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Short Note

Location Tag Adapted from Fitness Tracker Watch, Tested on Humpback Whales (*Megaptera novaeangliae*)

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Since 2004, we have conducted underwater observation research on humpback whales (*Megaptera novaeangliae*) on their North Pacific wintering grounds (Zoidis et al., 2008, 2014; Zoidis & Lomac-MacNair, 2017). To complement our long-term observational work, we investigated tagging as an additional method to examine intraspecific behavior and acoustic calls of individual whales underwater. Understanding context-specific behaviors, movements, or acoustic calls in marine mammals is enhanced with the use of bio-logging tags (Stimpert et al., 2015). Bio-logging tags allow for detailed data collection on marine mammal underwater activities, physiology, or behaviors, including location, movements, dive activity, calls, and swimming speeds. Tagging is typically not financially viable for small research entities, limiting the types and amounts of data that can be collected. We sought to remedy this with a novel approach to tagging—assembling custom tags utilizing an innovative method we designed using an inexpensive fitness tracker watch and then testing *in situ* to validate the tags' success. Our goals were (1) to investigate various low-cost tag configurations using a custom-designed and built datalogger prototype GPS tag; and (2) to assess if our prototype tags could add new behavioral data to help us build upon our previous decades of research on Hawaiian humpback whales.

Prototype Tag Design and Development

The Garmin Forerunner10 (GF10) fitness watch (Garmin Ltd., Olathe, KS, USA), commercially released in 2012, was selected as the commercial-off-the-shelf (COTS) watch for the prototype tag. The GF10, designed and marketed by Garmin for use by triathlon athletes, consisted of a waterproof wristwatch with an integrated GPS datalogger that recorded location, time, and movements (e.g., travel direction, speed). At the time of this study, the GF10 was one of the first waterproof GPS-capable fitness tracker watches commercially available for a retail price of $100 USD or less. This device was chosen because it was small, inexpensive, and could record precise locations with brief (3.5 s average) surface exposure. The GF10 is still available from third party vendors ranging from $35 to $100 USD, though fitness watches have advanced since this study. Using the GF10, we developed, field tested, and validated three prototype animal tag configurations:

1. Mini-GPS (Figure 1A) – Consisted of the GF10 attached using a resin filler to the following: a custom-designed flotation device (float; e.g., a cork-based fishing lure buoy), a saddle silicon suction cup (Cetacean Research Technology, Seattle, WA, USA), and a small marine VHF transmitter (Model A2414; Advanced Telemetry Systems, Isanti, MN, USA) used to track the humpback whale and locate the tag once it detached. Only used during field efforts in Hawaii.

2. GPS–B-Probe (Figure 1B) – Consisted of the GF10 attached externally to a syntactic-foam float (Figure 1B) with archival acoustic datalogger tag (Bioacoustic Probe™ [B-probe], Model B002B; Greeneridge Sciences, Inc., Santa Barbara, CA, USA). Used during field efforts in Hawaii and Mexico.

3. GPS–Acousonde (Figure 1B) – Consisted of the GF10 attached externally to a syntactic-foam float (Figure 1B) with an archival acoustic datalogger tag (Acousonde™, Model 3A, Greeneridge Sciences, Inc.). Only used during field efforts in Mexico.

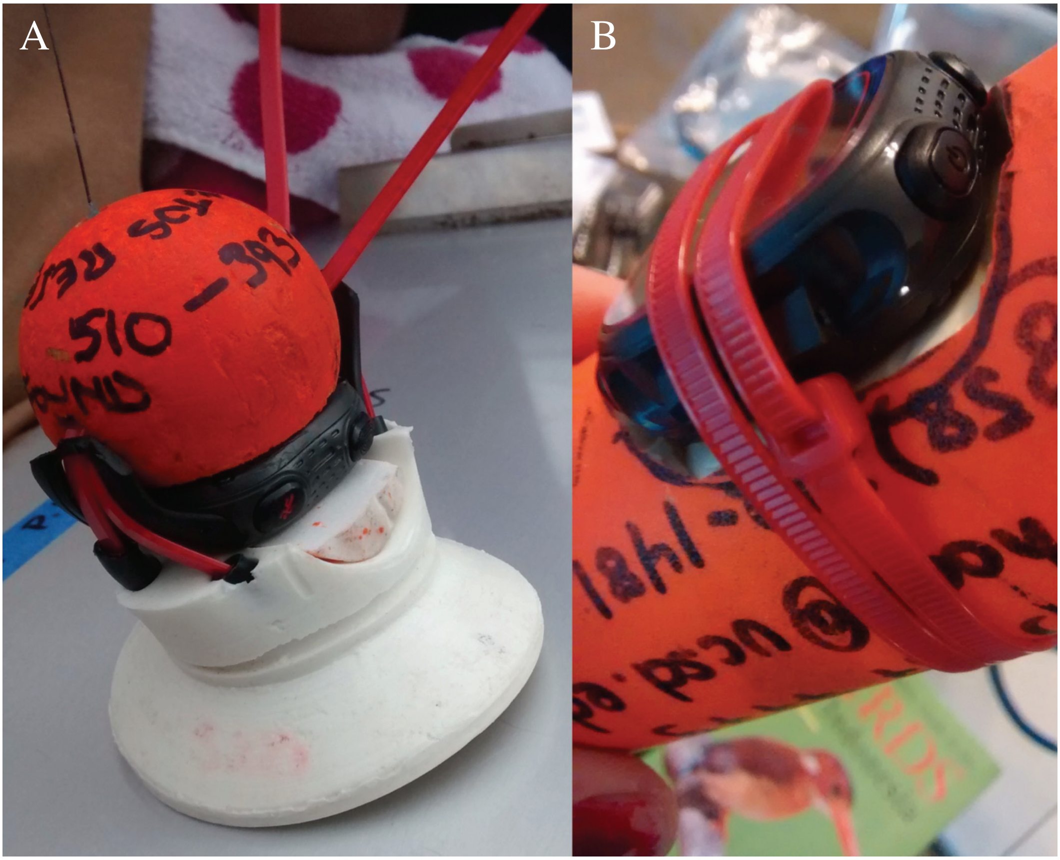

Figure 1. (A) Mini-GPS tag configuration with the GF10 fitness watch "sandwiched" between a small float and the suction cup, and (B) close-up image of GF10 attached to the GPS–B-probe or GPS–Acousonde tag float before being wrapped in electrical tape. (Photos courtesy of Kerri D. Seger)

Our protocol was to deploy the larger GPS–B-Probe and GPS–Acousounde tags on mothers and escorts when the opportunity presented itself. The mini-GPS tag was also attempted on mothers when we were not successful in attaching the GPS–B-Probe or GPS–Acousounde tags.

For the GPS–B-Probe and GPS–Acousounde tags configuration, the GF10 was attached externally to the syntactic foam float that was part of a B-probe or Acousonde tag assembly. A rotary tool (i.e., a dremel) was used to excavate a small cavity in the float for the GF10 to sit in with minimal protrusion. Finally, the GF10 was fastened to the float using Zip-ties™ (Figure 1B), with electrical tape wrapped over the Zip-ties™ and float to reduce drag and secure everything. In all configurations, the watch control buttons remained accessible to allow manual configuration. Two different VHF transmitters were used with the following specifications: (1) pulse rate of 38 pulses/min (ppm), pulse width of 15 ms, weight of 0.3 g, and center frequency of 164.023 mHz; and (2) pulse rate of 57 ppm, pulse width of 20 ms, weight of 0.3 g, and center frequency of 164.036 mHz. The mini-GPS tag was constructed by sandwiching the GF10 between the float and suction cup (Figure 1A).

The float consisted of a small, spherical fishing float cut approximately in half and reinforced with fiberglass and polyester resin. Holes were drilled through the hemisphere center to allow Zip-ties™ to pass through to secure all pieces together. A small cavity was excavated on the float's top to hold the small seabird VHF transmitter, with a small hole drilled through the float's middle to allow the antenna to protrude. A small polyester resin "spacer" was made to fill the gap between the suction cup "saddle" and the float so that everything fit tightly together once the whole package was secured with Zip-ties™. Finally, the entire tag assembly was wrapped tightly with Scotch® Super 33+ electrical tape (3M, St. Paul, MN, USA) with a transmitter inserted into the small bore at the cork float's top and glued into place with surfboard epoxy. Once attached, the VHF radio-transmitter was used to pick up the tags' signals. A custom PVC attachment was used for the GPS–B-Probe and GPS–Acousounde tags that gripped the cylindrical hardware of the tag, and a second custom PVC attachment was used for the mini-GPS that would cup the spherical flotation. Upon release from the humpback whale, many tag materials could be re-used for additional applications.

Simulations and Validation

To test and evaluate the accuracy and precision of the GF10 (in all three configurations), three simulation tests were conducted: (1) a stationary test (Test #1) through which the accuracy of the GF10 was determined at a fixed location near the coast; (2) Test #2, a "type-1" mobile test, was conducted on a moving research vessel through which precision of the GF10 was compared to another GF10 located a few meters away; and (3) Test #3, a "type-2" mobile test, was performed with both GF10 tags on a moving research vessel along with a boat-based GPS navigation system used for ground-truth comparison. These type-1 and type-2 mobile tests were performed during attempts to tag humpback whales to simulate whale movements and speed. For Test #1, the GF10 was turned on and positioned near an outdoor swimming pool located near the coast (to simulate an open ocean environment). A handheld GPS (Garmin GPSMAP 64 s) was used as the baseline to compare the GF10's location fixes. Both GPS devices were kept stationary at the site for a few hours to collect data. After simulation, location data from the GF10 and the handheld GPS were downloaded and imported as latitude and longitude values into a spreadsheet. Distances between each location fix recorded from the GF10 and the handheld GPS location fix were calculated using the Haversine function in a custom-written *MATLAB* script.

For Test #2, the first GF10 was attached to the person's wrist conducting tagging operations, and the second GF10 was located on the tag attached to the tagging pole's end. The pole's maximum length when fully extended was 3 m. Therefore, the range of distances possible between the two GF10 tags was between 0 to 3 m. After tests were conducted, data from both tags were downloaded, and the Haversine distance between concurrent data points (i.e., location estimates that occurred within 5 s of each other) were calculated and plotted. Results of this test were considered a measure of location precision with the assumption that both tags were moving at approximately the same speed and direction as a traveling whale.

For Test #3, location fixes for the GF10 positioned at the tagging pole's end were compared to those from a GlobalSat BU-353S-4 GPS used for navigation on the research boat. The antenna for the latter device was mounted on the research boat just below the front cabin window, about 3 m aft of the bow. The GlobalSat GPS was interfaced with a laptop computer running *Mysticetus*™ that was used to automatically save GPS location fixes to a database. The range of distances possible between these two GPS devices was 0 to 6 m. The location data from the GF10 and the boat's GPS were downloaded, saved to a spreadsheet, and the Haversine distances between all concurrent times (within 5 s of each other) were calculated and plotted. This test was considered a measure of accuracy, with the GlobalSat GPS considered the standard or ground-truth.

Like all GPS devices, the GF10 tag can obtain a location fix only when above the water's surface. Once a GPS tag is deployed on a humpback whale, the likelihood of how often it will successfully connect with a satellite is dependent on the duration the tag is above water and, thus, exposed to GPS satellites. This, in turn, is dependent upon how long the animal is at the surface (i.e., surface interval). To evaluate the likelihood of a GPS fix, we relied on data collected with the VHF transmitter from the tag as an estimate of time the tag was exposed to air while attached to the animal. The VHF transmitter's ping rate was two pings/s. The number of pings heard on the VHF receiver were counted whenever the whale was clearly visible at the surface. The four tagging events used for this dataset were all conducted on adult whales, with visual observations of their behaviors recorded, including surface interval times. Surface interval was estimated by dividing the total number of pings counted by two. Next, visual observation data were compared to GF10 data time stamps to determine if the GF10 recorded a location fix. If a location was not recorded, it was considered a failed connection ("miss"). If a fix was recorded, it was considered a successful connection ("hit"). Finally, surface interval times were plotted as cumulative distribution functions (CDFs) to quantitatively assess the minimum time above water required for a GF10 to obtain a GPS fix.

Additional analyses were conducted to determine maximum water depths that the GF10 could withstand. Manufacturer specifications stated the GF-10 was rated to 50 m depth. Depths the tags were exposed to while attached to a humpback whale were estimated using data collected from both GPS–B-probe and GPS–Acousonde tags with the GF10 attached. The datalogger on these tags record pressure in units of decibars (dbars) at a sample rate of one sample/s. These data were downloaded from the GPS–B-Probe or GPS–Acousonde tags using proprietary software (Greeneridge Sciences, Inc.) included with these tags. Pressure data were plotted as a time series (time vs dbars) using *MATLAB* to create graphs. Graphs were reviewed visually to determine greatest pressure value(s) (i.e., deepest depth).

Once a tag was recovered, location data from the GF10 were downloaded. Each data file was saved in .FIT format (a proprietary Garmin file type). The .FIT files were uploaded using an online mapping application called Strava (freeware available at www.strava.com) and were subsequently exported as .GPX (GPS exchange format) files. The exported .GPX files were uploaded to *ArcMap*, Version 10.3 (Environmental Systems Research Institute [ESRI], 2011), and were plotted to visually inspect tracks. Data were exported into *Excel* to extract latitudes, longitudes, headings, speeds, and timestamps of all GPS fixes in a .GPX format as column vectors. A custom-written *MATLAB* script was used to load these vectors, calculate the Haversine distance between concurrent coordinates, and plot data histograms and CDFs. Binomial regression analyses and a Generalized Linear Model (GLM) were also used to assess reliability of the GF10's data collection.

Locations and Approaches

In the Hawaiian Islands, we used the Mini-GPS and GPS–B-Probe (Figure 2). Tagging efforts took place 16 to 23 February 2015 in the ‘Au‘au Channel between Lanai and Maui from a small 7.9-m rigid, twin-hull catamaran motorboat. Underwater focal bouts and diver methods were part of our standard protocols (described in Zoidis et al., 2008, 2014) and provided additional behavioral data. In Mexico, we used the GPS–B-Probe and GPS–Acousonde tags. Tagging efforts took place in waters off San José del Cabo, Baja California Sur, Mexico, in February-March 2015, using a 6.1-m "panga" style open fishing boat. The data from Mexico were limited to data from tagging (i.e., no underwater visual efforts occurred). Efforts in both locations included detailed observation notes during all tagging attempts both before and after to assess baseline behavior of each group prior to and after tagging.

Tagging procedures were like those described by Stimpert et al. (2012) with some minor modifications. One of our goals was to test approach techniques and responses and compare those to Stimpert et al. (2012) for both active and resting groups. In resting or mother–calf (MC) groups, whales were approached at slow speed (< 5 kts) with broad, oblique approaches toward the animals. In faster travelling or active competitive groups, we used parallel approaches at higher

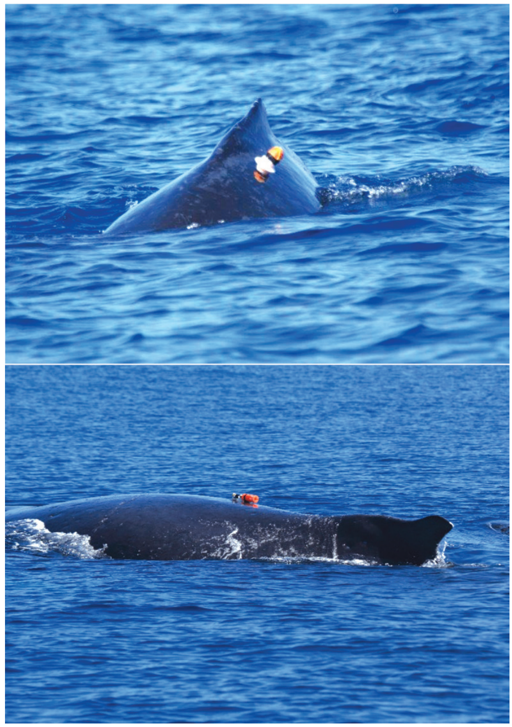

Figure 2. Mini-GPS (top) and GPS–B-Probe tags (bottom) attached to a humpback whale (*Megaptera novaeangliae*) off Hawaii (Photos courtesy of Andy Day; taken under NOAA Permit #20951)

speeds to match group speed (up to 12 kts) and closed the gap to tag using a direct course to a surfacing adult at their closest point of approach. We stationed the tagging researcher at the bow with an attachment pole (Figure 3). Aim was made as high on the whale's dorsum as possible (Goodyear, 1989; Lerczak et al., 2000), which allowed for the greatest exposure above water for the GPS tag to make contact with a satellite to ensure a data point. Video and photographs were taken during each approach and tagging attempt to later assess the technique used for approaches to animals exhibiting various behaviors.

To deploy each tag, a 3-m telescoping aluminum painter's pole with a custom-designed "tag holder" attached to the pole's end was used to secure the tag to the pole until it could be attached to a humpback whale. Once a whale was in range of the tagging pole, the tagger deployed the pole over the boat's side. Once the suction cup made contact with the whale, the tagger pulled 180° opposite to the tagging direction (90° in toward animal and 90° in the opposite direction of tagging) to release the tag from the PVC holder. Once the tag was attached to a whale, research personnel began tracking

Figure 3. Tag pole with Thomas F. Norris harnessed at the bow preparing to attach a GPS–B-Probe tag on a humpback whale in Hawaii (Photo courtesy of Andy Day; taken under NOAA Permit #20951)

behaviors (e.g., surface time, changes in behavior, etc., using the software program *Mysticetus*™). We also assessed if the group would provide an opportunity for coincident subsurface diver data collection. The receiving VHF antenna was set up, which allowed detection of the tag's VHF signal to facilitate whale tracking. The number of VHF beeps was recorded. Once VHF pings were consistently heard for longer than whales typically log at the surface, it was considered that the tag likely had fallen off the whale. The team then used the bearing of the VHF signal to search for and retrieve the tag. While in the field, the GF10 could be removed from the tag body, the data could be downloaded onto a computer, and the GF10 could then be re-inserted into the tag body (if battery life permitted) to use on another whale.

Three tag configurations were developed, field tested, and validated successfully via 19 total deployments on humpback whales during two ongoing research projects off Hawaii and Mexico (Table 1). Of the 19 deployments, six occurred off Hawaii and 13 off Mexico. Data from both study locations were utilized for testing tags and conducting simulations and validation tests. Data from Hawaii were further utilized for behaviors or social call information. Of the 19 successful deployments (i.e., tag was attached to whale), 63% (n = 12) resulted in GPS fixes (i.e., defined as a successful tagging event with data collected).

Of the 12 successful tagging events, seven lasted < 1 h, three lasted between 1 to 3 h, and two lasted > 4 h. The mean duration of data collection by all tag configurations was 79.3 min (SD = 104.5 min). In most cases, this result was related directly to the amount of time the GF10 remained attached to the whale. The GF10s were inspected after each retrieval, and none of the successful tagging events showed any obvious signs of damage either from water pressure effects or potential impacts with other whales. This was key as many deployments included whale-to-whale contact to the body area where the tag was attached.

Some of the unsuccessful tagging events were due to whale-to-whale contact, with tags being bumped or destroyed. For example, in Hawaii, the mini-GPS tag deployed on 18 February was attached; however, no data collection occurred because of whale-to-whale contact. The flotation was crushed by a second whale's body making contact, and the tag was broken as a result. Similarly, on 20 February, the GPS–B-Probe tag was retrieved; however, the GF10 had turned off at some point, likely occurring when the GF10 control buttons were accidentally bumped during tagging approach.

The GF10 was able to withstand water depths ranging from 8.8 to 164.0 m. On six of the 19 tag deployments, depths exceeded 50 m, and four of these were successfully recorded and downloaded from the GF10. The mini-GPS tag did not record depth as it did not have a pressure sensor. The two deployments that did not contain data after recovery (one from a 164-m depth record) were most

Table 1. Summary of tag deployments. Italicized rows depict tagging event results that were unsuccessful due to no data collection.

Date (d/mo/y)	Study location	Tag type	Duration of attachment (min)	Location on body	No. of GPS fixes
17/2/2015	Hawaii	GPS–B-probe	300	Spine, front of dorsal	431
17/2/2015	Hawaii	*Mini-GPS*	*326*	*Spine, front of dorsal*	*N/A*
18/2/2015	Hawaii	*Mini-GPS*	*242*	*(Moved) dorsal to side*	*N/A*
20/2/2015	Hawaii	*GPS–B-probe*	*250*	*Spine, front of dorsal*	*N/A*
23/2/2015	Hawaii	*Mini-GPS*	68	Spine, front of dorsal	5
26/2/2015	Hawaii	*Mini-GPS*	202	Left low, below dorsal	*N/A*
7/3/2015	Mexico	GPS–Acousonde	253	Spine, front of dorsal	98
8/3/2015	Mexico	GPS–Acousonde	53	Right side, beside dorsal	29
12/3/2015	Mexico	GPS–Acousonde	42	Left side, beside dorsal	15
12/3/2015	Mexico	GPS–Acousonde	6	Right side, slid low	12
13/3/2015	Mexico	GPS–Acousonde	165	Right side, 1 m down body	25
18/3/2015	Mexico	GPS–Acousonde	26	Left side, on backwards	7
18/3/2015	Mexico	*GPS–Acousonde*	*1*	*N/A*	*N/A*
22/3/2015	Mexico	GPS–Acousonde	9	Right side, low on body	35
22/3/2015	Mexico	GPS–Acousonde	17	Left side, front of dorsal	153
23/3/2015	Mexico	GPS–B-probe	2	*N/A*	5
23/3/2015	Mexico	GPS–Acousonde	73	Right side, low on body	93
24/3/2015	Mexico	*GPS–Acousonde*	*55*	*Right side, low on ribs*	*N/A*
24/3/2015	Mexico	*GPS–B-probe*	*52*	*Left side, behind dorsal*	*N/A*

likely due to an issue with design of the memory management firmware used in the GF10, not to the effects of pressure. It was later determined that once the GF10 ran out of memory, it did not save the most recently collected data but overwrote the oldest file. Unfortunately, this issue was not discovered until after the Hawaii field season was complete. Because the GF10 deployment that failed to record data functioned properly later (after data from memory was downloaded and GF10 reconfigured), the GF10 memory storage process was the most probable reason that location data were not recorded for those two deployments.

GF10 Tag Results

The number of location fix "hits" and "misses" for each time the tag was above water during a surfacing event was calculated and plotted as a CDF (Figure 4); misses and hits CDFs cross near the 3 s threshold. Therefore, in 60% of these datasets (depicted by the arrow in Figure 4), the GF10 successfully connected with a satellite because it was above the water's surface for at least 3.5 s. Looking at mean (and median) values, the average surface interval for a tagged animal was 3.5 s, which was 0.5 s longer than required to have at least a 60% chance of connecting with a satellite. To further examine these results, a binomial regression was used to test whether a threshold of time existed that could predict whether a location fix was recorded. A binomial regression analysis was conducted, with success (hit = 1; miss = 0) as the dependent variable and the number of seconds the tag was above the water surface as the explanatory variable. The results of the binomial regression indicated that if the GF10 was above the water surface for at least ~3 s, then there was greater than a 50% chance of getting a location fix ($p < 0.001$; alpha = 0.01).

For Test #1, the error distribution was plotted as a histogram, and also as a CDF of distances between the mini-GPS tag and the handheld Garmin GPSMAP 64 s (Figure 5). The actual distance between the two devices was just a few centimeters (i.e., ~0). It was assumed that

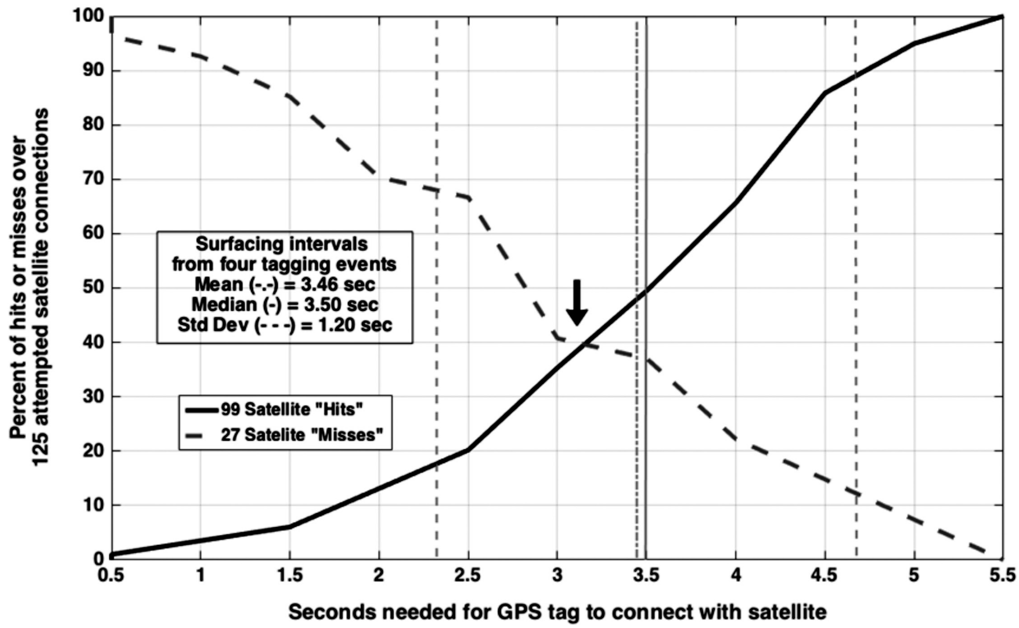

Figure 4. Cumulative distribution function (CDF) plots of hits vs misses of GPS satellite location fixes

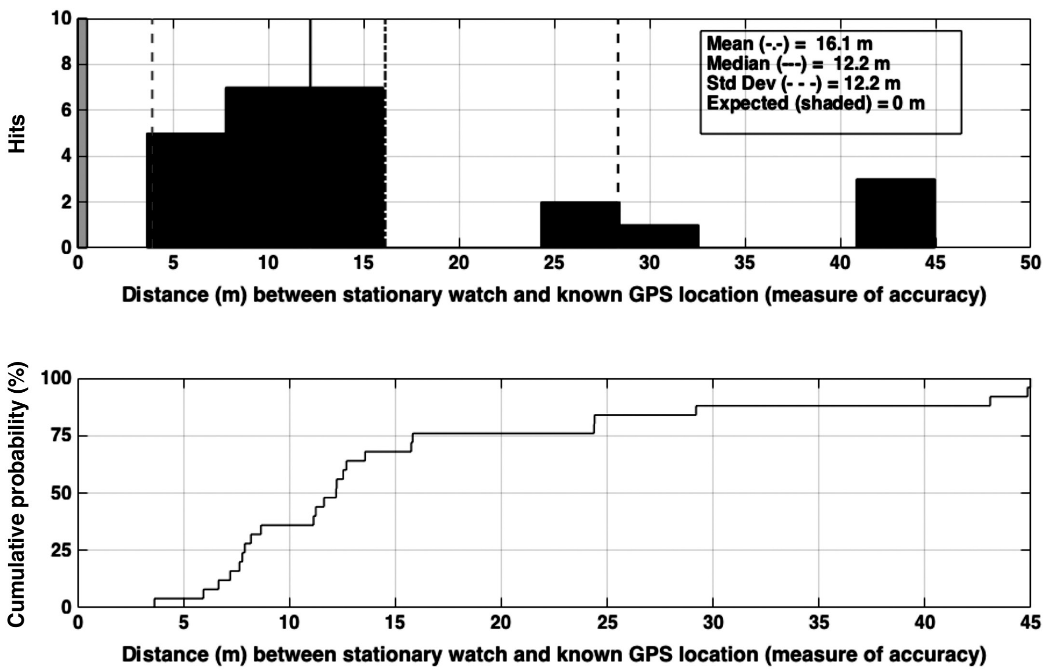

Figure 5. A histogram (top panel) and CDF (bottom panel) of the distances between location fixes made by a handheld Garmin GPSMAP 64s and a GF10 fitness watch located side-by-side on the deck of an ocean-side swimming pool

any values greater than zero were due to errors in GF10 location fixes. We found that 77% of location fixes (21 of 27 observations) occurred between ~5 to 16 m; 22% (*n* = 6 of 27) of location fixes had errors of between 24 and 45 m. Overall, the CDF plot indicates that over 70% of fixes had errors less than ~16 m, and half the fixes had errors less than 13 m.

The expected distances between the two tags in Test #2 should have been 0 to 3 m, which was the maximum possible distance between the two GF10s during this test. However, the location error was found to be two orders of magnitude smaller than that provided by most Argos technologies (Sims et al., 2009; Dujon et al., 2014) and was within the middle of the error range for Fastloc technology (Rutz & Hays, 2009). While a combination of errors from both tags would contribute to the overall error, the effect due to each of these could not be separated. Therefore, distances of less than 3 m were considered ideal, containing virtually no error in either GF10. The average error was ~22 m (Figure 6). Fewer than 5% of distances between the two GF10s had errors less than 5 m. The largest error was at 40 m, suggesting that location fixes from a mini-GPS tag attached to a swimming humpback whale was precise enough to locate a whale to within 40 m.

Test #3 was conducted by measuring the distance between concurrent location fixes recorded by the GF-10 on the mini-GPS tag and the boat-based navigation GPS. This distance was used as a measure of accuracy of the GF10. Distances recorded between these two devices ranged from 8 to 68 m. Only a few data points fell into the range of expected (i.e., no error) distances of 0 to 6 m. However, half the location estimates had errors of fewer than 35 m (Figure 7). Even the maximum location error of 68 m between the two GPS devices was the same order of magnitude that occurred in Test #2, and an order of magnitude more accurate than current Argos location technology. This error was also near the upper error range for Fastloc technology (Rutz & Hays, 2009).

A GLM post-hoc test was run to test for any effect of individual tagging events on the results of binomial regression tests, and to examine the minimum time above water that a tag must be available for a GPS location. Four tag deployments were included as a categorical variable. The null hypothesis was that both number of seconds the tag was above water and the tagging event (a categorical

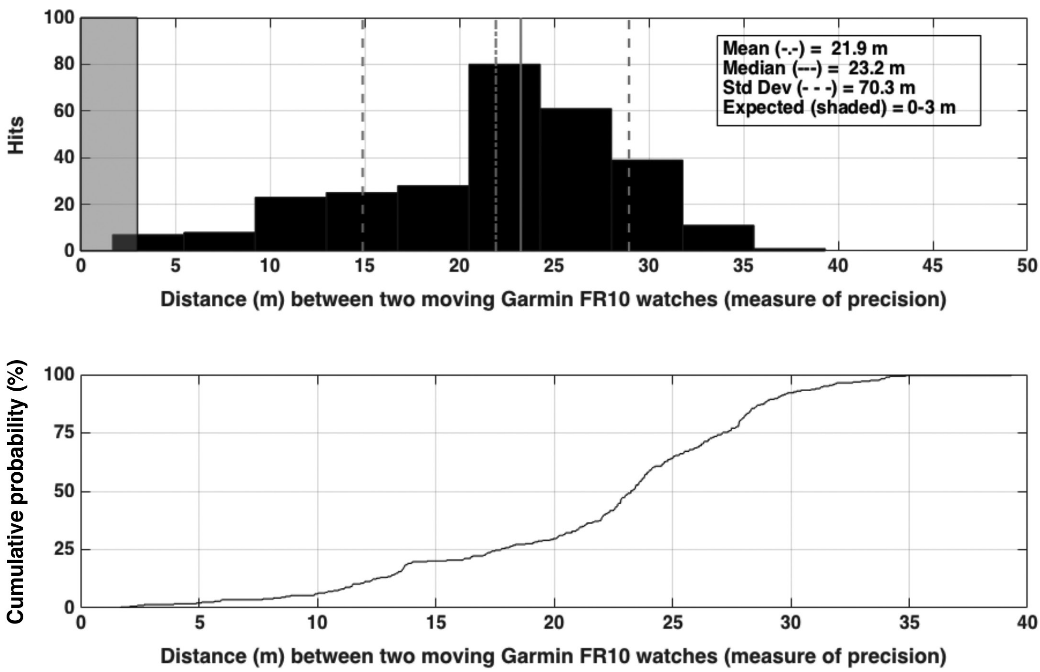

Figure 6. A histogram (top panel) and CDF (bottom panel) for results of mobile test type-1 (Test #2). In the top panel, the expected distance between the two GF10s (0 to 3 m), based on the actual distance between the two watches, is represented by the shaded bar. The median distance between the two is denoted by a solid line, the mean by a dash-dotted line, and the standard deviation by dashed lines.

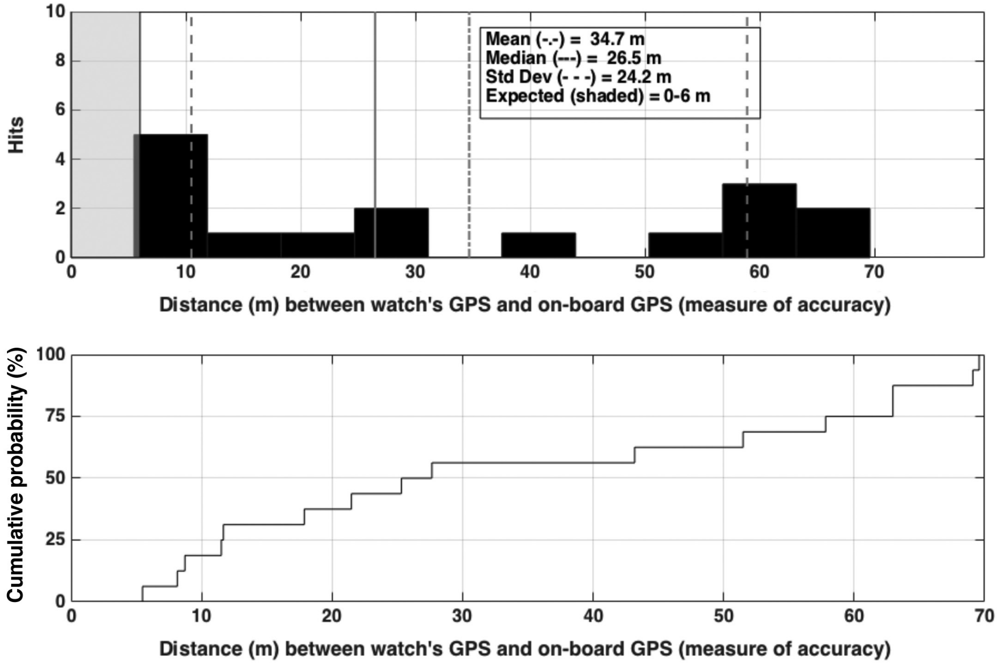

Figure 7. A histogram (top panel) and CDF (bottom panel) for the results of mobile test type-2 (Test #3). In the top panel, expected distance between the two GPS devices (0 to 6 m) is represented by the gray shaded bar and can also be explained as the maximum range possible between the two GPS devices.

variable) did not influence the success of attaining a satellite location fix. The null hypothesis was not rejected ($p = 0.287$; alpha = 0.01). These results of the GLM support pooling all tag data for the simple binomial regression model.

A whale track recorded from Mexico on 7 March 2015 with the GPS–Acousounde configuration, which was attached for over 4 h, was plotted (Figure 8). The longevity of this tag's attachment provided a very detailed track of the animal's locations and movements. This track was verified by the research vessel following the humpback whale as closely as allowable under permit (within 90 m). Other whale tracks were recorded from the two deployments off Hawaii in which location data were successfully recorded.

We successfully used a COTS device (i.e., a Garmin GF10 fitness watch) in a custom-built location tag that was developed for and field tested on wild marine mammals. Assembly of the watch configurations was inexpensive, and attachment of tags and data retrieval from them was straightforward. All configurations worked relatively and surprisingly well, albeit the mini-GPS tag deployments resulted in shorter deployment times than either of the two other configurations. Tracks obtained from animals tagged with the GF10 fitness watch had enough location fixes and sufficient accuracy to provide data and potentially be useful for tagging studies on the behavior, ecology, and other aspects of cetaceans with surface intervals exceeding ~3 s. The watch used was able to withstand water depths well over the rating of 50 m. Although results of field tests varied, tag configurations remained attached on animals for sufficient durations, collecting data for minutes and up to several hours, which was long enough to collect detailed location and movement information for humpback whales.

The GF10 watch used had some limitations in terms of battery life, memory, and its control buttons. The GF10 fitness watch model used in this study is outdated, and newer, more advanced models have improved battery and memory capacity. The GF10 battery was rated to last for up to 5 h in operational mode, which we verified. Three deployments lasted over 4 h, and two lasted 5 h or more. Battery life can be conserved by turning the watch on just prior to deployment.

The memory capacity of the GF10 was suitable for several 5-h deployments. We discovered a limitation with the default setting was that it erases the oldest file if the newest file was too large for the remaining memory space. This was

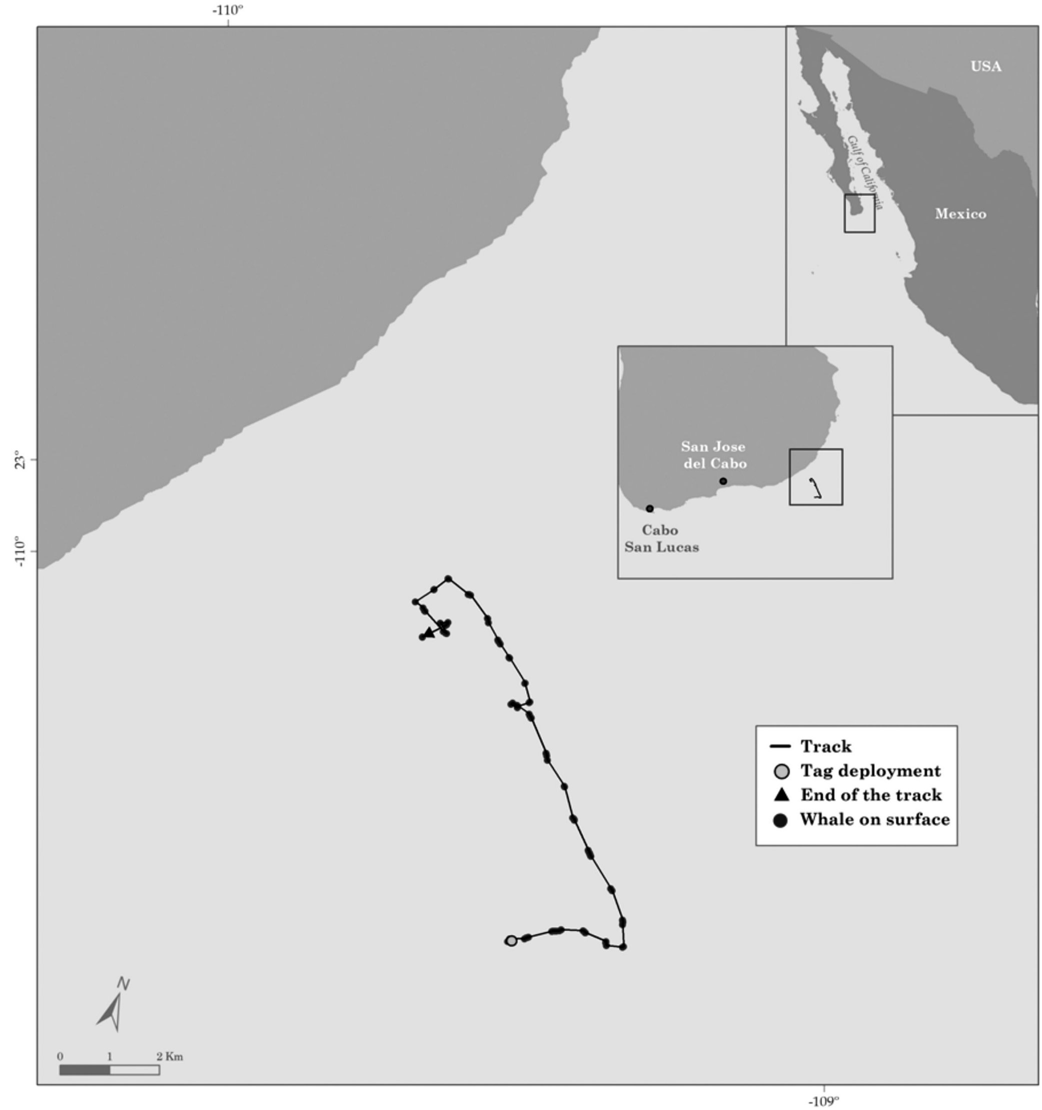

Figure 8. Example whale track off San José del Cabo, Baja California Sur, Mexico, on 7 March 2015, using data collected from the GF10. The humpback whale was tagged with a GPS–Acousonde. The open circle depicted at the bottom left of the track indicates the point at which the tag was attached. The tag remained attached to the whale for 4 h and 13 min. For additional details, see Table 1.

the case for two deployments until the issue was realized. Erasing the memory every few deployments is a wise safeguard against this situation. However, this requires that the GF10 or buttons on a newer watch be accessible in the field and that the screen is visible to verify configuration. The buttons were accessible in all tag configurations in this study, but that also made them accessible to being inadvertently pressed, especially in two situations: (1) when whales were in physical contact with each another or (2) when buttons were pressed accidentally during tagging and deployment activities.

The main limitations of our experimental tag configurations for successful deployment longevity was the attachment method, hydrodynamic drag of the tag, or some combination of these that resulted in relatively brief tag attachment times. The shorter deployments found with the mini-GPS tag were likely due to its relatively high-contour design. It is expected that a more hydrodynamic design of the tag package would allow the tag to stay attached for longer durations by decreasing drag forces. Further refinements to the tag package design, especially for the mini-GPS configuration, and additional improvements in tag attachment methods should significantly increase tag attachment durations. Importantly, we found tag data collection withstood breaching and significant rubbing and other contact between animals other than in two instances. Thus, it was determined that the GF10 watch was rugged enough to withstand typical activities of humpback whales on their breeding grounds, including enduring pressure from deep dives.

While our custom-designed tag worked on a large whale species with longer surface intervals and relatively shallow dives, it may not be possible to successfully collect data using these devices on animals with longer dive times or that dive to depths greater than 100 m such as pilot whales (*Globicephala* spp.), sperm whales (*Physeter macrocephalus*), and beaked whales. We theorize a greater depth capability might be achieved by encasing the watch in a small pressure resistant housing made of a plastic such as PVC or Delrin®. Any such designs would need to allow for access to the control buttons and ports to configure the device and download data, which would complicate their use with fitness watches. Devices that do not have control buttons or displays (e.g., the TRACE action sport tracking system) might allow potting them in epoxy or syntactic foam, which would further increase their pressure rating.

The location error found in Test #2 nonetheless indicated that a GF10 has an average precision of within approximately two to three whale lengths at the most, which is considered quite good precision for most whale tracking studies. One potential limitation of the GPS field tests was that the GF10 watch was compared to only two other types of GPS devices. Because all GPS units are expected to have different errors, this might have affected the accuracy of the test results. A better test would be to compare the GF10 results to a differential GPS (DGPS). This requires a DGPS reference signal, which is available around Maui, Hawaii, but not in the San José del Cabo, Baja California Sur, Mexico, area. We were not aware of this possibility while in the field in Hawaii and, thus, did not take advantage of it. We have not tested our tags further since this 2017 study due to funding limitations, the pandemic, and other factors.

The optimal position for attachment is generally on a whale's dorsal surface near the dorsal fin. This position allows a fitness watch (the GF10 or newer) to be exposed to GPS satellites for as long as possible, thus maximizing the possibility of a location fix. Attaching the tag at this location on an animal can be difficult under some field conditions and situations but is quite doable for experienced tagging researchers. The ~3 s average needed to obtain a location fix is also expected to have decreased with improvements in GPS fitness tracking technologies. The tag deployed on 23 March 2015 was located relatively low on the lateral side of the humpback whale's body, instead of on its dorsal surface. This whale only surfaced five times during the deployment event, each time for less than 1.5 s, and, as a result, a location fix was never obtained by the GF10. This supports the binomial regression results, which indicated that a tag must be above water for ~3 s to get a fix. Even though fixes were not obtained by this tag, its results were included so that representation of such "non-ideal" tag attachment locations sometimes occur in these studies.

Our field validation of three experimental tag configurations illustrates the usefulness of fitness trackers as alternate tagging technologies and provides a road map for future studies to have meaningful outcomes which increase the success of data gathering efforts. With a successful tagging approach, behavior and social sound data can be acquired, contributing to our overall knowledge on the ecology, behaviors, and social sounds produced by a tagged humpback whale and its proximate conspecifics. Future studies could focus on further testing and application using newer COTS technologies for marine animal tagging purposes.

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