Using Acoustic Tags to Track Juvenile Salmonids in Three Dimensions Within a Turbine Intake at Wanapum Dam, Washington, USA


ABSTRACT

Wanapum Dam on the Columbia River, Washington, has 10 Kaplan turbine units with a combined generating capacity of 1038 megawatts. To improve turbine passage survival for juvenile salmonids, a Fish-Friendly Turbine Unit (FFTU) was developed. The goal of this study was to evaluate the ability of acoustic tags to provide fine scale, sub-meter, three-dimensional tracks of juvenile salmonids as they pass through an operating turbine unit. Five hydrophones were deployed within the turbine intake, where water velocities were 4-6 ft s⁻¹ (1.2-1.8 m s⁻¹). A predictive mathematical model indicated that the majority of the array would exhibit tag position variability less than 1.5 ft (46 cm). Thirty two (32) juvenile steelhead (Oncorhynchus mykiss) between 150 and 195 mm in length were externally tagged with HTI Model 795E Acoustic Tags and Hi-Z balloon tags for recovery. Fish were released via a pipe within the intake. Acoustic tags transmitted at 25 pulses per second, with a coded pulse to improve position resolution. All 32 fish were tracked, and many tracks indicated substantial horizontal movement. Most fish followed the intake ceiling and moved downstream. A fixed location tag produced a maximum total range of X-Y-Z positions of 19 inches (49 cm).

INTRODUCTION

In November, 2004, Grant County Public Utility District (District) contracted with Hydroacoustic Technology, Inc (HTI) to conduct a pilot study to test if acoustic tags could be used to locate and track the fine-scale, three-dimensional movements of juvenile salmonids as they passed through a turbine intake.

HTI Model 290 Acoustic Tag Tracking Systems have been used to track juvenile and adult salmon in the Columbia River, Snake River, Sacramento River, and other river systems, as well as to track other species worldwide (Steig 2000, Steig and Timko 2000, Steig et al. 2001, Steig et al. 2002, Timko et al. 2001, Timko et al. 2002, Zapel et al. 2001, Ehrenberg and Steig 2003). Tens of thousands of individual fish have been tagged with Model 795 Acoustic Tags, most of those being juvenile salmonids released in the Columbia River Basin. Using Model 290 Systems, tagged fish were routinely tracked in three dimensions with sub-meter resolution (Timko et al. 2002), with some applications realizing sub-20 cm resolution (Zapel et al. 2002).

This study focused on the feasibility of using this technology within an operating turbine intake at Wanapum Dam, USA.

Site Description

Wanapum Dam (Figure 1) is located on the Columbia River at river mile 416, 19 miles upstream of Priest Rapids Dam and 38 miles downstream from Rock Island Dam. Normal maximum forebay elevation is 570 ft above MSL, and forebay depth at the powerhouse is
110 ft (relative to elev. 570 ft). Normal operating head is 82.5 ft. The dam has a 1540 ft-long powerhouse, oriented approximately with river flow, and an 830 foot-long spillway at approximately a 45° angle to flow.

The powerhouse has 10 Kaplan turbine units, numbered from north to south, with a combined generating capacity of 1038 megawatts. There are additional intake structures for six potential future units. Each turbine unit has three intake slots, designated A, B and C from north to south. Each turbine unit passes 14-16 kcf/s when operating under normal load. Each turbine intake at the trash rack is 60 ft high and 20 ft wide (see Figure 3). A Fish-Friendly Turbine Unit (FFTU) was installed in Turbine Unit 8 at Wanapum Dam, and was completed in early February 2005.

The spillway contains 12 tainter gates, each 66.5 ft tall by 50 ft wide. A surface-skimming sluiceway is located at the north end of the spillway. Spill Bay 12 closest to the sluiceway has been converted to a "top spill" overflow gate, capable of passing up to 20 kcf/s. Neither the spillway, sluiceway, nor top spill was operating during the study reported here.

Figure 1. Wanapum Dam on the Columbia River, Washington, USA.

METHODS
In-turbine tracking was conducted November 9-12, 2004, using a Model 290 Acoustic Tag System (Figure 2) deployed at Turbine Unit 5. Model 795E Acoustic Tags were externally attached to juvenile salmonids. In order to detect the acoustic signals and track the tagged fish, passive hydrophones were installed in the monitored turbine intake. As fish passed through the intake, the arrival time of each transmitted signal from each tag was recorded for each hydrophone. The differences in arrival times of signals from individual tags on each hydrophone were used to calculate each tagged fish's three-dimensional position.
Figure 2. *Model 290 Acoustic Tag System* with hydrophone and acoustic tags (not to scale).

**System Deployment**
In order to obtain three-dimensional positions, hydrophones must be deployed so that there is a direct line of sight to a minimum of four hydrophones from the tag. Each acoustic ping from the tag must be received by four hydrophones that are not located in a single plane (Figure 3). Typically, hydrophones are deployed with alternating shallow and deep deployments. In order to achieve the best resolution in all three dimensions (i.e., X, Y and Z), the separation between the four hydrophones should be equal.

The system was installed, calibrated, and tested prior to introducing tagged fish into the turbine intake. To locate and calibrate hydrophone positions, an acoustic signal was transmitted from each hydrophone to all other hydrophones.

The difference between the transmit time of the signal and the received time of signal was measured and recorded. This information was then used to calculate the distance between each hydrophone. By knowing the distances between every hydrophone pair (in both directions), hydrophone locations were determined to within 3 cm (1 inch) (Table 1). The turbine unit did not require dewatering for hydrophone and cable deployment or retrieval. Five hydrophones were mounted in a fixed manner for the duration of the study, and cables were strung from each hydrophone to the receiver unit which was located in a
trailer located over the intake of Turbine Unit 6. Two hydrophones were placed on wheel gate mounts (one surface, one bottom), and three hydrophones were placed on fyke net frames (surface, mid-water and bottom) (Figure 4). In this configuration, the volume defined by the hydrophones was the 20 ft (6 m) width of the intake, by 20 ft (6 m) thick (in the upstream/downstream direction) by 49 ft (15 m) high (at the bulkhead gate slot).

Table 1. Hydrophone positions in-turbine at Turbine Intake 5B, in X, Y and Z as well as surface/bottom orientation and general location (in feet).

<table>
<thead>
<tr>
<th>Hydrophone</th>
<th>Location (X)</th>
<th>Location (Y)</th>
<th>Location (Z)</th>
<th>Surface/Bottom</th>
<th>Location</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>117.1</td>
<td>100.6</td>
<td>105.3</td>
<td>Bottom</td>
<td>Fyke Frame</td>
</tr>
<tr>
<td>2</td>
<td>110.1</td>
<td>99.9</td>
<td>129.5</td>
<td>Middle</td>
<td>Fyke Frame</td>
</tr>
<tr>
<td>3</td>
<td>118.1</td>
<td>120.6</td>
<td>132.2</td>
<td>Top</td>
<td>Wheel Gate</td>
</tr>
<tr>
<td>4</td>
<td>101.6</td>
<td>100.0</td>
<td>151.4</td>
<td>Top</td>
<td>Fyke Frame</td>
</tr>
<tr>
<td>5</td>
<td>101.6</td>
<td>120.1</td>
<td>112.3</td>
<td>Bottom</td>
<td>Wheel Gate</td>
</tr>
</tbody>
</table>

Figure 4. Cross-section of a turbine intake at Wanapum Dam, showing the position of hydrophones and the fish release hose.
Acoustic Tags
HTI Model 795E Acoustic Tags (6.8 mm diameter x 18 mm long; 1.5 g in air and 0.80 g in water) were used for the pilot study described here. They operate at 307 kHz and have a typical source level of 155 dB. The tags can be programmed to emit an acoustic signal from 50 pulses/sec to 1 pulse/16 sec. An encoded, coded-phase modulated pulse is available that gains up to 11 dB in signal-to-noise, and detection ranges are up to 1 km in freshwater (Figure 5). Over 50,000 unique tag codes (ping rate-based) are available, and several hundred tags can be tracked simultaneously.

![Encoded Pulse](image)

**Figure 5.** Oscilloscope trace of the acoustic tag encoded pulse. The main peak of the pulse is the effective pulse width and is used for fish positioning.

Pulse rate and output power were programmed in the field just prior to attachment to the fish. Laboratory tests of Model 795E Acoustic Tags at 30 pulses/sec yielded a tag life of approximately 7 hr, with no significant loss in signal level.

The Model 795E Acoustic Tags used for this study were programmed in the field with an encoded pulse width of 3 msec, providing an effective resolution equivalent to a pulse width of 0.29 ms. Tags were programmed to ping 25 times/sec (i.e., every 40 msec).

Fish Releases
Acoustic tagged juvenile salmonids were released into the turbine intake through a 6 inch (15 cm) diameter release hose deployed in the center of the bulkhead gate slot, the exit to which was placed approximately 10 ft (3 m) below the intake ceiling (Figure 4). Each fish’s movement within the hydrophone array was tracked and displayed in three dimensions.

Average water velocities within the turbine intake ranged from 4-27 fps (Table 3). A tag ping rate of 25 pings/sec was used, which would provide a three-dimensional position for at least every 30 cm (1 ft) of travel to just beyond the wicket gates. During the pilot study velocities within the area where the five in-turbine hydrophones were deployed were approximately 4-6
fps, and here a ping rate of 25 pings/sec was estimated to provide a three-dimensional position for approximately every 5 cm (2 inches) of travel.

Table 3. Average water velocities in-turbine at Wanapum Dam, at a flow rate of 16 kcf/s (personal communication, Larry Weber, University of Iowa, September 25, 2002).

<table>
<thead>
<tr>
<th>Location</th>
<th>Area (sf)</th>
<th>Velocity (fps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trashrack</td>
<td>3960</td>
<td>4.0</td>
</tr>
<tr>
<td>Bulkhead Gate</td>
<td>3069</td>
<td>5.2</td>
</tr>
<tr>
<td>Wheel Gate</td>
<td>2510</td>
<td>6.4</td>
</tr>
<tr>
<td>Start of Scroll Case</td>
<td>3370</td>
<td>4.7</td>
</tr>
<tr>
<td>Stay Vanes</td>
<td>910</td>
<td>17.6</td>
</tr>
<tr>
<td>Open Wicket Gates</td>
<td>591</td>
<td>27.1</td>
</tr>
<tr>
<td>Centerline of Turbine Runner Blades</td>
<td>443</td>
<td>36.1</td>
</tr>
</tbody>
</table>

Data Collection and Analysis
All fish releases, tracking, and tailrace recovery were conducted November 10-11, 2004. Data were collected from the HTI Model 290 Acoustic Tag Receiver via a networked PC. Individual files were collected for each single acoustic tag released. Each individual acoustic tag file included raw tag signal data for all five hydrophones. These files were processed using the HTI data collection and analysis programs AcousticTag™ and MarkTag™. The ultimate output from these programs was hourly MS Access databases which included the X, Y, Z three-dimensional positions for each tag transmission for each tagged fish. Each individual in-turbine acoustic tag track was viewed in AcousticTag/MarkTag™ and Tecplot™ software. Plan and side views of each track were produced via Tecplot™.

Background noise levels in-turbine were measured using a storage oscilloscope, and by examining the on-screen displays of acoustic signals and noise provided by AcousticTag/MarkTag™ software when used in conjunction with the Model 290 Acoustic Tag Receiver.

Prior to the study there was concern that the confined, concrete quarters of the turbine intake might produce significant levels of acoustic signal multipath. Multipath levels typically vary with acoustic tag signal strength, pulse widths, and signal encoding measures. By using a storage oscilloscope and the signal displays available within AcousticTag/MarkTag during three-dimensional tracking of acoustic tags, the degree to which multipath interfered with tracking was assessed.

Following Ehrenberg and Steig (2002), modeling was performed in order to predict the precision around the three-dimensional locations of tags tracked within the hydrophone array (Figure 6). The model employed incorporated each hydrophone position (X, Y, Z) and the following variables: water temperature, tag signal pulse width, and ambient noise. A fixed acoustic tag was attached to the fyke net frame used to hold the three hydrophones deployed in the bulkhead gate slot. The fixed tag was attached to a thick plastic “cable tie”
located adjacent to the center hydrophone on the fyke net frame, and was approximately 15 cm (6 inches) downstream from the frame. The tag was programmed to operate with a 0.5 msec unencoded pulse, and to ping at 1.017 msec pulse separation interval (approximately 1 ping/sec).

In addition, an acoustic tag was placed into a tennis ball and released into the turbine intake via the fish release hose. It was expected that the tennis ball and the tag inside it would follow the flow lines and exhibit a straighter, more uniform trajectory than a fish, which could be expected to fight the flow and alter its trajectory within the flow. The tennis ball was cut in half, the acoustic tag sutured in place, and the tennis ball halves taped together.

By using data from the tracks of released acoustic tags, modeling of position error, and by monitoring (tracking) the position of an acoustic tag held stationary from the fyke net frame, the resolution of tag positions was estimated in each of the three dimensions (X, Y, Z), and for all three dimensions combined.

Figure 6. Centerline predicted position variability, following Ehrenberg and Steig (2002). View is looking downstream, with flow. Hydrophones are presented as black circles.
RESULTS

Assessing the In-Turbine environment
The ratio of signal strength to background noise levels was variable, but averaged approximately 12-15 dB. It was relatively easy to distinguish the continuous tagged fish transmissions from the background noise due to the tag signal’s consistent appearance compared to the random nature of the background noise (Figure 7). This was aided by the very rapid pulse rate used, 25 pulses/sec.

The fyke net frame was a massive structure comprised of large square steel tubes. The steel members introduced flow eddies on the downstream side of the frame that passed through the acoustic monitoring array. Also, movement of the fyke net frame within the guides in which it rested may have introduced acoustic noise. In addition, it is assumed that the hydrophones received acoustic noise generated by the high flow passing over them.

Figure 7. MarkTags™ display showing background noise levels, limited multipath, and the correlated pulses from an acoustic tag received by one hydrophone as the tag passed through the intake (appx. 5.25 seconds travel time).

Multipath levels were typical (Figure 7), and did not impact the ability to track acoustic tag fish in three dimensions, nor did they significantly degrade the resolution of three-dimensional positions.
Fish Tracks
The three-dimensional tracks for all 32 tracked fish are presented together in Figure 8. Fish released via the release hose entered the turbine intake well within the hydrophone array (Figure 4). Also, most fish releases were accompanied by entrained air injected into the hose during their release. In some cases, this air precluded successful tracking of the first few feet of a fish track. However, tracks for most released fish began immediately upon their exiting the release hose, and many were continuous to approximately 10 ft (3 m) beyond the downstream extent of the hydrophone array, at the wheel gate slot (Figure 9).

Once exiting the release hose fish tended to spread more quickly horizontally than vertically, probably influenced by eddies produced immediately downstream of the fyke net frame. Such movement is also consistent with a salmonid’s ability to rapidly orient itself by flexing it body horizontally. It is difficult to determine whether this was the result of active orientation, or due to flow eddies and turbulence downstream of the fyke net frame.

Figure 8. Plan and side views of the three-dimensional tracks for all 32 tracked fish (Wanapum Dam 2004).
Figure 9. Fish No. 8 three-dimensional track in-turbine in side view and plan view, released November 11 at 1100 hr. Hydrophones appear as black diamonds, and the exit to the release hose as a circle. (Wanapum Dam 2004).

Position Variability
Three indications of the variability in the positions of the acoustic tags in turbine all suggested that variability was from 20 to 50 cm (8 to 20 inches). That is, the maximum range of three-dimensional tag positions was < 20-50 cm (8-20 inches), or individual positions were < +/− 10-25 cm (4-10 inches).

Following Ehrenberg and Steig (2002), a three-dimensional contour plot of predicted tag resolution was calculated (Figure 6). Modeling indicated that the expected position variability within the array was less than 3.5 ft (107 cm), with the majority of the array expected to exhibit variability less than 1.5 ft (46 cm).
Figure 10. Three-dimensional tracks of the tennis ball with an acoustic tag in it, released November 11 at 1600 hr, in side view and plan view. Hydrophones appear as black diamonds, and the exit to the release hose as a circle (Wanapum Dam 2004).

The fixed acoustic tag that was attached to the fyke net frame adjacent to the center hydrophone was monitored throughout the study period and produced a total range of X-Y-Z positions of 19 inches (49 cm). This placement was at the edge of the hydrophone array, where the predictive model showed the position error increasing. Nevertheless, the standard deviations of the calculated positions for each dimension were low: X (across intake) 0.212 ft (0.065 m), Y (upstream to downstream) 0.154 ft (0.047 m), and Z (surface to bottom) 0.132 ft (0.040 m), n = 3069.

The track for the acoustic tag that was placed in a tennis ball (Figure 10) was relatively short, likely affected by air entrained in the release hose, air in the “fuzz” on the exterior of the tennis ball, and air inside the tennis ball. The track in plan view also appeared to follow an eddy induced by and immediately downstream of the fyke net frame (Figure 8). Unlike the
released fish, the tennis ball was an inanimate object. Its lateral movement supports the existence of a flow eddy downstream of the fyke net frame.

CONCLUSIONS

Deployment and retrieval of the Model 290 Acoustic Tag Tracking System was straightforward.

Fish were tracked throughout the volume covered by the hydrophone array, with no gaps or holes observed in the track data. In most cases tracks for tagged fish began immediately upon their exiting the release hose, and most were continuous to approximately 10 ft (3 m) beyond the downstream extent of the hydrophone array (i.e., beyond the head gate slot).

Three measures of the variability in the positions of the acoustic tags in turbine all indicate that maximum spread in three-dimensional tag positions was < 20-50 cm (8-20 inches).

Background noise levels were relatively high, but the encoded tag signals stood out well and were relatively straightforward to mark and track. Multipath was typically low, and did not present significant difficulty.

This pilot study has demonstrated the ability of acoustic tags to provide fine scale, submeter, three-dimensional tracks of juvenile salmonids as they pass through an operating turbine intake. The detailed route of travel through the turbine intake area provided by the acoustic tag warrants considering the use of this technique in future studies.

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REFERENCES CITED


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