Factors affecting detection probability and range of transmitters and receivers designed for the Juvenile Salmon Acoustic Telemetry System

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Abstract Acoustic telemetry allows collection of data on the movement and survival of fish and other aquatic organisms. The passive form of this technology uses transmitters (tags) and fixed receivers to record when an organism is present at a given location. Understanding and interpretation of these data depends on knowledge of the detection range and detection probability of the receivers. This study examines factors affecting performance of tags and receivers designed for the Juvenile Salmon Acoustic Telemetry System (JSATS) at a location in the Sacramento River in CA, USA. A group of tags ($n = 13$) of two power output levels, each transmitting a unique code at five second intervals, were manually moved past a set of two fixed receivers in upstream and downstream directions along transects of different distances from the receivers at two different speeds. The factors that significantly affected detection probability were tag orientation and tag movement direction. Tag orientation had the largest effect on detection probability, with higher detection rates when the tag's piezoelectric transducer was directed towards the receiver. Detection probability (proportion of transmissions detected) was 30–50% out to 160 m. Detection efficiency (proportion of tags regarded as present) was 99–100% when tags passed within 25 m and 84–96% within 135 m of a receiver. These results have implications for the design and interpretation of acoustic tracking studies and the orientation of transmitters when implanted into fish.

Introduction

Acoustic telemetry is a widely used and important tool for understanding movement, habitat use, behavior and survival in many aquatic organisms (Cooke et al. 2013; Klimley et al. 2013; Hussey et al. 2015). This technology has continued to advance over time, resulting in smaller and more sophisticated transmitters and receivers (Klimley et al. 1998; Voegeli et al. 1998; Ehrenberg and Steig 2003; Deng et al. 2015). Today, researchers have many options when choosing among acoustic telemetry systems, receiver types and transmitter types. Essential to choosing a new system, or interpreting results from an existing system, is an understanding of how system components perform in different habitats and conditions.

Receiver and tag performance is often determined by a range test (see review Kessel et al. 2014). For most systems, "performance" refers to the consistency and distance a receiver can detect a transmitter (henceforth tag). These metrics are often defined as the probability that a tag's signal will be detected by a receiver (detection probability), or the relationship between detection

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probability and the distance between receiver and tag (detection range, as defined in Kessel et al. 2014). Detection range is important for determining receiver spacing when multiple receivers are configured as gates/lines/curtains (Steckenreuter et al. 2017), grids (Kraus et al. 2018), or for interpreting detections from single receivers used to infer fish location in relation to habitat (Klinard et al. 2018). In the context of an acoustic telemetry study, these two metrics determine detection efficiency, which is the proportion of tagged fish detected passing by a location with one or more receivers. For studies of fish migration where the goal is to estimate survival through river segments defined by receiver gates, detection efficiency is a very important factor in determining precision of survival estimates (Melnychuk 2012).

Many factors can affect detection range including wind, currents, bottom type, temperature, turbidity, background noise, receiver location, receiver deployment method, tag distance from receiver, tag power output and number of tags present. The present study used the acoustic telemetry system referred to as the Juvenile Salmon Acoustic Telemetry System (JSATS). This system was developed by the U.S. Army Corps of Engineers (Portland District) to evaluate movement and survival of juvenile salmonids in the Columbia River Basin (McMichael et al. 2010). The design of JSATS tags and receivers is non-proprietary and intended to be used by multiple manufacturers to spur innovation and reduce costs. The objectives of this study were to examine the effect of tag orientation, movement rate and location on detection probability (proportion of transmissions detected), to determine the detection probability with increasing distance between tags and receivers and to determine the detection efficiency (proportion of tags regarded as present) for tags passing at different distances.

Methods

Study location

The study was performed on the Sacramento River near the city of Hood, California, USA; a location representative of much of the leveed lower Sacramento River and Delta. Here, the river runs in a north-south direction and the channel width is 170 m. There are built-up levees with rock rip-rap on both banks. The depth drops quickly near the banks to a uniform bottom depth of 4–5 m. Flows were relatively low during the test as is usual

for this flow-controlled section of the river during the summer months. A gauging station located 20 river kilometers upstream at Freeport (USGS FPT, 38.450°N, Lon 121.500°W) reported river flow of 453–566 m^3 s^{-1} and a water velocity of 0.55–0.68 m s^{-1} at the time of the field tests. Turbidity varied between 6 to 9 NTU measured at a station 200 m downstream of the study site (CDWR SRH, 38.368°N, 121.520°W). Winds were 9–16 km h^{-1} and the water surface was calm. All study data were on 7/10/2019 between 12:00 and 16:00 PST.

Receivers

Two receivers were deployed 15 m from the river right bank (Fig. 1) in a manner similar to current deployment methods used by several acoustic telemetry studies in this system. The receivers were produced by Lotek Wireless model WHS4350 receivers (69 cm length × 6 cm diameter) which were attached to the side of a 2.5 kg buoyancy float 45 cm long × 10 cm diameter and fitted with a plastic stabilizing fin (Fig. 2a). Each receiver was attached to an 18 kg metal weight by a 0.5 m cable tether. The weight was attached to a small tree on the bank by a 20 m long steel cable of 6 mm diameter. Receivers were deployed independently 37 m apart in water of 3.0 m depth. Each receiver's hydrophone was 1.0 m above the bottom. Each receiver location (latitude and longitude) was recorded with a handheld GPS (3–5 m accuracy, Garmin). The receiver's attached buoyancy kept the unit oriented about 15–20° from vertical.

Transmitters (tags)

JSATS tags were produced by Lotek Wireless of similar design as the "injectable" transmitter described by Deng et al. (2015). The pulse rate interval (PRI, time between transmissions) was set at a nominal five seconds with observed PRI between 4.98 to 5.02 s. Tag dimensions were 3.4 mm diameter and 15 mm length with a weight in air of 0.22 g (Fig. 2b). Tags were of two power outputs; high power ($n = 7$) at 160 dB re: 1μPa@1 m and standard power ($n = 6$) at 158 dB re: 1μPa@1 m. Although not a factor in this paper, the high power tag has reduced expected run time of 45 days compared to the standard power of 69 days.

Each tag was taped to the end of a 20 cm long plastic cable tie, leaving the tag's piezoelectric transducer (PZT) exposed (Fig. 2c). The tags were all oriented
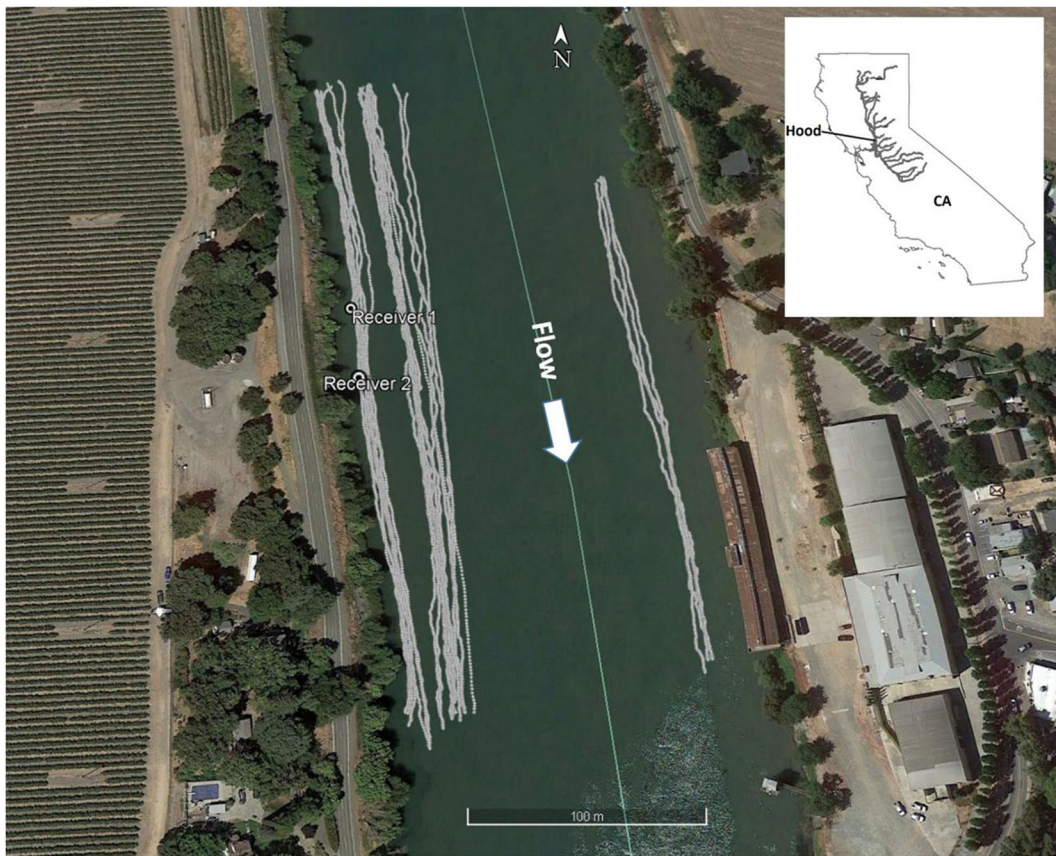
horizontally with transducers at the end of the cable tie. Each tag/cable tie was attached to a 1.5 m long rigid fiberglass rod with 2 cm spacing between tags. The rod was fixed to the stern of a kayak so that the tags were 0.7–1.2 m below the water surface (Fig. 2d). The kayak was paddled in upstream and downstream directions starting and ending 100 m away from the receivers. For all transects the kayak provided forward motion through the water, causing the tag-cable ties to fan out so that all tags were oriented in the same direction with transducer pointed away from the direction of travel. A GPS in the kayak recorded the latitude and longitude of the tags every second.

Receiver detection filtering

The JSATS tags operate at 416.7 kHz frequency to send a 31-bit code series modulated with binary phase-shift keying. Each tag code signal is sent in 744 μs. This very short signal duration greatly reduces the chance of signal collision, where two or more transmissions overlap in time, preventing the receiver from decoding any of them. The transmissions are decoded and recorded by receivers, including false positives. These include decodes arising from multipath (echoes of an actual transmission), mimics (distorted transmissions), or environmental noise. False positives were identified and removed by a sequence of filters similar to those described by Deng et al. 2017 (see supplementary information: https://www.nature.com/articles/srep42999#supplementary-information). First the receiver's detection record was filtered to keep only tag codes known to have been deployed. Then all the records for each tag code were compiled in chronological order. Any detection that occurred less than 0.3 s after the prior detection was regarded as multipath and removed from the file. Next a PRI filter was applied to the remaining detections of that tag

Fig. 2 **a** JSATS receiver with buoyancy tube, stabilizing fin and 18 kg weight. **b** JSATS pin transmitter (tag) with dimensions of 15 mm length × 3.4 mm diameter and weight of 0.22 g. **c** Transmitters attached to cable ties on rod which is suspended 0.7–1.2 m below water off the back of the kayak (**d**) Human powered kayak used to move tags past receivers

code. The general structure of the PRI filter requires a specific number of detections to occur within a specific time window and the time between successive detections must be a multiple of the nominal PRI. The specific values used for number of detections, duration of the time window, and tolerance of the estimated PRI were selected to maximize the detection probability of true positives and minimize that of false positives (Beeman and Perry 2012; Deng et al. 2017). The factor that has the largest effect on this relationship is the criterion for minimum number of detections within a limited time window. Increasing the minimum number can eliminate all false positives, but it will also eliminate some valid detections. After evaluating different values, this study used a minimum of four detections as the optimum value to reduce probability of false positives and increase probability of true detections. The factors for multipath (0.3 s) and time window (16.6 x PRI) were taken from Deng et al. (2017).

Raw receiver files were filtered based upon the following criteria:

1) retain only detections of expected tag codes that occur within time of tag deployment,
2) remove multipath detections which are successive detections of a given tag code that occur less than 0.3 s after the initial detection,
3) apply the PRI filter that required:

    a) four detections of specific tag code with time difference between first and fourth detection less than 16.6 times the tag's PRI (e.g. 5.0 s × 16.6 = 83 s),
    b) the PRI between pairs of successive detections of these four calculated with the formula:

$$PRIestimate = \frac{D_{t+1}-D_t}{round\left(\frac{D_{t+1}-D_t}{PRInominal}\right)}$$

where D_t = datetime of dection at time t

c) deviation of the estimated PRIs from the nominal to be within 20% of the nominal PRI, and

d) standard deviation of these three estimated PRIs be less than 0.025

Factors affecting detection probability

The 13 tags were moved past the two stationary receivers in three transects (see Fig. 1.); going directly over the receivers (0 m, $n = 8$), offset from the receivers by 25 m ($n = 12$), and offset from receivers by 135 m ($n = 4$). Repeated passes were made in alternating directions; southward (downstream) and northward (upstream). For the 0 and 25 m transect the speed was alternated between passes, slow (0.72 ± 0.12 m s^{-1} over ground (mean $\pm$ 1 SD)) and fast (1.16 ± 0.32 m s^{-1} over ground). Each pass was broken into an upstream of receiver portion (from receiver location latitude to highest latitude) and downstream of receiver portion (from receiver location latitude to lowest latitude). Each upstream/downstream portion of the pass was assigned a tag orientation based on the location and direction of travel. A positive speed through the water ensured that tag PZTs were always pointed directly behind the kayak. The PZT was oriented toward the receiver when moving upstream on the upstream side of the receiver or when moving downstream on the downstream side of the receiver. The PZT was oriented away from the receiver when moving upstream on the downstream side of the receiver or when moving downstream on the upstream side of the receiver.

Logistic regression (Mathworks MATLAB, *fitglm* with binomial distribution) was used to examine the influence of several predictor variables on detection probability for the 0 and 25 m transect passes. The 135 m transect passes were excluded because they were done with only one tag speed. The spatial extent of the tag passes were standardized to each receiver's location by truncating each tag pass to positions 100 m upstream to 100 m downstream of the receiver. The predictors were receiver unit (1906131 or 1906121), tag pass transect offset from receiver (0 or 25 m), tag speed (slow or fast), tag movement direction (upstream or downstream), tag location relative to receiver (0–100 m upstream or 0–100 m downstream), tag's PZT orientation relative to receiver (toward or away) and tag power level (high or standard). All of these predictors were treated as categorical variables in the analysis. The intercept

baseline represents the receiver unit 1,906,131, the 25 m transect, fast speed, southward direction, upstream tag location, PZT oriented toward receiver and tag standard power level.

Detection probability with distance

All tag passes for all three transect distances were used to calculate receiver-tag distance for each tag transmission. This required estimating the tag-receiver distance for each transmission and each successful detection. Transmission times were estimated to occur at the PRI from the first detection time of each tag. Positions for the estimated transmission were determined by matching the transmission times with GPS record. These tag transmission to receiver distances were binned by 10 m from 0 to 200 m. The proportion of transmissions detected in 10 m bins were compared for each receiver. Detection probability of each tag for each receiver was calculated as the number of detections divided by the number of estimated transmissions for each 10 m bin.

Field studies to estimate fish survival indicate a tagged fish as present if it has a minimum number of valid detections at a given array. The detection rate of a group of tagged fish passing a receiver location is used to estimate detection efficiency, which determines the precision of survival estimates. In the present study, 13 tags were moved past the two different receivers at three transect distances away from the receivers. When a tag had at least four valid detections (the minimum required) on a specific receiver during a pass, it was considered as detected. Detection efficiency was calculated for each receiver and each pass as the proportion of the 13 tags detected as present. The spatial extent of the tag passes was truncated as described above. The mean detection efficiency for each transect location was compared among the two receivers.

Results

Receiver detection filtering

The two receivers recorded over 21,000 raw (unfiltered) detections of the 13 tags (Table 1). Receiver1 recorded more multipath detections than the Receiver2. Multipath arise from signal reflections or echoes which are more common when reflective surfaces such as the bottom, water surface or bank substrate are closer to the receiver.

Table 1 Count of raw detections, percent multipath detections, percent false positives from PRI filter and total detects that passed the filter for 13 transmitters for each receiver for entire test period

Receiver	Total Raw Detects	% Multipath Detections	% PRI Filtered False Positives	Total Detects Passed Filter
Receiver1 (SN 1906121)	11,220	2.85	6.67	10,175
Receiver2 (SN 1906131)	9878	0.53	6.72	9214

Both receivers recorded a similar proportion of detections of valid tag codes that were classified as false positives by the PRI filter (6.67 and 6.72%).

Factors affecting detection probability

The predictors that significantly affected detection probability were tag orientation and tag movement direction (Table 2). Receiver unit, transect offset, tag speed, tag location and tag power level did not significantly affect detection probability. Tag orientation had the largest effect with increased mean (± 1 SD) detection probability when the piezoelectric transducer pointed toward the receiver (0.417 ± 0.127) compared to pointed away (0.205 ± 0.148) (Fig. 3). Tag movement direction had higher mean detection probability when tags were moving south or downstream (0.338 ± 0.166) compared to tags moving north or upstream (0.284 ± 0.177).

Detection probability with distance

Detection probability was calculated as the number of detections divided by the number of estimated transmissions for each tag for each 10 m bin. Mean detection probability varied with increasing distance between tag and receiver (Fig. 4). The two receivers had relatively high detection probability of 0.93 and 0.42 respectively at the 10 m bin. From distances of 20 to 110 m, the detection probabilities were relatively stable from 0.23 to 0.38. At distances of 120 to 160 m detection probabilities ranged higher from 0.50 to 0.75. From 170 to 200 m distances the detection probability declined to less than 0.13.

Examining data in terms of detection efficiency, which is defined as the proportion of tags with at least four valid detections during a transect pass, showed that both receivers had 100–99% detection efficiencies for the 0 and 25 m transect passes and 96.1 and 84.6% for the 135 m transects for Receiver1 and Receiver2 respectively (Table 3).

Discussion

During this study receivers had a false positive rate of 6.7%. Other acoustic tracking systems, such as the commonly used 69 kHz coded system, have relatively lower false positive rates of <0.05% (Simpfendorfer et al. 2015). Although removal of JSATS false positives can be quickly accomplished with code script routines. The presence of false positives is inherent in most acoustic telemetry systems and their identification and

Table 2 Logistic regression model summary of factors effect on detection probability for 20 passes of 13 JSATS tags, each transmitting every 5 s, moving past two JSATS receivers at two transect offset

Factor	Categories	Estimate	Std. error	t statistic	P value
(Intercept)		−1.663	0.223	−7.464	<0.001
Tag orientation	PZT toward or away from receiver	1.045	0.143	7.335	<0.001*
Tag movement direction	northward or southward	0.323	0.143	2.265	0.024*
Tag location relative to rec.	upstream or downstream	0.257	0.143	1.807	0.071
Transect offset from receiver	0 or 25 m	−0.073	0.141	−0.517	0.605
Tag speed	slow or fast	−0.084	0.138	0.607	0.544
Tag power level	standard or high	−0.203	0.139	−1.458	0.145
Receiver unit	SN 1906131 or 1906121	0.169	0.138	1.219	0.223

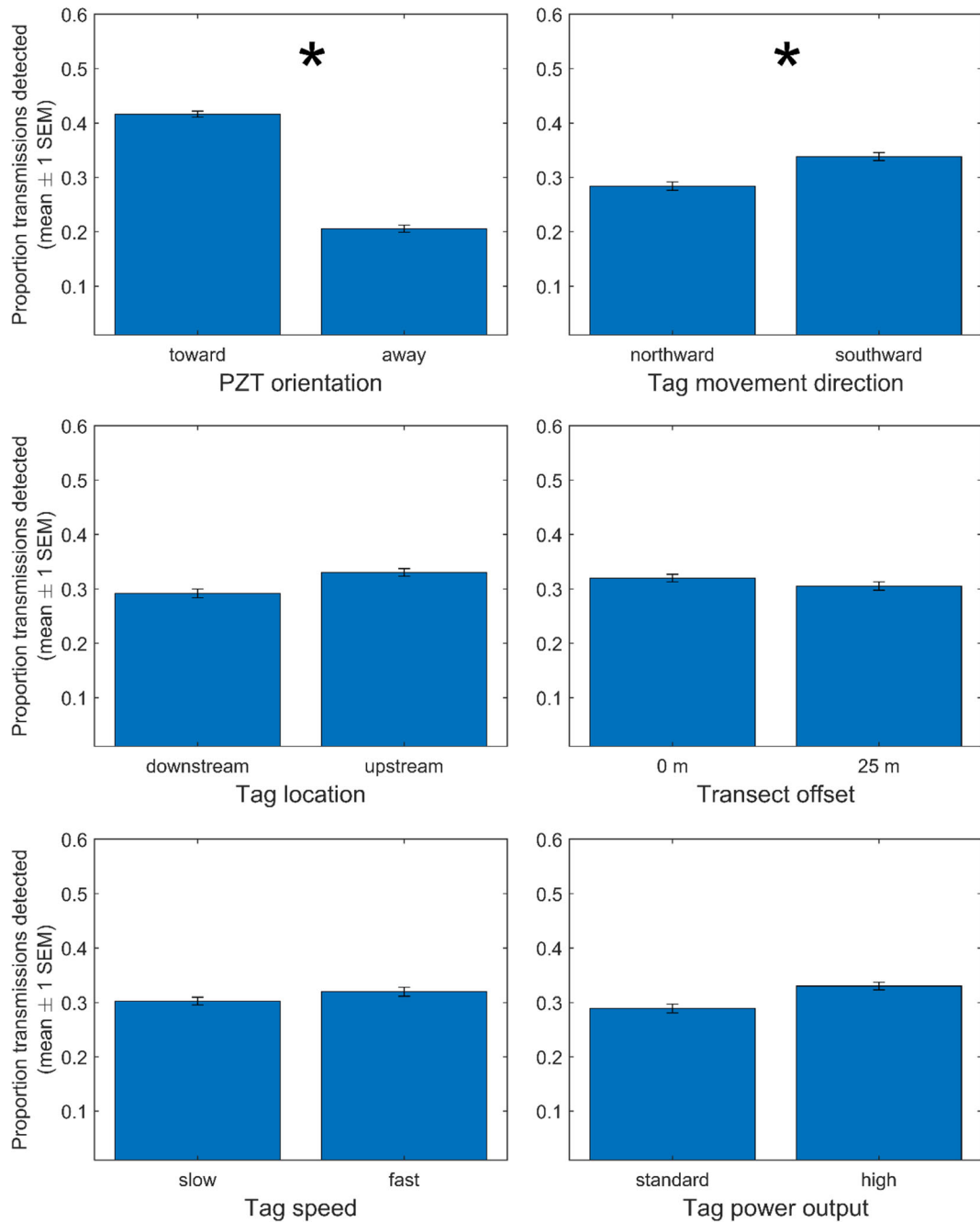*Statistically significant at α = 0.05

Fig. 3 Factors affecting the mean proportion of transmissions detected for 20 passes of 13 JSATS tags moving past two JSATS receivers at two transect offset distances. Error bars represent ±1 SEM. Those factors with significantly different treatments are noted with *

removal is a vital step to ensure unbiased interpretation of results (Beeman and Perry 2012).

The factors that significantly affected detection probability were tag movement direction and tag orientation. Detection probability was higher when tags were moving in the southward or downstream direction. This was likely the results of lower speed through the water of tags when moving downstream. Even though the speed over the ground was similar in both directions, because the river flow is southward, moving the tags

Fig. 4 Detection probability for 10 m distance bins for two JSATS receivers. Each data point represents the mean proportion of transmissions detected for 13 tags. Receiver1 are magenta circles. Receiver2 are black squares. Error bars represent ±1 SD
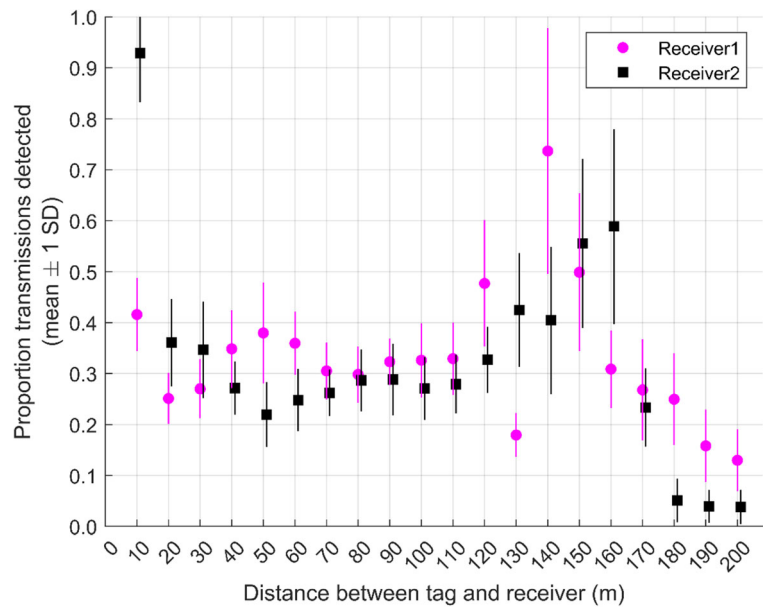
northward, against the flow, would create more turbulence around the tag which would reduce the quality of transmissions. This result is an artifact of the testing method and not likely to occur with tags implanted in the body cavity of a fish.

Tag orientation had the largest influence on detection probability and this factor is seldom reported in acoustic telemetry literature. This result is due to the fact that source levels of JSATS transmitters, and all other commercial acoustic fish transmitters, are not omnidirectional because the transmitter components behind the PZT block acoustic signals emitted from the back of the transmitter (Deng

et al. 2015). Laboratory testing of JSATS tags show a source level of 153–158 dB in the frontal 180° range of the PZT and reduced source level of 140 dB directly behind the PZT (Deng et al. 2015; Lu et al. 2016; Zang et al. 2019). This field study shows that detection rate was higher when the tag's PZT was pointing directly at the receiver and lower when the tag's PZT was pointed away from the receiver. This pattern was evident when tags were moving both with and against the current. Tags were tested in the horizontal orientation, which is how the tags would be oriented when internally implanted into juvenile salmon. Tag PZT orientation relative to the fish should be considered when deciding how to implant transmitters into fish. For example, if it is known that fish exhibit positive rheotaxis and migrate with their head oriented into the current, and if the tag's PZT is oriented toward the head of the fish then the receiver will have the highest detection probability for fish downstream of the receiver.

Another factor related to tag orientation is the receiver's field of detection. Water velocity during this study was relatively low compared to flows in winter and spring, which often exceed 2000 $m^3 s^{-1}$. In the presence of higher velocity flow, receivers deployed in a similar way would tilt in the current making the hydrophone point more downstream, resulting in higher detection probability of tags downstream of the receiver. Thus, in higher flows, tag PZT orientation should be toward the fish's head to increase detection probability, assuming that fish are positioning themselves head into

Table 3 Detection efficiency of 13 tags passing by a receiver at three transect distances from the receiver. Passes began 100 m upstream and ended 100 m downstream (or vice versa). Tags were Pin JSATS with a pulse rate interval of 5 s. Passes were performed by pulling the tags with a kayak at slow or fast speeds (0.6–1.0 m/s). Tags were about 0.7–1.2 m below the surface

Rec SN	Rec Name	Transect Location		
		(transect distance from receiver, n = passes)		
		Right Bank (0 m, n = 8)	Middle Right (25 m, n = 12)	Left Bank (135 m, n = 4)
1906131	Receiver1	99.0	100.0	96.1
1906121	Receiver2	100.0	100.0	84.6

the current. In addition, many receivers are deployed by attaching them to the downstream side of bridge supports, limiting the field of detection almost entirely downstream, which would favor detections of tags with PZTs oriented upstream.

This study demonstrated that JSATS receivers can detect 30–50% of tag transmissions out to 160 m. A previous field test of JSATS range at the Columbia River Bonneville Dam spillway, a high background noise environment, demonstrated detection probability of 98% up to 80 m and 10–40% at 120 m (Weiland et al. 2011; Fig. 9a). Another field test under low noise conditions and with JSATS tags of source level of 159 dB re: 1μPa@1 m suggests a detection range of 225 m (Lu et al. 2016). Detection probabilities for this study were generally less than 50%, similar to another study using a 69 kHz coded array with 41.4% (Simpfendorfer et al. 2008). However this is in the context of a range testing trial, which considers every tag signal transmission. If criteria similar to that of a field survival study were applied, where only four valid detections are required to indicate presence, then detection efficiencies would be much higher. Under this standard, observed detection efficiencies for transects close to the receiver were nearly perfect (99–100%), and fairly high (85–96%) for tags moving past on the opposite side of the river from the receiver.

Environmental conditions were good during this test with calm surface conditions, relatively low water velocity and low turbidity. Additional testing under less favorable conditions is required to determine how much detection range would be reduced in less benign environmental conditions. Because this study was a snapshot of results at one location, similar results should not be expected under different environmental conditions and in different locations along the river. Detection probability will vary as conditions change and should be monitored with properly located stationary reference tags (sentinel tags). Collection of data on detection range and probability at representative locations and over various conditions will help researchers understand how system performance changes, which will aid interpretation of results.

Authors' contributions The sole author, Arnold J. Ammann, collected data in the field, processed data, analyzed data and wrote the manuscript.

Data availability Raw data available upon request to primary author. Or will be provided to journal to enable direct link to files. Custom scripts to process and analyze data were made in Matlab. Code is available upon request to primary author. Or will be provided to journal to enable direct link to files.

Compliance with ethical standards

Conflicts of interest/Competing interests No conflicts of interest.

Ethics approval No live animals used in this study. Not applicable.

Consent to participate No live animals used in this study. Not applicable.

Consent for publication No live animals used in this study. Not applicable.

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