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Testing an autonomous acoustic telemetry positioning system for fine-scale space use in marine animals

Zy Biesinger [a,*], Benjamin M. Bolker [b], Douglas Marcinek [a], Thomas M. Grothues [c], Joseph A. Dobarro [c], William J. Lindberg [a]

[a] Program in Fisheries and Aquatic Sciences, University of Florida, 7922 NW 71st Street, Gainesville, FL 32653 USA
[b] Department of Mathematics and Statistics, McMaster University, 1280 Main Street West, Hamilton, Ontario L8S 4K1, Canada
[c] Institute of Marine and Coastal Sciences, Rutgers, The State University of New Jersey, 800 c/o 132 Great Bay Boulevard, Tuckerton, NJ 08087-2004, USA

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ABSTRACT

We tested the capabilities and limitations of a novel autonomous acoustic positioning telemetry system with data from fifteen field deployments off the Florida coast. Telemetry array coverage areas ranged between 100 and 300 m across. For fixed transmitters within the array, the fraction of transmissions leading to high-quality calculated position estimates averaged 44%, with wide variation. Positional accuracy was about 2 m. The choice of filtering strictness represented a trade-off between the accuracy and frequency of positions. There was substantial temporal variation, but no clear pattern (e.g., daily or tidal correlations) in frequency of positions. There was no spatial bias within the array. Array performance for stationary transmitters was robust to user errors in sound speed and hydrophone position estimates. Performance was less robust for a transmitter attached to an autonomous underwater vehicle moving through the array, with 22% of transmissions leading to position estimates. Overall the system produced reliable results, but as the use of acoustic telemetry in complex ecological studies increases it is important to recognize technological requirements and limitations.

1. Introduction

The need to understand complex space-use, behavioral, and ecological processes of animals in challenging aquatic systems is driving the development of novel acoustic telemetry technologies (Espinoza et al., 2011b; Lucas and Baras, 2000; Niezgoda et al., 2002; O'Dor et al., 1998). New positioning telemetry systems allow data collection at finer scales, over larger areas and longer times, and in less accessible locations than ever before (Andrews et al., 2011; Hanson et al., 2007; Parsons et al., 2003; Voegeli et al., 2001). Such detailed data enhance our ability to address complex ecological questions and are particularly important as spatial management tools (e.g., design of marine protected areas) are increasingly used to manage exploited species (Cooke et al., 2005; Feary et al., 2011). Though acoustic telemetry technologies are powerful tools, their proper use requires an understanding of their requirements and limitations. This is especially true for positioning telemetry arrays, which provide fine-scale animal position estimates.

Some active acoustic technologies require animals to be captured and fitted with acoustic tags, which allow the measurement of specific individuals' behavior (Heupel et al., 2006). In addition to uniquely identifying individuals, tags can report a wide range of environmental, physiological, and behavioral data (Carey and Lawson, 1973; Wolcott, 1995). Tagged individuals can be manually located with a directional hydrophone (Collazo and Epperly, 1995; Johnson et al., 2009; Zeller, 1999) giving position estimates. Tag detections by an omnidirectional hydrophone can be interpreted as presence/absence data or as position estimates with error around the position determined by the detection capability of the receiver (Clements et al., 2005; Heupel et al., 2004). Some work has been done using presence/absence information from multiple hydrophones and calculating two- and three-dimensional short-term center of activity locations, but not precise location estimates at a single time (Heupel et al., 2012; Simpfendorfer et al., 2012; Simpfendorfer et al., 2002).

In contrast, with acoustic positioning telemetry, when a particular tag transmission is received by at least three hydrophones, the two- or three-dimensional position solution can be calculated to within a few meters or less (Bergé et al., 2012; O'Dor et al., 1998; Voegeli et al., 2001), using differences in the times a single transmission arrives at multiple hydrophones (e.g., hyperbolic trilateration, Niezgoda et al., 2002). This technology requires the important distinction between a transmission's *detection* by individual hydrophones and its calculated *position solution* when detected by at least 3 hydrophones. In most instances, positioning telemetry can provide precise position estimates more often and for longer periods than manual tracking, allowing for finer scale movement and habitat use studies (Espinoza et al., 2011a).

The advantages of positioning arrays come with the extra requirements of very precise clock synchronization (typically achieved by

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[*] Corresponding author at: Department of Fisheries and Wildlife, Oregon State University, Nash Hall, Room 104, Corvallis, OR 97331, USA. Tel.: +1 541 737 1859; fax: +1 541 737 3590.
E-mail address: zy.biesinger@oregonstate.edu (Z. Biesinger).

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continuous cable or radio communication), enough hydrophones to cover the geographic scale of interest, accurate position estimates of each hydrophone, and an estimate of sound speed. Though all acoustic technologies are affected by the aquatic acoustic environment and deployment details, positioning telemetry technologies are particularly susceptible to noise, acoustic conditions, and user errors (Bergé et al., 2012; Cote et al., 1998; Heupel et al., 2006; O'Dor et al., 1998; Welsh et al., 2012).

New positioning telemetry systems, for example the Lotek Wireless© WHS 3050 MAP (Cooke et al., 2005; Cote et al., 1998; Niezgoda et al., 2002) or Vemco© VPS (Andrews et al., 2011; Espinoza et al., 2011b) use autonomous hydrophones, stationary beacon tags, and post-deployment positioning software, instead of continuous communication, to compensate for clock differences. In these systems, autonomous hydrophones potentially allow arrays to be deployed over larger areas and in deeper waters than traditional communicating positioning systems, without surface or shore exposure. Positioning telemetry has been used to study animal space and habitat use in many settings (Bégout and Lagardère, 1995; Hanson et al., 2007; Klimley et al., 2001; Semmens, 2008).

The added sophistication of positioning telemetry, especially autonomous systems, necessitates a clear understanding of system requirements and limitations in order to correctly interpret telemetry output. Post-processing computation produces metrics of the quality, or accuracy, of each calculated position solution, allowing users (e.g., of Lotek© systems) or the manufacturer (e.g., of Vemco© or HTI© systems) to filter telemetry output (Cooke et al., 2005; Hanson et al., 2007; Niezgoda et al., 2002). Studies using positioning systems have reported accuracies of 2 m or better (Cooke et al., 2005; Cote et al., 1998; Espinoza et al., 2011b; Niezgoda et al., 2002; O'Dor et al., 1998; Semmens, 2008). The reported fraction of tag transmissions resulting in reliable position solutions varied between 4 and 75%, depending heavily on the acoustic environment, tag strength, array geometry, and array spacing (Brown et al., 2010; Cooke et al., 2005; Geraldi and Powers, 2011; Niezgoda et al., 2002).

Few studies have purposefully evaluated positioning telemetry system performance, e.g., the fraction or accuracy of position solutions (Bergé et al., 2012; Ehrenberg and Steig, 2002; Espinoza et al., 2011b), temporal and spatial variations in system performance, or the effects of user input errors on performance. The degree of temporal variability in array performance is expected to reflect the array's susceptibility to temporal changes in acoustically important environmental variables, for example, temperature, salinity, weather and sea state, or water stratification. Spatial variation is expected to reflect performance differences due to array deployment geometry.

In 7 steps, we evaluated Lotek's© autonomous positioning system for several stationary and one moving transmitter. (1) We calculated the overall fraction and temporal variability of transmissions detected by single hydrophones at different distances. This can be done without deploying an entire array and aids in initial array design (Cooke et al., 2005). (2) We calculated the overall fraction and temporal variability of the fraction of transmissions resulting in position solutions with the array deployed at different spacings, and explored the interaction between data filtering and position solution accuracy. Detection and position solution fractions from our large datasets may be suggestive of position solution probabilities in future animal studies. (3) We estimated position solution accuracy of filtered data. (4) We described the spatial variation in the fraction and accuracy of position solutions. (5) We calculated the impact of sound speed changes (e.g., due to changing water temperature) or estimation errors on position solution fraction and accuracy. (6) We calculated the effect of errors in hydrophone position estimates on position solution fraction and accuracy. Using data from one transmitter attached to an Autonomous underwater vehicle, (7) we calculated the overall fraction of transmissions resulting in position solutions and position solution accuracy and calculated the impact of sound speed changes and errors in hydrophone position estimates on position solution fraction and accuracy. Results presented here using tags of known position, complement array performance using tags implanted in fish, and thus of unknown position, described in Biesinger et al. (2013).

2. Materials and methods

2.1. Study system

This study was conducted 30 km off the Florida coast in the Gulf of Mexico in 13 m of water, where the seafloor was characterized by a mix of low-relief hard-bottom and sand-bottom habitats (Parker et al., 1983). Hard-bottom was characterized by emergent limestone often covered with a veneer of sand and shell rubble, and typically sustained low algal, sponge, and soft-coral growth less than 0.5 m tall. Sand-bottom was characterized by deeper, bare sand. Part of the Steinhatchee Fisheries Management Area, our experimental, artificial reef system (Fig. 1) consisted of clusters of four, immediately adjacent, hollow cement hemispheres about 1 m tall, with holes allowing fish access to the interior. Each reef cluster had a 4 m^2 footprint. Each telemetry array deployment centered on a single reef, with no others within the array. Smaller experimental reefs in the system consisted of single cement hemispheres. All locations had relatively little turbulence from wave action or boat traffic, and no other structures, e.g., docks or hardened shorelines. We continuously measured water temperature with an Acoustic Doppler Current Profiler (ADCP, Teledyne RDI© Workhorse Sentinel, 600 kHz) approximately 1 km away.

2.2. Telemetry system: transmitters, hydrophones, and software

2.2.1. Transmitters

We used uniquely coded Lotek© 76 kHz transmitters of two basic types: *tags*, normally attached to animals, with (MA-TP16-25, 2 s interval, transmission length: 250 ms, 156 dB re 1 μPa at 1 m) and without temperature and pressure sensors (MA-16-25, 2 s interval, transmission length: 250 ms, 156 dB re 1 μPa at 1 m), and stationary *beacons*, used for clock synchronization, with (MA-TP16-50, 20 s interval, transmission length: 250 ms, 156 dB re 1 μPa at 1 m) and without temperature and pressure sensors (MA-16-50, 20 s interval). The MAP system uses a code-division-multiple-access (CDMA) scheme encoding information in waves that are extracted from a noise carrier signal based on correlation; it does not require time sharing of the acoustic channel and is therefore very robust against code collision and noise interference (Niezgoda et al., 2002). Because of this, the timing among signals can be and is invariant to 0.00001 s, in contrast to other common coding schemes such as pulse interval coding (PIC) that randomize transmission intervals (Grothues, 2009). Each complete transmission, termed a *symbol*, lasts on the order of milliseconds and is comprised of three *codes*, short acoustic bursts conveying ID and, optionally, sensor data. The duration of a complete symbol, or one of its constituent codes, is always short relative to the time that even a fast fish can move a single body length. Although these tags supported sensors, those data are not used to evaluate system performance and we do not report it here.

2.2.2. Hydrophone array

We used an array of five autonomous submersible dataloggers (Lotek© WHS 3050 MAP, 76 kHz), which we call hydrophones, each consisting of an actual omnidirectional hydrophone, a receiver, a datalogger, and a battery pack. Each hydrophone unit was mounted about 2 m above the seafloor using either posts driven into the underlying rock (for deployments lasting longer than a day) or temporary, weighted posts with a surface buoy adding vertical stability and independent GPS position estimates. All array deployments used the same basic geometry: a central hydrophone 10 m northeast