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The implications of location accuracy for the interpretation of satellite-tracking data

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Over the last two decades, satellite tracking with the Argos system has become a widely used tool, enabling the movements of a large variety of terrestrial, aquatic and aerial vertebrates to be recorded (e.g. Weimerskirch et al. 1992; Gudmundsson et al. 1995; McConnell & Fedak 1996; Morreale et al. 1996; Block et al. 1998; Boyd 1999; Polovina et al. 2000). The system uses transmitters (termed platform terminal transmitters or PTTs) that periodically (typically at an interval of around 60 s) send a short (typically 360–920 ms) radio signal (401.650 mHz), termed an uplink, to polar-orbiting NOAA satellites. The location of the transmitter is then calculated from the Doppler shift in the frequency of transmissions received by a satellite as it approaches and then moves away from the transmitter on a single overpass, with each location being assigned a level of accuracy.

A frequent use of satellite tracking is to document long-distance animal movements of hundreds or even thousands of kilometres. When plotting tracks over such spatial scales and describing the general pattern of movement, the inaccuracy of individual locations may be unimportant (e.g. Kjellén et al. 1997). However, once more detailed aspects of Argos tracking data are considered, such as the speed of travel or small-scale movements, then location accuracy is likely to become a much more important issue. For example, the speed of travel may be determined be dividing the distance between two Argos locations by the intervening time interval, but this calculation will be compromised if this distance is short and the location inaccuracy is high. Such problems may be particularly acute in marine studies where the diving behaviour of animals can severely limit the number of uplinks received on each satellite overpass and hence a high proportion of locations may be of low quality (e.g. Plotkin 1998). It is, therefore, surprising that the implications of location accuracy, while frequently acknowledged (e.g. Renaud & Carpenter 1994), are rarely considered in detail. Either of two simple filtering processes are generally used to remove 'erroneous' locations. First, when there are frequent locations of good accuracy, then poor-quality locations may simply be removed from the analysis (e.g. Gudmundsson et al. 1995; Boyd et al. 1998; Klomp & Schultz 2000). This is a valid procedure, but can clearly be used only in studies where good-quality locations are obtained frequently. Second, 'erroneous' locations may be removed because they necessitate an unrealistically high speed of travel from adjacent locations (e.g. McConnell et al. 1992; Luschi et al. 1996; McConnell & Fedak 1996; Hull et al. 1997; Catard et al. 2000). Again this approach is useful in removing the most erroneous locations. However, the problem here is that many of the calculated speeds, while 'biologically realistic', may still be inaccurate.

Given that the Argos system will continue to be widely used by biologists for the foreseeable future, it is important to develop analytical techniques that allow more robust information to be derived from the raw data. Here we examine the implications of Argos location accuracy for determining an animal's speed of travel. We develop some simple guidelines for the interpretation of Argos data that will have wide utility regardless of the species under study. Next we implement these guidelines using Argos data for a green turtle, *Chelonia mydas*, swimming across the South Atlantic and show how appropriate data analysis reveals systematic changes in the speed of travel during migration.

General Considerations

Argos assigns a quality index (termed the location class or LC) to each location. Since 1994, locations have been designated as LC 3, 2, 1, 0, A or B. Of these LC 3, 2, 1 and 0 may be provided only when at least four uplinks are received on an overpass; LC A occurs when a location is determined from three uplinks; and LC B when a location is determined from two uplinks. Argos (1996) state that the estimated accuracy in latitude and longitude is <150 m for LC 3, between 150 and 350 m for LC 2,

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between 350 and 1000 m for LC 1 and >1000 m for LC 0. While the exact terminology used by Argos has changed slightly between different versions of the user manual (e.g. Argos 1989, 1996), it is generally assumed that location errors follow a bivariate normal distribution around the true position, with the standard deviation of latitudinal location error (σ_x) equalling the standard deviation of longitudinal location error (σ_y) such that for LC 3, σ_x=150 m=σ_y; for LC 2, σ_x=350 m=σ_y; and for LC 1, σ_x=1000 m=σ_y (Keating et al. 1991). Argos is unable to assign a level of accuracy to LCs A and B.

In general terms, as the distance between two points (d_n) increases and the location accuracy (σ, where $\sigma=\sigma_x=\sigma_y$) improves, then the error on the calculated speed of travel will be reduced. To illustrate this effect we assumed that an animal travelled in a straight line at 2.5 km/h. We then randomly selected two positions between 0 and 400 km apart on the true course of the animal. To each of these positions we added a location error randomly selected from different levels of location accuracy (σ) and then calculated the speed of travel between the resulting locations. We used the same level of location accuracy for each pair of locations and ran, for each level, 40 000 simulations of speed of travel.

These simulations clearly show that the general pattern for the variation in the calculated speed of travel decreases as both (1) the distance between locations increases and (2) the location accuracy improves (Fig. 1). For σ values of 150, 350 and 1000 m (i.e. corresponding to LCs 3, 2 and 1), the 95% confidence interval on the calculated speed of travel was between 2.25 and 2.75 km/h (i.e. the true value $\pm$ 10%), when the distance between consecutive locations was >3, 5 and 12 km, respectively.

We can extend this analysis, to consider the minimum distance (d_{min}) that is required between two locations to attain this level of accuracy for the calculated speed of travel (i.e. 95% of values lying within the true value $\pm$ 10%) for other levels of location accuracy. For example, when σ=2000 m, d_{min}=23 km, when σ=5000 m, d_{min}=56 km and when σ=10 000 m, d_{min}=110 km (Fig. 2).

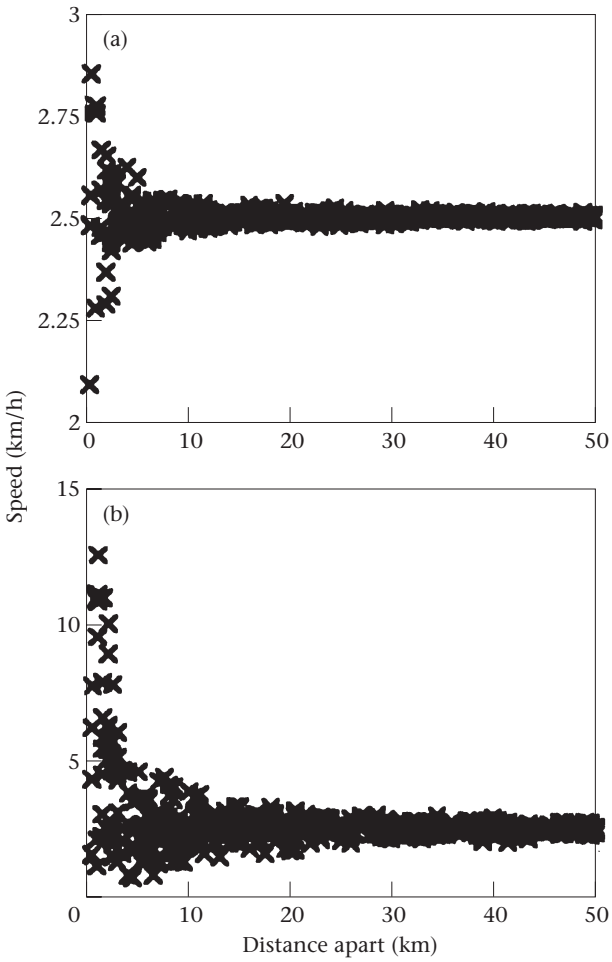

Figure 1. The calculated speed of travel as a function of the distance apart of two locations, for an animal moving at a constant 2.5 km/h. For each graph, a sample of 500 points are shown (to prevent the plot becoming too cluttered) from a total of 40 000 simulations. (a) Location accuracy σ=150 m (i.e. corresponding to LC 3), (b) σ=5000 m (this value selected simply to illustrate the effect of different levels of σ).

Direct Determination of Location Accuracy

To determine directly the accuracy of different classes of Argos location, we left PTTs switched on in fixed positions during fieldwork in 1997, 1998, 1999 and 2000 in Brazil (N=1 PTT switched on for 16 days) and at Ascension Island (N=8 different PTTs switched on for a total of 15 days). PTTs were Telonics models ST-10 and ST-14 (Telonics, Mesa, Arizona, U.S.A.), which we have used routinely to track turtles in various studies around the world. The true position of the PTT in each trial was calculated as the mean position of the class 3 locations.

These trials show the general pattern of decreasing accuracy moving from LC 3 to LC B (Table 1). The accuracies of location classes 3, 2 and 1 correspond approximately with those detailed by Argos, although σ_y was always greater than σ_x. Such a difference has been reported before (Keating et al. 1991) and suggests that the performance levels reported by Argos may need to be re-evaluated. However, the absolute difference between the performance levels given by Argos and those measured here is small and does not affect our subsequent analysis. Much more important for many animal-tracking studies are the accuracies of LC A and LC B, since these accuracies are not reported by Argos. In our trials the accuracy of LC A was comparable to that of LC 1. LC B had poorer accuracy than LC A, but the worst level of accuracy was found in LC 0.

Case Study: Deriving Accurate Speeds of Travel for a Migrating Green Turtle

To consider how knowledge of the interaction between location accuracy and the distance between locations can be used to improve the information derived from Argos tracking, we considered, as an example, real data for a green turtle migrating between Ascension Island and Brazil. This turtle was observed nesting on Ascension

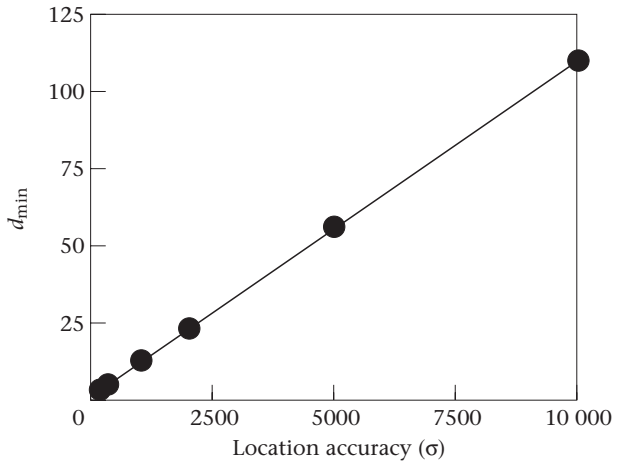

Figure 2. For different levels of location accuracy (σ), the minimum distance between two Argos locations (d_{min}) that is required to ensure that the calculated speed of travel lies within 10% of the true values on 95% of occasions. Simulations were run at σ=150, 350, 1000, 2000, 5000 and 10 000. d_{min} (in km)=0.0109σ (in m)+1.27 (r^2=1.0).

Table 1. For each location class (LC), the number of locations obtained when transmitters were in a fixed location, values for σ_x and σ_y and the mean±SD deviation of locations from the true position

LC	*N* locations	σ_x (km)	σ_y (km)	Deviation (km)
3	38	0.12	0.32	0.27±0.20
2	28	0.28	0.62	0.54±0.40
1	19	1.03	1.62	1.33±1.35
0	9	4.29	15.02	10.10±12.31
A	18	1.39	0.81	0.99±1.36
B	22	5.23	7.79	7.00±6.92

Island on the night of 1–2 June 1998. After egg laying was complete, a Telonics ST-10 PTT was attached to the head of the turtle with quick-setting epoxy. The last uplink was received from the transmitter 80 days later on 21 August. To date, this is the longest period a transmitter has remained functioning on an Ascension Island turtle and is the only turtle for which we have repeated locations both during the migration to Brazil and in the Brazilian coastal zone. Hence, of the turtles we have tracked from Ascension, this individual is the most appropriate for illustrating our approach for analysis of Argos data.

The study animal began to move away from Ascension Island on 4 June and arrived within 10 km of the coast of Brazil on 11 July. The turtle then travelled along the Brazilian coast until 20 July when its generally southerly coastal travel ceased and it remained in a restricted area until 21 August when the transmitter failed (Fig. 3a). During the 80 days for which the transmitter functioned, 268 locations were obtained.

To examine the speed of travel during the trans-Atlantic crossing and the subsequent southerly coastal travel, we first conducted an initial data screening. In this

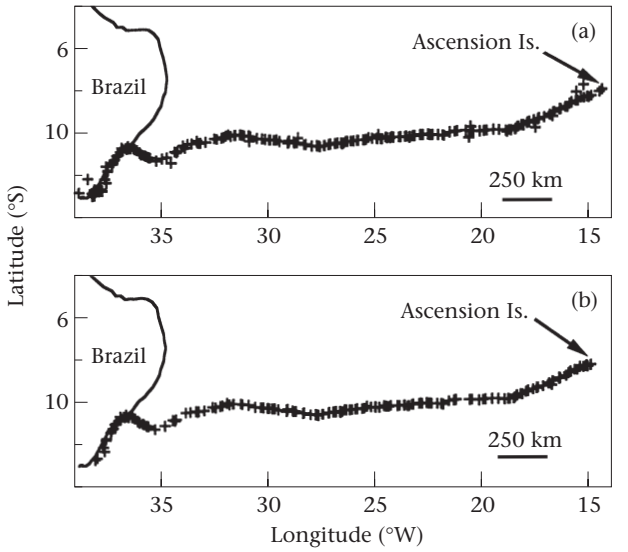

Figure 3. (a) All the locations obtained from a female green turtle at Ascension Island, which travelled westward to Brazil, then south along the coast of Brazil. (b) After the initial data screening (see text for details), the 178 locations used in subsequent speed of travel calculations.

screening we removed locations of LC 0 (since LC 0 provided the poorest accuracy, *N*=17); locations prior to the departure from Ascension Island (*N*=3); locations after the southerly travel along the Brazilian coast had ended (*N*=62); locations during the trans-Atlantic crossing that were clearly visibly anomalous (the anomalous nature of these locations was confirmed by all such locations necessitating a speed of travel of ≥13 km/h (*N*=7) which is unrealistically high for turtles; Luschi et al. 1998); and a location during the period of southerly coastal travel that was well inland. The data set for subsequent speed of travel analysis therefore had 178 locations (Fig. 3b), most of which were LC B (for LC 3, 2, 1, A and B, *N*=1, 5, 14, 53 and 105, respectively) for which we had measured values of σ_x=5.23 km and σ_y=7.79 km. The equation in the legend to Fig. 2 suggests that a minimum distance of around 86 km is required to obtain accurate estimates of speed of travel from such locations. Erring on the side of caution, we calculated the speed of travel from pairs of locations that were at least 90 km apart. Indeed as some of the locations used were of LC 2, 1 and A, which all had better accuracy than LC B, using locations with a minimum separation of 90 km was even more conservative. We automated the calculations with a macro written in Minitab (Minitab Inc., Pennsylvania, U.S.A.). In short, this macro started with the first location (loc-a_1) obtained during migration and then searched through all subsequent locations until the next location ≥90 km away was found (loc-b_1). The speed of travel between these two locations was then determined by simply dividing their distance apart (in km) by the intervening time interval (h). This same location (loc-b_1) was then never used again as the second location of a pair in the speed of travel calculation. In this way consecutive values for speed of travel were calculated independently. For the second location obtained during migration

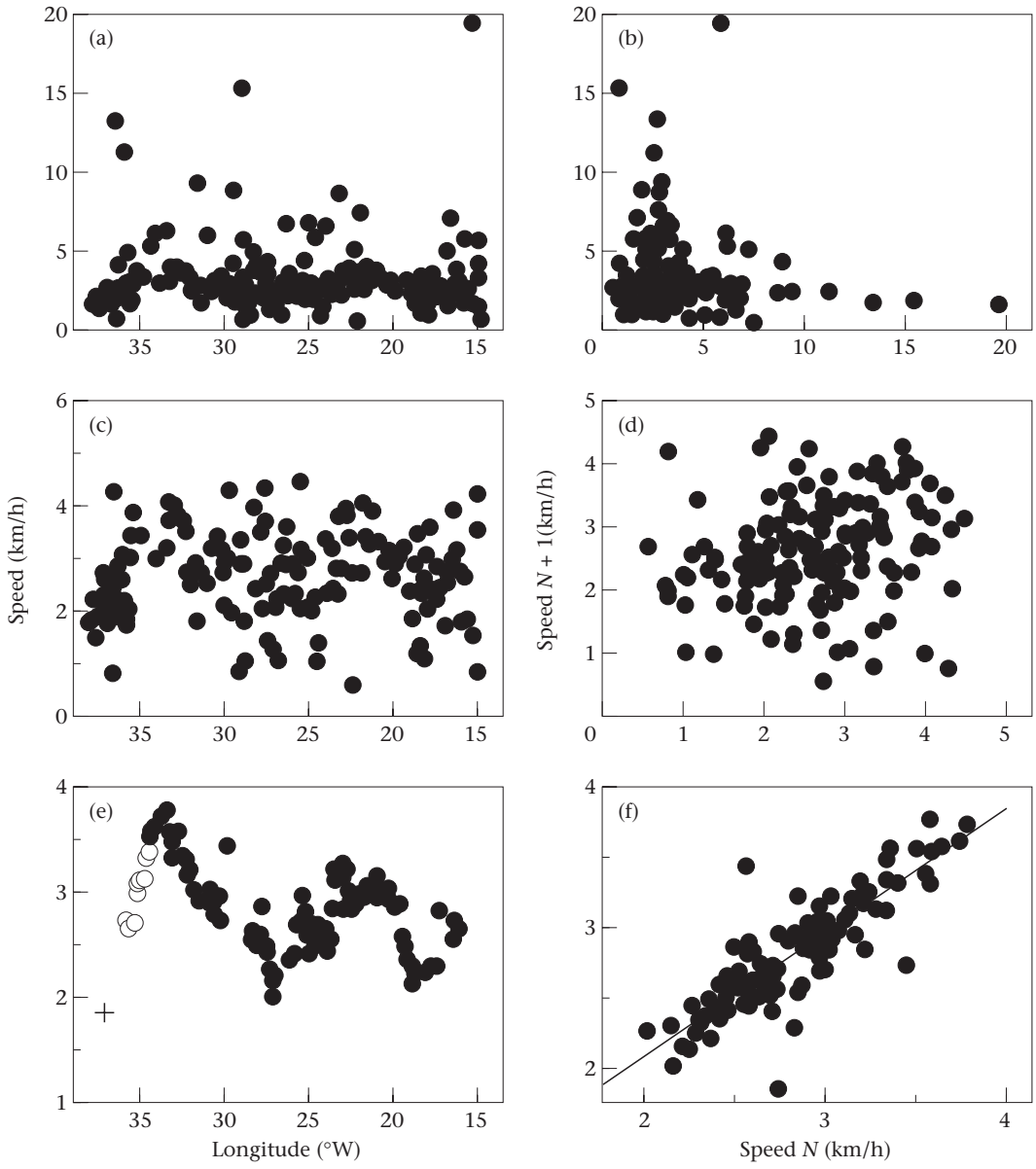

Figure 4. Speeds of travel of a female green turtle during migration from Ascension Island to Brazil and the subsequent southerly travel along the Brazilian coast and the autocorrelation between consecutive speeds. (a–b) Unfiltered data (for b, $F_{1,174}$=0.5, P=0.49). (c–d) Speeds of travel >5 km/h removed (for d, $F_{1,149}$=5.9, r^2=0.04, P=0.016). (e–f) Fully filtered data using only locations at least 90 km apart to determine speed (for f, $F_{1,110}$=283, r^2=0.74, P<0.001). For e, ●: speeds where both locations were obtained during oceanic migration; ○: speeds where one point was during oceanic migration and the other during coastal travel; +: speeds where both points were during coastal travel.

(loc-a_2), the procedure was repeated, and so on. Speeds of travel were subsequently discounted if the straightness index (calculated as the direct distance between locations loc-a_n and loc-b_n divided by the sum of the distances between all the intermediate locations, i.e. (loc-a_1 to loc-a_2)+(loc-a_2 to loc-a_3)+... (loc-b_{n-1} to loc-b_n) was <0.88. Consequently any effect on the calculated speed of travel of the turtle not travelling in a straight line was relatively minor.

So what are the effects of this analytical procedure? When the speed of travel was calculated from all consecutive locations, the calculated speeds varied considerably, with some up to almost 20 km/h which is biologically unrealistic (Fig. 4a). Also there was no autocorrelation between consecutive speeds (Fig. 4b). High speeds of travel may simply be removed from the data. For example we have previously used 5 km/h as the upper threshold for inclusion of speeds in subsequent analysis (e.g. Luschi et al. 1998). When we removed high speeds of travel, considerable variation remained in the data set (Fig. 4c) but a low level of autocorrelation appeared between consecutive speeds (Fig. 4d). However, once the full data analysis was implemented, with only locations ≥90 km apart to determine speed, then clear patterns emerged (Fig. 4e). For example, at about 22–27°W there was a general decline in the speed of travel, while at about

27–34°W there was a general increase. These systematic changes are also shown clearly when the autocorrelation between consecutive speeds of travel is plotted (Fig. 4f). Once the turtle arrived at Brazil and travelled southward along the Brazilian coast, its speed of travel clearly decreased.

Recommendations for Future Argos Tracking Studies

It is intuitively obvious that the accuracy of locations will impact the calculated speed of travel in any tracking studies but while this issue has been extensively explored for conventional radio tracking (e.g. Priede 1992) it has received much less attention for satellite tracking. The fundamental advantage of the approach we have detailed here is that it rigorously defines the impacts of location accuracy in Argos satellite-tracking studies and produces values for speed of travel that have known (and user-specified) accuracy. We conservatively set $d_{\min}$ with the accuracy of LC B. However, our approach could be modified to take into account any difference in the accuracy class for pairs of locations (e.g. a location of class B coupled with one of class A, 1 or 2) so that the speeds of travel over smaller spatial scales could be quantified if necessary. Similarly, if animals travel in extended arcs, rather than straight lines, calculations for the distance travelled might incorporate the straightness index of segments.

For marine studies where LCs A and B often dominate, it is clearly important to know the accuracy of these locations. However, this information is not provided by Argos and, consequently, little is known of the their respective accuracies (but see, for example, Britten et al. 1994 and Boyd et al. 1998). Hence it is prudent for researchers to determine the respective accuracies of LCs A and B for themselves. However, this may not be a simple procedure since the accuracy of these locations may be dependent on the exact nature in which they are generated. For example, a class A location obtained for a migrating turtle might not necessarily have the same accuracy as a class A location obtained for a turtle on its foraging grounds, because differences in diving behaviour may influence the time separation between uplinks which in turn may affect location accuracy. However, such subtle examination of the accuracy of class A and B locations is logistically impossible in many studies and the most reasonable approach to assess their accuracy, and that used here, is simply to use trials with PTTs in fixed locations.

Our examination of Argos locations from a single turtle migrating from Ascension Island to Brazil revealed hitherto undescribed variation in the speed of travel. These variations are systematic, with the turtle travelling slower over certain sections of the journey and faster over others. It is important to note that this systematic variation, as shown clearly by the autocorrelation between consecutive speeds, was based on independent pairs of locations, that is, both the locations used to calculate the first speed of travel were different to the two used to calculate the second speed of travel and so on. Hence this autocorrelation is not an artefact of our data analysis but represents a real biological signal. Similarly, once the turtle arrived at the coast of Brazil, the speed of travel decreased significantly. As such variations in speed have not been rigorously identified before, our understanding of their causality is still in its infancy. Factors that may contribute to this observed variation include hydrography, that is, the assistance to travel provided by prevailing currents; the proportion of time individuals spend actively swimming during migration rather than resting; or (for green turtles in coastal areas since these are benthic herbivores) the proportion of time they spend feeding.

In summary, the approach we have described here will allow the rigorous determination of variations in speed of travel for satellite-tracked animals. As the availability of environmental data collected over large spatial scales improves (e.g. from satellite observations) and the biological parameters provided via satellite transmitters increases (e.g. dive information), so hypotheses can be developed as to the causality of variations in speed of travel during long-distance movements.

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