Improved techniques for studying the temporal and spatial behavior of fish in a fixed location

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There are many situations when it is important to know accurately the behavior of fish as a function of time and space in a fixed, three-dimensional volume. One example is the optimal design of techniques that minimize the mortality of fish approaching hydroelectric dams or the cooling intakes of a power plant. The behavior of fish in other fixed volumes, such as estuaries and open rivers, is also of interest in the case of many migrating fish stocks. Both active (echosounding) and passive systems based on acoustic-emitting tags implanted in fish have been used to collect behavioral data. Active acoustic systems, including those with electronically and mechanically steered beams, only insinify a small part of the total volume of interest at any given time. Tag systems, on the other hand, can be used to monitor the behavior of tagged fish over the entire volume. A number of advances in the implementation, deployment, and analysis of acoustic-tag systems have been made over the past few years. These improvements include techniques for positioning optimally the receiving hydrophones to minimize the location measurement errors, the development of acoustic-signal waveforms that provide both unique target identification and accurate location estimates, and the development of tracking algorithms that associate and track the multiple returns from an individual fish. These various techniques are described. Guidelines are presented for selecting the various parameters for the tag system, including the positions of the hydrophones. Specific examples that compare the predicted and actual performance of the tag systems are described.

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Keywords: acoustic tags, fish behavior, fish movement, fish tracking, position accuracy.

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Introduction

Many studies have been conducted on monitoring the movement and behavior of fish using acoustic tags. Early studies were conducted with adult Pacific salmon (Oncorhynchus spp.), observing the upstream migrations (Trehellen, 1956; Johnson, 1960). Other studies were performed with juvenile Chinook salmon smolts (Oncorhynchus tshawytscha) in the Columbia River (Lederwood et al., 2000) and with juvenile Atlantic salmon smolts (Salmo salar), as they migrated through lochs, rivers, and estuaries in the United Kingdom and Canada (Thorpe et al., 1981; Solomon and Potter, 1988; Potter et al., 1992; Moore, 1995; Lacroix and McCurdy, 1996; O’Dor et al., 1998; Russell et al., 1998; Smith et al., 1998; Voegeli et al., 1998; Carr, 2000). The first reported fixed-tracking system was installed in a loch in Scotland (Hawkins et al., 1974). The location of fish was recorded every 15 min in order to determine its movement during night and day. The authors concluded that if the system could be automated, the position of the fish could be determined every second, and the swimming path of each fish could then be displayed.

One automated-tracking system has been deployed in the channels between Passamaquoddy Bay and the Bay of Fundy in the Atlantic Ocean (Lacroix and Voegeli, 2000). Another system has been developed for tracking fish on the seafloor at ocean depths of up to 6000 m (Bagley et al., 2000).

Many improvements have been made in recent years with the use of acoustic tags and automated tracking to monitor the swimming path of a fish every second. A tracking system has been developed and used for the past four years at Rocky Reach and Rock Island dams on the Columbia River (Steig et al., 1999, 2001, 2002; Steig, 2000; Steig and Timko, 2000). Other similar studies using this tracking system have been conducted at Lower Granite
Dam on the Snake River (Steig and Timko, 2001), Bonneville Dam on the Columbia River, North Fork Dam on the Clackamas River (Timko et al., 2001), Cowlitz Falls Dam on the Cowlitz River, and Chittendon Locks on the Washington Ship Canal (Timko et al., 2002). These studies utilized up to 32 omni-directional hydrophones placed in known locations. The acoustic-tag system determines the location of the tag, using the relative arrival time of the acoustic signal at a minimum of four hydrophones. Studies have been conducted in a Scottish loch to compare the theoretical position with the measured one (Smith et al., 1998). Using simulations, Kell et al. (1994) showed that the accuracy of the position measurements obtained with an acoustic-tag system depended on a number of factors. A direct method has also been developed for calculating the positional accuracy of the location of acoustic tags without the need for field measurements or Monte Carlo simulations (Ehrenberg and Steig, 2002). This article expands on the improved techniques for monitoring the movement of acoustically-tagged fish through space and time.

Theory of operation for tag-location, measurement systems

The operating principle of acoustic-tag systems is the same as that which accurately determines position via the Global Positioning Satellites (GPS) network. The acoustic tag transmits a signal that is received by at least four hydrophones. By knowing the positions of the four hydrophones, and measuring the relative arrival times of each signal at each hydrophone, it is possible to estimate the locations of the tagged fish. In particular, if we let $h_x, h_y, h_z$ specify the $x$, $y$, $z$ location of the $i$th hydrophone, and let $F_x, F_y, F_z$ specify the unknown $x$, $y$, $z$ locations of the tagged fish, then the travel time from the tagged fish to the $i$th hydrophone, $t_i$ is given by

$$t_i = \frac{1}{c} \sqrt{(h_x - F_x)^2 + (h_y - F_y)^2 + (h_z - F_z)^2}$$

where $c$ is the speed of sound. Unfortunately, we cannot measure the absolute travel time directly. We can, however, measure the differences between the arrival times of the signal at the various hydrophones $(t_i - t_j)$ as given by

$$t_i - t_j = \frac{1}{c} \sqrt{(h_x - F_x)^2 + (h_y - F_y)^2 + (h_z - F_z)^2}$$

$$- \sqrt{(h_x - F_x)^2 + (h_y - F_y)^2 + (h_z - F_z)^2}.$$

For four hydrophones, there are three such distinct “signal-arrival-time” difference equations. The system of non-linear equations is determined by solving for the tagged-fish coordinates, $F_x, F_y, F_z$, such that the mean-squared difference between the measured (left side of the above equation) and calculated time differences (right side of the above equation) are minimized. There are various algorithms for accomplishing the minimization.

If the arrival-time differences could be measured perfectly and if the locations of the receiving hydrophones and the speed of sound were known perfectly, the approach described above would provide an exact measurement of the location of the tagged fish. Unfortunately, the arrival-time measurements will be inaccurate due to noise and the values assumed for the hydrophone locations, and the speed of sound will not be exactly right. Approaches for minimizing the errors are described in the next section.

The acoustic signal on the direct path always arrives at a given hydrophone prior to any multi-path signal. Signal discrimination that determines the first signal arriving at each hydrophone is used to eliminate most multi-path signals prior to position calculations. If the direct signal is not detected at a given hydrophone, then detection of a delayed multi-path signal may result in systematic bias of the position estimates.

Minimization of the errors in the determination of tagged-fish location

There are two strategies that can be used to minimize the error in the measurement of the tagged-fish location. First, the type of acoustic signal transmitted by the tag and the associated signal processing in the acoustic receiver can be selected to minimize the error in the measured signal arrival time. Second, the hydrophone geometry can be chosen such that the sensitivity of the fish-position estimate to measurement errors in the signal arrival times is minimized.

The effects of added noise on the arrival-time estimates at a receiver have been analysed for a variety of communications, sonar and radar applications. It has been shown (Ehrenberg and Steig, 2002) that the standard deviation in the arrival time due to added noise is given by

$$\sigma_{\text{rms}} = \frac{1}{\sqrt{\text{SNR}_0 \times BW}}$$

where $\text{SNR}_0$ is the ratio of the signal power to noise power out of the receiver-matched filter, and $BW$ is the baseband signal bandwidth. In the case of the standard-pulsed, continuous-wave (CW) signal, $BW$ is the reciprocal of the pulse duration $T$. For example, a 1-ms long CW signal has a bandwidth of $1/0.001 = 1000$ Hz. If the received-signal level is 10 times greater than the noise standard deviation out of the matched filter ($\text{SNR}_0 = 100$ (20 dB)), then using this equation the standard deviation of the arrival-time measurement is 0.1 ms. With a CW pulse and a given transmitted acoustic-power level compared with the background-noise level, the standard deviation of the arrival time is determined. If one attempts to increase the signal-to-noise ratio by transmitting a longer pulse, the required bandwidth is decreased as the inverse of the pulse duration, and the denominator in the equation for the standard deviation remains constant. Similarly, if a shorter
pulse is used with a wider bandwidth, the increase in the bandwidth is cancelled by a decrease in the signal-to-noise ratio. The way to minimize this limitation is to use a wideband signal waveform rather than a CW pulse. The two types of wideband waveforms used in acoustic systems are the FM slide or “chirp” and the binary-coded signal. In both cases, a special type of receiver processing called matched filtering must be implemented. The use of FM slides for active acoustic systems was discussed in Ehrenberg and Torkelson (2000). An example of the type of modulation used for binary-coded signals is given in Figure 1.

When processed using a matched filter, this particular coded signal has a pulsewidth of about 7.5% of that of an equivalent CW pulse. The matched-filter outputs for the CW pulse and the coded signal are shown in Figure 2. The much narrower output of the matched filter for the coded signal results in a much smaller variance in the arrival-time estimate and a corresponding reduction in the measurement error of the fish location.

In addition to using signal waveforms that minimize the effect of noise, techniques have been developed for selecting hydrophone locations that are relatively insensitive to errors. Previous approaches have used simulations to determine the effect of hydrophone locations on the accuracy of the fish-location estimate. However, this process is extremely time consuming. The alternative approach is to use a differential analysis to derive an expression relating the arrival-time errors and the estimated fish-position error. The details of this derivation are contained in an earlier article (Ehrenberg and Steig, 2002). Using the results of this analysis, it is relatively easy to locate the hydrophones optimally to produce minimal errors. Some examples are presented in the subsequent discussion.

![Figure 1. Example of a modulation used for binary-coded, wideband signal.](image1)

![Figure 2. Matched-filter outputs showing the CW pulse and the coded signal.](image2)

**Tag system implementation**

Acoustic tags selected for these studies were 307kHz encapsulated, omni-directional pingers. The tags were 18-mm long and 6.5-mm in diameter (0.71 × 0.26 inches) and were encapsulated with a non-reactive, inert, low-toxicity resin compound commonly used for potting electronic circuitry. The weight of each tag was 1.5 g (0.053 oz) in air and <1.0 g (0.033 oz) in water. Transmit-power level was approximately 155 dB re 1 μPa@1 m. Pulse rates and pulse widths were programmable. The tags utilized encoded pulses, which increased the detection range, the signal-to-noise ratio, and the pulse-arrival resolution, resulting in decreased position variability. Nominal pulse intervals range from 1 to 6 s per pulse, with transmit pulsewidths of 0.5–3.0 ms. Once activated, the useful life of the tag has been found to extend up to 30 days, depending on operating parameters.

Pulse-rate encoding is used for detecting individual tags when multiple tags are simultaneously present within the coverage area. Up to 50 tagged fish can easily be tracked simultaneously by the tag receiver without confusion between the individual tags. Figure 3A, B is an example of echograms of the same detected signals from 24 tags operating simultaneously. The procedure for isolating the signals from a given tag follows from the method used for displaying the signals themselves. Each vertical scan in the plot shows the detected arrivals in a time window equal to the programmed pulse-repetition period of a particular tag. The horizontal axis corresponds to the scan number. For these plots, the number of scans along the horizontal axis corresponds to 1 h of data collection. The upper plot (Figure 3A) uses a time window of 4090 ms. Only signals from the tag programmed with this period will fall along a straight line. The lower plot (Figure 3B) is for the same dataset, but displayed using a time window of 5290 ms.
By using a simple tracking procedure for the data shown on these plots, all the arrival times for a particular tag can be isolated.

Predicted position error and hydrophone position

The error analysis described by Ehrenberg and Steig (2002) can be used to optimally select the locations of the hydrophones. The error contours for two hydrophone geometries shown in Figure 4 are an example of this. Figure 4A shows the predicted position error of a four-hydrophone array spaced approximately 15 m apart in the X and Y directions, but only 3-4 m apart in the depth (flat-box geometry). The position error in the center of the array in the square box (Figure 4A) is approximately 0.3 m. However, the position error in the center of the array of the flat box (Figure 4B) is much greater, approximately 0.5 m. In addition, the position error increases dramatically towards the corners of the box. Obviously, the position error is much smaller for a hydrophone array that is nearly square as compared with the one configured in the shape of a flat box, and the errors are much smaller in the interior of the box.

Predicted position error and field results

To verify consistent three-dimensional tag positioning over time (precision), a test was performed using a stationary tag
within a hydrophone array at Mayfield Dam on the Cowlitz River (Zapel et al., 2001). The tag was fixed to a rigid aluminum pole, which was positioned near the center of the hydrophone array, and its transmissions were monitored for 19 min. Of the 1140 individual pings produced by the tag (60 pings per minute for 19 min), three-dimensional solutions were derived for 1084 of the pings (95%). Physical measurements determined that the tag was located at a position of 8.641 m in the X-dimension, 13.914 m in the Y-, and 8.767 m in the Z-dimension (depth). The calculated measurements derived from the hydrophone array were in agreement with the physical measurements, which indicated that the array was accurately surveyed in place and was functioning correctly.

The standard deviations of the three-dimensional positions were compared with the calculated standard deviations (see Table 1). The measured standard deviation of the arrival time of the tag signal at the four hydrophones was used for calculating the predicted-position standard deviation. The actual and predicted-position standard deviations were similar in the X (0.153 versus 0.165 m) and Y (0.139 versus 0.144 m) dimensions. The actual and predicted-position standard deviations for the Z dimension were greater than those in the X and Y dimensions, but the difference in the position error was still within 8.5 cm.

Merging fish swimming-path results with river-flow data

Figure 5 shows how the three-dimensional tag data can be used to study the swimming path of a fish relative to the river flow. The water velocity in this example was estimated from a kinematic-flow model based on actual river-flow data. This kinematic model was calibrated and verified with actual river-velocity measurements. The water velocity is represented by color, with the blue shades corresponding to 0.0–0.3 m s⁻¹ water velocity, the green shades 0.3–0.8 m s⁻¹, and the yellow/red shades 0.8–0.9 m s⁻¹.

Table 1. The predicted- and actual-position standard deviation of a stationary tag at Mayfield Dam on the Cowlitz River in 2001. The hydrophones were located at positions (0.88, 18.96, 0.98 m), (13.64, 18.67, 9.67 m), (7.32, 1.27, 9.67 m), and (7.39, 1.27, 0.98 m).

| | Position’s standard deviation (m) |
|---|---|---|---|
| | X (m) | Y (m) | Z (m) |
| Actual (n = 1084) | 0.155 | 0.139 | 0.259 |
| Predicted | 0.165 | 0.144 | 0.174 |
Figure 5 shows the path of a steelhead smolt released on the morning of 14 May 1999. This fish followed the water-velocity contour of 0.8 m s⁻¹ downstream near the powerhouse wall. It then traveled perpendicular to the water flow until it reached the slow back eddy (<0.3 m s⁻¹) where it turned again and travelled downstream toward the end of the powerhouse. It ultimately passed into Unit 1.

Conclusions

Technological advances in the implementation and deployment of fish-tracking systems using acoustic tags have enhanced the utility of these techniques greatly. The use of coded pulses and matched-filter processing, for example, has been shown to significantly improved the accuracy of the tag-position measurements. Then again, data-processing methods for isolating the signals from individual tags allow many fish to be tracked simultaneously. Finally, analytical techniques that predict the tag-position error as a function of hydrophone placement are being used to select the optimal hydrophone placement prior to system deployment. In combination, these technological advances are providing an accurate technique for monitoring fish behavior in fixed spatial regions.

References


