
**A Split Beam Echosounder
Perspective on Migratory Salmon
in the Fraser River:**

**A Progress Report on the Split-beam
Experiment at Mission, B.C., in 1995**

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December, 1997



**Pacific Salmon Commission
Technical Report No. 8**

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Technical Report No. 8

A Split-Beam Echosounder Perspective on Migratory Salmon in the
Fraser River: A Progress Report on the Split-Beam Experiment at
Mission, B.C., in 1995

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ABSTRACT

This report summarizes first-year (1995) results of a cooperative Pacific Salmon Commission (PSC)/Canada Department of Fisheries and Oceans (DFO) split-beam hydroacoustic study of adult sockeye (*Oncorhynchus nerka*) and pink salmon (*Oncorhynchus gorbuscha*) migratory behaviour in the Fraser River at Mission, British Columbia, Canada. The purpose of the 1995 experiment was to design data collection methods and to gather information for analysis of potential sources of bias in the PSC standard (single-beam) hydroacoustic program conducted at Mission since 1977. The split-beam echosounder system tracked and recorded targets as they moved through the sound beam. Computer processing of these data allowed for analysis of the spatial distribution of fish targets in the water column and the direction and speed of salmon movement by the three-dimensional tracking of echoes from sequential insonifications of targets.

The following aspects of the 1995 split-beam program are presented:

- development of data acquisition methods;
- development of data processing protocols during and after the field season;
- results related to behavioural studies on fish targets during the sockeye and pink salmon migrations.

Fish tracking procedures were developed using the real-time data acquisition software provided with the HTI Model 240 split-beam echosounder system and subsequent off-line tracking software based on an algorithm developed by Y. Xie. A comprehensive filtering system was then applied to tracked targets to extract probable salmon targets while discarding tracks from debris, entrained bubbles and large resident fish. Analysis of fish behaviour centered on a total of 14,360 targets that survived the filtering process.

Preliminary results from the 1995 experiment indicated that most fish targets were in the mid-water portion of the water column during the passage of sockeye salmon in July-August. Fish migration distribution shifted to primarily near-shore, bottom-oriented schools during the pink salmon migration in September, 1995. The vast majority of salmon-size targets were tracked migrating upstream (98.4%) in the July 21-September 6 period. Tracking of individual fish during the pink salmon migration in September was not possible due to a high density of targets in a restricted area of the river. Average fish swimming speed increased over the study period as river discharge decreased. Conclusions relative to the potential sources of bias in the PSC standard hydroacoustic program will not be available until after 1998.

INTRODUCTION

The Pacific Salmon Commission (PSC) uses a downward-looking single-beam echosounder to estimate the passage of migratory sockeye (*Oncorhynchus nerka*) and pink (*Oncorhynchus gorbuscha*) salmon in Fraser River at Mission, B.C. (Woodey 1987). The program, hereafter referred to as the *standard hydroacoustic program*, consists of two components: transect and stationary soundings. These two operational modes are designed to provide data on two aspects of migratory salmon abundance. The first collects information on fish target density across the river; the second acquires statistics on migration speed. The data obtained from the standard program is processed using a duration-in-beam method (Thorne 1988), which leads to an estimate of salmon escapement past the survey site over a 24-hour period. The statistical handling of the data has been refined and improved recently (Banneheka et al. 1995). However, the accuracy of estimates depends on the validity of a number of assumptions. The following of which are the most important:

- all fish swim upstream along trajectories parallel to the river banks;
- the majority of the fish are distributed in the mid-water portion of the water column with few migrating near the river surface where they would not be insonified or near the river bottom where target returns would not be discernible from the bottom echo;
- few fish migrate in shallow water near where no sounding is taken by the survey vessel;
- fish swimming speed is negligible relative to the transecting speed of the survey vessel;
- fish behaviour is not altered by the presence of the survey vessel.

The first four assumptions define fish behaviour scenarios that are ideal for downward fish sounding; the last is related to fish and vessel interaction. Violation of any of these assumptions would result in bias in the estimate, as described in Banneheka et al. (1995). Therefore, it is essential that these assumptions be assessed in the river by independent measurements.

Under a joint agreement between the PSC and Canada Department of Fisheries and Oceans (DFO), a split-beam hydroacoustic experiment was designed and conducted at Mission during the salmon return season in 1995. The primary fish targets were sockeye and pink salmon. This experiment constitutes the first year of a four-year hydroacoustic study. The overall objective of the study is to evaluate the assumptions regarding migratory salmon behaviour that can affect abundance estimates from the standard PSC hydroacoustic program at Mission. However, the 1995 experiment focused on designing a hydroacoustic program at Mission to collect data for the evaluation. We used a split-beam echosounder system for the program to examine the distribution, direction of travel and swimming speed of salmon at the standard transect site. This system is similar to that used at Qualark Creek by DFO since 1993 (Mulligan and Kieser 1995). Operating from a fixed point on the river bank, we monitored migrating salmon without disturbing them. The split-beam echosounder system provides data which allows for the tracking of fish as they swim through the insonified volume. This provides direct measurements of the fish's acoustic size, swimming speed and trajectory through the beam. A narrow beam transducer was driven by the split-beam sounder and controlled by a mechanical rotator which made it possible to gain three dimensional fish distribution data with high resolution. Detailed descriptions of the split-beam system and references to the relevant research can be found in HTI (1993) and HTI (1994).

The purpose of this report is to describe the 1995 study by summarizing methods developed for split-beam data acquisition in the field, and the signal processing schemes developed during

and after the season. These data-collection and analysis protocols will be essential for future split-beam studies at Mission, B.C. In this document, we report findings regarding both sockeye and pink salmon migratory behaviour. The preliminary findings presented in this report do not constitute final answers to questions on the assumptions inherent in the standard hydroacoustic program. Additional studies in 1996-1998 are anticipated to provide comprehensive conclusions regarding potential sources of bias in the standard program.

DATA ACQUISITION METHODS

Study Sites

The 1995 split-beam experiment was conducted in the Fraser River near Mission, B.C. (Figure 1) located 80 kilometres upstream of the river mouth. The study site was approximately 2 km upstream of the railway bridge across the river at Mission. At this point the Fraser River is approximately 450 metres wide and varies in maximum depth with discharge over the salmon migration season from approximately 18 metres in June during the high run-off period to 12-13 metres in September-October at low flow. A tidal effect is present at the study site after the river discharge drops in late summer and fall. The river flow reverses at high tide when the flow is low in fall.

Data Sampling Hardware

The data sampling system consisted of the following hardware units:

- HTI¹ Model 240 split-beam digital echo sounder (DES) (Series Number: 153618);
- two acoustic transducers:
 - a) 4 × 10 degree elliptical beam transducer (Series Number: 306726);
 - b) 8-degree circular beam transducer (Series Number: 039868);
- HTI Model 340 split-beam digital echo processor (DEP);
- HTI Model 660 remote rotator controller;
- PT 25 Dual Axis rotator;
- Underwater positioning sensor which monitors depth, bearing and pitch of the transducer;
- Underwater tripod that held the transducer and positioning sensor in place.

Data Sampling Software

Software used for data acquisition included the following programs:

- HTI Digital Echo Processor (DEP) Software:
The software must be loaded into DES and DEP prior to data acquisition. The software package contains programs performing real-time signal processing, generating echograms, and displaying tracked targets on the screen. Refer to HTI (1994) for detailed descriptions;
- Underwater positioning software:
This software commanded the underwater positioning sensor and recorded data strings for depth, bearing and pitch of the transducer.

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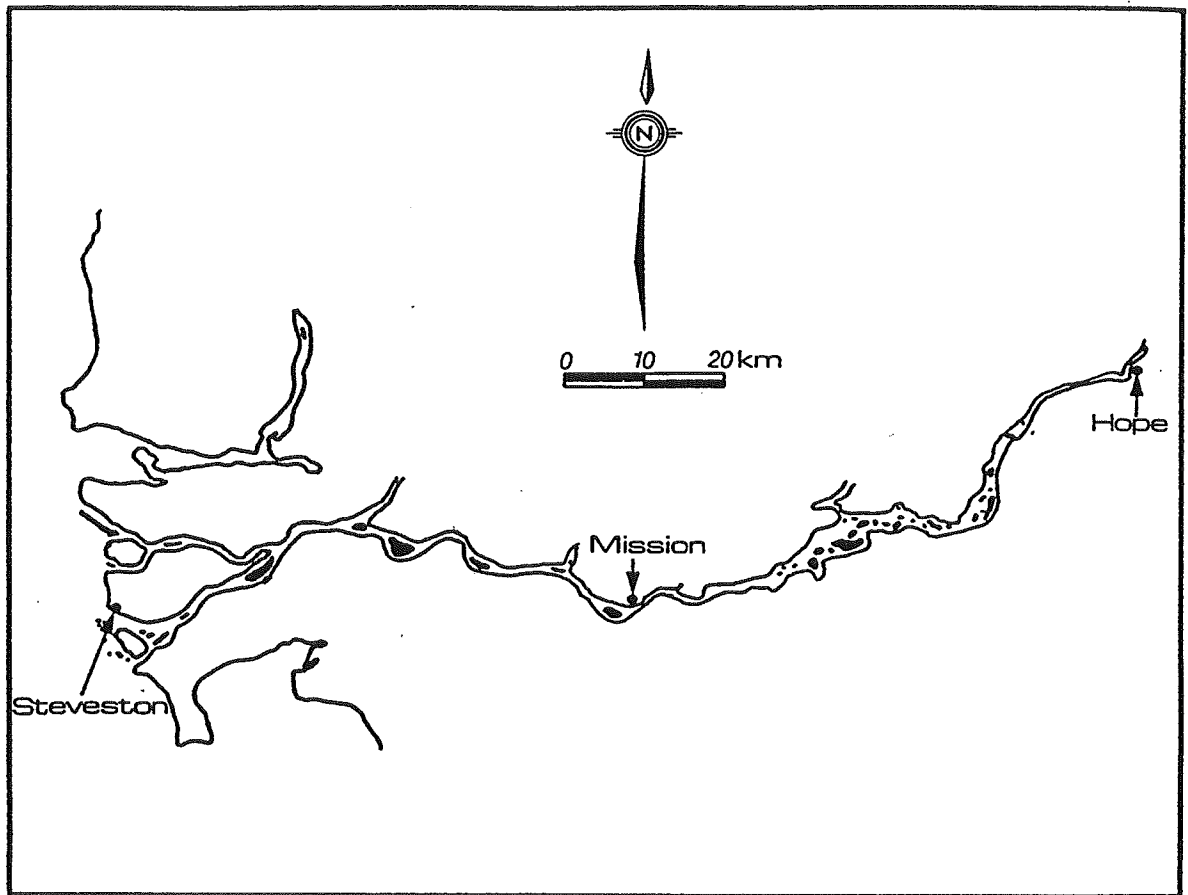


Figure 1. Location of the Mission hydroacoustic experimental site.

Instrument Setup and Configurations

All electronic components of the system including the split-beam sounder, digital echo processor and rotator controller, were set up inside the cabin of a working boat which was tied to a log-boom piling at the study site. A tide gauge attached to the piling permitted monitoring of water level. Using a differential global positioning system (DGPS), the location of the piling was determined to be $49^{\circ}08.175'N$ and $122^{\circ}16.466'W$. This location has since been chosen as a reference point for future hydroacoustic studies at Mission.

Acoustic transducers were mounted on a tripod deployed on the river bottom. The tripod was positioned primarily at two locations: 4 metres offshore and 8 metres inshore of the referenced piling. Transducers were linked to the echosounder via underwater cables. Transducer's aiming was controlled manually through a rotator controller, and monitored with the underwater positioning sensor.

The geometry of an insonified river volume by the split-beam echosounder is shown from both an aerial view and cross-river view in Figure 2. The coordinates of targets were expressed in an orthogonal Cartesian frame: upstream-downstream (X), vertical (Y) and range (Z).

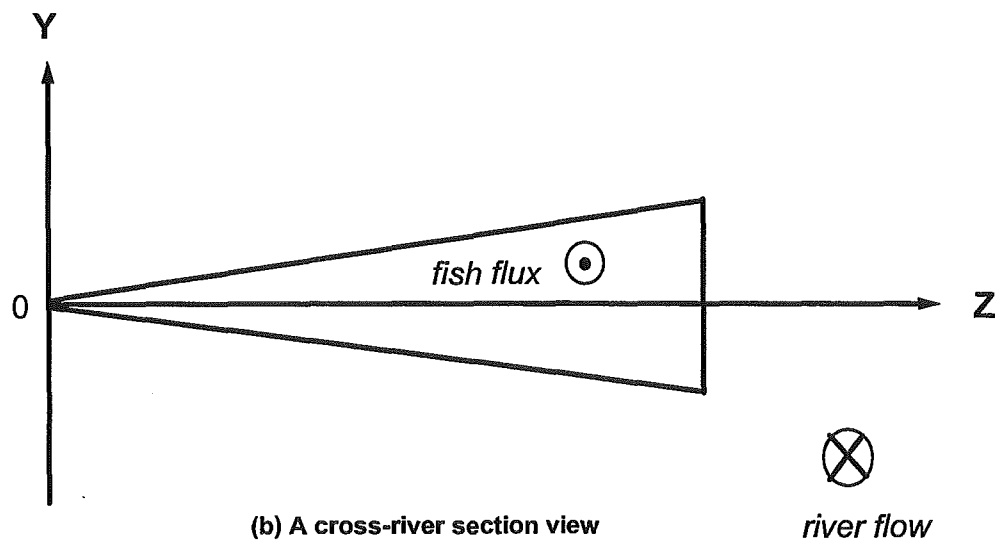
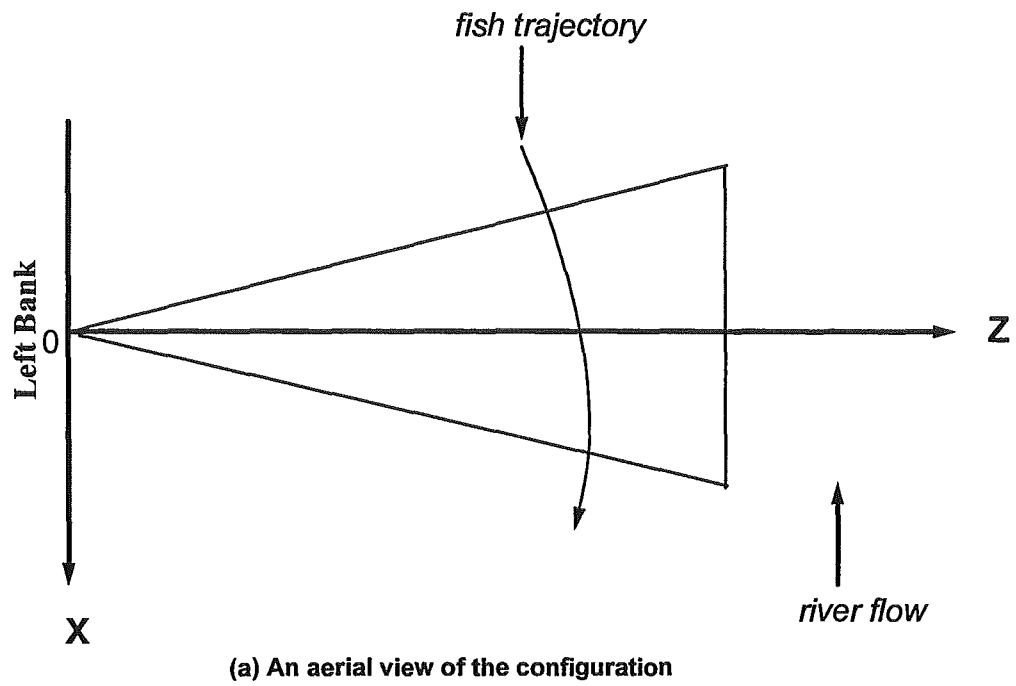


Figure 2. The Cartesian coordinate and the geometry of insonified volume by the 3-dB conical beam of the transducer.

FISH TRACKING WITH A SPLIT-BEAM ECHOSOUNDER

Insonification of Fish

The split-beam echosounder pinpoints an insonified fish by ranging the distance to the fish from the transducer location and by positioning fish locations within the sound beam. As a fish swims through the beam, its locations were tracked by sequential insonifications, and recorded as time series by the sounder. Once these locations are interpreted by a tracking program, they form a three dimensional fish trajectory. Figures 3 and 4 show the *X-Y* and *X-Z* perspectives of two individual fish (likely sockeye) swimming across a 4x10 degree beam. One can easily calculate statistical quantities related to the fish movements from the trajectory data. For example, estimates of the upstream (or downstream) length of the track (*X*), depth variation (*Y*), range variation (*Z*) and duration-in-beam (number of tracked pings) provide information for the calculation of swimming speeds in three dimensions. These statistical results are listed in Table 1 for the two fish identified in Figures 3 and 4.

Table 1. Statistics of two tracked fish shown in Figs. 3 and 4 by the split-beam system.

Fish Track I.D.	X(m):up-stream distance	Y(m): vertical variation	Z(m): range variation	Mean V_x in (m/s)	Mean V_y in (m/s)	Mean V_z in (m/s)	Average TS in dB	#of tracked pings
95	6.6	-0.76	2.25	0.717	-0.082	0.244	-28.29	46
105	4.76	0.28	0.95	0.952	0.056	0.19	-25.41	25

It is apparent from Figures 3 and 4 that fish are better tracked in the middle of the sound beam than near the beam edge: fish track 95 appeared in the middle of the sound beam and returned nearly twice as many echoes as fish track 105 which appeared in the upper edge of the beam.

Fish Tracking Software

In general, tracking means to follow a moving object through space and time. In our split-beam hydroacoustic experiment, fish tracking is accomplished by acquiring echoes from fish and reconstructing trajectories of individual fish from these echoes. Trajectory reconstruction from echoes requires a good knowledge of fish behaviour and performance of the split-beam echosounder system. In short, fish tracking is a sorting of seemingly randomly occurred fish echoes into fish tracks based on a pre-designed tracking model (or tracker). The accuracy of interpreted tracks rests heavily on the tracker which converts echoes into coherent fish trajectories. Normally, the tracker is built into a program that runs either in real time (concurrent with data collection) or after data acquisition. Unless users design their own tracker, they have very little control over the performance of a commercially available tracking software. However, one can always evaluate the quality of fish trajectories output by a specific tracker. For example, we know that the swimming speed of a salmon is limited, and its direction of travel is predominantly upstream. This means, statistically, a reasonable fish track should appear approximately to be a linearly function in space with a standard deviation in upstream direction *X* significantly larger than that in vertical (*Y*) and range (*Z*) directions.

Using this concept, we defined an X/Y aspect ratio, R_{XY} , for an output track as $R_{XY} = \text{Std}(X) / \text{Std}(Y)$. We found that a cutoff value of 4 for R_{XY} , i.e., $R_{XY} \geq 4$ would eliminate most erroneous tracks (a more precise definition² of R_{XY} has been developed for our 1997 split-beam data processing). We used this cutoff value of R_{XY} as one of the criteria for evaluating tracks output from our own fish trackers. An example of an acceptable tracked targets is seen in fish track 95 ($R_{XY} = 8$) in Figure 5 while an unacceptable fish track 3 ($R_{XY} = 1$) would be rejected for further analysis. An acceptable track shows minor fluctuations from the best-fit linear trajectory. Poor tracks contain a large number of points that deviate significantly from the linear trajectory. The same analysis could be extended to three dimensions.

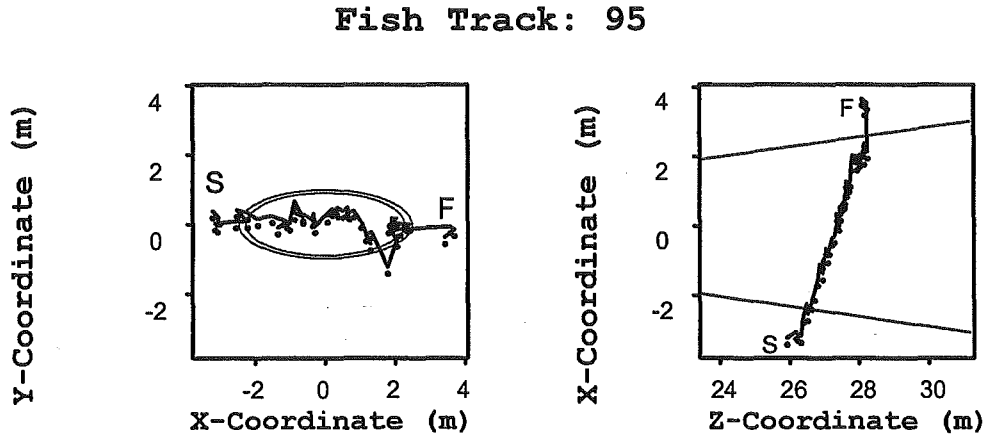


Figure 3. Projections of fish track 95 onto X-Y and X-Z planes with letters S and F indicating the Starting and Final points for the insonified track. The two ellipses are the 3-dB beam pattern projections on the X-Y plane at two ranges where the fish enters and exits the 3-dB beam cone as shown on X-Z plane.

² The latest definition of R_{XY} involved 3 steps:

- Step 1: find a linear-fitting function for the track;
- Step 2: rotate the X-Y frame until X axis is parallel to the slope of the linear-fitting function;
- Step 3: calculate standard derivations for the track on the rotated X-Y frame.

Fish Track: 105

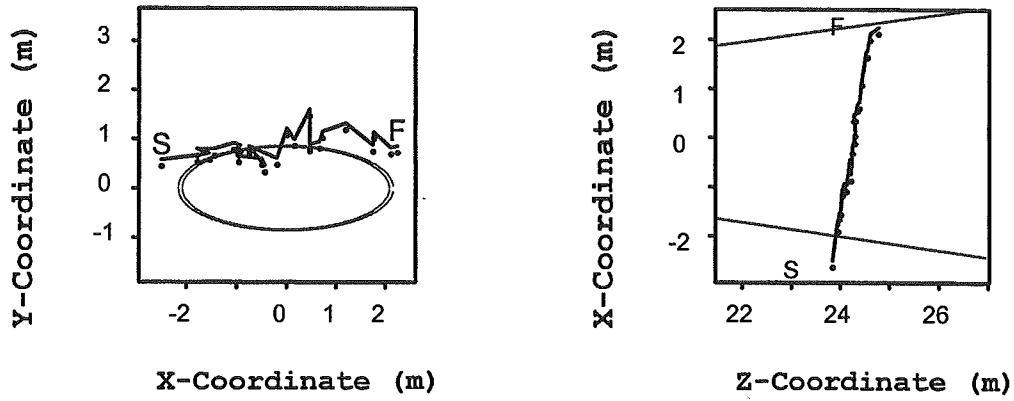


Figure 4. Projections of fish track 105 onto X-Y and X-Z planes.

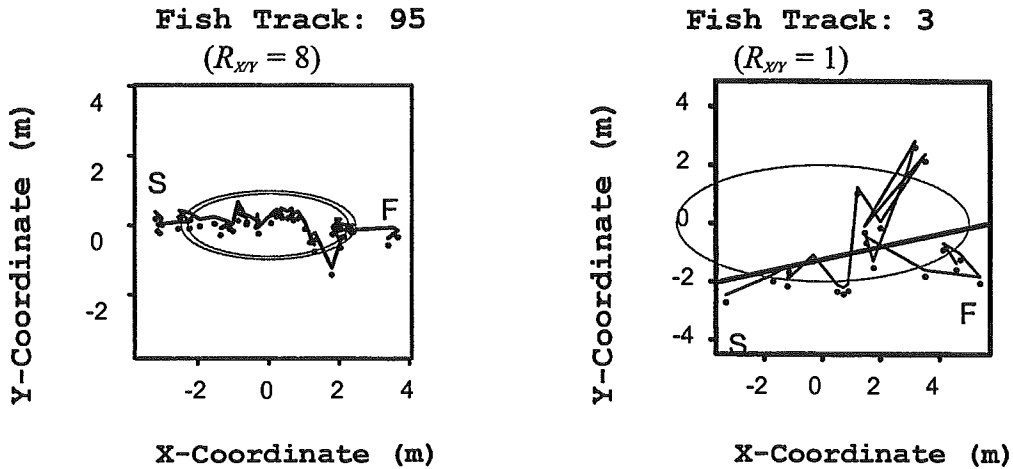


Figure 5. Examples of accepted fish track ($R_{XY} = 8$) on the left graph, and rejected fish track ($R_{XY} = 1$) on the right graph. The straight line is the best-fit through the points.

Real-Time Fish Tracker

A real-time HTI tracker was originally the only fish tracking software available for data processing during the split-beam experiment. The software was built into the digital echo processor of the echosounder system. The tracker examined fish echoes and output them as fish trajectories. The performance of this tracker was sensitive to adjustable parameter inputs for the tracking algorithm adopted in the software. Lacking information on the design of this tracking algorithm, we had chosen an existing set of parameters for the HTI tracker to handle fish echoes acquired at Mission. This set of parameters had worked well at Qualark Creek where the fish passage is at short range. However, the riverine environment at Mission presented unique problems for fish tracking. Fish were distributed over a much larger volume of the river. Therefore, the parameters used at Qualark were not suitable for Mission. A new set of parameters was arrived at through experimentation after the season. This led to much improved but still unsatisfied performance of the HTI tracker on Mission data. The HTI tracker tended to break up long tracks into smaller segments for fish tracks detected at ranges greater than 30 metres, which could result in over-counting of migratory fish. Since the real-time tracker competed with data logging process over CPU time, it could also cause lock-ups of the echosounder system during medium-high or high density periods, thus interrupting data acquisition.

Off-Line Fish Tracker

In order to resolve fish tracks at variable ranges and densities, an off-line fish tracking algorithm was developed to process the raw echo data obtained with the split-beam echosounder. The algorithm was implemented in a program using C language which could be executed on a microcomputer. The tracker built fish tracks by post-processing the raw echo data based on range-dependent tracking criteria and showed remarkably good tracking performances for fish targets at larger ranges at Mission.

The off-line tracker was chosen for post-season data processing due to its satisfactory tracking performance, flexibility, ease of use and, most importantly, our understanding of its algorithm. A detailed description of the tracker's algorithm and fish-tracking criteria is in preparation.

SPLIT-BEAM DATA PROCESSING: *TRACE-COUNTING*

In this section, we present a data processing protocol designed to handle raw echoes obtained with the split-beam system. A flow-chart (Figure 6) shows the signal processing procedure that recovers fish trajectories from raw echoes: a *trace-counting* technique for migratory fish. Such a technique is applicable for lower fish densities. We will focus our discussion on data processing that leads to trace-counting of fish. If fish density becomes very high, then a narrow beam transducer should be employed for fish sounding. This will minimize the effect of multiple reflection of echoes among adjacent fish so that trace-counting remains feasible. It seems that a 4x10 degree transducer handled sockeye data well at densities seen in the 1995 season. However, a narrower sound beam is evidently necessary for collecting highly clustered pink salmon data such as that seen in 1995.

The following sections describe the main processors used in the trace-counting procedure.

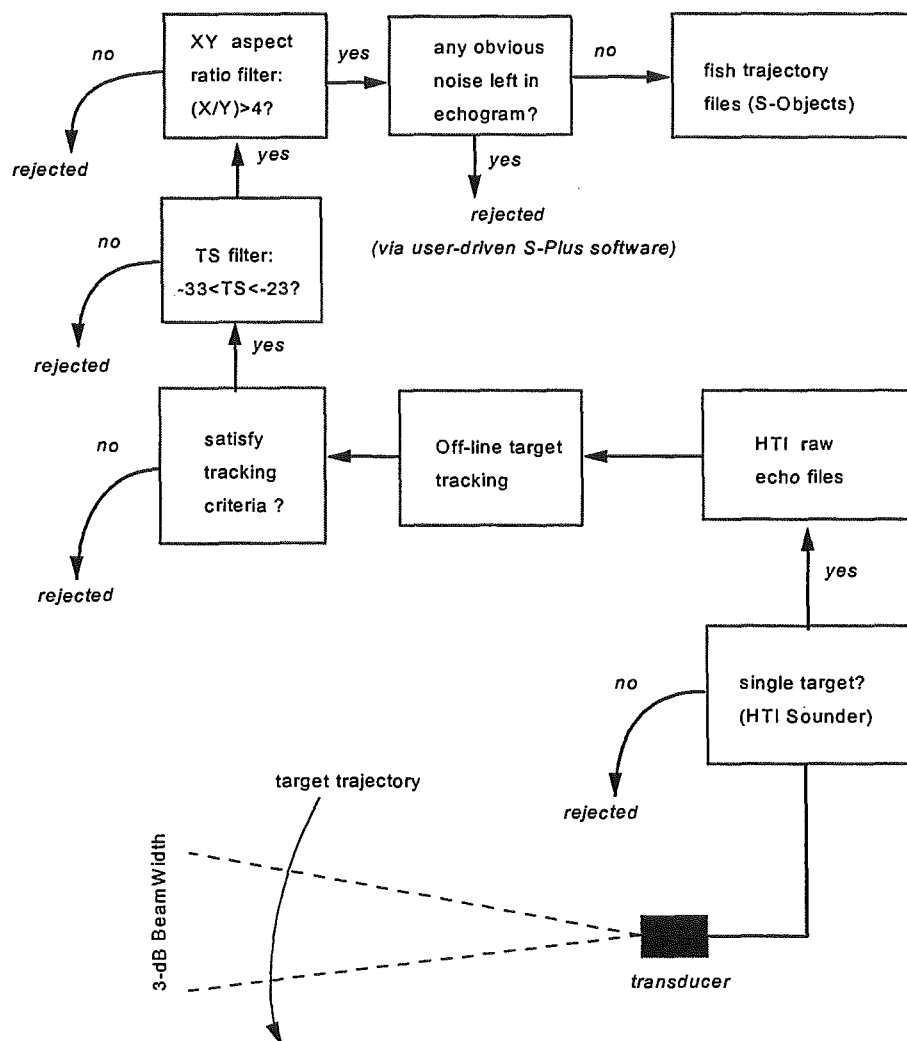


Figure 6. Flow-chart showing signal processing procedures designed for the split-beam experiment on fish tracking.

Single Target Criterion

The HTI split-beam echosounder is designed to record echoes from single targets only. This is accomplished by comparing the pulse width of returned echoes with that of transmitted pulses. If the backscattering signals are due to a single fish in the far-field, it is likely that the corresponding echoes would retain pulse widths comparable to the transmitted pulse widths. As a result, these echoes will be registered by the sounder. The single target criterion rejects echoes from high density fish groups because sound pulses reflected from closely spaced fish tend to have pulse widths that are significantly longer than the transmitted pulses. In addition to the single target criterion, the HTI echosounder also imposes a number of other conditions to filter the echo signals. For example, the signal level of a raw echo must exceed a preset voltage threshold to be accepted by the digital echo processor (DEP). For detailed descriptions of these criteria, refer to HTI (1994).

Off-Line Sorting of Fish Echoes into Fish Tracks

Individual echoes that satisfy the single-target criteria are processed by HTI's *Digital Echo Processor* to obtain information on target characteristics including location and target strength. This information is then saved in an ASCII file for further processing. In our case, we entered these raw echo files into the off-line tracker for trajectory construction. The tracker was set up on a PC in such a manner that it could batch process the raw echo files, therefore automating the tracking process. The output target traces from the tracker were then further filtered to extract fish tracks using the following filtering processes.

Extracting Salmon Targets Based on Acoustic Size

The Fraser River at Mission carries debris of various kinds: from wood chips to submerged floating logs. These objects were present in the river as false targets for acoustic fish sounding. Another interfering factor was the frequent passage of tug-boats on the river which generated bubble plumes that served as strong backscattering targets for the split-beam echosounder. There was also a biological factor interfering with our acoustic monitoring of sockeye and pink salmon at Mission. While these two primary salmon species use the Fraser River to reach their spawning grounds, other species such as white sturgeon (*Acipenser transmontanus*), reside in the river, and appear in the sound beam from time to time causing false-counting. Debris, bubbles and resident fish are false targets and must be removed from output tracks. The removal of these targets were accomplished by three major processors: the target strength (TS) filter, the X-Y trajectory filter and the user-driven noise remover. The first two processors were automated as batch-processing jobs on a PC and they required no user interaction; the last processor required user interaction with the data via data processing software. The main functions of these processors are described in the following sections.

Love (1977) found a relationship between fish length and its target strength, which made it possible to relate measured acoustic target strength to fish-size. Based on this relationship, we designed a target strength (TS) filter to eliminate obvious non-salmon targets by comparing their acoustic sizes with the range of salmon target strengths. A TS range of -33 dB to -23 dB was used for sockeye salmon based on their track-averaged TS values. Tracks showing averaged TS values outside this range would be rejected by the filter. The TS filter was effective in removing tracks of very small or very large targets such as bubbles, small fish or submerged logs and large fish such as sturgeon.

Extracting Salmon Targets Based on Track Geometry

The off-line tracker performed well at recognizing salmon trajectories from a series of echoes due to a single fish, but it failed at times when the echoes were from a school of fish. Trajectories for this case often showed large fluctuations in X-Y plane. Another factor responsible for poor tracking performance was the occasional tracking of stationary targets. These situations could result in confused fish trajectories such as fish track 3 in Figure 5. Since fish counts with the split-beam system was not required, we simply discarded these poor tracks. The rejection was accomplished by using a XY-trajectory filter which calculated the standard deviations of the X and Y coordinates of individual fish tracks. The ratio of standard deviation of X coordinates over that of Y provided a measure of X/Y aspect ratio (R_{xy}) for the corresponding track. Tracks with R_{xy} value less than 4 were rejected. We found that the filter was effective in removing poor tracks, but occasionally, it also removed reasonable tracks especially if the threshold for R_{xy} was set too high.

Removal of Non-Salmon Tracks via User-Driven Software

After target strength and trajectory filtering, we normally obtained a very clean target data file with a few noisy tracks still present in the data file. These non-fish tracks were then removed by interactive software. The routines developed by N. Olsen (1995) for the DFO Qualark Split-Beam Program proved to be effective in visual examination of fish tracks obtained with the split-beam system. These routines were created under the S-Plus environment (Statistical Sciences, 1995) allowing for interactive data manipulation on the computer screen. Tracks that appeared to be non-salmon targets could be manually removed from the echogram.

Examples Of Split-Beam Data Processing Results

To illustrate the data-processing scheme described above, we present three echograms (Figures 7, 8 and 9) of sequentially processed target tracks. Echoes displayed by these echograms were collected over a 6-minute interval of moderate sockeye density using a 4x10-degree transducer. Raw data had been processed with the filters outlined above (Figure 6). The data contained echoes from migratory salmon and also a stationary target located at about 65-metre range.

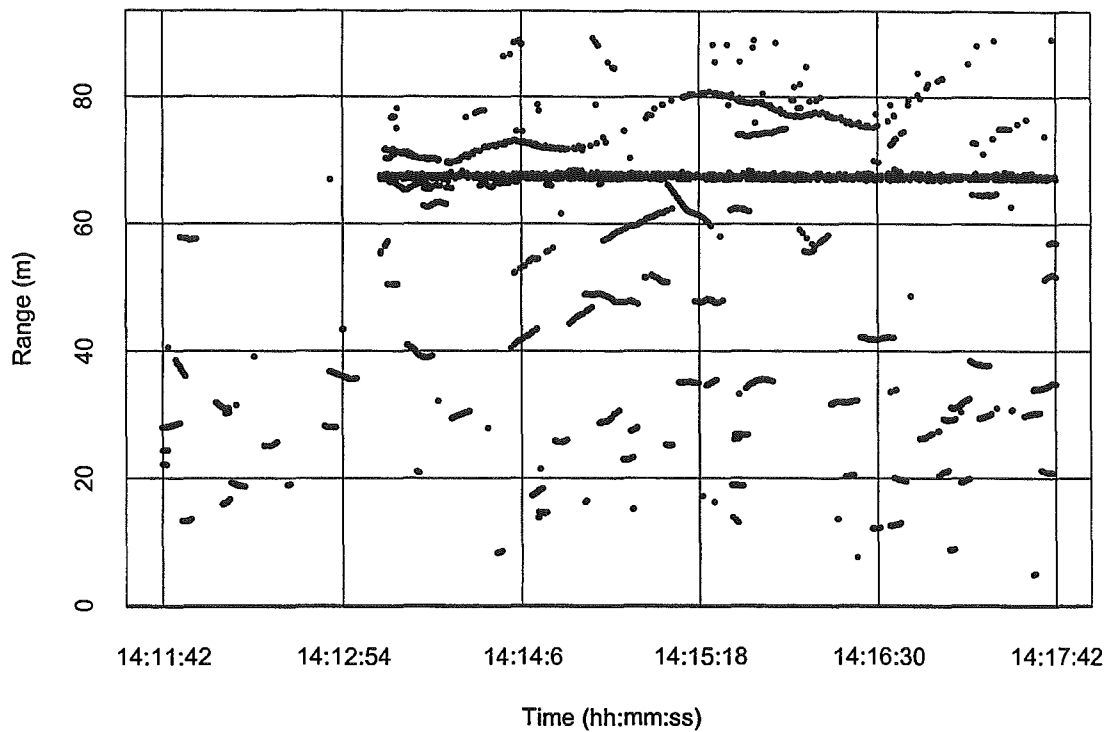


Figure 7. Raw echoes acquired by the HTI split-beam sonar with a 4x10- degree transducer. Fish targets are believed to be dominated by sockeye salmon.

Figure 7 shows the raw echoes acquired with the HTI split-beam system, i.e., all the echoes have passed criteria set up by the HTI sonar. These echoes have not been sorted out as fish tracks at this stage though some of them appear to be coherent tracks. It is apparent from this echogram that there is a stationary target at 65-metre range. Most of the echoes from this target have been accepted by the HTI sonar. The raw data file shown in Figure 7 was processed with the off-line tracker to yield fish trajectories. These trajectories were then filtered through a mean target strength range from -33 dB to -23 dB. The resulting fish tracks are shown in Figure 8. A comparison between Figures 7 and 8 confirms that the off-line tracker and TS filter have eliminated the majority of the noisy tracks from the raw echo data. However, the stationary target still leaves a long trace in the tracked data. A detailed examination of this target shows that the projected trajectories of these tracks onto the X-Y plane are quite random resulting in X/Y aspect ratios close to 1:1. Therefore, we can use the trajectory filter to remove these echoes. A cleaned echogram based on the filtering of tracks with X/Y aspect ratios ≥ 4 is shown in Figure 9. Comparing this echogram with that in Figure 8, we see that the stationary tracks are completely removed. Also removed are individual noisy tracks between time marks of 14:12:54 and 14:14:60 at range of approximately 62 metres. At this stage, it does not seem necessary to use the interactive software to further clean the echogram: the filters have adequately cleaned this data set.

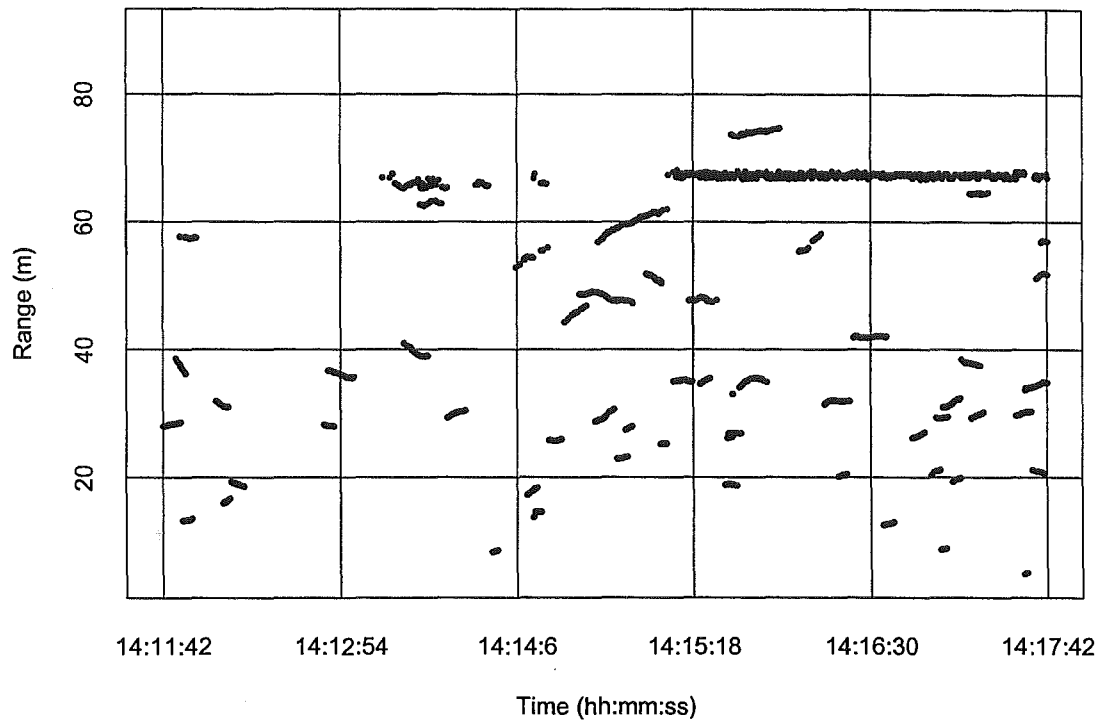


Figure 8. Fish tracks identified by the off-line tracker from the raw echoes shown in Figure 7. Trajectories are filtered with a TS filter with a passing band from -33dB to -23 dB.

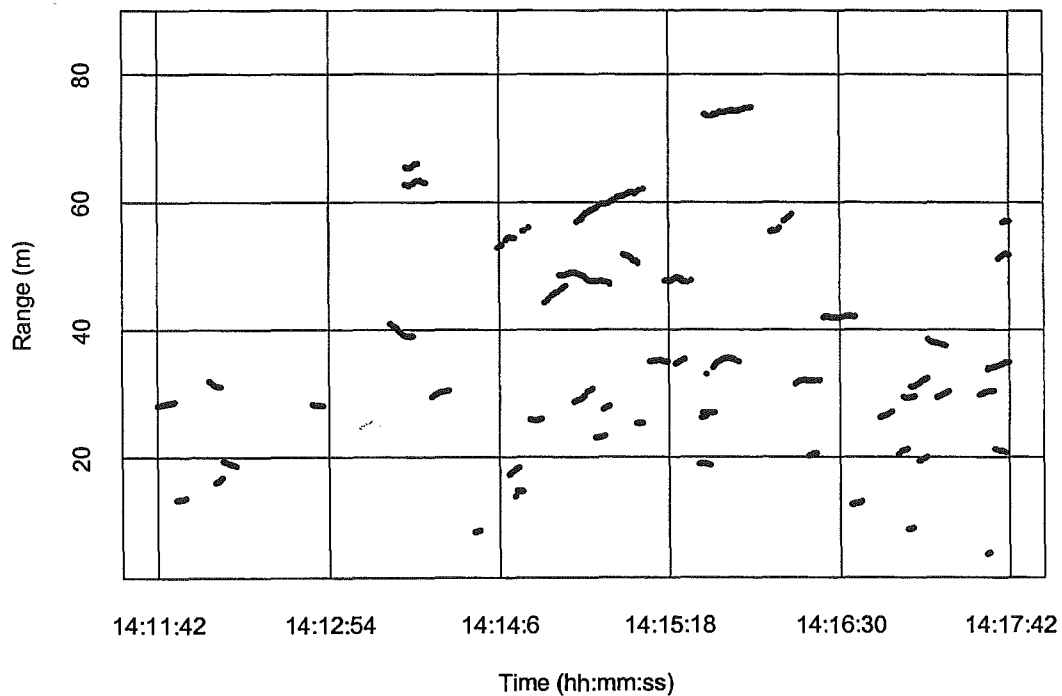


Figure 9. Fish tracks further filtered by an X-Y trajectory filter with a cutoff of X/Y aspect ratio ≥ 4 .

The above example demonstrates the effectiveness of our data-processing scheme in achieving reasonable fish tracks from the raw echoes. A few reasonable traces in the raw echogram (Figure 7) may have been removed during the process; however, we succeed in eliminating most of false tracks so that our final fish track data are reliable.

RESULTS

Results of the 1995 split-beam echosounder experiment on migratory salmon behaviour are divided into the time period that sockeye predominated in the migration (July 21- Sept. 6) and later, when pink salmon predominated (mid-September). Raw echoes have been processed via the signal processing protocol described above to obtain daily data on individual fish tracks. Most data were collected during daylight hours between 0800-1700 with two overnight data sets in the second half of September.

Sockeye Salmon Migration Period

Migration Speed

We were able to estimate direction of travel and swimming speed from data on individual fish trajectories. Our first goal was to determine if the upstream migration speed varied over the season. To achieve this, we processed more than 100 raw echo files acquired with the HTI split-beam echosounder from July 21 to September 6. Fish tracks during this period of time were detected primarily from sockeye salmon although minor numbers of chinook and pink salmon might have also been detected. The mean speed of travel was calculated for the tracked targets during observational time periods varying from 15 to 60 minutes. These data were plotted against day of year (Figure 10) along with discharge measured at Hope, B.C. (Figure 1) and water level readings at Mission. The clustered data points of the mean swimming speed were caused by the discontinuous data logging mode implemented in the field program for the month of August (6-8 hours of data logging per day). The data show the following features of migrating sockeye:

- upstream fish migration speed increased from 0.55-0.7 m/s at the beginning of August to approximately 0.7-0.9 m/s by the end of August. Fitting of swimming speed data to time resulted in a simple linear relationship between the migration speed (y) and Day of Year (x):

$$y = 0.00542 \cdot x - 0.508 \quad (m/s)$$

which yielded a correlation coefficient of 0.61 and a standard deviation of 0.08 m/s.

- the increase in migration speed coincided with the decrease in river discharge (or flow). Presumably, river velocity decreased with the drop in discharge over the summer, thus allowing a faster migration speed relative to shore. Direct measurements of flow speed were, however, not made.

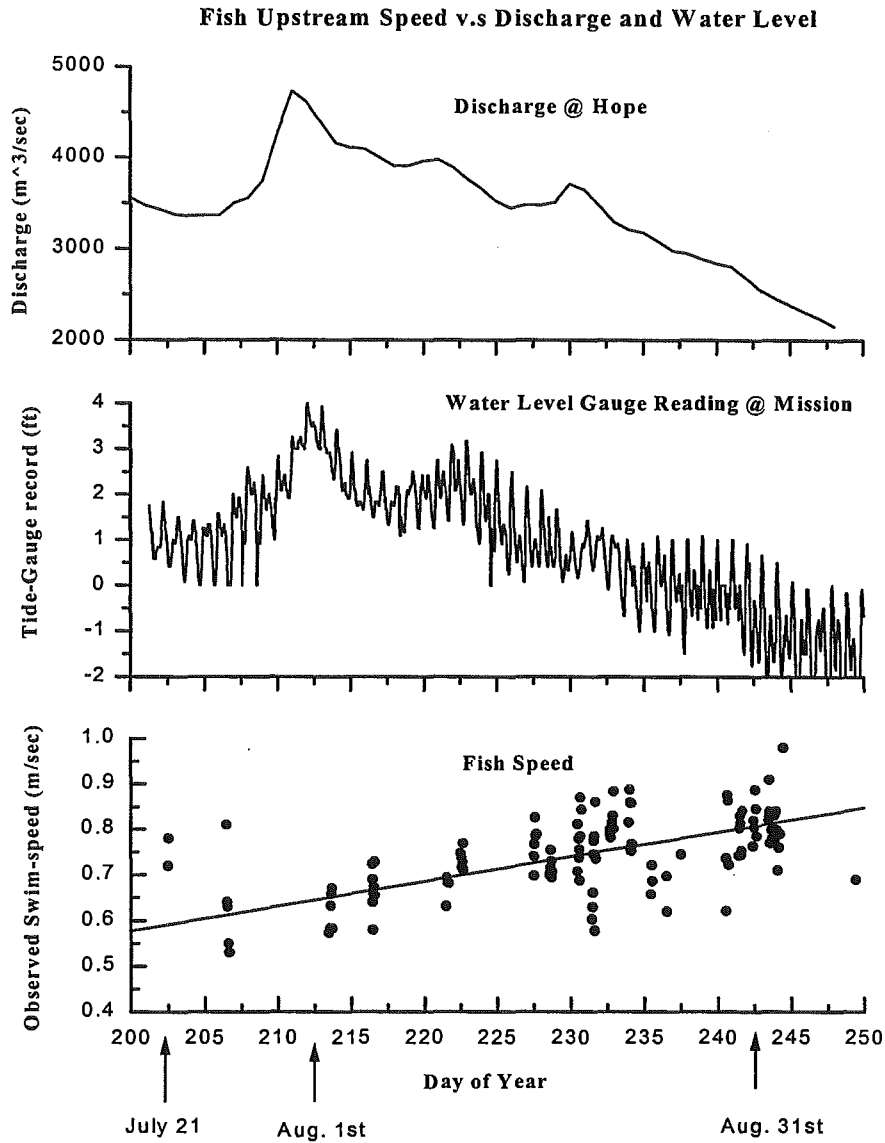


Figure 10. Fish upstream swimming speed (bottom) observed July 21-September 6, 1995, compared to river discharge at Hope (top) and river level at Mission (middle). Migration speed was related to time (day of year) by $y = 0.00542 \cdot x - 0.508$ (m/s).

We also examined the distribution of fish swimming speed along the 3 orthogonal directions, namely up/downstream (X), vertical (Y) and cross-river (Z) axes. Histograms of these three velocity components (Figure 11) were based on 180 individual fish tracks observed on August 31. The data revealed that:

- most fish moved upstream ($X > 0$) with a significant non-zero mean speed of 0.72 m/s;
- both the vertical (Y) and cross-river (Z) components were negligible: the mean vertical and cross-river components were 0.054 m/sec and 0.029 m/sec, respectively;
- fish show smaller fluctuations of swimming speed from the mean speed in vertical direction than in cross-river direction: 0.072 m/sec vs. 0.213 m/sec;
- very few tracked targets were observed moving downstream (negative values of X-component). This implies an evident upstream swimming pattern for salmon.

Migration Direction

We can also transform the statistics of swimming velocity into that of migration angles with respect to the river bank. Since observed fish trajectories were referenced to an X-Y-Z coordinate frame originating from the transducer with the Z-axis being perpendicular to the river flow, we were able to calculate the migration angles for individual fish. We can use either the raw trajectory data or linear functions obtained from trajectory fitting for swimming angle calculation. Because functions derived from linear fitting algorithms showed smoother tracks than the raw track data, these linear functions were chosen for estimating swimming angles for individual fish tracks. The histogram of swimming angles in Figure 12 was based on 3038 well-tracked salmon tracks, which show a mean migration angle of 1.61 degrees (a zero-degree angle corresponds to a migration direction parallel to the river bank). Thus, most fish migrated upstream and they did so on average with linear trajectories parallel to the river banks. This conclusion is consistent with the velocity histograms in Figure 11.

Number of Upstream vs. Downstream Swimming Fish

Between July 21 and September 6, the split-beam system observed a total of 14,135 well-tracked upstream fish and only 225 downstream targets. Because of the discontinuous data-logging mode, we present these numbers as a function of individual observations in Figure 13 rather than time. The bottom graph in Figure 13 provides the ratio of number of downstream fish to upstream fish for each observation. It is apparent that the high ratios of downstream targets (up to 35%) occurred only at times when the total observed number of fish was low while for most occasions the ratio was negligible. The higher fraction of downstream targets when upstream abundance was low suggests that these downstream targets were primarily drifting debris or resident fish. The overall percentage of downstream targets was 1.6% of the total tracked targets.

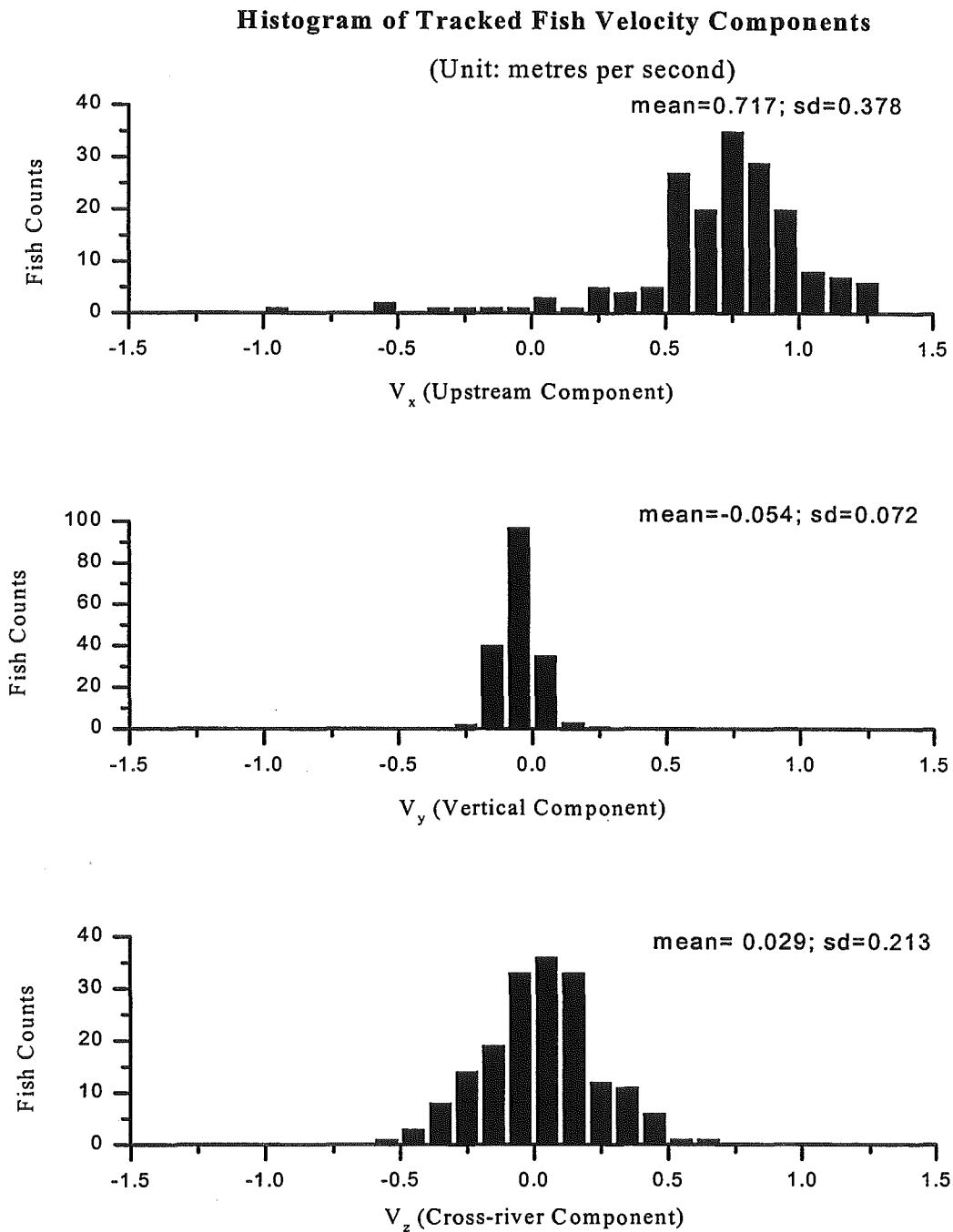


Figure 11. Histograms of X, Y and Z components of fish swimming velocity for August 31, 1995. The data were based on 180 individual fish identified by the split-beam system and signal processing software.

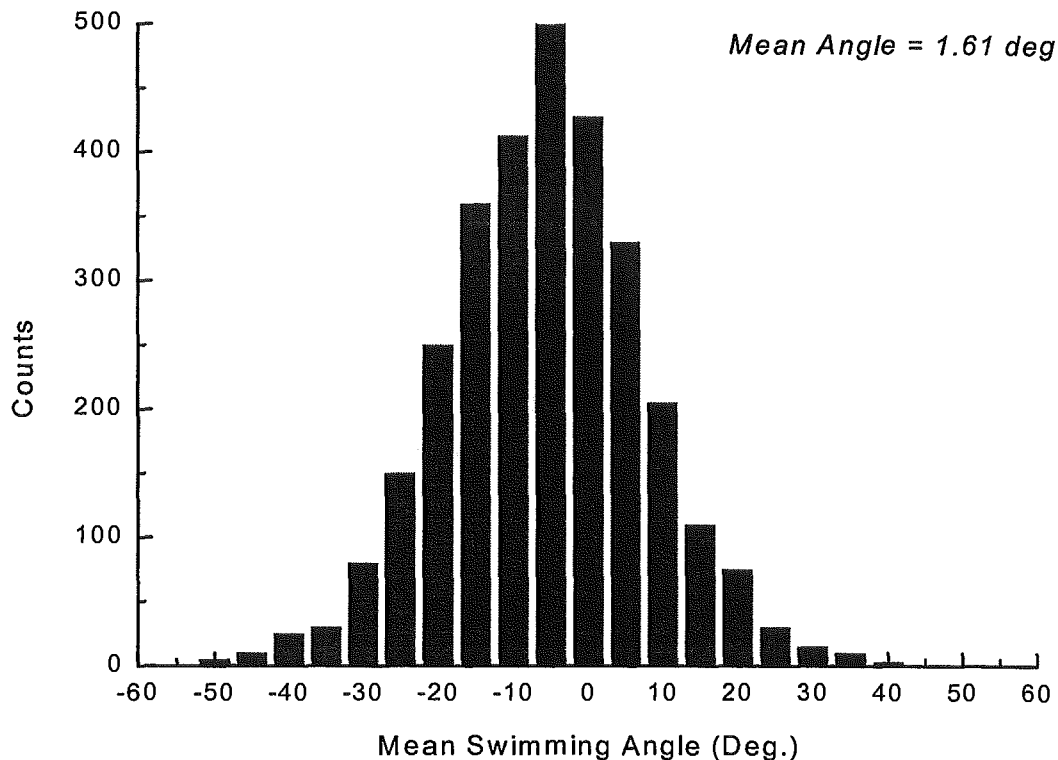


Figure 12. Histogram of fish swimming trajectory with respect to river bank (an angle of zero degrees corresponds to a swimming angle parallel to the shore). The histogram results are based on 3,038 well-tracked fish.

Spatial Distributions

One of the objectives of the split-beam project is to investigate the vertical and horizontal distribution of fish using the tracked target data. With a 4x10-degree transducer, we acquired 4 hours of split-beam data at 4 separate aimings on August 1 (1-hour soundings for each aiming). The cumulative fish distribution in the Y-Z plane (the river cross section) over these 1-hour soundings was estimated by calculating the mean Y- and Z-coordinates over the individual fish tracks. Figure 14 consists of two graphs displaying the cumulative fish distribution in the Y-Z plane. The top graph is a density plot of the distribution based on number of targets observed on 0.25m by 0.25m grids. Darker grays correspond to higher fish cumulative density. The bottom graph is a scatter plot displaying the cumulative fish locations on the Y-Z plane. These two plots indicated that sockeye salmon were relatively uniformly distributed vertically in the water column but that they tended to concentrate in the first 60 metres from the left bank shore. However, this latter observation may be an artifact of the decrease in target detection probability with increased range and the shadowing of the lowest-aim sounding by the uneven bottom. An improved design of aiming scheme and detection probability model for the transducer will be

needed to obtain the true fish distributions for future hydroacoustic experiments. Also, data sets covering much longer time frames need to be looked at as patterns may emerge over the whole season which may not be detected over a 24-hour time scale. Nevertheless, our data indicated no overwhelming evidence of fish concentrations near the surface or river bottom.

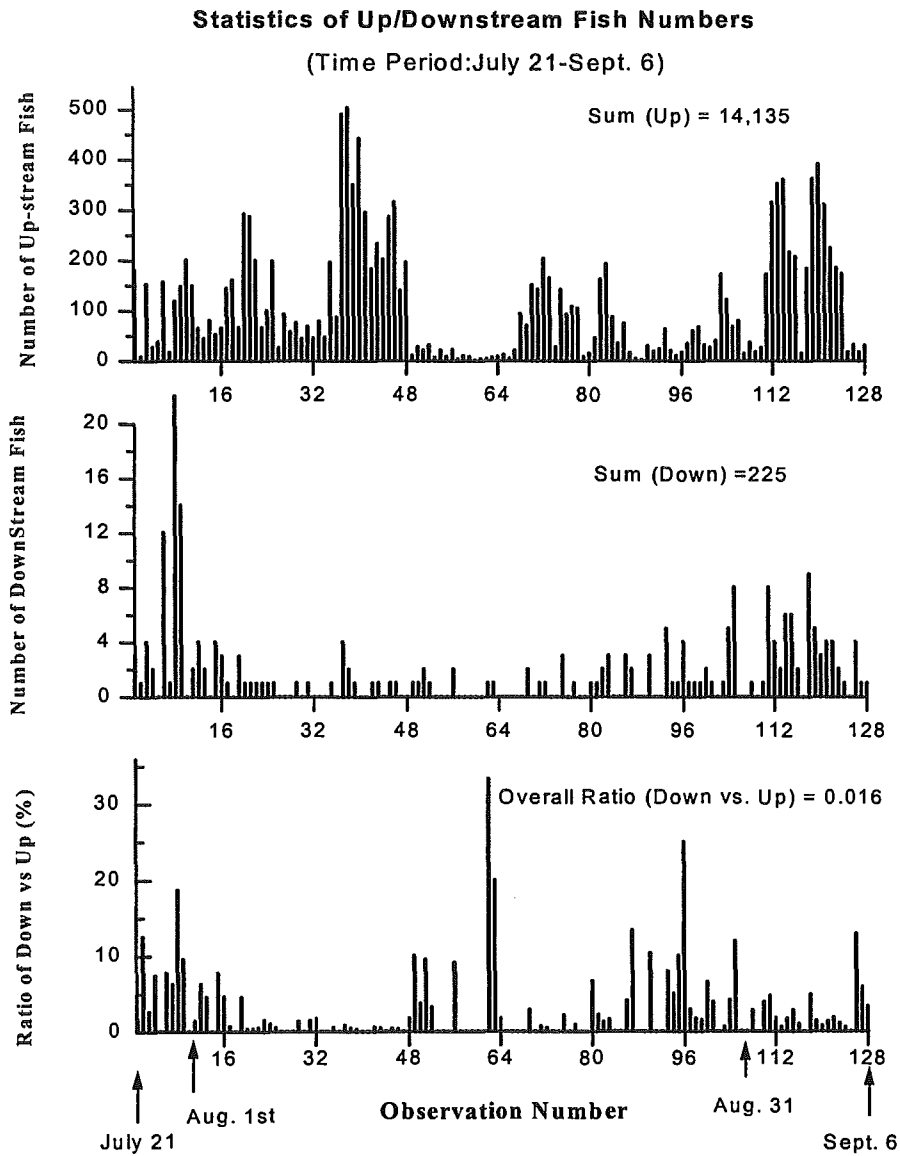


Figure 13. Number of identified upstream swimming fish (top) as a function of individual split-beam soundings; Number of identified downstream swimming fish (middle); Ratio of numbers of down-stream fish to up-stream fish (bottom).

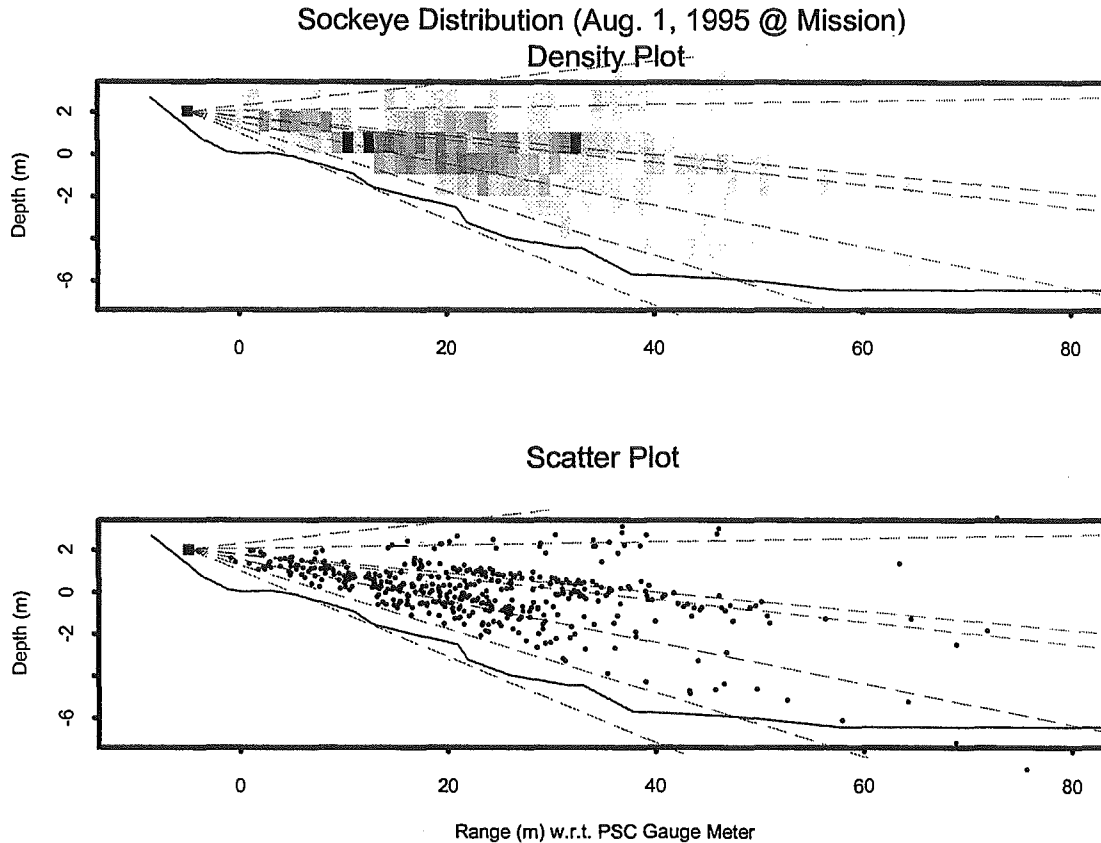


Figure 14. Cumulative spatial distribution of sockeye salmon based on one-hour sounding at 4 aimings with the 4x10-degree transducer. The top graph is a density plot with gray scales showing fish concentrations on the cross-river plane: darker regions correspond to higher fish concentrations. The bottom graph is a scatter plot showing target locations on the cross-river plane. Dashed lines indicate the areas of the water column insonified by the 3-dB sound beam at 4 aimings.

Pink Salmon Migration Period

Large numbers of pink salmon began to migrate past Mission in mid-September, 1995. Our split-beam echosounding data indicated that pink salmon tended to move in schools, and their passage was localized near the shore and close to the bottom. Such behaviour resulted in larger sets of split-beam data for the pink migration period than that for the sockeye. The echo density due to pink salmon was so high that it made tracking of individual fish impossible. Consequently, we could only infer fish behaviour through visual evaluation of the raw target returns acquired with the split-beam echosounder.

Spatial Distributions

Echograms collected during the peak period of pink salmon migration showed high density targets in the river (Figure 15). This echogram results from highly localized fish passage along the river bottom. The cumulative spatial distribution of pink salmon is better illustrated by density and scatter plots using the bottom topography as reference. Density and scatter plots (Figure 16) show the distribution of pink salmon based on 15-minute soundings by two transducers: an inshore 4x10-degree transducer and an offshore 8-degree transducer. The inshore transducer insonified out to approximately a 40-metre range with a 4-degree vertical beam while the off-shore transducer covered a 60-metre range before its 8-degree beam hit the bottom. The inshore transducer showed fish echoes beginning at 10-metre range; some of these echoes were from the tripod of the offshore transducer (Figure 16). The echogram shown in Figure 15 is based on the sounding from the 4x10-degree transducer. We were unable to perform the data-filtering procedures on such high density echo data to remove non-salmon signals as we did for sockeye. Our fish-trackers (both the real-time and off-line trackers) could no longer handle such high density echo data. we used the interactive software developed by N. Olsen (DFO) to manually remove noise from the echogram.

The phase correlation among the split beams allows for accurate positioning of point targets only. Once the beam strikes the bottom, the point source target assumption is no longer valid. Consequently, fish targets on the river bottom cannot be resolved by the split-beam system. The resultant phase lags derived from echoes blended with bottom reflections show large fluctuations resulting in uncertain target-depth positioning. Therefore, these echoes are rejected.

The bottom reflection limits the operating range of all backscattering sonar systems. The range limit is approximately 50 metres in the case displayed in Figure 16. Nevertheless, the system still provides information on pink salmon distribution within a 50-metre range from shore.

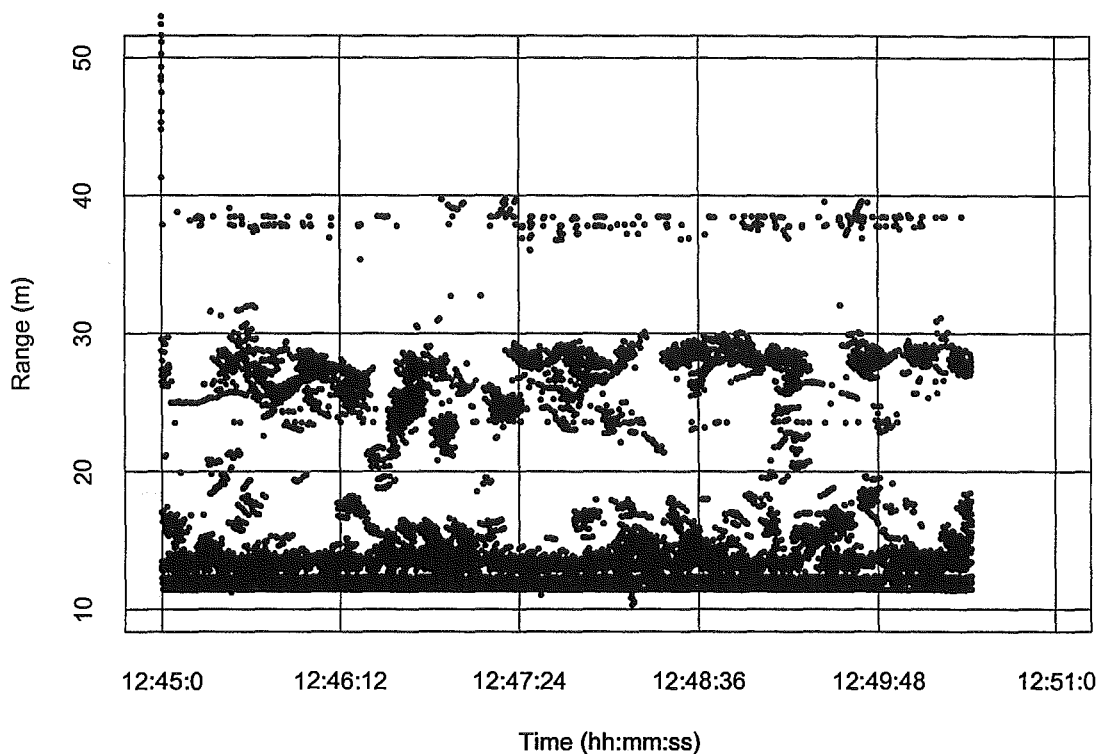
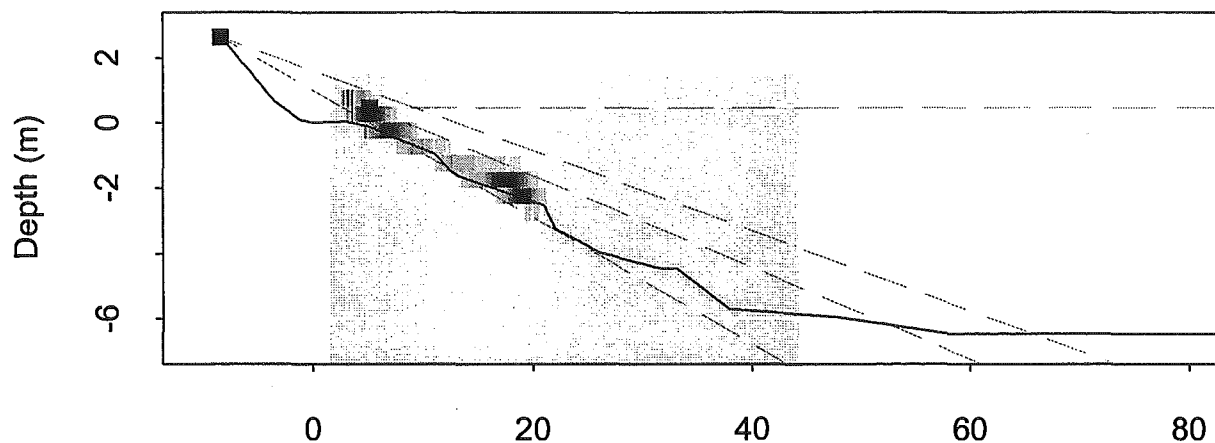


Figure 15. Echogram showing localized high-density distributions of targets during the 1995 pink salmon migration. The echogram is based on raw echoes collected by the split-beam sounder (fish-tracking becomes impossible due to high density echoes) . The data were acquired with the 4x10-degree transducer deployed very close to shore. The apparent solid lines at ~ 10m range is due to insonification of the offshore tripod by the inshore transducer (see Figure 16 for geometry).

Pink Distribution (Sept. 19, 1995 @ Mission) Density Plot



Scatter Plot

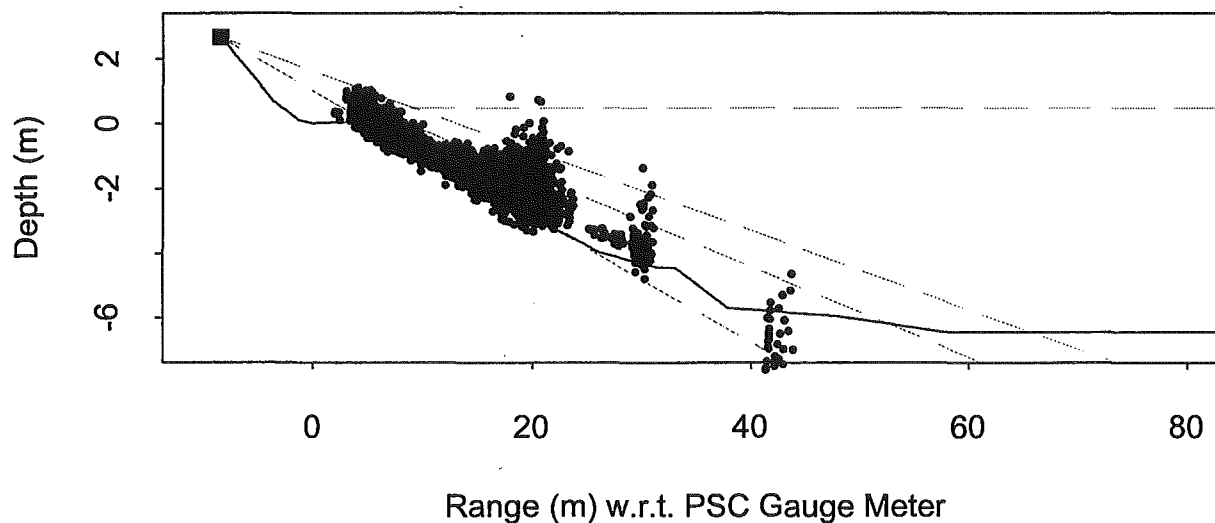


Figure 16. A 15-minute cumulative spatial distribution of pink salmon. Raw echoes were collected with two transducers: a 4x10-degree transducer deployed inshore from the gauge meter and an 8-degree transducer deployed offshore. The representation is similar to Fig. 14 except that the pink salmon distribution was obtained from the raw echo data by the sounder. Pairs of dashed lines originating from the two transducer locations illustrate the 3-dB sound beams for the corresponding transducers.

Example of Possible Fish Reaction to Survey Vessel

A fundamental assumption employed in the standard echosounding program by the PSC is that fish are insensitive to the presence of the survey vessel. One of the objectives of the 1995 split-beam program was to determine whether or not fish react to the echosounding vessel as it approaches them. This was to be accomplished via tracking of targets when the vessel was in the vicinity of the split-beam system. However, a split-beam system is not an ideal tool for such an investigation due to its small sampling volume. Nevertheless, there were occasions when the system observed both the wake from the PSC survey vessel and anomalous fish migration behaviour.

Synoptic scanning of the water column began in late September with 5 minutes of soundings at each vertical aiming. The 4x10-degree inshore transducer scanned the entire water column by stepping through a vertical aiming range from -8 degrees to +20 degrees at 4-degree increments. It was found that when the aiming was high, fish targets were less concentrated making it possible for the software to track individual trajectories. At this time, both pink and sockeye salmon were abundant. Bubbles and other noise generated by the transect boat and other vessels resulted in a large number of non-salmon targets in the surface water. The non-salmon targets were insonified by the split-beam transducer at high aimings together with salmon targets. After cleaning, the tracks of the salmon targets provided us with information on how fish reacted to the approaching vessel. During the presence of the PSC boat, a portion of these targets were tracked moving downstream although such observations occurred only occasionally in our data. One such echogram was taken as the PSC boat made an 180-degree change in its heading near the south bank. As the boat headed towards the north bank, it left a plume of bubbles in the insonified volume. These bubbles resulted in a large number of echoes on the echogram. The transducer was aimed at a vertical angle of 14 degrees in the water column for this sounding. Fish were found moving overwhelmingly downstream approximately 2 minutes before the wake was visible on the echogram. This was a reasonable time interval during which the boat came within 40-metre range to the south bank, turned around near the south bank and headed towards the north bank. The lightened tracks in the echogram indicate those downstream moving fish. It appears that there is a correlation between boat presence and anomalous fish behaviour. Whether this is a cause-effect event is a question that remains to be answered based on further investigation. These data sets, however, provided a starting point for future studies of boat-avoidance effect.

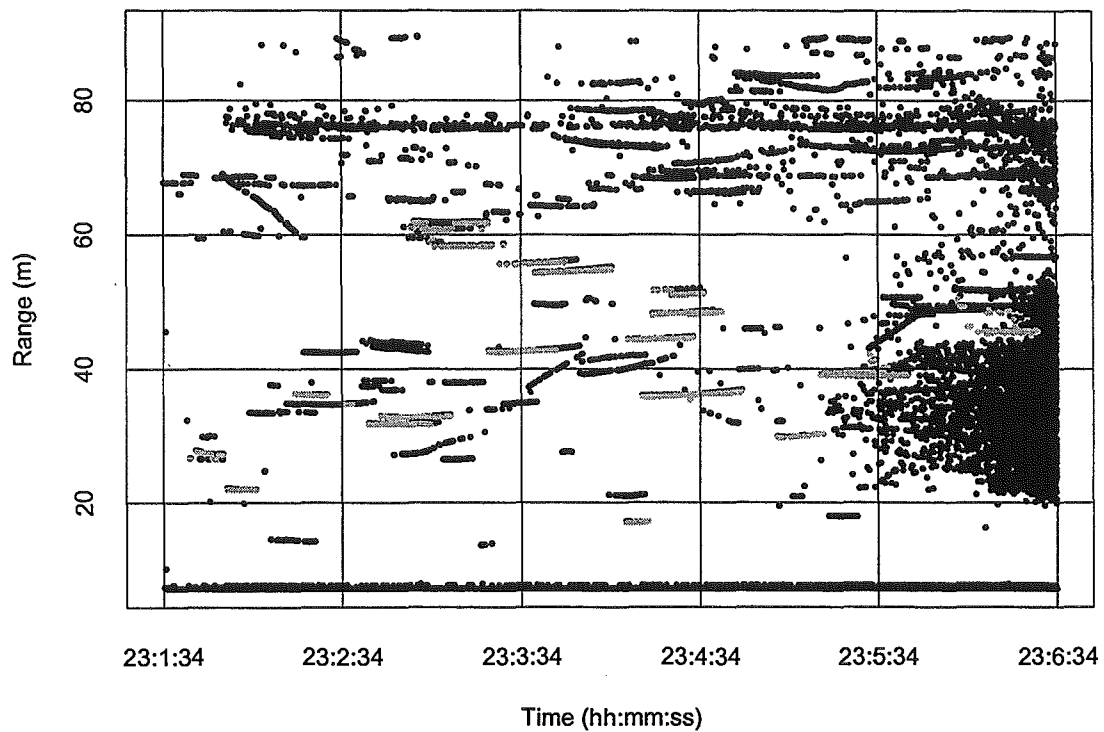


Figure 17. Echogram showing a significant portion of downstream tracks in the presence of boat-wake of the PSC transect vessel indicated by large plumes of bubble noise in the echogram. The lightened tracks correspond to the well tracked downstream fish identified with the processing software.

CONCLUSIONS

The split-beam echosounding system proved to be an effective survey instrument for examining behaviour of migratory salmon at Mission. The tracked target data acquired with this system provided information on fish behaviour for both sockeye and pink salmon. The findings of the 1995 split-beam program at the Mission site are summarized as follows:

- More than 98% of tracked targets were observed moving upstream implying that salmon were the predominant targets and that nearly all were moving upstream;
- The majority of upstream moving targets (salmon) followed trajectories parallel to the river bank or current;
- The migration speed of the salmon varied approximately from 0.5 m/sec to 1 m/sec, and was inversely correlated with the river flow;
- Targets tracked during the sockeye migration period showed a fairly uniform distribution making individual fish tracking possible;
- Targets observed during the pink salmon migration were found very close to the river bottom and in large schools. Such behaviour makes hydroacoustic estimation difficult and individual fish tracking impossible;
- *Circumstantial evidence* obtained with the split-beam echosounder system in September indicated that fish reacted to an approaching vessel by deviating from their normal upstream migration courses.

Data gathered in 1995 were instructive in planning future studies with the split-beam echosounder system at Mission. However, we conclude that they are not sufficient to evaluate the program's objectives, i.e., to determine if, and to what degree, potential sources of bias may affect the standard hydroacoustic program estimates of salmon abundance. Studies in 1996-98 will be designed to accumulate sufficient data to both conclude whether or not biases exist and to measure the extent of the bias, if any.

REMAINING ISSUES AND FUTURE WORK

The 1995 split-beam program confirmed that a split-beam echosounder system can be used at Mission to examine behaviour of migratory salmon. While we acquired useful fish tracking data with this instrument in 1995, important issues remains to be resolved in future studies. These issues are listed below, and form part of the objectives for 1996 field program.

Detection Probability:

The 1995 analyses were based partly on the raw echoes obtained by the split-beam echosounder, particularly for analyses on spatial distribution of fish targets. However, targets located near the centre of the sound beam and at closer ranges to the transducer have a better chance of being detected by the split-beam system than those located in the beam periphery or at greater distance from the transducer. In other words, the detection probability of a target depends on the target's location with respect to the sound beam. Therefore, in the future we must remove the effect of non-uniform detection probability so that we can derive objective fish distributions from these raw echoes. To achieve this goal, we plan to model the detection probability for the split-beam echosounder at Mission. Such modeling must be based on *in situ* measurements of the detection rates of a standard target by the split-beam echosounder at various ranges and angles.

Automation of Vertical Scanning of the Water Column:

The amount of hydroacoustic data collected by the split-beam system in 1995 is inadequate to obtain information on both spatial and temporal variations in salmon distributions at Mission. This is due to the under-sampling of echo data in both space and time. In 1996, we will automate the scanning process using HTI's scanning software. The rotator controller will be programmed through the software to aim the transducer at preset aimings for data collection. Such automated data logging mode will provide nearly-continuous soundings of fish targets over a longer daily period (e.g., overnight data collection) and in a much larger volume than a fixed aiming sounding can achieve.

Tracking of PSC Transecting Vessel with GPS System:

To acquire data on fish reaction to the PSC standard hydroacoustic program survey vessel, we purposely aimed the split-beam transducer in such a way that the sound beam intercepted part of the transecting routes of the vessel near the south bank. However, there were no measurements on the relative positions of the vessel to the transducer site. The only indication of the vessel presence in the sound beam was the presence on the echogram of large numbers of echoes from the boat wake as shown in Figure 17. To examine if or how fish react to an approaching survey vessel, we must know the positions of the vessel and fish targets more precisely. Since fish are tracked by the split-beam echosounder in an X-Y-Z coordinate defined by the orientation of its transducer, the relative position of the vessel to fish can be easily calculated if vessel's trajectories are tracked in the same reference frame as fish trajectories. In 1996, we plan to install a differential GPS (Global Positioning System) unit on board the survey vessel to record its position. The clock of the digital echo processor of the split-beam system will be synchronized with the time provided by the GPS unit. With synchronized GPS position data and split-beam hydroacoustic data, we will be able to obtain relative positions between the vessel and tracked fish. This will help us identify boat-avoidance effect from the split-beam data.

Range Limit of the Split-Beam Echosounder with Narrow-Beam Transducers:

To investigate migratory behaviour of salmon across the river at Mission, we want to sample as much volume of the river as possible with the split-beam transducers. However, all backscattering sonar systems are limited to a certain probing range. This range limit depends not only on the 3-dB beam width of the transducer but also on the riverine environment where the sonar system operates. At Mission, we found that a transducer with a 4-degree beam height could collect data out to only 100 metres, which is approximately a quarter of the full river width. In 1996, we plan to experiment with a narrow beam transducer with possibly a 3-dB beam limit of 2×10 degrees in order to extend the range (Z) of tracked targets and minimize the horizontal distribution artifacts due to the limited detection probability for targets beyond 60 metres of range with the 4×10 degree transducer.

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