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Feasibility of Tracking Fish with Acoustic Transmitters in the Ice Harbor Dam Tailrace

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The Juvenile Salmon Acoustic Telemetry System (JSATS) has been used at many dams but has never been deployed in the near-dam tailrace environment. The use of JSATS in the tailrace is of interest to fishery managers to evaluate downstream passage behavior of juvenile salmonids and dam approach behavior of upstream migrating adult salmon and lamprey. The acoustic noise level and detection range of JSATS were studied to determine the feasibility of deploying JSATS in the Ice Harbor Dam tailrace. The noise level measured from the powerhouse deck was less than 104 dB re 1 μPa except for the turbine outlet near the spillway, and 350 m downstream of the dam, the noise level was less than 106 dB. The measured noise levels would allow a theoretical detection range of 100 m to 350 m and 85 m to 320 m, respectively. Validation experiments showed that the detection range is 113 to 184 m using hydrophones deployed from the powerhouse deck and 148 m using hydrophones deployed 500 m downstream of the dam.

Tailrace egress times and routes are important factors that affect the survival rates of downstream migrating juvenile salmon. Improved understanding of the behavior and egress of turbine-passed fish can help refine turbine operations and design. The tailraces of Federal Columbia River Power System (FCRPS) hydropower projects are of special concern to fishery managers and the U.S. Army Corps of Engineers because they expose migrating juvenile salmon to the greatest predation risk in the Columbia River system[1]. In a review of John Day Dam tailrace research, Anglea et al.[2] associated powerhouse and spillway operations with delay and risk of predation in the tailrace and suggested that route-specific survivorship and predator studies would be helpful. They observed that, "Spill patterns and operational conditions which cause smolts to have longer tailrace residence times will also concentrate smolts which may attract predators," and that, "Route-specific survival studies and predator monitoring studies are needed to better understand these risks."

Fish passage survival estimates are generated regularly through biological studies at FCRPS dams[3]. These biological studies involve tagging release groups of fish and tracking their progress through one or multiple projects. Fish passage survival studies have varying objectives such as route-specific passage survival, spillway passage efficiency, spillway weir passage efficiency, and turbine juvenile bypass system survival. Understanding the behavior and predation risk of turbine-passed fish in the tailrace at FCRPS projects can provide additional insight to these fish passage survival studies. Behavioral studies of adult salmonids and Pacific lamprey fish-ladder approach and passage are also of interest and would benefit from tailrace tracking. Collecting accurate vertical and horizontal position data for these species during their migratory approach at projects and fish ladders could provide information useful for improving structures and operations to facilitate upstream passage during crucial migration periods. Downstream passage and survival of juvenile salmonids and kelts may be better understood by improving our knowledge of the distribution and behavior of fishes approaching the turbine intakes, spillbays, juvenile bypass systems, and draft tube exits and in the tailrace after passage.

Mapping the tailrace noise environment and evaluating detection precision and positions of JSATS tags at Ice Harbor Dam is important because precise estimates are used for determining parameters such as sample size for developing and implementing biological studies in the 2015 to 2017 time period after the turbine runners in units 2 and 3 have been replaced[4]. The results of tailrace tracking at Ice Harbor Dam may provide sufficient methods for replication at other FCRPS projects, potentially leading to standardized biological study designs and implementation plans in the future.

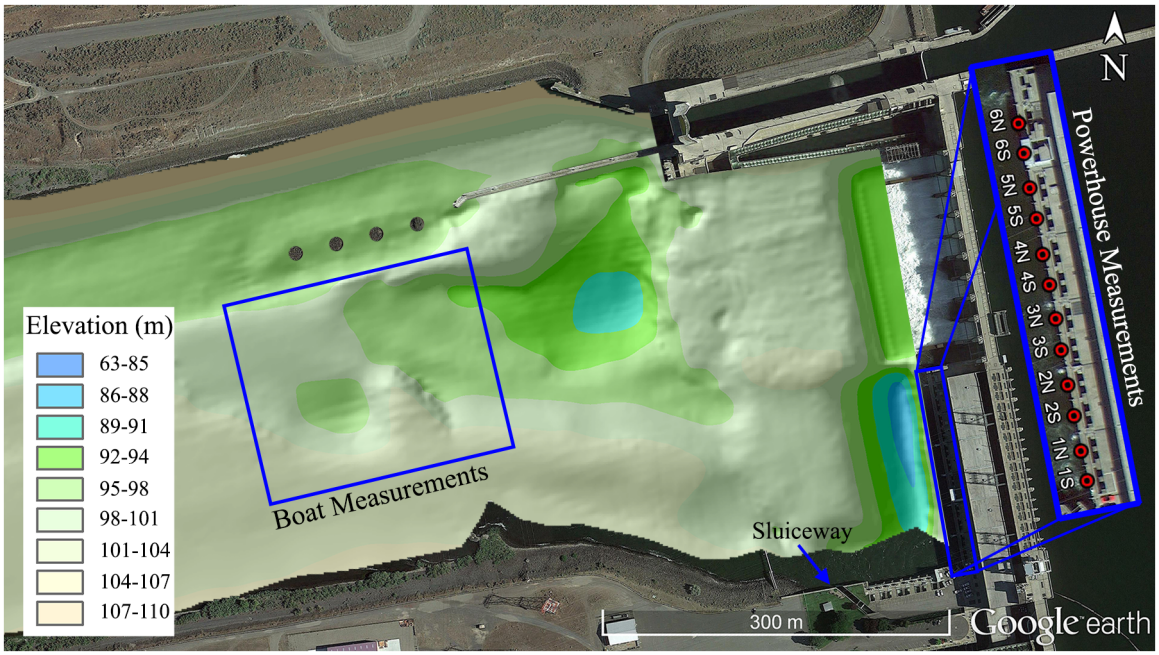

Figure 1 | Bathymetry and acoustic noise measurement locations at Ice Harbor Dam.

JSATS receivers have been deployed at large hydroelectric dams, in free-flowing sections of the FCRPS, and in the estuary of the Columbia River[5–8]; however, this technology has not been employed in near-dam tailrace zones. The levels and varying characteristics of background noise in the tailrace within the bandwidth of JSATS-receiving hydrophones is a key factor that must be known and understood for *a priori* design of receiving-system arrays to detect and observe (i.e., track) the behavior of JSATS-tagged juvenile salmon in the tailraces of FCRPS dams.

We deployed stationary and mobile JSATS receivers and beacons in the tailrace at Ice Harbor Dam located on the Snake River 16 river kilometers from its confluence with the main stem of the Columbia River in south-east Washington State. The dam is 860 m long and 30.5 m tall, and consists of a six-unit powerhouse, a 10-bay spillway, a navigation lock, two fish ladders, and a removable spillway weir. Construction of the dam began in 1955, and the project started operations in 1961 with three 90-megawatt (MW) turbine units. Three 111-MW turbine units were added in 1976. The powerhouse has a generating capacity of 603 MW, with an overload capacity of 693 MW. All six units are six-blade Kaplan turbines.

Three important factors were considered when evaluating the performance of the JSATS in the tailrace: noise level, signal strength, and multipath interference. As an acoustic signal travels from the source (e.g., JSATS tag) to receiver (e.g., hydrophone) it is attenuated due to geometric spreading and absorption[9]. The received signal must be 6 dB higher than the background noise to be successfully decoded[8]. Due to reflections and refraction, the signal may travel along multiple paths from source to receiver and under the right conditions two or more of these components will interfere. The Ice Harbor Dam tailrace is shallow and a reflected copy of the signal is more likely to overlap the line of site signal.

The background acoustic noise varies depending on the measurement location and operating conditions at the dam. Tailrace conditions in the vicinity of the spillway stilling basin were prohibitive for data collection. This highly turbulent environment provided unsafe working conditions while turbulence and high water velocity would not allow for JSATS hydrophones (cabled or autonomous) to be placed in this area. For this reason we focused data collection efforts on the immediate powerhouse tailrace and downstream of immediate spillway stilling basin. For this study, we measured noise from the powerhouse deck and at various locations from a boat in the tailrace during various operating conditions (Figure 1). The acoustic noise level at the dam is affected by spill rate, the tailrace water level, and the powerhouse outflow. We classified treatments consisting of three spill levels (i.e., high, low, and no spill), three powerhouse operations (i.e., typical, high, and low), and two tailrace water surface elevations (i.e., high and low). The spill level is considered high when it is more than the average rate, which is 1590 m^3/s, and the spill level is considered low when it is less than the average [DART River Environment Graphics & Text]. The powerhouse operation is considered typical when the powerhouse flow rate is between 624 and 1545 m^3/s. It is considered low when it is below the range and high when it is above the range. The tailrace elevation is high when the water elevation in the tailrace is above the typical elevation (i.e., 103.3 m above mean sea level [MSL]) and low when it is below the typical elevation.

Results

Receiving System Sensitivity. The measured noise level in the JSATS frequency band in the laboratory tank depended on which type of hydrophone, data acquisition (DAQ) system, and amplifier were used. For this study, two different types of hydrophones, two different types of DAQ systems, and two different types of amplifiers were used (see Methods-Noise level measurement systems). The two types of hydrophones used to measure the noise level in the Ice Harbor Dam tailrace were: Sonic Concepts (SC) 001 and RESON TC4014-5 hydrophones. The SC 001, the hydrophone used in the JSATS and in the range testing, is very sensitive to frequencies in the JSATS frequency band. The RESON 4014 is a broadband hydrophone and is not as sensitive to frequencies in the JSATS frequency band. Noise levels (NL) measured by SC 001 hydrophones were more than 8 dB lower than those measured with TC4014-5 hydrophones (Table 1).

Much of the collected data contained significant amounts of noise that may be seen in the spectrums of the acoustic signals (Figure 2). The spikes are possibly due to electrical noise. The equipment used to measure the hydrophone output voltage, the hydrophone, and how the equipment was grounded affected the amplitude of these noise spikes.

Table 1 | Measured sensitivity at 416.7 kHz (center of JSATS band) and the noise level of each hydrophone in the JSATS frequency band in the laboratory tank

Hydrophone Name	Hydrophone Model	Cable Length (m)	Amp Model	Amp Gain (dB)	DAQ Model	Sensitivity (dB re 1 V/μPa)	NL (dB re 1 μPa)
Boat 1	TC4014-5	10	VP2000	20	USB-6366	−169	106
PH 1	TC4014-5	100	VP2000	20	PXIe-6124	−169	108
PH 2	TC4014-5	100	VP2000	20	PXIe-6124	−169	105
PH 3	SC_001	30.5	SR5100	30	PXIe-6124	−152	97
PH 4	TC4014-5	100	VP2000	20	PXIe-6124	−170	106
PH 5	SC_001	30.5	SR5100	30	PXIe-6124	−151	93

Noise Level. The noise floor in the JSATS frequency band of data collected at each location was similar to that collected in the laboratory. Data collected in the field often would have significantly more impulsive spikes. These spikes caused the average noise level to rise and occur more often and have larger amplitude when the flow through the dam is greater.

Noise data were collected from a boat on eight different days. The area in which boat noise data were collected was divided into a rectangular grid composed of 15 × 15 m squares. The average noise level in the JSATS band was then calculated in each square. The noise level ranged from 105 to 115 dB re 1 μPa. Over 90% of the measurement area had a noise level less than 106 dB re 1 μPa.

Noise data were collected from the powerhouse deck on 10 separate days. The noise level in the JSATS band varied considerably based on the operation of the dam and how close the deployed hydrophones were to the spillway. During the high-flow period in the spring of 2013, measurements were taken on three days. Both the SC 001 cabled hydrophone and the RESON TC4014 hydrophones deployed in front of turbine unit 6 on high-flow days measured a noise level greater than 111 dB re 1 μPa. The mean measured noise level was less than 105 dB re 1 μPa for hydrophones deployed south of turbine unit 5 or on low-flow days (Table 2).

Dam Range Testing. To validate the detection range estimated from the noise measurements a JSATS cabled system was deployed from the powerhouse tailrace deck and a large remote controlled boat with an onboard Global Positioning System (GPS) was used to position transmitters at different locations in the tailrace. Four different transmitter types (three types of tags and one type of beacon) were used in range testing. All transmitters had a nominal source level of 156 dB re 1 μPa. The beacons are omnidirectional and the tags are slightly directional. The results for all three sets of hydrophone locations were combined and averaged by the type of transmitter used (Figure 3). Linear trend lines were fit to the data for each type of transmitter with the assumption that the detection efficiency should be 100% at 0 m. The different types of tags performed approximately the same. Using the same detection range definition used for the JSATS acceptance testing that was performed to award the contract to the vendor who would manufacture the autonomous node receivers for the US Army Corps of Engineers (i.e., the distance at which detection efficiency drops to 20%), the approximate detection range for the different tags attached to the remote-controlled boat is 113 m. The beacons attached to the remote-controlled boat had a larger detection range of 136 m; the detection range of the beacon located by the sluiceway used for trash bypass, which is located along the south wall of the tailrace (see Figure 1 and 5), ranged from 166 to 184 m.

Mobile Range Testing. In addition to the dam range testing, additional testing was performed just outside the boat-restricted

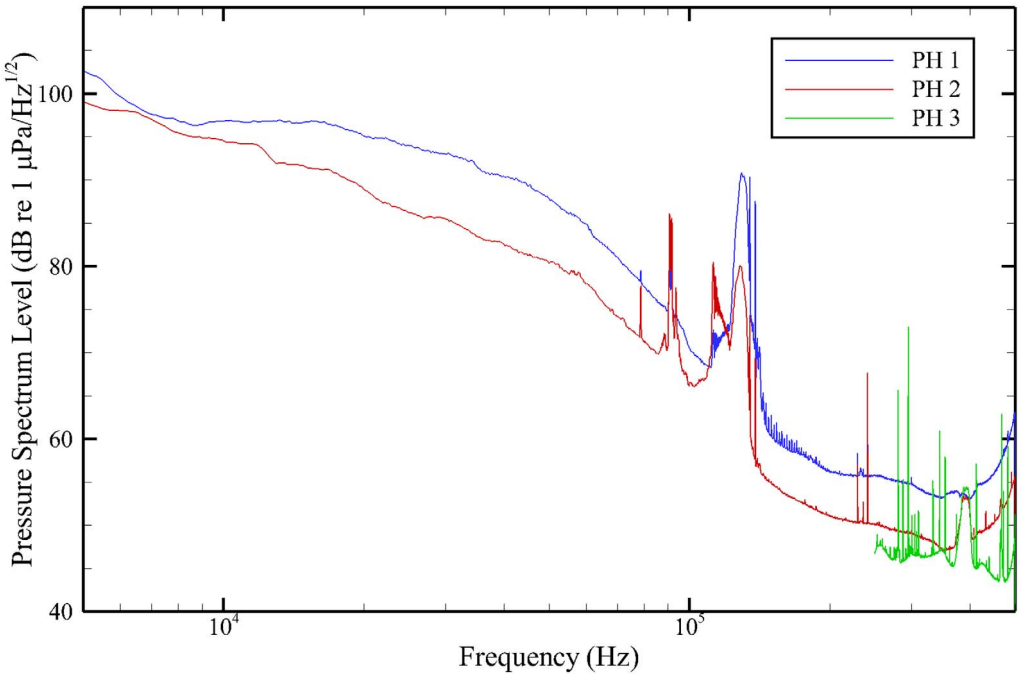

Figure 2 | PSL of data collected from the powerhouse deck. The turbine outflow was low, there was no spill, and the tailrace elevation was high.

Table 2 | Average noise levels on various days, at different powerhouse (PH) turbine unit outlets (e.g., 6N is the north outlet of turbine unit 6 and 4N/5S is between turbine units 4 and 5, see Figure 1), and treatments on the powerhouse deck for each hydrophone (i.e., PH 1, PH 2, etc., see Table 1 for details)

Date	Elevation	Spill	PH Outflow	PH 1 Turbine	PH 1 NL (dB re 1 μPa)	PH 2,3 Turbine	PH 2 NL (dB re 1 μPa)	PH 3 NL (dB re 1 μPa)	PH 4,5 Turbine	PH 4 NL (dB re 1 μPa)	PH 5 NL (dB re 1 μPa)
10/19/2012	High	None	Typical	6N	107	6S	103	99	N/A	N/A	N/A
10/29/2012	High	None	Low	6N	106	5S	102	101	N/A	N/A	N/A
10/29/2012	High	Low	Low	6N	107	5S	102	100	N/A	N/A	N/A
11/5/2012	Low	Low	Low	6N	108	6S	105	102	N/A	N/A	N/A
11/6/2012	High	None	Typical	6S	106	6N/6S	105	105	N/A	N/A	N/A
11/6/2012	High	Low	Typical	6S	106	6N/6S	104	104	N/A	N/A	N/A
11/7/2012	Low	None	Low	6S	106	6N/6S	102	99	N/A	N/A	N/A
11/7/2012	High	None	Low	6S	106	6N/6S	101	98	N/A	N/A	N/A
11/7/2012	High	None	Typical	6S	106	6N/6S	102	98	N/A	N/A	N/A
11/7/2012	High	Low	Low	6S	106	6N/6S	103	101	N/A	N/A	N/A
11/7/2012	High	Low	Typical	6S	106	6N/6S	103	100	N/A	N/A	N/A
4/23/2013	High	Low	Low	2N	106	1N	102	101	N/A	N/A	N/A
5/2/2013	High	Low	Low	2N	106	1N	102	100	N/A	N/A	N/A
5/14/2013	High	High	High	N/A	N/A	N/A	N/A	N/A	6S	117	116
5/14/2013	High	Low	High	4N/5S	109	4S	104	104	6S	115	114
5/16/2013	High	Low	High	N/A	N/A	N/A	N/A	N/A	6S	113	111
5/18/2013	High	Low	Typical	3N	106	4S	102	101	4S	102	101

zone using two manned boats and autonomous node receivers. One of the boats was anchored at different locations with a cabled JSATS receiving system onboard, the autonomous node receivers were deployed approximately 500 m downstream of the dam, and the second boat was either anchored at different distances or allowed to drift past the other boat and autonomous node receivers. Results from the stationary tests and the drift tests (Figure 4) were combined and averaged for the three hydrophones used. Once again, using the same detection range definition used for JSATS acceptance testing, the detection range for the stationary boat-to-boat testing using a beacon was 154 m. For drift testing, the detection range was similar at 148 m.

Data from each autonomous receiver were processed and revealed significant variability in the results among receivers. The approximate detection range was between 75 and 100 m. The median depth that these autonomous receivers were deployed at was 5.8 m.

Discussion

Typically, thermal noise dominates ambient noise above 50 kHz[10]. The thermal noise spectrum level is 25 dB re 1 μPa^2/Hz at 100 kHz and increases by 6 dB/octave[11]. Using the above relationship, the thermal noise level in the JSATS frequency band is 92 dB re 1 μPa. All baseline noise measurements in the lab were above the thermal limit (Table 1). The measured noise level varied considerably because

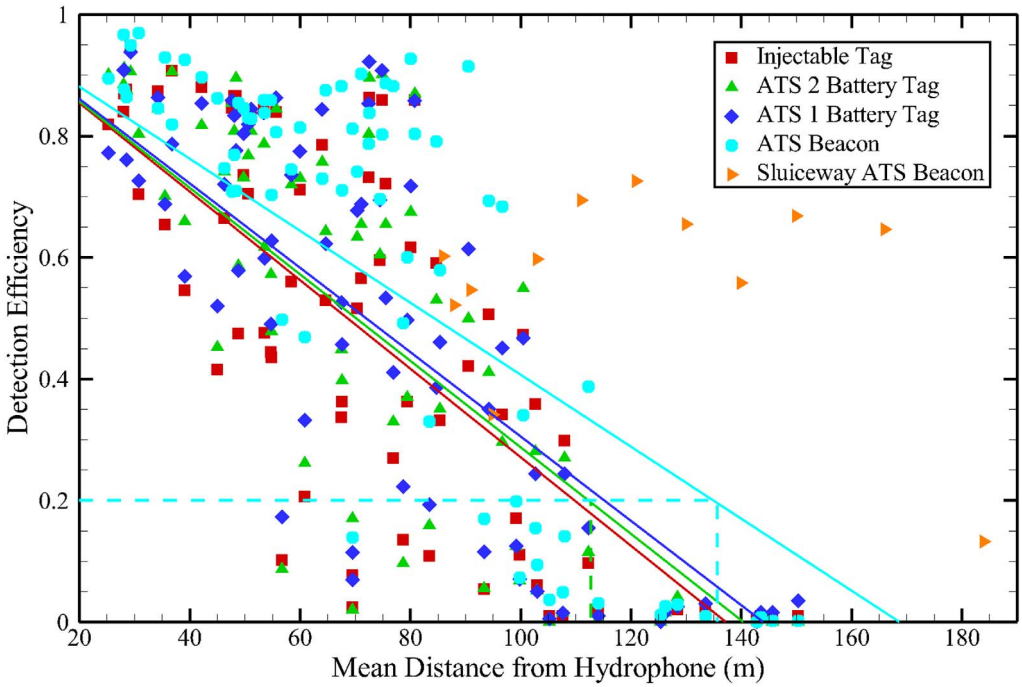

Figure 3 | Range testing results in the immediate powerhouse exit.

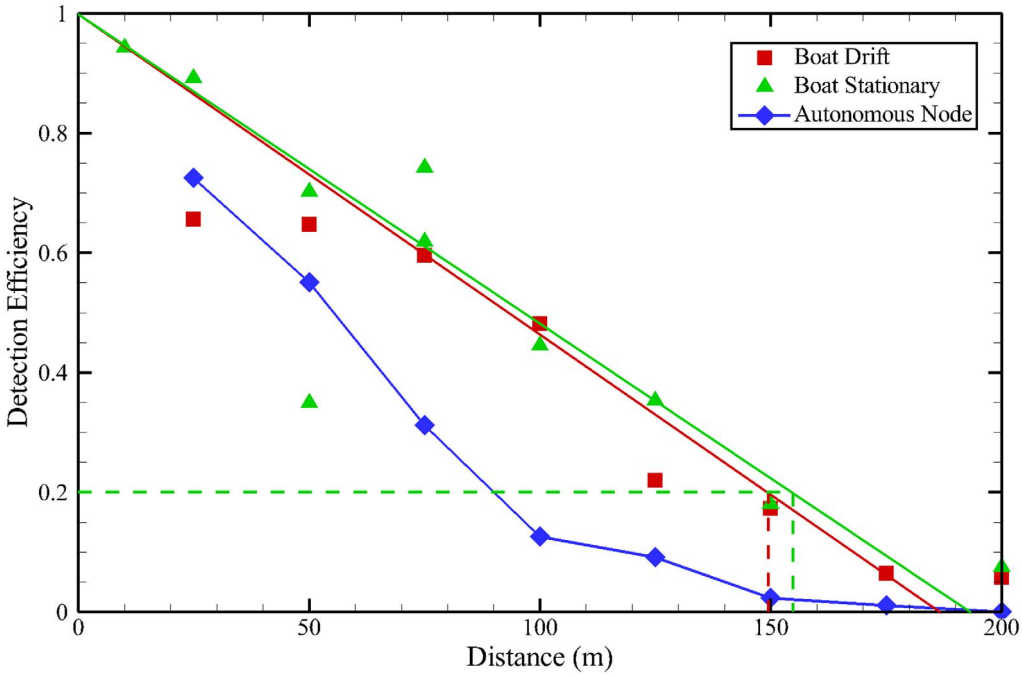

Figure 4 | Autonomous receiver range testing, boat-to-boat stationary, and boat-to-boat drift results using an Advanced Telemetry Systems (ATS) beacon.

each hydrophone, DAQ, and amplifier system had different noise floors.

In the Ice Harbor dam tailrace, the noise level measured from the powerhouse deck was affected by the flow through the dam. The mean noise level as measured by a SC 001 hydrophone (i.e., the hydrophone model currently used in JSATS) deployed in front turbine unit outlet 6S (50 m from spillway) was 114 dB re 1 μPa. At the same time, a SC 001 hydrophone deployed in front of turbine unit outlet 4S (100 m from the spill) measured a noise level of 104 dB re 1 μPa. A NL of 104 dB re 1 μPa would allow detection of tags at over 100 m distance assuming spherical spreading and 340 m assuming cylindrical spreading. During high flow through the dam, the measured noise level was significantly higher near the spillway (i.e., 10 dB higher at turbine unit outlet 6S). The detection range will be significantly limited for hydrophones deployed near the spillway during high-flow periods.

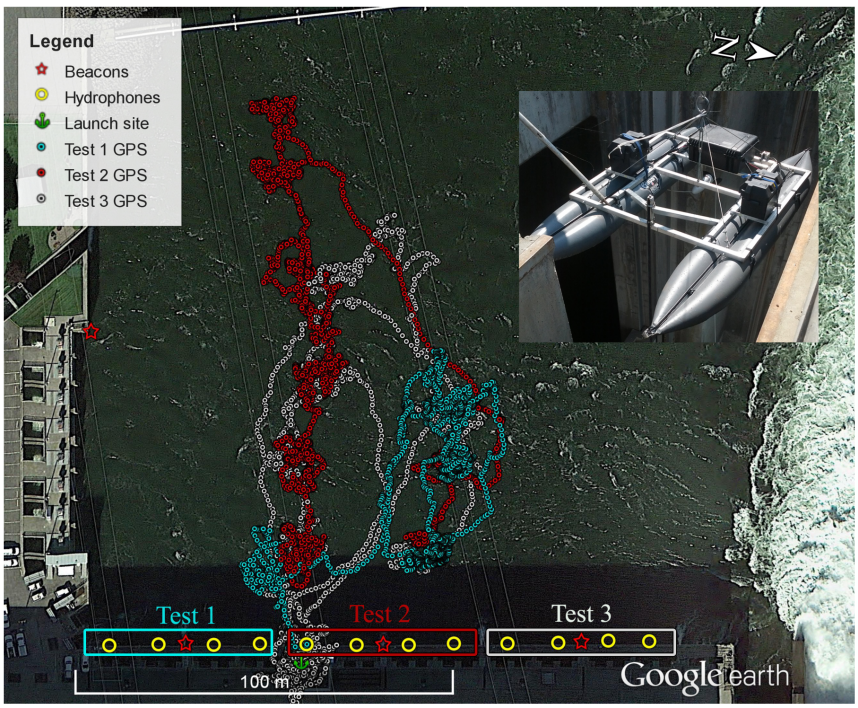

Figure 5 | Locations of hydrophones, beacons, and GPS tracks of the remote-controlled boat for each test. The insert photo shows the remote-controlled boat being deployed from the powerhouse deck.

In April 2008, range testing performed in the Bonneville dam forebay had a detection range greater than 120 m[8]. In the immediate tailrace of the Ice Harbor dam powerhouse, the detection ranges of the hydrophones lowered from the powerhouse deck were 113 m for tags and 136 m for beacons mounted to the remote-controlled boat. Due to the high flow, it was difficult to keep the remote boat facing the same direction. The tags do not have an omnidirectional beam pattern and they may not have been facing the hydrophones in an ideal direction. The beacons have a more uniform beam pattern so they are less likely to be affected by the orientation of the boat. The beacons mounted on the dam near the sluiceway had a detection range between 166 and 184 m. Since the line of sight path from beacon to hydrophone was all in water deeper than 8 m, signal reflections off the surface and bottom are not likely to arrive simultaneously with the line of sight transmission. The remote boat at distances far from the dam was in water that was less than 3 m deep. Since the signal travelled through shallow water, this may have increased the multipath interference.

The noise level measured by a TC4014 from a boat 350 m downstream of the dam was less than 106 dB re 1 μPa. The measured noise level is about the same as what the hydrophone measured in the lab. The actual noise level is likely lower. The estimated detection range in this region is 85 m assuming spherical spreading and 320 m assuming cylindrical spreading. The detection range for the boat-to-boat testing was in between these ranges. For the tailrace region 500 m downstream of the dam, the detection range for the stationary boat-to-boat testing using a beacon was 154 m and 148 m for drift testing. One possible explanation for the increased detection range compared with the remote-controlled boat testing is that, at the distance the boat-to-boat testing took place (approximately 500 m from the dam), noise levels are not influenced significantly by dam operations, and as a result, noise levels are lower.

Several autonomous receivers, also deployed downstream of the dam, at a median depth of 6 m had a detection range between 75 and 100 m. This relatively lower detection range may result from multipath interference. The median depth at which these autonomous receivers were deployed is shallower than the depth typically used for deploying autonomous receivers. At the autonomous receiver array deployed 1 km downstream of Lower Monumental Dam for the 2013 JSATS survival study, the median deployment depth of the autonomous receivers were 8.2 m, and at the array 1 km downstream of Little Goose Dam, the median depth was 8.8 m.

The acoustic noise measurements and validation experiments show that it is possible to detect acoustic tags used in JSATS at all measured locations. The detection ranges of JSATS cabled hydrophones from validation experiments were from 113 to 184 m. The tailrace bathymetry and the flow through the dam were important factors affecting the detection range. This information can be used for designing biological studies where there is interest in tracking fish in the tailrace of other hydro projects.

Methods

Noise level measurement systems. The acoustic noise environment in the Ice Harbor Dam tailrace was measured with broadband acoustic measurement systems. These systems typically consisted of a data acquisition (DAQ) system, hydrophones, and voltage preamplifiers. Two DAQ systems were used—a National Instruments USB-6366 (National Instruments Corporation, Austin, Texas) and a National Instruments PXIe-1073 chassis with a National Instruments PXIe-6124 card installed. Both systems used a voltage range of ±5 V, had 16-bit resolution, and collected data at 2.0 MHz and 2.5 MHz, respectively. The high sampling rates allow analysis of the noise level in the JSATS frequency band (416.7 ± 75 kHz).

Two different types of hydrophones were used to collect data: 1) RESON Model TC4014-5 (RESON A/S, Slangerup, Denmark), and 2) SC 001 (Sonic Concepts Inc, Bothell, Washington). The TC4014-5 hydrophone has a sensitivity of −186 ± 3 decibels (dB) re 1 V/μPa from 25 Hz to 250 kHz and a usable frequency range of 15 Hz to 480 kHz. A RESON Model VP2000 (EC6081) amplified the signal by 20 dB and passed frequencies between 500 Hz and 1 MHz. The SC 001 hydrophone has a sensitivity of −180 dB re 1 V/μPa at 416.7 kHz. The ATS SR5100 receiver (ATS, Inc., Isanti, Minnesota) powered the hydrophone and also amplified and filtered the signal from the hydrophone. A gain control voltage of 0.5 V was applied to the receiver so the signal would be amplified by 30 dB. The signal is filtered by a three-pole Bessel filter centered at 416.7 kHz and a bandwidth of 150 kHz.

Sound pressure data are presented in the Sound Pressure Level (SPL) and the Power Spectrum Level (PSL) formats. SPL is the mean square sound pressure expressed in decibels relative to a reference pressure, which is 1 μPa. PSL is SPL in a one-hertz band. A 500th-order finite impulse response digital filter was used with the hydrophone calibration data to filter noise from the JSATS frequency band of interest, which is 416.7 kHz ± 75 kHz. The frequency responses of the hydrophone and filter were multiplied to convert voltage to a pressure value.

Calibration. Each hydrophone used in the field was tested and calibrated in the acoustic tank located in the Pacific Northwest National Laboratory (PNNL) Bio-Acoustics and Flow Laboratory[12], which is accredited by the American Association for Laboratory Accreditation. This tank is lined with anechoic material. A broadband spherical hydrophone (Model TC 4034, RESON, Slangerup, Denmark) transmitted 200-μs pulses at a known SL. Each hydrophone to be calibrated was placed, with the hydrophone tip down, 1 m from the transmitter in the tank. The hydrophone was connected with the same cables and amplifiers used in the field. The output voltage from the hydrophone and amplifier being calibrated was sampled at 2.5 MHz with a National Instruments DAQ card. Ten pulses were measured for each frequency at each angle. The sensitivity was measured at 36 different angles equally spaced about the horizontal axis.

Field Noise Measurements. The hydrophones and a water-level data logger (Model HOBO U20-001-03, Onset Computer Corporation, Bourne, Massachusetts) were mounted on a rope and lowered into the water. The water-level data logger can measure water depth up to 76.2 m and has a maximum error of 0.1 m. The distance from the water-level data logger to each hydrophone tip was recorded. Lead weights were mounted at the end of the rope to limit the movement of the hydrophones in the water current.

Before a measurement system began to collect data, its performance was tested *in situ* with JSATS 2-s beacons. These beacons transmit a 744-μs signal with a SL of 156 dB re 1 μPa. The beacons are placed in the water a known distance from the hydrophones, so the SPL of the signal can be estimated. During noise measurement testing, the boat was either in a fixed position (i.e., anchored) or allowed to drift with the current. The depth of the Ice Harbor Dam tailrace is less than 3 m in some measurement areas. To keep the hydrophone from hitting the bottom and being damaged, it was deployed to a depth of 2 m.

To measure the noise level at different points at the powerhouse deck, hydrophones were deployed in front of different turbine unit outlets. The hydrophones were deployed to a minimum depth of at least 3 m; noise measurements were taken at these points. The hydrophones were often deployed in two pairs to cover two different points along the powerhouse deck simultaneously.

Signal-to-Noise Ratio. The signal-to-noise ratio (SNR) must be greater than a determined threshold for the signal to be detected and decoded correctly. To successfully detect and decode a JSATS tag code, an SNR of 6 dB is required[8]. The SNR of received tag signals varies with the noise level (NL), the source level (SL), and transmission loss (TL) of the transmitted signal.

$$SNR = SL - TL - NL$$

Transmission loss, which increases as the distance between the source and the receiver increases, can be divided into two loss factors—geometric spreading and attenuation.

$$TL = TL_{geometric} + TL_{attenuation}$$

$$TL_{attenuation} = \alpha\, r$$

The attenuation coefficient (α) for pure water can be estimated from the water temperature, the water depth, and the frequency of the transmitted signal[13].

$$\alpha = 0.00049\, f^2\, e^{-T/27 - D/17}$$

where f is the frequency of the sound, T is temperature in degrees Celsius, and D is the depth of the propagating sound source in kilometers. The attenuation coefficient does not vary much with depth but is significantly affected by temperature. The attenuation coefficient increases as the water temperature decreases.

Geometric transmission loss of the acoustic tags in water, which results from spherical or cylindrical spreading loss, can be estimated as a logarithmic loss of signal strength with increasing distance from the source[9].

$$\text{For cylindrical spreading loss, } TL_{geometric} = 10\, log(r)$$

$$\text{For spherical spreading loss, } TL_{geometric} = 20\, log(r)$$

Geometric transmission loss is likely neither perfectly cylindrical nor perfectly spherical, but is a combination of both losses. Because the geometric spreading loss

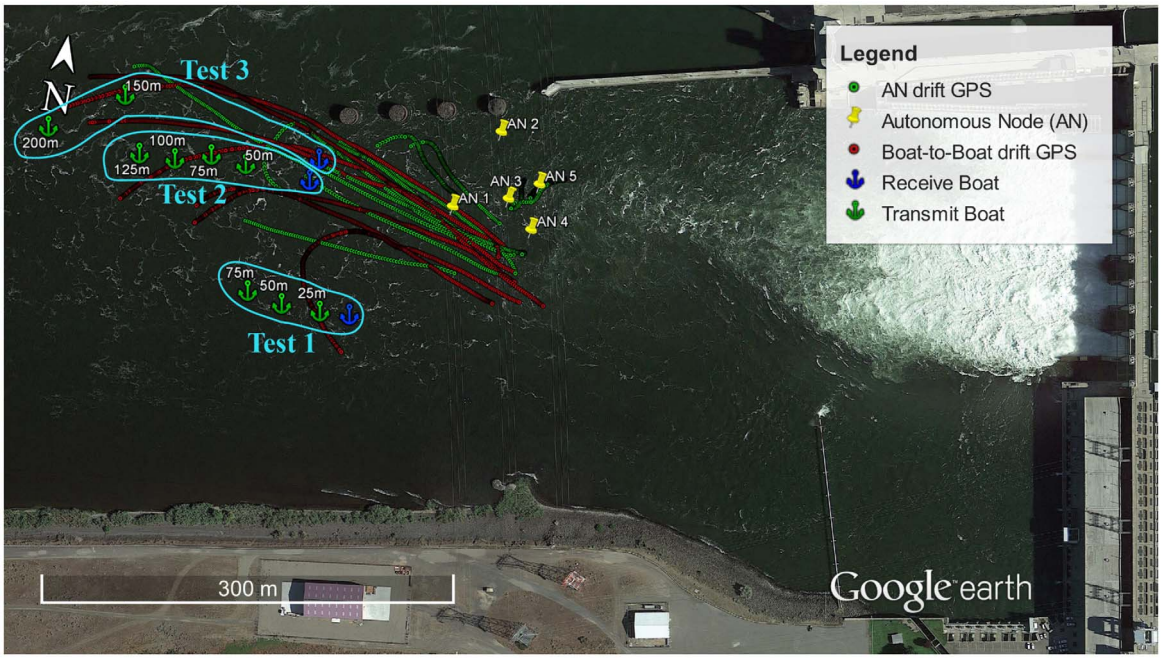

Figure 6 | Position of the receive boat, autonomous nodes, and the GPS tracks for each drift of the transmit boat.

will not be greater than that described by spherical spreading, we use spherical spreading for conservative range estimates based on the background noise level.

The detection range may further be limited by multipath interference, when the reflections and the transmitted signal overlap. The number of reflections increases in shallow water, leading to increased multipath interference. Because the water depth in the tailrace typically is shallower than the forebay, multipath interference is more severe in the tailrace than the forebay.

Dam Range Testing. A JSATS cabled system with four hydrophones identical to the type used during the noise evaluation was deployed from the powerhouse deck. The hydrophones were deployed from the deck using ropes and weights that were secured to the handrail. The water-level data logger was attached just above each hydrophone to record the depth at which it was deployed. The four hydrophones were deployed in three separate locations spanning two turbine units during testing: turbine units 1 and 2, 3 and 4, and 5 and 6 (Figure 5). The gain supplied by the amplifier to the waveforms collected by the hydrophones was 50 dB.

A 2.7-m-long, remote-controlled boat (Figure 5) was used to perform range testing within the immediate vicinity of the powerhouse. This remote-controlled boat was originally developed for evaluating the accuracy of three-dimensional tracking in the forebay of dams equipped with JSATS cabled arrays[5,8]. For the range testing, a total of four beacons and seven tags were attached to a steel pipe. The HOBO U20-001-01 water-level data logger was used to measure the depth of the beacons and tags below the water surface, as well as the water temperature. To record the location of the remote-controlled boat during testing, a handheld Garmin Oregon 450 GPS (Garmin International, Inc., Olathe, Kansas) was placed within a waterproof enclosure attached to the boat. An ATS beacon positioned near the exit of the sluiceway was used for range testing in addition to the beacons and tags attached to the remote-controlled boat.

For each set of hydrophone locations, the remote-controlled boat was steered to a position a given distance from the dam and held relatively stationary for 5 min before proceeding to the next location. Because of the turbulent flow conditions in the tailrace, the boat could be operated only in front of turbine units 2 through 4 and at a maximum distance of 150 m.

Mobile Range Testing. Range testing was performed just outside the boat-restricted zone using two manned boats and autonomous node receivers (Figure 6). One boat (referred to as the "receive boat") was used to deploy a JSATS cabled system. The receive boat was anchored at a fixed position facing upstream with all sources of potential acoustic noise turned off (e.g., motor, depth sounder, etc.). Three JSATS hydrophones were deployed from the aft and bow of the receive boat. The hydrophones were deployed to approximately the middle of the water column with each hydrophone depth recorded by the HOBO U20-001-03 water-level data logger. An ATS beacon deployed from the receive boat was used only for verifying the proper operation of the JSATS cabled system before beginning the tests.

The second boat (referred to as the "transmit boat") was used to deploy an ATS beacon. The beacon was deployed at approximately the middle of the water column. Prior to any data collection, all sources of potential acoustic noise were turned off.

Two types of range tests were performed between the two boats—stationary points and drifts. For the stationary tests, the transmit boat was anchored facing upstream at locations as much as 200 m downstream of the receive boat, which was approximately 500 m downstream of the dam. For the drift tests, the transmit boat was allowed to slowly drift unpowered downstream starting approximately 150 m upstream of the receive boat and ending up as much as 200 m downstream of the receive boat.

Range testing also was performed using an array of five JSATS autonomous receivers. The autonomous receivers were deployed[14] downstream of the spillway just past the entrance to the navigation lock. The transmit boat was used to perform drifts downstream from the array of autonomous receivers. Starting near the array, the transmit boat was allowed to drift unpowered a distance of up to 200 m downstream of the array.

Range Testing Processing. Raw detection data were decoded before being processed according to methods developed for the JSATS survival studies. Data were filtered to remove duplicate decodes from reflections (i.e., multipath signals). Results of the drift tests were processed by grouping the detections into 25-m bins (e.g., 0 to 25 m, 25 to 50 m, etc.) and calculating the detection efficiency for each bin.

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Author contributions

Z.D.D., B.A.T., and M.A.W. conceived and designed the experiments. J.M.I., J.J.M., and R.P.M. performed the experiments. J.M.I. and J.J.M. analyzed the data. J.M.I., Z.D.D., J.J.M., and B.A.T. wrote the paper. All authors reviewed the manuscript.

Additional information

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