Active Fish Tracking Sonar (AFTS) for Assessing Fish Behavior

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Summary

Digital active fish tracking sonars (AFTS) were used in 2001 to study fish movement in response to intake occlusion plates at The Dalles Dam on the Columbia River. AFTS provides three-dimensional fish tracks by aligning the axis of the split-beam transducer with a fish target. High-speed stepper motors move the transducer so that a tracked target remains on-axis.

Occlusion plates with J-extensions covered the top half of the turbine intakes to produce a fish friendly near-dam environment. Two AFTS were positioned at the center of Main Unit 1, one each for monitoring plates IN and OUT conditions. The occlusion plates had pronounced effects on fish movement along the dam. They appeared to decrease westward movement, decrease movement toward the dam (especially in front of the turbine intake), and decrease downward movement toward the turbines.

Fish fate into a particular areas was determined using Markov chain analysis. The sluiceway (a safer passage route) zone of influence was larger with the occlusion plates IN than OUT. Moreover, the probability of passage out the turbine/bottom sides of the sample volume was about 50% lower with occlusion plates IN than OUT.

1. Introduction

Development of long-term protection measures for juvenile salmon at The Dalles Dam is a high priority in the endeavor to increase smolt survival through the Federal Columbia River Power System. The Dalles Dam does not have turbine intake screens, so the only non-turbine passage routes for downstream migrants are the sluice outfall and spillway. Estimates of project-wide fish passage efficiency (FPE, non-turbine passage divided by total passage) range from 80 to 90%, depending on the percentage of spill, among other factors [1]. Thus, there is a need to improve FPE at this critical passage point in the Columbia River.

In 2001 at The Dalles Dam (TDA), prototype turbine intake occlusion plates with 8 m “J”-extensions were evaluated as a new means of preserving juvenile salmon (Figure 1). The occlusion plates covered the upper half of the intakes at Fish Units 1-2 and Main Units 1-5 and caused the turbines to draw water from deeper in the forebay. The premise behind the J-occlusions is that deepening the turbine flow net will decrease entrainment into turbines of juvenile migrants naturally oriented toward the surface. Thus, the intent of the J-occlusions was to decrease turbine entrainment while increasing sluiceway and/or spillway passage, thereby increasing project-wide FPE and, ultimately, fish survival.

As part of the overall J-occlusion evaluation effort, we collected data on smolt movements in front of Sluice 1-2 from April 24 to June 1, 2001, using two digital acoustic fish tracking sonars (AFTS) developed by BioSonics. Other researchers used radio telemetry and hydroacoustic techniques to assess the performance of the J-occlusions, i.e., estimate FPE, spillway and sluiceway efficiencies, and spill, sluice, and turbine passage rates. The sonar tracker data will be useful to interpret and explain the J-occlusion performance data, which will be the “bottom-line” for decisions about the J-occlusions.

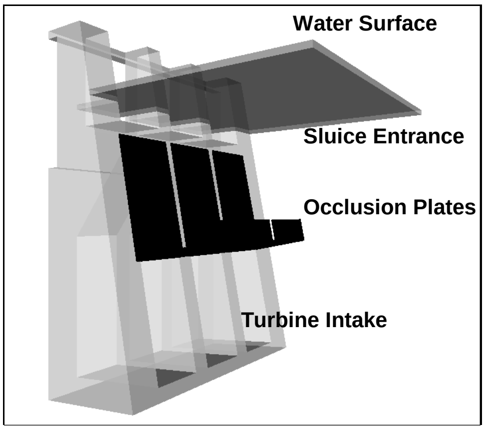


Figure 1. Perspective drawing of TDA Powerhouse Unit 1 showing occlusion plates with J-extensions relative to turbine intakes and sluice entrances.

The objectives of the sonar tracker study were to:

1. Describe smolt movements in terms of observed fish directions and movement fates, with and without J-occlusions in place. Fates are probabilities to which side of the sample volume a tracked fish will exit.

2. Assess specific hypotheses about smolt movements, including:

- the zone of influence of the sluiceway as determined by fate probabilities will be larger with J-occlusions than without;
- the overall probability of passage toward the spillway (west) will be higher with J-occlusions than without;
- the overall probability of passage toward the turbines will be lower with J-occlusions than without.

2. Methods

Our general approach was to intensively sample fish movements in the region immediately upstream of a sluiceway entrance at TDA. We used an active fish tracking sonar (AFTS). AFTS as applied at a dam (described below) was first applied in 1995 at Ice Harbor Dam, and later at John Day Dam and The Dalles Dam [2]. AFTS was also a key element in the Behavioral Acoustic Tracking System that is used to track acoustic-tagged fish [3][4]. Split-beam acoustics [5] is a main component of AFTS.

2.1. Active Fish Tracking Sonar - AFTS

The components of an AFTS system (Figures 2 and 3) include a 200 kHz BioSonics DT4000 digital split-beam echo sounder, a 7° split-beam transducer, two high-speed stepper motors for dual axis rotation, a controller unit, a laptop computer, a desktop computer, and cables.

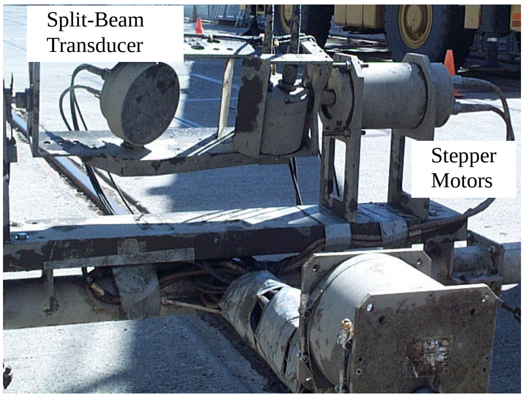


Figure 2. Underwater components of the active fish tracking system

AFTS is based on the principle of tracking radar, and a simple description follows. Once a fish was detected after the transducer was randomly aimed into the sample volume, two high-speed stepper motors aligned the axis of the digital split-beam transducer on the target. As the fish moved from ping to ping, deviation of the target from the beam axis was calculated and a predictive tracking algorithm was applied to re-aim the transducer, thereby tracking the target. The predictive tracking algorithm was a discounted least-squares fit [6], where the most recent velocity estimate (magnitude and direction) was weighted by unity, the next most recent by one-half, the next by one-fourth, the next by one-eighth, and so on. If no target was detected after 30 sec of pinging at a given position, the aiming angles were changed to another random position. The ping rate was approximately 10 pps. The echo sounder threshold was set at –60 dB on-axis. For each ping the target was tracked, data on fish X, Y, Z position relative to the transducer and target strength were recorded to disk. Fish position resolution can be inferred from the angular resolution (± 0.35°). At 10 m from the transducer, this would amount to ± 6 cm, and at 1 m the error would be ± 0.6 cm.

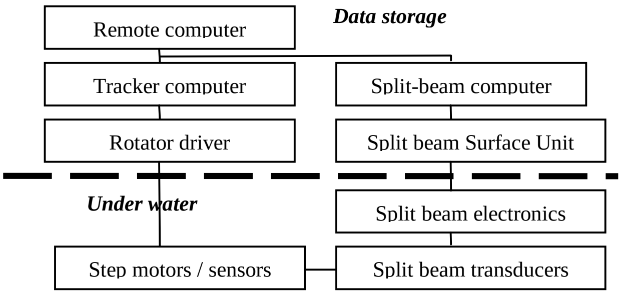


Figure 3. Schematics showing AFTS tracker and split-beam components and data flow from at the Dalles Dam via network

Two AFTS systems were deployed at Main Unit 1-2. One was mounted on the tip of the J-extension to sample fish movements when the J-occlusions were in place (Figure 4). The other was mounted about 20 m deep on a trash-rack to sample fish movements when the J-occlusions were out of the water (Figure 5). The primary area of interest for both trackers was a region 10 m wide, 15 m from the dam, and 10 m deep immediately in front of Sluice1-2.

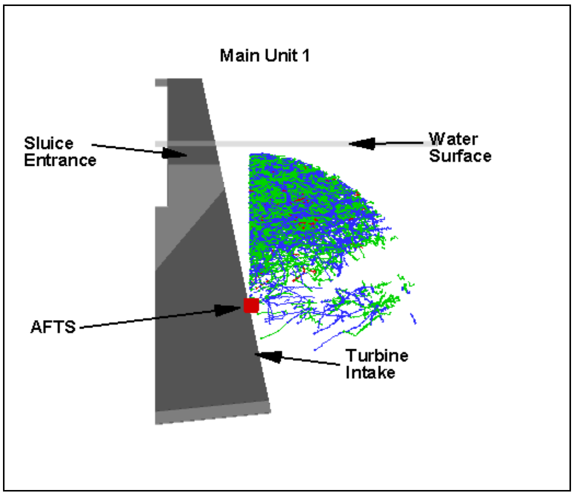


Figure 4. Side view of sample volume for condition with J-occlusion plates installed. Volume is all tracked fish.

2.3. Direction of movement based on identified fish tracks

Fish track directionality relative to the presence of J-occlusions, night versus day and spill condition can be characterized using proportions based on individual track regressions in each of the three dimensions: along the dam, upstream/downstream and up/down. The movement proportions were based on the results of linear regressions applied on each fish track for each dimension separately to estimate three components of movement, as in the following example for the *X*-dimension:

$$X_t = A_x + B_x t \qquad (1)$$

where, A_x and B_x are the y-intercept and slope coefficients of the linear regression for the X-dimension and t is time. Linear regression (1) though all positions comprising a track was more representative of track movement in its entirety than data from just the end points.

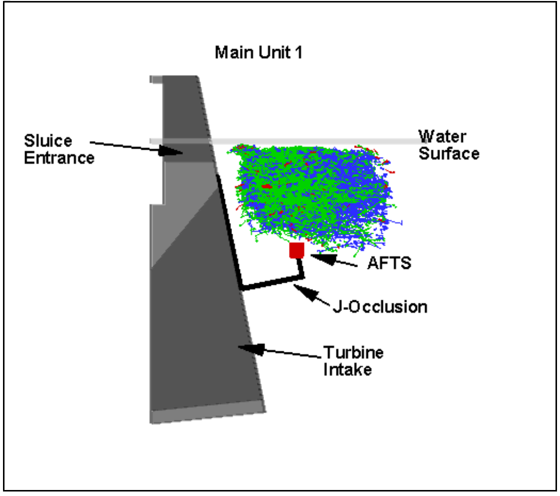


Figure 5. Side view of sample volume for condition with J-occlusion plates removed. Volume is all tracked fish.

Using a common sample volume (Figures 4 and 5), summary proportions and variances were calculated for direction of movement separately for each dimension (*X* east/west; *Y* toward/away; *Z* up/down) for each condition (J-occlusions IN/OUT, day/night, and spill/no spill) as follows:

$p_i = \frac{a_i}{m_i}$, the estimated proportion on day *I*

where a_i is the number of tracked fish with a particular sign of regression slope (positive or negative) and m_i is the total number of tracked fish. The overall estimate across *n*-days of a particular treatment condition is:

$$p = \frac{\sum_{i=1}^{n} a_i}{\sum_{i=1}^{n} m_i} \qquad (2)$$

with associated estimated variance

$$Var(p) = \frac{1-f}{n\bar{m}^2}\left[\frac{\sum_{i=1}^{n} a_i^2 - 2p\sum_{i=1}^{n} a_i m_i + p^2 \sum_{i=1}^{n} m_i^2}{n-1}\right]$$

where f=0 (i.e., the finite population correction is ignored) and where

$$\bar{m} = \frac{\sum_{i=1}^{n} m_i}{n}.$$

2.4. Markov analysis of fates based on individual fish tracks

Fates (where fish tracks exited the sample volume) are expressed as probabilities of passage toward a particular area, e.g., the sluiceway. To determine fate probabilities, we applied a Markov analysis [7], which described smolt movement as a stochastic process. A couple key ideas [7] are: (a) a Markov process $\{X_t\}$ is a stochastic process with the property that, given a value X_t, the values of X_s, for $s>t$ are not influenced by the values of X_u for $u<t$, and (b) transition probabilities are functions not only of the initial and final states, but also of the time of transition as well. When the one-step transition probabilities are independent of the time variable, then the Markov chain has stationary probabilities. The Markov-chain analysis for the 2001 TDA sonar tracker study included the following assumptions:

- The movements can be described by a one-step Markov process. In other words, movement decisions are based on the smolt's current position and not upon the prior history getting to that position.
- The transition probabilities are estimated from independent fish observations.
- The transition matrix is stationary.

The three-dimensional sample volume in front of Sluice 1-1 was divided into cells (modified for fate analysis as follows: 0.5 x 0.5 x 0.5 m for *X*, *Y*, *Z*, respectively). The sample volume was decreased to reduce the size of the Markov matrices: X = -3.0 to 3.0 m, Y = 3.0 to 15.0 m, and Z = –6.0 to –0.5 m. At the boundaries (sides) of the volume, we defined these passage fates:

- Sluice – cells on side facing the sluiceway, 0.0 to 4.0 m deep;
- Turbine – cells on side facing the sluiceway, 4.0 to 6.0 m deep;
- West – west side cells;
- East – east side cells;
- Bottom – bottom cells of the volume;
- Reservoir – cells of side facing the reservoir upstream;
- Unknown – no movement.

The Markov transition matrix was a square matrix the size of *k* x *k*, where *k* is the number of distinct cells being modeled (k = 3,168). The *i*,*j*-th element in the *i*-th row of the j-th column of the transition matrix was the estimated probability (p_{ij}) of moving from cell *i* to cell *j* in the next time step. These probabilities were estimated by:

$$\hat{p}_{ij} = \frac{x_{ij}}{n_i} \tag{3}$$

where,

n_i = number of observations of smolts in the *i*-th cell;

x_{ij} = number of observations where a smolt in cell *i* moved to cell *j* in the next 1 s time step.

The cells that bordered the sides of the volume of interest (sluice, turbine, west, east, bottom, and reservoir) were set to unity to absorb any movement that reached a particular "fate." Non-boundary (including surface) cells were checked to ensure non-zero and non-unity values. If zero or unity was present in an *i*,*i* cell after building the matrix T from a set of data, then the closest *i*,*i* cell in Cartesian space was found that contained data and was used to augment that particular set of *i*,*j*'s. This process created a situation that guaranteed fish movement to one of the absorbing boundaries if there was movement to begin with.

The transition matrix T for one time step (1 s) was then used to estimate the transition for two or more time steps as:

T^q

where, q = the number of time steps. For this study, q = 4,096 so that the Markov process reached stability, i.e., the resultant matrix did not change with additional time steps:

T^{4096}.

The probabilities for each of the seven fates for each of the 2,728 cells of the resultant matrix, not including border cells, were then assumed to describe where the fish moved.

The fate probabilities from the Markov-chain analysis were used to calculate “probability indices” for assessing specific hypotheses about the effects of the J-occlusions. A probability index (*PI*) for a given condition is the average fate probability over all cells in the sample volume, as follows:

$$PI = \frac{\sum_{i=1}^{m}\sum_{j=1}^{n}\sum_{k=1}^{o} F_{i\,jk}}{m \cdot n \cdot o} \tag{4}$$

where, F_{ijk} is the fate probability for the i-th cell along the dam the j-th cell away from the dam, and the k-th cell deep.

3. Results

Table I shows the number of fish tracks recorded by AFTS. Table II presents results based on regressions slopes. The proportion of fish moving westward toward the spillway (out of the total west plus east; the *X*-dimension) was 11% higher with J-occlusions IN than OUT. The proportion of fish moving toward the dam (out of the total toward plus away; the *Y*-dimension) was also 11% during IN than OUT. And, the proportion of fish moving upward (out of the total up plus down; the *Z*-dimension) was 12% higher with J-occlusions IN than OUT. In general, movement proportions toward the dam and upward were 3-4% stronger during day than night. When water was spilled, the proportion of fish moving westward toward the spillway was 12% higher than during no spill.

Table I. Observed fish tracks: Descriptive track statistics are shown for J-occlusions IN and OUT.

		IN	OUT
Day	Pings	579,801	191,904
	Tracks	16,402	4,146
	Pings/track	35	46
Night	Pings	963,296	291,053
	Tracks	19,831	5,450
	Pings/track	49	53
Combined	Pings	1,543,097	482,957
	Tracks	36,233	9,596
	Pings/track	43	50

Table II. Observed fish tracks: Summary mean proportions with 95% confidence levels for direction of movement separately for each dimension (*X, Y, Z*) for J-occlusions IN, OUT, day, night, no spill, and spill. Movement directions obtained from signs of regression coefficients for each dimension of each fish track (regression of position on time).

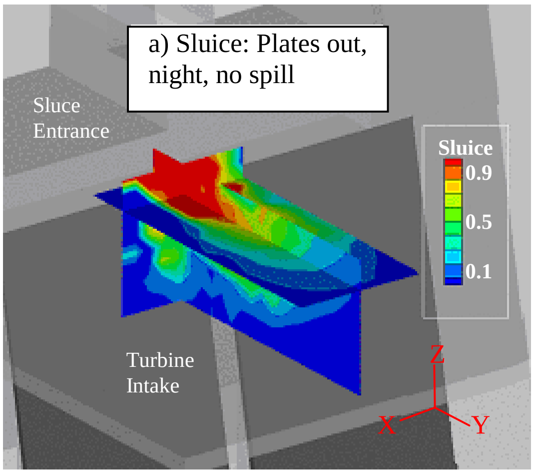
	X		Y		Z	
	EAST (+)	WEST (-)	AWAY (+)	TOWARD (-)	UP (+)	DOWN (-)
IN	0.48 ±0.01	0.52 ±0.01	0.41 ±0.01	0.59 ±0.01	0.50 ±0.01	0.50 ±0.01
OUT	0.37 ±0.01	0.63 ±0.01	0.30 ±0.01	0.70 ±0.01	0.38 ±0.005	0.62 ±0.005
Day	0.46 ±0.04	0.54 ±0.04	0.37 ±0.03	0.63 ±0.03	0.50 ±0.03	0.50 ±0.03
Night	0.47 ±0.02	0.53 ±0.02	0.42 ±0.02	0.58 ±0.02	0.47 ±0.02	0.53 ±0.02
Spill	0.36 ±0.04	0.64 ±0.04	0.38 ±0.03	0.62 ±0.03	0.52 ±0.02	0.48 ±0.02
No Spill	0.48 ±0.02	0.52 ±0.02	0.40 ±0.02	0.60 ±0.02	0.48 ±0.02	0.52 ±0.02

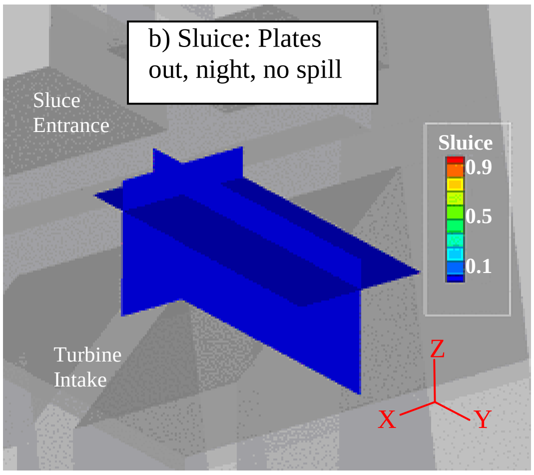
In conclusion, the direction of movement proportions indicated that with the J-occlusions IN resulted in less movement to the west, less movement toward the dam, and less movement downward in the water column than with them OUT.

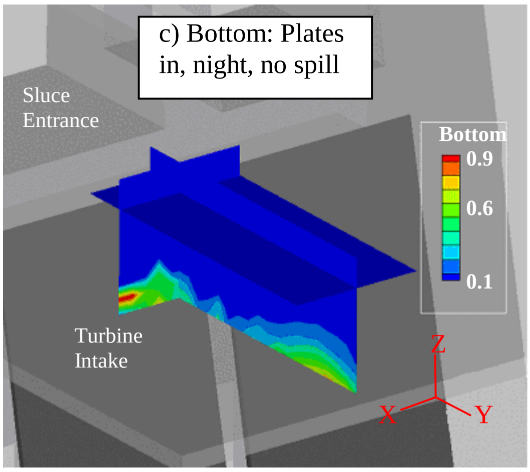
Prominent differences were observed between J-occlusions IN and OUT. West fate (4) was 37% higher during day and 34% higher during night with plates IN than OUT. East fate was 24-24% higher IN than OUT. Sluice fate was 12% higher IN than OUT during day and, during night (6a vs. Figure 6b), sluice fate was negligible with plates OUT. Turbine/bottom fate was 12% higher IN than OUT during night (Figure 6c vs. Figure 6d); no differences during day.

West fate with J-occlusions OUT was the largest (0.59-0.66), followed by east (0.34-0.35) and sluice (0.22-0.25) with plates IN. The reservoir fate was the smallest (0.02-0.04).

In summary, effects of the J-occlusions on smolt movements were evident as noticeable, distinct differences in movement patterns between the IN and OUT conditions. Mean fish velocities, movement proportions, and fate probabilities all demonstrated differences between J-occlusions IN and OUT. Generally, the J-occlusions appeared to cause fish in the nearfield of Sluice 1-2 to decrease westward movement, decrease movement toward the dam, and increase upward movement in the water column. If these patterns translate to passage, then we would expect the J-occlusions to result in decreased turbine and increased sluiceway fish passage rates.







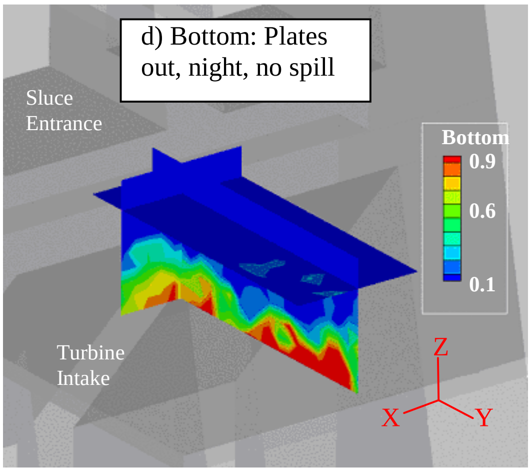


Figure 6. Fate probabilities (red>.9, blue<.1) as a result of Markov chain analysis. These (a-d) are a subset of all conditions: for night, plates in, out, with spill and no spill.

Acknowledgements

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