Fish Behavior Measured by a Tracking Radar-Type Acoustic Transducer near Hydroelectric Dams

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Abstract

Recent studies of fish behavior around hydroelectric dams have used acoustics with split-beam methodology. A complementary methodology called the tracking transducer takes advantage of split-beam capabilities for expanding fish behavior investigations.

In a fixed deployment, the transducer remains static while fish move through the beam. Transducers mounted on rotators allow expansion of spatial coverage, but tracking is still limited for individual fish. In this study we applied the principle of tracking radar, aligning the antenna beam axis with a target, with an acoustic transducer and dual-axis rotators to track individual fish over longer periods of time. Deviation of the target from the beam axis produces a correction to point the axis toward the target. At the same time data regarding the fish position and movement, and acoustic size are recorded to hard disk. Individual fish tracks are visualized in AutoCAD.

Tracks at Ice Harbor Dam, Snake River in 1995 showed that fish were drawn into the bypass sluiceway when it operated, and that the depth of fish, as they approached the dam, determined turbine entrainment. In 1996, at The Dalles Dam, Columbia River the tracking transducer showed that fish trajectories were steeper

into turbine intakes when occlusion plates were installed in front of the intakes. The study of fish behavior around spillway overflow weirs at John Day Dam, Columbia River, showed that as near-surface fish approached the weirs they sounded and attempted to move away from the spillway. In general, however, most fish tended to follow streamlines of flow, except later in the season when non-salmonid species were present.

In conclusion, the tracking split-beam offers the possibility of providing intermediate track lengths and detailed behavioral information of individual fish in the near-dam forebay hydraulic environment. This should be another valuable tool to assist in evaluation of fish bypass or collection facilities.

Introduction

Since the early 1980s acoustical systems have been applied to study the behavior of fish near and around hydroelectric power plants (Thorne and Johnson 1993). In most cases, a transducer, or a series of transducers are deployed in fixed positions and aimed at a predetermined angle to maximize the transducer beam pattern within a defined area of concern.

In the usual fixed deployment, the transducer remains in a static position while fish move through the beam. The static position of the transducer limits the amount of information describing the direction of movement and behavior of fish.

The principle of tracking radar, aligning the antenna beam axis with a target, has been applied with an acoustic transducer for tracking fish targets. Little civilian application of tracking radar principles has been applied in hydroacoustics, although monopulse (meaning an estimate per transmission pulse) or tracking radars have been widely used for tracking aircraft. Previous acoustic work includes a phase steered array composed of many elements, which is very complicated and expensive (Jaffe 1995). Our approach was relatively simple: control of the aim of the transducer is accomplished with a PC and enclosed (waterproof) stepper motors. The new result is called the tracking transducer.

Monopulse radar principles have been well established (Sherman 1984). Deviation of the target from the beam axis produces a correction that is applied to drive the target toward the axis. The earliest tracking radars were conical scanners. Present day tracking radars use monopulse or simultaneous lobing. By definition, monopulse systems estimate target parameters with a single pulse. A split-beam transducer is an example of an acoustic monopulse device.

A split-beam transducer was attached to a dual-axis rotator system to track fish targets in the same way that monopulse radars track aircraft. Tracking sonar is useful in determining direction of fish travel. Moreover, the mechanical system allows a considerable expansion in traditional sampling volume. Data from tracking sonar are more easily quantifiable than sector scanning sonar results because of our understanding of scientific quality split-beam echosounders.

The fish behavior studies determined direction, velocity, path, and vertical and horizontal placement of fish within the water column in front of turbines and spillways. Fish behavior was determined by actively tracking fish with an acoustic transducer and recording their positions and acoustic sizes over the time period they could be “locked on to”. This development is an extension of split-beam methodology (MacLennan and Simmonds 1992).

The first application of the tracking sonar, at Ice Harbor Dam on the Snake River (Figure 1), demonstrated the advantage of employing motor-controlled transducers in acoustic surveys of fish behavior in the vicinity of fish bypass systems (BioSonics 1996). Building upon that experience, the system was deployed at The Dalles Dam on the Columbia River near turbine intake occlusion structures (BioSonics 1997a). Two tracking systems were recently used to determine fish reactions in response to installation of spillway overflow weirs at John Day Dam. In addition, success has been made to track acoustic tags, with the promise of future usefulness in determining fish behavior (Johnson et al. 1998).

Methods

The output of the split-beam echosounder provides information on the fish location. In general, a split-beam transducer is electrically divided into two orthogonal sets of paired receivers. An acoustic signal is transmitted and reflected from a fish. This echo encounters the two sets of receiving elements allowing the direction of arrival of an echo to be determined. An acoustic wave front propagating towards the transducer arrives at different times at the four quadrants causing the phase angle of the electrical output signal from the receivers to differ. One angle (often called alongships) is determined from the electrical phase difference between one set of receiving elements, and a second angle (athwartships) is estimated from the orthogonal elements (MacLennan and Simmonds 1992).

These phase angles in the form of a telegram can be outputted via a serial port of an acquisition PC (which is connected to the split-beam echosounder) to a second PC. The telegram contains single-echo detections for one ping: header, time tag, number of single echo detections, depth (meters), compensated target strength (the estimated acoustic size of the fish, referred to as TS in dB), alongships angle (degrees), and athwartships angle (degrees). The second PC containing tracking control software captures the telegram. The transducer is installed in a two-axis aiming armature rotated by high-speed stepper motors that are controlled by the second computer receiving the echosounder directional signals. The stepper motor control software receives the alongships and athwartships angle measurements and then actuates the stepper motors to keep the main axis of the transducer beam aimed on the target, thereby tracking the target (Figure 2). Software had the capability to "lock on" fish targets and "radar track" their trajectories while continually changing the transducer angle to intercept the fish.

The operation of the tracking transducer is simple: center the fish on the acoustic axis, and then follow its path while measuring its acoustic size. To accomplish this, the split-beam phase angles, γ (alongship) and ψ (athwartship) needed to be compensated by the stepper motor angles θ and ϕ (Figure 2).

The following mathematical analysis assumes an absolute coordinate system (x, y, z). The x-axis runs along the dam to the right when facing away from the dam, the y-axis points up, and the z-axis points away from the dam. Let the unit vectors in the absolute coordinate system be $\hat{\imath}$, $\hat{\jmath}$, and $\hat{k}$. Then unit vectors of the rotated coordinate system (ξ,η, and ζ) of the transducer are:

$$\begin{aligned} e_\xi &= \cos\theta\hat{\imath} - \sin\theta\sin\phi\,\hat{\jmath} - \sin\theta\cos\phi\,\hat{k} \\ e_\eta &= \cos\phi\,\hat{\jmath} - \sin\phi\,\hat{k} \\ e_\zeta &= \sin\theta\hat{\imath} + \cos\theta\sin\phi\,\hat{\jmath} + \cos\theta\cos\phi\,\hat{k} \end{aligned} \tag{1}$$

The unit vector to a fish target is approximately:

$$e_\rho = \sin\psi\, e_\xi - \sin\gamma\, e_\eta - \sqrt{1-\sin^2\gamma-\sin^2\psi}\, e_\zeta \tag{2}$$

In terms of the stepper motor coordinate system the unit vector to the fish is:

$$\begin{aligned} e_\rho \quad &= \left(\cos\theta\sin\psi \ +\sin\theta\sqrt{1-\sin^2\gamma-\sin^2\psi}\right)\hat{i} \\ &\quad + \left(-\sin\theta\sin\phi\,\sin\psi \ +\cos\phi\,\sin\gamma \ +\cos\theta\sin\phi\sqrt{1-\sin^2\gamma-\sin^2\psi}\right)\hat{j} \\ &\quad + \left(-\sin\theta\cos\phi\,\sin\psi \ -\sin\phi\,\sin\gamma \ +\cos\theta\cos\phi\sqrt{1-\sin^2\gamma-\sin^2\psi}\right)\hat{k} \end{aligned} \tag{3}$$

The new stepper motor angles required to follow the fish are:

$$\begin{aligned} \theta' \ &= \ \sin^{-1}\left(\cos\theta\sin\psi \ +\sin\theta\sqrt{1-\sin^2\gamma-\sin^2\psi}\right) \\ \phi' \ &= \tan^{-1}\left(\frac{-\sin\theta\sin\phi\,\sin\psi \ +\cos\phi\,\sin\gamma \ +\cos\theta\sin\phi\sqrt{1-\sin^2\gamma-\sin^2\psi}}{-\sin\theta\cos\phi\,\sin\psi \ -\sin\phi\,\sin\gamma \ +\cos\theta\cos\phi\sqrt{1-\sin^2\gamma-\sin^2\psi}}\right) \end{aligned} \tag{4}$$

Ice Harbor Dam, Spring and Summer 1995

Much of the methodology was developed for the tracking transducer in the Ice Harbor smolt behavior study. The fish behavior study required the knowledge of direction, velocity, path, and vertical and horizontal placement of fish within the water column in a 15 m radius in front of the sluiceway collectors. The sluiceway slots were manipulated by being either open or closed.

The tracking transducer system consisted of a PC-controlled 120 kHz Simrad EY 500 split-beam fisheries echosounder and split-beam transducer, a second PC with Keithley-Metrabyte dual-axis controller board, interface with stepper motor drivers and limit switch detection hardware, and an underwater armature using two Superior stepper motors.

The tracking transducer was located about 10 meters below the surface at turbine unit 4B and at the edge of the 1.8 m vertical slot (Figure 3). This seven degree (full beamwidth at half power) circular split-beam transducer was used to monitor behavior in front of the sluiceway and slot at unit 4.

During operation, the transducer rotator angles were reset every 10 minutes to point in a specific direction systematically chosen. The echosounder was operated at approximately ten pings per second. However, because of inability to control pinging by the stepper motor computer and the stepper motor movement, i.e. the desire to only move without compromising accurate position estimation, every other ping was discounted, and as a result the effective operation used 5 pings per second. As the system tracked targets, the transducer moved to point toward the last target position. When a target was lost, the transducer did not move until a new target was acquired, or it was reset at the end of 10 minutes.

Target selection and tracking was controlled by a number of parameters. The selection parameters include initial target position and returned signal strength. The range of compensated target strength in which the system would select a new target to track was -60 dB to -30 dB. Once selected, the target's signal strength on subsequent pings was ignored. The target range criterion originally was a minimum distance (radius) from the transducer, between 1.0 and 15.0 meters. Targets outside this range would not be selected for tracking. The position criterion was changed on 6 June to Cartesian (X,Y,Z) limits, in order to better define the survey volume, which were: along dam, -20.0 to 20.0 meters; away from dam, -2.0 to 23.0 meters; and up/down, -15.0 to 10.0 meters. Positive values are right (approximately to the south), away (upstream, approximately east), and up, respectively. Once selected, a target was tracked until lost or physical tracking limits were reached.

Tracking parameters were used to define tracking errors. If the target density was too high, the system was unable to tell which target matched the one tracked on the previous ping. If the second closest target was less than three times as far away as the first choice, the track was ended. If the speed of the tracked target was greater than 2.0 meters/sec, the track was ended. If a target could be tracked immediately following the end of the previous track, a mark was added the file to show that the best possible target continued to be tracked. The data were inspected manually at those marks to make the determination if it was a new target. In later studies, at other locations, tracking parameters evolved, as the tracking system became better understood.

Other tracking inconsistencies were possible due to irregular system operation or errors. If there was more than 1.0 second between pings, a track was marked as ended. If there were two pings at the same time (due to the limited precision of the EY500 sonar time tags), the track was marked as ended. As with the other tracking errors, these points in the data were examined manually if necessary to determine what occurred. Files were filtered for a minimum of 5 pings per track, and the resulting files were examined manually for tracking errors, date inconsistencies and system positioning errors.

A combined file was manually divided into separate files based on the time ranges that the sluice gate was open or closed. These files were used to generate IGES files (.IGS extension) for AutoCAD plotting and statistics files (*.STA) extension. The IGES format is a standard CAD drawing exchange format used to transfer drawings between different CAD programs. The three-dimensional *.IGS file data were then read by AutoCAD and examined in various orientations. To mark target direction for monochrome plots, tracks end with a reference symbol. Reference lines of 1 meter are provided on the X, Y, and Z axes, with the origin at the face of the transducer.

The Dalles Dam, Spring and Summer 1996

The application of the tracking transducer at The Dalles Dam was intended for determining fish trajectory as affected by manipulations of flow in front of turbine and sluiceway intakes. The Dalles Dam turbine gallery is divided into two sections, the greatest being the main units and the other two downstream fish units. The study focused on two locations: location 1 between Fish Unit (FU) 2-2 and Main Unit (MU) 1-1, and location 2 between and Main Unit 2-3 and Main Unit 3-1. The tracking transducer was positioned on the piernose face at a depth of 9.5 m at location 1 and at a depth of 10.5 m at location 2. Location 1 was sampled during the “spring” study, and location 2 was sampled during both the spring and summer studies. Figure 4 shows a three-dimensional view of the transducer at location 1 in relation to the fish unit and main unit structures, and location 2 was similar.

The Dalles Dam experiment’s intention was to create a zone of transition by covering the top half of the turbine entrance so that fish might avoid entering turbines. Data from the tracking transducer were categorized into periods of turbine occlusion (upper half occluded versus completely open turbine entrances), by time period (spring or summer and day or night), by location (location 1 between FU 2-2 and MU 1 or location 2 between MU 2-3 and MU 3-1), and by three different target strength intervals (-55 to -45 dB, -45 to -35 dB and above -35 dB). Location 1 was further blocked into data in front of the fish unit and data in front of the main unit. Data were blocked into day and night periods. The beginning of day and night was taken from a computer program for sunrise and sunset, from *Astronomy*, April 1984, pp. 75-77.

The range of compensated target strength in which the system would select a new target to track was -55 dB to -30 dB. Once selected, the target's signal strength on subsequent pings was ignored. The target range criterion originally was a minimum distance (radius) from the transducer, between 1.0 and 15.0 meters. Targets outside this range would not be selected for tracking. The position criteria also included Cartesian (X,Y,Z) limits, which were: along dam, -20.0 to 20.0 meters; away from dam, -2.0 to 23.0 meters; and up/down, -15.0 to 10.0 meters.

Positive values are right (approximately to the east), away (upstream, approximately north), and up, respectively. Once selected, a target was tracked until lost or physical tracking limits were reached. In practice, the volume sampled was limited to a 12 m radius around the transducer, at which distance the -17.5 dB (one way) sidelobes of the transducer encountered the surface.

Tracking parameters were used to define tracking errors. If the target density was too high, the system was unable to tell which target matched the one tracked on the previous ping. If the second closest target was less than three times as far away as the first choice, the track was ended. If the speed of the tracked target was greater than 4.0 meters/sec, the track was ended. If a target could be tracked immediately following the end of the previous track, a mark was added to the file to show that the best possible target continued to be tracked.

During operation, the transducer angles were systematically set to a new randomized pointing direction every 10 minutes. The split-beam echosounder was again operated effectively at 5 pings per second.

John Day Dam, Spring and Summer 1997

Overflow weirs were placed into spillways 18 and 19 as an experiment to attract fish to surface flows at the spillways and to hopefully prevent them from entering turbines. The fish behavior study determined direction, velocity, path, and vertical and horizontal placement of fish within the water column in front of these spillways. Two BioSonics 420 kHz DT6000 split-beam systems were used for the tracking systems to determine travel routes and velocities of fish within roughly 15 meters of the spillway weirs. The tracking systems were lowered about 18 meters below the surface, resting on the spillway ogee below anticipated fish passage routes. The BioSonics circular split-beam transducers transmit a six degree beam (full beamwidth at half power) with -30 dB sidelobes (one way). Three clear advances were made over the two previous studies in preparing the tracking transducer system for the John Day study. First, the serial link between the rotator control computer and echosounder control computer was used to control the pinging of the echosounder. This increased ping rate capability and thus tracking capability by a factor of two. Second, predictive fish following was added to the rotator control program. The algorithm predicted incremental movement in Δx, Δy and Δz separately using the following equation (shown for Δx):

$$\Delta x = \frac{\left(x_i - x_{i-1}\right) + 0.5\left(x_{i-1} - x_{i-2}\right) + 0.25\left(x_{i-2} - x_{i-3}\right) + 0.125\left(x_{i-3} - x_{i-4}\right)}{1.875} \tag{5}$$

Third, the 420 kHz signals are quieter than those at 120 kHz and the beam had much lower sidelobes allowing better performance near structures.

The tracking transducer’s primary duty is to follow individual fish. The resulting data are measured or apparent fish positions from which velocity vectors, $\bar{V}_{apparent}$, can be estimated as the change in position divided by the change in time. $\bar{V}_{apparent}$ is the sum of the water velocity, $\bar{V}_{water}$, and the “real” fish vector (i.e. fish effort vector), $\bar{V}_{effort}$. The relationship is defined as

$$\bar{V}_{apparent} = \bar{V}_{effort} + \bar{V}_{water},$$

from which the fish effort vector can be estimated as

$$\bar{V}_{effort} = \bar{V}_{apparent} - \bar{V}_{water}.$$

The x, y, and z components of the fish effort vector follow:

$$V_{x,effort} = V_{x,apparent} - V_{x,water},$$

$$V_{y,effort} = V_{y,apparent} - V_{y,water}, \text{ and}$$

$$V_{z,effort} = V_{z,apparent} - V_{z,water}.$$

Water velocity was measured at various stations in a physical model the John Day Dam located at the Waterways Experiment Station, Vicksburg, MS. It has 3 full bays (and an additional one half on each side). Velocities were estimated with and without bulkheads (weirs) in bays 18 and 19 at a pool elevation of 264.0 ft, and stop openings (left to right) 2, 6, 6, 2, 2. However, the stop opening should have been 3, 4.5, 4.5, 6 and 7 looking downstream left to right. Therefore, the velocity measurements at spillbay 18 and 19 were corrected by multiplying by 4.5 / 6. Because the model data were taken at spillbay 18, their mirror image was used for spillbay 19 velocity estimates. Sample measurements were then extrapolated to estimate the water velocity vector at a particular fish position in three-dimensional space.

Results

In addition to tabulated and descriptive results, fish tracks at all locations were graphically examined in three dimensions using AutoCAD, and example figures are presented for the John Day Dam.

Ice Harbor Dam

The system was monitored for several weeks, from 26 May until 20 June. The numbers of fish tracked with five pings or more were 424 when the sluiceway was off and 466 fish when the sluiceway was on.

Table 1 presents averages of fish tracking data organized by sluiceway condition and in three depth ranges: 0-5m, 5-10m and greater than 10 m. Statistics averaged were 1) speed, 2) time tracked, 3) distance tracked, 4) velocity factor, 5) depth, 6) target strength, and 7) unit direction vectors.

Average fish speeds were the same in the two sluice conditions, 0.6 m/s. However in the sluice on condition, speed was highest in the upper water column (0-5 m) and higher than the sluice off condition (0.8 versus 0.7 m/s). The velocity factor showed that the fish meandered more at the surface (0-5 m depths), and this behavior was apparent in the AutoCAD representations.

The most striking feature of the average statistics is that the Z component of the unit vector in the upper water column was -0.4 for the sluice off condition and +0.1 for the sluice on condition. This represents a significant downward movement of fish in 0-5 m depths when the sluiceway was closed. In addition there was higher toward sluiceway movement (Y component of the unit vector) when the sluiceway was open (-1.0 versus -0.9) in the upper water column. It is interesting to note that at the end of the study, i.e. after June 16, there is slight downward movement of fish in the 0-5 m depths (Table 1) when the sluice was on.

Fish below 5 m depth showed a downward movement regardless of sluiceway condition. The average downward movement was only slightly less when the sluice was on in both the 5-10 m depths (-0.79 versus -0.90) and 10+ m (-0.66 versus -0.78).

The Dalles Dam

Vector statistics were generated from 3m (depth) x 3m (normal to dam face) x data block (width) volumes. These data corresponded to the data blocks: by occlusion plate installation, by diel period, by target strength, by location, and by study period (spring versus summer). A minimum of three fish tracks was required before an average vector was estimated for any block. Vector plots and vector statistics were made to correspond to volume blocked.

In general, when occlusion plates were removed fish tracks and vectors were more horizontal and toward the dam in the vicinity of turbine intakes. When the plates were installed fish traveled in a more vertical and downward direction into the turbine intakes. There was little evidence that near-to-dam fish were able to avoid downward trajectory when occlusion plates were installed. In mid-May, fish entered the sluiceway with greater velocity during the daytime than at night. Ancillary data (BioSonics 1997b) showed that daytime sluiceway entrainment was significantly higher than at night.

A strong down-river component was found at all depths. This downstream component was strongest at location 2, between main units 2 and 3. Movement was strongest at the deeper depths. The

4.5 m and 7.5 m deep blocks (3m to 9 m depths) appear to have the smallest magnitude downstream component. As fish approach the dam they appear to make more effort to avoid the dam. Fish in the 3 m to 12 m depths also appeared to have smaller approach velocities. These observations suggest a zone of transition between fish in the upper 3 meters and those in deeper depths. One hypothesis is that fish in the upper 3 meters are easily able to enter the sluiceway, while a transition zone exists from roughly 3 to 9 meters from which fish may be drawn below or escape into the upper level.

Larger fish appear to be more able to move against the flow, shown for those fish with average TS greater than -35 dB, even in close proximity to the turbine intake. Smaller acoustically sized fish entered the sluiceways, fish units, and main units. Some fraction of these smaller acoustically sized fish probably avoided entrainment entirely, passing downstream toward spillways.

There was more downstream movement in the upper 6 meters at the second location upstream of the fish units. Although there was considerable temporal separation in the data, one interpretation of this finding is that fish passing by the main units are more likely to enter the fish units’ sluiceway or fish units.

John Day Dam

The movement or trajectory of fish upstream of spillbays 18 and 19 was analyzed by plots of apparent fish movement, and partitioned by day and night as well as weir in and weir out (Figure 5). Plots of fish effort vectors were also examined for weir in and weir out conditions. Summary statistics were made by spatially blocking the data into 3m x 3m cross-sectional volumes. The study was divided into three periods: spring (May 5 to June 6), summer (June 7 to July 11) and extension (July 12 to July 24), 1997.

The tracking transducer recorded apparent fish movement that represents the sum of water-induced motion (water velocity) and the fish’s swimming movement (fish effort). Thus, apparent movement is governed in part by fish behavior. Tables 2 and 3 present summary statistics for fish tracks for combined day and night periods for the 2 locations and for the weir in-out conditions.

Fish velocities toward the spillway were largest in the spring and considerably less in summer and extension periods. Fish were distributed higher in the water column during the spring. They tended to be higher in the water column in the weir in condition than in the weir out condition during the spring and summer. Fish movement had greater toward surface components during the spring and summer. During the spring there was a larger toward Washington-side movement in both weir in and out conditions, but only spillbay 19 data showed this tendency during the summer period.

Table 3 shows that the number of fish tracked (normalized by the hours of system operation) was influenced by the weir placement. During the spring the number tracked per hour was highest with the weir in place. However, the number tracked per hour was less with the weir in during the summer. During the spring and summer 70-80% of the fish were moving toward the spillway regardless of weir placement. In both periods the percentage in the upper water column was higher with the weir in, but highest percentage in spring. The longest track was 27 m, during the extension period. Figure 6 shows the average fish apparent and effort vectors (after subtracting water velocity from apparent velocity) in 3m x 3 m blocks in transverse section at spillbays 18 and 19 for the spring period. Fish moved downward and away from the weir in the upper water, with some indication of moving with flow close to the weir. Fish appeared to try to move away from the spillway within 9 m of the weir slot (weir removed) and, farther away, to actively swim toward the dam. In both the summer and extension periods fish also moved downward and away from the dam near the surface although with more meandering farther away from the dam and less active swimming toward the dam.

Fish were distributed at all depths within the set range limit of the tracking transducer systems, roughly 25 meters upstream of the pier nose face. The effect of the flow downstream toward spillbays on apparent fish movement appeared fairly consistent with distance upstream, in the spring and summer periods, when movement downstream is prevalent. In the extension period however, fish appeared to be milling. The fish effort vectors showed that the fish moved more actively away from the dam in the extension period than in spring and summer, thus holding position. The extension period may include larger non-salmonid species capable of moving against flow in front of the spillbays. The fish track plots from the three periods indicated fish vertical distribution is generally unaffected by day and night conditions, however fish movement appears more motivated during the day, and more aligned with stream lines at night.

Discussion

The tracking transducer methodology offers a way to “see” fish movement over longer periods of time than with conventional methods. Some track lengths at the John Day Dam were nearly 30m. These kinds of close range data would be impossible to acquire with conventional fixed systems.

The tracking limitations of the tracking sonar are based in stepper motor angular velocity, the ping rate of the split-beam sounder, the fish speed, and the detection limits of the split-beam transducer. The Simrad transducer was limited by a maximum one way gain compensation of 6 dB and thus about ±4.95 degrees of beamwidth. The BioSonics transducer had slightly larger aperture (±5.7 degrees) and was constrained by phase “wrap-around”.

Pinging at five pings per second, the maximum fish movement and thus angular tracking rate is 25 degrees per second, assuming the target is initially on-axis. The recent advance to 10 pings per second increases angular tracking speed by two (about 50 degrees per second).

The stepper motor control software used a weighted prediction. It receives the alongships angle, and athwartships angle measurements then programs the stepper motors to keep the main axis of the transducer beam aimed on the target, thereby tracking the target. Future application can use other predictive trackers such as Kalman filtering (Beard et al. 1994). Predictive tracking increased the capability to track fish behavior, both lengthening recorded tracks and allowing faster speeds to be recorded.

A tracking transducer system can provide many benefits over the conventional fixed-beam transducer system. The ability to track fish as they move through the water while centering the fish on the acoustic axis, can provide specific information regarding the fish behavior and target strength. This ability to continuously track fish can be applied toward many research and management applications. Some examples include separating large prey from baitfish, predator/prey interaction studies, direction of movement near and around structures (oil platforms), riverine enumeration studies, as well as behavioral studies around structures such as hydroelectric dams and natural and artificial reefs.

At Ice Harbor Dam’s 4B sluiceway and 6’ wide vertical slot configuration, the tracking transducer showed that fish meandered at the surface but did so less and approached the slot when the sluiceway was open. This was true in the upper 5 m of water. Below 5 m there is significant movement into the turbine intakes. The tracking transducer shows advantages over fixed systems (for example Ransom and Ouellette 1988) for behavior observation. They suggested that fish were found in depths of 1 to 2 m while we show fish are distributed down to and past the level of the turbine intake at Ice Harbor Dam. The tracking transducer data compare well with the present mobile survey data that found an abundance of fish in the 4-5 m depths (BioSonics 1997b). This new tool suggests that the fish behavior is to move into the sluice as long as the fish remain above 5 m. Hydrodynamic theory suggests that streamlines present in the upper 5 m near dam may be shallower away from the dam. Thus fish found at 4-5 m could be entrained if they are passive and do not move to the upper streamlines.

At the Dalles Dam, the tracking transducer performed best in deeper depths. As a result there were less data for fish traveling at depths shallower than the bottom of the sluiceway intake. This was especially true during sampling at the second location between main units 2 and 3. The majority of fish tracks were taken just below the level of the sluiceway intake at location 2. Near-surface noise was one reason for the smaller number of fish tracks close to the surface. Transducers with low sidelobes should be used in future studies in similar acoustic noise backgrounds, for example at John Day Dam. Recently (August 1998) the predictive tracking algorithm has been extended several pings into the future. Adult salmon were tracked with tracks nearly 50 m long from a fixed barge on the Fraser River. Currently, the system has the capability of tracking a single fish over a time period. In the future, it is hoped that more than one fish can be tracked by utilizing predictive tracking and taking advantage of the extremely high speed of the stepper motor system. The tracking transducer can move in excess of 140 degrees per second. One half of a hemispherical volume can be scanned in less than 10 seconds with a ping rate of 10 pings per second. Much of the 1995 behavioral study effort at Ice Harbor Dam was spent on developing the tracking split-beam system. It became immediately apparent that the approach offered considerable advantages. In particular, the tracking split-beam system offers the potential to bridge the gap between radio tracking and conventional fixed location acoustics. Radio tracking provides long tracks of fish movement. However, because of the effort and cost involved the sample size is small. Conventional fixed location acoustics provide detailed information on relative rates of passage at specific points, with very large sample sizes. However, it is apparent from the observed milling behavior, the horizontal differences in both abundance and diel behavioral patterns, and other intriguing diel patterns of fish passage, that the approaches and near-field behavior can be complex, and that behavior may provide critically important information with regard to the effectiveness of surface biological collectors. Non-tracking split-beam systems can provide directional information, but only over the same limited dimensions as conventional fixed-location acoustics. In contrast, tracking split-beam offers the possibility of providing intermediate track lengths, and especially, detailed behavioral information in the near field, that is not only valuable in its own right, but can considerably enhance the value of the radio tracking and conventional fixed location information. We also successfully tracked 200 kHz acoustic tags with the tracking transducer (Johnson et al. 1998) and this new capability should be valuable in augmenting the array of tools to study and evaluate fish bypass facilities.

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