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An accuracy assessment of ultrasonic transmitter locations determined by mobile telemetry in aquatic systems

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Underwater telemetry is a common and effective method to evaluate gear efficiency and the behaviour, physiology and mortality of free-ranging fish (Winter 1996; Lucas & Baras 2001; Wanner *et al.* 2007; Guy *et al.* 2009; Cooke *et al.* 2013; Friedl *et al.* 2013). A telemetry system basically consists of a transmitter that emits radio (27–300 MHz) or ultrasonic signals (27–300 kHz), an antenna or hydrophone that detects the signal (passively or actively) and a receiver that decodes signals into audible sounds (Winter 1996). Each type of telemetry system has a set of advantages and disadvantages (Cooke *et al.* 2013). This study evaluates accuracy of acoustic telemetry, but the approach is similarly useful for radio telemetry. As a directional hydrophone is aligned with a signal's source, the signal becomes stronger, and thus, direction of the transmitter can be interpreted. However, as distance between the transmitter and hydrophone is reduced, direction of the signal becomes increasingly difficult to distinguish until a point that direction is no longer distinguishable; this point can be interpreted as the location of the transmitter.

The ability to distinguish transmitter direction and estimate a transmitter location using an acoustic telemetry system can be affected by the engineering aspects of the telemetry system (Priede 1986) and also the physical environment, bio-fouling and background noise (Stasko & Pincock 1977; Heupel *et al.* 2006; Bergé *et al.* 2012; Cooke *et al.* 2013). Accuracy of transmitter locations can limit inference from telemetry locations. For instance, accuracy was shown to influence the degree to which animal movement estimates could confidently be measured (Laundre *et al.* 1987). The objectives of this study were to directly measure accuracy of acoustic transmitter locations and also assess the use of global positioning system (GPS) coordinates as an alternative for measuring accuracy.

This study was conducted at two sites, Hipple Lake and the upstream, riverine section of Lake Sharpe approximately 13 km downstream from Oahe Dam, both within the Missouri River, South Dakota, USA. Hipple Lake is a 178 ha backwater of upper Lake Sharpe near Pierre, South Dakota. Average depth in Hipple Lake was about 2.0 m (D. A. James, personal observation). Lake Sharpe is a 128-km long, flow-through reservoir that extends from Oahe Dam near Pierre, South Dakota, downstream to Big Bend Dam near Chamberlain, South Dakota. The combined riverine and lacustrine areas of Lake Sharpe have a surface area of 25 000 ha, a maximum depth of 23.5 m and a mean depth of 9.5 m (Fincel *et al.* 2013).

Two types of ultrasonic transmitters (Sonotronics, Inc., Tucson, AZ, USA) were used during this study. One type was model CT-05-36; each transmitter was 63.0 mm long, had an outside diameter of 15.6 mm, weighed 10.0 g and had an expected battery life of 36 months. Each CT transmitter had a reported range of 1000 m (Sonotronics, Inc.), presumably under optimal conditions, although detection range can vary according to environmental conditions (Cooke *et al.* 2013). The other transmitter type was model PT-4; each was 25.0 mm long, had an outside diameter of 9.0 mm, weighed 2.3 g, had an expected battery life of 90 days and a reported range of 750 m. Both transmitter types had the same frequency range (69–83 kHz) but differed in output power (i.e. source level). The output power range of the CT and PT transmitters was 142–144 and 134–136 decibels, respectively. Each individual transmitter emitted a unique aural code that allowed for identification of individual transmitters. To reduce any potential bias due to varying signal strength among transmitters, the transmitter for each trial was randomly selected from 20 CT transmitters and 15 PT transmitters; any single transmitter was used a maximum of three times.

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Each transmitter was placed in a small mesh bag tied to a small float. The mesh bag was attached to a 4.5-kg anchor with a 15-cm piece of twine. When placed in the water, this configuration allowed each mesh bag and transmitter to suspend in the water column about 15 cm above the substrate to mimic the position of a benthic-oriented fish. Lines (70 m length) were tied to the anchors, and using a boat, each transmitter was placed at unique locations 10–60 m from the shoreline in each study area. After placing transmitters out of view from the person locating the transmitters, the end of the line was secured to shore for later retrieval.

A Sonotronics model USR-96 active receiver and DH-4 directional hydrophone were used to determine the location of hidden transmitters. The hydrophone was fixed to a 5-cm-diameter aluminium pipe mounted vertically to the outside of the tracking boat in a manner that allowed it to be rotated 360°. The tracking boat had a bow-mounted trolling motor equipped with an 'anchor' function that integrated a GPS, motor and steerage to maintain the boat's geographic position on the water.

To estimate the location of a hidden transmitter, personnel in one boat (i.e. trackers) used the hydrophone and sensitivity (i.e. gain) adjustment of the receiver to locate the transmitter and manoeuver the tracking boat to a position where the hydrophone was located directly above the location where the transmitter direction was not distinguishable. The trackers used the 'anchor' function of the trolling motor to hold the boat at the perceived position of the transmitter where location coordinates were recorded with a handheld GPS (Garmin GPSMAP 76S; Garmin International, Inc., Olathe, KS, USA) and depth was measured with a boat-mounted depth finder. The personnel that hid the transmitter (i.e. planter crew) then used the line attached to the anchored transmitter to manoeuver their boat to the actual position of the transmitter. A fibreglass tape was used to measure the distance between the estimated (i.e. hydrophone) and actual position (i.e. location of anchored transmitter where line was vertical in the water) of the hidden transmitter to quantify error of the transmitter location. The fibreglass tape was easily tossed from one boat to the other during the measuring process. The planter crew also used a handheld GPS to obtain location coordinates, a boat-mounted depth finder to measure depth (m) and a Marsh McBirney Flow-Mate flow meter (Hach, Loveland, CO, USA) to estimate surface current velocity at the actual location of the hidden transmitter.

The estimated and actual location coordinates were imported into ArcMap 10.1 Geographic Information System (GIS) software (ESRI, Redlands, CA, USA) to determine the distance between them. Accuracy was defined as the distance from the actual to the estimated transmitter coordinate location. The directional bearing (0–360°) from the actual to the estimated transmitter location was also quantified.

Trials were conducted to determine whether accuracy was affected by different trackers, water body type and transmitter type. One trial was defined as one tracker locating 10 transmitters. Two trials were conducted for both the CT and PT transmitters (i.e. one trial each in Hipple Lake and Lake Sharpe for each transmitter type). Two different trackers completed the set of four trials. Thus, for all eight trials, CT and PT transmitters were located a total of 80 times. Each of the 80 hidden transmitter locations was unique (i.e. each transmitter was moved after being located one time). The trackers had limited previous experience with locating ultrasonic transmitters. Prior to this study, all trackers received about 2 h of training and practice locating transmitters.

A factorial design (three-way ANOVA) was used to test for differences in accuracy among the main effects of water body, transmitter type and tracker and their interactions. A Kruskal–Wallis analysis was used to test whether accuracy measured by GPS coordinates was different from the measured accuracy. A Rayleigh test (Zar 1999) was conducted using the directional bearing data to attest for a directional difference between the actual and estimated transmitter locations. The Rayleigh test is a circular uniformity test that tests the null hypothesis that the sampled population is uniformly (i.e. randomly) distributed around a circle. Statistical significance was declared at $\alpha = 0.05$ for all tests.

The mean surface water velocity was 0.55 m s^{-1} in Lake Sharpe ($n = 20$, SE = 0.03; range: 0.28–0.84) and was zero in Hipple Lake. The depth of hidden transmitters was greater in Lake Sharpe (mean = 4.1 m; SE = 0.1; range: 2.5–5.5) than in Hipple Lake (mean = 1.7 m; SE = 0.1; range: 0.5–2.4; $H_{1,80} = 59.4$; $P < 0.001$).

The ANOVA indicated that none of the interaction terms were significant (water body*transmitter: $F_{1,72} = 0.05$, $P = 0.83$; water body*tracker: $F_{1,72} = 0.04$, $P = 0.83$; transmitter*tracker: $F_{1,72} = 0.93$, $P = 0.34$; water body*transmitter*tracker: $F_{1,72} = 0.08$, $P = 0.77$); thus, interactions were removed from the analysis to test for main effects. Accuracy did not differ between water body ($F_{1,76} = 0.16$, $P = 0.69$), transmitter type ($F_{1,76} = 1.67$, $P = 0.20$) or tracker ($F_{1,76} = 1.40$, $P = 0.24$). The least square means ± SE for accuracy of water body were 6.6 m ± 0.7 in Lake Sharpe and 6.3 m ± 0.7 in Hipple Lake. The least square means for accuracy of CT transmitters were 7.2 m ± 0.7 and 5.8 m ± 0.7 for PT transmitters. The least square means for accuracy of tracker one and two were 5.9 m ± 0.7 and 7.1 m ± 0.7, respectively. Overall, mean accuracy was 6.5 m ± 0.2.

Assessment of accuracy using GPS coordinates and a GIS compared with physically measuring accuracy indicated that physical measurements were generally more accurate, although not significantly different ($H_{1,80}$ = 1.5; $P = 0.22$). Accuracy determined from GPS/GIS was estimated at 8.2 m ± 0.9, while the assessed accuracy obtained from physical measurements was 6.5 m ± 0.2.

The Rayleigh test did not indicate any directional bias of an estimated transmitter location relative to its respective actual location (Fig. 1). Both PT ($z = 1.52$; $P > 0.05$) and CT ($z = 0.08$; $P > 0.05$) estimated transmitter locations were uniformly distributed around the actual location of hidden transmitters. Overall (i.e. PT and CT transmitters pooled), estimated transmitter locations were also uniformly distributed ($z = 0.84$; $P > 0.05$; Fig. 1).

Personnel, transmitter type or water body type (lotic or lentic) were not found to influence the accuracy of an estimated transmitter position in this study. After a couple hours of training and practice, relatively inexperienced trackers located hidden transmitters with similar accuracy, which suggests using multiple trackers would not introduce additional location error to a telemetry study. The use of both CT and PT transmitters, despite output power differences of ~10 decibels, resulted in similarly accurate estimates of location. Although water velocity in the riverine section of Lake Sharpe made boat manoeuvering and locating transmitters seem more difficult to the trackers, estimates of accuracy were not different from those in Hipple Lake (zero water velocity). Although accuracy due to differences in water depth was not specifically tested, accuracy of location estimates was not different between Lake Sharpe (deeper) and Hipple Lake (shallower). However, the least accurate sample (location error = 25.6 m) was from the shallowest recorded depth (50 cm), which supports the thought that exceptionally shallow water (<30 cm) could be a constraint to acoustic telemetry (Stasko & Pincock 1977; Cooke *et al.* 2013). These results suggest that accuracy was similar for transmitters with different output power in different aquatic habitats (i.e. lotic and

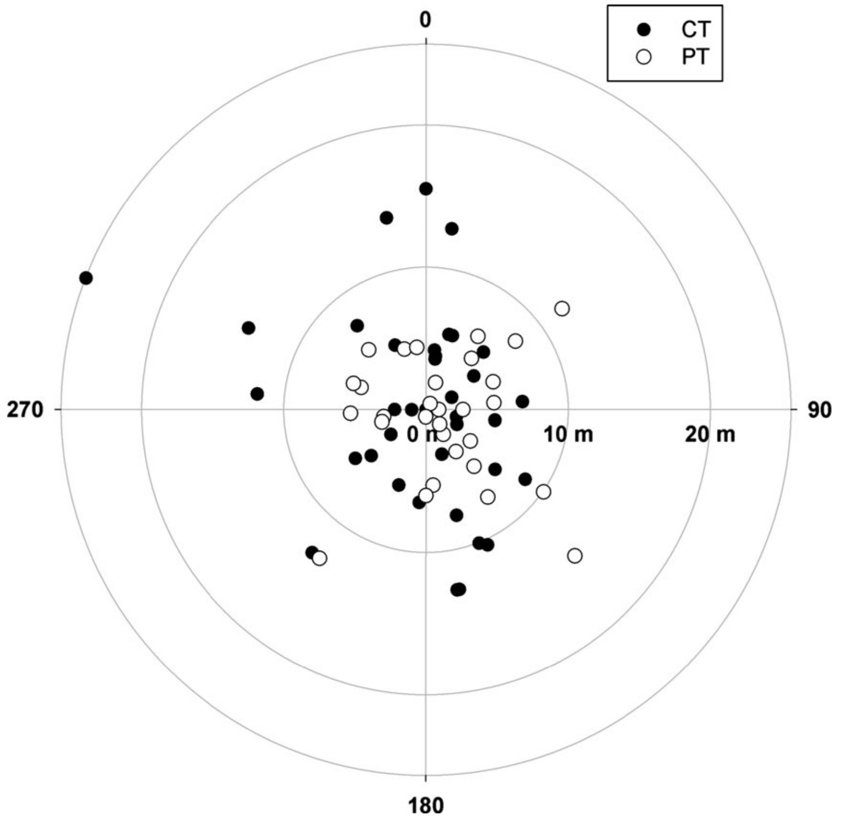

Figure 1. Circular distribution plot displaying uniformity (i.e. randomness) of estimated transmitter locations relative to its actual location (centre of diagram). Location of each CT (larger output power; dark circle) and PT (smaller output power; open circle) transmitter types in the diagram represents the direction and distance from its actual location.

lentic) at a variety of depths (0.5–5.5 m), at least for the telemetry system used in this study.

The accuracy measurement from this study (6.5 m) was less than that reported from mobile telemetry studies by Bassett & Montgomery (≤20 m; 2011), Herrala *et al.* (<30 m; 2014), Vrieze *et al.* (16 m; 2011) and Wall & Blanchfield (<15 m; 2012). While these studies reported accuracy, many others did not, and fewer provided detailed methods or data that were used to support the reported accuracy estimates. For example, Web of Science (http://apps.webofknowledge.com/; accessed May 2014) was used to search seven major fisheries journals from 2009 to 2013 for studies that used acoustic telemetry to track fish. Of 65 articles, 51 employed passive techniques and 14 reported use of mobile telemetry. Only three (21%) of the mobile telemetry articles reported a measure of location accuracy. One of the three articles did not indicate how accuracy was determined. Reasons for not reporting a measure of accuracy are not known, but perhaps assessing accuracy is too tedious and time-consuming or quantifiable methods to do so are not well known. In any case, this study provides a framework for how to quantify accuracy.

Knowledge of location accuracy estimated by telemetry is crucial to understand what research question can be adequately addressed. For example, location estimates accurate to 30 m (Herrala *et al.* 2014) could provide inference for movement of far ranging organisms (Jordan *et al.* 2006); but for questions regarding conditions at the location of an organism, such as current velocity or substrate (Riedle *et al.* 2006; Trested *et al.* 2011), accuracy to 30 m would be uninformative. Known accuracy should be considered when assessing animal movement because the magnitude of an animal's movement that can confidently be measured is dependent on location error (Laundre *et al.* 1987). For example, because accuracy was determined to be 5.9 m (SE, 0.7; James *et al.* 2003) for a radio telemetry study of brown trout, *Salmo trutta* L., a fish was not considered to have moved unless it was located at least 6.6 m from its previous location to account for location error (James *et al.* 2007). In studies that use telemetry to assess the capture efficiency of gears for targeted individuals (Guy *et al.* 2009), the gear type in question must be able to sample an area large enough to account for error in location estimates to ensure the targeted individual is within the sampled area.

Transmitter power has been shown to influence accuracy. In one study, for example, although transmitters with stronger signals were more easily detected, transmitters with weaker signals were more accurately pinpointed (How & de Lestang 2012). Detection distance is affected by numerous factors (Shroyer & Logsdon 2009), but all other factors being equal (e.g. frequency, environmental conditions), greater power transmitters are more easily detected at longer ranges than weaker transmitters (Priede 1986). However, a stronger transmitter's signal direction becomes indistinguishable at a greater distance from a hydrophone than a weaker transmitter's signal; thus, accuracy could decrease as detection distance increases. Given that accuracy was not different between the higher power (CT) and lower power (PT) transmitters in this study, the higher power transmitter is a better option when detection distance is more important than accuracy.

Directional bias of location estimates was not apparent in this study. Sound reflection of shore banks has been posited to hinder performance of telemetry systems (Bergé *et al.* 2012). Although distance to the shoreline was not specifically tested in this study, the shoreline, which was within 60 m of transmitter locations in both lentic (Hipple Lake) and lotic (Lake Sharpe) systems, did not appear to bias the directionality of the estimated transmitter. Similarly, river current did not bias locations up- or downstream of actual transmitter locations.

Directly measuring the distance between the estimated and actual transmitter locations with a measuring tape provided a reliable estimate of accuracy. When the GPS-derived accuracy estimates were compared with the measured accuracy, an additional mean error of ~1.7 m was apparent, but this source of variation was not statistically significant. Because GPS-derived accuracy was not different than measured accuracy, the use of GPS provides a simpler alternative to quantify accuracy and probably would not affect accuracy of geographic coordinate locations often collected in telemetry studies (Jordan *et al.* 2006; Neely *et al.* 2010; Trested *et al.* 2011). Use of high precision GPS units, location augmentation techniques (e.g. differential correction; Leick 1990) or both could be used to further reduce location error.

The accuracy of a telemetry system and knowledge that the accuracy requirement for a research study is satisfied should be known prior to beginning a project. Conducting an accuracy assessment similar to the one in this study provides answers to both of those questions. While the methods used in this study would suffice for aquatic systems similar to the two in this study, implementing them in other systems, such as high velocity, turbulent waters may be more difficult.

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