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Accuracy and precision of fish-count data from a "dual-frequency identification sonar" (DIDSON) imaging system

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The reliability of sockeye-salmon (*Oncorhynchus nerka*) count data collected by a dual-frequency, identification sonar (DIDSON) system is evaluated on the basis of comparisons with visual counts of unconstrained migrating salmon and visual counts of salmon constrained to passing through an enumeration fence. Regressions fitted to the DIDSON count data and the visual count data from the enumeration fence were statistically indistinguishable from a line with slope = 1.0 passing through the origin, which we interpret as agreement in both counts. In contrast, the regressions fitted to the DIDSON count data and the unconstrained visual count data had slopes that were significantly <1.0 ($p < 0.001$) and are consistent with an interpretation of systematic bias in these data. When counts of both unconstrained and constrained fish from the DIDSON system were ≥50 fish event^{-1}, repeated counts of the DIDSON files were observed to produce the same counts 98–99% of the time, respectively, and based on the coefficient of variation, counts of individual passage events varied <3% on average. Therefore, the DIDSON count data exhibit high precision among different observers. As an enumeration fence provides a complete census of all fish passing through it, we conclude that fish-count data produced by the DIDSON imaging system are as accurate as visual counts of fish passing through an enumeration fence when counts range up to 932 fish event^{-1}, the maximum count recorded during our study, regardless of the observer conducting the count. These conclusions should be applicable to typical riverine applications of the DIDSON system in which the bottom and surface boundaries are suitable for acoustic imaging, the migrating fish are adult salmon, and the transducer is carefully aimed so that the beams ensonify the area through which the salmon are migrating.

Keywords: aiming protocol, data quality, high-frequency identification mode, imaging sonar, reliability, salmon escapement, sockeye salmon, validation.

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Introduction

The Fraser River in British Columbia supports the largest assemblage of sockeye-salmon (*Oncorhynchus nerka*) stocks on the west coast of North America (Northcote and Larkin, 1989). About 150 populations have been identified by natal lake or stream and one of four run-timing groups (early Stuart, early summer, summer, late run) and are aggregated into 20 stocks for management purposes. Fisheries managers need reliable escapement data that represent all fish in a stock returning to spawn in a given year, because sockeye-salmon fisheries are managed to achieve stock-specific escapement goals (Noakes *et al.*, 1990).

Mark-recapture programmes (MRPs) are used to estimate the escapement of returning sockeye-salmon stocks expected to exceed 25 000 fish in pre-season forecasts (Woodey, 1984; Schubert, 1998). Efforts to enhance production of sockeye salmon in the Fraser River by increasing wild (natural) spawning escapement have increased the number of stocks assessed with MRPs in the past 15 years. This growth in the use of MRPs has increased pressure on the limited assessment resources of management agencies

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because MRPs are more labour-intensive and costly to operate than other methods of estimating escapement. A 75 000 fish-escapement threshold for MRP implementation was used in 2004, and investigations into alternative approaches for escapement estimation that reduce costs while maintaining assessment coverage and accuracy were initiated to address these resource limitations and competing priorities.

Single- and split-beam acoustic techniques have been used since 1977 at Mission, British Columbia, to estimate gross escapement of all sockeye-salmon stocks into the Fraser River (Woodey, 1984; Banneheka *et al.*, 1995; Xie *et al.*, 2002). These acoustic methods have not been applied to stock-specific escapement in natal streams because suitable sites have not been identified and because of the perception that acoustic-training requirements are great and that data analysis is complex. The dual-frequency identification sonar (DIDSON), developed for naval use in harbour surveillance and underwater mine detection (Belcher *et al.*, 2001), may overcome some of the perceived limitations with conventional acoustic systems. A DIDSON system uses sound to produce near video-quality images of fish at ranges up to 15 m in high-frequency mode (1.8 MHz) and up to 40 m in low-frequency mode (1.1 MHz). The DIDSON system has been used to assess salmon behaviour near dams (Moursund *et al.*, 2003) and to enumerate autumn Chinook salmon (*O. tshawytscha*) redds (Tiffan *et al.*, 2004), demonstrating that it is a useful tool for fisheries applications.

Our paper is part of a larger research programme to determine where and how the DIDSON system can be used in the Fraser River to deliver reliable and cost-effective estimates of sockeye-salmon spawning escapement. Herein we evaluate the reliability of escapement data collected by the DIDSON system on the basis of accuracy and precision criteria. Our objectives are first to determine the precision of manual counts of migrating salmon from a DIDSON imaging system among individual observers, and second to assess the accuracy of these count data by comparison with visual counts of unconstrained migrating salmon and visual counts of migrating salmon constrained to passing through an enumeration fence. Once installed and fish-tight, an enumeration fence provides a complete census of a spawning population and is considered the most accurate method for estimating salmon escapement in clear waters in British Columbia (Cousens *et al.*, 1982).

Material and methods

Field sites

Sockeye salmon were counted at the Henry's Bridge road crossing of the Chilko River, and at a fish-enumeration fence on the Stellako River (Figure 1). The Chilko River is a glacial, clear-water system that supports one of the largest sockeye-salmon runs in the Fraser River watershed. The river flows 89 km northeast from Chilko Lake to its confluence with the Chilcotin River, and has an average discharge of $42.2\ \mathrm{m^3\,s^{-1}}$ (1928–2003 data; Water Survey of Canada website accessed on 2 February 2005). The Stellako River is part of the Nechako system in central British Columbia and is also a clear-water river with an average discharge of $20.6\ \mathrm{m^3\,s^{-1}}$ (1951–2003 data; Water Survey of Canada website accessed on 2 February 2005) that flows 13.5 km northeast from Francois Lake into the west end of Fraser Lake. Two sockeye-salmon stocks migrate into the Stellako River: a small, early-summer run bound for the Nadina and Nithi Rivers on Francois Lake, and a larger summer run that spawns in the Nechako and Stellako Rivers. An enumeration fence is installed and operated annually from late August to early October to assess the portion of the summer-run stock that spawns locally in the Stellako River (Schubert, 2000).

Henry's Bridge is the only road crossing of the Chilko River and is located about 12-river km downstream of the outlet from Chilko Lake and below the lower limit of known sockeye-salmon spawning in the river. The river is 37 m wide at this site, has a maximum depth of approximately 1.5 m, and estimated current velocities of $2.5–3.0\ \mathrm{m\,s^{-1}}$ when our visual counts and the DIDSON data were collected in August 2004. Water flow is largely unidirectional, but turbulent, with small standing waves, especially in the centre of the river. The cross-sectional profile at Henry's Bridge is relatively flat (Figure 2), with short, steep banks, and the bottom substratum consists of small boulders (20–40 cm), cobble, and gravel, which do not impede sound transmission at the site. Sockeye salmon tend to migrate near the bottom within 5 m of both banks because of the high water velocities, and are easily visible to an observer stationed above the shoreline. Chinook salmon are also present in the Chilko River, but at Henry's Bridge this species tends to be found in the faster water within 15 m of the banks. All sockeye salmon at this site were observed actively migrating upstream.

The Stellako River enumeration fence is located about 0.5 km upstream of a large lagoon about 1 km from the river mouth on Fraser Lake (Schubert, 2000). The river is 33 m wide at the fence site, 1.0 m deep across most of the cross-section, has a bottom substratum consisting of sand and gravel, and exhibits a unidirectional, laminar-flow pattern. The enumeration fence was installed straight across the river (Figure 3) rather than in an upstream "V" alignment, as described previously by Schubert (2000). The fence comprised 3.0-m panels constructed of aluminium conduit poles 2.5 cm in diameter and 1.5 m long, inserted through holes in steel U-channel stringers at 5 cm intervals. In all, 12 panels were deployed, beginning and ending on the banks well beyond the wetted width of the river. Each panel was anchored to the substratum by angle iron 2-m long, braced diagonally on the downstream side of the fence, and a 1-m apron of plastic fencing was placed along the base and covered with two rows of sandbags on each side to add support to the fence panels and prevent erosion under the base of the fence. Chicken wire was attached to supports on top of the fence and angled

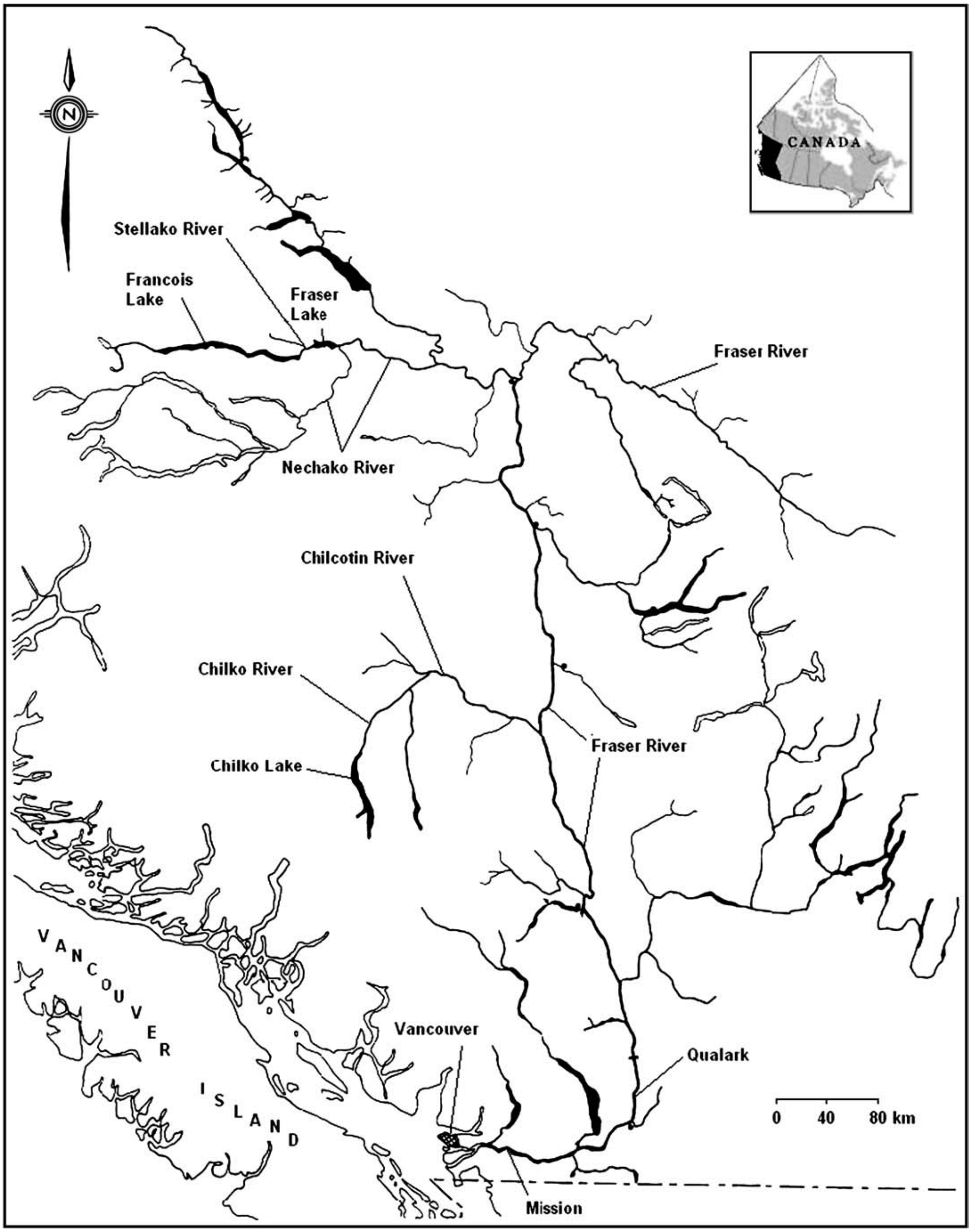

Figure 1. The locations of the Chilko River and Stellako River study sites in the Fraser River watershed, British Columbia, Canada. Other features and place names mentioned in the text are also shown.

downstream to stop fish from jumping over the fence. When fish were observed holding below the fence, several poles in the centre were removed to create a 23-cm opening or gate. A covered platform and bright lamp beside the gate permitted continuous observation regardless of weather or light conditions (Figure 3). In addition, the apron next to the platform was enlarged to approximately 2 × 2 m with white sandbags, to provide contrast for observers counting fish through the gate (Figure 3).

Data collection

The DIDSON system was operated in high-frequency mode (1.8 MHz) at both sites. In this mode, 96 horizontally

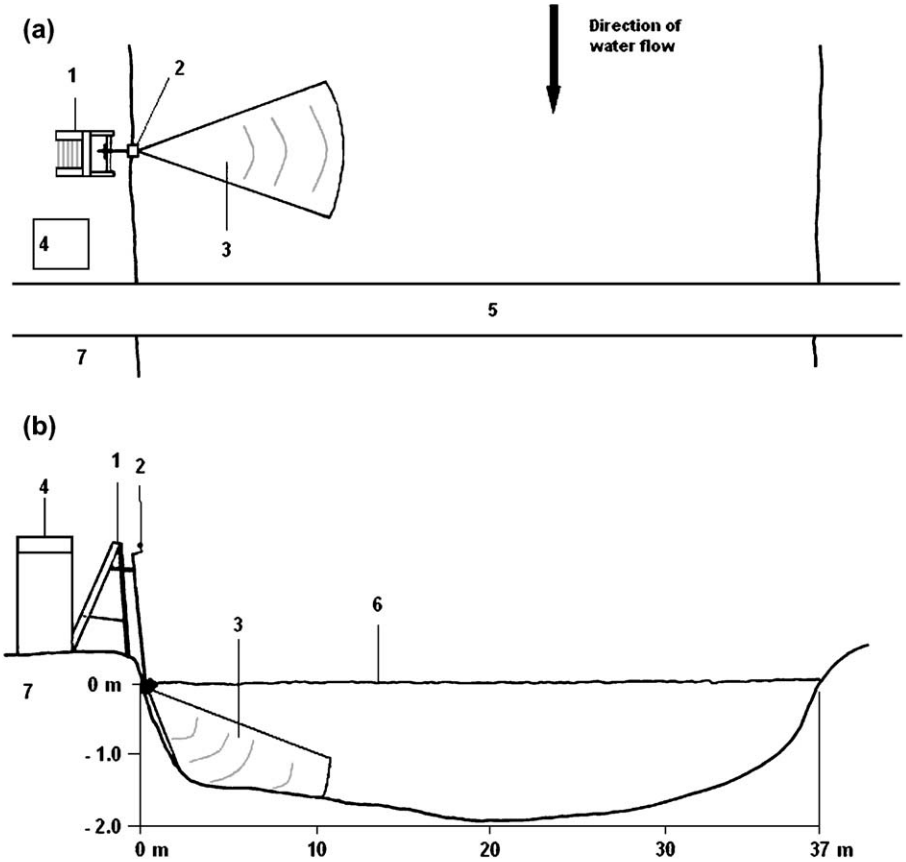

Figure 2. A schematic overhead (a) and side view (b) of the study area at Henry's Bridge on the Chilko River, showing the deployment of the DIDSON imaging system and the water volume ensonified by the beams using a −16.5° aim. Numbers refer to the following features: 1, modified stepladder; 2, DIDSON transducer mounted to adjustable pole mount; 3, ensonified water volume; 4, topside equipment shed; 5, bridge deck; 6, water surface; 7, right river bank. Note that the vertical and horizontal scales differ. River banks are labelled right and left relative to an observer facing downstream.

arranged beams produce images from a field of view that is nominally 12° vertically and 29° horizontally, and these images have sufficient resolution to permit identification of different classes of objects (big fish, small fish, debris) and direction of movement, but not necessarily species unless there are clear and consistent differences in size or behaviour. The system has a dynamic range of 90 dB, was operated at the maximum receiver gain of 40 dB, and time-varied gain, TVG, range compensation was applied to the display data, but not to the raw digital data. The sensitivity of the DIDSON system is sufficiently high that no additional threshold was needed to remove noise from the data. All digital data were collected and post-processing of fish counts were carried out using Version 4.47 of the DIDSON operating-system software (Sound Metrics Corporation, 2004).

The DIDSON images are formed with line-focused beams, which map a point or line on an object plane to a line on the image plane, rather than point-focused beams as used by optical systems such as video cameras (Belcher *et al.*, 2001). The transducer is usually orientated to project sound beams with a small grazing angle to the bottom so that each beam ensonifies a narrow outgoing line on the bottom as a function of time, and the return echoes are recorded to a file (raw data) and mapped to the display (display data), where TVG and other image analysis procedures can be applied. Targets, including fish, are displayed as if viewed perpendicular to the surface and directly above the target. The parallel horizontal arrangement of beam elements allows individual fish in the ensonified volume to be resolved by differences in their horizontal (upstream–downstream) and range dimensions (*x*- and *z*-dimensions in Cartesian coordinates) but not their vertical (surface–bottom, or *y*), dimension because each beam element is a single-beam transducer (Belcher *et al.*, 2001). The raw digital data are displayed as an image frame built in sequence from the echoes received by 4 (low frequency) or 8 (high frequency) sets of 12 beams fired simultaneously (Belcher *et al.*, 2001; Sound Metrics Corporation, 2004). This interlacing technique (or ping cycle) prevents

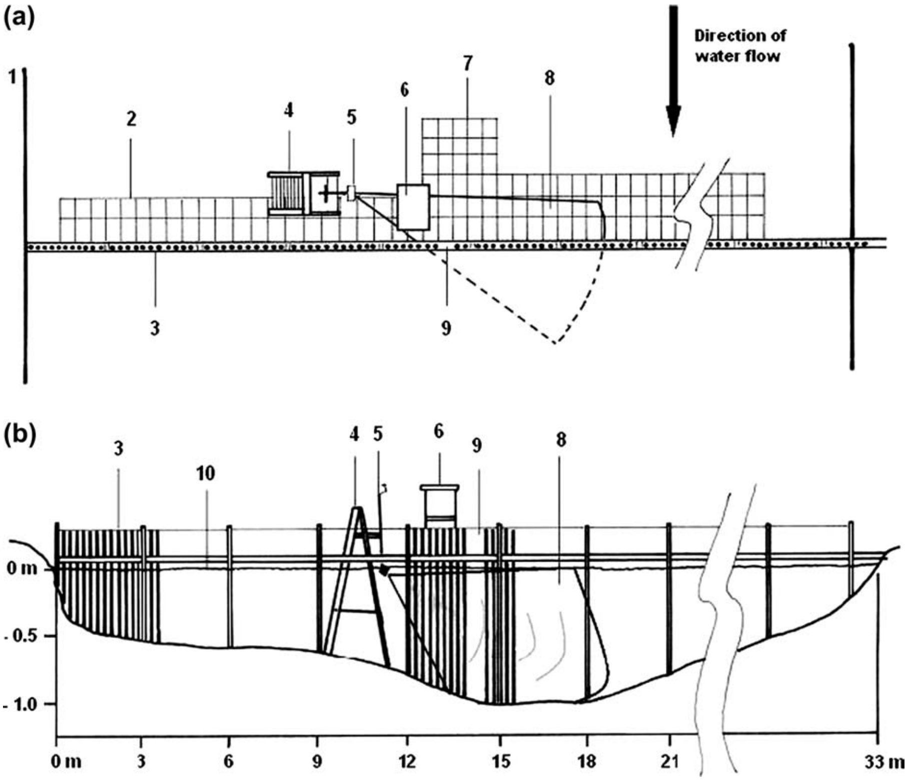

Figure 3. A schematic overhead (a) and side view (b) of the study area at the Stellako River fish-enumeration fence, showing the deployment of the DIDSON imaging system and the water volume ensonified by the beams using a −8° aim. Numbers refer to the following features: 1, right river bank; 2, apron sandbags; 3, weir or enumeration fence; 4, modified stepladder; 5, DIDSON transducer mounted to adjustable pole mount; 6, visual-counting platform; 7, enlarged and contrasting sand bag background for visual counting; 8, ensonified water volume; 9, gate or fence opening for fish passage; 10, water surface. Note that the vertical and horizontal scales differ. River banks are labelled right and left relative to an observer facing downstream.

cross-talk because adjacent beams are not fired simultaneously, but it also means that movement before the ping cycle is complete will degrade fish images in the frame.

We deployed the DIDSON system at both sites from an adjustable pole mount attached to a stationary aluminium stepladder anchored to the bottom or shoreline by four rebar pins (1 m long × 1 cm diameter) hammered into the substratum (Enzenhofer and Cronkite, 2005). The pole mount provides precise pan and tilt capabilities for riverine applications and allows the transducer to be moved up or down as the water level changes. The system was positioned so that the lens was 8–10 cm below the surface, and the transducer was aimed at a downward angle relative to the water surface and perpendicular to the water flow. An iron T-bar was placed on the downstream side of the transducer to prevent wobble, which otherwise was visible as background movement in the images, causing blurring in some fish images.

Unconstrained fish passage: Chilko River

We made 24–30-min, timed comparisons of visual and DIDSON-based fish counts at Henry's Bridge between 08:00 and 16:30 from 18 to 20 August 2004. The DIDSON system was deployed from the right bank (i.e. the bank on the right side of an observer facing downstream), and data were recorded over a 10-m range, beginning 0.42 m from the transducer and extending out to 10.42 m (Figure 2). Visual counts were made simultaneously by an experienced observer (GMWC or HJE) wearing polarized glasses and stationed on the aluminium stepladder overlooking the DIDSON system (Figure 2). All salmon-sized fish moving within 10 m of the right bank were counted, using a bridge pylon in the water as a range reference point. The DIDSON system was aimed at −16.5° relative to the water surface for 20 of the 24 comparisons, and the remaining four comparisons were made with a beam aim of −8°. If the migrating salmon are bottom-orientated as they pass through the site, then the inadequate coverage of the bottom region at the higher −8° aims should result in lower DIDSON-based counts than the respective visual counts. We did not assess beam coverage for either aim because the high water velocities at the site prevented physical mapping of the ensonified volume with a suitable target (i.e. determining where the edges of the beam were located in the water column and along the bottom).

Visual counts of migrating Chinook and sockeye salmon were compiled separately because the two species were easily identified by their colour: Chinook salmon are uniformly blue−grey, and sockeye salmon are typically red in the body with a green head when they reach the Henry's Bridge site. The visual counts for each species were pooled for analysis because we have not yet developed a robust and reliable protocol for species identification using the DIDSON system.

Fish counts from the DIDSON images were produced independently by three observers (JAH, GMWC, HJE) several days after collection and without reference to the visual counts. We used a standardized protocol that specified a playback speed of 12 frames s^{-1} for review, almost twice the speed of recording (7 frames s^{-1}), from start to finish with no stopping or pauses. Although the DIDSON software has the ability to remove fixed or stationary background objects from the images during playback to highlight moving objects, we did not use the feature. A tally of fish moving upstream was compiled by each observer using a hand-counter. Holding fish and downstream-moving fish were not counted, either during playback of the DIDSON files or during the visual-counting process on-site. Fish that were clearly moving upstream, but had not disappeared from the field of view when a DIDSON file ended, were included in the count.

Constrained fish passage: Stellako River

The Stellako River fish-enumeration fence is staffed 24 h a day throughout the migration period. After installation, the fence provides a complete census of all sockeye salmon migrating upstream, including daily counts of adults, jacks (precocious males), and tagged (if present) fish (Schubert, 1998). During normal operations, fish are allowed to continue upstream of the fence only when a sufficient number have pooled below it. A gate in the fence is opened to allow the visual counting of the waiting fish as they pass through the fence, then closed until more fish are observed to be waiting. Count data are tallied hourly, then summed to produce daily counts.

We deployed the DIDSON system 11 m from the right bank, 1.25 m upstream of the enumeration fence, and 2.5 m behind the counting platform (Figure 3) from 1 to 10 September 2004. The transducer was aimed −8° relative to surface and perpendicular to flow (parallel to the fence). The system was programmed to collect images over a 5-m range, starting 1.67 m from the transducer and extending to 6.67 m. This combination of aim and range was chosen to eliminate blind zones near the surface and bottom through which fish could move undetected, and to ensure that fish were detected as they were coming through the gate in the fence, which was visible on the right (downstream) edge of the images at a range of 3.5 m.

The DIDSON system was programmed to record continuously during the 10-day period, because fence openings occur at irregular intervals and times and for varying durations, including periods when the authors were not on-site. As the visual counts of fish through the enumeration fence are compiled on an hourly basis, the DIDSON data were recorded in 60-min date- and time-stamped files. Fence staff recorded the approximate gate-opening and -closing times, and we used these times to select and edit only those data files in which fish were moving through the fence. During normal operations of the fence, the focus is on counting sockeye salmon only. As we do not have a reliable species identification protocol for the DIDSON at present, fence staff were asked to tally all salmon-sized fish moving through the fence, and these data were pooled in our analysis. More than 95% of the fish counted at the fence were sockeye salmon, but occasionally Chinook salmon or rainbow trout (*O. mykiss*) were included in the upstream counts.

In all, 73 DIDSON files and associated fence counts were compiled for analysis over a 10-day period at the Stellako River. Three of the authors (JAH, GMWC, HJE) were randomly assigned 19 or 20 files for counting, and the remaining 14 files were given to the same authors and used for estimating count precision. Because we were attempting to produce the best counts possible, the files were reviewed at a playback speed that was comfortable for counting, and each observer was allowed to pause and rewind if necessary. The background subtraction feature was not used. Fish were counted as they moved through the fence gate visible in the images, because the large number of mountain whitefish (*Prosopium williamsoni*) and rainbow trout milling around within our field of view on the upstream side of the fence was, especially at night, often sufficient to obscure sockeye salmon once they passed through the gate. Fish moving upstream through the fence gate were tallied on a hand-counter. Fish that were clearly moving upstream, but had not disappeared from the field of view when a DIDSON file ended, were included in the upstream count. Occasionally, a fish turned downstream through the fence only to reappear soon afterwards moving upstream. These fish were only counted once.

Data analysis

All fish-count data (visual and DIDSON) were analysed on an event basis where an event is either a 30-min timed set (Henry's Bridge) or the period of time during which the enumeration fence was open and fish were counted (Stellako River). We used this approach because we were interested in the accuracy and precision of the counting process. The accuracy and precision of the DIDSON-based counts probably depend on the density of fish in the ensonified volume, and this is not always reflected in derived variables such as fish-passage rate (fish $time^{-1}$).

The fish-count data from Henry's Bridge and the Stellako River represent two measures of the same phenomenon, consisting of a series of paired values that would be expected to exhibit a linear trend when plotted. Either an "errors-in-variables" procedure (Schnute *et al.*, 1990) or an orthogonal regression is used to analyse linear data when both variables are subject to error stemming from biological and measurement variability. The "errors-in-variables" approach treats the error in each variable independently, using conventional least-squares regression to fit Y on X and X on Y, minimizing the vertical distances from the data points to the fitted line, whereas orthogonal regression treats the error in both variables simultaneously by minimizing the perpendicular distances from the data points to the fitted line. We used the "errors-in-variables" approach in this paper because orthogonal regression assumes knowledge of the expected variance ratio, σ_X^2/σ_Y^2, which was not available to us *a priori*.

Two regressions were fitted to the visual and DIDSON-count data, representing the two extremes. First was a conventional least-squares regression which assumes that the independent variable is measured without error or, more practically, that the magnitude of error in the independent variable is negligible relative to the error associated with the dependent variable:

$$\hat{Y} = A_0 + A_1 X, \tag{1}$$

where $\hat{Y}$ is the estimated DIDSON count based on the observed visual count, X, and A_0 and A_1 are the regression coefficients for the intercept and slope, respectively. Second was a regression which assumes that all errors are associated with the independent variable, where

$$\hat{X} = B_0 + B_1 Y, \tag{2}$$

and

$$Y = -\frac{B_0}{B_1} + \frac{1}{B_1}\hat{X}, \tag{3}$$

and $\hat{X}$ is the estimated visual count based on the observed DIDSON count (Y), and B_0 and B_1 are the estimated intercept and slope coefficients for the regression, respectively. The true relationship between the independent and dependent variables lies in the region bounded by these regressions, which we refer to and plot here as lower bound (LB, Equation (1)) and upper bound (UB, Equation (3)), respectively. As there is no exact method for determining the confidence interval of parameters estimated by the "errors-in-variables" model unless the ratio, σ_X/σ_Y, is known (Kendall and Stuart, 1979), we bootstrapped 1000 replicate samples and estimated the mean regression coefficients and their upper and lower 95% confidence limits. We used these limits as representative of the confidence intervals around the regression coefficients estimated by the "errors-in-variables" analysis.

Three possible outcomes for describing the true relationship between the visual and DIDSON-count data are foreseeable. First, the true relationship bounded by the LB and UB regressions is coincident with a line with slope of 1.0 that passes through the origin, i.e. the $y = x$ line, interpreted as meaning that both counting methods agree. Second, the true relationship is parallel to but not coincident with the $y = x$ line, i.e. the intercepts differ significantly from 0, consistent with a constant bias (or offset) in the count data. Third, the true relationship is not parallel to the $y = x$ line, also consistent with a conclusion that the counting data are biased, but the bias varies systematically as the counts increase.

Precision refers to the repeatability of a count between different methods or different individuals for the same event. For analytical purposes, the DIDSON-count data were categorized into low (<50 fish event^{-1}) and high (≥ 50 fish event^{-1}) passage periods based on visual inspection of the plotted data and our expectation that precision and accuracy may be affected by the number of fish moving through the acoustic beams. The 50 fish event^{-1} threshold marks a change from high to low variance in the count data on our plots. Lack of precision and accuracy will have more serious impacts on escapement estimation when fish density is relatively high. We assessed the precision of DIDSON counts among individuals stratified by passage rate using the coefficient of variation (CV) and average per cent error (APE, Chilton and Beamish, 1982) as measures of precision, where

$$\mathrm{CV} = \sqrt{\frac{\sum_{i=1}^{R}\left(X_{ij} - \overline{X}_j\right)^2}{\overline{X}_j^2}} \times 100 \tag{4}$$

$$\mathrm{APE} = \frac{1}{N}\sum_{j=1}^{N}\left[\frac{1}{R}\sum_{i=1}^{R}\frac{\left|X_{ij} - \overline{X}_j\right|}{\overline{X}_j}\right] \times 100, \tag{5}$$

and N is the number of events (14) counted by R observers (3), X_{ij} is the ith count of the jth event, and $\overline{X}_j$ is the average count of the jth event. The CV is a measure of the precision of counts from different observers for the jth event, and the APE measures the average precision over all N events in the data set. APE is used in fish-ageing literature to compare the precision of different ageing methods, observers, or ageing of different species.

Results

Unconstrained fish: Chilko River

Visual counts of unconstrained fish at Henry's Bridge ranged from 7 to 142 fish event^{-1}, of which 92.4% ($n = 1162$ fish) were sockeye salmon and the rest ($n = 96$ fish) were Chinook salmon. Average DIDSON counts for these events ranged from 12 to 150 fish and were, on average, 4.4 fish event^{-1} greater than the visual counts when the DIDSON system was aimed at $-16.5°$ ($n = 20$ events; Table 1). Both measures of count precision (APE and CV) improved at higher counts (Table 1), although the improvement was <2% for each measure. Repeated independent counts of the DIDSON files would be expected to produce the same counts 96.7% of the time when counts were <50 fish, and 98% of the time

Table 1. Precision among observers manually counting fish in DIDSON files from Henry's Bridge on the Chilko River (unconstrained fish) using two aims of the DIDSON system and the Stellako River (constrained fish).

Site	Aim (°)	DIDSON count	*n*	CV (%)	APE (%)
Chilko River	−16.5	<50	9	4.83	3.29
	−16.5	≥50	11	3.02	2.04
	−8	22−61	4	9.63	6.93
Stellako River	−8	<50	8	17.1	13.96
	−8	≥50	7	1.7	1.20

CV is the coefficient of variation and APE the average per cent error (see text for calculations), and *n* is the number of events recorded at a specified aim. Precision is based on three independent counts of each file.

when counts were ≥50 fish. Aiming the DIDSON system higher in the water column (−8°) lowered the precision of its counts, as measured by a doubling in CV from 4.83% to 9.63%, and in APE from 3.29% to 6.93% (Table 1). The −8° aim resulted in visual counts exceeding the DIDSON counts by 6 fish on average ($n = 4$ events).

The counts of unconstrained fish at Henry's Bridge followed a linear trend with homogenous variance after $\log_{10}$ transformation, and the majority of points lay above the $y = x$ line, particularly when counts were <50 fish event^{-1} (Figure 4). The lower and upper boundary regressions fitted to the count data when the DIDSON system aim was at −16.5° (Figure 4) were:

> LB: $\text{DIDSON} = 0.3061\,\text{Visual}^{0.8477}$; $r^2 = 0.98, n = 20, p < 0.0001$;
> UB: $\text{DIDSON} = 0.2827\,\text{Visual}^{0.8622}$; $r^2 = 1.0,\ n = 20, p < 0.0001$.

The visual counts accounted for 98% of the variability in the DIDSON data, as expected. Although the estimated slopes of the LB and UB regressions differ significantly from 0 ($p < 0.0001$), the 95% confidence intervals around both slope estimates do not include a value of 1.0 (Figure 5). These results are consistent with the scenario in which the count data are biased systematically since neither relationship is parallel to a line with slope of 1.0.

Constrained fish: Stellako River

Visual counts of fish at the Stellako River enumeration fence ranged from 1 to 932 fish event^{-1}, and 98% ($n = 6786$ fish) were sockeye salmon. The remaining 2% were Chinook salmon, rainbow trout, and mountain whitefish. Concurrent DIDSON counts ranged from 1 to 856 fish event^{-1} and were highly correlated ($r^2 = 0.96$) with the visual counts. The precision of DIDSON counts

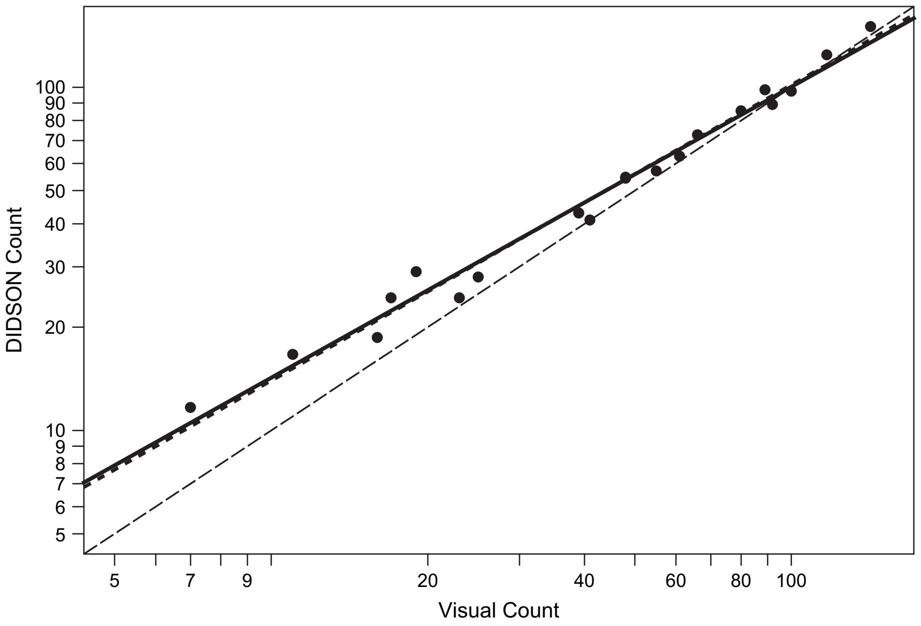

Figure 4. Lower (solid line) and upper (short dashed line) boundary regressions representing extreme assumptions concerning error fitted to $\log_{10}$ transformed fish-count data from Henry's Bridge, Chilko River, 18−20 August 2004. The long dashed line is the 45° line of equality, where $x = y$.

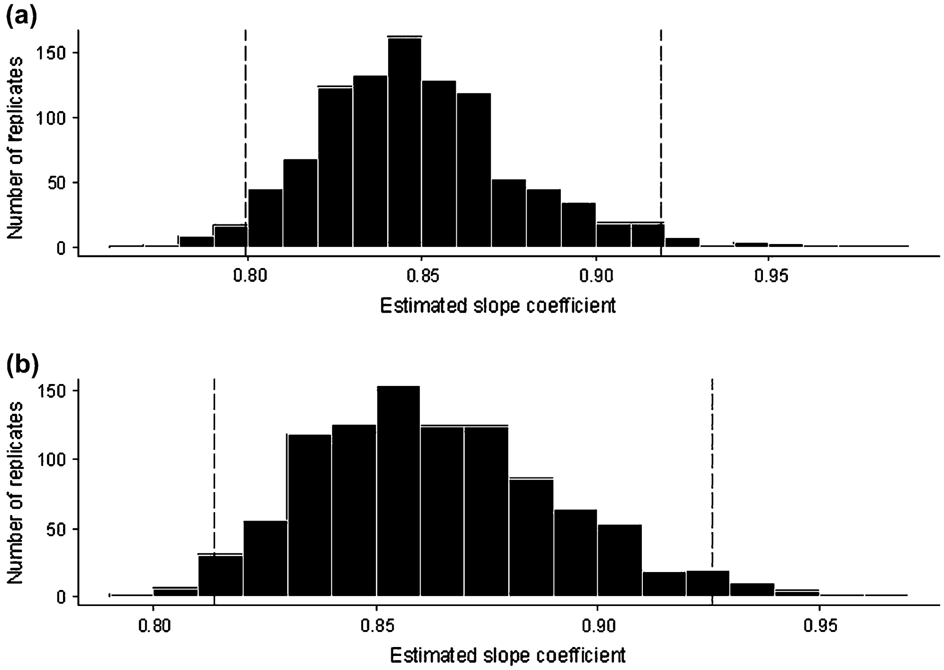

Figure 5. Bootstrapped estimates ($n = 1000$) of slope coefficients for the lower (a) and upper (b) boundary regressions shown in Figure 4. Dashed vertical lines are the lower and upper 95% confidence limits of the slope estimates.

among observers (CV) improved from 17.1% to 1.7% when ≥ 50 fish event^{-1} were counted (Table 1). Based on the APE, repeated independent counts of the DIDSON files would be expected to produce the same counts 86.0% of the time when counts were <50 fish event^{-1} and 98.8% of the time when counts were ≥ 50 fish event^{-1} (Table 1). Most salmon moved through the enumeration fence between 21:00 and 08:00, and most of the count data, whether

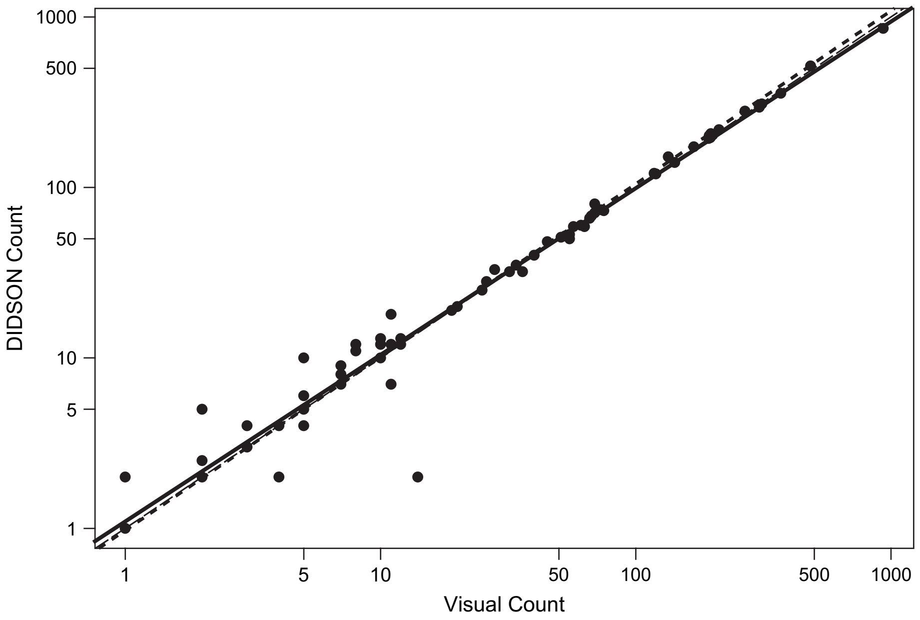

Figure 6. Lower (solid line) and upper (short dashed line) boundary regressions representing extreme assumptions concerning error fitted to $\log_{10}$ transformed fish-count data from the Stellako River fish-enumeration fence, 1—10 September 2004. The long dashed line is the 45° line of equality, where $x = y$. The line of equality is largely hidden by the lower and upper boundary regression lines.

<50 fish event^{-1} or ≥50 fish event^{-1}, were compiled from the dark period.

Log$_{10}$ transformation homogenized the variance in the count data, which exhibit a linear trend when plotted (Figure 6). The lower and upper boundary regressions fitted to count data of constrained fish from the Stellako River enumeration fence (Figure 6) were:

LB: $\text{DIDSON} = 0.04110\,\text{Fence}^{0.9774}$; $r^2 = 0.96$, $n = 73$, $p < 0.0001$;
UB: $\text{DIDSON} = -0.0124\,\text{Fence}^{1.0159}$; $r^2 = 1.0$, $n = 73$, $p < 0.0001$.

Both the LB and UB regressions are coincident with the $y = x$ line passing through the origin, because the bootstrapped 95% confidence limits around the estimated slopes and intercepts contain values of 1.0 (Figure 7) and 0 (Figure 8), respectively.

Discussion

Acoustic estimates of salmon escapement are produced by the application of a protocol that consistently detects all fish in the ensonified space and differentiates migrating salmon from milling salmon (non-migratory), resident fish, debris, and other non-fish targets during post-processing. Some judgement is inherent in this process, so there is some variability in counts of migrating salmon among counters. We found that the precision of counts produced from the DIDSON system increased as the number of fish counted increased (Table 1). This finding was not unexpected, because small differences among observers (e.g. 1 fish) when the number of fish is low have high leverage on measures of precision. High precision combined with accuracy is the most desirable combination of attributes for count data. As most salmon in the Fraser River migrate at relatively high density, achieving high precision and accuracy when fish density is high is important, because these data have a greater impact on the error associated with the resulting escapement estimates than imprecision at low fish densities. Based on past experience at Mission and Qualark on the lower mainstream Fraser River (Enzenhofer and Cronkite, 2000; Xie *et al.*, 2002), we expect that the density of fish passing a typical sonar site will be >50 fish event^{-1}, so the finding that the precision of DIDSON counts is greatest when these counts are ≥50 fish event^{-1} is important from a practical perspective.

Although the DIDSON-count data exhibit a high degree of precision, whether they represent the true number of migrating salmon depends on the accuracy of the protocol used to collect the data. Our comparison of count data at the Stellako River enumeration fence showed that the true relationship is coincident with the $y = x$ line passing through the origin (Figures 6–8), which means that the two methods of counting agree. As an enumeration fence provides a complete census of the spawning population once it is installed and fish-tight (Cousens *et al.*, 1982),

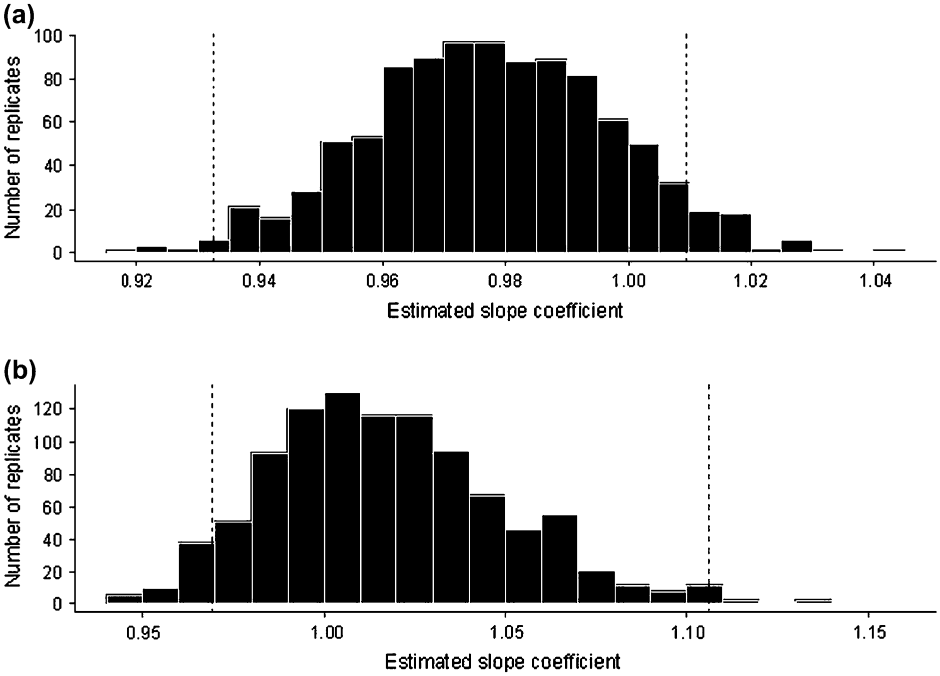

Figure 7. Bootstrapped estimates ($n = 1000$) of slope coefficients for the lower (a) and upper (b) boundary regressions shown in Figure 6. Dashed vertical lines are the lower and upper 95% confidence limits of the slope estimates.

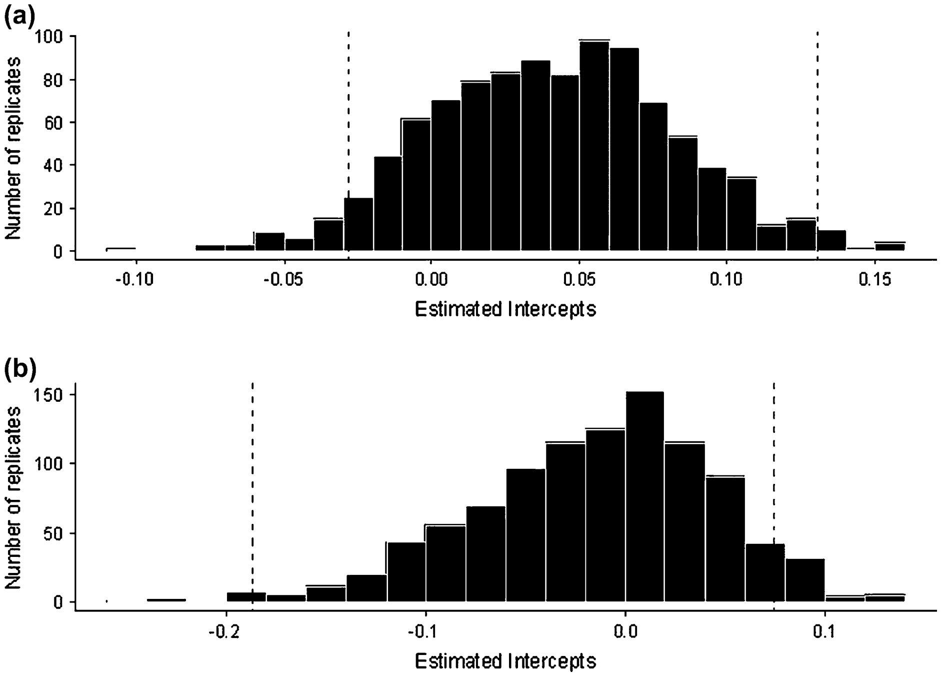

Figure 8. Distribution of bootstrapped intercept coefficients for both the lower (a) and upper (b) boundary regressions shown in Figure 6. Dashed vertical lines are the lower and upper 95% confidence limits of the estimated intercepts.

we conclude that estimates of fish passage obtained with the DIDSON system are as accurate as enumeration fence counts, at least over the range of fish counts here recorded (1−932 fish event^{-1}). An important aspect of this conclusion is that the DIDSON protocol includes careful aiming and verification of complete detection of all fish between the surface and bottom within a specified range. We used a single aim (−8°) at the Stellako River enumeration fence to ensure that there were no blind zones near the surface or bottom through which fish could pass the acoustic site undetected (Figure 3), and this objective was manually validated on-site with a target. When this protocol is followed during the deployment and aiming of the DIDSON system at other sites, the resulting count data will be both correct (i.e. according to the protocol followed) and accurate.

An important limitation of the DIDSON system is that the vertical position of a fish in the ensonified volume of water (i.e. y-dimension) is unknown to the user because the transducer consists of a horizontal array of single-beam elements that cannot measure target angle in the beam (Belcher *et al.*, 2001). Knowing this constraint, the aiming protocol here emphasized an approach that compares the capability of the DIDSON system with the objective of detecting all fish in a specified volume of water. The ensonified volume was manually validated on-site with a salmon-sized target to minimize the acoustic blind zones near the surface and bottom of the water column. This protocol required that the DIDSON system be deliberately aimed at an oblique angle into the bottom (Figures 2 and 3) to maximize near-bottom detection of fish. We were able to aim this way because the DIDSON system does not require phase measurements, which are sensitive to noise and boundary effects, to determine target position in the beam. In contrast, riverine applications of split-beam systems use a similar approach, but are aimed parallel to the bottom because these systems use phase measurements to correct target strength for target position in the beam and are therefore less tolerant of interference or distortion of the fish signal by the bottom boundary (Mulligan, 2000).

Careful aiming and validation of the aim should assure reliable fish detection with the DIDSON system, but this assurance is also limited by the ability to discriminate between individual fish. When the density of fish in the ensonified volume exceeds some threshold, saturation will occur and fish in the same beam elements at different elevations will not be distinguishable as separate targets. The onset of saturation from high fish density would likely be observable in the display data as the overlapping and crossing of fish paths. The density threshold at which this bias begins is not easily defined for the DIDSON system, because saturation depends on several factors, including the range and volume over which the density persists. The DIDSON counts here approached 1000 fish event^{-1}, probably well below the limit at which saturation begins to bias count data.

Saturation of a split-beam system occurs when multiple targets are in the pulse volume, which is defined by the pulse length and the effective beam cross-section at a given range. Enzenhofer *et al.* (1998) found that acoustic counts of migrating salmon were negatively biased when fish density, measured as the number of fish per linear metre of flashboard per counting interval, in the ensonified volume was >408 fish $\mathrm{m}^{-1}\,\mathrm{h}^{-1}$, corresponding to passage rates >2000 fish h^{-1}. The onset of saturation was characterized by an inability to track individual fish through the acoustic beam correctly when echo density within the beam was sufficiently high, as would be the case when multiple fish pass simultaneously through the beam at the same range. The performance of the DIDSON system with manual counting would be expected to equal or exceed that of the split-beam system tested by Enzenhofer *et al.* (1998), but we cannot ascertain the upper threshold at which the bias attributable to the inability to distinguish targets at different elevations in the same beams will become apparent. Even with this limitation, estimates of fish movement (direction and velocity) and net upstream flux (upstream−downstream fish) should still be possible with the DIDSON system when fish densities exceed those observed on the Stellako River. The DIDSON transducer can be rotated through 90°, so aligning the transducer vertically rather than horizontally (Enzenhofer and Cronkite, 2005) during deployment. This vertical alignment allows a user to validate the position of fish in the water column with respect to the y-dimension, i.e. elevation, while keeping range data in common during both horizontal and vertical alignments.

The visual and DIDSON-count data from Henry's Bridge exhibit systematic bias over the range of counts observed (Figure 4). The DIDSON counts were greater than the concurrent visual counts when a $-16.5°$ aim was used, averaging 4.3 ± 3.1 (s.d.) more fish per event when fish counts were <50 fish event^{-1}. As the DIDSON counts are as accurate as visual counts of fish through the Stellako River enumeration fence, the difference between the DIDSON counts and the visual counts probably reflects the difficulty in visually detecting single fish near the bottom in a turbulent environment, and the variable impact of sun glare from the water surface on visual counts. This hypothesis is supported by the results from the higher aims ($-8°$; $n = 4$ events), in which the visual counts were greater than the DIDSON counts by an average of 6 ± 8.1 (s.d.) fish event^{-1}, and the DIDSON counts were less precise ($\mathrm{CV} = 9.63\%$) than counts produced from the lower aims ($\mathrm{CV} = 3.84\%$; Table 1). We conclude from these findings that our assumption on the bottom orientation of migrating salmon at Henry's Bridge was correct and that our visual counts of unconstrained fish systematically underestimated the number of salmon migrating upstream along the right bank of the Chilko River.

Potential deployments of the DIDSON system to estimate spawning-ground escapement of Pacific salmon (*Oncorhynchus* spp.) or other species of salmon (e.g. Atlantic salmon, *Salmo salar*) will be limited by the fact that the maximum range of detection is 15 m in high-frequency mode and 40 m in low-frequency mode (Belcher *et al.*, 2001; Sound Metrics Corporation, 2004). Most DIDSON applications would likely attempt to use the former mode, but even the latter mode is likely to provide better acoustic-target recognition and resolution than a split-beam system operating at the same site. Successful enumeration of migrating salmon with a DIDSON system depends on the migrating fish exhibiting shore-orientated behaviour, i.e. swimming within 15−40 m of either bank, or the installation of weirs in the river to constrict the migration range of fish to the ensonified water volume. Shore-orientated migratory behaviour is typical of sockeye salmon migrating through high-velocity environments in the Fraser River (Woodey, 1984; Enzenhofer and Cronkite, 2000), which places fish in an appropriate area for acoustic counting without resorting to weirs. Based on the results presented here, we conclude that when migrating fish are shore-orientated or the migration range is restricted by weirs so that fish can be ensonified by a DIDSON acoustic-imaging system in high-frequency mode, then the resulting count data are accurate. These count data also exhibit very high precision among different observers doing the manual counting, especially when counts are ≥ 50 fish event^{-1}. Although similar conclusions may be appropriate for data collected in the low-frequency mode, formal assessment of precision and accuracy is needed in this case because the greater ranges and poorer target resolution involved may affect fish counts when using low frequency.

Other factors such as background noise, boundary conditions, aeration, water temperature, and turbidity also affect the fish-detection ability of sonar systems (MacLennan and Simmonds, 1992), including DIDSON. The effect of water temperature and turbidity on signal attenuation and scattering, respectively, are negligible at the ranges covered by the DIDSON system compared with the effect of TVG and the uncertainty concerning the TVG function that should be applied to an imaging system (20 log R, 40 log R, or some other function). However, of more importance for sonar estimates of salmon escapement is the effect of turbulence and air entrainment, because high-velocity, turbulent environments tend to elicit the shore-orientated migratory behaviour in salmon required for successful enumeration. The Henry's Bridge site on the Chilko River is turbulent, but the DIDSON system was successful because sockeye salmon migrate through less turbulent areas along the banks. Although the DIDSON system can produce images of adult fish in highly turbulent environments (unpublished data), turbulence and air entrainment adversely affect both the range over which detection occurs and the probability of detecting smaller fish, particularly salmon smolts or other small-bodied species.

Sockeye salmon mark-recapture programmes in the Fraser River are typically designed to estimate salmon escapement by sex with 95% confidence limits of ±25% of the estimate (Schubert, 1998). This design goal was met by 8 of 12 sockeye-salmon MRPs operating in 1994. Simpson (1984) reported that MRP estimates of sockeye-salmon escapement (across years and river systems pooled) were, on average, 21.3% greater than concurrent enumeration-fence escapement estimates, with a 95% confidence interval ranging from +8.0 to +56.3% of the fence estimates. Based on these findings, Simpson (1984) concluded that the mark-recapture estimates of sockeye-salmon escapement were positively biased relative to the fence estimates, and that the magnitude of the bias was not consistent among river systems or among years within a river system. In contrast, the spawning-escapement estimates produced by the DIDSON imaging system are unlikely to be biased relative to the estimates produced by an enumeration fence (Figure 6), at least over the range of fish counts (1–932 fish event^{-1}) observed. The DIDSON system is likely to improve the quality of salmon-escapement data in terms of accuracy and precision relative to the data quality obtained from the mark-recapture programmes currently used on the Fraser River.

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References

Banneheka, S. G., Routledge, R. D., Guthrie, I. C., and Woodey, J. C. 1995. Estimation of in-river fish passage using a combination of transect and stationary hydroacoustic sampling. Canadian Journal of Fisheries and Aquatic Sciences, 52: 335–343.

Belcher, E. O., Matsuyama, B., and Trimble, G. M. 2001. Object identification with acoustic lenses. *In* Proceedings of Oceans 2001 Conference, 5–8 November, Honolulu, Hawaii, pp. 6–11. Marine Technical Society/IEEE.

Chilton, D. E., and Beamish, R. J. 1982. Age-determination methods for fishes studied by the groundfish program at the Pacific Biological Station. Canadian Special Publication of Fisheries and Aquatic Sciences, 60. v+102 pp.

Cousens, N. B. F., Thomas, G. A., Swann, C. G., and Healey, M. C. 1982. A review of salmon-escapement estimation techniques. Canadian Technical Report of Fisheries and Aquatic Sciences, 1108. 122 pp.

Enzenhofer, H. J., and Cronkite, G. 2000. Fixed-location hydroacoustic estimation of fish migration in the riverine environment: an operational manual. Canadian Technical Report of Fisheries and Aquatic Sciences, 2312. iv+46 pp.

Enzenhofer, H. J., and Cronkite, G. 2005. A simple adjustable pole mount for deploying DIDSON and split-beam transducers. Canadian Technical Report of Fisheries and Aquatic Sciences, 2570. iii+14 pp.

Enzenhofer, H. J., Olsen, N., and Mulligan, T. J. 1998. Fixed-location, riverine hydroacoustics as a method of enumerating migrating adult Pacific salmon: comparison of split-beam acoustics vs. visual counting. Aquatic Living Resources, 11: 61–74.

Kendall, M., and Stuart, A. 1979. The Advanced Theory of Statistics. 2. Inference and Relationship, 4th edn. Macmillan, New York.

MacLennan, D. N., and Simmonds, E. J. 1992. Fisheries Acoustics. Chapman & Hall, London.

Moursund, R. A., Carlson, T. J., and Peters, R. D. 2003. A fisheries application of a dual-frequency, identification sonar, acoustic camera. ICES Journal of Marine Science, 60: 678–683.

Mulligan, T. 2000. Shallow-water fisheries sonar: a personal view. Aquatic Living Resources, 13: 269–273.

Noakes, D. J., Welch, D. W., Henderson, M., and Mansfield, E. 1990. A comparison of preseason forecasting methods for returns of two British Columbia sockeye salmon stocks. North American Journal of Fisheries Management, 10: 46–57.

Northcote, T. G., and Larkin, P. A. 1989. The Fraser River: a major salmonine production system. *In* Proceedings of the International Large River Symposium, pp. 172–204. Ed. by D. P. Dodge, Canadian Special Publication of Fisheries and Aquatic Sciences, 106.

Schnute, J. T., Mulligan, T. J., and Kuhn, B. R. 1990. An errors-in-variable bias model with an application to salmon hatchery data. Canadian Journal of Fisheries and Aquatic Sciences, 47: 1453–1467.

Schubert, N. D. 1998. The 1994 Fraser River sockeye salmon (*Oncorhynchus nerka*) escapement. Canadian Technical Report of Fisheries and Aquatic Sciences, 2201. ix+62 pp.

Schubert, N. D. 2000. The 1994 Stellako River sockeye salmon (*Oncorhynchus nerka*) escapement: evaluation of pooled Petersen and stratified mark-recapture estimates of a known population. Canadian Technical Report of Fisheries and Aquatic Sciences, 2303. x+56 pp.

Simpson, K. 1984. The accuracy of mark-recapture estimates of escapements. *In* Proceedings of the Workshop on Stream Indexing for Salmon Escapement Estimation, West Vancouver, B.C., 2–3 February 1984, pp. 209–225. Ed. by P. E. K. Symons, and M. Waldichuk, Canadian Technical Report of Fisheries and Aquatic Sciences, 1326.

Sound Metrics Corporation. 2004. Dual-frequency Identification Sonar. DIDSON Operation Manual. V4.47.15. Sound Metrics, Seattle, WA. 44 pp.

Tiffan, K. F., Rondorf, D. W., and Skalicky, J. J. 2004. Imagining fall Chinook salmon redds in the Columbia River with a dual-frequency identification sonar. North American Journal of Fisheries Management, 24: 1421–1426.

Woodey, J. C. 1984. Escapement estimation in the management of Fraser River sockeye salmon. *In* Proceedings of the Workshop on Stream Indexing for Salmon Escapement Estimation, West Vancouver, B.C., 2–3 February 1984, pp. 119–132. Ed. by P. E. K. Symons, and M. Waldichuk, Canadian Technical Report of Fisheries and Aquatic Sciences, 1326.

Xie, Y., Mulligan, T. J., Cronkite, G. M. W., and Gray, A. P. 2002. Assessment of potential bias in hydroacoustic estimation of Fraser River sockeye and pink salmon at Mission. B.C. Pacific Salmon Commission Technical Report, 11. vi+42 pp.