Use of Dual-Frequency Identification Sonar to Verify Split-Beam Estimates of Salmon Flux and to Examine Fish Behaviour in the Fraser River

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November 2005

Pacific Salmon Commission Technical Report No. 16

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Correct citation for this publication:
Xie, Y., A. P. Gray, F. J. Martens, J. L. Boffey and J. D. Cave. 2005. Use of Dual-Frequency Identification Sonar to Verify Salmon Flux and to Examine Fish Behaviour in the Fraser River. Pacific Salmon Comm. Tech. Rep. No. 16: 58 p.

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ABSTRACT

Beginning in 2004 the Pacific Salmon Commission implemented a split-beam sonar system to provide real-time estimates of salmon abundance returning to the Fraser River at Mission B.C., replacing less robust single-beam technology which had been in operation since 1977. Dual-frequency identification sonar (DIDSON) provides more detailed information on underwater objects and provides an opportunity to verify some important assumptions in the split-beam methodology. Analysis of DIDSON information confirmed that the left-bank split-beam system produces valid estimations for upstream fish-flux in the “commonly insonified zones” for the two comparable technologies. Analysis of a limited amount of DIDSON information indicated that the “nearest-neighbour” extrapolation method used in the split-beam fish flux model produces reasonable estimates of fish flux at high passage rates in the blind zone. DIDSON studies indicated that the direction of travel and swimming speed of fish migrating in the middle of the channel were not significantly different from similar statistics routinely collected from the left-bank split-beam system. Unknown “fish-like” targets previously observed near the right bank and other indiscernible targets were clearly identified as debris. Also, in the area of the right bank, salmon were clearly identified as migrating towards the shore, but still oriented upstream. DIDSON studies confirmed that fish react to the transecting vessel by changing their normal upstream swimming direction. This avoidance behaviour was found to be more sensitive to the vertical separation between fish and the vessel than the horizontal separation. Trials were also conducted using the DIDSON technology at an upstream site near Boston Bar B.C. and the technology was found to be applicable for the riverine conditions in that area.

INTRODUCTION

The Pacific Salmon Commission (PSC) used a downward-looking single-beam echo sounder system (Biosonics Model 105) to estimate the daily abundance of migratory salmon in the Fraser River at Mission, B.C during annual salmon return seasons between 1977 and 2003. The single-beam sonar technology is able to gain reliable abundance information when the behaviour and distribution of fish conform to the key theoretical assumptions in the abundance-estimation model (Banneheka et al. 1995). However, when these assumptions are violated, the system produces biased estimates. One of the major limitations of this technology is that the system cannot provide direct measurements of direction of travel and swimming speed of detected migrating fish. Since the goal of the Mission Hydroacoustic program is to estimate net upstream migratory salmon abundance, the inability to estimate target speed and direction of travel renders the single-beam based estimates less reliable and less defensible.

Following the findings and recommendations by a working group (Mission Hydroacoustic Facility Working Group, 1994) appointed by the 1994 Fraser River Sockeye Review Board (Report of the Fraser River Sockeye Public Review Board, 1995), the PSC and DFO formed a joint research program in 1995 to examine various single-beam assumptions on fish behaviour with a then state-of-the-art sonar technology, the split-beam sonar. The main focus of the program from 1995 to 1998 (Phase 1 study) was on the distribution and behaviour of fish. These findings were compared with the key assumptions on the distribution and behaviour in the single-beam abundance-estimation model as described by Banneheka et al. 1995. The quantitative results from these studies answered key questions such as the ratio of downstream flux over the upstream flux and swimming speed. A net upstream flux estimation model was also proposed for both the split-beam and single-beam estimators (Xie et al, 1997, and 2002). From these findings the PSC-DFO Hydroacoustic working group concluded that a split-beam sonar system would be a more reliable and robust estimator for estimating net upstream salmon flux at the Mission hydroacoustic site.

From 1999-2002, a Phase 2 study was directed on the feasibility of implementing a split-beam hydroacoustic estimator at the site for in-season management use. The findings from this study demonstrated that a split-beam estimator could be implemented technically and logistically at the site for in-season use. In 2003, the split-beam estimator was first put into operational phase during the field program season to test the response of the system to provide information for in-season management. The results were satisfactory and, the Fraser River Panel approved the implementation of the split-beam system as the primary estimator of abundance for the in-season management of Fraser River sockeye in 2004.

A sonar system is a non-lethal and less intrusive estimation tool as compared to traditional biological sampling methods such as mark-recapture or test-fishing methods for the enumeration of fish abundance in a confined riverine environment. A properly designed and deployed sonar system can readily sample large proportions of the migration in time and space, resulting in large sample sizes and precise estimates of fish passage. The system can also record temporal and spatial features of underlying fish population. However, a hydroacoustic sample is merely an electronic (sonic) record of the corresponding object and as such it cannot provide sufficient details to positively identify the form of the object that is reflecting the sound. Because many underwater objects can produce sonic records for the hydroacoustic system, it is critical that non-fish targets (noise) be eliminated from the database used to estimate salmon abundance. Although a number of target-classification and filtering techniques have been adopted for discriminating noise from fish data, acoustic estimates of fish abundance should be verified by independent counting methods. The commonly adopted method for verifying hydroacoustic fish counts in a clear water environment is to conduct a visual count of fish passage in the vicinity of the hydroacoustic counting site. However, the visual counting method cannot be used in the Fraser

River at Mission, B.C. as the water is turbid with very limited visibility when viewed either from the surface or underwater. The turbidity plus the large river width of up to 400 metres make it very difficult to verify the hydroacoustic fish counts at this site. Because of these difficulties, the Mission hydroacoustic estimates of salmon abundance were never verified at the site with the visual counting method. This lack of verification makes the hydroacoustic estimation less defensible even for the more advanced split-beam sonar system. Such verification requires an innovative observation tool.

In 2001, acousticians and sonar engineers from the Applied Physics Laboratory of the University of Washington in Seattle, Washington developed a high-resolution image sonar system, the *dual-frequency identification sonar,* abbreviated as DIDSON, (Belcher, et al, 2002). DIDSON operates at a mega-hertz frequency and provides a 29^{o} two-dimensional view-field with 0.3^{o} azimuthual resolution when operating in the 1.8-MHz identification mode. This unique sonar-beam allows users to visually identify detailed shapes of underwater objects. The sharp azimuthual resolution and the ease of use and interpretation of the image information make DIDSON one of the best tools for observing fish behaviour and, in some applications, for identifying different species in a turbid riverine environment such as the lower Fraser River at Mission, B.C. In the summer of 2004, the Pacific Salmon Commission purchased a standard DIDSON unit with a grant from the 2004/2005 Southern Boundary Restoration and Enhancement Fund. The PSC Hydroacoustics Group conducted a number of trials and experiments with the DIDSON unit at the Mission Hydroacoustic site in late 2004 field season and in the entire 2005 field season. Our DIDSON work focused on five objectives:

1. Estimate fish flux in areas commonly insonified by the DIDSON and by the left-bank split-beam system to verify the left-bank split-beam estimates;

2. Estimate fish flux in blind zones of the left-bank sideward-looking split-beam system;

3. Identify the mysterious fish-like targets off the right bank, and identify previously indiscernible targets thought to be debris;

4. Obtain information on fish behaviour in the middle section of the river and measure avoidance-behaviour in the presence of the mobile sounding vessel.

5. Assess the feasibility of the DIDSON technology at an upstream site near Boston Bar, B.C., about 15 km upstream from Hell’s Gate, and 165 km upstream from Mission, B.C.

This report presents analyses and findings pertaining to these 5 objectives.

MAIN FEATURES OF THE STUDY SITE

The Pacific Salmon Commission's Mission Hydroacoustic salmon estimation station is located 80 km upstream from the mouth of the Fraser River (Figure 1). The maximum river width at the site is approximately 450 metres during periods of high river discharge. The maximum water depth varies from approximately 18 m in June during high run-off to 12 m in October at low discharge. The river flow is influenced by tides and during extreme high tides the river may occasionally reverse its flow. Due to strong currents in the deepest channel near the right bank (Figure 2), the majority of fish use near shore areas to migrate upstream (e.g. Figure 3). The river at the site is turbid with a very limited visibility giving the river a brown color and making visual fish-counting impossible. Figure 4 is a site photo taken from the left bank. The iron dolphin in the photo is a reference point for positioning individual fish targets detected by the split-beam sonar systems. Throughout this report, we use the terms *left bank* and *right bank* to refer river banks. The bank on the left-hand-side when one faces downstream is defined as the left bank and the bank on the right-hand-side is defined as the right bank. Using this convention for the Mission site, the left bank is on the south side, and the right bank is on the north side of the river (see Figure 1).

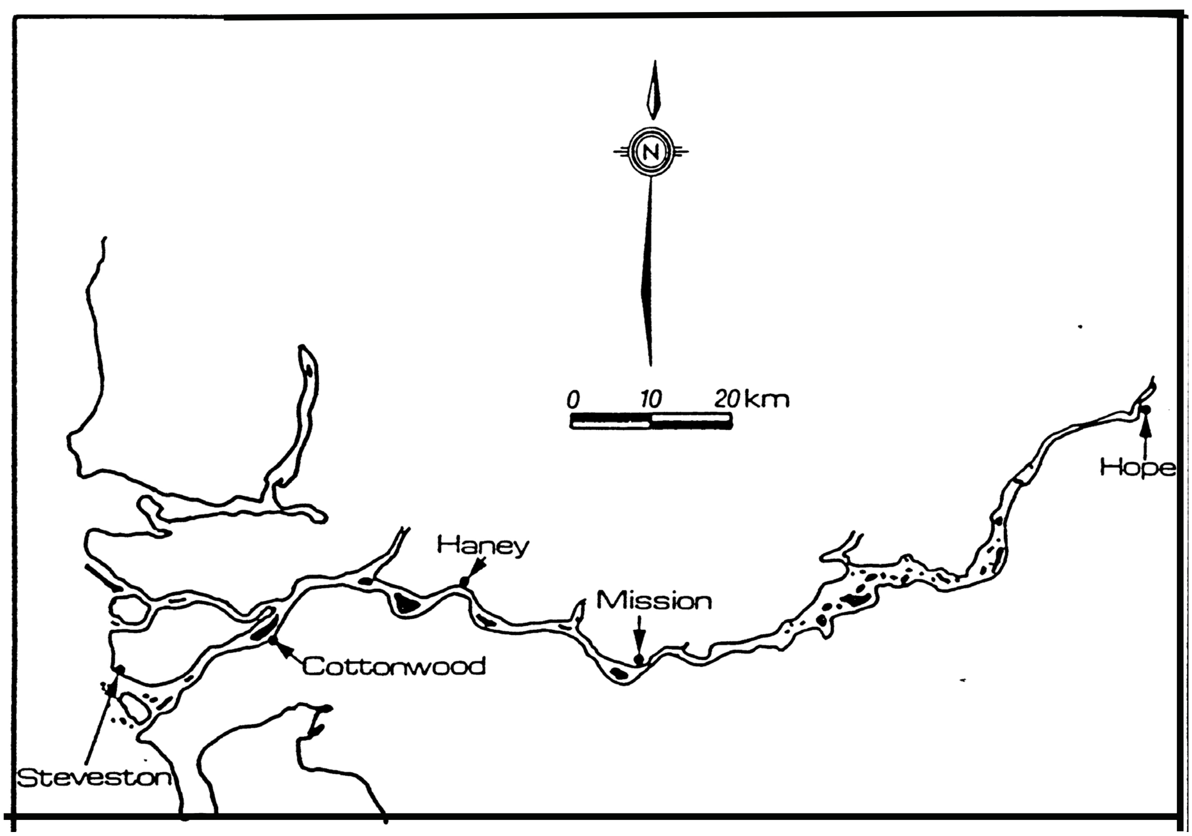

Figure 1. Site map of the PSC Mission hydroacoustic salmon estimation station. Also shown is the location of the town of Haney in Maple Ridge, B.C. (about 20 km downstream from Mission) where a daily test fishing program is carried out during the salmon return season to provide species composition statistics for daily hydroacoustic estimation of total salmon past Mission.

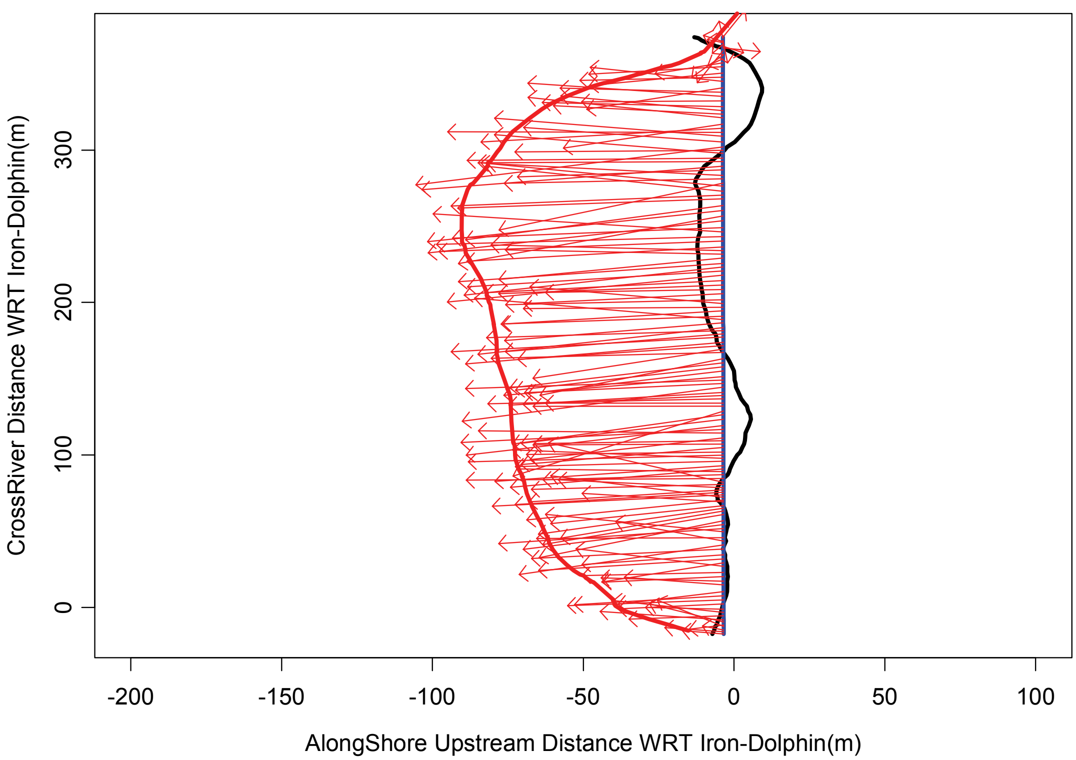

Figure 2. Depth-averaged flow vectors (red arrows) across the river at the site obtained on July 14, 2005 by a transect survey using a 1200-kHz RDI Workhorse-Sentinel ADCP (Acoustic Doppler Current Profiler) unit. The dark-line is the transect trajectory; the red-line is the smoothed speed magnitude across the river. The mean flow speed is 1.2 m /s with a maximum speed of 2.1 m/s in the deepest channel near the right bank. The mean flow direction is at a bearing of 230 degrees. A small scale local eddy structure was detected near the right bank where the flow deviated from the mean downstream direction. The 2-D positions of measured flow vectors were referenced to the iron dolphin shown in Figure 4.

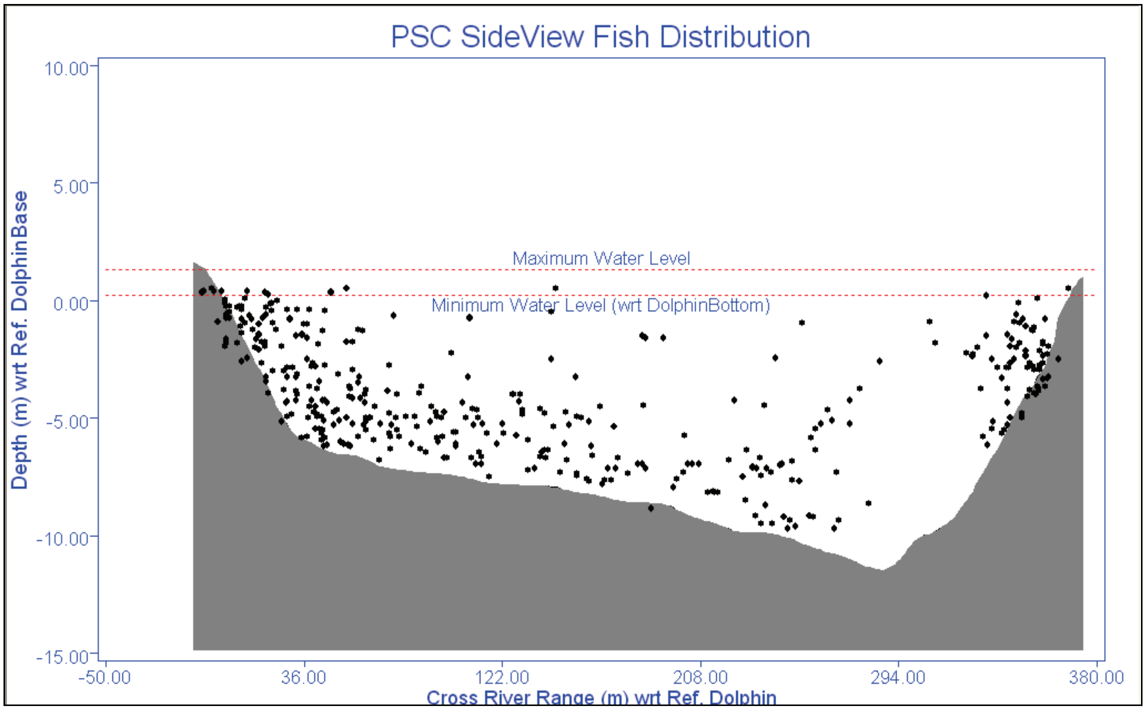

Figure 3. River profile and typical fish distribution (the solid dots) at the PSC Mission hydroacoustic salmon estimation station.

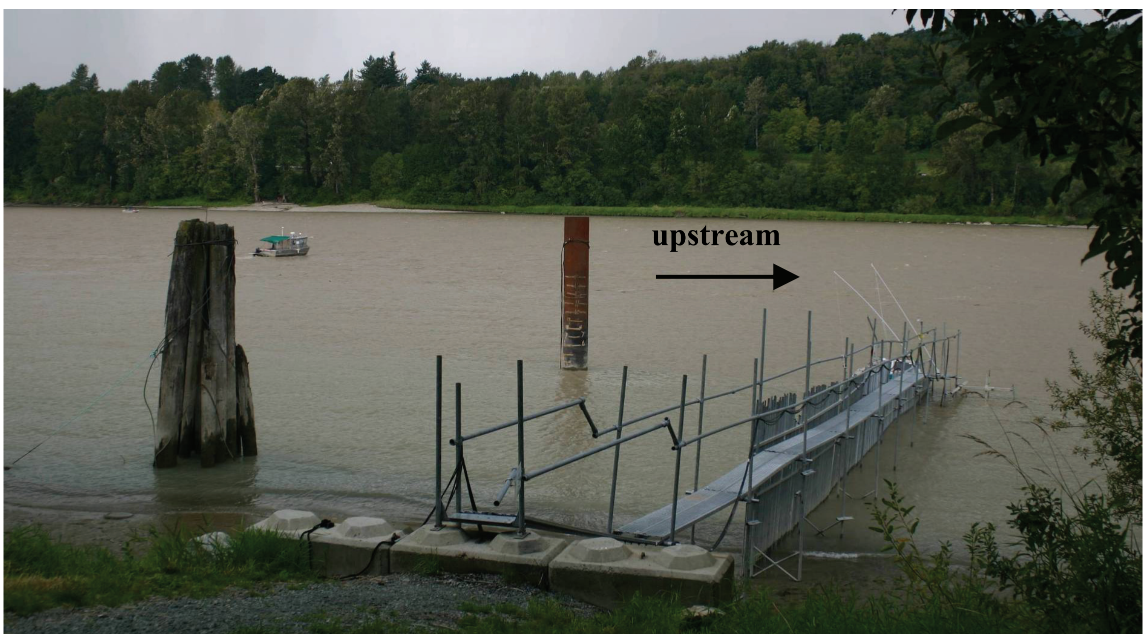

Figure 4. Site-photo of the Mission hydroacoustic station taken in September 2004. The iron dolphin is the reference point for positioning individual fish targets detected by the split-beam sonar systems. The location of this reference point is estimated by a differential GPS system as 49°08.175'N, and 122°16.466'W. Also shown are the PSC echo-sounding vessel *Rita* and a fish-deflection weir (approximately 35 metres in length) on the left bank. The weir prevents fish from swimming behind the sound-beam.

THE SPLIT-BEAM FISH-FLUX ESTIMATOR

The split-beam fish-flux estimator consists of two sampling components that are presently implemented at the site. The two sampling systems provide fish samples to a flux estimation model for estimating net upstream salmon flux near the left-bank and across the rest of the river cross-section. This section provides brief descriptions of the two sampling systems, and the flux model. More detailed descriptions can be found in Xie et al. (2002) and Chen et al. (2002).

Sampling Configurations

While a shore-based side-looking fixed aspect split-beam sonar beam provides target information that is easily interpreted, the beam is range-limited by river boundaries and reverberation noise at large ranges. The alternative approach is to deploy a downward-looking transducer on a moving vessel to conduct transect-sampling of the river. The present sampling system consists of both components as outlined below:

1. a shore-based sideward-looking multi-aim sampling system is deployed to sample an offshore cross-section from the left bank up to 100 metres in range. The sampling system is comprised of two split-beam transducers of elliptical beam-widths of $2^{o} \times 10^{o}$ and $4^{o} \times 10^{o}$, respectively.

2. a vessel-based downward looking transect-sampling system is deployed to sample the entire river. The sensor used for this system is a 15^{o} circular-beam transducer. Although the transect-sampling system covers the entire river-cross section, only the information collected in areas beyond the maximum coverage range of the left-bank system is utilized for deriving the offshore fish flux from the left bank.

The sampling areas by the two systems for the river cross-section are outlined in Figure 5.

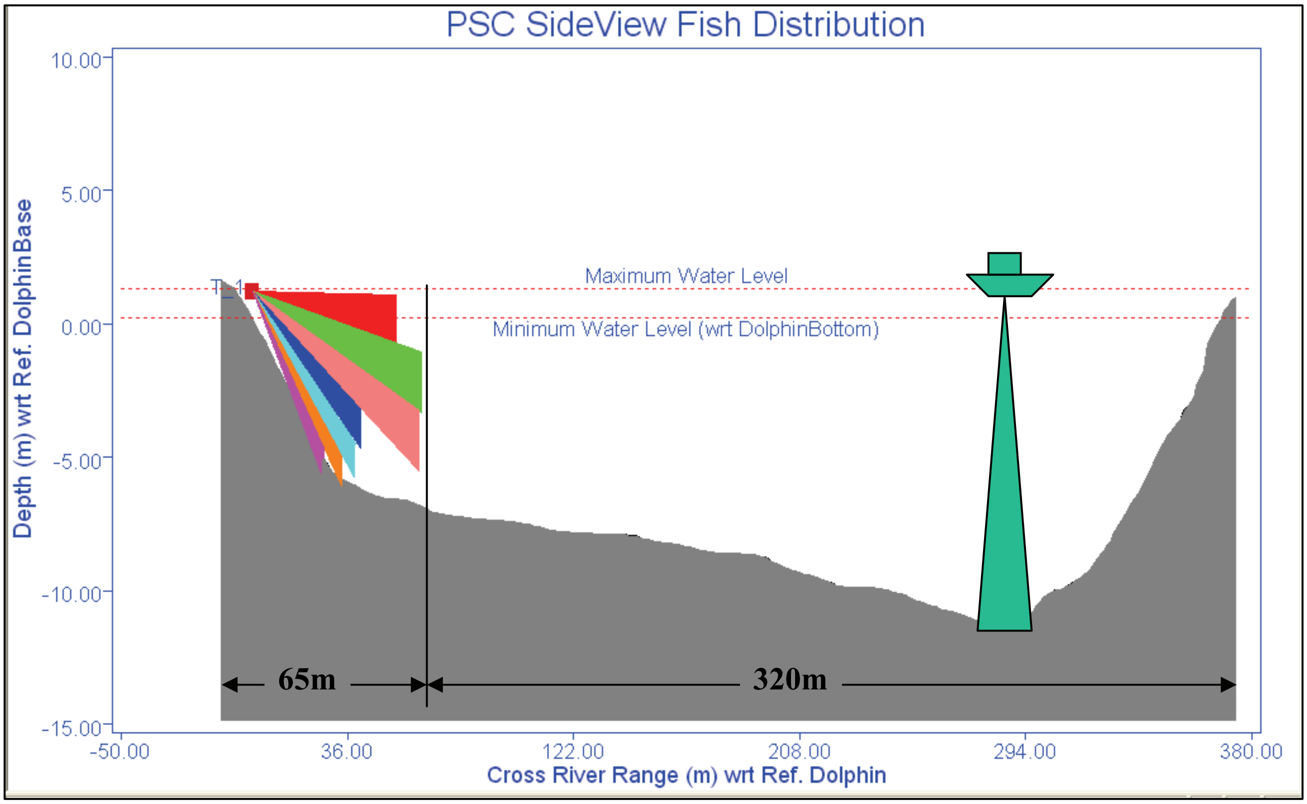

Figure 5. Sampling geometry and coverage areas of the shore-based and the vessel-based split-beam systems presently adopted for the Mission hydroacoustic salmon-estimation program.

The left-bank shore-based system uses a systematic hourly sampling scheme with 10 aims sampling the water column sequentially for ten 6-minute segments by the two transducers. This results in a sampling effort of 10-15%, relative to the total fish abundance passing the cross-sectional area covered by the acoustic beams. In 2005 the average sampling effort of the left-bank system was 13.5%. The transect-sampling system samples the entire river (except the blind zones near the river boundaries). On average, a total of 165 transects are conducted daily. However, the information provided by the transect-samplings does not contain time-integration of fish-flux as per the left-bank fixed aspect system. Historical records indicate that the transect-sampling system samples less than 1% of the total abundance past the site. The 2005 data show an average sampling effort of only 0.4% of the total abundance by the transect-sampling system.

Fish-flux Estimation Model

In 2002, the PSC-DFO joint hydroacoustic working group proposed a net upstream fish flux model (Equation (2) of Xie et al, 2002). The basic assumptions of the model are:

1. an upstream migrating fish has a net upstream velocity component when observed in an adequate time interval and space, and
2. a resident fish has a zero net upstream velocity component when observed in an adequate time interval and space.

These assumptions led to a simple net upstream fish-flux model:

$$N = U - D \qquad \text{[fish]} \qquad (1)$$

where U and D are the time-and-area integrated fish-flux in the upstream and downstream directions, respectively. N is the time-and-area integrated net upstream fish-flux. Here, the integrating time-interval is simply the sampling time and the integrating area is the sampling area perpendicular to the upstream migration direction. This flux model is applicable to any sampling methods that are designed to sample fish in the upstream and downstream directions. In the following, we briefly explain how to apply this model, respectively, to the split-beam data collected by the shore-based sideward-looking system, and the downward looking mobile sampling system.

The application of the flux model to the left-bank split-beam data

The application of (1) to the data collected by the shore-based sideward-looking split-beam sampling system is straightforward. Assuming that over a 24-hour time period, the 7 beams shown in Figure 5 sample 6 minutes of fish-flux per hour on the cross-section outlined by the beam geometry, we can interpret the total upstream fish counts over this 24-hour time-period from these 7 aims U as:

$$U = \sum_{i=1}^{24} \int_0^{360} \left[\int_s (\rho_+ \cdot v_+)_i \, ds \right] dt \qquad \text{[fish]} \qquad (2)$$

where S is the total sampling area by the 7 beams, the value of 360 corresponds to the hourly sampling time of 360 seconds by each of the 7 beams, and i indices each of the 24 hours. Note: U is a dimensionless quantity. The kernel function ($\rho_+ \cdot v_+$) [fish/(m^2·s)] inside the integrations is the upstream fish-flux where ρ_+ [fish/m^3] and v_+ [m/s] are the density and swimming speed of upstream fish. In practice, we assume that the sampling system provides an unbiased estimate for U. Then by using Formula (2) we can estimate the number of upstream fish passing through cross-section S per second. So, (2) can be rewritten as

$$\frac{U}{24 \times 360} = \frac{\sum_{i=1}^{24} \int_0^{360} \left[\int_s (\rho_+ \cdot v_+)_i \, ds \right] dt}{24 \times 360} \qquad \text{[fish /s]} \qquad (3)$$

The same interpretation of the data can be provided for the downstream flux component. The resulting net upstream number of fish passing through S per second is estimated as

$$\frac{N}{24 \times 360} = \frac{U - D}{24 \times 360} = \frac{\sum_{i=1}^{24} \int_0^{360} \left[\int_s (\rho_+ \cdot v_+ - \rho_- \cdot v_-)_i \cdot ds \right] dt}{24 \times 360} \qquad \text{[fish /s]} \qquad (4)$$

The total number of net upstream fish passing through the monitoring area in this 24-hour time-interval, denoted as M_1, is then estimated by linearly expanding (4) to 24 hours. That is:

$$M_1 = (24 \times 3600) \times \frac{N}{24 \times 360} = 10 \times N = 10 \times (U - D) \qquad \text{[fish]} \qquad (5)$$

However, the total number of net upstream fish passing through the entire left-bank area should also include an amount of flux passing through the area that is not directly sampled by the left-bank system (i.e. in blind zones near the surface and bottom; see Figure 5). This amount of flux, denoted as M_0, is estimated by extrapolating estimated flux in the sampled area to the un-sampled area using a geo-statistical model. We present a further discussion on M_0 in a subsequent section. Therefore, the total number of net upstream fish passing through the left-bank area within the maximum sounding range of the shore-based system is: $M_0 + M_1$.

The application of the flux model to the mobile split-beam data

The flux model can also be expressed in a modified form as:

$$N = (U + D) \times (1 - 2 \cdot \frac{D}{U + D}) = (U + D) \times (1 - 2 \cdot R_d) \qquad \text{[fish]} \qquad (6)$$

where $R_d = D/(U+D)$ is the downstream flux ratio (relative to the total flux). This is a convenient form of the flux model for the interpretation of fish data acquired by a system that can only provide reliable estimation of fish density whereas the velocity information is obtained from other means. The current mobile split-beam system is unable to obtain reliable measurements of fish speed and direction of travel from mobile samplings. This limitation of the system means that the data from the mobile samplings can only be used for the estimation of fish density. The adopted approach to handling the mobile split-beam data is to utilize the speed information and the downstream flux ratio estimated from the left-bank system, and the density information obtained from the mobile system to construct an estimator for N from (6). The detailed derivations of the flux model are given in Appendix 1. The resulting estimator for the total number of net upstream fish in a 24-hour time interval across the river, denoted as M_3, is:

$$M_3 = (24 \times 3600) \times n \qquad \text{[fish]} \qquad (7)$$

where n is the number of net upstream fish passing through the entire cross-section per second, and is estimated by the following formula:

$$n = \frac{m_T \cdot v_+}{L} \cdot \left[1 - (1 - \frac{v_-}{v_+}) \cdot \frac{D}{D + U \cdot v_- / v_+} \right] \cdot \left[1 - 2 \cdot \frac{D}{D + U} \right] \quad \text{[fish /s]} \quad (8).$$

In the above expression, U and D are the upstream and downstream fish-flux integrated over the sampling time and sampling area by the left-bank system. v_+ and v_- are upstream and downstream fish swimming speeds estimated from the left-bank data. m_T is the averaged number of detected fish per transect estimated from the mobile split-beam data. Note: m_T is a volumetric integration of fish density by the moving sound-beam, a dimensionless quantity. L is a depth-averaged beam-width of the 15^o sound-beam across the river. An important assumption in estimator (8) is that the behaviour (speed, direction of travel) of fish migrating inside the shore-areas near the left-bank is equivalent to those fish migrating in the rest of the river (i.e. outside the monitoring area of the left-bank system).

The estimator for the daily upstream salmon flux past Mission

The total number of net upstream fish per second across the entire river, denoted as M, is estimated by merging the flux in the inshore area of left bank estimated by the shore-based system with flux estimated in the off-shore area by the mobile system. The final form of the estimator for the daily total salmon flux past Mission is:

$$M = M_0 + M_1 + M_3(r > r_c) \qquad \text{[fish]} \qquad (9)$$

where r is the cross-river range relative to the iron dolphin, and r_c is the maximum coverage range by the left-bank sounding system. The expression of M_3 ($r > r_c$) denotes the offshore portion of M_3 from the left bank. To assess the accuracy and potential biases of this estimator, we need to answer the following key questions about the estimator:

- How accurate is the left-bank system in estimating fish-flux in the sampled inshore area?
- How accurate is the extrapolation method in estimating the flux in the left-bank un-sampled area?
- Does swimming behaviour of fish vary across the river? If so, how large is the bias in the estimation when using left-bank data to infer behavioural statistics of fish migrating in the middle channel and near the right bank?
- Do fish avoid the transect vessel?

Attempts were made to address some of these questions in the past but with limited success due to limitations of the then available observation tools (Xie, et al, 2002). Innovative technologies are required to re-examine these important issues at the site. The DIDSON technology provides such an opportunity.

KEY FEATURES OF DIDSON SONAR

The main features and limitations of the DIDSON sonar in comparison to the split-beam sonar in fisheries applications are summarized below.

Advanced features

1. DIDSON sonar operates in a mega-hertz frequency range and insonifies fish with a large azimuthal composite beam of 29^o as shown by Figure 6(b). This composite beam consists of 96 fan-shaped narrow beams. Each of the 96 individual beams has a 2-dimensional angular resolution of 0.3^o by 12^o. The composite beam provides not only a complete coverage of the entire body of a typical salmon target but also a range-dependent azimuthal resolution for the body shape of imaged fish. For example, at a 10-m range, the composite beam provides a 5m × 2m rectangular imaging area, which is more than adequate for insonifying the entire body length of a typical adult sockeye. The resulting image of the fish has a 5-cm resolution along the azimuthal direction of the composite beam. In comparison, a $4^o \times 10^o$ split-beam transducer, operating in kHz frequency range, produces an elliptical acoustic footprint of respective major and minor axes of 1.7 m and 0.7 m at 10-m range, which can insonify the entire fish but provides no spatial resolution in either the major- or minor-axis direction for the fish. The resulting target information consists of only a few peak echoes from the major scattering organs such as the swim-bladder, the head and/or the tail. It is difficult for users to visually relate these echoes to the original shape of the fish. Figure 6 schematically illustrates the difference in sonic views of a fish by a split-beam sonar and a DIDSON sonar.

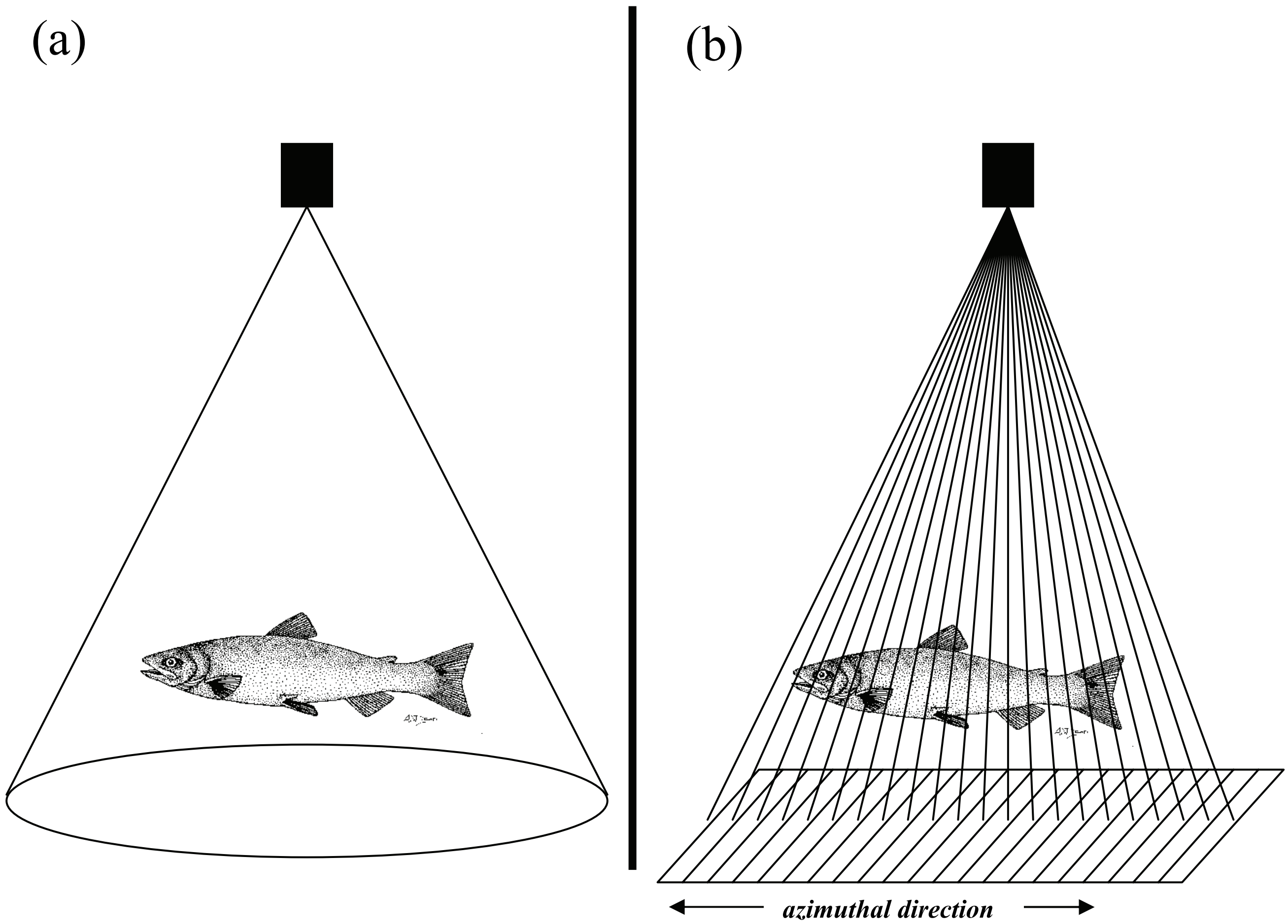

Figure 6. Sonic views of a fish by (a) a split-beam sonar beam which provides no lateral resolution, and (b) by a DIDSON sonar beam that provides a sharp azimuthal resolution revealing the shape and body structure along the azimuthal direction of the beam.

2. The duration of a probing sound-pulse from a standard DIDSON unit is 32 microseconds for a range window of 9 metres. This narrow pulse provides a range-resolution of 1.8 cm, i.e., targets with range-separations exceeding 1.8 cm can be resolved by the sonar system. In contrasting to the DIDSON pulse-width, the pulse-width from a split-beam system is usually in the order of hundreds of microseconds as the system needs longer pulses to carry enough energy for probing a large riverine environment. However, these longer pulses result in a lower range-resolution. For example, probing the river with 0.2-ms pulses, a split-beam system can only resolve targets with range-separations that exceed 15cm.

3. DIDSON can also image fish at fast frame rates of up to 21 frames per second. When images are played back continuously, they appear as a movie capturing the dynamic behaviour of a swimming fish. This movie-type of information is a tremendous help to users in visually distinguishing fish from non-fish targets in the image data.

4. The target information provided by DIDSON sonar is visually intuitive. Users require little specialized training to understand the output image data while the highly simplified

target information provided by a split-beam sonar system requires a substantial amount of training and working experience for proper interpretation.

5. DIDSON allows direct measurements of length of a fish although a calibration factor must be applied to the raw DIDSON measured length data to estimate the true length.

These unique features make DIDSON a powerful observation tool for identifying fish targets from other non-fish targets in a turbid riverine environment. Figure 7 presents comparative target information for a Fraser River sturgeon (*Acipenser sp.*) acquired by one frame of DIDSON image and by a simulated split-beam system by taking maximum echo voltages from a few return pings from the fish.

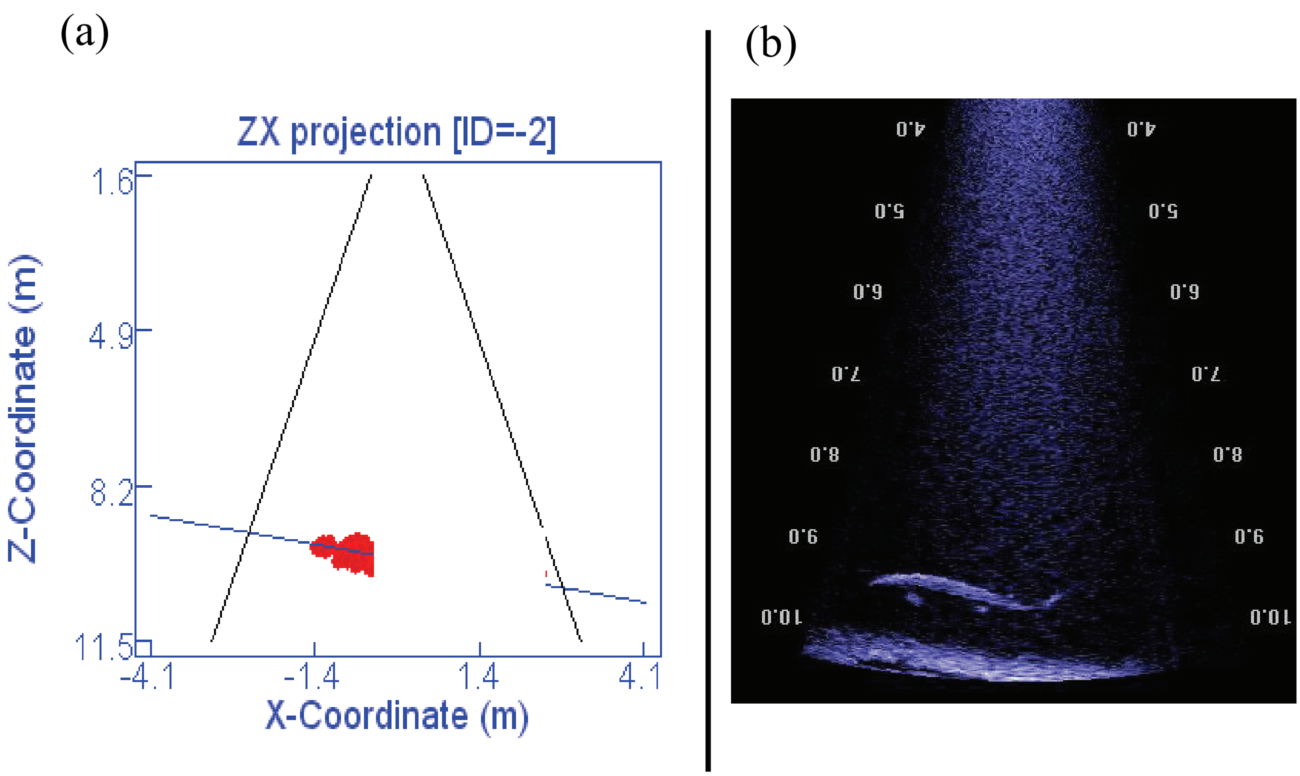

Figure 7. Target information of a Fraser River sturgeon acquired by (a) a split-beam sonar, which shows a cluster of target positions estimated from a few pings of peak echoes from the dominating scattering organs of the fish such as the swim-bladder, the head and the tail, and by (b) a DIDSON sonar with one frame of the image data which reveal the shape, the body length of 2.1m, and the detailed structure of the fish such as the fins, the head and the tail.

While it is difficult to correlate the cluster of target positions with the sturgeon from the split-beam data, there is no question that the target is a large fish based on the DIDSON image. Furthermore, the DIDSON image shows the characteristic body and fin shape of a sturgeon with an estimated body length of 2.1m.

Limitations

1. DIDSON technology produces a line-focused composite beam as opposed to a point-focused beam. Although the 96 line-focused beams provide a sharp azimuthal resolution on insonified targets in the azimuthal direction along the 29-degree beam angle, the system provides no angular resolution along the direction of the12-degree beam angle. As a result, DIDSON can only measure the position of a detected target in range and azimuthal directions as defined in a cylindrical Cartesian frame. A split-beam sonar system can measure the target position in a 3-dimensional space along range, azimuthal and polar directions as defined in a spherical Cartesian frame.

2. The maximum operating range of a standard DIDSON unit is about 40 metres when operating in the 1.1-MHz detection mode. This range-limit is reduced to 20 metres when operating in the 1.8-MHz identification mode. A $2^{o} \times 10^{o}$ split-beam transducer is capable of reaching maximum sounding ranges beyond 100 metres in a quiet and clear underwater environment.

The first limitation means that DIDSON cannot provide 3-D information on fish distributions in the river. The second limitation means that DIDSON is not an ideal tool for enumerating fish in the lower Fraser River where fish can distribute over a river-width of a few hundred metres. Coverage of the entire river would require multiple units. However, we can use DIDSON to estimate fish-flux in local areas of the river or in the upper Fraser River where channels are narrower and fish are forced by mid-channel fast currents to migrate within a few metres from the banks. For detailed technical descriptions of DIDSON sonar, readers are referred to Belcher, et al (2002).

DIDSON ASSESSMENT OF FISH-FLUX ESTIMATION IN THE SPLIT-BEAM SAMPLING ZONES

The range limitation prevented us from using DIDSON to assess fish-flux estimation by the left-bank split-beam system for the entire sampling range from the shore. However, we were able to conduct such an assessment within the operating range of the DIDSON. In the following, we present comparisons of flux estimations between the DIDSON and left-bank split-beam systems within a 40-m range from the left bank in an area that is completely insonified by the split-beam transducers. For the convenience of description, we refer to this area as “the commonly sampled area”.

Method

We used the DIDSON to verify the fish-flux estimation produced by the left-bank split-beam system by adjusting the aiming angle of the 12^{o} DIDSON beam to obtain the best fit of the DIDSON beam coverage to the near shore cross-section insonified by the split-beam transducers within a 40-m range, forming the commonly sampled area between the two systems. On an hourly basis, the fish-flux in this common area was sampled with a 100% effort by the DIDSON beam whereas the same flux was sampled with approximately 20% effort by the two split-beam transducers. The 20% effort resulted from the 3 non-overlapping spatial samplings of the common area by the $4^{o} \times 10^{o}$ transducer and the 7 non-overlapping samplings of the same area by the $2^{o} \times 10^{o}$ transducer with each sampling taking 6 minutes of data. The spatial sampling geometries of the two systems are illustrated in Figure 8. The detailed sampling effort of the two split-beam transducers is summarized in Table 1. The hourly net upstream fish flux through this common area was estimated independently from the two systems. For the split-beam system, individual fish targets were identified by tracking the split-beam raw echo data with an alpha-beta algorithm (Blackman and Popoli, 1999), and the resulting tracks were visually examined for their swimming trajectories, traveling velocities, and target-strength readings. Fish targets acquired from the DIDSON sonar were identified by visual reading of the DIDSON image files. The reading methods are described in Appendix 2. To achieve spatial similarities between fish samples obtained by the two systems, we deployed the DIDSON unit approximately 1.5 metres upstream from the split-beam transducers as shown in Figure 9. This ensured that the two systems monitor the same area of flux.

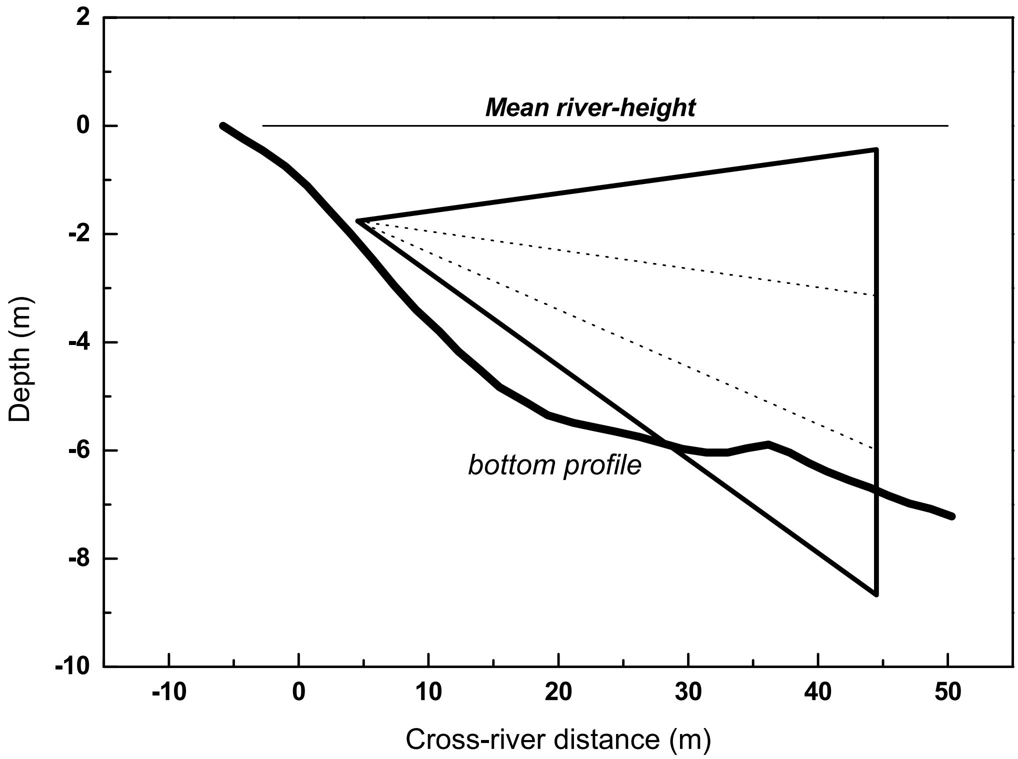

Figure 8. The commonly sampled area by the 12° DIDSON beam aimed at -4° and the two split-beam transducers. Also shown are 3 sub-triangle areas (separated by the two dotted lines) sampled by a 4°×10° split-beam transducer at 3 aims with 6-minute sampling at each aim. The 3 aims of samplings were followed by 7 aims of samplings by a 2°×10° transducer (not shown in the figure).

Table 1. Summary of hourly sampling efforts by the 4°×10° and the 2°×10° split-beam transducers for the common area.

Hourly sampling efforts by the two split-beam transducers

Time interval (min)	0-6	6-12	12-18	18-24	24-30	30-36	36-42	42-48	48-54	54-60
Aim (deg)	-8	-4	0	0	-2	-4	-6	-8	-10	-12
Xducer (4x10deg)	on	on	on	off	off	off	off	off	off	off
Xducer (2x10deg)	off	off	off	on	on	on	on	on	on	on

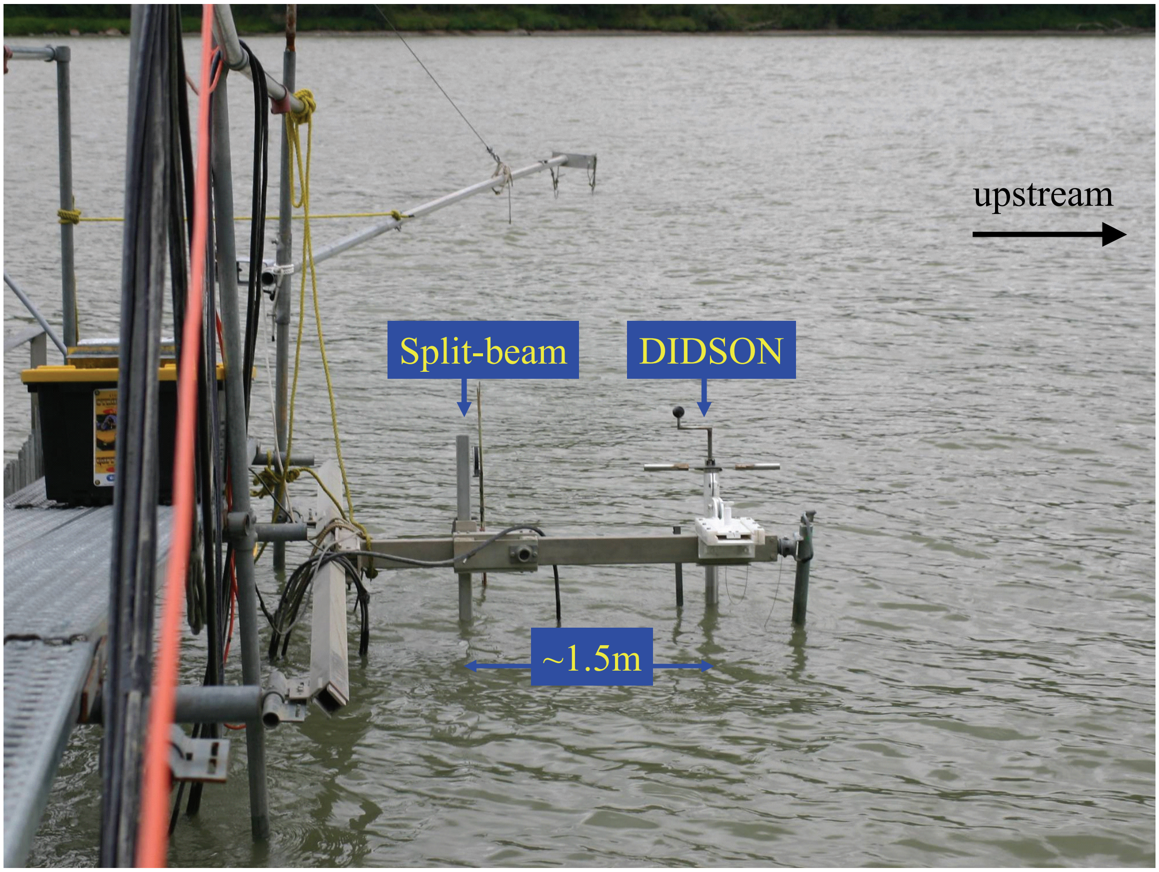

Figure 9. Photo showing the deployment location of the DIDSON unit relative to the left-bank split-beam transducers. The cross-bar and rotating-handle on the DIDSON deployment shaft allowed users to adjust the bearing and the pitch angle of the DIDSON unit.

Results

Flux comparisons

We collected 36 hours of continuous flux data from both the DIDSON and the two split-beam transducers in the common area using the above described sampling method. The 36-hour period covered 1.5 days between August 22 and 23, 2004. Figure 10 shows the hourly upstream fish flux time-series from the two systems for this time period.

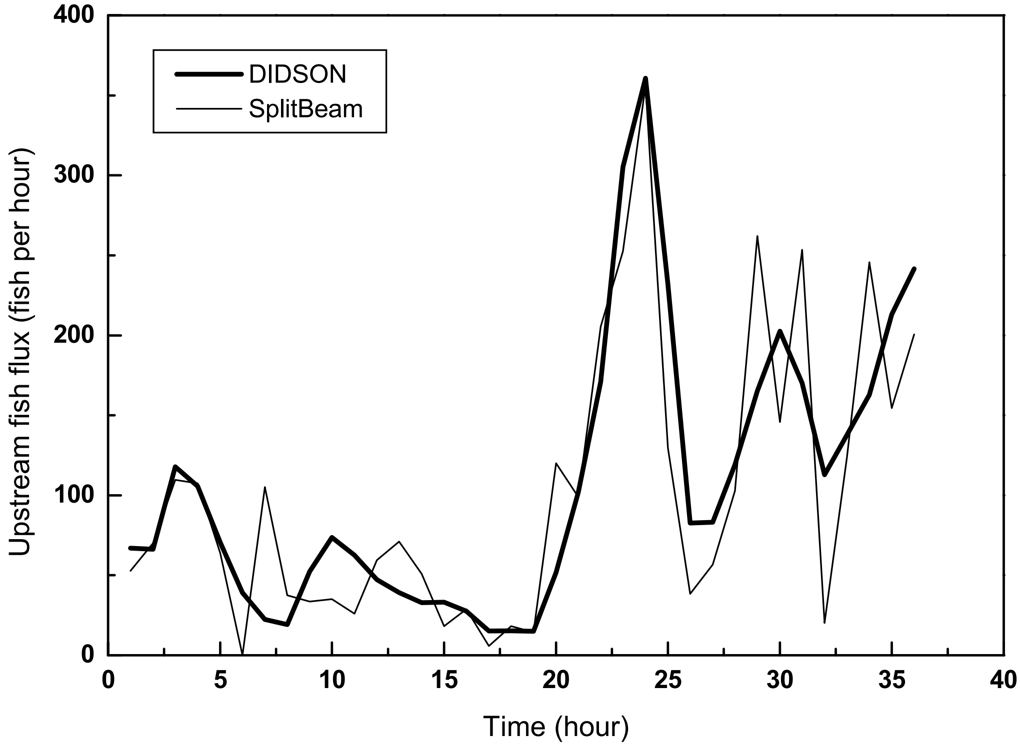

Figure 10. Hourly net upstream fish-flux for the 36-hour time period starting at 00:00 Aug 22, and ending at 13:00 Aug 23, 2004. The two time-series are significantly correlated (r = 0.86).

Due to the difference in sampling efforts between the two systems, and the random errors in recognizing fish targets from both the split-beam and the DIDSON data, we expect a certain degree of temporal differences between the two flux estimations as shown in Figure 10. Aside from these differences, the overall temporal trends of the two estimations are very similar with a cross-correlation coefficient of 0.86, and a statistically significant linear regression slope of 0.88 with a p-value < 0.001. The two time series also possess similar variances of 7389 (the DIDSON flux) and 7776 (the split-beam flux) with an F-statistic of 0.95 and a p-value of 0.881. The auto-correlation coefficients for both time series showed little serial-correlations once the time lag exceeded 1 hour justifying a conventional statistical testing on the two estimates. A 2-sample t-test for the two hourly-flux time-series indicated that their means (106 for the DIDSON and 102 for the split-beam) were not statistically different (t = 0.218, p = 0.828). A formal Kolmogorov-Smirnov test on the relationship between the two flux distributions resulted in a k-s statistic of 0.111 corresponding to a p-value of 0.982. From this test we concluded that the two distributions of the 36-hour flux estimates obtained from the DIDSON and the split-beam systems were from the same population. A practically informative estimate for in-season management is the time-integrated (or time-cumulated) fish-flux past a monitoring station on a daily basis. Based on the two independent hourly flux estimates, we calculated cumulative flux estimates for the two systems. The resulting estimates showed a relative difference of 4% in the two grand totals (3835 vs. 3674) but this difference was not statistically significant (Figure 11). These comparisons verified that the split-beam estimate of upstream fish flux was statistically similar to the DIDSON estimate in the common area.

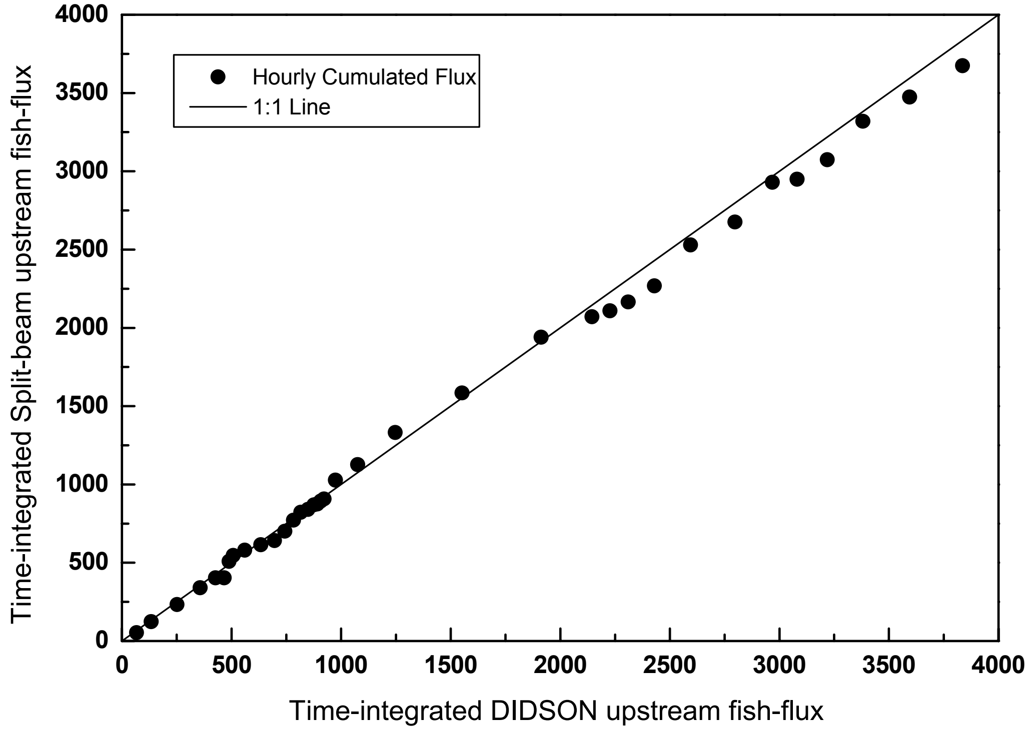

Figure 11. Time cumulative net upstream fish-flux estimates by the two estimators. The cumulated totals at the end of the 36-hour time period are 3835, and 3674 for the DIDSON and the split-beam sonar, respectively. The means of the two hourly estimates are 106, and 102, respectively, which are statistically similar (p = 0.828).

<u>*Behavioural comparisons*</u>

The two datasets also allowed us to conduct behavioural comparisons between fish targets observed from the two systems. We focused these higher level analyses on two aspects of observed swimming behaviour by the two systems:

1. Orientations of swimming trajectories relative to a common direction. In this case, we chose the direction perpendicular to the acoustic axis of the split-beam transducers as the referencing direction. The image data from the DIDSON was re-aligned with the split-beam acoustic axis in post-processing stage as the axis of DIDSON was aimed approximately 13^{o} upstream relative to the split-beam transducers acoustic axis;

2. Swimming velocity in a 2-dimensional space: upstream (x) and cross-river (z).

The trajectory orientations for a fish target detected by the split-beam system, denoted as α, is estimated as $\alpha = arctan(s)$ where s is the slope of z-position vs. x-position based on the raw track data. This slope is estimated from a linear regression model of $z = s \cdot x + k$. The trajectory orientation for a fish detected by the DIDSON system, denoted as β, is estimated as $\beta = arctan(ss)$, and ss is estimated by the following formula:

$$ss = \frac{r_2 \cos\theta_2 - r_1 \cos\theta_1}{r_2 \sin\theta_2 - r_1 \sin\theta_1} \qquad (10)$$

where r_1 and θ_1 are the 1st identifiable range and azimuthal angle of a fish as it enters the view-field, and r_2 and θ_2 are the last identifiable range and azimuthal angle of the fish as it exits the view-field. Formula (10) is an estimator of the trajectory orientation based on two target positions. This estimator can be made more robust if more positions of the fish are read from the image. We carried out the orientation analysis on 1,324 and 545 upstream targets from the DIDSON and split-beam systems for this 36-hour time period. Figure 12 shows the distributions of trajectory orientations of fish targets from these two systems. The point estimates of means from these two distributions were not statistically different (p = 0.995). A Kolmogorov-Smirnov test on the two orientation datasets was carried out and we could not reject the null-hypothesis that the two distributions were from the same population (p = 0.074) at the 95% confidence level. The overall shapes of the two distributions appear to be similar.

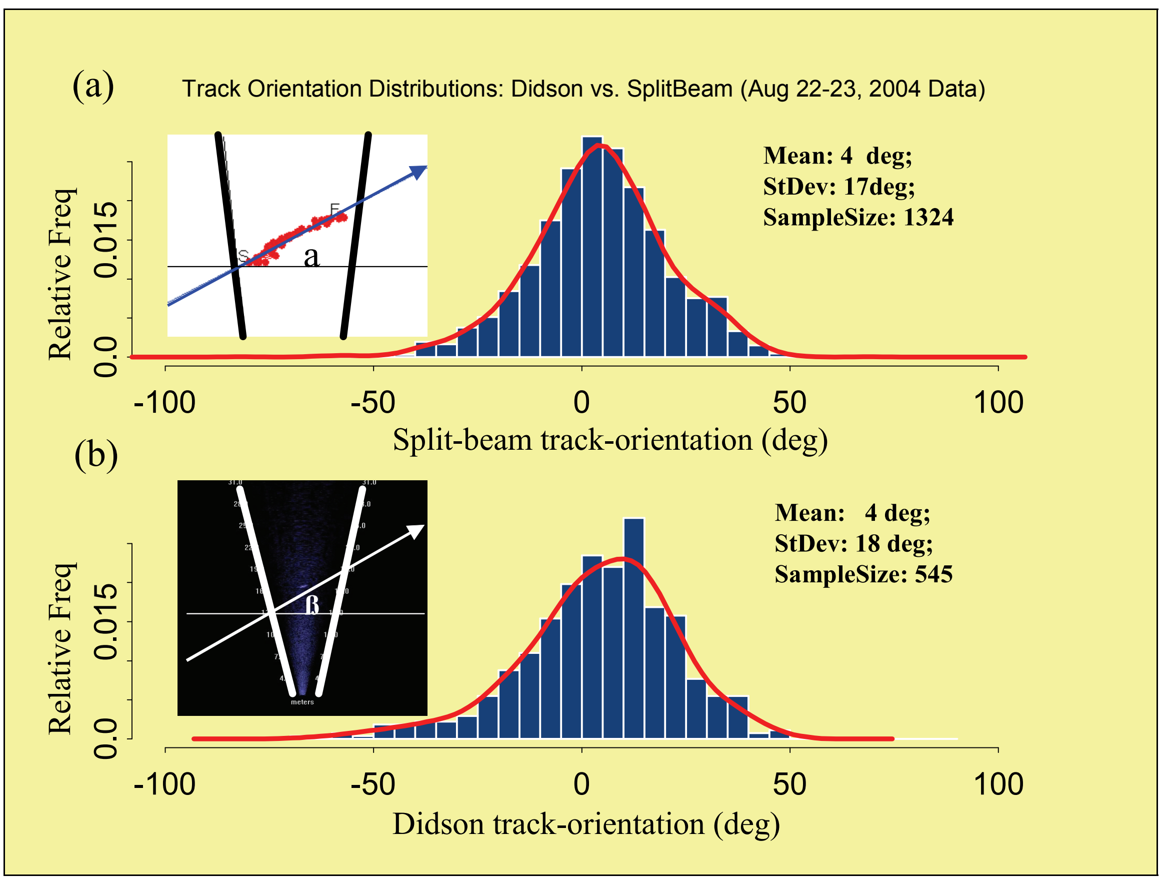

Figure 12. Distributions of trajectory-orientations of upstream fish detected by (a): the split-beam system, and (b): the DIDSON sonar in the common area over the 36-hour time-period. The smooth curves are estimated densities from the raw histogram data using an algorithm by Bowman and Azzalini (1997). The two sub-plots show the definitions of orientation angle α and β for the two systems.

The 2-D velocity of fish targets identified by the split-beam system, denoted as v_x and v_z, were estimated by linearly fitting the raw x-position and raw z-position track data to time (pings). The estimation models are:

$$x = v_x \cdot (n - n_0) / pr + x_0 \,, \qquad \text{[m /s]} \qquad (11)$$

$$z = v_z \cdot (n - n_0) / pr + z_0 \qquad \text{[m /s]} \qquad (12)$$

and

$$v = \sqrt{v_x^2 + v_z^2} \qquad \text{[m /s]} \qquad (13)$$

where n_0 and n are the 1st and the last ping number of the track, and pr is the ping rate (pings per second), and v is the magnitude of the 2-D velocity vector. The 2-D velocity for fish identified by the DIDSON sonar, denoted as u_x and u_z were estimated through the entrance and exit position information obtained from DIDSON images. The estimation models are:

$$u_x = \frac{r_2 \sin\theta_2 - r_1 \sin\theta_1}{F_2 - F_1 + 1} \times FR \qquad \text{[m /s]} \qquad (14)$$

$$u_z = \frac{r_2 \cos\theta_2 - r_1 \cos\theta_1}{F_2 - F_1 + 1} \times FR \qquad \text{[m /s]} \qquad (15)$$

and

$$u = \sqrt{u_x^2 + u_z^2} \qquad \text{[m /s]} \qquad (16)$$

In the above expressions, F_1 is the frame number when the fish is identified as it enters the view-field, and F_2 is the frame number when the fish exits the view-field; FR is the frame-rate (in frames per second); u is the magnitude of the 2-D velocity vector. Figure 13 shows the distributions of 2-D velocity magnitudes for the two datasets. The point estimates of means from these two distributions are statistically different with DIDSON showing a mean speed that is 10% lower than that estimated by the split-beam system. This discrepancy is partially due to the possibility that DIDSON observed proportionally more small fish than the split-beam. Despite this discrepancy in average speeds, the overall shapes of the two distributions retain some similar characteristics. For example, both are skewed towards lower speeds; both indicate a dominant mode around the typical salmon-like migration speed of 0.8 m/s at this time of the year plus a less prominent mode at a speed around 0.25 m/s. This lower-speed subpopulation is probably related to resident fish or other species of smaller sizes migrating upstream.

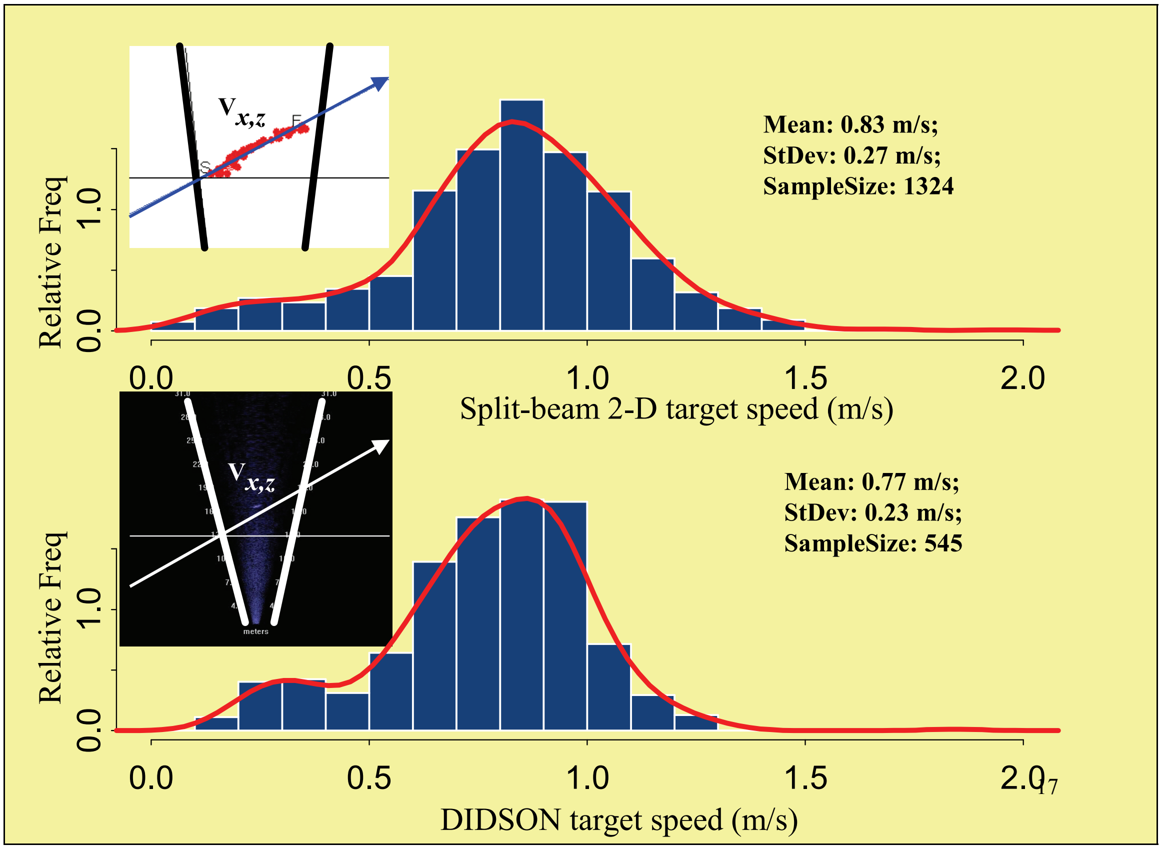

Figure 13. Distributions of 2-D velocity magnitudes of upstream fish detected by the split-beam system (the upper panel), and by the DIDSON sonar (lower panel) in the common area over the 36-hour time-period. The two sub-plots show the 2-D velocity vector measured by the two systems.

A regression model for target-strength and fish-length for Mission split-beam data

A regression model relating side-aspect target-strength to body-length was also derived from the 1324 split-beam fish, and 545 DIDSON fish used for the analysis of behavioural comparisons presented in Figures 12 and 13. The resulting regression model is:

$$TS = 23.7 \times Log_{10} L - 73.8 \qquad [dB] \qquad (17)$$

where target-strength TS is in decibels, and fish-length L is in centimetres. The slope of this model is quoted from the findings from a 1997-1998 Finish-Swedish study on hydroacoustic assessment of salmon in the River Tornionjoki funded by the European Commission (Final Report of EU Study Project 96-069, 1999). The intercept of -73.8 dB was derived from the TS data of the 1324 split-beam fish and the length data of the 103 sockeye obtained from the PSC August 21, 2004 test-fishing catches conducted near Haney, B.C., (see Figure 1). Measured lengths L_D of the 545 DIDSON fish were transformed to estimates of the true lengths L_T by an empirical formula of

$$L_T = L_D - 1.36 \times R \times \tan(\varphi) \qquad [m] \qquad (18)$$

where R is target range in metres, and φ is the azimuthal angular resolution of DIDSON. φ is 0.4^{o} for detection mode, and 0.3^{o} for identification mode. The correction factor 1.36 in (18) was estimated by calibrating DIDSON readings of the diagonal length of a known target that was placed along the azimuthal direction of the acoustic beam at a 7 m range. In theory, this correction factor is constrained between 0 and 2.

The performance of the model in predicting sockeye length-frequency distribution from measured side-aspect target strength data was evaluated by comparing the length-frequency distribution of the 1324 spit-beam fish with that of the 545 DIDSON fish. Figure 14 shows the two distributions. The point estimates of means from these two distributions (58 cm vs. 59 cm) were not statistically different according to a Welch Modified test (p = 0.644). With a Kolmogorov-Smirnov testing on the two distributions we could not reject the null hypothesis that the two distributions were from the same population (p = 0.113; 95% C.I.). The overall shapes of the two distributions are similar. Both are skewed towards small lengths. We emphasize that Formula (18) is an empirical relation which was only verified at the calibration range of 7 metres at our site. The correction factor in (18) may also depend upon range and length of interested targets. Nevertheless, it is encouraging that the two independent models of (17) and (18) led to similar length-distributions for the two independent datasets (split-beam vs. the DIDSON).

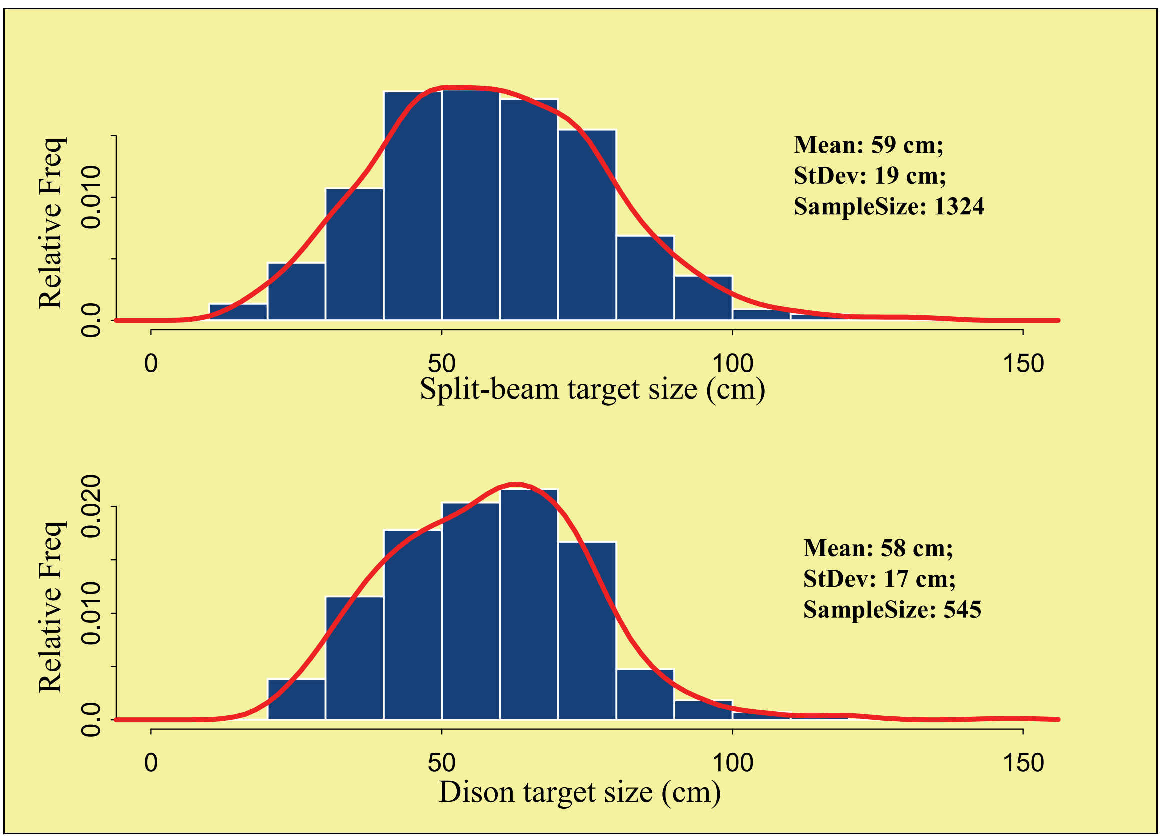

Figure 14. Distributions of fish lengths estimated by the split-beam system (the upper panel) and by the DIDSON system (the lower panel).

DIDSON ASSESSMENT OF FISH-FLUX ESTIMATION IN THE SPLIT-BEAM BLIND ZONES

The uneven profile of the river-bottom (as shown in Figure 8) prevents the split-beam sonar from grazing along the bottom to insonify the bottom-oriented fish for long ranges. The bottom features block the probing sound-beam at a certain range causing it to be ineffective in detecting targets beyond that range. The range limitation by the bottom is critically dependent upon the aiming angle of the beam and transducer distance off the bottom. Thus, the near-bottom area, shadowed from acoustic insonification by the split-beam transducers is the *split-beam blind zone*. Figure 15 shows an example of the cross-section of a blind zone near the left bank.

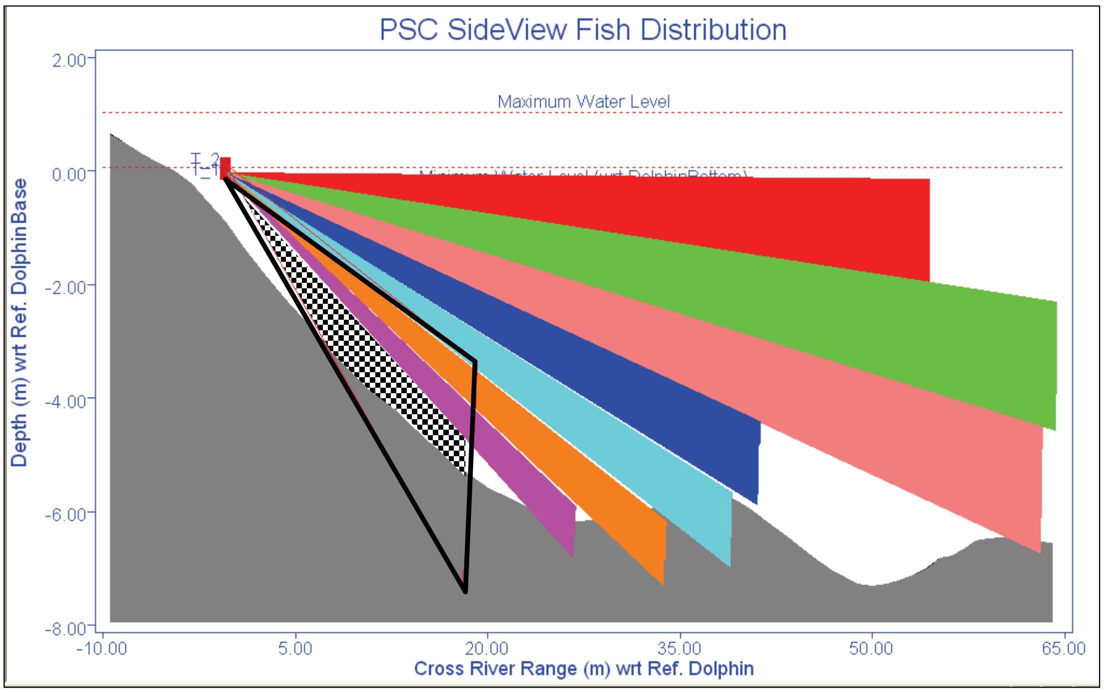

Figure 15. Example of a split-beam blind zone: the area under the pink-coloured beam-coverage area is not sampled by the $2^o \times 10^o$ split-beam transducer due to interferences of bottom features (not shown by the smoothed profile). The heavy lines outline a geometrical sampling area by the 12-degree DIDSON-beam aimed at -16^o relative to the river-surface. The area highlighted with the checker pattern is a partial blind zone over which DIDSON data were used to assess the split-beam fish-flux extrapolated from the sampled areas above the blind zone.

The current split-beam model estimates fish-flux in the blind zone by extrapolating the flux estimates from the insonified area using a nearest-neighbour model (Bowman and Azzalini, 1997). The extrapolated flux needs to be assessed for its accuracy with direct measurements of the flux in the blind zone through other means. DIDSON provides an opportunity for this assessment. In late September of 2005, we conducted an experiment off the left bank to measure fish-flux in a split-beam blind zone with the DIDSON unit.

Method

We deployed equipment for the experiment in a similar fashion to that described in the previous section. To sample fish in the blind zone, we aimed the DIDSON unit at -16^o, i.e., focusing most of its coverage area in the near-bottom blind zone. The sampling geometry of the 12^o DIDSON beam in relation to the sampling area of the 2^o×10^o split-beam transducer-beam is shown in Figure 15. The DIDSON beam only overlapped the sampling area by the 2^o×10^o transducer-beam at 2 lowest aims of -10^o and -12^o, respectively. We call this overlap area the “commonly insonified area” by the two systems. The remaining 12-degree beam area sampled a portion of the split-beam blind zone highlighted by the checker pattern in Figure 15. We call this area the “partial blind zone”. Since the DIDSON image data showed strong bottom interference by an in-shore plateau extended to 6-m range, our comparative analysis was limited to a range segment in the partial blind zone from 6 to 20 metres.

Because DIDSON could not resolve vertical positions of fish when the unit was deployed in the orientation as shown in Figure 15, we were unable to partition imaged fish into the commonly insonified area and the blind zone. This made it impossible to conduct a direct comparison of split-beam extrapolated flux and DIDSON flux in the blind zone. To overcome this limitation we assumed that DIDSON detected the same amount of flux as the split-beam transducers in the commonly insonified area. The DIDSON fish-flux in the partial blind zone was then estimated by subtracting the split-beam flux in the commonly insonified area from the DIDSON flux measured by the entire 12-degree beam.

Results

Using the sampling configuration described above, we collected 18 hours of DIDSON data concurrently with the split-beam data off the left bank. The two datasets provided the basis for the blind zone flux analysis. Detailed examination of DIDSON image data collected from this time period revealed that there were two types of fish in terms of body-lengths. These are:

1. upstream migrating fish of adult salmon sizes with a mean body-length around 50 cm;
2. upstream migrating fish of small sizes with a mean body-length of less than 30 cm. Two very distinctive features of these smaller fish were observed:
    a) they appeared to be migrating in areas extremely close to the bottom and well below the sampling zone by the split-beam transducer as shown in Figure 15;
    b) they appeared to be migrating in schools with each school comprising very large numbers of individuals.

The identity of these small-sized fish has not been ascertained. As a result, DIDSON detected fish of mixed species in the partial blind zone. Figure 16 is an estimated length-distribution of 430 fish detected by DIDSON on September 22, 2005. Also shown is the fit to the distribution by two normal distributions by assuming that the resulting distribution originates from two species of different mean lengths. The fitting was obtained from a non-linear fitting algorithm provided in S-Plus (S-Plus, 2000) with the objective of minimizing the squared sum of residuals between the original distribution and the modeled distribution.

The length distribution of fish detected by the split-beam system for the same time period was also estimated by applying the regression model of (17) to the measured TS values of 730 fish targets. The estimated length-distribution from the split-beam data is shown in Figure 17, together with the length-distribution of the DIDSON fish. It appears that the split-beam system detected a significantly higher portion of large-sized fish than the DIDSON sonar. The large mean body-length of 81 cm probably corresponds to the migration of chum salmon past Mission in late September. The lack of small fish (< 30 cm) in the split-beam data is consistent with the hypothesis that the transducer beam of the split-beam system was too high to effectively sample these extremely bottom-oriented small migrating fish. The different species-compositions in the split-beam and DIDSON data made it difficult to carry out direct comparisons of the two flux estimates in the blind zone. To overcome this difficulty, we utilized the estimated compositions between small and large fish in the DIDSON data to 'remove' small fish from the comparison analysis. The fitting of the length-distribution of DIDSON fish (Figure 16) indicates that 55% of the fish detected by DIDSON belong to small fish, and 45% fall into the category of large fish.

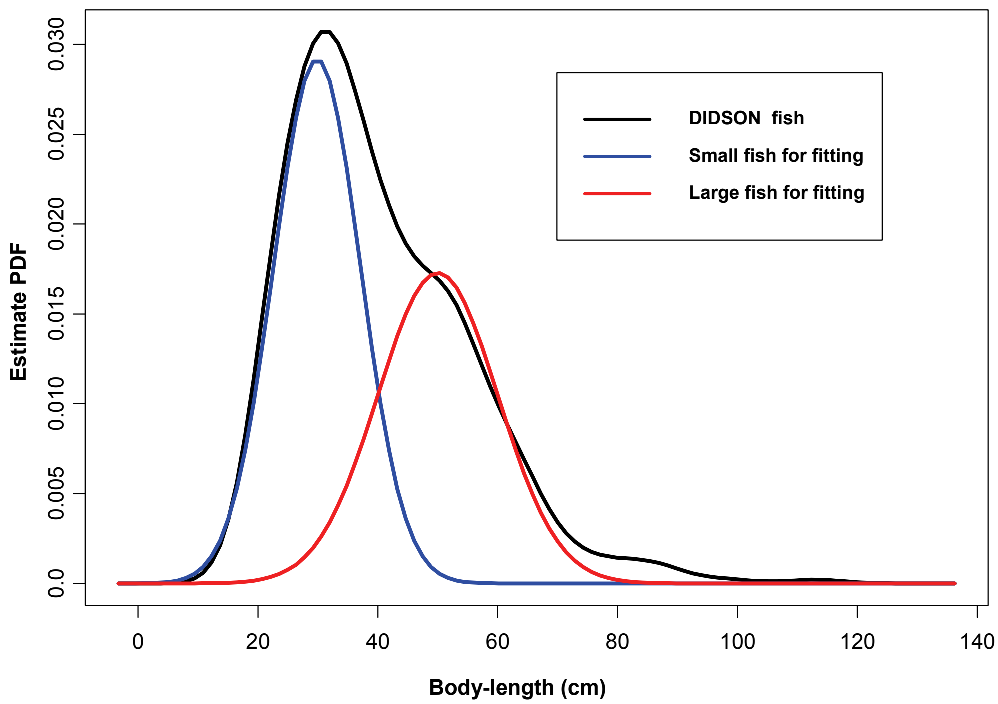

Figure 16. Length-distribution of 430 fish detected by DIDSON during the experiment (dark-line). The distribution is fitted to two normal distributions (red and blue lines) constructed from the two assumed underlying populations: small- and large-sized fish with means of 30 cm and 50 cm, and standard deviations of 7 cm and 10 cm, respectively.

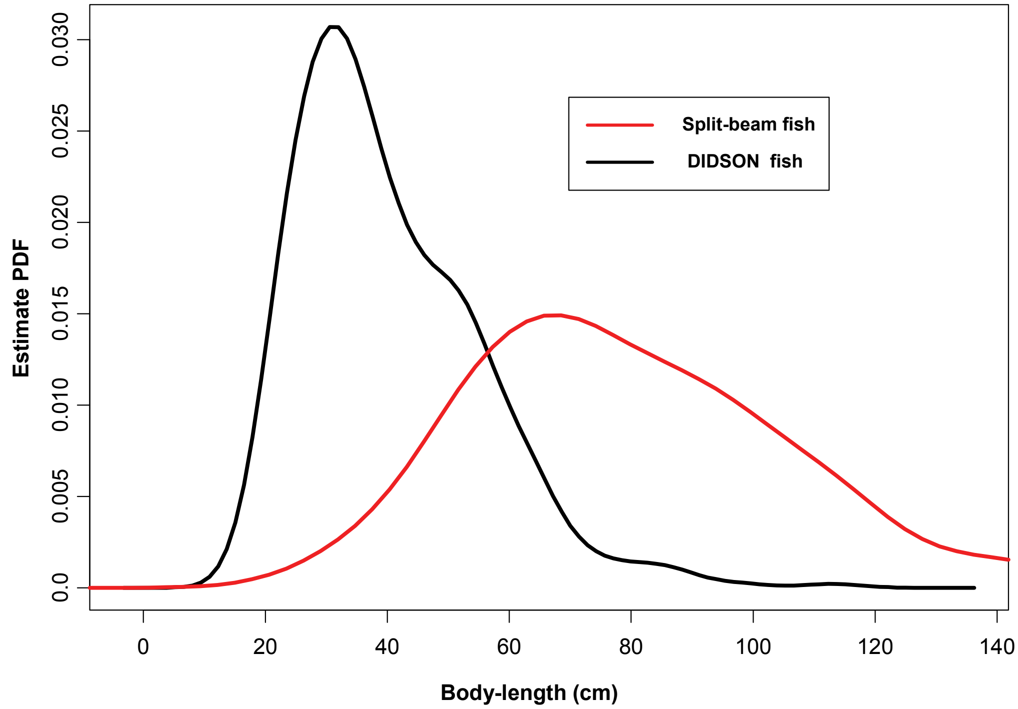

Figure 17. Length-distribution of 730 fish detected by the split-beam system during the experiment (red-line) with a mean of 81 cm and a standard deviation of 28 cm. The length-distribution of the 430 DIDSON fish is also shown (dark line) for comparisons.

For the two heaviest passage hours from 1500 to 1700 on September 22, the split-beam model estimated a total of 839 upstream fish in the partial blind zone, and the DIDSON sonar observed a total of 897 large-sized upstream fish (Table 2). We also observed a significant change in length-compositions of DIDSON observed fish during very low salmon passage hours from 0100 to 0200 on September 24 when the unit detected a vast majority of small sized fish (< 30cm), resulting in only 30% of large-sized fish. Table 2 is a summary of flux comparisons in the partial blind zone based on 4 hours of DIDSON and split-beam data.

Table 2. Summary of comparisons of estimates of upstream fish flux between the DIDSON and the split-beam systems in the blind zone.

Date	Hours	2-hr DIDSON flux	2-hr Split-beam flux
22-Sep-05	1500 & 1600	897	839
24-Sep-05	0100 & 0200	62	31

The overall comparison shows a 9% relative difference between the two estimators for the blind zone. It appears that the nearest-neighbour extrapolation method provided a reasonable estimate of fish-flux in the blind zone for the heavier passage hours resulting in only a 6% relative difference between the two estimates. That the split-beam system failed to effectively sample the small fish is advantageous as these non-salmon species would likely cause a significant high bias in our salmon-flux estimation had they been included in the estimation database. To illustrate this bias effect, we conducted a numerical comparison between the two flux estimates by including all the small fish in the DIDSON data. This resulted in a DIDSON estimate of 4649 upstream migrating fish in the partial blind zone, which was more than 5 times higher than the split-beam estimate.

DIDSON OBSERVATIONS OF DEBRIS AND FISH OFF THE RIGHT BANK

Assumptions inherent in the current split-beam estimator are that fish behaviour and the acoustic characteristics of debris are uniform across the entire river. These assumptions, as a result of our inability to obtain reliable measurements of fish-behaviour parameters from the mobile split-beam system, must be examined and validated so that we can assess the potential bias in upstream fish-flux estimations across the entire river. The estimator (Formula (8)) uses the assumption of uniform fish behaviour to extrapolate behavioural statistics measured off the left bank by the shore-based system to the middle channel and northern section of the river. These statistics are required by the estimation model for the mobile split-beam data to estimate fish-flux beyond the sampling area covered by the left-bank system. The key parameters are downstream ratio of fish-flux and swimming speed in the upstream and downstream directions. Another key parameter in Formula (8) is m_T, the averaged number of fish targets detected per transect. m_T (related to fish density) is estimated from the data acquired by the mobile split-beam transducer deployed from the transect vessel. It may be affected by two opposing biases caused by the mobile sampling system that:

1. overestimates fish density by including non-fish targets due to degraded information from the mobile split-beam data, and
2. underestimates fish density by under-sampling fish targets in shallow waters when the downward looking sound-beam becomes increasingly blind, and fish start avoiding the vessel as the vessel approaches the shore-areas.

We present results on fish behaviour and characteristics of debris based on our DIDSON/split-beam work conducted near the right bank area and in the middle channel of the river in the 2004 and 2005 seasons.

Debris off the right-bank

From 1999 to 2002, several attempts were made using split-beam sonar on the right bank to examine characteristics of both fish and debris. The data-acquisition method for the split-beam work on the right bank was similar to that designed for the left bank split-beam work, i.e., a shore-based sideward-looking system was deployed to sample the water column with a $2^o\times10^o$ and a $4^o\times10^o$ transducer at multiple aims. In 2002, data were collected on the right-bank in July and August. These data confirmed a pattern of downstream targets near the surface that were observed from previous years, and appeared to be large debris discharged from upstream. Most of these debris targets were drifting downstream off the right bank where strong currents created a prominent turbulence zone as illustrated by acoustic scattering of an eddy-like structure shown in Figure 18. A right bank target-distribution was obtained on July 30, 2002 by a $4^o\times10^o$ split-beam transducer deployed on the right-bank (Figure 19). A strong surface-oriented pattern of downstream targets were identified by the split-beam system. These targets, unlike typical downstream targets observed off the left bank, showed a large mean target strength of -35 dB. Note: the maximum sounding range was limited to 40 metres for the surface aim as indicated in Figure 19. The data from a $2^o\times10^o$ transducer with a maximum sounding range of 50 metres indicated that these surface-oriented downstream targets were distributed over a large surface area from the inshore area to the turbulence zone.

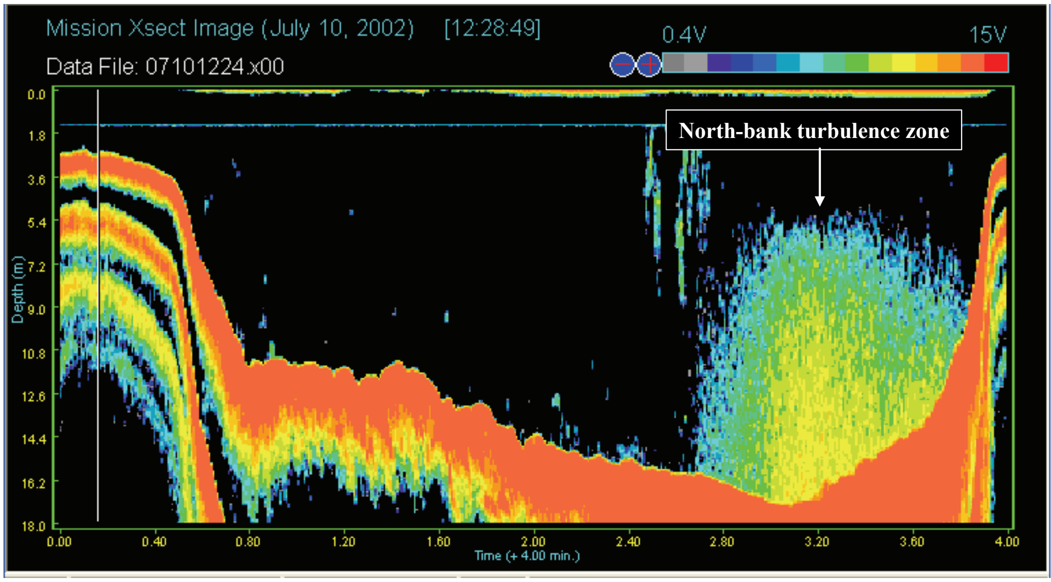

Figure 18. Echogram acquired by a transect-sampling of the river at the site with a downward looking single-beam 32° transducer showing a prominent acoustic scattering zone near the right-bank at the site where a turbulence structure is present.

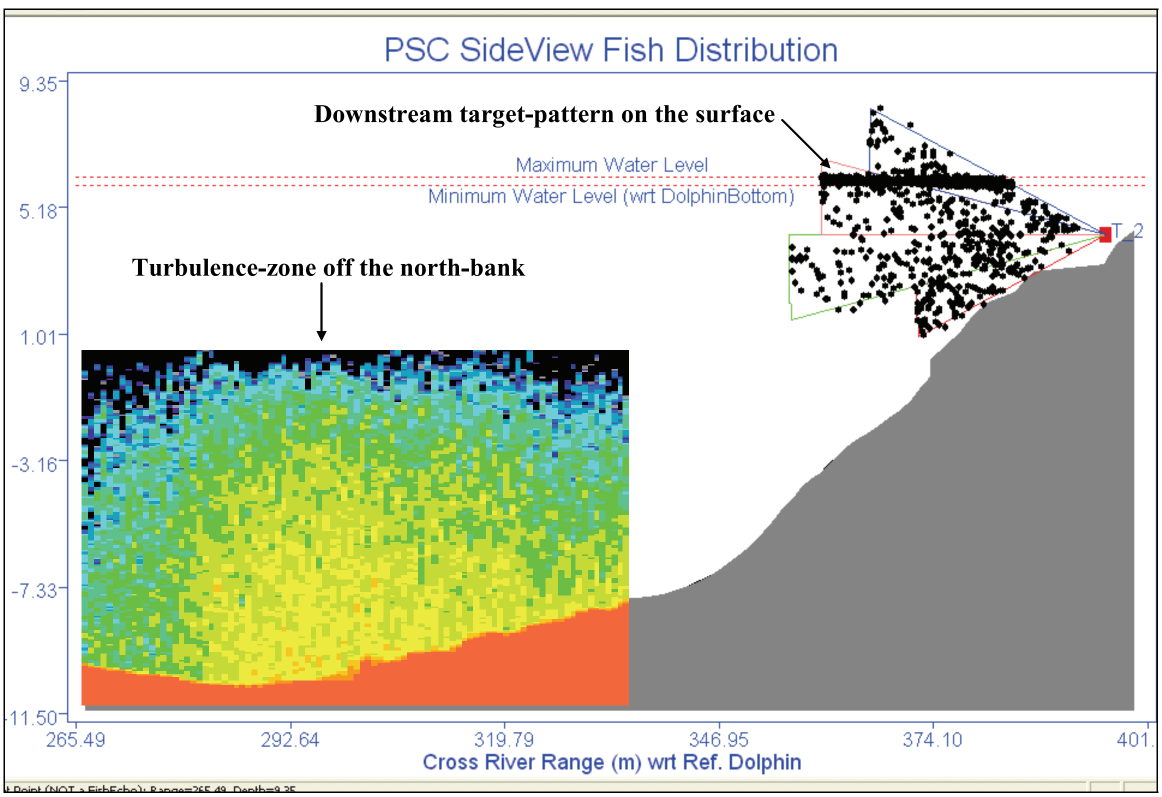

Figure 19. Right-bank target distribution obtained by a $4^{o}\times10^{o}$ split-beam transducer on July 30, 2002 with a maximum sounding range of 40m. A strong pattern of surface-oriented downstream targets were identified with a mean target-strength of -35dB. Also shown in the figure are the off-shore portion of the acoustic pattern of the right-bank turbulence, and its approximate location from the transducer. The in-shore portion of the turbulence is not shown in the figure.

Although these surface-oriented downstream targets were likely to be debris drifting down from upstream, their larger TS readings presented an alternative hypothesis that these targets were milling or abnormally migrating fish. However, ascertaining the nature and identity of these targets was impossible without the aid of a specialized technology, given the murky riverine conditions. These mysterious large downstream targets off the right bank remained unidentified until their acoustic images could be examined using the DIDSON system in 2004.

To overcome range-limitations of DIDSON in the examination of these downstream targets near the right bank, we deployed the DIDSON unit from the PSC's regular echo-sounding vessel so that we could image any section of the river from the vessel. To image the right-bank targets near the turbulence zone, the vessel was positioned at a location about 40 metres offshore from the right bank and 30 metres from the northern boundary of the turbulence zone (Figure 20). The 1.8-MHz identification mode was used to image the targets, and the maximum sounding range was set to 11 metres.

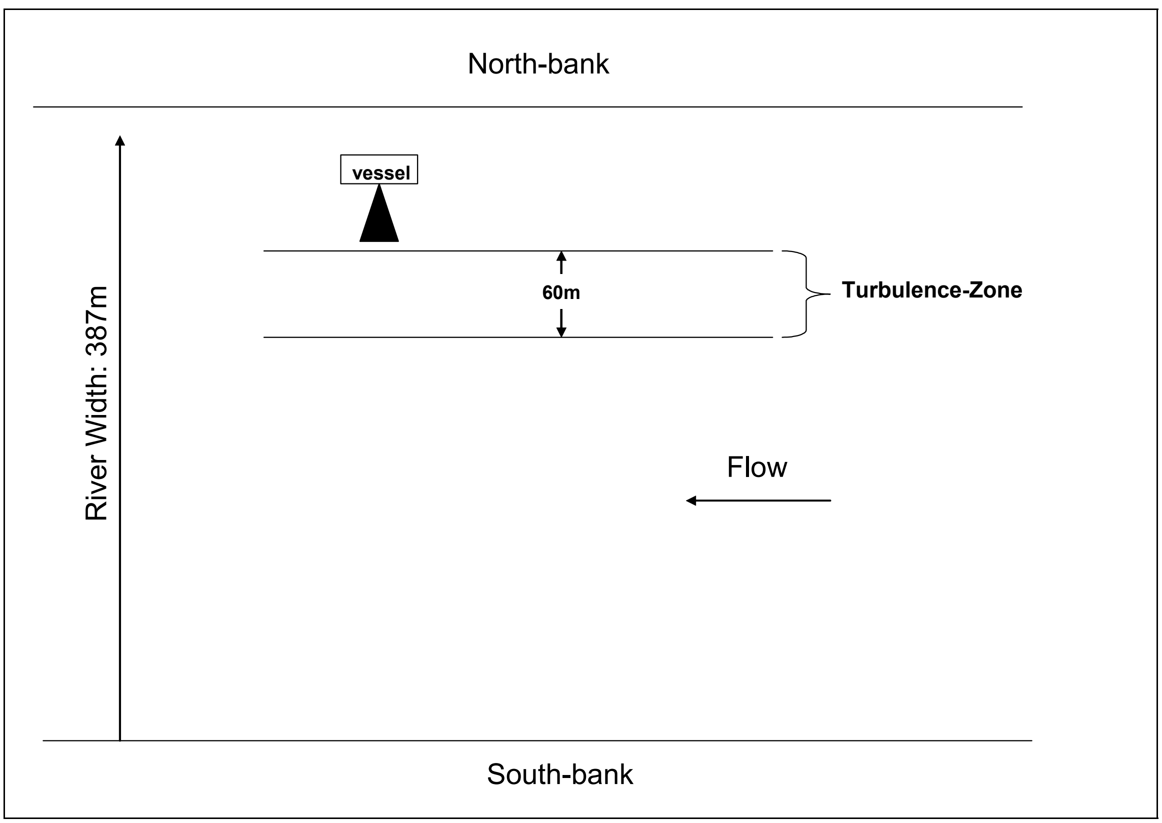

Figure 20. Schematic illustration of the configuration of the September 2, 2004 DIDSON experiment off the right-bank to image targets near the turbulence zone. The solid triangle outlines the coverage area by the 29-degree DIDSON beam.

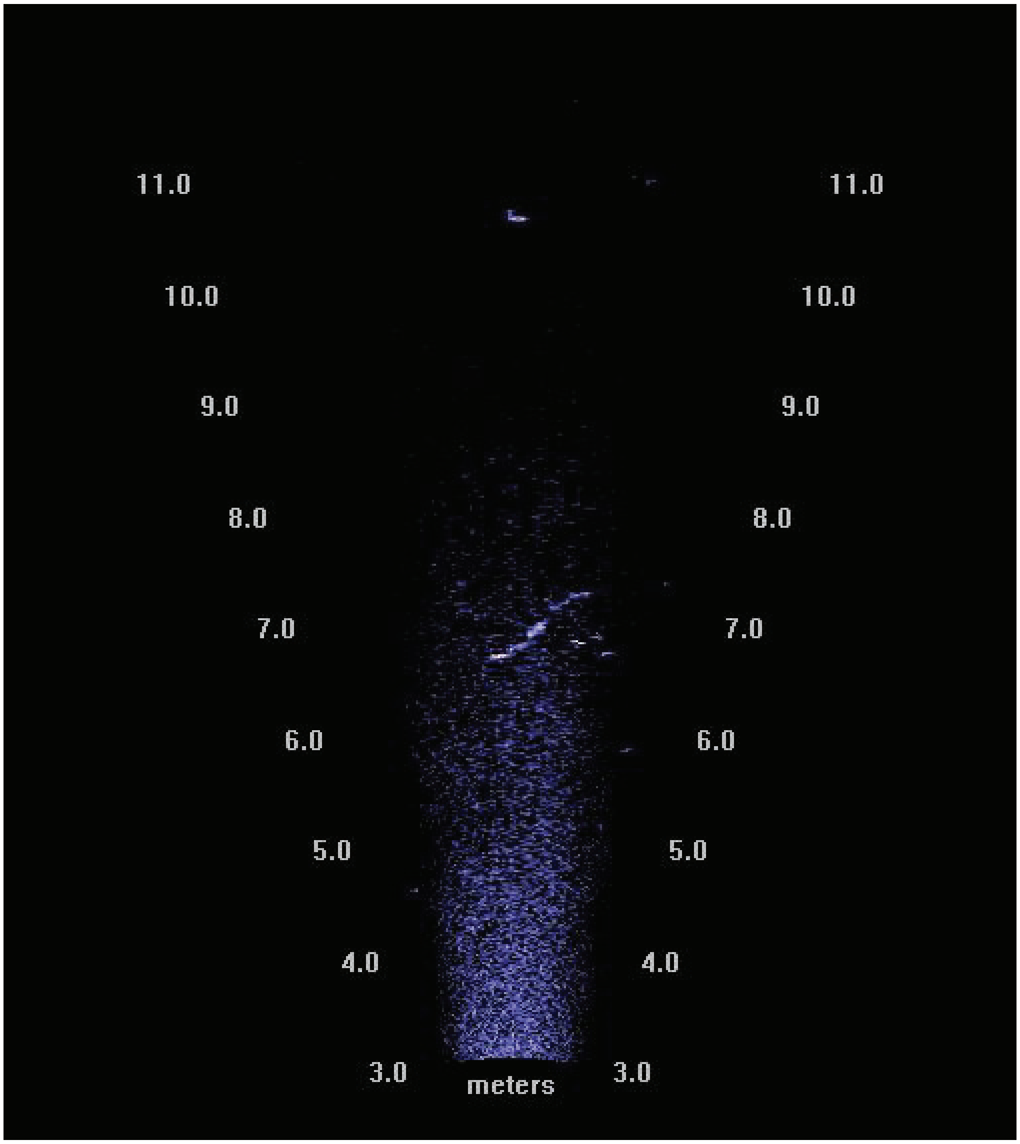

Figure 21. A DIDSON image showing a 1-m long tree-branch drifting downstream together with a few other small debris targets in the range bin between 7 and 8 metres from the DIDSON.

A few hours of image data were collected near the turbulence zone on September 2, 2004. A large number of downstream targets were captured by the DIDSON image. By viewing these images using the real-time play-back function of the DIDSON software, it was confirmed that most of these downstream targets were tree-branches, tree-trunks, logs, and other types of non-fish targets (Figure 21). Downstream fish were also observed but they appeared to be small fish of other species rather than adult salmon.

Fish targets and their behaviour near the right-bank

The river section off the right bank is an important location where fish migrate upstream. Historical data based on the transect-sampling indicate that 10 to 20% of salmon migrate upstream in an area approximately 60 metres off the right-bank at Mission. The current split-beam estimator system does not provide direct measurements on fish-flux in this key area. Fish-flux across the right-bank area is estimated via Formula (8) by assuming that these fish behave similarly to fish migrating near the left-bank. Several attempts were made prior to the 2005 season to assess fish behaviour with sideward-viewing split-beam systems. While we learned a few unique features of migratory behaviour of fish in this area from these attempts and the corresponding split-beam data, we were unable to ascertain the behaviour and the nature of fish-like targets by independent means. With DIDSON, the observed fish-behaviour unique to the right bank could be verified, and the potential impacts of this behaviour on estimation accuracy could be assessed using Formula (8).

In the 2005 field program season, a comprehensive experiment on fish-behaviour and fish-flux measurements was conducted using a combination of the DIDSON and a split-beam system on the right bank. The split-beam system used a $4^o \times 10^o$ transducer to sample the water column at 3 vertical angles of 0^o, $-2\,^o$, and -6^o. The transducer was aimed at a cross-river bearing of approximately 150 degrees. The DIDSON was deployed within a 20-m range upstream from the split-beam transducer at two separate locations to image the river at a cross-river and upstream bearing, respectively, with a maximum sounding range of 25 metres (Figure 22).

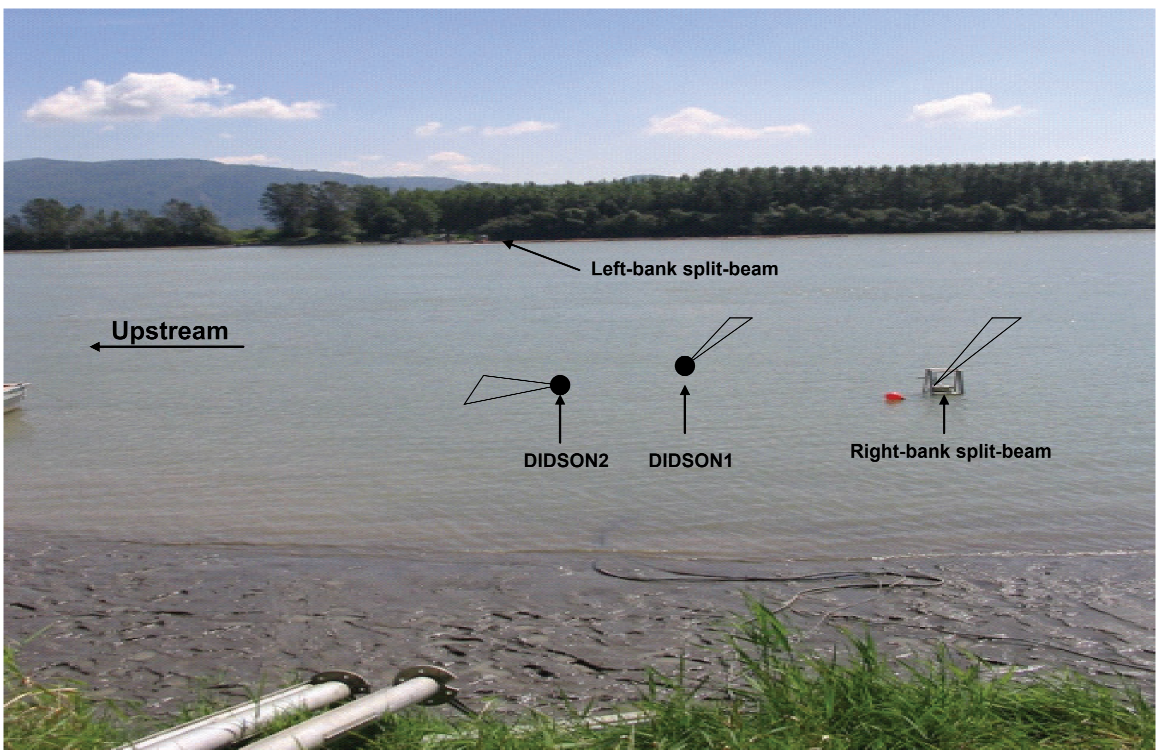

Figure 22. Photo taken from the right bank showing the locations of the two shore-based split-beam systems, the two deployment locations of the DIDSON, and the corresponding bearings of the sound-beams.

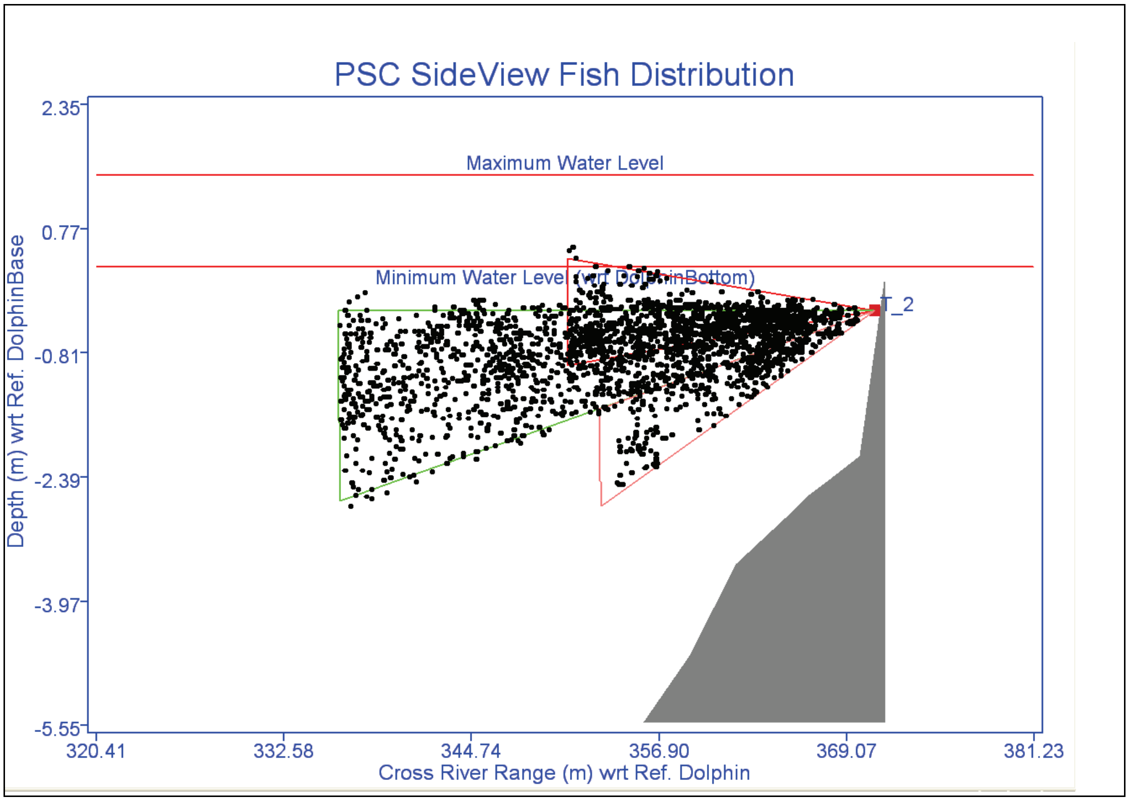

Figure 23. Target-distribution near the right-bank obtained by a $4^{o}\times10^{o}$ split-beam transducer with vertical aims of 0, -2 and -6 degrees on August 19, 2005.

Most targets insonified by the right-bank split-beam system on Aug 21, 2005 were oriented in an upstream direction and were distributed uniformly throughout the upper water column (Figure 23). In comparison to the left-bank upstream targets, these right-bank upstream targets displayed a distinctive shoreward orientation in their migration trajectories, a feature observed in 1999, and 2001 from the right-bank split-beam data. The shoreward orientation is evident on the echogram and with the corresponding target trajectories on the cross-river and upstream coordinates (Figure 24a&b) where the target is shown to display a significant on-shore movement of 10 metres. To identify the nature of these upstream targets, we deployed the DIDSON unit at two nearby locations from the split-beam transducer (Figure 22). Image data were acquired with the DIDSON unit at these two locations with a cross-river and upstream bearing. The data confirmed that these targets were indeed upstream migrating fish with strong on-shore movement. In the image example shown in Figure 25, the fish displayed a 10-m displacement towards the shore as they migrated upstream.

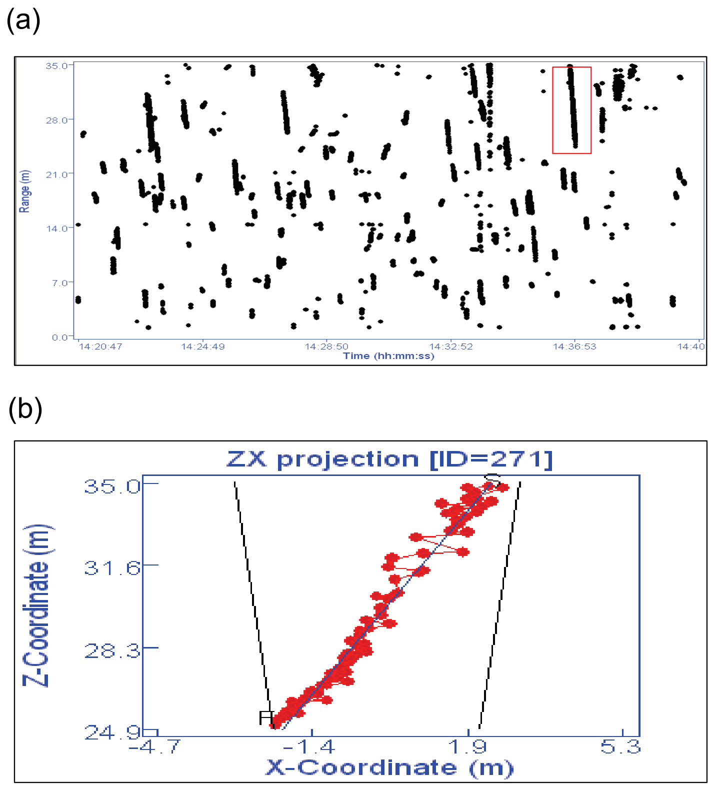

Figure 24. (a): A 20-miniute echogram view of typical right-bank upstream target tracks obtained by a 4°×10° split-beam transducer at -2° aim on August 19, 2005; (b): A cross-river (*Z*) vs. along-shore (*X*) view of the trajectory of the track outlined in (a). Letter *S* and *F* are the entrance, and exit points of the target relative to the beam.

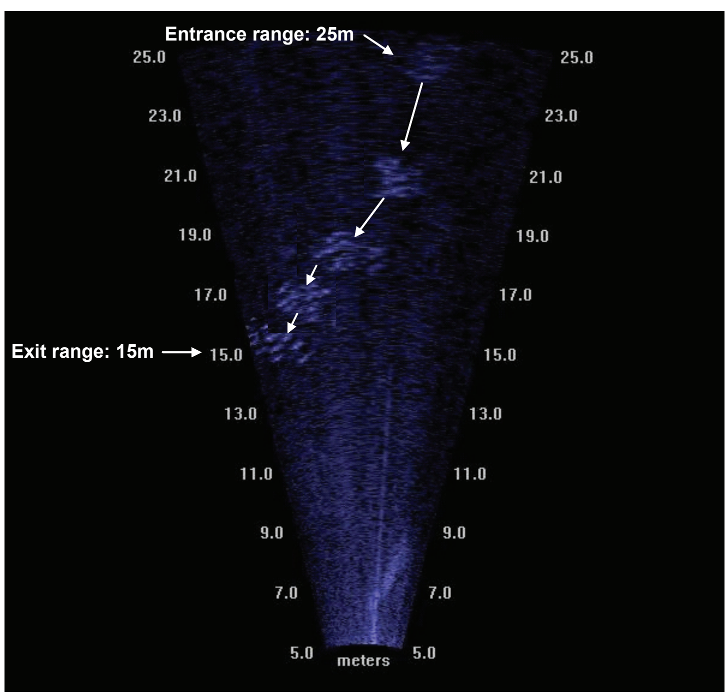

Figure 25. Five merged snap-shots of a school of upstream migrating fish. Arrows outline a general travel direction of the fish-school. The image data were obtained with the DIDSON unit on August 19, 2005 near the right bank. The bearing of the DIDSON unit was almost parallel to the bearing of the split-beam transducer for the data shown in Figure 22, i.e., aiming at a cross-river bearing.

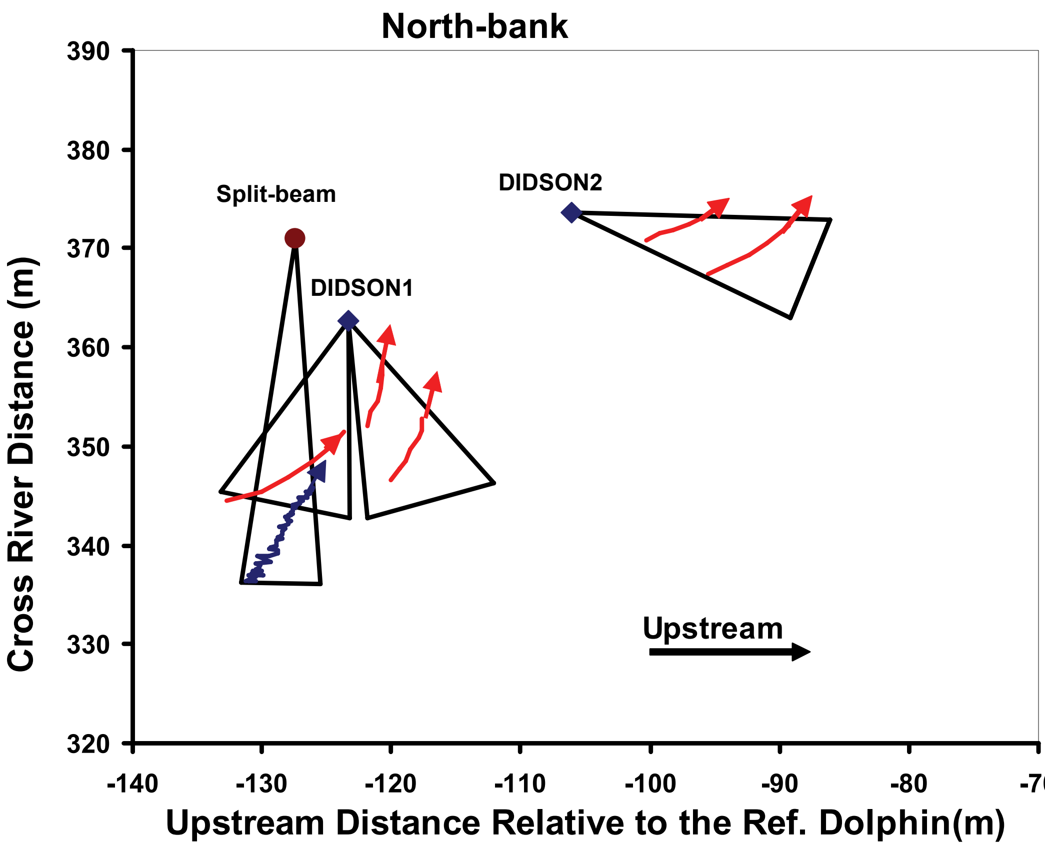

Figure 26. Typical trajectories of upstream migrating fish observed by a $4^o \times 10^o$ split-beam transducer (the blue arrow), and a DIDSON unit (the red arrows) deployed at the two locations near the split-beam transducer. These data were obtained on August 19, 21 and 24, 2005. Also shown are the respective azimuthal view-fields of 10^o and 29^o for the $4^o \times 10^o$ and the DIDSON transducers.

Figure 26 shows typical upstream fish trajectories obtained from DIDSON and the right-bank split-beam transducer during the experiment. Both systems observed large inshore movements by fish migrating upstream near the right bank. With the confirmation from the DIDSON of identities and behaviour of detected targets by the split-beam system, we were able to assess behavioural differences between fish migrating off the left-bank and right-bank areas from the data acquired by the left-bank and right-bank split-beam systems. Table 3 summarizes behavioural statistics of fish migrating near the left bank versus fish migrating near the right bank from 5 days of the split-beam data collected from both banks. Means of the statistics were estimated by taking the average of corresponding statistic over the total samples from these 5 days.

Table 3. Summary of 3 behavioural statistics on fish migrating off the left- and right-bank areas based on 5 days of split-beam data obtained from the left and right-bank systems.

Date	Downstream ratio (%)		Upstream speed (m/s)		Trajectory angle wrt shoreline (deg)	
	Left-bank	Right-bank	Left-bank	Right-bank	Left-bank	Right-bank
19-Aug-05	3.8	9.6	0.83	0.70	3.1	16.7
28-Aug-05	4.4	2.5	0.74	0.62	3.1	11.8
29-Aug-05	7.1	2.7	0.76	0.62	3.5	12.2
30-Aug-05	4.3	3.4	0.74	0.62	4.8	12.2
31-Aug-05	2.1	3.5	0.67	0.61	6.7	9.4
Grand means	4.5	3.2	0.74	0.62	4.5	11.5

It appears that fish migrating near the left bank show a slightly higher downstream ratio than that of fish migrating near the right bank. However, fish migrating in the right-bank area display significantly greater on-shore movements than fish migrating near the left-bank. This results in a smaller speed-component in the upstream migration direction for the right-bank fish. The upstream speed of right-bank fish is approximately 16% smaller on average than the left-bank fish. Therefore, the application of upstream speed of the left-bank fish to the right-bank fish would inflate the resulting right-bank fish-flux estimated from Formula (8) if all other variables in (8) are estimated accurately.

Fish behaviour in the middle channel of the river

Although a majority of the salmon are observed migrating upstream near the left bank area at the hydroacoustic site at Mission, there is migration throughout the river. Historical data indicate that about 10-15% of salmon travel upstream through the middle channel. As previously stated, the current split-beam estimator system does not provide direct measurements on swimming speed and direction of travel for fish in this area. The acoustic sampling of fish targets by conventional sonar systems in this area is more challenging than in near-shore areas due to stronger currents, deeper water, and relatively smaller numbers of fish available for sampling. In 2005, tests were conducted using the DIDSON to monitor fish behaviour in the middle section of the river at the site. These trials demonstrated that DIDSON is an effective sampling tool in such an environment due to its larger sampling volume and the superior target-identification power in comparison to a conventional sonar system.

The trials were carried out on the PSC's regular echo sounding vessel. As the vessel conducted a total of 3 stationary soundings each day in the middle of the river, the DIDSON was launched from the vessel to image fish during these opportunities. A total of 30 minutes of image data were collected at approximately 2400 hour of August 26, 2005 from the sounding station in the middle channel. The DIDSON was deployed with its 12^{o} beam on the cross-river plane so that the 29^{o} high-resolution beam could be best utilized to monitor swimming speed and direction of travel for fish migrating upstream and downstream (Figure 27). The sonar head was aimed at a pitch angle of 45^{o} downward relative to the river surface so that the system only monitored the fish migration in the vicinity of the vessel but not right beneath the vessel to minimize any effect from the boat on the natural behaviour of the fish. The maximum sounding range in the water was approximately 15 m, and the vessel was anchored without the engine running.

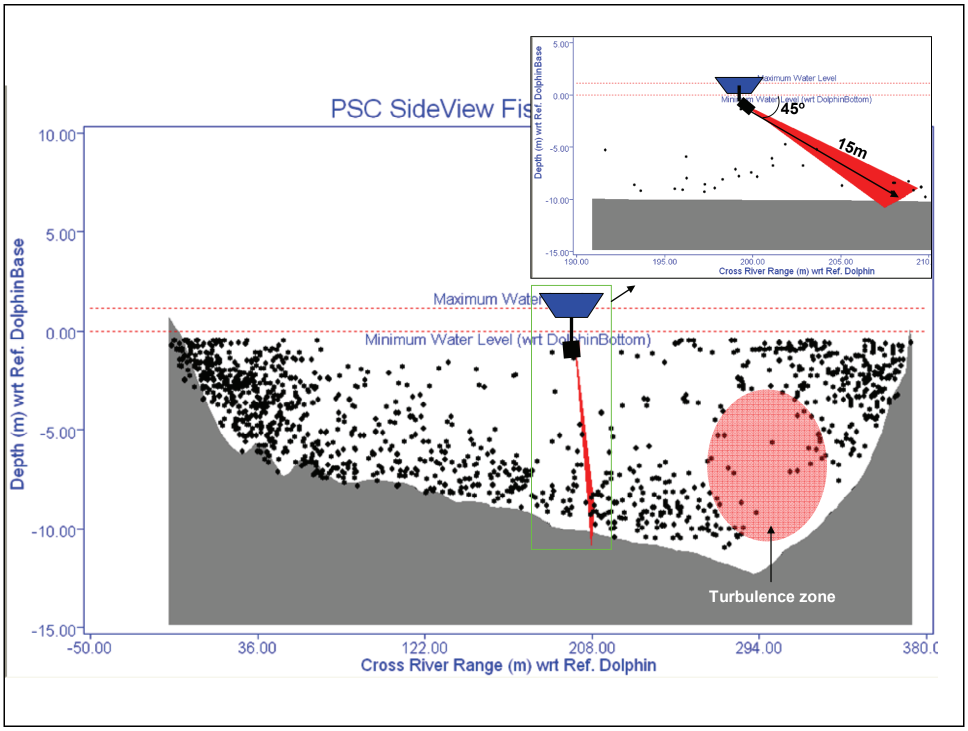

Figure 27. Configuration of the DIDSON experiment on monitoring fish behaviour in the middle section of the river on August 26, 2005. The main plot is a cross-river view of the sampling position and the sampling area by the DIDSON 12-degree beam relative to the turbulence zone and the two bank areas. Note: the pitch angle of 45° is severely distorted in the main plot because the vertical plotting scale is greatly exaggerated relative to the horizontal scale. The subplot shows the sampling geometry in detail with the same vertical and horizontal scales. The dots are fish targets detected by a downward-looking single-beam transducer.

From the image data, we identified a total of 36 fish, and estimated their behaviour using the behavioural statistics of downstream ratio, and upstream swimming speed. The results are summarized in Table 4 together with the corresponding statistics estimated by the left-bank system for the same hour. From these limited data, it appears that the downstream ratio of fish migrating in the middle channel of the river was reasonably well represented by the left-bank fish. However, the upstream migration speed of fish in the middle channel was approximately 13% lower than that of the left-bank fish. Therefore, the application of upstream speed of the left-bank fish to the middle-channel fish would inflate the middle-channel fish-flux estimated from Formula (8) if all other variables in (8) are estimated accurately.

Table 4. Summary of behavioural statistics of fish migrating in the middle channel of the river and fish migrating near the left bank. The results were based on 36 fish observed by DIDSON in the middle of the river, and 225 fish observed by the left-bank split-beam system around the mid-night hour on August 26, 2005.

Downstream ratio R_d (%)		Upstream speed v_x (m/s)	
DIDSON R_d in the middle channel	Split-Beam R_d near left bank	DIDSON v_x in the middle channel	Split-Beam v_x near left bank
5.5	5	0.72	0.82

DIDSON OBSERVATIONS OF FISH REACTIONS TO THE MOBILE SOUNDING VESSEL

A key question with regard to vessel-based mobile sampling of fish-flux in a riverine environment is: do fish avoid the vessel? This was a question formally raised by the Mission Hydroacoustic Facility Working Group in the assessment of the Mission hydroacoustic facility during the 1994 Fraser River Sockeye Review (Mission Hydroacoustic Facility Working Group, 1994). This question must be answered before we can investigate more specific questions such as: does the reaction of fish to the vessel result in biased estimates of fish passage? and if so, how large is the bias? The PSC-DFO Hydroacoustic Working Group made several attempts from 1995-1999 to observe and quantify the effect of the avoidance of the vessel by salmon. These attempts include the following trials:

1. using a shore-based sideward-looking HTI split-beam system and focusing the sound-beam in the shore-area where the PSC sounding vessel potentially intruded the migrating salmon;
2. using a BioSonics active tracking sonar system to insonify and follow individual migrating fish as the vessel approached them. The sonar aim was automatically adjusted according to echo strengths from these targets;
3. using a Simrad EK-2000 multi-beam sonar system on-board the vessel to insonify a very large fan-shaped (up to 180 degrees) cross-section centred from the vessel to view fish behaviour in the presence of the vessel.

The first approach resulted in some limited qualitative evidence that fish avoid the approaching vessel (Xie, et al, 2002). The second approach was inconclusive due to the interference from bubbles and boat-noise with the echo signals from the fish as the vessel approached it. The noise overwhelmed the signal from the fish causing the active sonar to lose the tracking of the fish and its movements at the critical stages of potential reactions (Cronkite et al, 2000, and Hedgepeth et al, 2000). The third approach was affected by strong interferences from the river boundaries in an environment where the water-depth was less than 20 metres. The acquisition of high-resolution information on the vessel avoidance behaviour proved to be the most difficult task in comparison to the data collection activities for investigating other sources of bias that may affect the hydroacoustic estimation of salmon abundance at Mission. This was primarily because of the limitations of conventional acoustic technologies. However, the DIDSON technology provides an opportunity to utilize a high-resolution imaging sonar system to investigate fish behaviour in response to the sounding vessel. In this section we present some qualitative findings of avoidance behaviour. The quality of the information collected with DIDSON in this investigation provides opportunities for analyses of fish behaviour in the presence of the vessel. These pending analyses will lead to a quantitative understanding of how fish react to the vessel. Results from these analyses will also lead to a quantitative assessment of boat avoidance effect on the estimation of m_T in Formula (8), thus allowing us to assess the amount of bias in the flux estimation by the mobile sampling system.

Method

The DIDSON was deployed in shore-areas on both banks between August 30 and September 4, 2005 to collect information on avoidance behaviour. This period coincided with very high daily salmon passages of approximately 500,000 per day. We aimed the DIDSON 29-degree view-field to cover the areas where the transect-sounding vessel approached the shallow waters and turned to travel in the opposite direction for the next transect (Figure 28). These turning zones in the shallow water were considered to be the locations where the avoidance of the vessel by the fish would be most clearly observed.

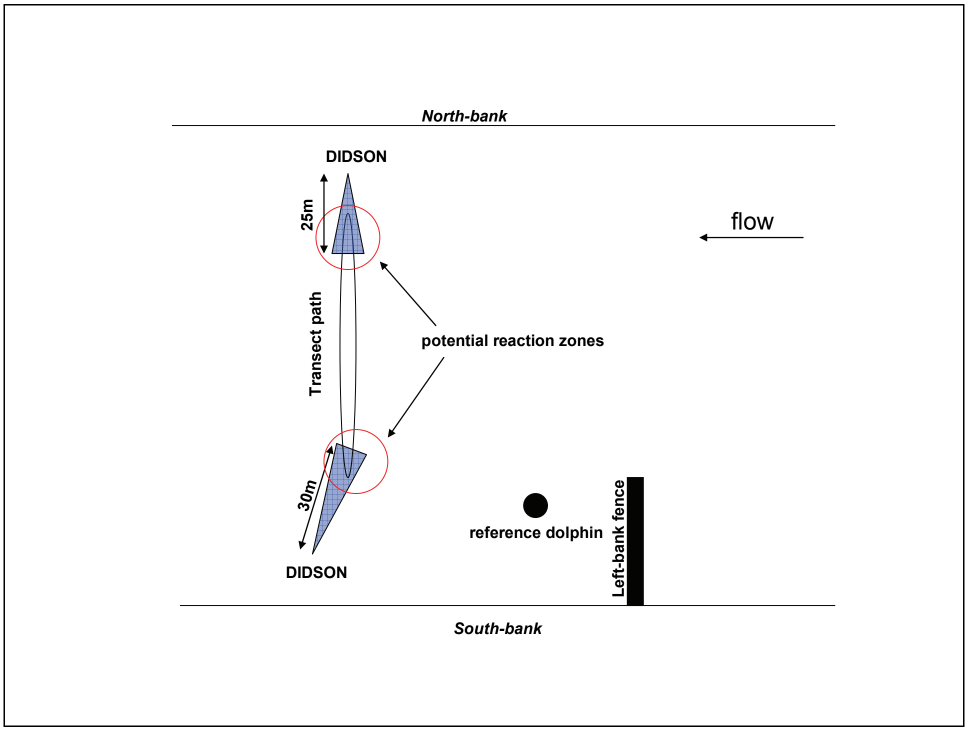

Figure 28. Deployment of the DIDSON to investigate the avoidance of the vessel by fish on both banks from August 30 to September 4, 2005.

The 2-dimensional reaction zones on a river-surface coordinate were estimated by the vessel positioning data based on the GPS receiver on-board the vessel and the observed fish position data acquired by the DIDSON sonar. These two time series of positioning data (vessel vs. fish) were transformed onto a 2-dimentional local cross-river vs. upstream Cartesian frame using the reference dolphin as its origin. Since DIDSON could not resolve the vertical position of a fish as deployed in the experiment, only the depth strata in which fish were observed relative to the surface (or bottom) from DIDSON's vertical aiming angle could be estimated. As a result, we could only provide the limits of the third-dimension of reaction zones (the depth) using the maximum water depth at the range (from the DIDSON) where a fish was observed.

The second consideration was that while fish in the upper water column within the draft-depth of the sounding vessel would avoid the vessel by taking evasive movements, fish migrating in deeper depths might not necessarily react to the vessel. To examine avoidance effects of fish at different depths, two DIDSON deployments (Figure 29) were implemented at the site as follows:

- The DIDSON was deployed from a small vessel anchored off the right-bank from September 2-4, 2005 to monitor fish reactions at a fixed depth-stratum right beneath the surface. This setup, with a maximum sounding range of 25m, ensured the monitoring of reaction behaviour of fish near the surface;

- The DIDSON was deployed on a tripod anchored on the bottom near the left bank from August 30-31, 2005. The unit was kept at a fixed depth of approximately 30 cm off the bottom. Fish were imaged in fixed depth strata of up to 3.8 m relative to the bottom. This setup, with a maximum sounding range of 30 m, ensured the monitoring of the reaction behaviour of fish for a varied vertical distance between the vessel and the fish. The variation of this vertical distance was facilitated by a large change of river-depth of 1.2 m at the site due to the large tidal influence that occurred during the measurements.

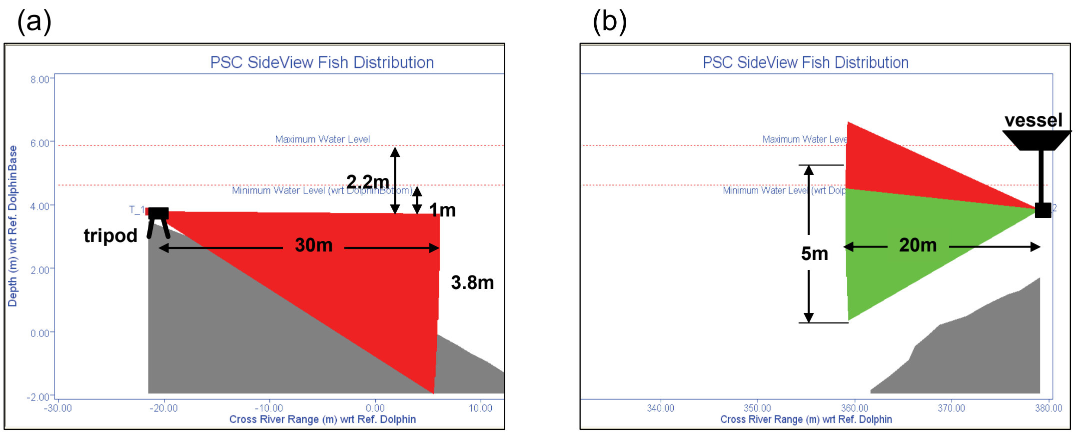

Figure 29. (a) A cross-river view of the DIDSON 12^o beam coverage on a cross-section off the left-bank. The red triangle outlines the beam-coverage of a shore area up to 30 m at -6^o aim; (b) A cross-river view of the DIDSON 12^o beam coverage on a cross-section off the right bank. The green triangle outlines the coverage area at -4^o aim during high-water, and the red triangle outlines the coverage area at +2^o aim at low water (the full-beam outlined by the red colour is partially covered by the green colour in this plot).

Results

We identified a total of 47 potentially interacting events from the GPS vessel position data between August 30 and 31, 2005 on the left-bank. Of the 47 events, the DIDSON observed 31 events that showed strong avoidance behaviour from the image data while the remaining events did not show signs of evasive actions even though the vessel moved directly above the fish. Figure 30 shows a normal upstream migration pattern observed by the DIDSON on the left-bank. This is contrasted by Figure 31 which shows a strong deviation of a group of upstream migrating fish from their normal migration direction in responding to the intrusion of the vessel.

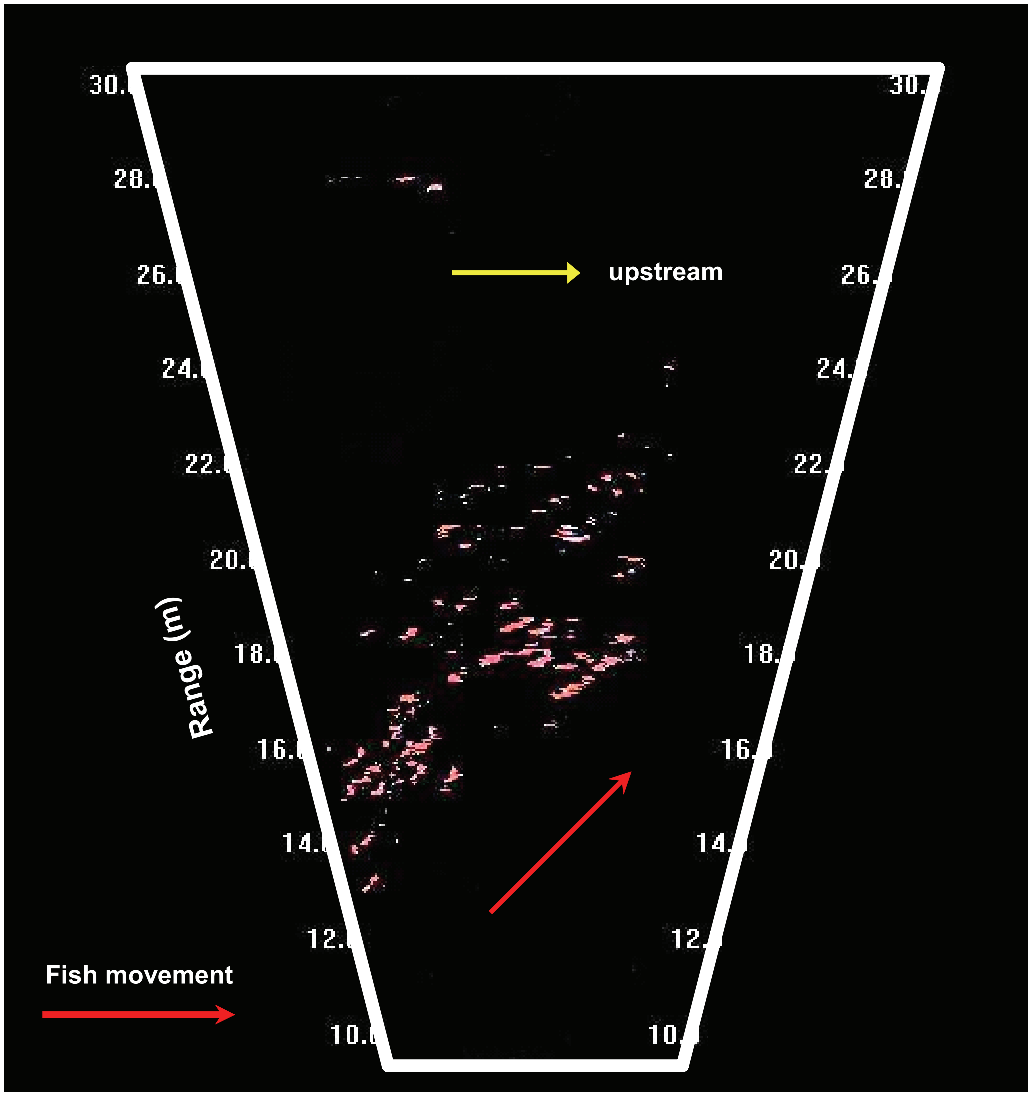

Figure 30. DIDSON image of upstream migrating fish observed on August 30, 2005 near the left bank. The arrow indicates a general migration direction of the fish.

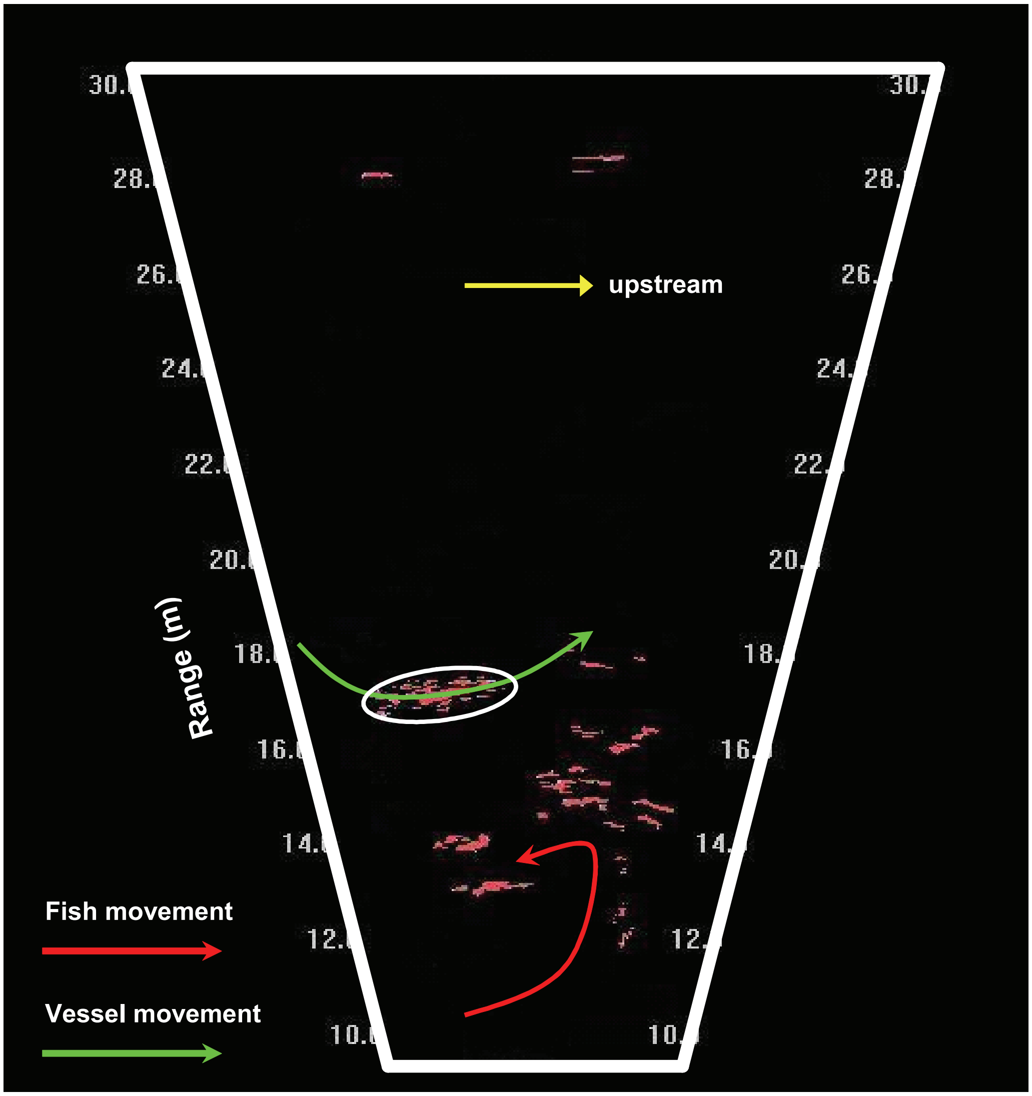

Figure 31. DIDSON image of reactions of a group of upstream migrating fish to the intrusion of the echo sounding vessel near the left bank. The red arrow outlines a general deviating behaviour of these fish from their normal upstream migration direction. Also shown are the echoes from the vessel's hull (circled) and its moving trajectory according to the on-board GPS system.

To provide an idea on time and space scales of the reaction, we plot in Figure 32 the detailed moving trajectory of a reacting fish and the corresponding vessel trajectory in the reaction zone.

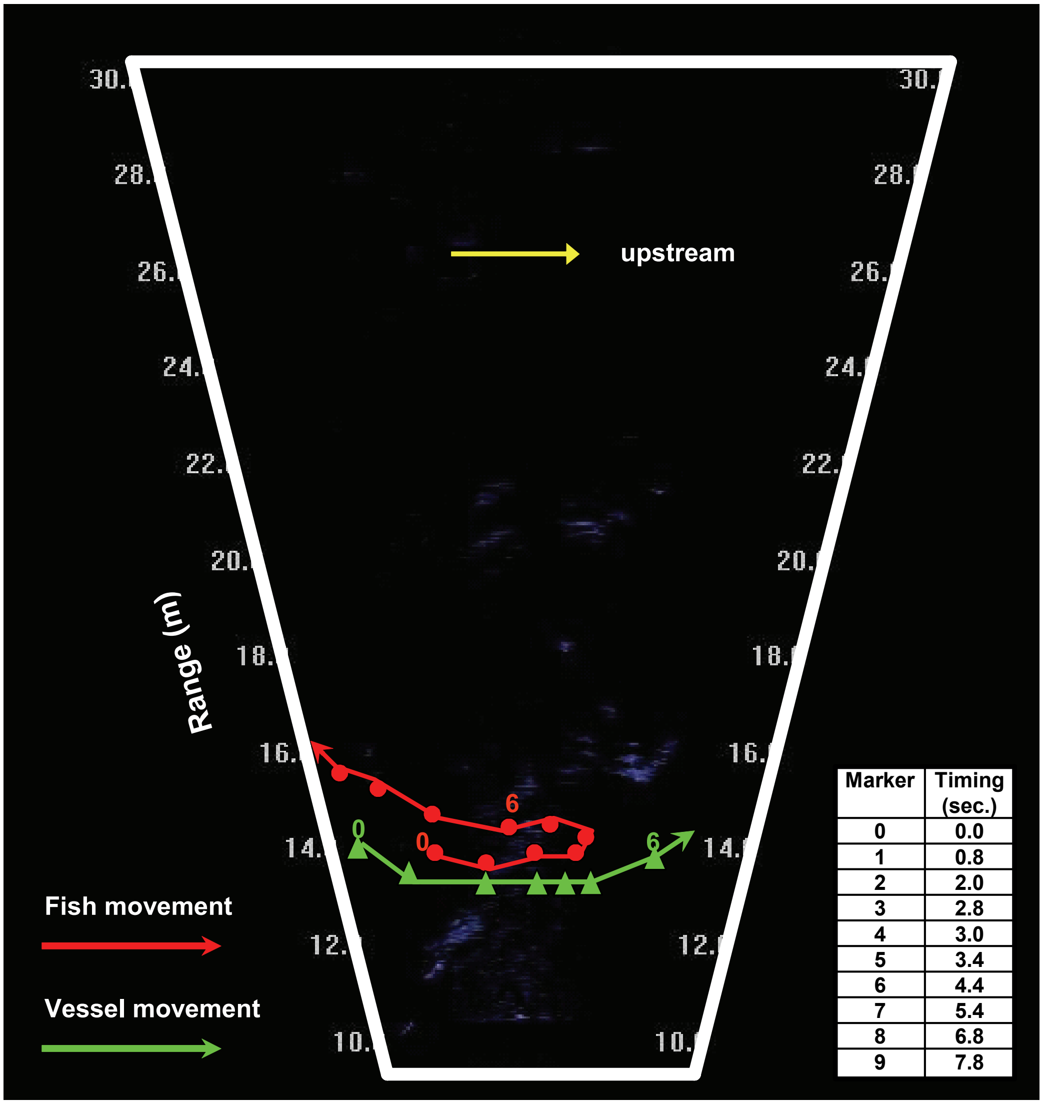

Figure 32. Detailed avoidance behaviour of an upstream migrating fish in reaction to the intrusion by the approaching echo sounding vessel. Also shown are the timings and sequentially marked locations of the fish and the vessel. This event was captured by the DIDSON unit deployed off the left bank on August 31, 2005.

From the right-bank data of the experiment, we identified a total of 21 potentially interacting events from September 2-3, 2005. Of the 21 events, 20 were observed by DIDSON that showed strong reaction behaviour to the vessel. This is consistent with the fact that the right-bank DIDSON was focused on reaction behaviour of fish that were distributed largely right beneath the vessel. As a result, they were susceptible to strong intrusion effect by the vessel. The effect of avoidance behaviour on the estimation model of (8) is to negatively bias the fish density measurements on m_T. If all other variables in (8) are estimated accurately, the avoidance effect alone would low-bias the estimate in shore-areas at low-tides. The magnitude of this bias also depends on the cross-river fish distribution. The greater the fraction of fish migration in shore-areas, the greater will be the potential negative bias resulting from the boat-avoidance effect.

ASSESSMENTS OF DIDSON APPLICATIONS TO AN UPSTREAM SITE AT BOSTON BAR

In recent years, concern has been raised about differences between abundance estimates made in the lower river at Mission and upstream estimates from spawning ground escapements plus upriver catch. The source of these differences is due to a combination of errors in the associated estimation components in Mission escapement, spawning escapement and upriver catch, plus any unknown en route mortality between Mission and the spawning grounds. It is difficult to quantify the loss due to en route mortality, but this loss is likely an important source of difference in years of adverse migratory conditions. An abundance estimation system at an upstream site will provide additional monitoring information for these important stocks and could provide information on the possible sources of the differences between estimates. It would also permit managers to take actions in responding to shortfalls identified during the season to ensure escapement targets reach the spawning grounds. In the 2005 field program season, a 2-day DIDSON trial was carried out in the Fraser River at Boston Bar, B.C. to assess the feasibility of enumerating migrating sockeye salmon with the DIDSON system at this upstream site. This feasibility study indicated the considerable potential to monitor fish passage at this location with the DIDSON technology. In this section, we present some preliminary results acquired from the 2-day DIDSON trial at Boston Bar site from September 6-7, 2005.

Site features

Boston Bar is located approximately 15 km upstream of Hell's Gate which has been a point of difficult passage to salmon migration in recent years, especially during high water and high temperature events (Figure 33). Boston Bar is also a short distance above Sawmill Creek, which is a significant boundary between upper and lower river First Nations fishing areas. The site chosen for the DIDSON trials was on the right bank (west bank) of the Fraser River at Boston Bar. The site-access was through the Boston Bar First Nation Band's saw mill and lumber yard (Figure 34). Direct access to the site was limited by a sandy embankment that limited vehicle access to 300 metres across rocky and sandy beach. To avoid any back currents or eddies where fish might mill we chose a site just north of Scuzzy Creek, and located approximately 1 km downstream from the North Bend Bridge. Using a global positioning system, the site was located at 49^{o}52.24'N, and 121^{o}26.90'W. The width of the river was approximately 170 metres with a fast flow of greater than 2 m/s near the shore area of the right bank. The bottom profile off the right bank sloped at an angle of roughly -20°. The bottom structure was made up of medium sized (30 cm) rocks and cobbles. Water clarity was low and fish could not easily be detected by eye. The area had a number of eddies although no fish were detected milling in the area where the DIDSON was deployed.

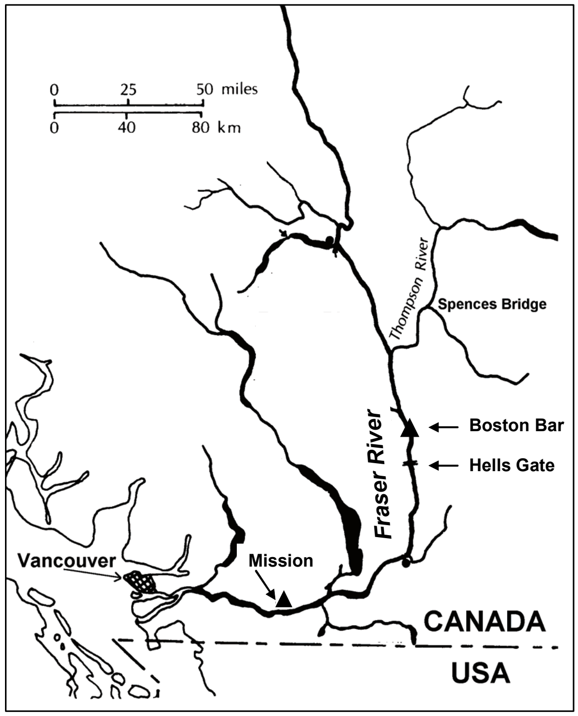

Figure 33. Map showing a potential upstream hydroacoustic site in Boston Bar, B.C. The site is approximately 15 km upstream from Hell's Gate, and 165 km upstream from the PSC Mission hydroacoustic site.

Figure 34. Photo showing the DIDSON deployment site at Boston Bar. Also shown is the working tent on the right bank for shielding electronics and computer equipment used for data collection.

Method

The DIDSON unit was deployed off the right bank (about 2 m from the shoreline) using a vertical frame at a depth of 0.15 m relative to the river surface and aimed at -20° with a maximum sounding range of 10 m (Figure 35). The bottom profile was estimated from a few bottom-oriented fish and the rocks imaged by the DIDSON at different ranges. A total of 16 hours of continuous image data were collected from 1600 hours (September 6) to 0800 hours (September 7). The DIDSON unit was also tested by rotating its 29-degree beam-plane to a roll angle of 36° relative to the river surface while keeping the pitch of the central axis of the acoustic beam at -20 °. The purpose of the second test was to assess if the 2-dimensional view-field could be utilized to obtain vertical distribution information of fish assuming they migrate at constant depths. A total of 1 hour of image data was collected for the second test.

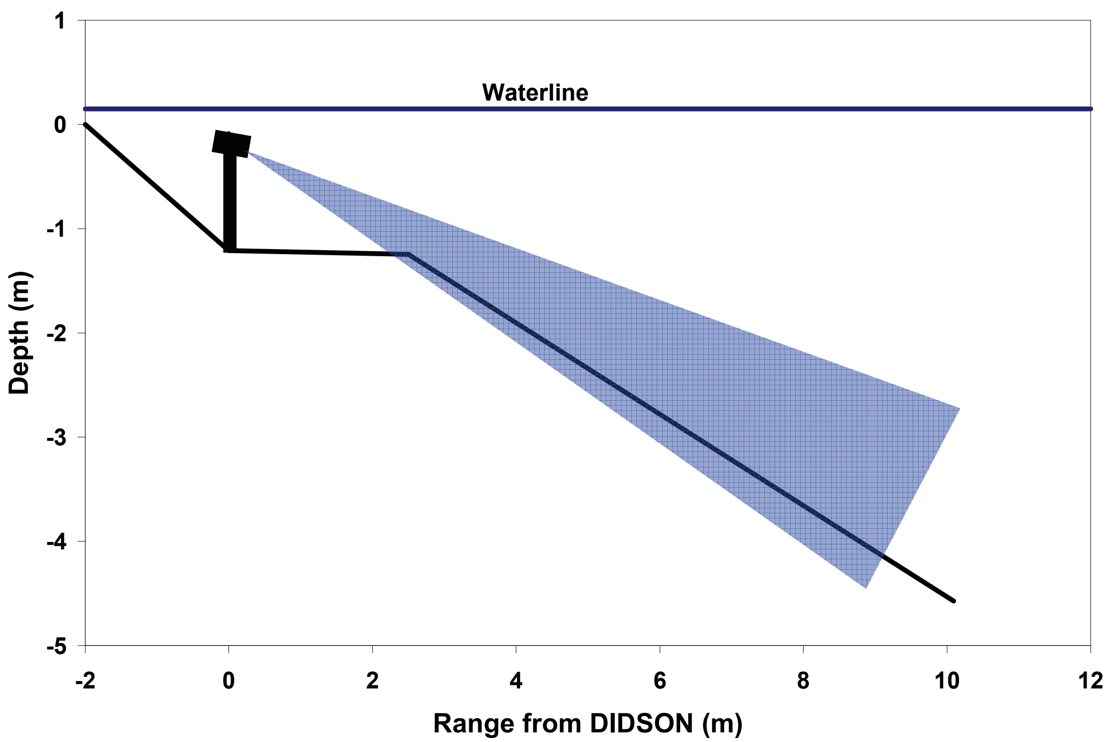

Figure 35. DIDSON sampling geometry on the right bank of Boston Bar site. The bottom profile was estimated from a few bottom-oriented fish and the stationary rocks identified from the images. The DIDSON's 12-degree beam was aimed at -20° with a maximum sounding range of 10 metres.

Results

Image data collected by DIDSON at zero-roll angle

The 16 hours of DIDSON image data revealed that most fish migrated within a 6 m range from the shore-line with limited migration occurring at 10 m range. Smaller fish seemed to move closer to shore while larger individuals moved further offshore. This was probably due to the very rapid currents in the middle channel that forced fish to migrate in areas very close to shore and the bottom. The image data indicated very few fish going downstream. Figure 36 is an example image showing 3 typical in-shore migrating fish, which represented typical behaviour for the majority of detected fish at this site during the 16 hour monitoring period. Their averaged speed, length and duration in the view-field are 0.38 m/s, 51 cm and 1.4 seconds, respectively.

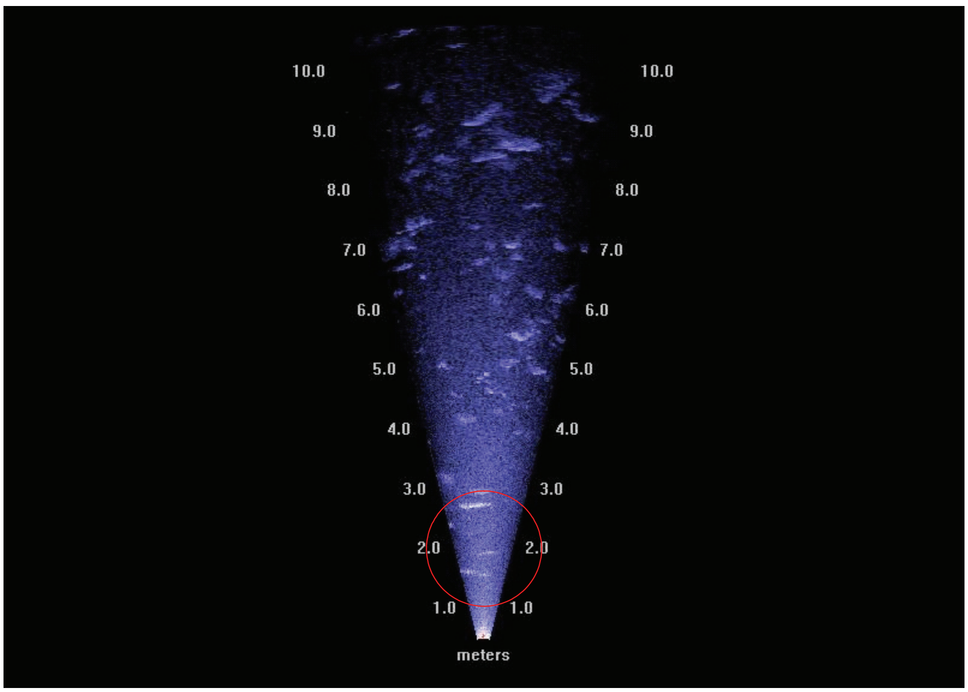

Figure 36. DIDSON image showing 3 upstream migrating fish (outlined by the circle) within 3 metres from DIDSON or 5 metres from the shore-line of the right bank at Boston Bar site. The other features in the image are rocks and cobbles.

Image data collected by DIDSON at 36°-roll angle

By rolling the 29-degree beam-plane to an angle of 36° relative to the river surface, we can hypothesize depth-information of a detected fish by correlating the apparent locations of the fish trace on the image (the azimuthal plane) to its physical depth. The key assumption to the success of this application is that fish swim through the view-field at fixed depths. The correlation between the imaged fish path and its depth using this deployment technique is schematically illustrated in Figure 37 for a top-side-down DIDSON deployment.

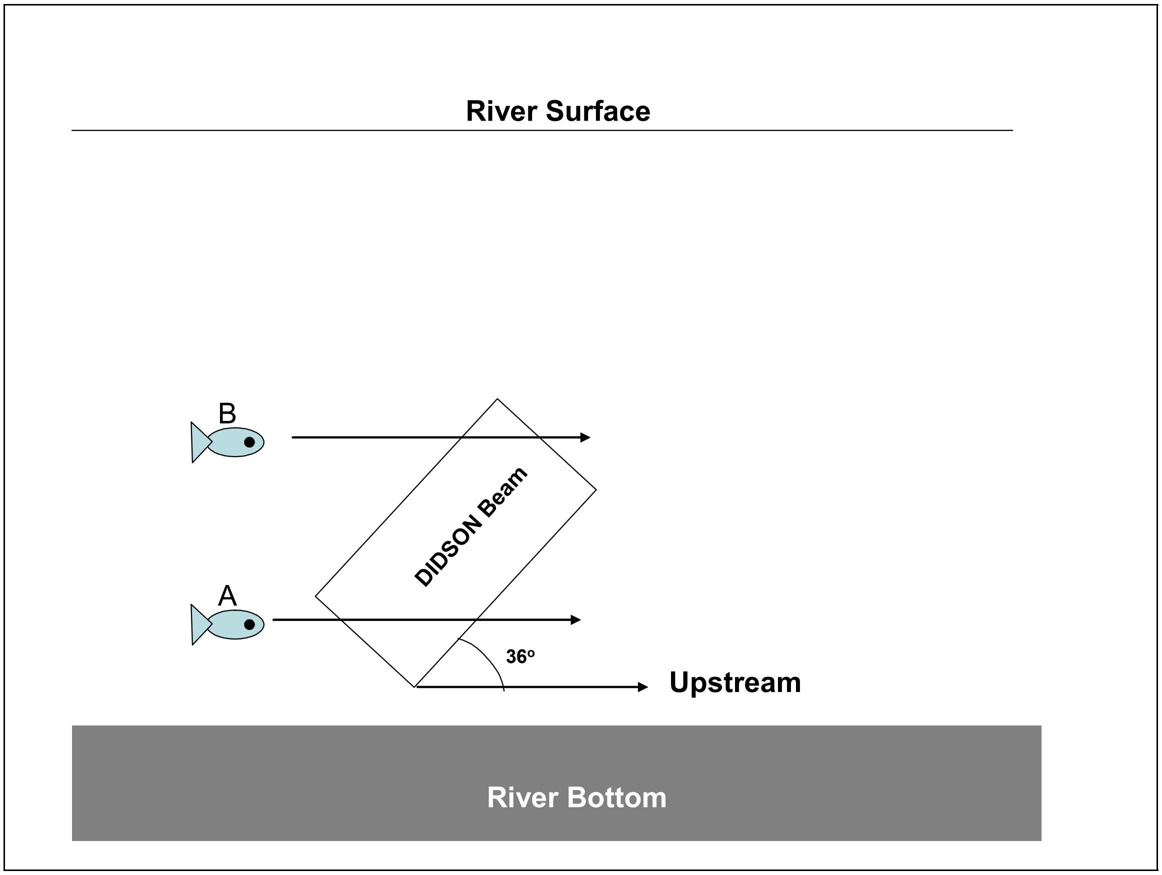

Figure 37. Schematic illustration of imaged fish path by a tilted composite DIDSON beam vs. fish depth.

Using either the entrance angle θ_1 or exit angle θ_2 from the image data (the angle Theta measured from DIDSON images) for a given fish path, we expect the following relationships for the geometry outlined above:

1. Fish migrating near the bottom of the insonified water column will have larger θ_1 or θ_2. As a result, bottom-oriented fish will enter the view-field from its right edge and disappear near the centre of the beam as illustrated by Fish A in Figure 37. The deeper the fish, the larger the θ_1 or θ_2. Also, imaged path-lengths become shorter on the right side of the view-field for fish passing through the beam in deeper water;
2. Fish migrating near the top of the insonified water column will have algebraically smaller θ_1 or θ_2, (or larger negative values for θ_1 and θ_2). As a result, surface-oriented fish will enter the view-field near its centre and exit the beam from its left edge as illustrated by Fish B in Figure 37. The shallower the fish, the smaller the θ_1 or θ_2. Also, the imaged path-length becomes shorter on the left side of the view-field for fish passing through the beam in shallower water.

These characteristics allow us to establish a quantitative relation between θ_1 or θ_2 and fish depth in the insonified water column by a DIDSON beam.

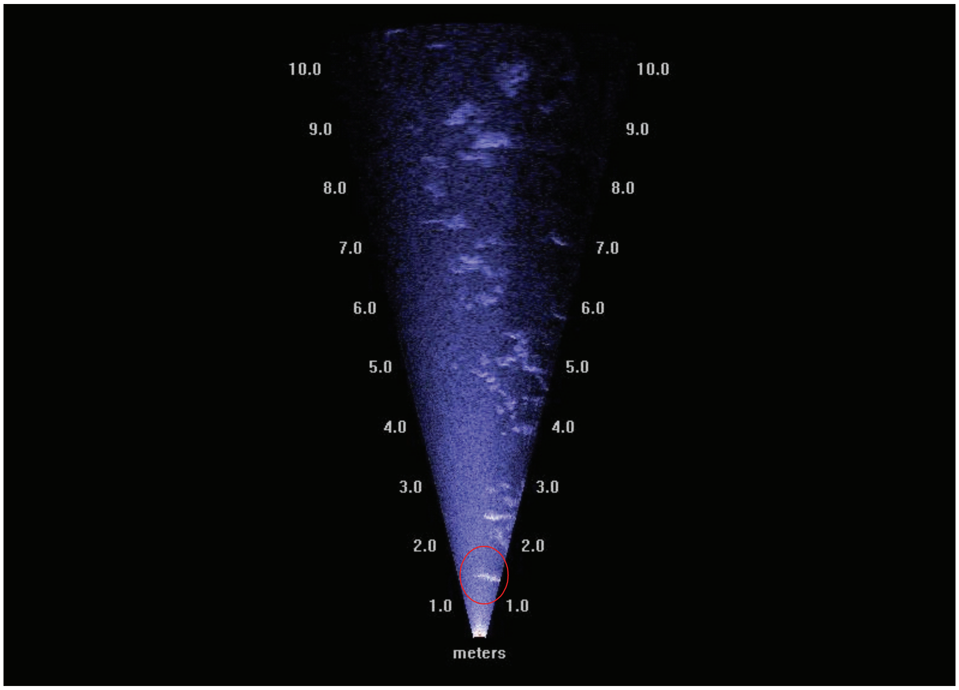

Figure 38. A typical image of an upstream migrating fish detected by a composite DIDSON beam tilted at 36^o relative to the river surface. The imaged fish is outlined by the circle.

Figure 38 shows a typical example of imaged fish path at the site when the azimuthal beam-plane was tilted at 36^o. The entrance angle θ_1 for this imaged fish is 10.5^o, and the exit angle θ_2 is 1.5^o indicating that this fish migrated in the lower portion of the water column insonified by the DIDSON composite beam. A total of 490 fish images were examined in detail using the method described in Appendix 2. The resulting behavioural statistics indicated that the vast majority of these 490 fish entered the beam on the right-side of the beam and disappeared in the middle of the beam as illustrated in Figure 38. The average entrance angle θ_1 was 11^o and the average exit angle θ_2 was -0.6^o indicating that all of these fish migrated in the lower portion of the water column. This provided strong evidence that most fish were migrating very close to the bottom at this upstream site. The mean body length was 54 cm and the mean swimming speed was 0.4 m/s, in contrast to the mean body length of 59 cm and the mean swimming speed of 0.89 m/s for the 400 fish observed on the right-bank by DIDSON on August 19, 2005 at Mission. All of the 490 fish were found migrating upstream.

Logistical recommendations

If an in-season deployment is required to apply the DIDSON technology for enumerating fish passages at this site, we propose the following recommendations for the work:

1. Cables to the DIDSON unit and the other sensors should be secured to reduce the wear and tear on them due to strong drag by currents.
2. The deployment frame (Figure 34) should be secured by an anchoring cable such as a tethering line made of a quarter inch airline cable to prevent downstream debris from dislodging the frame.
3. A more permanent structure is required for housing all the electronics and computer equipment in a safe and secure environment.
4. A user-friendly software system should be developed for quick downloading of the information onto high-capacity storage media for archiving and near real-time processing of the data.
5. A 2-3 m weir structure should be deployed to force fish to swim through the DIDSON view-field. A longer weir would be too cumbersome and unnecessary.
6. The last 300m of the roadway leading to the right bank of the site should be paved to make the site more accessible by vehicles.

CONCLUSIONS

The DIDSON trials at Mission, B.C. in the 2004 and 2005 salmon return seasons and the DIDSON feasibility study at Boston Bar site in the 2005 season resulted in some important findings and conclusions relating to the 5 study objectives outlined in our proposal to the Southern Boundary Restoration and Enhancement 2004/2005 Fund Committee. We summarize these findings as follows.

1. *Verification of the left-bank split-beam estimator in common sampling areas*

   The DIDSON experiment conducted in August 2004 and subsequent analyses confirmed that the left-bank split-beam system produced valid estimations for upstream fish-flux in conditions under which the experiment was conducted. The sample sizes for this comparison were large, and the experiment covered a continuous time period of 36 hours. More comparisons should be made for different time periods and migration conditions when multiple species of different sizes are present in the river.

2. *Verification of the left-bank split-beam estimator in the split-beam blind zones*

   The DIDSON September 2005 experiment and subsequent analyses indicated that the nearest-neighbour extrapolation method produced reasonable estimates of fish-flux in the blind zone during high salmon passage hours in comparison to the DIDSON estimates. The relative difference was within 6% between the two estimates. The comparison of DIDSON flux with the split-beam flux in the blind zone areas was not straightforward because:

   (a) DIDSON could not resolve fish position along its 12-degree beam-angle making direct measurements of fish-flux in the blind zone difficult.
   (b) During the period when the study was undertaken, the DIDSON detected very large numbers of small-sized upstream migrating fish which were distributed very close to the bottom. These bottom-oriented fish were not sampled by the split-beam transducers and therefore were not included in the data for the nearest-neighbour extrapolation model.

   Our approach to the first problem was to assume that both DIDSON and the split-beam systems detected a similar amount of flux in the commonly insonified zone so that we could use the split-beam flux to partition the DIDSON total flux into two parts: flux in the common area and flux in the blind zone. Our approach to the second difficulty was to partition the DIDSON flux according to the length-distribution and to use the flux contributed by large sized fish only for the comparison. Although we collected many hours of data from this experiment, we were limited to about 6 hours of good quality data for the analysis as the aiming of the DIDSON unit was unexpectedly changed around 1800 hours on September 22 making the beam face too much upstream to effectively image upstream migrating fish. Additional quality data are required to test the robustness of the extrapolation method. The detection of massive numbers of small sized (<30 cm) upstream migrating fish by DIDSON is an important finding. It confirms the speculation that there are other species than salmon migrating upstream past Mission. These small sized upstream migrating fish would have been a source of very large bias had they been included by the split-beam system as part of the salmon-flux. We hope to deploy beach-seine gear in the near future at the site to ascertain these non-salmon species. Fortunately, these small fish are distributed very close to the bottom, and below the sample areas of the split-beam transducers at the regular sampling aims.

3. *Debris and fish behaviour near the right bank and in the middle channel of the river*

   DIDSON successfully detected downstream debris targets near the right bank turbulence zone. These debris targets included large tree branches with TS readings comparable to salmon sizes. DIDSON confirmed the large in-shore movements of upstream migrating fish observed by the right-bank sideward-looking split-beam system. From a limited image dataset we also found that fish behaviour in the middle of the channel was not as different as previously thought in comparisons with fish migrating near the left bank. The estimated upstream speed and downstream ratio near the right bank and in the middle section of the river will help quantify the bias of flux estimation by the current method.

4. *Reaction of fish to the vessel*

   DIDSON confirmed that fish do react to the transecting vessel by changing their normal upstream swimming directions. However, it appeared that such avoidance behaviour depended more on the vertical spacing between fish and the vessel than their horizontal separating range. The behaviour data will allow a quantitative analysis of the avoidance behaviour and the bias effect from such behaviour on the measurements of fish density by the mobile sounding system allowing us to assess amounts of bias in the mobile flux estimation from this source of bias.

5. *DIDSON trial at Boston Bar*

   From the 16 hours of DIDSON data collect at Boston Bar, we are confident that this technology can be applied at this location to enumerate fish abundance. An estimate produced at this upstream location will strategically help in-season estimates of abundance for various stocks and provide information for multiple purposes.

Our DIDSON trials in the lower Fraser River at Mission, B.C. and in the upper Fraser River at Boston Bar proved that DIDSON technology is applicable at these locations for assessing migration behaviour and enumerating abundance of various salmon stocks. Our DIDSON work covered a number of areas of interest at Mission and Boston Bar in the 2005 field program season and part of the 2004 season. The information obtained by this technology has provided insight on fish behaviour and the performance of the primary split-beam estimator. However, because only one DIDSON unit was available for these experiments, the resulting data are limited to time and spatial scales over which the observations were made. We can use these findings to guide more intensive studies in these areas with the DIDSON technology in the future provided adequate resources are available.

ACKNOWLEDGEMENTS

We thank Herman J. Enzenhofer, George M. W. Cronkite and John A. Holmes of the Department of Fisheries and Oceans of Canada for their generous assistance and advice in both the field work and consultation meetings during this project. We would also like to thank the Boston Bar First Nation for their invaluable assistance on the study at Boston Bar. This work was funded by the 2004/2005 Southern Boundary Restoration and Enhancement Fund.

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APPENDIX 1: DERIVATION OF FLUX ESTIMATION MODEL FOR THE MOBILE SPLIT-BEAM DATA

The net upstream fish-flux F for anywhere in the river channel is estimated as:

$$F = \rho_+ \cdot v_+ - \rho_- \cdot v_- \qquad \text{[fish /(m}^2\cdot\text{s)]} \qquad \text{(A1)}$$

F is the fundamental variable that determines the resulting number of fish migrating upstream. However, this variable can hardly be measured directly by a sampling system. Most sampling systems provide estimations of spatial and/or temporal integrations of F. In our applications, the left-bank shore-based split-beam system integrates F in both time and space as expressed by Formula (2) (page 8) for the upstream component. On the other hand, the mobile split-beam system integrates F in space only, i.e., across the width of the river. To derive an appropriate estimator for F from the mobile data, we rewrite (A1) in a modified form as follows:

$$F = \rho_+ \cdot v_+ - \rho_- \cdot v_- = (\rho_+ \cdot v_+ + \rho_- \cdot v_-) \times \left[1 - 2 \cdot \frac{\rho_- \cdot v_-}{\rho_+ \cdot v_+ + \rho_- \cdot v_-}\right] \qquad \text{(A2)}$$

The 1st factor can be rewritten as

$$\begin{aligned} \rho_+ \cdot v_+ + \rho_- \cdot v_- &= \rho_+ \cdot v_+ + \rho_- \cdot v_+ + \rho_- \cdot v_- - \rho_- \cdot v_+ = (\rho_+ + \rho_-) \cdot v_+ - \rho_- \cdot (v_+ - v_-) \\ &= (\rho_+ + \rho_-) \cdot v_+ \cdot \left[1 - (\frac{\rho_-}{\rho_+ + \rho_-}) \cdot (1 - \frac{v_-}{v_+})\right] \\ &= \rho_T \cdot v_+ \cdot \left[1 - R_T \cdot (1 - R_v)\right] \end{aligned}$$

where ρ_T is target density for both upstream and downstream fish, R_v is the ratio of downstream speed over upstream speed, and R_T is the downstream fish density ratio, i.e.,

$\rho_T = \rho_+ + \rho_-$,

$R_v = \dfrac{v_-}{v_+}$, and

$R_T = \dfrac{\rho_-}{\rho_+ + \rho_-}$.

Substituting the above expression to (A2) leads to

$$F = \rho_T \cdot v_+ \cdot \left[1 - R_T \cdot (1 - R_v)\right] \cdot \left[1 - 2 \cdot R_d\right] \qquad \text{(A3)}$$

where R_d is the downstream fish-flux ratio defined as

$$R_d = \frac{\rho_- \cdot v_-}{\rho_+ \cdot v_+ + \rho_- \cdot v_-}.$$

Note the difference between R_d and R_T. (A3) is algebraically equivalent to (A1).

We now apply (A3) to the mobile data to estimate fish-flux passing the entire river cross-section per second, denoted as n. It follows that

$$n = \int_S F \cdot dS = \int_S \rho_T \cdot v_+ \cdot \left[1 - R_T \cdot (1 - R_v)\right] \cdot \left[1 - 2 \cdot R_d\right] \cdot dS \qquad \text{[fish /s]} \qquad \text{(A4)}$$

where the integrating area S is the cross-section of the river sampled by the mobile system. The integration of density can be estimated with the daily mobile data derived by Xie (2002) as

$$\int_S \rho_T \cdot dS = \frac{m_T}{L}$$

where m_T is the averaged number of detected fish per transect estimated from the daily mobile split-beam data, and L is a depth-averaged beam-width of the 15^o sound-beam across the river. The other 4 variables in (A4) v_+, R_v, R_T, and R_d are estimated from the daily left-bank split-beam data as:

$$v_+ = \frac{\sum_{i=1}^{M_+} u_+}{M_+},$$

$$v_- = \frac{\sum_{i=1}^{M_-} u_-}{M_-},$$

$$R_T = \frac{D}{D + U \cdot v_- / v_+}, \text{ and}$$

$$R_d = \frac{D}{D + U}$$

where u_+ and u_- are estimated upstream and downstream fish speed with M_+ and M_- being their sample sizes from the left-bank system; U and D are area-and-time integration of the left-bank flux by the left-bank system. The resulting estimator for n is:

$$n = \frac{m_T \cdot v_+}{L} \cdot \left[1 - (1 - \frac{v_-}{v_+}) \cdot \frac{D}{D + U \cdot v_- / v_+}\right] \cdot \left[1 - 2 \cdot \frac{D}{D + U}\right] \qquad \text{[fish /s]} \qquad \text{(A5)}$$

Xie (2002) also proposed an unbiased estimator for variance of n.

APPENDIX 2: READING AND INTERPRETATION OF DIDSON IMAGE DATA

Criteria were developed for visual reading of image data acquired by DIDSON sonar. These criteria led to the differentiation of fish from debris or noise in the imaging data. Fish targets have a variety of observable identifying features such as changing swimming angle, varying speed, tail movements (flexing), greater pixel-intensities and larger target-sizes. On the contrary, debris and noise, such as entrained air bubbles, maintain a constant travel-direction, orientation angle, and a steady speed controlled mainly by the river flow. The images of these non-fish targets tend to have large variations in shapes and sizes with no visible body movements as they move through the DIDSON view-field.

Range-binning was used to count fish targets, to identify their locations in the view-field, and to classify their directions of travel in 3 categories defined as upstream, downstream, and milling. The range-bin for an imaged fish was determined by a time (or frame)-weighted range as the fish swims through the beam. The basic parameters recorded for each target included:

- File name;
- Range-bin;
- Direction of travel;
- Frame position;
- DIDSON deployment position;
- DIDSON header ID for the image file;
- Reading comments.

Repetitive patterns in the image were recognized as being possibly caused by bottom oriented stationary targets, such as ropes from anchors and lost objects. These non-fish targets tended to appear at fixed distances throughout the entire image file. They must be excluded from the database.

Fish behaviour was estimated from the image data. The key parameters included length, speed, and orientation of swimming trajectory.

The basic parameters read for length estimation included:

- Frame position;
- Range;
- Azimuthal angle (Theta);
- Diagonal length.

The basic parameters read for speed and orientation estimations included:

- Entrance frame number, range and azimuthal angle;
- Exit frame number, range and azimuthal angle;
- Frame rate.

Avoidance behaviour was determined by the observation of fish targets in response to the approaching sounding vessel. The basic parameters recorded included: frame number, range and azimuthal angle on a frame-by-frame basis.