustic signals were amplified with a 40 LogR time-varied-gain. The transmitted pulse width was 0.2 ms with a pulse repetition rate of ten pings per second. Significant reverberation was not noted within the ranges used for these experiments. Echoes were rejected if they did not meet minimum amplitude of 150 mV, equivalent to a –43.4 dB target on axis. We used a pulse acceptance window between 0.1 and 0.3 ms (the same values used for our riverine applications). Further analysis of the data using other amplitude and pulse width acceptance criteria was possible by reprocessing the DAT data.

The complete system was calibrated in December 1999 at the manufacturer's calibration facility. In addition, an in-situ target calibration was performed using a 38.1 mm tungsten carbide sphere, which produces a nominal target strength of –39.5 dB in freshwater (MacLennan and Simmonds, 1992) and for which we observed a target strength of –39.1 dB. Target strength values were calculated from the mean backscattering cross section, σ, according to the following definition (Foote, 1987):

$$\overline{TS} = 10\log(\bar{\sigma}/4\pi)$$

This method was used for all mean target strength values (Table 1).

The echo processor selected single-target echoes and relevant data were written to a computer file. The acoustic system could display a plot on the computer monitor of the target's vertical (Y) and horizontal (X) position within the beam cross section. This display was helpful for aiming the transducer and for placement of targets in the beam.

2.3. Experimental design

The experimental configuration is shown in Fig. 1. The split-beam transducer was affixed to a piling at one end of the wharf. The area enclosed by the wharf was 10 m × 25 m, with a water depth of 2.2 m at the shallow end and 2.5 m at the deep end. The beam was aligned so that bottom and surface signals did not exceed the minimum detection threshold at maximum range. This type of beam alignment is similar to that commonly used to observe fish migration in rivers. We moved a series of single- and multiple-target configurations through the beam at approximately 0.5 $m.s^{-1}$, a velocity that is similar to fish swimming speeds observed in the river (Xie et al., 1997). Flooded lead-filled plastic sphere targets (10 cm diameter) that produce echoes of similar target strength as adult salmon (approximately –32 dB) were used. These targets had an 8-mm hole at the top to allow air to escape and were the same as those used by Kieser et al. (2000).

Table 1
Target configurations passed through the 4° × 10° beam of the 200 kHz split-beam system at Cultus Lake. X and Y are horizontal and vertical target separation. All targets were 10 cm diameter plastic spheres. All configurations, except no.1, were passed at a nominal speed of 0.5 m.s^{-1} through the beam parallel to the X-axis. SD: Standard deviation.

	Number of events	Target configuration	Mean target strength and (SD) dB[a]	Mean detection probability and (SD)	Position measurement error in X, metres	Position measurement error in Y, metres
1	1	Single stationary	–30.22[b] (2.50)[c]	0.99	0.101	0.147
2	14	Single moving[d]	–33.63 (0.97)	0.64 (0.09)	0.223	0.207
3a	20	Two separated in range, closest (1.5 m separation)	–31.80[e] (0.54)	0.76 (0.09)	0.182	0.120
3b	20	Two separated in range, farthest (1.5 m separation)	–32.30 (0.63)	0.74 (0.08)	0.147	0.162
4	14	Two separated in Y (1 m separation)	–30.55 (0.48)	0.90 (0.04)	0.145	0.127
5a	14	Two separated in X, middle (2 in beam, 1.5 m separation)	–31.24 (0.97)	0.86 (0.08)	0.615[f]	0.175
5b	14	Two separated in X, start (1 in beam, 1.5 m separation)	–32.09 (0.68)	0.75 (0.08)	0.179	0.190
5c	14	Two separated in X, end (1 in beam, 1.5 m separation)	–31.68 (0.55)	0.81 (0.07)	0.177	0.160
6a	20	Four separated in range, closest (1 m separation)	–32.16 (0.71)	0.80 (0.06)	0.117	0.116
6b	20	Four separated in range, second (1 m separation)	–33.32 (0.98)	0.69 (0.09)	0.144	0.162
6c	20	Four separated in range, third (1 m separation)	–32.84 (1.03)	0.63 (0.08)	0.199	0.173
6d	20	Four separated in range, farthest (1 m separation)	–32.62 (0.91)	0.71 (0.09)	0.157	0.180
7a	20	Two separated in range, closest (0.25 m separation)	–31.64 (0.49)	0.71 (0.07)	0.134	0.116
7b	20	Two separated in range, farthest (0.25 m separation)	–34.75 (1.01)	0.34 (0.09)	0.180	0.151
8a	20	Two separated in range, closest (0.15 m separation)	–31.72 (0.61)	0.63 (0.08)	0.146	0.110
8b	20	Two separated in range, farthest (0.15 m separation)	–34.25 (1.39)	0.16 (0.06)	0.202	0.165
9a	20	Two separated in range, closest (0.15 m separation, 0.04 to 0.4 ms pulse window)	–31.75 (0.57)	0.69 (0.07)	0.150	0.109
9b	20	Two separated in range, farthest (0.15 m separation, 0.04 to 0.4 ms pulse window)	–34.58 (1.04)	0.19 (0.08)	0.219	0.163
10	20	Four separated in X (1 m separation)	–29.69 (0.52)	0.77 (0.04)	0.504	0.195

(a) calculated from the mean backscattering cross section;
(b) echo by echo target strength;
(c) mean backscattering cross section standard deviation (SD) transformed to target strength by: $SD_{(dB)} = 10\log(\bar{\sigma} + SD)/\bar{\sigma}$;
(d) results discarded due to unexpected shift in target strength possibly resultant from target modifications;
(e) used as the reference single moving target example; and
(f) position measurement error when both targets were in the beam.

The coordinate system used for this experiment is the left-handed coordinate system that is commonly used for riverine acoustic work. It aligns the positive Z-axis out into the river, the X-axis is the upstream/downstream direction and Y-axis is the surface/bottom direction. The dual-axis rotator was used to aim the beam for minimum surface and bottom interference as judged with an oscilloscope. A single target was then suspended in the beam at the range at which the targets would be deployed. The operator observed the real-time (X, Y)-position of the target on the computer monitor and adjusted the monofilament suspension line to ensure that the target was located close to the axis of the beam. All data sets were then collected with this same configuration of beam alignment.

Each data set was made up of as many as 100 horizontal passes of a target configuration, (hereafter referred to as events), through the beam. Each target configuration consisted of a given number of targets with specific relative orientation and separation (Table 1). Operators at either end of the wharf pulled the array deployment lines attached to the middle of the 3-m wooden doweling, which held the suspended targets. The wooden doweling, with a pulley at each end, travelled along two guy lines attached to the sides of the wharf (Fig. 1). The velocity for each event was approximately constant and the target was pulled through the beam until it was no longer detected. Acoustic data files containing the three-dimensional location and transmission time for each echo (Ehrenberg and Torkelson, 1996) were created for each target configuration and written to the PC. This information was used by the real-time tracker and later for post-processing with the PSC split-beam editing software.

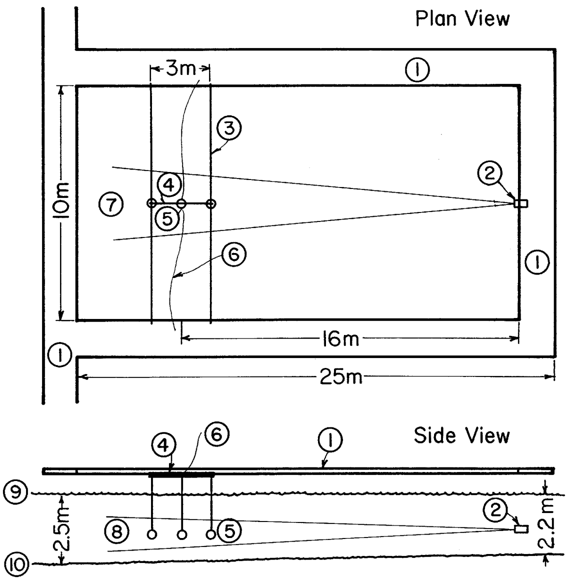

Fig. 1. Schematic showing a plan and side view of the study area. (1) Board walkway. (2) 4° × 10° transducer. (3) Guy lines. (4) 3 m wooden doweling. (5) 10 cm diameter plastic spheres suspended from doweling with nylon monofilament line. (6) Doweling deployment lines. (7) Horizontal (–3 dB) nominal beam width. (8) Vertical (–3 dB) nominal beam height. (9) Water level. (10) Bottom.

Target configurations included two targets separated in Y, four targets separated in Z and four targets separated in X. For two targets separated in either Z or X, we removed two of the targets from the four-target configurations and adjusted the spacing as desired. Fig. 1 shows the plan and side views of three targets separated in Z. The separation distances between the targets are given in the descriptions for each example.

2.4. Data analyses

A least squares regression was fit to the X vs. ping and Y vs. ping position data for all of the target configurations to estimate measurement error in the position data. The X- and Y-coordinate residuals were calculated and the standard deviation of these residuals gives the position measurement error in X and Y (Table 1).

For two targets separated in X, we divided each of the 14 events into start, middle and end by determining the ping at which the target was first detected on the edge of the beam, the ping at which interference between the targets began and ended, and the ping at which the target was last detected. To test if our observations were consistent with the true geometrical arrangement of the targets, we predicted the separation between the two targets using the acoustic data. We noted the X-position at the ping number when the first target entered the beam and the X-position of the ping just prior to the onset of interference. By subtracting these two positions we predicted the distance between the two targets for each of the events.

To test for significant differences in the mean of the event-by-event target strength, we used two-sample *t*-tests that assumed unequal variances. Using quantile-quantile plots (S-PLUS 2000, 1999), we determined that the mean target strengths for the plastic sphere targets were reasonably Gaussian in their distributions, allowing the use of robust statistical methods.

3. Results

3.1. Reference target

The ten different target configurations used in our experiments are summarised in Table 1. We initially made measurements of a single moving target (Table 1, no.2) but later found that some minor modifications made to that particular target for deployment purposes appeared to give lower target strengths when compared with the other non-modified targets used in the experiment. This problem was recognised during the post-experimental analyses and only applied to the single moving target events. We decided to use the closest target of two targets separated by 1.5 m in range as our reference single-target for comparative purposes (Table 1, no.3a). We believe that the target at further range did not affect the closer target and therefore the closer target possesses the characteristics of a single moving target (Fig. 2). This configuration provided the reference for comparisons with subsequent multiple-target data.

3.2. Single moving target

Fig. 2 displays various views of a typical event using a single moving target (Table 1, no.3a, closest of two separated by 1.5 m in range as explained above). The important features to note in this single target event are the consistency of the target strengths and the systematic movement in the X-direction over time.

The target statistics are given in the caption for Fig. 2. The mean target X-speed of –0.47 m.s^{-1} was equal to the mean X, Y, Z vector speed, indicating that the target travelled through the beam in a straight line in the X direction. The speeds in the Y- and Z-axes are close to zero, consistent with a straight trajectory in the X direction. The detection probability (P_d) represents the number of accepted return echoes divided by the number of pings transmitted between the first and last times of target detection. The mean target strength for this track is given (mean TS) and the next statistics show the mean target position in X, Y and Z. The mean Z-position for the single target was approximately 16 m; however, throughout the experiment the target ranges were between 16 and 19 m, depending on the number and orientation of the targets. The change in Z (Delta Z) for the target shown in Fig. 2 is close to zero as the target is moving in a straight line, perpendicular to the beam axis.

The target strength was lower when the target was in motion through the water. The overall average echo-by-echo

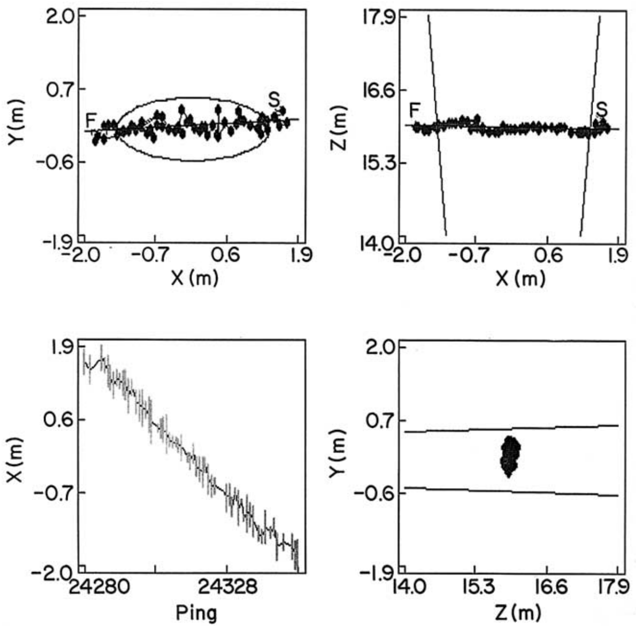

Fig. 2. Data from an event for a single moving target. The upper plots show the target position in the YX and ZX planes for a single moving target. The small ellipse represents the size of the sound-beam relative to the target trace. The 'S' and 'F' indicate the start and finish of the track. A least squares fitted line is drawn through the target trajectory to show the straight-line approximation of the target path. The lower left plot displays the X coordinate vs. the ping number. The lengths of the bars are proportional to the target strength of each echo. The bottom right plot displays the target position in the YZ plane. The track statistics are X-speed = –0.47 m.s^{-1}, Y-speed = –0.06 m.s^{-1}, Z-speed = –0.01 m.s^{-1}, total speed = 0.47 m.s^{-1}, P_d = 0.81, mean TS = –32.77 dB, mean X = –0.03 m, mean Y = 0.04 m, mean Z = 15.94 m, Delta Z = –0.10 m.

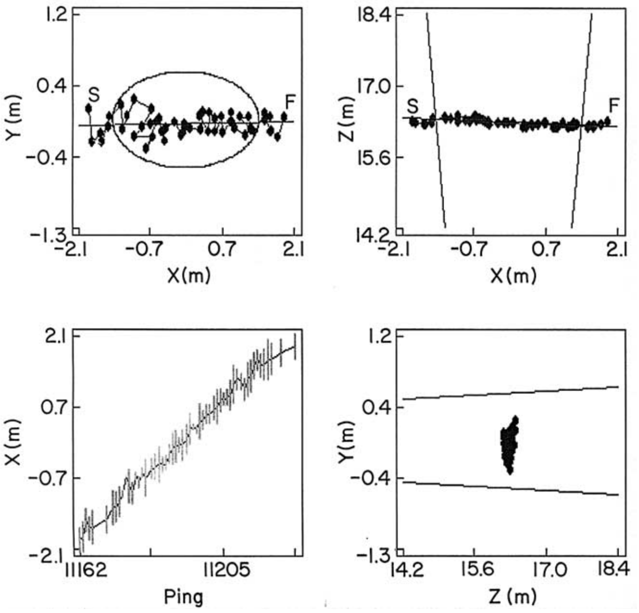

Fig. 3. Various views of a two-target event with targets separated by 1 metre in Y (up/down). The track statistics are X-speed = 0.59 m.s^{-1}, Y-speed = –0.02 m.s^{-1}, Z-speed = 0 m.s^{-1}, total speed = 0.59 m.s^{-1}, P_d = 0.85, mean TS = –30.80 dB, mean X = 0.13 m, mean Y = –0.07 m, mean Z = 16.27 m, Delta Z = –0.01 m.

target strength for the moving single target was –31.80 dB (Table 1, no.3a). The mean target strength for the same spherical target when it was stationary in the beam was significantly larger at –30.22 dB (two-sample *t*-test, $\alpha = 0.05_{\text{2 tail}}$: $t = 9.88$; df = 2312.51; $P = 0$).

3.3. Moving targets separated in Y

The two moving targets were separated by 1 m vertically, with the targets equidistant above and below the horizontal axis (Table 1, no.4, Fig. 3). The targets were located near the edges of the beam, as indicated by the vertical on-axis –3 dB beam pattern boundary of 1.2 m at this range. The echoes above and below the horizontal beam axis on the Y vs. X plot may hint at two targets, but this is not at all definitive. In addition, the apparent target separation displayed on the Y vs. X plot in Fig. 3 is much less than the true separation of one metre. We often see similar events in the fish data that cannot be reliably interpreted, since for this case we do not know the actual target configuration. The echograms for such events would likely be interpreted as single-target events without prior knowledge of the target configuration.

The strongest evidence for more than one target separated in Y is the positive bias in target strength, but this is only because we know the target strength for the single moving target. For this configuration, the mean target strength was –30.55 dB (Table 1, no.4), which was significantly higher than the mean of –31.80 dB for the single moving target (two-sample *t*-test, $\alpha = 0.05_{\text{2 tail}}$: $t = -13.23$; df = 30.1; $P = 0$).

3.4. Moving targets separated in range

Various centre-to-centre distances between targets and numbers of targets were used in this orientation. We will discuss the data sets using two targets, separated by 0.25 m (Table 1, no.7) and 0.15 m (Table 1, no.8) in Z, and also four targets separated by 1 m in Z (Table 1, no.6), as they best illustrate the results. It should be noted that the alignment in Z is parallel to the Z-axis. From a physical point of view, the radial alignment of targets is of special interest as shadowing and forward scattering will be at a maximum. We chose not to look at radial alignment at this time, as we wanted to mimic the fish passage we have observed in rivers. Fish travel approximately parallel to each other through the beam and may only fully shadow each other for short periods during their passage.

Fig. 4a displays a magnified portion of the echogram for two targets separated by 0.25 m in Z. Two distinct targets can be seen on the echogram at this separation, but many fewer echoes are present in the second, longer-range track. The track at longer range is displayed with vertical lines for those cases when unpaired echoes (echoes recorded from the longer-, but not the shorter-range target) were recorded.

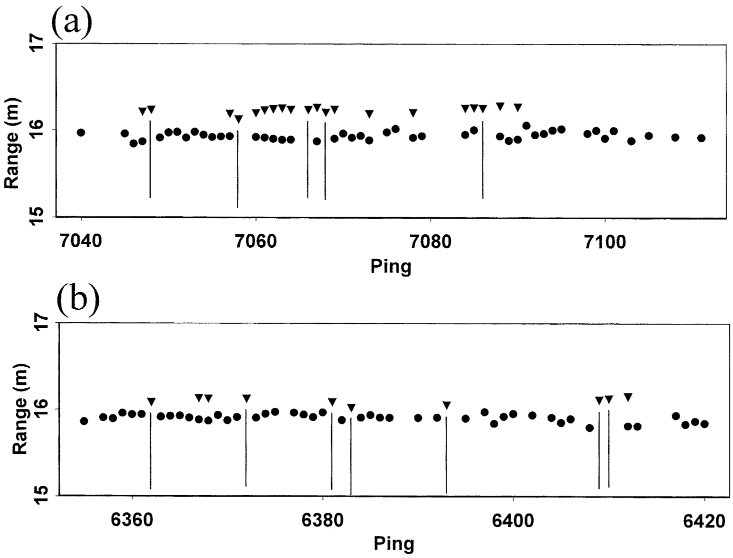

Fig. 4. **(a)** Magnified echogram of an event with two targets separated by 0.25 m in Z. Two distinct targets can be seen on the echogram but fewer return echoes are present in the longer range track. The track at longer range is displayed with vertical lines for those cases when unpaired echoes (echoes recorded only from one target) were recorded. **(b)** Magnified echogram of an event with two targets separated by 0.15 m in Z. The targets are distinguishable from each other on the echogram.

Fig. 5a displays an event for the closer target at 0.25 m separation. The mean target strength for these events was –31.64 dB (Table 1, no.7a). Fig. 5b displays the longer-range target for the same event, which is shadowed by the closer target. The mean target strength dropped by 3.1 dB and the probability of detection dropped to 0.34 (Table 1, no.7b). The position error increased for the shadowed targets at this separation (Table 1, no.7a,b).

Fig. 4b presents a magnified portion of the echogram for an event with the targets separated by 0.15 m. The two targets are still distinguishable from each other on the echogram at this decreased separation. Fewer resolved echoes are present for the longer-range shadowed target, since the interference between the two targets has increased as their separation has decreased (Fig. 6). The same types of effects were present (Table 1, no.8a,b) as for the 0.25 m case. The second shadowed target showed a 2.5 dB decrease in mean target strength and a drop in detection probability to 0.16. The shadowed target at 0.15 m had even greater position error than that at 0.25 m separation.

With a wider pulse width acceptance window (0.04–0.4 ms) (Table 1, no.8a,b, no.9a,b), the mean detection probability for the targets separated by 0.15 m in Z increased from 0.63 to 0.69 for the closer target and from 0.16 to 0.19 for the farther, shadowed target. Similar results

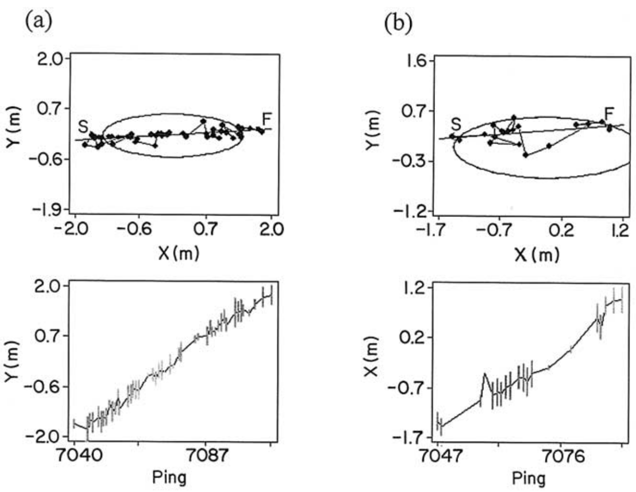

Fig. 5. **(a)** Closer target of the two targets shown in Fig. 4a. **(b)** Farther shadowed target of two targets shown in Fig. 4a. Note the decrease in the number of resolved echoes.

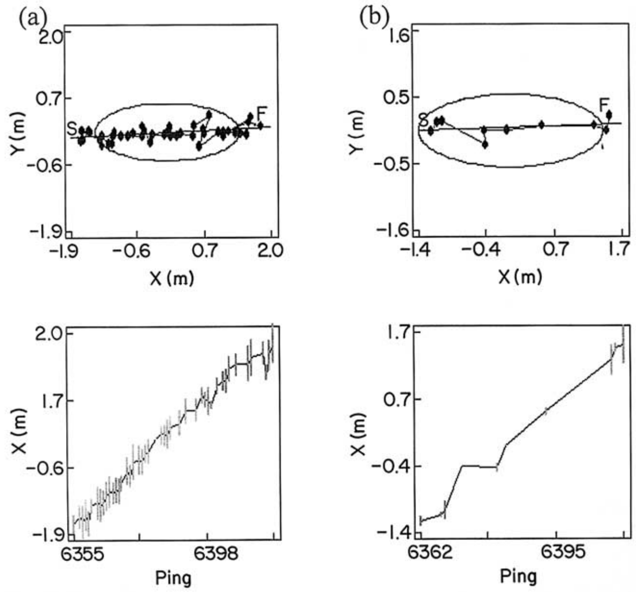

Fig. 6. **(a)** Closer target of two targets shown in Fig. 4b. **(b)** Farther shadowed target of two targets shown in Fig. 4b. Note the decrease in the number of resolved echoes.

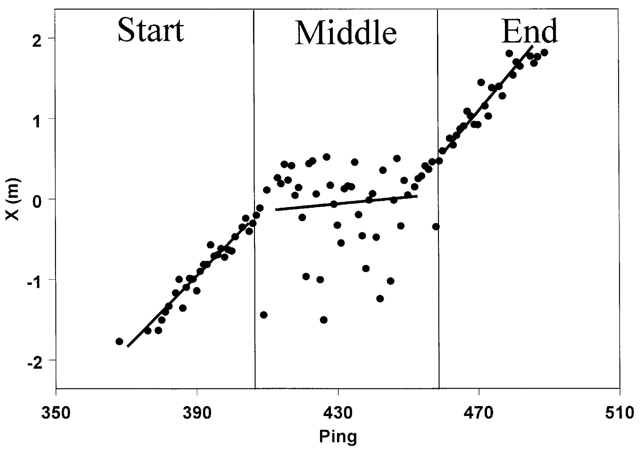

Fig. 7. X vs. ping plot for two targets separated in X showing the characteristic echo pattern and the division of the track into start, middle and end segments.

were obtained for the two targets separated by 0.25 m in Z. The wider pulse width acceptance window had negligible effects on target strength and position error.

When we passed four targets through the beam with one-metre separation in Z, the target strength decreased from 0.5 to 1.2 dB, detection probability decreased from 0.09 to 0.17, and position error increased by up to 0.082 m for the shadowed targets (Table 1, no.6a-d).

3.5. Moving targets separated in the X dimension

We analysed the events for two targets separated by 1.5 m in X to determine the effects of interference when multiple targets were in the beam at the same range (Table 1, no.5). There was no indication from the echogram that more than one target was present in the beam. The scatter for X vs. ping is shown in Fig. 7 for event number 5 and displays a distinct pattern. The movement in the X-direction begins as systematic, changes to random and then back to systematic. This characteristic pattern was found for all of the two target events. From this pattern, we divided the tracks into three distinct segments by ping number. We refer to these as start, middle and end.

Fig. 7 displays the event divided into start, middle and end with least squares regression lines drawn for each segment of the event. We calculated the variance of the residuals about the regression lines for each segment of each event. We compared the three sets of log-transformed variances with a two-sample *t*-test to see if the segments of the tracks were significantly different in their X-distributions (Box et al., 1978). There was a highly significant difference in the variance of the residuals of X between the start and middle segments (two-sample *t*-test, $\alpha = 0.05_{\text{2 tail}}$: $t = -12.13$; df = 17.30; $P = 0$) and the middle and end segments (two-sample *t*-test, $\alpha = 0.05_{\text{2 tail}}$: $t = 12.40$; df = 17.69; $P = 0$). By contrast, the start and end segments did not show a significant difference (two-sample *t*-test, $\alpha = 0.05_{\text{2 tail}}$: $t = -0.17$; df = 25.94; $P = 0.87$). When two targets are present in the beam (Fig. 7), interference between the two unresolved echoes occurs and the position error of X and Y increases (Table 1, no.5a-c). This signature may allow the identification of multiple-target events with data from migrating fish.

The average predicted distance between the two targets separated in X was 1.7 m with a standard deviation of 0.32 m for the negative X-segments and 1.42 m with a standard deviation of 0.36 m for the positive X-segments. An asymmetry was measured in the beam pattern factor at first detection for the two sides of the beam at this range. The mean beam pattern factor at which the target was first detected was –5.03 dB for the – X (left) side of the beam and –4.06 dB for the + X (right) side of the beam. The mean separation for both sides of the beam for all of the events was calculated at 1.56 m. This is similar to the true distance between the targets that was set at 1.5 m. It is not possible to use this method to predict target separation when both targets are in the beam as the X- and Y-position information is inaccurate, due to the interference between the two targets.

The target strength variance was analysed in the same way as for the residuals of X. The same relationship was observed, i.e., the variance in target strength was significantly lower for the start than the middle (two-sample *t*-test, $\alpha = 0.05_{\text{2 tail}}$: $t = -3.62$; df = 22.07; $P = 0.002$) and significantly lower for the end than the middle (two-sample *t*-test, $\alpha = 0.05_{\text{2 tail}}$: $t = 3.02$; df = 22.82; $P = 0.006$). The start and end segments were not significantly different (two-sample *t*-test, $\alpha = 0.05_{\text{2 tail}}$: $t = -0.62$; df = 25.91; $P = 0.54$). By contrast, the mean target strength when both targets were in the beam was measured at –31.24 dB, which was not significantly higher than the mean measured for the single moving target (two-sample *t*-test, $\alpha = 0.05_{\text{2 tail}}$: $t = 1.9$; df = 18.6; $P = 0.07$) (Table 1, no.3a, 5a).

For four targets separated by one metre in the X-dimension, there was no indication from the echogram that multiple targets were passing through the beam (Table 1, no.10). Fig. 8 presents multiple views for one event. The indications that more than one target was present in the beam are in the Y vs. X and X vs. ping plots. The Y vs. X plot displays relatively scattered echoes when compared with a single target event (Fig. 2). The X vs. ping plot displays several deviations from systematic movement in X over time. The target strength was positively biased when several targets were in the beam at the same time. The mean target strength for the four targets was measured at –29.69 dB, which was significantly higher than the mean measured for the single moving target (two-sample *t*-test, $\alpha = 0.05_{\text{2 tail}}$: $t = 12.6$; df = 37.9; $P = 0$). As the number of targets in the beam at the same range increases, the positive bias in target strength also increases. The position measurement error also increases for those pings when multiple targets are in the beam.

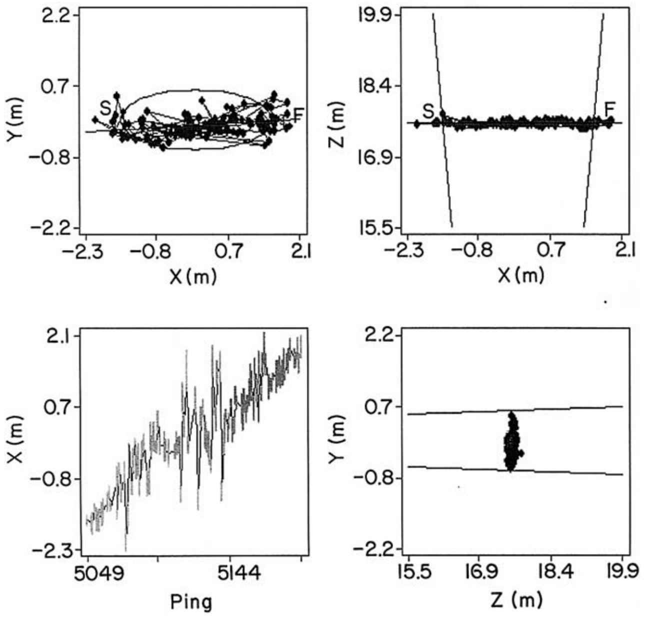

Fig. 8. Various views for four targets separated by 1 m in X. The track statistics are X-speed = 0.25 m.s^{-1}, P_d = 0.78, mean TS = –30.48 dB, mean X = 0.19 m, mean Y = –0.12 m, mean Z = 17.63 m, Delta Z = 0.00 m.

3.6. *Relating target events to fish data*

We gained some insight into the effects of multiple targets in the beam from the above target experiments. To determine if we could find examples using fish data that would appear similar to what we had observed with targets, we searched some of our data files taken at the riverine split-beam acoustic site at Mission, British Columbia, Canada. The data we examined were from a period of high-density sockeye salmon migration during the 1998 season. We thought that in high-density situations the sockeye would likely be travelling close enough to each other that more than one fish would be in the beam at the same time, thus causing interference similar to that seen in our target experiments. In fact, we found it straightforward to identify some of these events.

Fig. 9 shows a magnified view of an echogram observed at Mission in 1998. Two fish tracks are labelled as (*a*, single-fish) and (*b*, double-fish). Fig. 10a displays the X-position vs. ping number for the single-fish track and shows the characteristic, systematic movement in X for a single target as was seen in Fig. 2. Fig. 10b displays what we believe to be a double-fish event, as it displays the characteristic signature of two targets separated in X, with apparent random movement in X for the middle segment of the track as was seen in Fig. 7.

Several of these double-fish events were found in these data and the pattern was similar to that displayed in Fig. 10b. Sometimes there was an asymmetry in the random X-movement segment of the event, e.g., towards the start or the end of the event. This is to be expected due to the possibility of variable spacing of fish as they pass through the beam. Double-fish events could sometimes be identified from the echogram view, as they often appeared longer in the time axis than the surrounding single-fish tracks. However, this trait in itself was not adequate for identification.

Another characteristic of our riverine data appeared similar to the target data presented in Fig. 3. This is when two targets simultaneously pass through the beam at the same range separated in Y, but not in X. Examples of this type of track proved somewhat more difficult to find (they

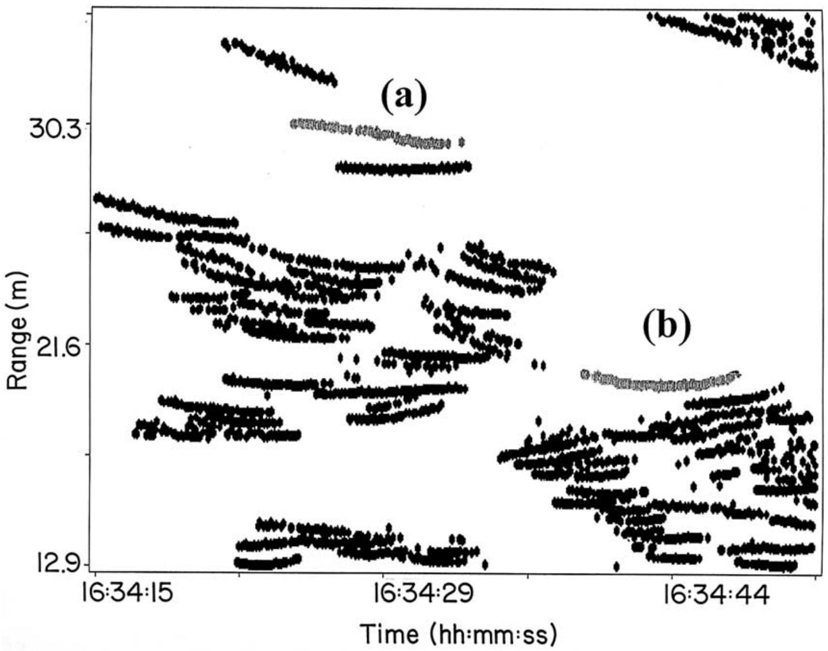

Fig. 9. Magnified view of an echogram of high-density sockeye salmon migration observed at Mission in 1998. Two fish tracks are labelled as **(a)** single-fish and **(b)** double-fish, according to what they are suspected to be from the experimental results.

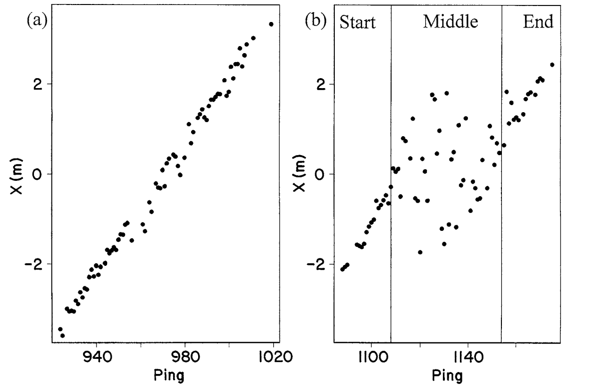

Fig. 10. X position vs. ping number for these suspected single- and double-fish tracks. **(a)** Displays the single track and shows systematic movement in X. **(b)** Displays what we believe to be a double-fish event, as it displays the characteristic signature of two targets separated in X, with random movement in X for the middle segment of the track.

may be less common for behavioural reasons) but were found in the sockeye data. The track on the echogram did not give any indication of multiple fish in these cases. Fig. 11 gives an example and shows a similar pattern to the two targets separated in Y (Fig. 3), particularly in the Y vs. X plot. These fish have a small separation in range as can be seen from the Z vs. X and Y vs. Z plots, which helps in their identification. Due to the many possible configurations of two fish passing through the beam separated in Y, there can be much variation in the pattern shown in Fig. 3.

4. Discussion

One consideration when using plastic spheres, as done in this study, is the potential difference between the acoustic attributes of the targets compared to the fish in the wild. The spheres show similar target strength values to salmon, but differences may exist in their forward scattering properties. It is possible that these differences could produce different shadowing results for targets separated in range, compared to what might be observed for actively migrating salmon. It is difficult to measure the effects of shadowing for actively migrating salmon, but we plan to repeat some of these experiments using freshly killed salmon in an attempt to determine if the shadowing effects appear similar.

When targets are lined up one behind the other in range, there is an effect on both detection probability and target strength for the shadowed targets. For four targets separated by 1 m in range, the target strength was negatively biased by approximately 1 dB for the shadowed targets and the detection probability was typically about 0.12 lower (Table 1, no.6a-d). For two targets separated in Z the effects were more pronounced as the separation distance decreased. For two targets separated by 0.25 m and 0.15 m, the mean target strengths for both shadowed targets were negatively biased by more than 2.5 dB with decreases in detection probability of 0.37 and 0.47 respectively (Table 1, no.7a-b, no.8a-b).

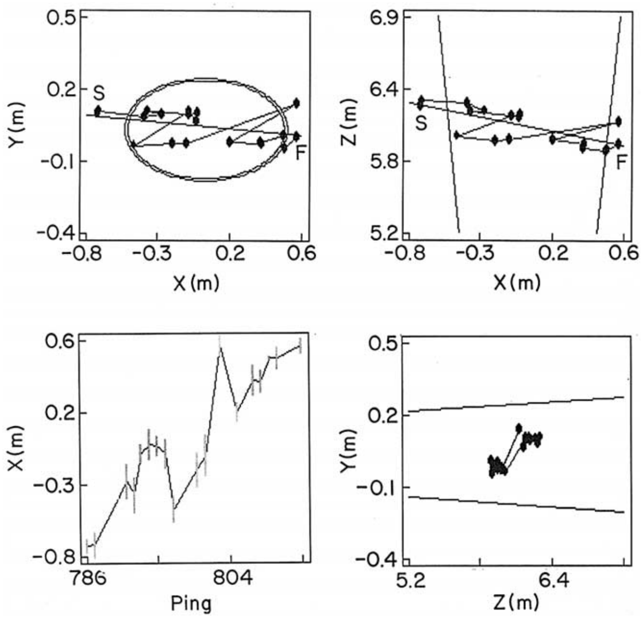

Fig. 11. A fish event believed to be two targets passing through the beam at the same time separated in Y and at similar range. The track statistics are X-speed = 0.49 m.s^{-1}, Y-speed = –0.04 m.s^{-1}, Z-speed = –0.11 m.s^{-1}, total speed = 0.50 m.s^{-1}, P_d = 0.68, mean TS = –29.53 dB, mean X = –0.03 m, mean Y = 0.01 m, mean Z = 6.07 m, Delta Z = –0.30 m.

The decreased detection of the longer-range target may be partly due to the single-target selection criteria used by the acoustic system. These criteria cause the rejection of echo data if the return echo pulse width is outside the range set in the software. Another factor may be the shadowing of the target at longer range as reported by Appenzeller and Leggett (1992) and Sun and Gimenez (1994). This is of particular concern for lake and ocean surveys that use echo integration to measure fish density, as a reduction in backscatter intensity will lead to a reduction in the fish biomass estimates.

Using the echosounder settings listed in section 2.2, we could separate targets down to about 0.15 m spacing in Z, but we found a decrease in detection probability at this separation for the shadowed target. Mulligan (personal communication) found that he could identify fish events reasonably well down to about 0.30 m separation, but if the salmon were closer than this, far fewer echoes were resolved. Although not directly comparable, it is interesting to note the results of Patrick et al. (1991), which indicated that their 420-kHz sounder was limited in target range separation below 0.25 m at a transmitted pulse of 0.1 ms under laboratory conditions. This loss of resolved echoes causes difficulty for tracking algorithms, as there is less information to work with. Our experiment represents a more ideal situation, as background noise levels were lower than those found in rivers and we were using targets that have less variable acoustic properties than live fish. Therefore we were able to measure smaller target separations, but we still experienced significant differences in detection probability. Opening up the pulse width acceptance criteria allowed the system to accept more echoes and fill in some of the echo gaps in the tracks. This may help with tracking, as more data would become available to the tracking algorithm. This increase in the number of resolved echoes with an increase in the pulse width acceptance window was less apparent in fish data. This was likely due to the fish targets being less like point-source targets and also more variable in their Z separations than the targets used in this experiment (Mulligan, personal communication).

Moving targets separated in range are more easily distinguished from each other than are moving targets at the same range, separated in X or Y. This is due to deterioration in the phase measurement that is used to obtain the X and Y positions. The acoustic interference causes inaccurate position information. However, information contained in the systematic X-movement and the target strength data as presented in section 3.5 may allow us to improve our interpretation of these events. It may be possible to apply these techniques to situations where fish are closely following each other through the beam, and therefore allow more accurate estimation of fish movements and the number of fish.

To put this interference effect into perspective, assume one uses an elliptical beam with widths of 4° vertical by 10° horizontal (common for riverine applications). At a range of 10 m, the beam is 1.75 m wide on the X-axis between the –3 dB points. Fish passing through this beam on axis would have to be at least 2 m apart to avoid these interference effects. Salmon migrating up rivers often follow each other very closely and the acoustic interference this causes will adversely affect the accurate estimation of fish flux.

If more than one target is in the beam at the same range, not only is there an effect on the measurement of target position, but the target strength measurement shows a positive bias when compared with a single moving target. This effect has been documented for stationary targets (Soule et al., 1995, 1996; Foote 1996; MacLennan and Menz, 1996). We obtained the same positive bias in target strength when we moved two or more targets through the beam at a given range. The mean target strength was 0.56 dB higher for two targets separated by 1.5 m in X and 1.3 dB higher for two targets separated by 1 m in Y (Table 1, no.5a, no.4). The positive bias for the two targets separated in Y was significantly higher than for the single moving target, but the positive bias for two targets separated by 1.5 m in X was not significant. We expect that if the targets were positioned more closely in X than 1.5 m, then this target strength bias may become significant. For four targets separated by 1 m in X, the target strength showed positive bias, which may be due to the closer spacing of the targets (Table 1, no.10). Evidence of bias in estimates of target strength obtained with a split-beam echosounder have been presented for stationary targets by researchers such as Soule et al. (1995). These authors found that for multiple targets, the thresholding would tend to reject those echoes that are out of phase, thus preferentially accepting in-phase targets, which led to a positive bias in target strength.

Two targets separated in Y showed a significantly higher target strength than the two targets separated in X (two-sample *t*-test, $\alpha = 0.05_{\text{2 tail}}$: $t = 2.4$; df = 18.95; $P = 0.03$). We hypothesise that this may have been due to the elliptical beam geometry of the transducer. The targets separated in Y were located near the edge of the beam for much of their path. The beam width was calculated at approximately 1.1 m for the Y-axis and the targets were separated by 1 m vertically. Targets measured near the edge of an acoustic beam have been shown to have a positive bias in target strength due to the fact that only the larger amplitude echoes are able to break the threshold and be recorded (Weimer and Ehrenberg, 1975; Fleischman and Burwen, 2000). The two targets separated in X were further from the edge of the beam and so did not display as large a bias. This is illustrated by the mean beam pattern factor for two targets separated in X (–2.60 dB) and two targets separated in Y (–4.21 dB). These two-target events may have somewhat inaccurate beam pattern factors recorded due to the interference affect of multiple targets, but, on average, the targets separated in Y appeared farther off axis than did the targets separated in X.

An unexpected result obtained from these experiments was the positive bias in target strength for the single stationary sphere (Table 1, no.1, no.3a). It appeared that the act of moving the sphere through the water caused a significant reduction in target strength. We have no concrete explanation for this result at this time, but put forward the idea that this may be due to the motion of the water over the target's surface (Kieser, personal communication). The flow of water over the target's surface will cause irregularities in flow and these may have the effect of modifying or attenuating some of the sound energy, therefore causing a decrease in the measured target strength. We are planning further experiments with the use of plastic spheres and standard targets to see if this result is repeatable.

These target experiments allow us better interpretation of fish behaviour that we see in the acoustic data for live fish. The types of detection problems we have documented here are relevant to estimating fish passage in the riverine environment. It may be that schemes to categorise tracks into single-, double- and multiple-fish events may increase the accuracy of estimation. The shadowing effect is of concern in the riverine environment for estimation of fish numbers as a strong reduction in detection probability was noted. This reduces the data available to tracking algorithms, which reduces track quality and therefore the accuracy of the estimates of passage. Also, if some form of echo integration is being attempted, or if the data are being collected at very long ranges where detection probability is low, this decreased detection would affect the estimates. Echo integration is not commonly used in rivers at this time, as riverine species are generally not evenly distributed throughout the beam cross section (Enzenhofer et al., 1998).

However, the shadowing effect is of greater concern when target strength measurements are made in the marine environment as other researchers have indicated (Soule et al., 1995, 1996; Foote, 1996; MacLennan and Menz, 1996). For this case, the characteristic patterns presented here may allow the acoustician to distinguish more accurately the single-fish traces and therefore lead to more accurate target strength determination for single-fish events.

The single-target selection criteria built into this acoustic system are also a factor in the loss of echo data when multiple targets are moving through the beam. These criteria work as intended for deriving target strengths, for tracking resolved targets and for rejecting echoes from multiple target events. However, the system removes all evidence of the unresolved echoes received from multiple target events. This is problematic for tracking and counting fish in environments with multiple targets as tracking algorithms will have access to reduced data.

Split-beam acoustic systems are capable of measuring the three-dimensional positions of moving targets. There are limitations, as shown by several other researchers, for distinguishing targets and measuring target strength when multiple targets are present in the beam. We have observed some of the effects of these limitations in our fish data and have been able to relate these effects to our target experiments where the properties and configurations of the targets are known. Our experiments show the interactions between the targets that cause secondary scattering and extinction. These are violations of the basic assumptions in acoustic theory. We presently cannot correct for these violations but we can be forewarned of their existence.

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