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Mobile Positioning of Tagged Aquatic Animals Using Acoustic Telemetry with a Synthetic Hydrophone Array (SYNAPS: Synthetic Aperture Positioning System)

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Abstract.—We present a new acoustic telemetry method for efficiently estimating positions of tagged marine and freshwater animals using vessel-based active tracking. Vessel-based tracking can require considerable time and effort, which limits both study area size and the number of tagged animals possible for telemetry studies. However, the recently-developed SYNAPS (Synthetic Aperture Positioning System) tracking method allows efficient collection of fine-scale movement information for many tagged animals within large study areas, and therefore enables large surveys to be conducted in a methodical and cost-effective manner. SYNAPS computes position estimates of tagged animals by means of hyperbolic positioning using the geographic location of a mobile hydrophone synchronized with signal detections to create a synthetic hydrophone array. Here we describe the process of tracking with SYNAPS, quantify accuracy and precision of position estimations, and provide guidelines for tracking procedures. SYNAPS position estimates were compared with known positions of fixed tags in both marine (Alaska, USA) and freshwater lake (Ontario, Canada) systems. Accuracy of position estimates ranged from 1.2 m using hull-mounted hydrophones and survey-quality GPS equipment to 23.4 m using towed hydrophones and a navigation-grade GPS receiver. This new tool will facilitate spatially explicit management applications such as aquatic protected area design and essential fish habitat designation by increasing the ability of acoustic telemetry to characterize movement of marine animals at different scales.

Introduction

Understanding the geographic distribution and movement of animals is important for effective management and conservation of ecological systems. However, understanding the spatial ecology of aquatic animals is difficult because tools used for their direct observation (e.g., submarines, remotely operated vehicles, camera sleds, animal-borne imagery, or scuba) are often expensive, labor intensive, and constrained to a very limited field of view. Movement of aquatic animals such as fish and invertebrates can be inferred through surveys that determine population distribution for multiple size classes in different seasons, but to understand the mechanisms that underlie their movement, it is usually necessary to determine the movement of individual animals. Traditional methods of studying individual movement generally rely on recovering tagged animals (Lucas and Baras 2000). However, that method provides location information for only two points in time, release and re-capture, and can only be used on species that are readily re-captured (e.g., through scientific sampling or fisheries).

Technological advances in recent decades have provided researchers with the ability to use electronic tags to study movement of individually tagged animals (Sibert and Nielsen 2001). Acoustic telemetry, which employs tags that actively transmit an acoustic signal that can be received by moored or mobile hydrophones, is frequently used to study the spatial ecology of fish and other aquatic organisms in freshwater and marine systems. Receiver arrays can be deployed as checkpoints or curtains and document the movement of animals as they pass these reception zones at scales ranging from hundreds of meters to kilometers (Thorstad et al. 2000; Welch et al. 2002; Domeier 2005). However, some types of hydrophone arrays with overlapping detection ranges can provide continuous, fine-scale position estimates of tagged animals within a small study area, typically less than a square kilometer (Niezgoda et al. 2002; Cooke et al. 2005; Rigby et al. 2005; Jorgensen et al. 2006; Hanson et al. 2007; Jørgensen et al. 2007). As long as the tagged animal moves inside the confines bounded by the fixed array footprint, continuous two or three-dimensional estimates of movements can be made based on the time it takes the signal from the tagged animal to reach each hydrophone within the reception range. Fixed arrays with the capacity of positioning fish within the scale of several meters work well for animals that are relatively stationary, have home ranges that are contained within the reception range of multiple array hydrophones, or are physically constrained within a small area (e.g., lakes).

Mobile tracking methods can be used in large, open systems where tagged animals can easily move outside the boundaries of a fixed array's reception range. However, the significant effort necessary to obtain position estimates prohibits large study areas and/or large numbers of tagged animals from being monitored. During mobile tracking, hydrophones are towed, affixed to a tracking vessel, or periodically dropped overboard to monitor signals from a single tagged animal. The position of the tagged animal can be estimated using directional bearings to maneuver the tracking vessel to the location that produces the greatest signal power detections (Stone et al. 1992; Holland et al. 1996; Clabough et al. 2007; Ng et al. 2007), by means of triangulating two or more bearing estimates (Collazo and Epperly 1995), or by simply inferring position from vessel location at the time of signal detection (Hoolihan 2005; Taggart et al. 2008). Regardless of the method employed, the time necessary to obtain a position estimate increases in proportion to the desired estimate precision. Moreover, since mobile tracking typically relies heavily on the operator, subjectivity and human fatigue can impact data quality. The need to focus on one animal at a time, the time necessary to achieve accurate position estimates, and the endurance capacity of human operators create constraints that often limit the size and scope of a study.

Here we present a new telemetry method, SYNAPS (Synthetic Aperture Positioning System), which offers an efficient and automated approach to obtaining accurate position estimates for many tagged animals in large study areas using mobile tracking. We describe the SYNAPS telemetry method and present results from controlled field experiments in marine (Alaska, USA) and freshwater lake (Ontario, Canada) systems that demonstrate its performance. In addition, we provide advice for customizing equipment configurations and vessel maneuvers to achieve different research objectives.

Background: SYNAPS Theory and Application

SYNAPS is a postprocessing method for calculating position estimates for an underwater tag using a signal detection record and the GPS track of the vessel moving in the vicinity of the tag. SYNAPS position estimation occurs in two steps (detailed below). First, a synthetic hydrophone array, or aperture, is created using the detection record and GPS locations of the boat. This synthetic array is conceptually analogous to a fixed hydrophone array that can produce very precise position estimates for a tagged animal within its boundaries. Second, hyperbolic positioning, a common method for calculating geographic positions based on signal time difference of arrival at different locations, is utilized to construct an error surface for estimating the position of the tag. Hyperbolic positioning is also used to obtain position solutions for fixed hydrophone arrays (Niezgoda et al. 2002). By incorporating depth information from pressure-sensing tags, a complete three-dimensional position solution for tagged animals can be formed. Metrics for assessing the quality of position estimates are based on the spatial arrangement of the hydrophones in the synthetic array as well as characteristics of the resulting error surface.

The method is based on the MAP telemetry system (Lotek Wireless Inc., Newmarket, Ontario), which uses CDMA signal technology (code division multiple access, also commonly used for cell phone signal transmission). The MAP telemetry system allows increased tracking efficiency through 1) automatic tag detection and decoding by a receiver, 2) reception of transmissions from all tags on the same frequency, and 3) the ability to receive simultaneous transmissions from multiple tags without signal collision detection losses (Niezgoda et al. 2002; Cooke et al. 2005). The MAP telemetry system also provides a constant, precise tag burst rate and a high resolution tag detection timestamp on the receiver, which are both necessary for estimating tag positions using SYNAPS.

Creating the synthetic array

The first step in SYNAPS processing consists of creating a synthetic spatial array of hydrophones from a temporal sequence of hydrophone detections. Individual signal detections are linked to the geographical location of the hydrophone when the signal was detected using the detection timestamp and the vessel GPS track (Figure 1). The time corresponding to the precise burst interval is subtracted from consecutive timestamps in the detection record. After the portion of the time difference that is caused by the tag burst interval is removed from each time stamp, only time-of-arrival (TOA) information, which is a function of the distance between the tag and hydrophone, remains. In

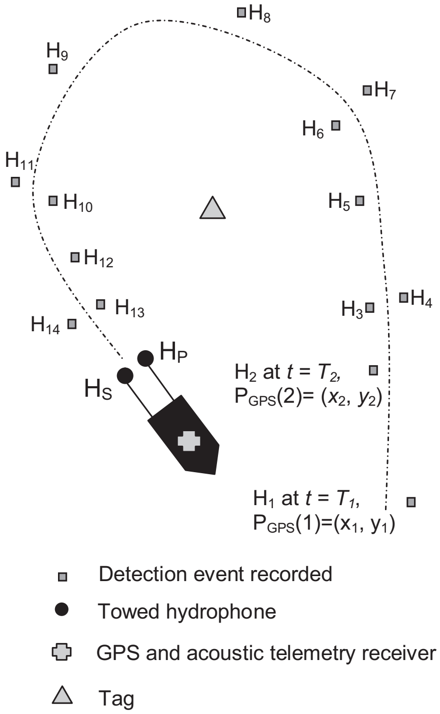

FIGURE 1. Synthetic array consisting of 14 hydrophone detections created by a vessel towing port and starboard hydrophones (HP and HS) in the vicinity of a stationary test tag.

this manner, the temporal collection of detection events by one or two hydrophones is converted into a spatial array of detection events at the same point in time (analogous to many hydrophones), where each location on the synthetic array contains signal TOA information.

Hydrophone positions used to create the synthetic array are derived from the GPS location of the vessel. The SYNAPS program interface provides options for calculating hydrophone positions for both vessel-mounted and towed hydrophone configurations. Vessel-mounted hydrophone positions are calculated using X and Y offsets from the GPS antenna. To estimate the geographical location of towed hydrophones, SYNAPS employs an inertial model that uses the vessel GPS position, the depth of the hydrophone, the horizontal GPS offset, and the distance at which the hydrophone is towed behind the vessel.

Calculating tag position estimates

The second step in SYNAPS processing consists of generating an error surface based on the TOA measurements at each hydrophone on the synthetic array. TOA measurements cannot be directly used to compute fish positions because the tag and receiver do not share a common clock. Instead, we employ the time-difference-of-arrival (TDOA) between pairs of hydrophones in the array in combination with the principle of hyperbolic positioning to compute tagged animal locations (Oppermann et al. 2004). TDOA values, or the net difference in time required for the signal to reach each hydrophone in the pair, are converted to distance values (range-distance-of-arrival, RDOA) using the speed of sound in water. For each pair of hydrophones in the array, a hyperbolic curve describes the possible locations of the tag that would produce observed RDOA values (Figure 2). The common intersection point of hyperbolic curves from all hydrophone pairs in the array corresponds to the estimated position of the tag.

Although there are a number of approaches that can be taken in deriving a solution to the hyperbolic positioning (Oppermann et al. 2004), SYNAPS utilizes a set of equi-spaced grid points representing hypothetical tagged animal locations. For each hypothesized tag location, expected RDOA values are calculated based on distances between the hypothesized location and synthetic array hydrophones. The mean-squared-error (MSE) between observed and expected RDOA values at each SYNAPS grid point is then used to transform the grid into a two-dimensional error surface. The grid point with the minimum MSE value is selected as the estimated tag position. The distance between grid points can be changed during processing in SYNAPS to support specific spatial resolution requirements for different applications.

Quantification of position estimation accuracy and precision

SYNAPS processing also provides two major metrics that describe the quality of the resulting position estimates. First, the dilution-of-precision metric (DOP) that is used to describe the precision of hyperbolic positioning estimates in fixed arrays (Niezgoda et al. 2002) can be applied to position estimates obtained using synthetic arrays from SYNAPS. The DOP is a function of hydrophone array geometry and fundamental time measurement resolution of the receiver (Figure 2). The second metric, the "residual," is based on characteristics of the error surface (e.g., shape and size of the minimum error zone) that reflect the stability of the position estimate.

SYNAPS application

The SYNAPS position estimating process is based on the assumption that an ini-

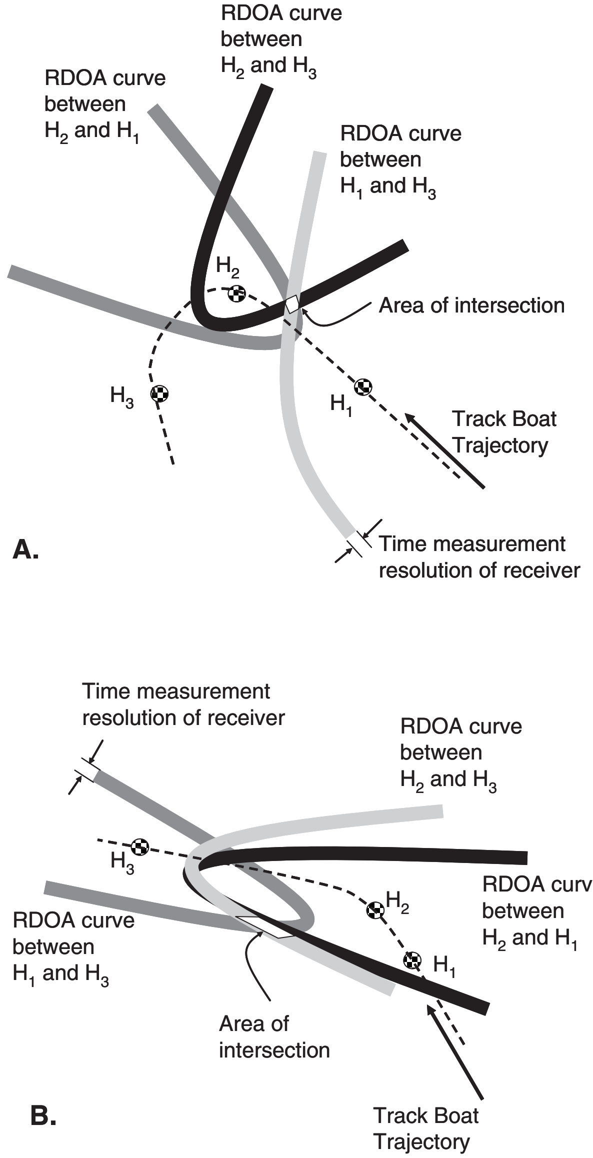

Figure 2. Hyperbolic positioning for a synthetic array with three hydrophones. Intersection of RDOA (range difference of arrival) curves indicates the position of the tag. The width of the RDOA lines is determined by the time resolution capability of the receiver. DOP (dilution of precision) is the size of the area where RDOA curves intersect; Figure **A** has higher precision (smaller intersection area) than Figure **B**.

tial error surface (derived from a minimum number of hydrophones) can evolve to provide a unique and numerically stable position estimate by adding a sufficient number of hydrophones to the synthetic array (Figure 3). SYNAPS uses threshold values for the DOP and the residual to determine whether a stable position estimate has been obtained from a given synthetic array.

In practice, the SYNAPS program lets

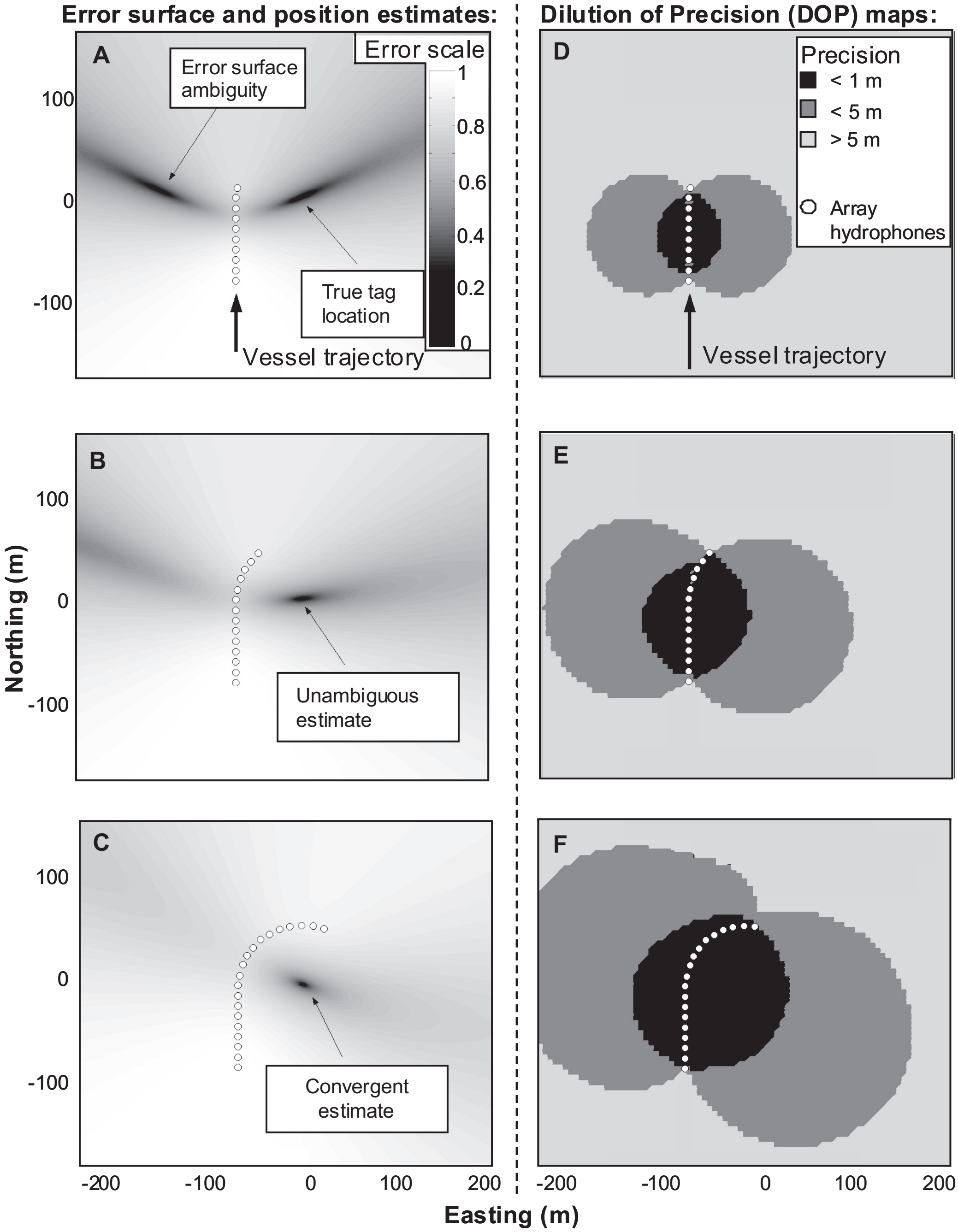

FIGURE 3. Interpolated error surfaces (**A–C**) and DOP (dilution of precision) maps (**D–F**) for a theoretical vessel maneuver around a tag located at (0,0) demonstrate a stable position solution following addition of subsequent hydrophones to a synthetic array. A straight-line trajectory for the first 10 hydrophones in the detection record produces an ambiguous error surface with two mirrored minimum error locations (**A**), despite a precision level of less than 5 m in the vicinity of the tag, as shown by the DOP map (**D**). Changing the vessel trajectory and increasing the number of hydrophones in the synthetic array to 20 eliminates positional ambiguity (**B**) and improves precision performance in the area of the tag (**E**). Optimal array geometry yields a stable, "convergent" solution (**C**) and sub-meter precision in the area around the tag (**F**).

the user specify values for processing parameters, merges a telemetry detection record with a GPS file, calculates positions, and generates a text file containing position estimates. The program begins processing a tag detection record by selecting a user-specified minimum number of hydrophones in an array and using those hydrophones to calculate a position estimate and estimate precision. If neither threshold for position quality is met, the program adds the next hydrophone in the detection record to the synthetic array and re-calculates the position. Processing continues in this manner until either a threshold value (for either metric) is achieved or the user-specified maximum number of hydrophones in an array is reached. The program then selects the next minimum number of hydrophones from the detection record (no hydrophones from the first synthetic array are included in the second) and begins calculating using hydrophones from the second synthetic array in the detection record. This process continues until the end of the detection record is reached.

Repeating SYNAPS processing of a detection record using different input values and averaging the resulting position estimates can result in a more robust position estimate, as altering certain processing parameter values can create synthetic arrays with different numbers and spatial arrangement of hydrophones. The key input parameters that can be varied during processing to provide different combinations of hydrophones in synthetic arrays for a given detection record are: 1) minimum and maximum number of hydrophones in a synthetic array, 2) specification of which hydrophones are to be used in the calculation (port only, starboard only, or both), and 3) maximum allowable time gap in GPS or telemetry record set.

Other input parameters that typically are not changed during processing for the same detection record include SYNAPS grid size, sound speed in water, depth of the tag (obtained from pressure-sensing tags), tag burst interval, hydrophone position offsets from GPS locations, and the inertial coefficient used to estimate the location of towed hydrophones. SYNAPS grid spacing can be adjusted to accommodate different levels of precision in hydrophone positions, estimate precision level requirements versus processing time, and estimated movement rate of the tagged animal.

Methods: Performance Assessment

In order to assess SYNAPS performance, we conducted field tests with stationary test tags using different equipment configurations (i.e., hydrophones and GPS) and study area locations. Fieldwork was conducted in a freshwater lake in Ontario, Canada, a glacial fjord in southeastern Alaska, and a sheltered marine harbor in southeastern Alaska.

Field testing methods

Warner Lake, Ontario.—In August 2007 we conducted a controlled experiment in Warner Lake, a freshwater lake in eastern Ontario contained within the boundaries of the Queen's University Biological Station (QUBS; 44°31'N, 76°22'W). The primary objective of the Warner Lake test was to assess the upper limits of SYNAPS accuracy and precision performance using differential GPS and hull mounted hydrophones. The experiment was conducted using a 4 m aluminum hulled boat equipped with a DGPS unit (Trimble TSC; Trimble, Sunnyvale, California) with 0.5 m precision, a two-port telemetry receiver (MAP600 RT, Lotek Wireless Inc., Newmarket, Ontario) and 2 hydrophones mounted in the bow. Rigid PVC piping was used to offset the hydrophones at a fixed distance from the gunwales. Vertical sections of PVC piping were also used to maintain the hydrophones at a constant depth of 1 m below the keel of the boat. A coded acoustic tag (Lotek MAP11_4, 5 s burst interval) was moored in 2 m of water and a survey of the location made using the DGPS with its antenna placed directly over the moored location (UTM 390264 m ± 0.5 m, 4931530 m ± 0.5 m). GPS records were collected with the tracking boat moving at an average speed of 1 m per second (m/s) along a circular trajectory around the moored tag. Overall, approximately 180 detection records were collected per hydrophone over a 15-min detection period. Telemetry and GPS data were postprocessed to produce a set of convergent position solutions using a 1 m SYNAPS grid setting. Accuracy was determined by calculating differences between the actual and estimated locations on the x-axis, the y-axis, and total (net) distance.

Glacier Bay, Alaska.—From December 2005 through May 2006, test tags were deployed as part of a telemetry study in Glacier Bay, Alaska (58°50'N, 136°06'W) to characterize seasonal movement of red king crabs and adult female Tanner crabs (S. James Taggart, Julie K. Nielsen, and Thomas C. Shirley, Texas A&M University Harte Research Institute, unpublished data). This study required eight tracking trips throughout the winter and spring of 2006. Prior to conducting tracking during each trip, a test tag was deployed in the study area to ensure that the telemetry equipment was functioning properly. We compared test tag positions estimated using SYNAPS to actual test tag locations to measure the accuracy and precision of SYNAPS using towed hydrophones and a 3 m resolution GPS.

Test tags (Lotek MAP16_50, 5 s burst interval) were attached to buoy line 2 m above an anchor and deployed from the vessel. The vessel position when the anchor was dropped was recorded with a WAAS-enabled Garmin GPS 76 (Garmin International Inc., Olathe, Kansas). Slight error in the true locations of test tags occurred as a function of the 3 m precision of the GPS used to record vessel location at test tag deployment combined with a possible slight drift of the test tag anchor in tidal currents before it reached the bottom (test tag depths ranged from 78 to 147 m).

Tracking was conducted using a 17 m research vessel, the *R/V Alaskan Gyre*. Two omni-directional hydrophones (LHP-1, Lotek Wireless, Inc., Newmarket, Ontario), one on each side of the vessel, were towed at an average depth of 20 m using depressor v-fins; hydrophones were located approximately 40 m aft of the vessel while under tow at 2 m/s. A WAAS-enabled Garmin 76 GPS with 3 m resolution was used to record vessel position every second. Telemetry data were recorded using a two-port telemetry receiver (Lotek MAP600 RT).

To account for different vessel trajectories, and thus large variation in the spatial arrangements of hydrophones in synthetic arrays, between test tag maneuvers on different tracking trips, two different synthetic array size ranges were used in SYNAPS processing. For each tag, first a minimum of 15 and a maximum of 20 hydrophones were used, followed by a minimum of 20 and a maximum of 30 hydrophones. Data were processed in SYNAPS using a grid size of 10 m, which was chosen as a conservative estimate of the error that results from using vessel GPS positions with 3 m resolution to estimate towed hydrophone positions using the inertial model. Solutions were calculated using arrays comprised of 1) both hydrophones, 2) port only, and 3) starboard only. Accuracy was determined by calculating differences between the actual and estimated locations on the *x*-axis, the *y*-axis, and total (net) distance for position estimates resulting from all different processing parameter values

Taku Harbor, Alaska.—Because obtaining a precise independently surveyed location for the test tags deployed in Glacier Bay was difficult, additional research was necessary to provide a controlled assessment of SYNAPS accuracy and precision in a marine environment. Therefore, in June 2007 we conducted additional field research to determine the upper limits of SYNAPS performance using a WAAS-enabled Garmin 76 GPS with 3 m resolution. Research was conducted in Taku Harbor (58°04'N, 134°01'W), located 35 km southeast of Juneau, Alaska.

During these field experiments we strove to reduce possible error sources that could hinder unbiased measurement of accuracy and precision. We chose a sheltered study site that would provide the ability to moor test tags at a precisely known position and constant depth. We reduced error in hydrophone positioning by deploying a hydrophone over the side of the vessel at a shallow depth instead of towing it behind the vessel at greater depths, as described above for the Glacier Bay test tag experiments. Finally, we eliminated adverse effects of poor spatial arrangement of hydrophones in the virtual arrays by maneuvering the vessel in a circular trajectory around the test tags.

Three test tags (MAP16_332, 5 s burst interval) were deployed at a depth of 8 m from the center of a 45-m floating dock that was secured to pilings. The dock was not connected to shore, so it could be circled by the tracking vessel. Positions of the test tags were obtained by averaging position estimates from a WAAS-enabled Garmin 76 for 10 min.

Tracking was conducted using the 13.4 m *S/V Ijsselmeer*. An omni-directional hydrophone was deployed on the port side of the tracking vessel at a depth of 2 m using a 13.6 kg hydrodynamic sounding weight. A WAAS-enabled GPS with 3 m resolution was used to record vessel position every second. The GPS antenna was attached to the cleat directly above the hydrophone suspension point. At tracking speed (1.3 m/s), the hydrophone was 0.5–0.75 m aft of the GPS antenna and was very stable in the water column. Telemetry data were recorded using a two-port telemetry receiver (MAP600 RT, Lotek Wireless Inc. Newmarket, Ontario). The vessel circled the tags in a 100 m radius. The average depth in the study area was 30 m.

Detection records for the three test tags contained 1,363, 1,212, and 1,534 signal detections. Telemetry and GPS data were post-processed to produce a set of convergent position solutions using a minimum of 20 and a maximum of 30 hydrophones for 1 m, 5 m, and 10 m SYNAPS grids.

Results: Performance Assessment

Field testing

Warner Lake, Ontario.—Results from field verification experiments in Warner Lake indicate that SYNAPS is capable of providing sub-meter position estimates, equivalent to those obtained using a differential GPS, if hydrophone positions are known precisely. The mean error in SYNAPS position estimates was 1.0 m (Table 1; Figure 4). The mean precision of the estimates (DOP ± 0.8 m) was similar to the precision of the DGPS used to obtain the control location of the test tag (Table 1).

The DOP values that qualify position solution precision for these estimates approach the maximum time resolution of the receiver (i.e., 1/4800 s, or approximately 0.6 m when scaled by a sound speed of 1,480 m/s). This level of precision is a direct result of using a circular boat trajectory to create an optimal arrangement of hydrophones in synthetic array geometries; it demonstrates the importance of boat maneuvers for SYNAPS performance.

Glacier Bay, Alaska.—Using towed hydrophones and a 3 m precision GPS, we were

Table 1. Accuracy and precision of SYNAPS test tag comparisons from Warner Lake, Ontario for A) hydrophone 1 only, B) hydrophone 2 only, and C) both hydrophones (see Figure 4).

Synthetic Array	Time (s)	X error (m)	Y error (m)	Total error (m)	DOP* (±m)	Number Hydrophones
A) Hydrophone 1 only						
1	135	2	–1	2.2	1.5	20
2	165	0	0	0.0	0.6	20
3	146	1	1	1.4	0.7	20
4	152	1	1	1.4	0.6	20
5	106	1	1	1.4	1.0	20
B) Hydrophone 2 only						
1	150	0	–1	1.0	0.6	20
2	175	0	0	0.0	0.6	20
3	126	2	0	2.0	0.6	20
4	186	1	0	1.0	0.6	20
5	166	1	–1	1.4	1.0	20
C) Hydrophones 1 and 2						
1	125	1	–2	2.2	1.3	32
2	90	1	0	1.0	0.6	20
3	80	0	0	0.0	0.7	21
4	80	1	1	1.4	0.7	26
5	80	–1	–1	1.4	0.9	29
Mean	130.8	0.7	–0.1	1.2		
(± SE)	(9.4)	(0.2)	(0.2)	(0.2)	0.8	21.9

*Dilution of precision

able to achieve better than 20 m accuracy for moored test tag position estimations. Test tags deployed in different locations throughout the study area and at different times throughout the research project had similar error in position estimation. Mean distance between estimated and actual positions for each test tag ranged from 10.4 to 23.4 m and averaged 16.7 m (Table 2).

Vessel maneuvers around the test tag deployed on March 3, 2006 (Figure 5), at a depth of 85 m, provided the lowest total error of all test tags (Table 2). This is an example of precision produced with optimal arrangement of hydrophones resulting from a circular tracking vessel trajectory. Position estimates differed from known locations by an average of –6.2 m on the x-axis and –2.4 m on the y-axis (Table 3).

Taku Harbor, Alaska.—Results indicate that the upper limits of SYNAPS accuracy and precision are roughly equivalent to the resolution of the GPS used to obtain positions of hydrophones. Using a GPS with 3 m precision to determine hydrophone locations, mean distance between estimated and actual positions for each test tag ranged from 3.9 to 4.4 m using a 1 m SYNAPS grid (Table 4).

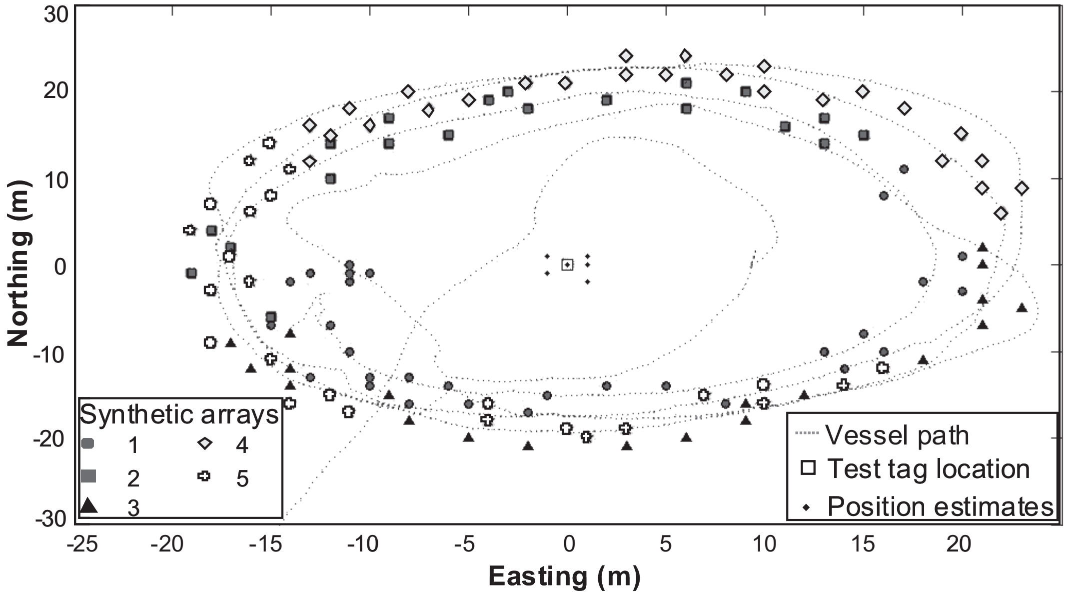

FIGURE 4. Synthetic arrays and estimated test tag positions from field testing at Warner Lake, Ontario. The five synthetic arrays were created using both hydrophones 1 and 2 (see Table 1C for accuracy and precision of estimates resulting from these arrays).

TABLE 2. Accuracy and precision of SYNAPS test tag comparisons in Glacier Bay, Alaska, which were deployed during six tracking trips in 2006.

Test tag Date	Depth (m)	Avg. X error (m) ± (SE)	Avg. Y error (m) ± (SE)	Avg. total error (m) ± (SE)	Avg. DOP* (±m)	Avg. no. hydro-phones
9 February	115	–8.0 (0)	2.0 (10.0)	16.2 (1.8)	11.53	21.7
3 March	85	–6.2 (2.5)	–2.4 (1.8)	10.4 (1.8)	11.58	22.1
27 March	135	9.7 (2.2)	–10.5 (1.8)	18.0 (1.6)	11.28	17.6
11 April	138	12.3 (4.7)	–4.6 (3.8)	23.4 (3.2)	11.84	20.7
27 April	147	5.6 (6.6)	3.9 (3.5)	19.7 (2.7)	11.14	21.6
11 May	78	–0.4 (2.4)	5.7 (3.0)	12.4 (2.4)	10.10	20.8

* Dilution of precision

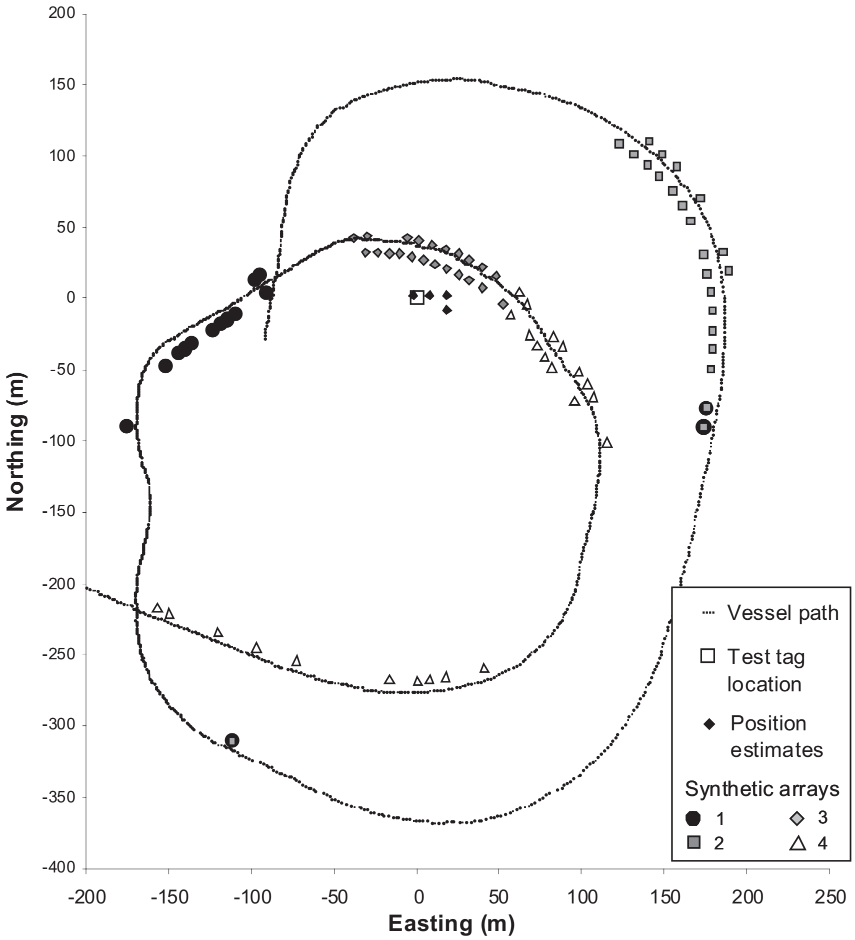

Figure 5. Synthetic arrays and estimated positions for a Glacier Bay test tag set at 85 m depth on 3 March 2006, using two towed hydrophones (see Table 3C for accuracy and precision of estimates resulting from these arrays).

Discussion

SYNAPS is a flexible new telemetry technique that can be used to study animal movement at different scales. It fills a gap in methods available for studying movement at scales that fall between the fine-scale, continuous positioning provided by fixed arrays (Cooke et al. 2005) and the large-scale, presence/absence positioning provided by acoustic curtains (Welch et al. 2002). It is particularly valuable for studying the movement of mobile animals in unconstrained areas, such as large lakes or marine systems, where tagged animals could quickly move beyond the range of fixed arrays.

SYNAPS can be performed with a variety of equipment configurations that allow individual researchers to address trade-offs between scale and precision and respond to challenges from specific study area conditions. Using SYNAPS, locations of tagged animals can be determined using towed hydrophones that can search large study areas efficiently with an accuracy of 20 m or better, whereas sub-meter accuracy can be obtained using slower-moving vessels with hull-mounted hydrophones and a differential

Table 3. Comparison of SYNAPS estimates to actual tag location (actual–estimated) for a test tag deployed 3 March 2006 at a depth of 85 m in Glacier Bay (see Figure 5 for estimates in part C). A 10 m SYNAPS grid was used in the estimate calculations.

Synthetic Array	Time (s)	X error (m)	Y error (m)	Total error (m)	DOP* (±m)	Number hydrophones
A) Hydrophone 1 only						
1	200	–3	–10	10.4	11.23	17
2	165	–3	0	3.0	13.19	25
3	160	7	–10	12.2	12.89	25
4	295	–13	–10	16.4	9.27	20
B) Hydrophone 2 only						
5	215	1	2	2.2	11.23	20
6	155	–9	2	9.2	11.08	30
C) Hydrophones 1 and 2						
7	556	–8	8	11.3	10.94	15
8	305	–18	–2	18.1	11.97	23
9	65	2	–2	2.8	12.67	22
10	275	–18	–2	18.1	11.36	24
Mean	239.1	–6.2	–2.4	10.4	11.58	22.1
(±SE)		(2.5)	(1.8)	(1.8)		

*Dilution of precision

GPS. For individual research plans, choice of hydrophone configuration, GPS resolution, number of hydrophones (one or two), tracking protocols, and SYNAPS processing parameters can be decided based on 1) precision required to achieve research goals, 2) study area characteristics (size, depth, wave height, water column stratification), 3) tagged animal movement rate, and 4) tracking vessel size.

Equipment configuration options

GPS.—Because hydrophone positions are always derived from the vessel GPS, the quality of the GPS instrument used can greatly affect estimate precision. For projects requiring the highest precision (e.g., underwater surveying or fine-scale behavioral studies), a differential GPS with submeter precision should be used. Otherwise, a handheld WAAS-enabled GPS can provide 5–20 m precision, depending on hydrophone configuration, for stationary targets or slow-moving animals.

Hydrophone configuration.—Hydrophone configuration options consist of 1) hull-mounted, 2) deployed over the gunwale of the vessel, and 3) towed behind the vessel on v-fins. Although rigid hull attachment removes a large portion of the hydrophone position uncertainty compared to towed hydrophones, there are significant drawbacks for using this configuration. Unless the hydrophone is mounted through the hull, tow speeds can be severely limited as a result of structural vibration in the mounting apparatus (authors, personal observation). Although outfitting a vessel with through-hull hydro-

Table 4. Accuracy and precision of SYNAPS estimates from test tags at in Taku Harbor, Alaska, calculated using SYNAPS grid sizes of A) 10 m, B) 5 m, and C) 1 m.

Tag number	Avg. X error (m) ±(SE)	Avg. Y error (m) ±(SE)	Avg. total error (m) ±(SE)	Avg. DOP* (±m)	Avg. no. hydrophones
A) 10 m grid					
1	1.6 (0.7)	–2.4 (0.6)	7.1 (0.4)	7.3	20.7
2	0.4 (0.7)	–1.6 (0.9)	6.1 (0.7)	7.9	20.5
3	1.2 (0.8)	–0.9 (0.5)	5.8 (0.7)	7.8	20.3
B) 5 m grid					
1	0.3 (0.8)	–1.5 (0.6)	5.3 (0.8)	3.8	20.2
2	0.7 (0.5)	–1.4 (0.5)	5.0 (0.4)	4.8	21.2
3	0.8 (0.4)	–2.1 (0.4)	4.5 (0.2)	3.8	20.7
C) 1 m grid					
1	0.2 (0.4)	–1.7 (0.4)	3.9 (0.2)	1.4	22.5
2	0.5 (0.5)	–2.1 (0.5)	4.4 (0.3)	2.9	22.9
3	1.7 (0.3)	–3.0 (0.3)	4.3 (0.2)	1.3	22.5

*Dilution of precision

phones is viable, high costs and lack of equipment portability make this option restrictive. Simply suspending the hydrophones over the side of the vessel on a weighted line will work for small vessels that have only 1–2 m between the water and the gunwale, however hydrophones become vulnerable to contact with the vessel in swells or stormy weather. Towed hydrophones allow higher tracking vessel speeds than rigid, hull-mounted configurations. Towed hydrophones may provide better signal reception in deep waters (>100 m) or where the water column is stratified by positioning the hydrophones at a greater depth in the water column. The flexible SYNAPS program interface allows researchers to deploy hydrophone configurations that will meet the needs of specific applications.

Vessel maneuvers.—The spatial arrangement of hydrophones in the synthetic array greatly affects the accuracy and precision of position estimates, and tracking protocols that balance required precision and scale should be designed accordingly. If greater precision is required, the tracking vessel should attempt to achieve a semicircle trajectory around the tagged animal. If precision is not required, straight-line transects that cover large areas in a short amount of time may be conducted. Setting a zigzag transect course through the study area is an example of a tracking protocol that provides greater precision with transect searches of large study areas.

Number of hydrophones.—Although SYNAPS can be employed using only one hydrophone, using two hydrophones can increase its efficiency. Using the MapRT receiver (Lotek Wireless Inc) it is possible to obtain bearings to tagged animals in real-time if the vessel receives a signal on both hydrophones simultaneously (Clabough et al. 2007). Real-time navigation in the vicinity of a tagged animal allows the operator to ensure that an optimal (or acceptable) spatial arrangement of hydrophones, (e.g., a circular trajectory around the tagged animal) is achieved.

Potential applications of the SYNAPS method

SYNAPS is useful for studying the movement of sedentary or relatively slow-moving animals in large study areas. For example, SYNAPS was used to obtain position estimates for 30 female and male red king crabs and 50 adult female Tanner crabs in a 100 km^2 study area in Glacier Bay, Alaska over a six month telemetry study (S. James Taggart, Julie K. Nielsen, and Thomas C. Shirley, Texas A&M University Harte Research Institute, unpublished data).

SYNAPS would also be an appropriate tool for animals that are capable of faster swim speeds, but have sedentary periods (e.g., Pacific halibut *Hippoglossus stenolepis*), or for animals that exhibit defined home ranges (e.g., demersal rockfish such as certain *Sebastes* sp. or lingcod *Ophiodon elongatus*). Although SYNAPS has yet to be field-validated for faster-moving animals such as whales or salmon, altering the SYNAPS grid size, tag burst interval, vessel speed, or hydrophone separation may allow reasonable solution precision for more mobile animals.

Summary

SYNAPS constitutes an advance in telemetry technology that will allow researchers to answer a wider range of ecological questions for aquatic animals. Although mobile tracking methods have existed for 30 years (Arnold and Dewar 2001), SYNAPS is capable of yielding more precise position estimates with much less effort than is expended for other methods. In addition, if tagged animals are aggregated, one vessel trajectory can provide precise positions for many tagged animals. This positioning efficiency, when combined with the ability of the MAP telemetry system to detect many tagged animals at the same frequency and instant in time, provides researchers with a telemetry tool that allows fine-scale positioning of many animals over much larger study areas.

The availability of movement information for aquatic animals is becoming increasingly important for management and conservation. For example, designing and assessing effectiveness of aquatic protected areas requires quantifying movement rates (e.g., spillover rates or ontogenetic movement from nursery to adult areas). In addition, it is helpful to be able to understand mechanisms that underlie such movement (Cooke et al. 2004). Because the ability to obtain precise position estimates in an efficient manner is an important part of achieving a mechanistic understanding of animal distribution and movement (Cooke 2008), SYNAPS can be expected to provide significant contributions to the management and conservation of aquatic species.

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