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The accuracy of Fastloc-GPS locations and implications for animal tracking

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Summary

1. Over recent years, a major breakthrough in marine animal tracking has occurred with the advent of Fastloc-GPS that provides highly accurate location data even for animals that only surface briefly such as sea turtles, marine mammals and penguins.

2. We assessed the accuracy of Fastloc-GPS locations using fixed trials of tags in which >45 000 locations were obtained. Procedures for determining the speed of travel and heading were developed by simulating tracks and then adding Fastloc-GPS location errors. The levels of detail achievable for speed and heading estimates were illustrated by using empirical Fastloc-GPS data for a green turtle (*Chelonia mydas*, Linnaeus, 1758) travelling over 3000 km across the Indian Ocean.

3. The accuracy of Fastloc-GPS locations varied as a function of the number of GPS satellites used in the location calculation. For example, when Fastloc-GPS locations were calculated using 4 GPS satellites, 50% of locations were within 36 m and 95% within 724 m of the true position. These values improved to 18 and 70 m, respectively, when 6 satellites were used. Simulations indicated that for animals travelling around 2·5 km h^{-1} (e.g. turtles, penguins and seals) and depending on the number of satellites used in the location calculation, robust speed and heading estimates would usually be obtained for locations only 1–6 h apart.

4. Fastloc-GPS accuracy is several orders of magnitude better that conventional Argos tracking or light-based geolocation and consequently will allow new insights into small-scale movement patterns of marine animals.

Key-words: satellite telemetry, animal tags, sensitivity analysis, positioning error

Introduction

Understanding the movements of animals over a range of spatial and temporal scales lies at the heart of many ecological studies (Nathan 2008; Nathan *et al.* 2008; Nathan & Giuggioli 2013). Consequently, there are several well-established approaches for tracking a range of species. Acoustic tracking is used to follow marine and freshwater species that do not surface, such as fish and invertebrates (Espinoza *et al.* 2011; Moland *et al.* 2011; Coates *et al.* 2013). Radiotracking using earth-based receivers is used to follow animals over fairly short distances (typically a few kms) (White & Garrott 1990; Millspaugh & Marzluff 2001; Godfrey & Bryant 2003). Argos satellite tags and light-based geolocator tags have both been widely used to track large-scale movements, sometime many tens of thousands of km (see the Bridge *et al.* 2013 review). However, often these techniques provide only fairly course quality locations: for example, Argos locations typically have an accuracy of several hundred metres to several km while positions estimates from light-based geolocation are accurate to only tens of km (Hays *et al.* 2001; Teo *et al.* 2004; Witt *et al.* 2010).

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Set against this backdrop of established technologies that have existed for a decade or more, there have been some major recent advances in animal biotelemetry (Rutz & Hays 2009). In particular, for high-resolution tracking, GPS tracking has emerged for terrestrial animals and flying birds, where there is near-continuous line of sight with satellites overhead; while Fastloc-GPS has emerged as an approach that provides high-resolution locations for widely ranging marine species that are only briefly visible to the GPS satellites (Schofield *et al.* 2007; Rutz & Hays 2009). As such Fastloc-GPS is a major breakthrough for marine animals that only surface briefly, such as sea turtles and marine mammals. Conventional GPS receivers take several seconds to generate a location estimate from a 'warm start', knowing current time within 20 s, current position within 100 km and having valid almanac data. This has precluded their use on such marine taxa (Lehtinen, Happonen & Ikonen 2008; Tomkiewicz *et al.* 2010). However, Fastloc-GPS overcomes this problem and involves the rapid (typically 10's of milliseconds) acquisition of GPS data when an animal surfaces and subsequent post-processing to derive position estimates (Tomkiewicz *et al.* 2010). Trials by the company that developed Fastloc-GPS (Wildtrack Telemetry Systems Ltd., Leeds, UK) have shown that locations are generally within a few 10's of metres of the true position (Bryant 2007), and some limited trials by users have confirmed this general level of accuracy (Hazel 2009; Costa *et al.* 2010; Hoenner *et al.* 2012). Here, we conduct a comprehensive assessment of the accuracy of Fastloc-GPS locations using fixed trials in which almost 45 000 Fastloc-GPS locations were obtained. Hence, the outcomes of these trials will inform the ever growing user community using this technology.

Furthermore, it is widely known that the accuracy of tracking data influences the ability to distinguish biological signals from sampling noise in the analysis of movement patterns (Bradshaw, Sims & Hays 2007; Hurford 2009). For example, with Argos location data that have been used for 20 or more years, we have previously shown how inaccurate speed of travel estimates are obtained if calculated for locations that are too close in time: in that case, the location inaccuracy may dominate compared to actual movement made by the animal. So, for example, with Argos data we have previously suggested that locations need to be >100 km apart (i.e. 2 days apart if the animals are travelling at 50 km day^{-1}) in order to calculate accurate speeds of travel (Hays *et al.* 2001). In this same way, here we consider how the accuracy of Fastloc-GPS locations can be built into subsequent procedures for calculating speed of travel and heading, parameters that lie at the heart of many movement studies (Sato *et al.* 2007; Bartumeus *et al.* 2008; Codling, Plank & Benhamou 2008; Wilson *et al.* 2013).

Material and methods

TRIALS WITH FASTLOC-GPS TAGS IN A FIXED LOCATION

Between 14 May and 26 November 2013, 257 tags of assorted models equipped with Fastloc-GPS were deployed (at approximately 47°40′ 36″N, 122° 08′ 10″E) in an open space with an unobstructed view of the sky. Tags were always deployed in the same general area within 4 m of each other. Raw GPS data snapshots were collected and pre-processed into pseudo-ranges onboard the tags using the Fastloc system (Version 2.3, Wildtrack Telemetry Systems Ltd.). The DAP Processor (Version 3.0, Wildlife Computers, Redmond, WA) obtained the relevant daily broadcast satellite ephemeris data (maintained by NASA http://cddis.gsfc.nasa.gov) and post-processed the pseudoranges into location estimates. For each location, the software reported; the number of satellites used, the ID numbers of those satellites, the estimated timestamp error, and the 'residual' value of the solution. The total number of satellites can vary due to their availability within the view of the sky. The 'residual' value is a measure of how well the solution matched the observed data.

We assumed that the average of all locations obtained from an individual tag represented that tag's true location.

IMPLICATIONS OF FASTLOC-GPS ACCURACY FOR SPEED OF TRAVEL AND HEADING DERIVATION

To investigate how location accuracy could impact calculations for speed of travel and heading (relative to geographic north), we started with theoretical tracks for animals travelling in straight-lines at various different speeds. Straight-lines were selected simply to aid computational efficiency but will not impact the overall conclusions. We assumed speeds of travel of 1 km h^{-1}, 2·5 km h^{-1}or 5 km h^{-1} (24, 60, 120 km day^{-1}). This range of speeds covers those typically seen in travelling marine animals such as sea turtles, marine mammals and penguins (see the Sato *et al.* 2007 review of swimming speed estimations for these taxa). To locations along the straight-line tracks, we added a location error randomly selected from the empirical errors found in the fixed trials. We selected location errors corresponding to those based on 4, 5 or 6 satellites, as they represent the largest expected errors. Speed and heading were then calculated by subsampling the simulated track at different time steps ranging from 1 to 24 h. In this way for combinations of locations obtained with 4, 5 or 6 satellites, we estimated 125 000 speed of travel and heading estimates.

To determine if a sampling interval between Fastloc-GPS locations would be long enough to produce an accurate speed and heading estimate, we defined a quality criterion corresponding to 95% of estimated speeds and headings being within 10% and 10°, respectively, of the true values (similar to Hays *et al.* 2001).

STUDY CASE: DERIVATION SPEED OF TRAVEL AND HEADING DURING MIGRATION OF GREEN TURTLES

Using procedures developed from the fixed location trials and the calculations with simulated tracks, we examined the level temporal detail that was possible for speed of travel and heading estimates using a previously published track for a green turtle (*Chelonia mydas*). The turtle migrated across the Indian Ocean from breeding areas on Diego Garcia in the Chagos Archipelago (Hays *et al.* 2014b). This turtle was equipped with Fastloc-GPS Argos tag, that is the tag had a Fastloc-GPS receiver combined with an Argos transmitter to remotely relay the data (for full description see Hays *et al.* 2014b). To process these data, they were first filtered using a threshold residual value of 35. We then removed the remaining erroneous locations looking visibly erroneous when the tracks were viewed in Google Earth. An analysis of the speed of travel always confirmed, these locations necessitated unrealistic speeds of travel (>200 km day^{-1}). We designated the start of the postnesting migration as the time at which the turtle left Diego Garcia and began it oceanic crossing, which continued until it arrived at the foraging ground. We next calculated speed and heading using the corresponding sampling interval determined from track simulations. We assumed a 2·5 km h^{-1} average speed of travel (Luschi *et al.* 1998; Hays *et al.* 2014b).

To assure the veracity of the calculated speed and heading time-series during migration, we calculated the autocorrelation of these values between each location at time t and t+1 (Hays *et al.* 2001). We expect a high autocorrelation value if the speed and heading estimations are coherent (Dray, Royer-Carenzi & Calenge 2010).

All analysis and simulations were performed using R software version 3.0.1 (R Development Core Team 2009). Autocorrelation value for heading was calculated using the package CircStats (Lund & Agostinelli 2014).

Results

TYPICAL LOCATIONS ACCURACY

Fixed trials produced a total of 45 157 snapshots with the number of satellites used to calculate locations ranging from 4 to 11 (Table 1). Locations using 4–8 satellites represent 93·9% of total data. For each Fastloc-GPS location, we calculated the deviation from the assumed true position (distance in metres).

Table 1. Accuracy statistics of a fix trial experiment involving 257 Fastloc-GPS tags and 45 157 locations

Number of satellites used for location calculation	4	5	6	7	8	9	10	11
Number of locations of unfiltered data	9898	9835	8882	7704	6096	2295	371	76
Number of locations of filtered data	9718	9819	8869	7692	6080	2282	367	76
95th percentile of unfiltered data (m)	1163	169	71	43	34	28	24	19
95th percentile of filtered data (m)	724	165	70	43	33	27	22	19
75th percentile of unfiltered data (m)	118	55	30	22	19	16	13	15
75th percentile of filtered data (m)	109	55	30	22	19	16	13	15
50th percentile of unfiltered data (m)	37	29	18	14	12	10	8	7
50th percentile of filtered data (m)	36	29	18	14	12	10	8	7
25th percentile of unfiltered data (m)	17	16	10	8	7	6	5	5
25th percentile of filtered data (m)	17	16	10	8	7	6	5	5

Plots of the deviation of locations showed that the number of satellites used in the position calculation had a clear impact on location accuracy, with locations calculated using more satellites tending to be more accurate (Fig. 1). For example, when Fastloc-GPS locations were calculated using 4 satellites, 50% of locations were within 36 m and 95% within 724 m of the true position. When they were calculated using 6 or more satellites, at least 50% of locations were within 18 m and 95% within 70 m of the true position illustrating the increase of accuracy (see Table 1 for each number of satellites statistics). The 'residual' value generated with each Fastloc-GPS location was also related to the location accuracy (Fig. 2). However, this relationship was not simple. Rather, high residual values were more often associated with inaccurate locations, while for Fastloc-GPS locations that had low residual values, then the accuracy could be either good or poor. So selecting a residual value of 35 to filter locations will certainly help to remove some of the most inaccurate Fastloc-GPS locations, but not all. Filtering in this way using a residual value of >35 had a particularly marked impact on removing the most inaccurate locations obtained with 4 satellites. Before filtering 95% of locations were within 1163 m of the true location. After filtering, this value decreased to 724 m. However, when looking at a distance within which 50% of locations were found, these values before and after filtering were much closer, being 37 m and 36 m, respectively (Table 1).

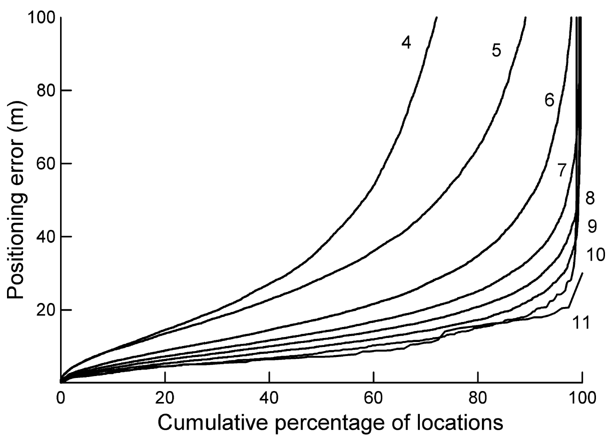

Fig. 1. The deviation of Fastloc-GPS locations (in metres) from the true position based on the number of GPS satellites (black numbers) used in the position calculation. The deviation was sorted by magnitude before plotting. This way, we can readily assess the distance from the true location that 50% or 95% of locations would fall within. To improve readability, the deviation from true location axis is truncated at 100 metres.

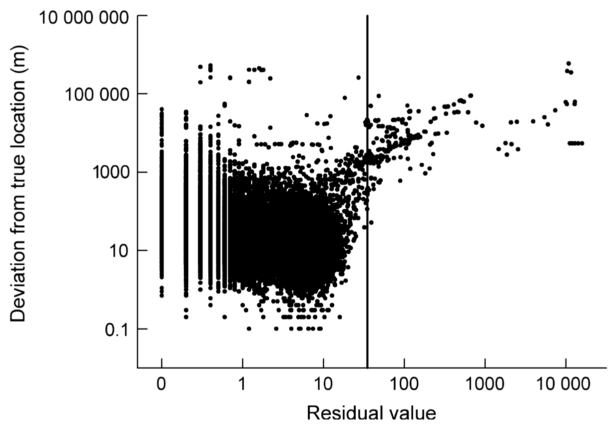

Fig. 2. The deviation (in metres) of Fastloc-GPS locations from the true position for 45 157 Fastloc-GPS locations as a function of their residual value. The residual value is used as a quality index by the manufacturers to filter and remove a fraction of the locations with low accuracy. A residual value of 35 is typically used (vertical solid black line). More than half of locations (27 011, 59·8%) have a residual value between 1 and 10.

ESTIMATING THE SAMPLING INTERVAL FOR SPEED AND HEADING DERIVATION

The probability that accurate speed of travel and heading estimates were calculated tended to increase as the time interval between locations lengthened. For example, in a very conservative way, across all combinations for the number of satellites used in the Fastloc-GPS calculations, accurate speeds and headings were obtained on more the 95% of occasions, when locations were more than 12 h apart, regardless of whether the animal was travelling at 1 or 5 km h^{-1} (Fig. 3). However, as the time interval between locations became shorter, then the number of satellites used in the Fastloc-GPS location became increasingly important as did the speed of travel of the animal. For example, for an animal travelling at 2·5 km h^{-1}, accurate (within 10% and 10°, respectively) speeds and headings were

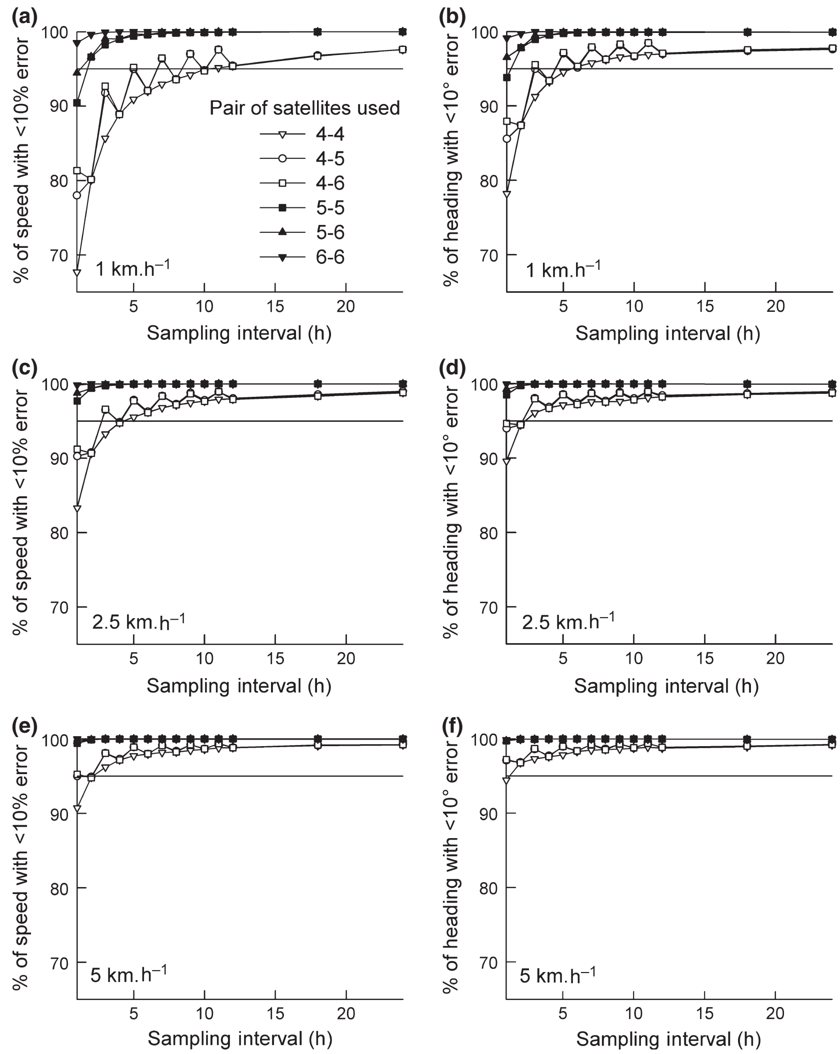

Fig. 3. Sensitivity analysis of the impact of location accuracy and number of GPS satellites used in the location calculation on speed of travel and heading estimation. Three different speeds of travel where considered [1 km h^{-1} (a, b), 2·5 km h^{-1} (c, d) and 5 km h^{-1} (e, f)]. Sampling intervals range from 1 to 24 h. Speed of travel and heading estimates tended to be more accurate when the animal was travelling faster, when more GPS satellites were used in the calculation of the Fastloc-GPS position and when the time interval between locations increased. We consider a sampling interval is long enough when 95% of speed of travel and heading estimates have an error less than 10% or 10°, respectively. A solid horizontal line indicates this threshold on the plots.

obtained on more the 95% of occasions when the interval between locations was 6 h for pairs of locations determined using combinations of 4–4, 4–5 and 4–6 GPS satellites and 1 h for pairs of locations determined using combinations of 5–5, 5–6 and 5–6 GPS satellites. In short, there was a step increase in the utility of the Fastloc-GPS locations when ≥5 GPS satellites were used in the location calculation.

STUDY CASE ON GREEN TURTLES TRACKS

The tracked turtle migrated from the Chagos Islands to the Somalian coast (Fig. 4). Most (84·6%) of the locations were calculated using 5 or more satellites, meaning we can expect 80·4% of the data to have an accuracy of 169 m or less (Table 1). The number of daily locations ranged from 1 to 37 with a mean of 20 (SD = 9) locations per day. Time interval between two uplinks ranged from 14 min to 42 h with a mean interval of 1 h 15 min. Following the results of our track simulations, we calculated the speed of travel and heading with a sampling interval of 6 h for pairs of locations that included at least one location calculated using 4 GPS satellites, while a sampling interval of 1 h was used for all other possible pairs (i.e. 5 or more GPS satellites used in the location calculation). Speed of travel and heading showed marked variations during the migration with a high autocorrelation (r = 0·90 for speed of travel and r = 0·92 for heading, Fig. 4). During the oceanic crossing, the speed of travel of this turtle varied between about 0·5 km h^{-1} and almost 6 km h^{-1}, a 12-fold variation. Heading tended to change monotonically for several days indicating a gradual change in course heading. For example, between 25 January 2013 and 28 January 2013 heading changed from 347° to 298°. Then interspersing these monotonic changes in heading were several reversals in heading. For example, around 02 February 2013, the heading had been increasing from 273° to 320°, but then reversed and changed back to 265°. The heading reversals corresponded with distinct turns in the track (Fig. 4).

Discussion

Our study provides a comprehensive assessment of the accuracy of Fastloc-GPS locations and hence will help inform efforts to extract the most biological information from the extensive Fastloc-GPS tracking data sets that are now emerging for a diverse range of taxa. These taxa include pinnipeds (Costa *et al.* 2010; Vincent *et al.* 2010), fish (Sims *et al.* 2009; Evans *et al.* 2011), turtles (Hazel 2009; Schofield *et al.* 2010;

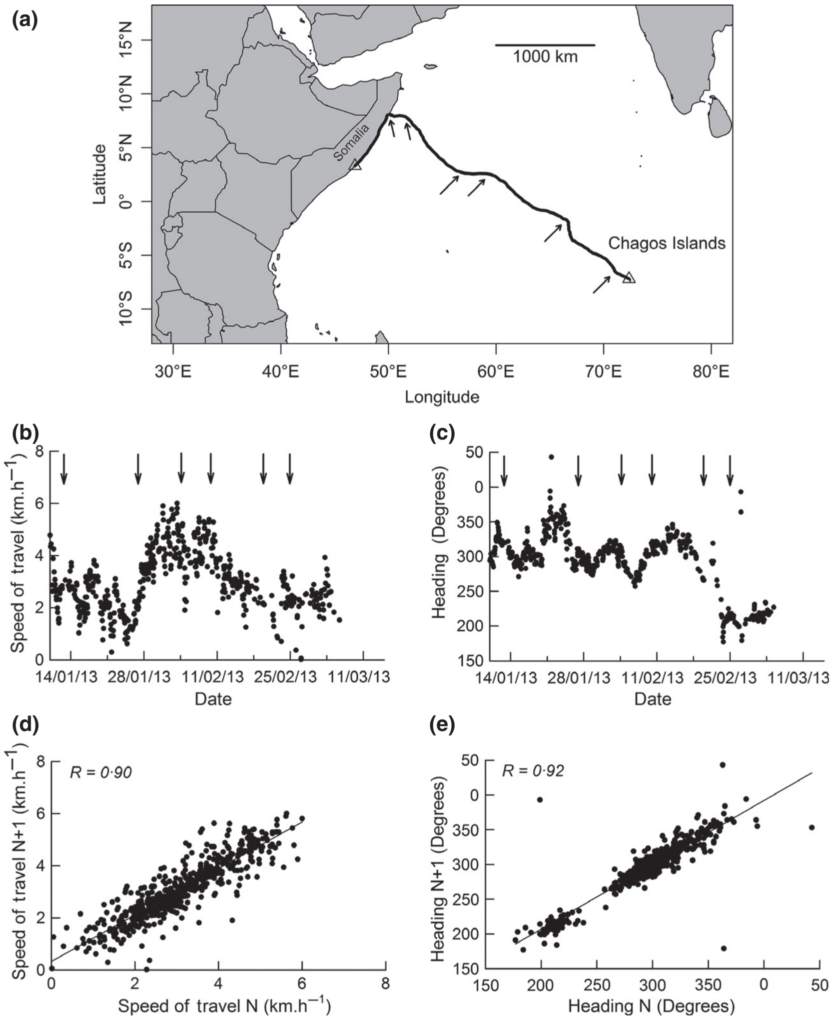

Fig. 4. Track of a green turtle migrating from the Chagos Islands to coast of Somalia (a). Triangles show the start and end of the migration, and black arrows show the main turns observed during the migration. Speed of travel (b) and heading (relative to the north) (c) for this turtle as a function of time. The black arrows correspond to the turns indicated in (a). Speed of travel and heading autocorrelation (d and e) between a value at time N and N+1.

Hays *et al.* 2014b), whales (Mate 2012) and penguins (Bost *et al.* 2011). To investigate Fastloc-GPS accuracy, previous trials have been performed before by the developer of this technology (Wildtrack Telemetry Systems Ltd.) using fixed location trials (Bryant 2007). Scientists on the field also used Fastloc-GPS tags as a crosscheck reference to investigate Argos locations accuracy (Hazel 2009; Costa *et al.* 2010; Hoenner *et al.* 2012). Our results are broadly in accord with these previous findings. For example, we reported that locations obtained with 4 GPS satellites were within 724 m of the true position on 95% of occasions, and 36 m on 50% of occasions, while the respective values reported by Bryant (2007) were 810 and 50 m.

So our results provide confirmation of the accuracy of Fastloc-GPS. Clearly, Fastloc-GPS provides much more accurate locations than other approaches that have been used over recent decades for tracking marine species that range widely. For example, conventional Argos tracking typically gives locations that are a few km from the true position. Witt *et al.* (2010) reported that 95% of Argos locations of quality A and B (these often dominate in marine tracking studies), were within $3{\cdot}5 \pm 9{\cdot}2$ km and $14{\cdot}3 \pm 135{\cdot}6$ km of the true position, respectively. Similarly, light-based geolocation provides fairly crude position estimate. Fudickar, Wikelski & Partecke (2012) have reported that light-based geolocator position estimates are typically up to 200 km from the true position. Set against this backdrop it is clear that Fastloc-GPS provides at least an order of magnitude improvement in location accuracy (i.e. if more than 5 satellites are used to calculate a location, the improvement will be approximatively 10–40 times better than the average Argos accuracy and 1100 times better than light-based geolocators). This opens up the way for more detailed analysis of the spatiotemporal patterns of animal movement (Schofield *et al.* 2007, 2013a; Hazel 2009; Hays *et al.* 2014b). For terrestrial animals and flyers (birds and bats), the necessity for fast acquisition of GPS ephemeris is not so important and regular GPS tags can be used which take several seconds to determine a position from switch on (Tomkiewicz *et al.* 2010).

Bajaj, Ranaweera & Agrawal (2002) report typical GPS accuracy ranges in wildlife tracking are between 18 and 91 m and can be reduced to less than ten metres if a differential correction is applied (Rempel & Rodgers 1997). For 8 different GPS collars models used for animal tracking, Villepique *et al.* (2008) reported than typically 50% of locations were between 5 and 20 metres and 95% of locations between 20 and 68 metres of their true location. This is similar to the accuracy of

Fastloc-GPS locations calculated using 6 or more satellites, that is about two-thirds of the locations we recorded from a migrating turtle. In short, these considerations suggest that Fastloc-GPS is often as accurate as GPS locations provided in terrestrial animal tracking.

Our results confirm that the ‘residual’ value provides a useful first step in filtering Fastloc-GPS data as it removes some of the largest location outliers. This type of filtering is typically reported in manuscripts describing Fastloc-GPS results and often done automatically by manufacturers (Sirtrack 2010; Witt *et al.* 2010; Shimada *et al.* 2012). In particular, our results show that this filter applies importantly to locations obtained with 4 GPS satellites. Once 5 or more satellites are used in location calculations, then few locations will be removed by this filter. But overall the residual value provides a less clear indicator of the location accuracy compared to the number of satellites used in the location calculation.

As well as describing Fastloc-GPS accuracy, we also explored the implications of location accuracy for estimates of speed of travel and heading. This problem is simple to understand conceptually, but harder to build into a rigorous analysis. Conceptually, it is widely known that as the true distance between two locations decreases, so the inaccuracy of the location estimates will increasingly dominate the calculations for speed of travel and heading (Hays *et al.* 2001; Bradshaw, Sims & Hays 2007; Hurford 2009). Importantly, users need to know when reliable speeds and heading estimates are likely to be obtained under a range of different scenarios. For example, if an animal travels 250 m in 15 min (i.e. 1 km h^{-1}) could this speed be accurately measured with Fastloc-GPS? In a previous study, Schofield *et al.* (2010) estimated speed of travel of loggerhead turtles (*Caretta caretta*, Linnaeus, 1758) tagged with Fastloc-GPS using one location per day. Assuming a speed of 2·5 km h^{-1}, we showed that interval can be reduced to 6 h if the locations are calculated using 4 satellites and to 1 h if they are calculated using at least 5 satellites increasing the number of possible speed of travel and heading estimations. So our simulations of animals moving at different speeds should provide some simple rules-of-thumb for users to correctly interpret Fastloc-GPS data. Of course, further smoothing of the tracking data and/or incorporation into models that take account of the location error structure (e.g. state space models, Jonsen, Flemming & Myers 2005) may refine the interpretation of Fastloc-GPS tracking data but will still need to incorporate estimates of location accuracy.

The value of Fastloc-GPS tracking is that it will allow users to explore the details of migration routes and space use in more detail than previously. For example, many studies have tracked sea turtles (reviewed in Hays & Scott 2013). In almost all previous cases, conventional Argos tracking has been used. So while there are some descriptions of routes followed and some movement metrics (e.g. the straightness of routes, see Luschi *et al.* 1998 or Hays *et al.* 2014a), details of changes in speed and heading over time-scales of a few hours are poorly described. These same considerations apply to marine mammals, fish and penguins that are remotely tracked rather than are equipped with high-resolution loggers that can directly measure performance (e.g. speed) but need to be removed for data recovery. Similarly radiotracking and Argos tracking have been used to estimate home-ranges used by sea turtles and other marine taxa (Bjørge, Bekkby & Bryant 2002; Seminoff & Jones 2006; Frere *et al.* 2008; Tougaard, Teilmann & Tougaard 2008), but here again the increased accuracy of Fastloc-GPS will allow more informed estimates of space use (Schofield *et al.* 2013b; Hays *et al.* 2014a). This utility of Fastloc-GPS was evidenced in the track of a green turtle travelling across the Indian Ocean that showed small-scale variations in speed and heading. Most likely, these variations are due to changes in the animals swimming as well as the impact of variable ocean currents. Using Fastloc-GPS, the relative roles of swimming versus currents could be assessed (Fossette *et al.* 2012; Galli *et al.* 2012; Hays *et al.* 2014a). Such detailed assessment of the routes followed may allow more informed assessments of navigational mechanisms used in long-distance migration as well as allowing the impact of currents on migration to be more closely addressed (i.e. for turtles Lohmann & Lohmann 1996; Hays *et al.* 2003; Lohmann, Luschi & Hays 2008).

Here, we have only investigated the impact of Fastloc-GPS accuracy on migrating green turtle tracks. Yet different species have already been tagged using this technology and we expect an increase of Fastloc-GPS use in next years. To process these future tracks, we advise users to use methodologies that: filter data using a threshold residual value and then take account of the number of GPS satellites used in each location calculation to derive an appropriate time interval (i.e. for a migrating green turtle 6 h if one location in a pair is calculated using 4 satellites, 1 h otherwise) over which speed of travel and heading can be estimated.

Funding and authors' contributions

Green turtle Fastloc-GPS tracking data were supported by a grant to GCH from the Darwin Initiative Challenge Fund grant (EIDCF008), the Department of the Environment Food and Rural Affairs (DEFRA) and associated fieldwork approved by the Swansea University Ethics Committee and the BIOT Scientific Advisory Group (SAG) of the U.K. Foreign and Commonwealth Office. GCH conceived the project. TL assembled the fixed trial data. AD and GCH analysed the data and wrote the manuscript with contributions from all authors.

Data accessibility

The Fastloc-GPS fixed trials data set is accessible as supporting information.

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Supporting Information

Additional Supporting Information may be found in the online version of this article.

Data S1. Excel file containing all locations calculated during the fixed trials.