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Fixed-location riverine hydroacoustics as a method of enumerating migrating adult Pacific salmon: comparison of split-beam acoustics vs. visual counting

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Abstract – A split-beam hydroacoustic system with automatic tracking of individual fish is being used to estimate the number of upstream migrating adult Pacific salmon in the Fraser River in British Columbia, Canada. To determine the bias and variance of the estimates of migrating fish numbers produced by this system, we compare simultaneous acoustic and visual estimates. These data demonstrate that, as fish densities increased, both a 4° × 10° and an 8° transducer produced lower estimates than the visual count. However, in the region of fish densities typically observed for migrating salmon, the 4° × 10° transducer estimates did not differ significantly from the visual count. A detailed description of the experimental configuration is given, including how the acoustic and video data were synchronized. Analyses of the data indicate that the size and shape of the acoustic beam has a pronounced effect on the bias of the acoustic estimates. In addition, the performance of the tracking software deteriorates as fish densities become very high. © Ifremer-Elsevier, Paris

Anadromous species / stock assessment / split-beam sonar / *Oncorhynchus nerka* / *Oncorhynchus gorbuscha* / Canada (British Columbia)

Résumé – Système acoustique fixe utilisé en rivière, en tant que méthode de comptage de saumons du Pacifique en migration : comparaison entre des estimations acoustiques par faisceau scindé et des comptages « visuels ». Le suivi automatique des trajectoires de poissons considérés individuellement grâce à un sondeur à faisceau scindé est utilisé pour estimer le nombre de saumons du Pacifique en migration dans le fleuve Fraser, en Colombie britannique, Canada. Afin de déterminer le biais et la variance des estimations du nombre de poissons en migration produits par ce système, nous comparons des estimations « acoustiques » et « visuelles ». Ces données démontrent que lorsque les densités de poissons augmentent, les deux transducteurs (elliptique 4° × 10° et circulaire 8°) donnent des estimations inférieures à celles obtenues par comptage « visuel ». Cependant, dans la région où les densités de poissons sont habituellement observées pour la migration des saumons, les estimations réalisées avec le transducteur elliptique (4° × 10°) ne sont pas différentes du comptage visuel. Une description détaillée de la configuration expérimentale est donnée, ainsi que le mode de synchronisation des données acoustiques et vidéo. L'analyse des données indique que la taille et la forme du faisceau utilisé ont un effet notable sur les biais des estimations acoustiques. De plus, les performances du logiciel utilisé pour le pistage des poissons se dégradent lorsque les densités deviennent très fortes. © Ifremer-Elsevier, Paris

poissons anadromes / estimations des stocks / acoustique / *Oncorhynchus nerka* / *Oncorhynchus gorbuscha*

1. INTRODUCTION

Split-beam hydroacoustic systems are used to estimate numbers of migrating adult Pacific salmon (*Oncorhynchus* sp.) returning to spawn in their natal rivers [2, 3, 9, 10, 12, 13, 14]. Acoustic systems offer the advantages of being a noninvasive and nondestructive means of estimating the number of fish passing a

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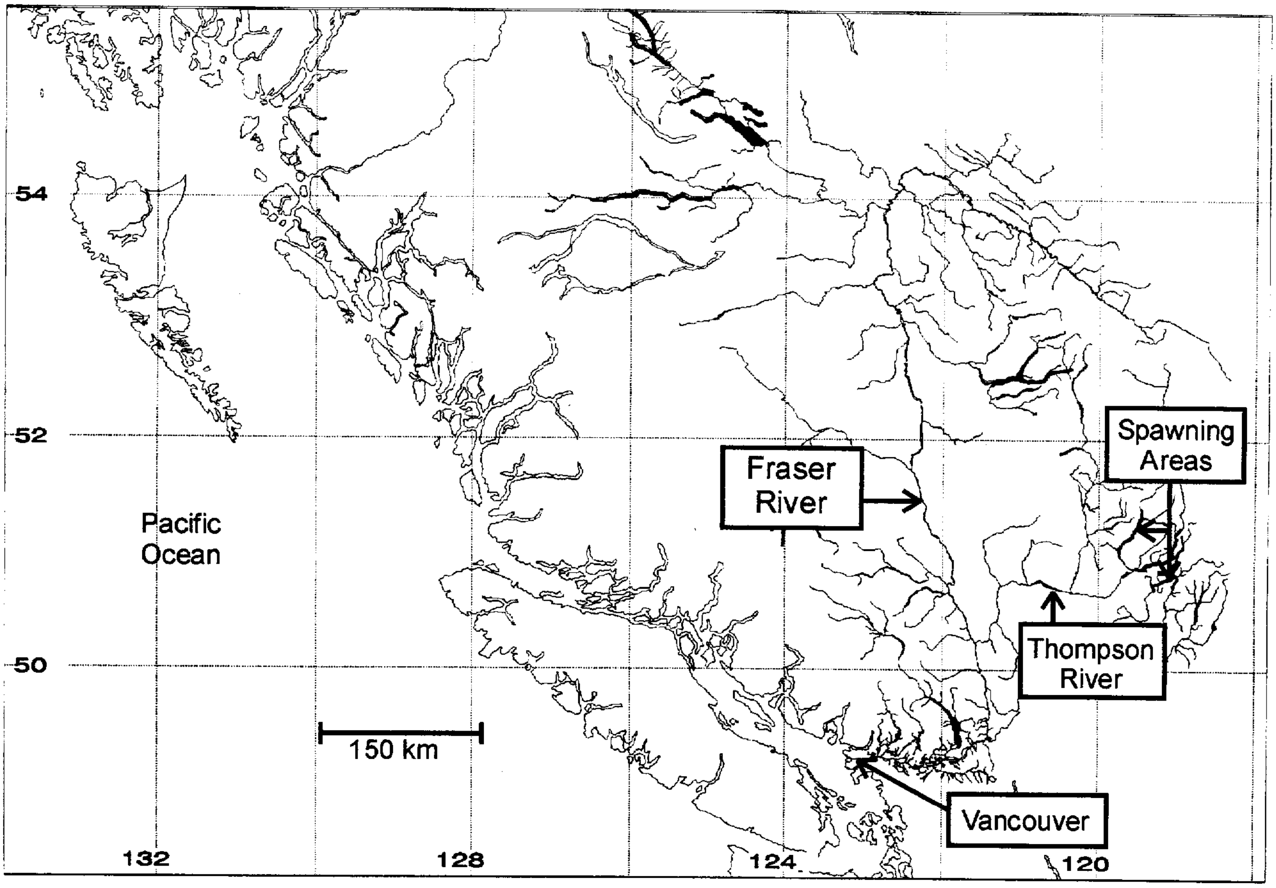

Figure 1. Map of British Columbia, Canada, indicating the study area on the Thompson River at Spences Bridge.

sampling site on the river [1, 6]. We are currently developing this type of system to estimate the number of sockeye salmon (*Oncorhynchus nerka*) returning to the Fraser River in British Columbia, Canada. The Fraser River is the largest producer of salmon in Canada, with annual returns of adult sockeye of up to approximately 20 million [16]. After commercial, sport and aboriginal catches, escapements of up to 4-5 million fish reach their spawning areas. The number of fish passing an acoustic monitoring site during one 24 h period of the spawning migration might be as low as less than 100 to as high as 500 000. Can a split-beam acoustic system with automatic tracking of individual fish produce reliable estimates under such circumstances?

After 3 years of operation in the Fraser River, we had reached the stage of development of acoustic techniques where examination of the accuracy of our estimates was warranted. Therefore, a comparison between the acoustic estimate and a simultaneous visual count was conducted on the Thompson River, a clear water tributary of the Fraser River. We consider this test to be a calibration experiment, since it allowed us to measure the bias and variance of the acoustic estimates. The test also demonstrated that the accuracy of these estimates is affected by several factors, for example, the trajectories of fish swimming through the acoustic beam, the fish density distribution within the beam, and the ability of the automatic fish-tracking algorithm to track individual fish.

This paper describes the design and physical details of the calibration experiment. Data analysis is limited to comparisons of estimated numbers of fish migrating through the beam.

2. MATERIALS AND METHODS

The calibration experiment was performed on a mixture of sockeye salmon and pink salmon (*O. gorbuscha*) migrating up the Thompson River at Spences Bridge, British Columbia. This site was chosen because it could be configured to be similar to our normal field site on the Fraser River and because the Thompson River is clear, while the Fraser River is too turbid to allow such an experiment. Therefore, the

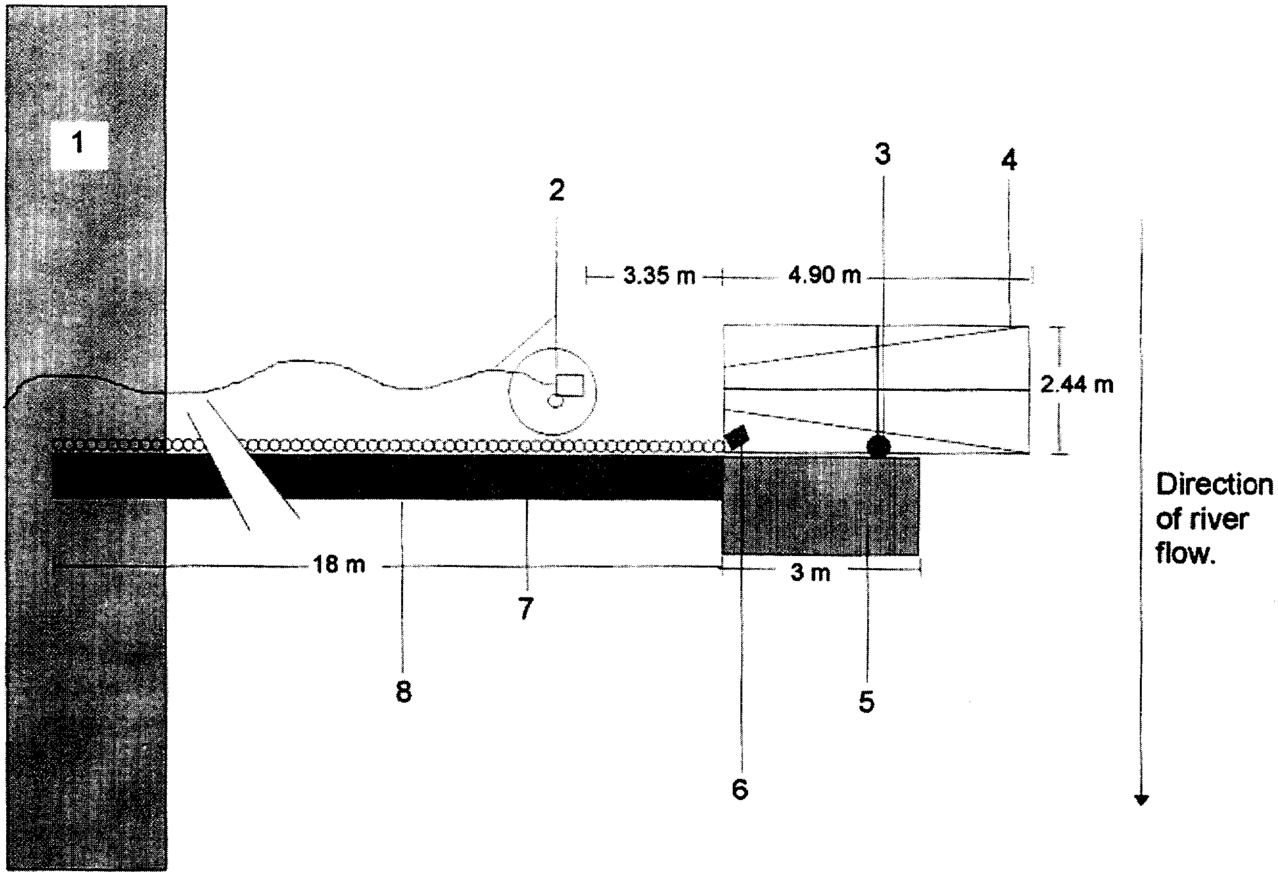

Figure 2. Overhead schematic of the study area. (1) River bank. (2) Transducer pod. (3) Overhead camera mounted on tower. (4) Sample platform. (5) Observation tower. (6) Underwater camera. (7) Deflection fence. (8) Walkway.

layout was intentionally arranged to reproduce the characteristics of the Fraser site. We used a calibrated split-beam acoustic system with a three-dimensional target-tracking algorithm to monitor fish migration in real-time [4, 7, 8], while video data were recorded by both overhead and underwater cameras. The fish passing through the acoustic beam were video taped, visually counted, and acoustically detected and tracked.

2.1. Study area

The site on the Thompson River was 200 m downstream from the Trans-Canada Highway bridge at Spences Bridge, BC (*figure 1*). At this location the river is approximately 150 m wide with a bottom slope of 13°. All of the acoustic and video measurements were made from the right bank within proximity of an access road. The goal of the experiment was to compare visual and acoustic estimates, not to estimate the number of fish migrating upstream. The following selection criteria were used to choose an appropriate site for both acoustic and visual counts.

The Spences Bridge site exhibited relatively low turbulence. Turbulent flow can entrain air bubbles that reflect acoustic waves, creating background noise that reduces system performance. Increased turbulence results in decreased detection efficiency for a given target. Visual clarity at the site was at least 3 m. This was important for recording images of fish passing in front of the underwater camera. For the overhead camera, water clarity was less important since all fish migration occurred in water less than 3 m deep. The river bottom was relatively free of large boulders that can interfere with fish detection. This allowed us to aim the acoustic beam close to the bottom, reducing the chance that fish could migrate undetected under the beam.

The fish were of the same species and weight range as are found in other commercially important salmon runs. Therefore, these results should be applicable to other areas, such as the Fraser River, where visual counts are not possible. The fish were actively migrating upstream. Fish that exhibit milling behavior (i.e. that remain in a local area for an extended period of

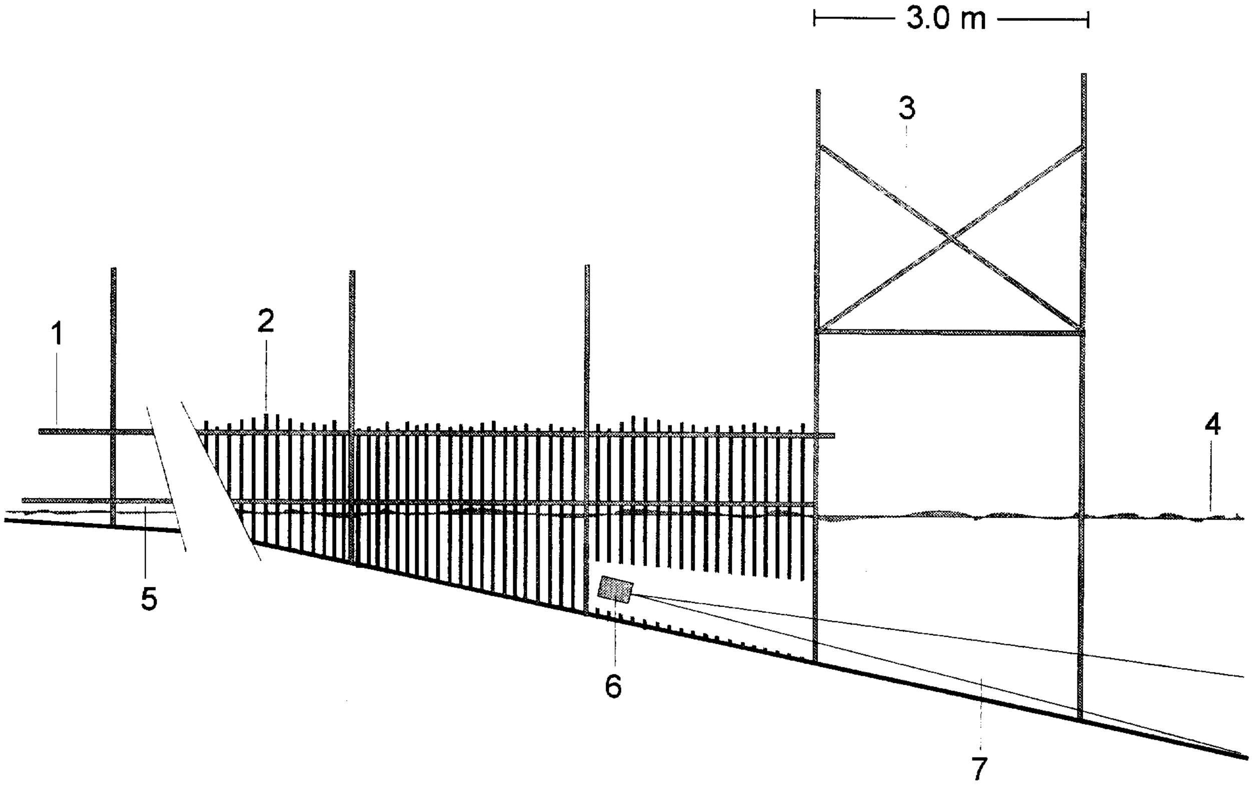

Figure 3. Side view schematic of the deflection fence, walkway, tower, and acoustic ramp showing placement of the transducer. The acoustic beam boundaries shown are for illustrative purposes only. (1) Handrail. (2) Deflection fence. (3) Observation tower. (4) River surface. (5) Walkway. (6) Transducer. (7) Acoustic beam.

time) present a problem, since a single fish may be counted several times as it passes back and forth through the beam. Fish migrated near shore and close to the river bottom, a pattern which is duplicated in other river systems with moderate to high flow rates.

2.2. Experimental design

A schematic of the experimental area is shown in *figure 2*. Hydroacoustic measurements were made with a fixed location, digital split-beam system and a specific configuration that was designed to reproduce the deployment and instrumentation settings normally used at the Fraser River site. A shore-based transducer was aimed perpendicular to the shoreline and as close as possible to the bottom. As fish migrated through the beam, simultaneous recordings were made with a digital echo processor, a chart recorder, a digital audio tape recorder (DAT), an overhead video camera, and an underwater video camera. Sampling periods were usually 30 min in duration, with start and end times synchronized between the video and acoustic systems. A deflection fence was used to move fish away from the transducer to a distance at which the acoustic beam was large enough to cover the height of the water column containing the majority of migrating fish. A platform composed of heavy steel grates wrapped in white cloth was placed on the river bed.

The acoustic system produced both a chart paper echogram of the raw data and an estimate of the total of the number of tracked fish per sampling period. The echogram was intended for subsequent manual analysis by an experienced person to compare with the automatic estimate of tracked fish number. The DAT recordings and video tapes provided permanent records of the raw data measured by the acoustic and visual systems.

A video camera mounted on an observation tower recorded an overhead view of the sampling area. This view was displayed on a video monitor so that visual counts of migrating fish could be tallied from this monitor for each sampling period. An underwater camera was located on the river bottom and aimed such that it's field-of-view covered a portion of the acoustic beam. The video tapes recorded from these two cameras provide information on the three-dimensional position and movement of fish through the acoustic beam.

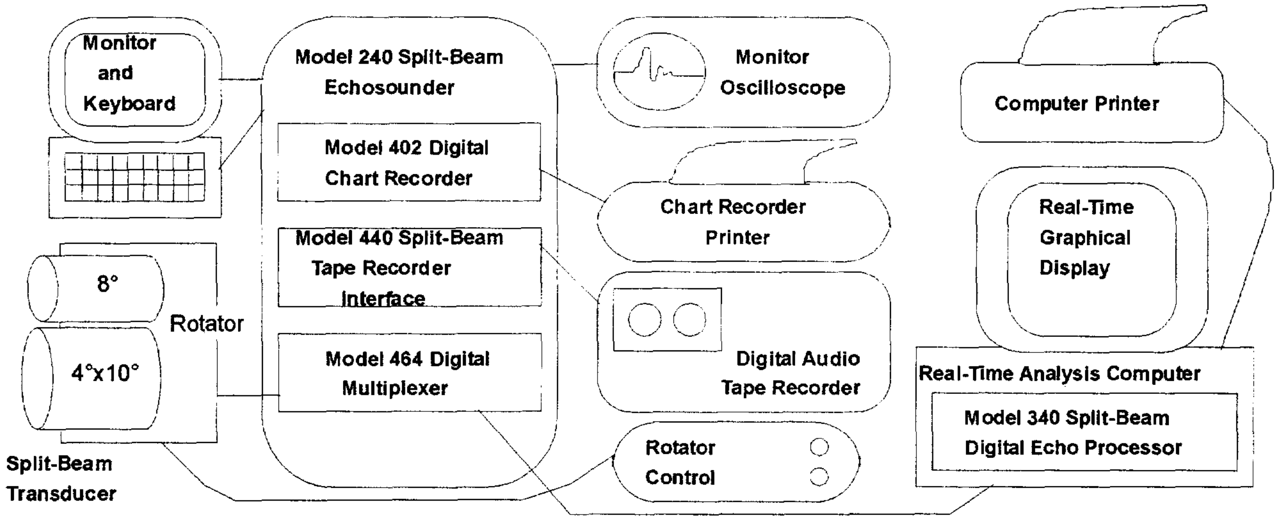

Figure 4. Schematic diagram of the HTI Inc. Model 240 Split-Beam Hydroacoustic System as configured for the experiment at Spences Bridge.

2.3. Construction on site

A fish deflection weir and walkway with a counting tower were built on the site (*figure 3*). The 18 m walkway consisted of SHUR GRIP galvanized steel grating supported by a brace system constructed of 3.5 cm schedule-40 galvanized pipe. We used commercially available KEE KLAMP slip-on pipe fittings to join all pipe sections and to allow us to make adjustments during assembly at the site. Support braces were placed every 3.7 m and anchored to the river bottom with three steel pins. The fish deflection fence ran the length of the upstream side of the walkway and was constructed of 1.9 cm galvanized conduit pipe placed on 5.7 cm centres. Each pipe could be removed from its holder for maintenance and cleaning of the fence. A 1.2 × 3 m tower was added to the end of the walkway and was constructed of the same materials as the walkway. The platform of the tower was 2.1 m above the water surface and gave a clear view of the entire sample area for both the observer and the overhead video camera.

An underwater platform was installed adjacent to the upstream side of the tower and was oriented perpendicular to the riverbank (*figure 2*). This platform was used to define the boundaries of the acoustic beam and to provide a background for viewing and video taping. We painted the nominal beam width of the 4° × 10° elliptical transducer on the platform, which was sectioned into 1 m grid marks to help with visual location of the fish. The area covered by the platform coincided with a range from 3.35 to 8.25 m of the acoustic beam. Construction material consisted of white GEOTECH landscape fabric set between heavy wire screen and formed four 1.22 × 2.44 m panels. We used 5 × 5 × 0.64 cm screen for the bottom and 1.9 cm wire mesh for the top screen. Panels were fastened together and 1.9 cm × 3 m rods added to the underside to form a level surface. Divers were required to install the platform, set anchor ropes, and place sandbags as required.

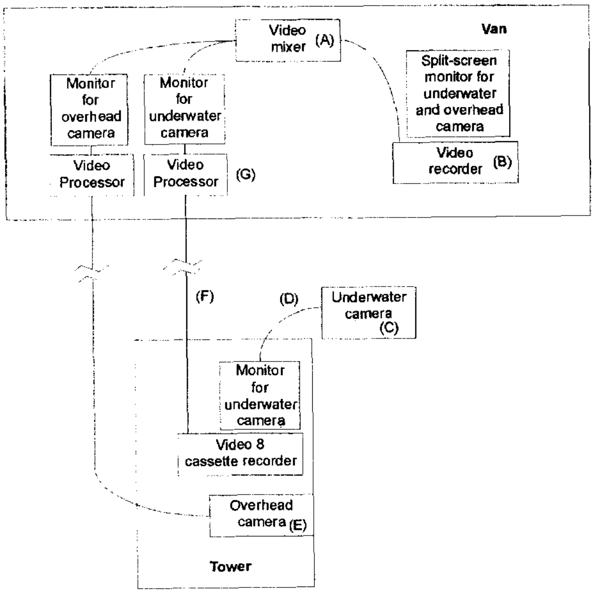

Figure 5. Schematic of video recording configuration. (A) Videonics MX-1 video mixer. (B) Betamax SL-HF900 video recorder. © Sony TR101 Hi8 video camera / recorder. (D) 14m video cable. (E) Sony V220 8mm camera. (F) 35m RG6 coaxial cable. (G) Sony model 15-1955B video processors.

2.4. Acoustic data collection

We used an HTI Model 240 Digital Split-Beam Hydroacoustic System [7, 8], that included three-

Table I. Estimated fish counts by 3 different viewers from a set of 12 video recordings. The final column gives the coefficient of variation (in per cent) of the three estimates for each video recording.

Video	Viewer 1	Viewer 2	Viewer 3	Coeff. of Var. (%)
1	1 973	2 006	1 981	0.87
2	2 614	2 578	2 686	2.09
3	4 103	4 234	4 140	1.62
4	965	976	984	0.98
5	1 542	1 578	1 552	1.19
6	1 406	1 444	1 412	1.44
7	708	713	721	0.92
8	453	451	465	1.66
9	650	641	678	2.94
10	668	667	663	0.40
11	493	480	500	2.07
12	4 269	4 354	4 255	1.25
			Mean	1.45

Table II. Fish passage estimated from echo processor counts and visual counts at Spences Bridge, 1995.

Date	Start time (h:min)	Duration (h:min)	Echo processor count (fish^{2}h^{-1})	Visual count (fish^{2}h^{-1})	Transducer
22-Sep-95	12:07	01:06	1 888	3 044	4° × 10°
26	12:28	00:30	3 976	7 604	
	13:13	00:30	3 740	8 038	
	14:42	00:31	3 386	5 553	
	15:21	00:25	4 082	6 682	
27	11:32	00:30	4 627	5 366	
	12:13	00:54	3 876	5 645	
	13:33	00:30	6 224	8 266	
	15:03	00:29	4 755	6 715	
	18:28	00:29	2 925	1 971	
28	10:27	00:30	4 976	5 346	
	11:06	00:30	3 742	4 076	
	18:22	00:30	2 190	2 244	
29	08:25	00:30	2 885	3 854	
03-Oct-95	09:30	00:29	1 713	1 721	
	10:10	00:30	1 441	1 409	
	13:53	00:30	4 126	5 448	
4	08:49	00:30	2 249	2 822	
	09:28	00:30	1 703	1 785	
	11:55	00:39	914	1 066	
	18:20	00:28	1 566	1 357	
5	08:11	00:49	776	815	
	09:08	00:29	1 249	1 329	
	10:41	00:31	1 044	967	
	11:18	00:41	847	737	
	15:46	00:49	550	565	
22-Sep-95	14:58	00:31	1 047	5 166	8°
26	16:22	00:30	999	4 651	
27	08:48	00:30	1 270	4 546	
	09:25	00:30	1 520	5 860	
	10:42	00:30	1 174	3 962	
	19:08	00:25	336	535	
28	08:39	00:30	416	4 082	
	09:14	00:30	993	3 660	
	09:49	00:30	931	3 288	
	11:50	00:30	1 063	6 143	
	13:28	00:30	1 756	8 510	
	14:03	00:29	1 629	6 320	
	17:45	00:30	1 065	3 101	
03-Oct-95	12:06	00:30	483	2 729	
	12:45	00:30	583	3 836	
4	10:11	00:30	572	929	
	10:48	00:50	570	865	
	14:03	00:30	696	3 866	
5	09:57	00:35	348	856	
	13:20	00:30	980	1 328	
	13:56	00:29	1 080	1 692	
	14:37	00:29	904	1 423	
	15:12	00:24	755	1 178	
6	08:10	00:29	413	2 941	
	08:47	00:29	282	2 347	
	09:35	00:29	1 054	2 093	

dimensional target tracking software for the experiment (*figure 4*). This system included a 200 kHz Model 240 Digital Echo Sounder, two 150 m lengths of transducer cable, a 4° × 10° elliptical and an 8° circular transducer, an oscilloscope, a dot-matrix printer, a monitor and keyboard, a digital-audio tape recorder, and a 486 DX computer equipped with a Model 340 Digital Echo Processor board. Transducers were attached to a Remote Ocean Systems dual-axis underwater rotator, mounted on an aluminum tripod, and operated from a fixed location near the river bank. The electronic components were housed in a mobile van and powered by a 5 kW gasoline generator.

The echo sounder was operated at 25 W transmit power and –18 dB total receiver gain. Pulse width during data collection was 0.2 ms with a pulse repetition rate of 10 pings per second. To provide target tracking data, acoustic signals were amplified with a 40 LogR time-varied-gain.

Data from single-target echoes were processed by the echo processor and written to a computer file. This file was further processed by the real-time tracking algorithm to indicate those echoes that grouped into reasonable trajectories for migrating fish. The transducer transmits simultaneously on all four split-beam quadrants, but receives the return signals from the four quadrants independently [15]. Signals from the four quadrants are amplified and combined by the echo sounder to form four, half-beam components: up, down, left, and right. The shift in the phase between these four components is used by the echo processor to calculate the vertical and horizontal off-axis angles for an echo. Thus, three-dimensional position data is measured for each echo. Knowing the position and associated time for each echo permits estimation of direction of travel, target speed, and target strength.

In order to be classified as coming from a migrating a fish, echoes had to satisfy the following selection criteria (see Ehrenberg J.E. and Torkelson T.C. [4] for a more complete description of the single-target selection criteria and the target tracking algorithm). We used a minimum echo amplitude threshold of 200 mV, equivalent to a target strength of approximately –40 dB. For a 0.2 ms transmitted pulse width, we used a maximum of 0.3 ms and minimum of 0.1 ms for the echo signal. A minimum of four accepted echoes, none having more than a seven-ping gap between echoes,

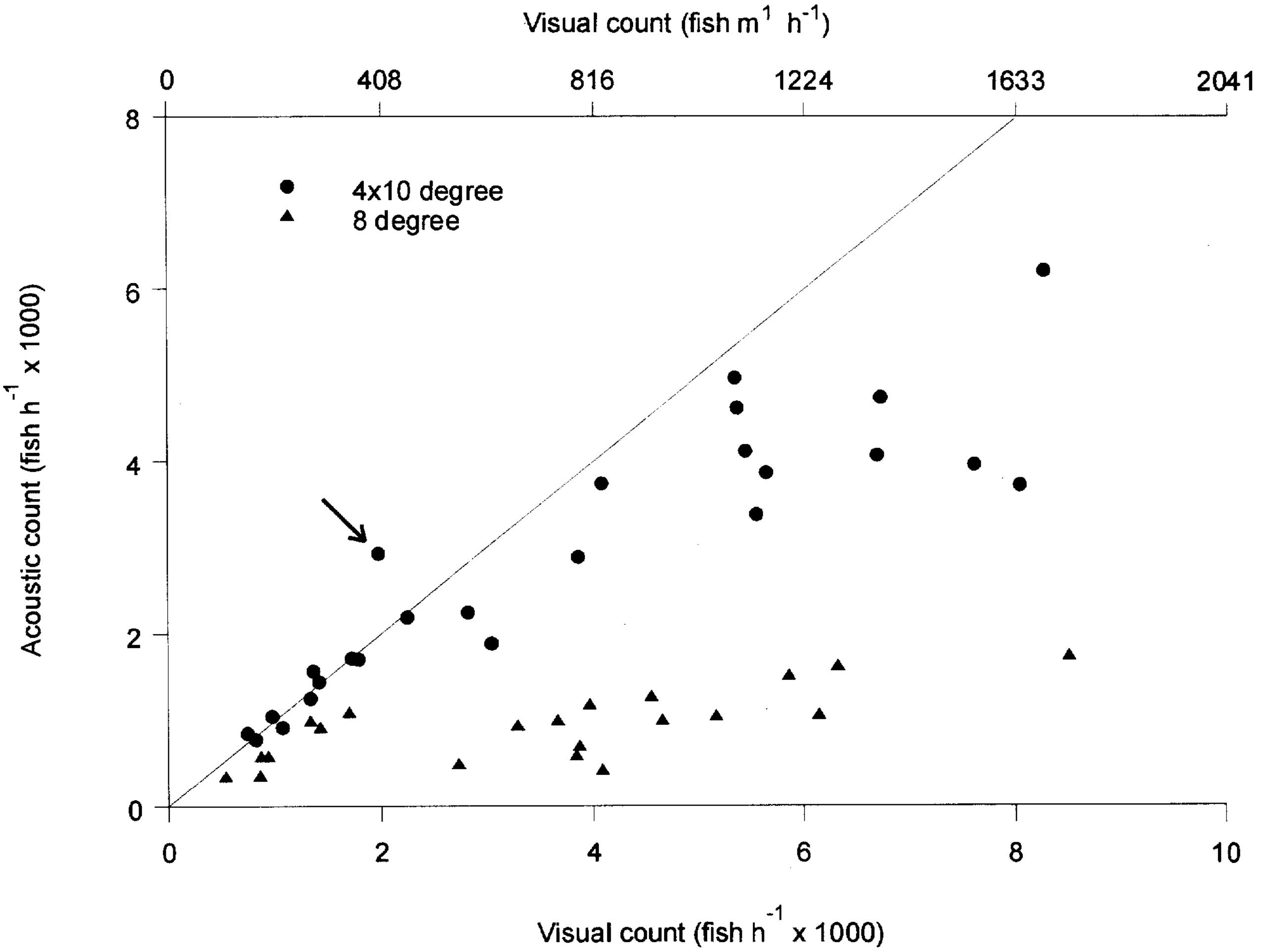

Figure 6. Relationship between acoustically and visually counted migrating salmon. The solid line denotes equal values of visual and acoustic counts. The arrow denotes an anomalous observation (see text).

was required for each fish trajectory. Maximum range from the transducer was set to 8.25 m, which coincided with the end of the sample platform. Echograms produced by the echo sounder were collected using the same 200 mV threshold used for target tracking. Single-fish trajectories were interpreted from the echogram by applying the same minimum number of echoes and maximum missing-echo gap used by the digital echo processor.

We used a target frame [5] to align our acoustic beam with the –3dB beam angles painted on the sample platform. A target deployed mid-water from the target frame was placed on the beam axis between the painted beam lines. The transducer was rotated until the target appeared as a strong signal on the oscilloscope. Once the target had been located by this crude procedure, a real-time program was used to display the vertical and horizontal position of the target on the computer monitor. The beam was then further rotated until the echoes from the target coincided with the beam axis. Next the beam was rotated vertically until the bottom signal appeared strong, but below the 200 mV threshold. The aiming angles displayed by the rotator in this position were recorded and used for subsequent re-aiming. We determined the minimum distance above the bottom for which an echo from fish could be observed to be ≈ 10-13 cm by use of an artificial target (10 cm diameter, air-filled plastic sphere) with the same mean target strength as observed for the migrating salmon.

The data files for tracked fish include the apparent direction of travel, i.e. upstream or downstream. We have found that most of the downstream migrating targets come from tracked fish trajectories that have considerable random scatter with little apparent systematic direction of movement. We suspect that these tracks represent multiple fish targets misinterpreted by the software and identified as single-fish tracks. There-

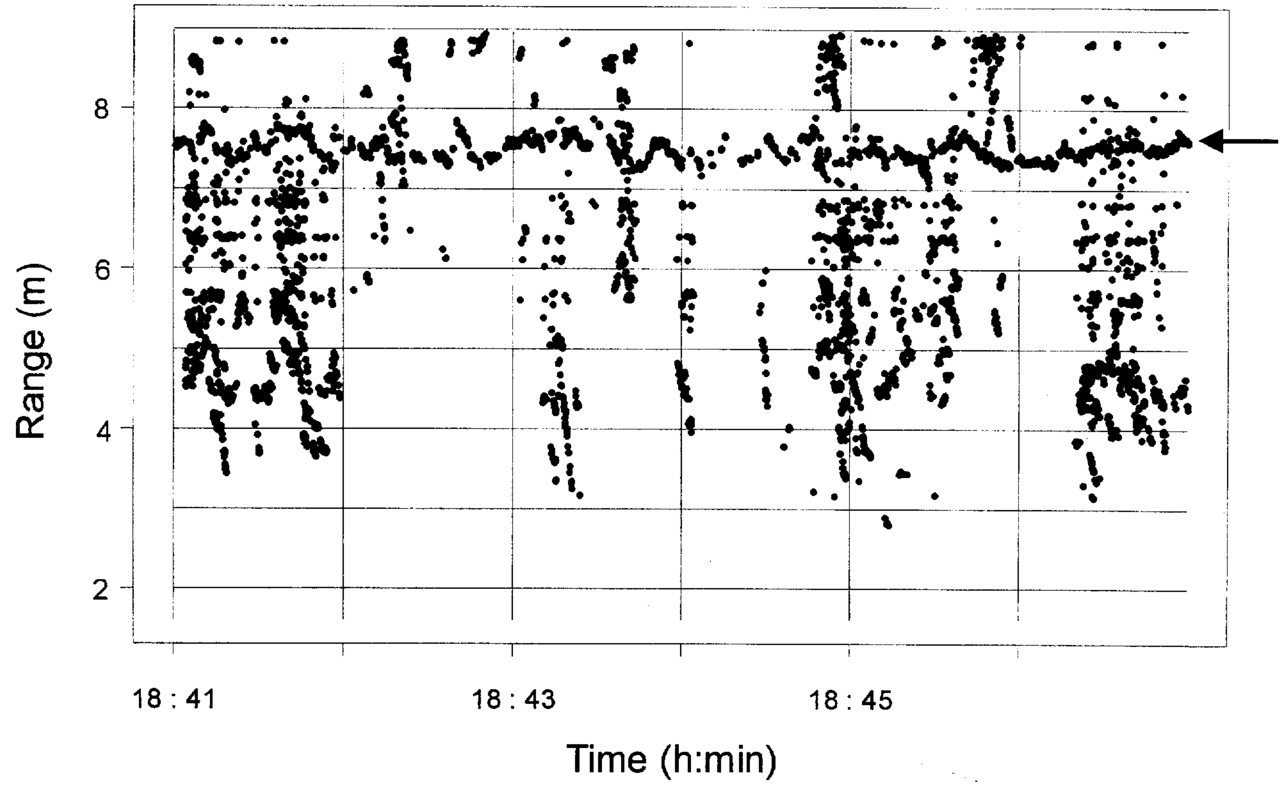

Figure 7. Echogram showing evidence of a stationary target (heavy line indicated by the arrow) in the beam.

fore, we subset the tracked fish targets into those that have an upstream/downstream correlation vs. time >0.9 and those where this correlation is <0.9. The tracks with high correlation coefficient are predominantly composed from tracks whose trajectories through the beam seem to be reasonable for fish movement; whereas, those with low correlation coefficient are erratic with no predominant direction of movement. The downstream-moving targets from the high correlation tracks typically are 1-2 % of the overall targets. By contrast, if all tracked targets are used to partition direction of movement, 10-20 % of the fish are typically identified as downstream. Our estimates of the number of migrating fish come from the total number of tracked targets, irrespective of their correlation with time or assigned direction of movement. Thus, we have found that total target number is well estimated by the tracking algorithm, however, accurate estimation of direction of fish movement requires selection of the best tracked single-fish targets.

2.5. Video data

A schematic of the video recording configuration is shown in *figure 5*. Two video cameras were used to record the migrating fish, an above-water camera (AWC) and an underwater camera (UWC). The AWC was a camcorder equipped with a wide-angle lens and Polaroid filter. It was mounted 3.5 m above the water surface using a mount attached to the counting tower and aimed at the sample platform. The UWC camcorder included a wide-angle conversion lens and was enclosed in an aluminum underwater housing. The housing was equipped with a 14 m long cable that: (i) supplied electric power to the camera, (ii) transmitted the video signal to equipment on shore, and, (iii) contained a LANC-connection to control the camera functions with a remote controller. This housing was mounted on an aluminum pole positioned about 30 cm off the bottom, and was aimed along the sample platform.

Before the UWC was enclosed in the underwater housing, the date and time recording functions were set, remotely controlled functions and video transmission were checked, camera focus was set to manual, and the iris control was set to automatic. A similar check was performed for the AWC, except that both focus and iris control were set to manual. Final positioning and focusing of the AWC was performed through the camera view-finder, while for the UWC, this was accomplished by using a TV monitor on the tower and the remote controller. The AWC recorded video data on it's internal tape drive, while the UWC recorder was on the counting tower. Thus, we avoided

Table III. Fish passage estimated from echo processor counts, visual counts, and echogram trace counts at Spences Bridge 1995.

Transducer	Filename	Duration (h:min)	Echo processor count	Visual count	Echogram trace count
4° X 10°	A2760930	00:29	856	860	753
	1009	00:30	721	705	679
	A2770927	00:30	854	895	1 011
	1154	00:39	609	710	770
	1820	00:28	750	650	713
	A2780811	00:49	646	678	841
	0908	00:29	623	663	801
	1040	00:31	547	507	622
	1117	00:41	579	504	628
	1545	00:49	458	470	616
8°	A2691621	00:30	500	2 327	467
	A2700847	00:30	635	2 273	632
	0925	00:30	760	2 930	698
	1042	00:30	587	1 981	590
	1908	00:25	140	223	138
	A2710839	00:30	208	2 042	222
	1150	00:30	532	3 073	523
	1328	00:30	878	4 255	905
	1403	00:29	814	3 158	762
	1745	00:30	533	1 552	527
	A2761206	00:30	242	1 366	278
	1245	00:30	294	1 934	435
	A2771011	00:30	286	465	294
	1048	00:50	475	721	454
	A2781512	00:24	314	490	348
	A2790810	00:29	206	1467	268
	0847	00:29	141	1172	237
	0935	00:29	526	1 044	543

raising the UWC to change tapes, a procedure that would jeopardize the camera alignment.

The video signals from the AWC and UWC were each transmitted through 35 m-long RG 6 coaxial cables to monitors in the mobile van (*figure 5*). Video processors were used to enhance the signals before displaying them on the monitors, since the distance between the counting tower and the mobile van was large and deterioration of the video signal was anticipated. From the monitors the AWC and UWC signals were transmitted to a mixer where they were combined to appear side by side. Next, the mixed picture was recorded and displayed on a video monitor. This process allowed time synchronization of the single-view video tapes during later analysis. Video tapes were either Hi-8 ME-120 or Sony Betamax L-750.

Once the cameras were in place, the viewing areas were adjusted. The AWC was set to view the entire sample platform, while the UWC was aimed to have the right edge of the field of view be parallel with the downstream edge of the sample area and to cover as much of the acoustic beam as possible. Therefore, the UWC did not record all of the fish that passed over the sample platform and through the acoustic beam. The number of salmon migrating past the sample platform were counted from the AWC monitor in the equipment van. The combination of Polaroid filter and video processor created a clearer image on the monitor than was visible by eye from the observation tower. The count was made for each fish that passed both of the –3 dB beam lines painted on the sample platform. Fish that passed only one of these lines and then moved off the sample platform before passing the second line were extremely infrequent and ignored. The visual count represented only the upstream migrating fish. There were no downstream migrating fish observed in the video data.

A subset of the video recordings was recounted to obtain an estimate of the variability of the visual counts. Two people independently counted this subset of 12 video recordings which was chosen to span the range of fish passage rates (*table I*). The three independent estimates of fish count yielded an average coefficient of variation of 1.45 %.

3. Simultaneous recording of video and acoustic data

Data collection consisted of simultaneous recordings of:

1) above-water caneva, AWC video signal,
2) underwater caneva, UWC video signal,
3) combined AWC and UWC signal,
4) echogram,
5) acoustic data files,
6) tape recording of the acoustic signals,
7) visual count tallied from the AWC video monitor.

Synchronization of acoustic and video recordings was accomplished as follows. Before the start of a recording session, flash cards with tape identification number, time, date, and camera type were prepared and placed in each camera's field-of-view. Four people were required, each one responsible for a specific task. The synchronization process was dominated by the fact that a 17 s delay occurred between starting the acoustic system and the first acoustic transmission, and storage of the acoustic data. Therefore, we adopted an audio countdown procedure as follows. The acoustic system was started. Seven seconds later, a 10 s audio countdown was initiated and transmitted to the video camera operators via hand-held radio. Each camera had a separate operator who started video taping followed by the removal of the cards at the end of the countdown. In the van at the end of the countdown, one operator started the DAT recorder while the other started the Beta recorder and began the visual count. The card removal and initiation of the acoustic data files were thus begun with a typical time discrepancy of less that one second.

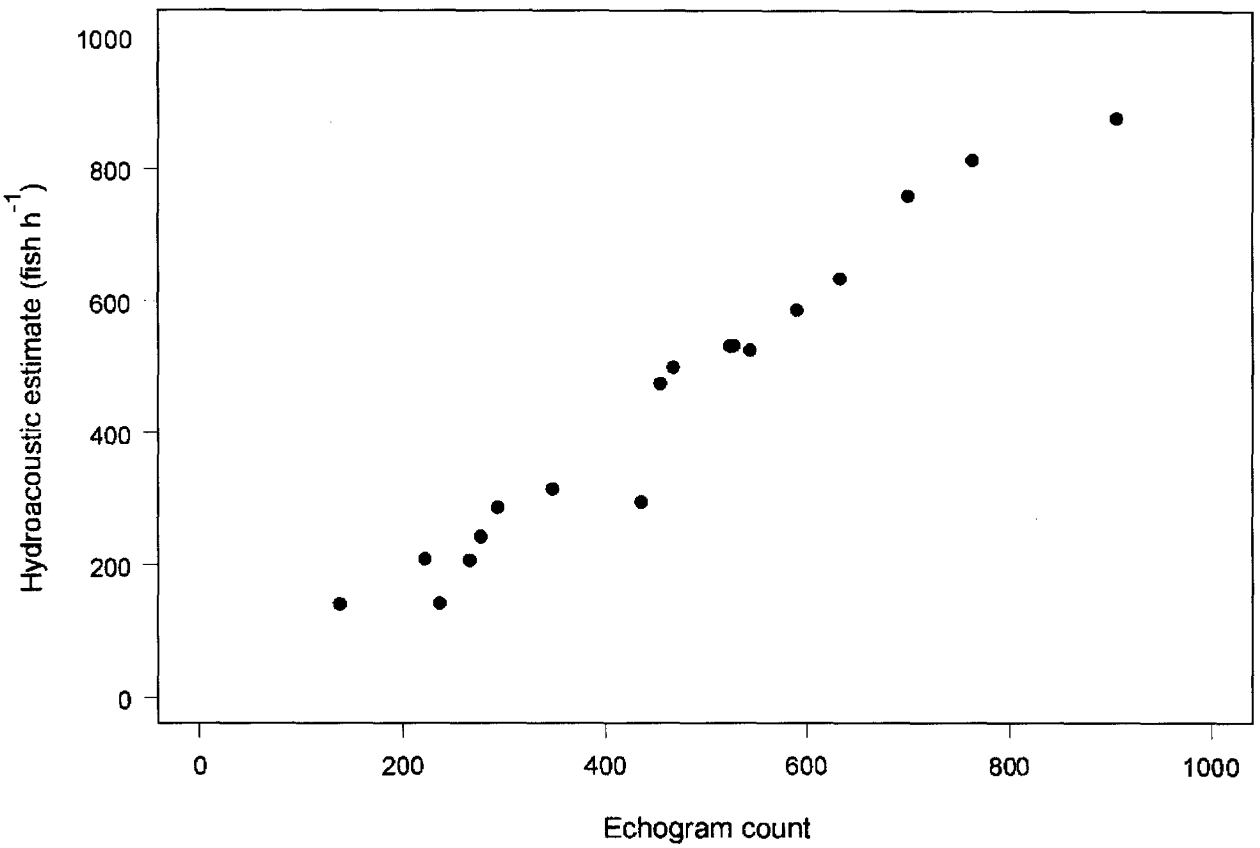

Figure 8. Relationship between echogram trace count and hydroacoustic estimate (generated by the echo processor) for data obtained using the 8° transducer.

4. RESULTS

A total of 52 data sets were collected between September 22 and October 6, 1995; 26 using the 4° × 10° elliptical transducer and 26 with the 8° circular transducer (*table II*). We attempted to ensure that a range of migration rates was observed by each transducer. Both the visual and acoustic counts were converted to an hourly migration rate. The visual count, which we consider to be the actual number of fish migrating over the sample platform, ranged from 535 to 8 510 fish · h^{-1} for the 8° transducer data and from 565 to 8 266 fish · h^{-1} for the 4° × 10° transducer data.

4.1. Comparison of acoustic and visual counts

The 4° × 10° transducer data are less biased for all count rates than are the data from the 8° transducer (*figure 6*). Both transducers demonstrate reduced detection efficiency (lower slope for a straight line fit) as the count rate increases past a threshold of approximately 2 000 fish · h^{-1}.

The acoustic estimate includes counts of fish tracked as moving upstream and those tracked as moving downstream. We knew from visual observation that downstream movement of migrating salmon was extremely rare at this site. We believe that many of the fish tracked as downstream targets result from incidents when more than one fish are in the beam and the tracking algorithm confuses one fish trajectory with another. This hypothesis is strengthened by the observation that, at higher count rates, a larger proportion of the fish were identified as downstream migrants. Thus, the tracking algorithm appears to perform reasonably with respect to the total number of fish estimated; however, the direction of migration becomes more confused as the migration rate (and also the fish density) increases.

Investigation of the observation marked with an arrow in *figure 6*, which has a echo processor estimate of 2 925 fish · h^{-1} and visual estimate of 1 971 fish · h^{-1}, demonstrates the impact of stationary targets on the tracked fish estimate. An echogram of these data shows a persistent target appearing at a range of approximately 7.5 m (*figure 7*). This target was a small, bottom-dwelling resident fish and could be seen milling over the sample platform in the video recording. The automatic tracking algorithm is configured so

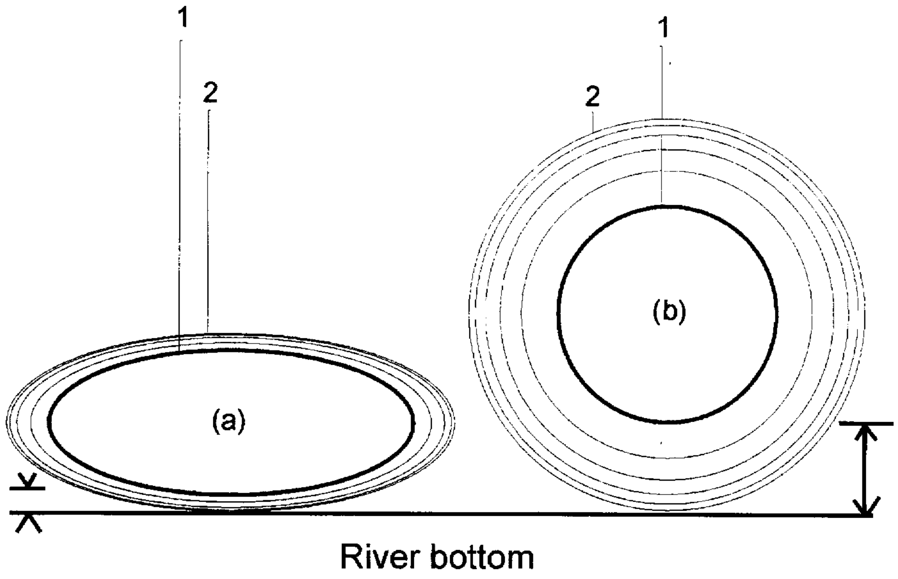

Figure 9. Schematic representation of beam sensitivity over the cross-sectional areas of the 4° × 10° (a) and 8° (b) acoustic beams. The comparative scale is exaggerated for illustrative purposes only and is not intended to conform to actual measures of beam sensitivity. (1) 80 % detection boundary. (2) 0 % detection boundary.

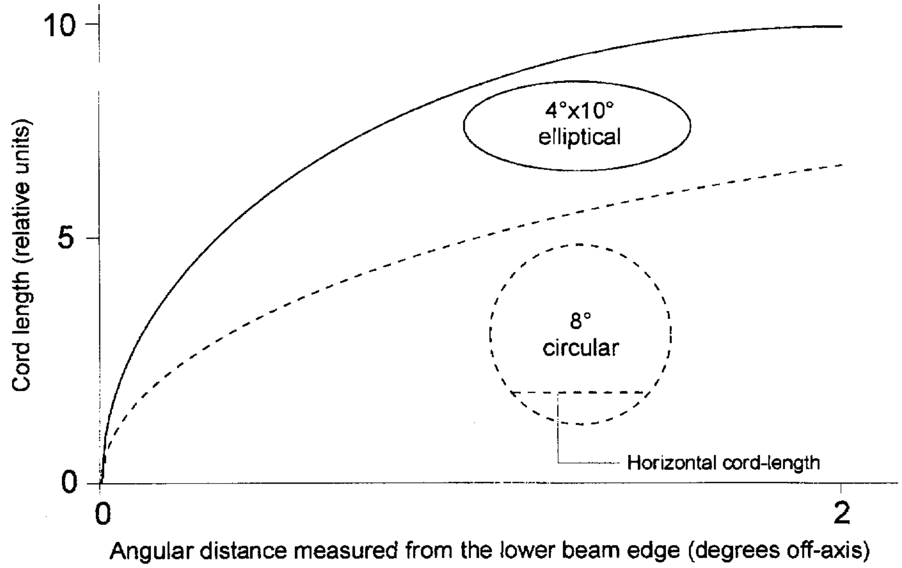

Figure 10. Comparison of horizontal cord length for 4° × 10° and 8° acoustic beams. Cord length for each beam is plotted from the beam edge, upwards for 2 degrees of off-axis beam angle.

that when there is a gap of 7 or more pings between echoes, or when more than 200 echoes are received from the same target, a new target number is assigned. Thus, targets such as this, which remain in the beam or move in and out of the beam, can contribute significantly to the overall count. These types of targets can usually be easily identified in the acoustic data and eliminated from the estimate.

4.2. Comparison with echogram count

To examine the performance of the tracking algorithm, we estimated the number of fish by manually counting fish traces on the echograms (*table III*). We found that, as the fish migration rate increased, it became more difficult to estimate the number visually from the echogram. This situation was expected and

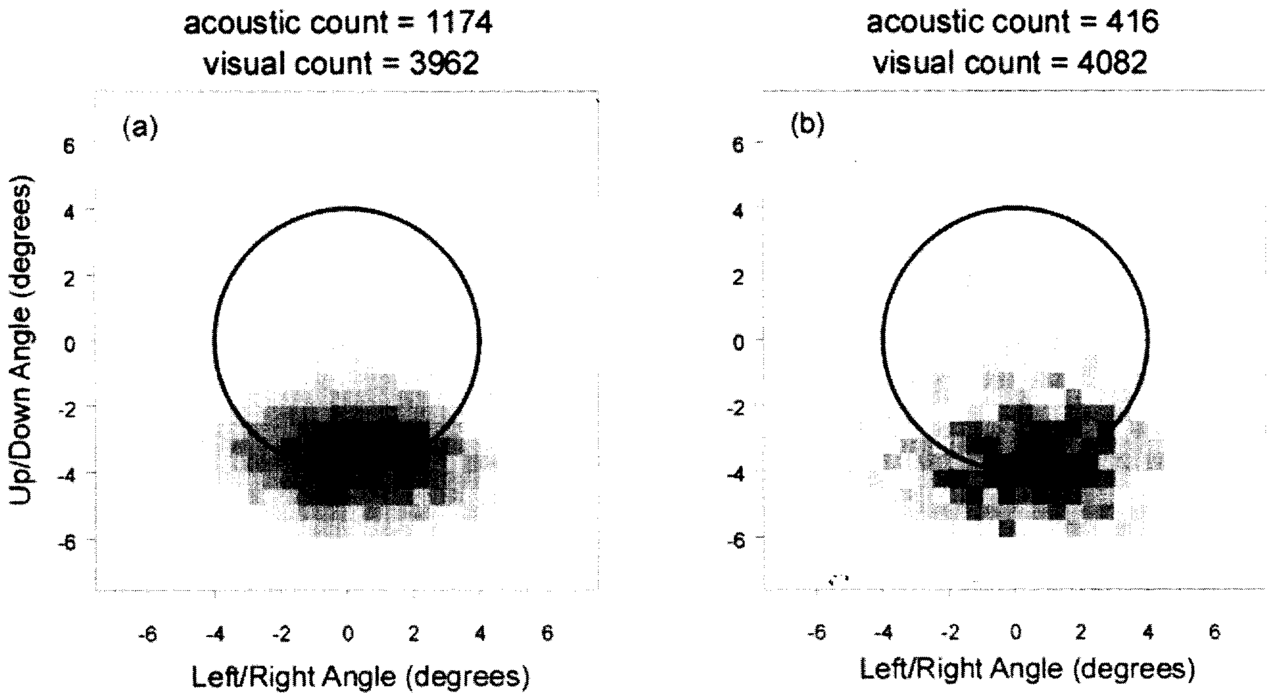

Figure 11. Target densities recorded using the 8° transducer during fish migration rates of approximately 4 000 fish · h^{-1}. Target density is indicated by shades of gray; darker shades indicate higher densities.

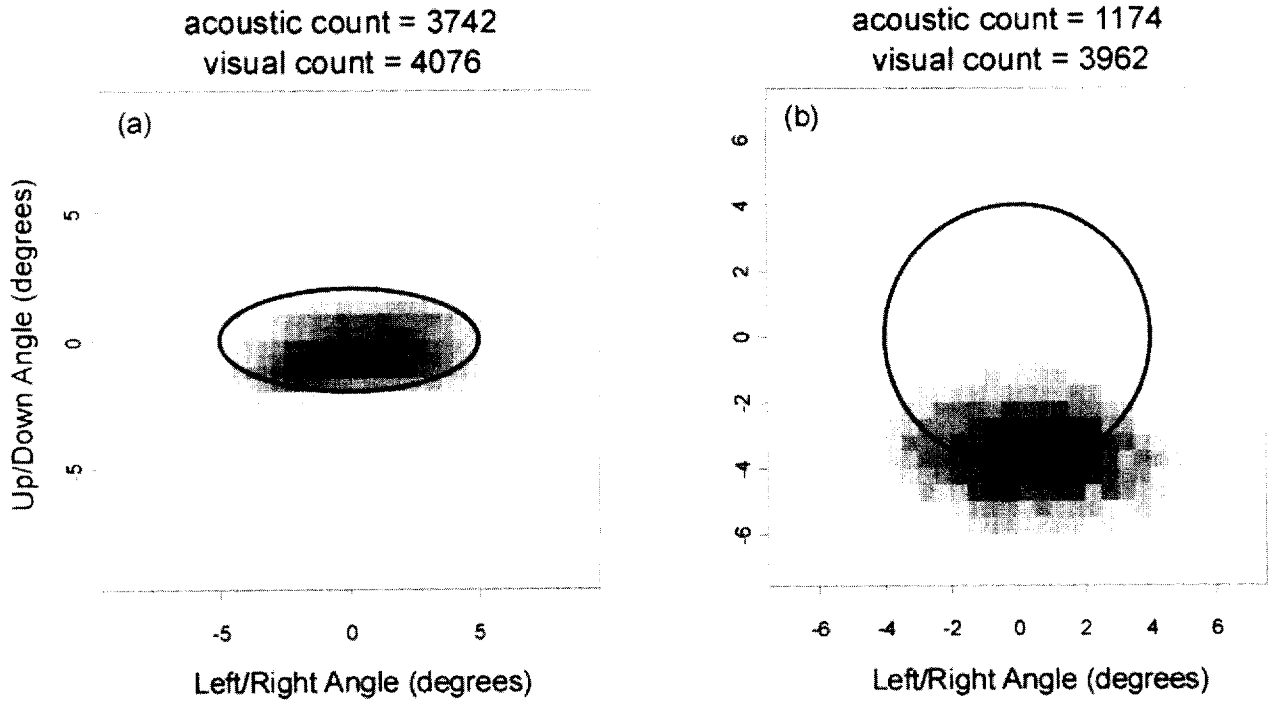

Figure 12. Comparison of echo density during fish passage of approximately 4 000 fish · h^{-1} using a 4° × 10° transducer (a) and an 8° transducer (b). Target density is indicated by shades of grey; darker shades indicate higher densities.

mirrored the performance of the automatic tracking algorithm. To determine if the underestimation of the acoustic counts using the 8° transducer was due to poor performance of the tracking algorithm, we compared the automatic tracking results with counts made manually from the echogram (*figure 8*). These data have a correlation coefficient of 0.98 with a 95 % confidence interval of 0.93-0.99 obtained from a bootstrapping process with 1 000 replications. Thus, the underestimation is not related to poor tracking.

5. DISCUSSION

Several factors affect the performance of a split-beam hydroacoustic system used for enumerating upstream migrating salmon. At Spences Bridge, fish migrate close to the river bottom and near shore, a pattern which is typical of rivers with moderate to high flow rates [2, 13, 16]. The shape and acoustic characteristics of the transducer used has considerable influence on the bias of the acoustic estimates when fish are distributed in this manner. Our data demonstrate that fish detection probability is substantially higher with a 4° × 10° elliptical transducer than with an 8° circular transducer under these circumstances. The probability of detecting a target remains relatively high inside the –3 dB beam contour, but falls off rapidly outside this central area of the beam cross section. The rate at which fish detection falls is similar to the slope of the beam pattern. Therefore, for the vertical (or 4°) axis, the detection probability for the 4° × 10° acoustic beam should drop off to some fixed value in half the distance that would be obtained with the 8° beam. This means that the 8° transducer must be aimed approximately two times higher above the river bottom than the 4° × 10° transducer in order to avoid interference with the substrate (*figure 9*), and thus would miss detecting fish that passed under the beam.

Another factor that results in higher fish detection probability for 4° × 10° transducer is the elliptical shape of the beam. If we assume that fish swim parallel to the river bottom, then their trajectories through the acoustic beam will be parallel to the horizontal beam axis. For a given vertical distance above the bottom of the beam, the horizontal chord length is shorter and increases more slowly for the 8° beam than for the 4° × 10° beam (*figure 10*). Thus, fish swimming at the same speed remain in the 4° × 10° beam longer and the probability of detecting sufficient echoes to track them is increased.

For fish traveling near the river bottom, the result of these two effects is that a much smaller proportion will be tracked with the 8° transducer then with the 4° × 10° transducer. This result can be observed in *figure 11*, which shows fish densities in the 8° beam during periods of relatively high migration rate (≈ 4 000 fish · h^{-1}). In panel (a), a larger proportion of detected echoes falls within the –3 dB beam contour (indicated by the circle) than in panel (b). The ratio of the automatic tracking estimate to visual count is 0.30 and 0.10 for panels (a) and (b), respectively.

Figure 12 demonstrates the effect of beam shape combined with fish distribution. For panel (a), the proportion of detected echoes falling within the –3dB beam contour (indicated by the ellipse) is 0.93 while for panel (b) it is 0.65. The ratio of automatic tracking estimate to visual count is 0.92 and 0.30 for panels (a) and (b) , respectively.

The ability of the tracking algorithm to track individual targets at high echo density also has an affect on the bias of the acoustic estimates. When migration rates were more than 2 000 fish · h^{-1}, the proportion of fish tracked declined for both the 4° × 10° and 8° transducers (*figure 6*). Video footage of these higher passage rates reveal multiple fish passing through the acoustic beam simultaneously. The tracking algorithm is often unable to track targets correctly under these circumstances. By contrast, at lower fish densities the automatic tracking estimates agreed well with manual counts from the echogram for data taken with both transducers. Thus, at low echo densities the bias of the 8° transducer data is not due to poor performance of the tracking algorithm, but rather due to low fish detection probability. At higher echo densities, the data from both transducers is probably affected by tracking problems. Therefore, an echogram trace count can only verify that a tracking algorithm is performing satisfactorily, it cannot be used to verify the true number of migrating fish.

Our observations cover a wide range of fish passage rates from ≈ 400 to 8 000 fish · h^{-1}. Passage rates greater than 2 000 fish · h^{-1} are unusually high for sockeye migration, even in the Fraser River. For most salmon streams, passage rates will be considerably lower than 2 000 fish · h^{-1} [9, 10, 13, 14]. Thus, for the typical case, our results demonstrate that accurate estimates can be readily obtained using the automatic tracking software. The degradation of the estimates at higher passage rates is most likely related to the difficulty of tracking fish at high fish densities [4]. Therefore fish density is probably more relevant to tracker behavior than fish passage rate. Since the fish were only counted for both the acoustic and visual estimates when they were within the bounds of the sample platform (which covered fish within the range 3.35-8.25 m from the transducer), *figure 6* has axes labelled for fish passage rate and fish passage density.

Our results were affected by factors other than the acoustic system we used. Deployment configuration, ping rate, parameters used for fish tracking, migratory behavior, and signal-to-noise ratio will all influence the accuracy and precision of the fish passage estimates. We selected the controllable factors to duplicate the conditions that exist at our operational site on the Fraser River. Different values for these factors might give very different results to those presented here.

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