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# Moderating Argos location errors in animal tracking data

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## Summary

**1.** The Argos System is used worldwide to satellite-track free-ranging animals, but location errors can range from tens of metres to hundreds of kilometres. Low-quality locations (Argos classes A, 0, B and Z) dominate animal tracking data. Standard-quality animal tracking locations (Argos classes 3, 2 and 1) have larger errors than those reported in Argos manuals.

**2.** The Douglas Argos-filter (DAF) algorithm flags implausible locations based on user-defined thresholds that allow the algorithm's performance to be tuned to species' movement behaviours and study objectives. The algorithm is available in Movebank – a free online infrastructure for storing, managing, sharing and analysing animal movement data.

**3.** We compared 21,044 temporally paired global positioning system (GPS) locations with Argos location estimates collected from Argos transmitters on free-ranging waterfowl and condors (13 species, 314 individuals, 54,895 animal-tracking days). The 95th error percentiles for unfiltered Argos locations 0, A, B and Z were within 35·8, 59·6, 163·2 and 220·2 km of the true location, respectively. After applying DAF with liberal thresholds, roughly 20% of the class 0 and A locations and 45% of the class B and Z locations were excluded, and the 95th error percentiles were reduced to 17·2, 15·0, 20·9 and 18·6 km for classes 0, A, B and Z, respectively. As thresholds were applied more conservatively, fewer locations were retained, but they possessed higher overall accuracy.

**4.** Douglas Argos-filter can improve data accuracy by 50–90% and is an effective and flexible tool for preparing Argos data for direct biological interpretation or subsequent modelling.

**Key-words:** accuracy, animal movement, Argos, Douglas Argos-filter, Movebank, satellite telemetry

## Introduction

The Argos System (Argos, www.argos-system.org) is a global satellite-based data collection and location system operated by *Collecte Localisation Satellites* (CLS) which has been used to track animal movements since the mid-1980s (Fancy *et al*. 1988; Harris *et al*. 1990; Seegar *et al*. 1996). Between 1997 and 2011, the number of concurrent animals being tracked with the Argos System increased from *c*. 1200 to 8000 (CLS America, pers. comm.). Satellite telemetry has proven its efficacy in obtaining new information about species distributions (BirdLife International 2004), migration routes (Mate, Lagerquist & Calambokidis 1999), habitat use (Fischbach, Amstrup & Douglas 2007) and foraging ecology (Weimerskirch *et al*. 1993; Le Boeuf *et al*. 2000) and has made important contributions to wildlife management and conservation (Seegar *et al*. 1996; Blumenthal *et al*. 2006).

Argos receivers are on several (4–5) polar-orbiting satellites, providing year-round worldwide coverage. As a satellite passes overhead, perceived Doppler shifts in the transmissions (messages) from tags, called platform transmitter terminals (PTTs), are recorded and used to estimate the PTT's location (Fancy *et al*. 1988; CLS 2011). Many contemporary PTTs also have global positioning system (GPS) receivers that communicate GPS locations as data embedded in the Argos messages. Hence, Argos-linked GPS receivers obtain both Doppler-derived (hereafter 'Argos locations') and GPS-derived locations.

The accuracy of Argos locations has important effects on the ultimate uses of the data for science and conservation. CLS assigns each location to one of seven location quality classes (LCs). Locations derived from four or more messages are assigned LC values 0–3, depending on an estimate of location

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error radius (Table 1). Accuracy cannot be estimated for locations derived from three or two messages, which are, respectively, assigned LC values A and B. Locations deemed 'invalid' by Argos are assigned LC Z. In animal tracking studies, it is common for the majority of locations to be comprised of lower-quality LCs: 0, A, B or Z (Le Boeuf *et al.* 2000; Austin, McMillan & Bowen 2003; Soutullo *et al.* 2007; Freitas *et al.* 2008; Witt *et al.* 2010).

Argos animal tracking locations commonly do not attain the levels of accuracy reported by CLS (Le Boeuf *et al.* 2000; Costa *et al.* 2010; Witt *et al.* 2010). By comparison with PTTs used to benchmark the Argos System, animal tracking PTTs have lower output power and are further subjected to the degrading effects of temperature change, movement and weakening of the antenna's radiation efficiency because of close proximity to a living animal (Harris *et al.* 1990). Field trials have shown Argos location error to increase with speed of movement, impaired visibility of the PTT to the satellite (because of vegetation, topography, etc.), rapid changes in temperature, and slow repetition rate and duty cycle (Nicholls, Robertson & Murray 2007).

The prevalence of low-quality locations in animal tracking applications necessitates treatment of the raw data to exclude implausible locations. Several filtering algorithms have been developed to judge location plausibility based on movement rates (McConnell, Chambers & Fedak 1992), turning angles (Keating 1994) or a combination of both (Austin, McMillan & Bowen 2003; Freitas *et al.* 2008). While filtering algorithms reduce data volume, they markedly improve overall accuracy among retained locations.

Location errors have been addressed with smoothing algorithms that weight Argos locations based on estimated error and time between locations, both in a generalized (Freeman *et al.* 1997) and in a species-specific framework (Thompson, Moss & Lovell 2003). Location errors also have been used to guide probabilistic allocations of animal occupancy within gridded cells across a study area (Tougaard, Teilmann & Tougaard 2008). Tremblay, Robinson & Costa (2009) developed a novel method to estimate individual movement paths from Argos locations by bootstrapping random walks with forward-biased particle motion, while incorporating estimates of location error and physical boundaries (e.g. a marine animal crossing overland).

**Table 1.** Argos Doppler location class (LC) accuracy as estimated and documented by CLS (2011), based on the least-squares method of location derivation

| Location class | Estimated error radius | Number of transmissions |
|---|---|---|
| 3 | <250 m | ≥4 |
| 2 | 250–500 m | ≥4 |
| 1 | 500–1500 m | ≥4 |
| 0 | >1500 m | ≥4 |
| A | No estimation | 3 |
| B | No estimation | 2 |
| Z | Invalid location | |

Doppler location errors are not strictly isotropic; the CLS error radius is calculated as $\sqrt{wr}$, where $r$ and $w$ are the semi-major and semi-minor axis lengths of an estimated error ellipse.

Sophisticated statistical approaches have applied state-space models that couple an observation model (tracking locations and error estimates) with a hypothetical process model such as correlated random walk (Jonsen, Flemming & Myers 2005; Patterson *et al.* 2008). The process model predicts a future state (e.g. location) of an individual given its current state, and the observation model then weights the predictions by likelihood of the empirical data and may also provide interpolation of locations along the track (Johnson *et al.* 2008; Royer & Lutcavage 2008; Patterson *et al.* 2010). Before applying state-space models to Argos location data, it is advisable to first exclude outlier locations (Royer & Lutcavage 2008; Patterson *et al.* 2010).

Our primary goal is to describe structure and performance of the Douglas Argos-filter algorithm (DAF), as implemented within the Movebank tracking database (www.movebank.org). DAF is a threshold filter with several user-prescribed parameters that allow its performance to be tuned to accommodate species' movement characteristics and study objectives. DAF has been used by several tracking studies (Douglas 2006); however, the algorithm's convenience was previously limited by its dependency on Statistical Analysis System software (SAS® Institute Inc., Cary, NC, USA).

A secondary goal is to broaden awareness of Movebank, a free online infrastructure available to all researchers for storing, managing, sharing and analysing animal movement data. Movebank supports animal tracking data collected by a range of methods, including Argos Doppler, GPS, radiotelemetry, light-level geolocators, and banding or unique markings (Kranstauber *et al.* 2011). Data owners maintain full control of their data and can choose from a spectrum of data-sharing options from entirely private to fully public. Movebank also provides an increasing number of analytical tools including automated track annotations based on global weather, ocean, vegetation and land-use data sets.

## Materials and methods

### ARGOS DATA PROCESSING IN MOVEBANK

Movebank users can upload text files of Argos data in the original diagnostic (DIAG) format or upload tracking data in a converted tabular format and use Movebank's interface to translate the tabular variable names to the DIAG naming convention. Movebank also offers a live-feed option to users with active transmitters. Users provide their Argos credentials, after which Movebank connects to the Argos data server every 6 h to import new data. Live feeds can be configured to email up-to-date data summaries (including Google™ Earth format files) to a user-defined recipient list on a user-defined schedule.

Doppler location estimates always include two location solutions – a 'true' location and a 'mirror' location (CLS 2011). CLS judges which solution is most likely correct and names it the primary location (LAT1/LON1) in the DIAG format, along with the alternate location (LAT2/LON2). Roughly 3% of CLS' judgements are incorrect among animal tracking data (see results). Consequently, a Movebank algorithm independently chooses between the primary and alternate locations along an animal's entire track by determining the set of points that result in the shortest path through all combinations of primary and alternate locations, ignoring class Z locations. The algorithm then makes a second pass and fills in either the primary or alternate class Z locations while keeping decisions from the first pass fixed. All distances in Movebank are calculated as great circle routes (orthodromes) using the World Geodetic System 1984 reference ellipsoid.

## THE DOUGLAS ARGOS-FILTER ALGORITHM

The DAF offers three filtering methods of increasing complexity: (i) the 'maximum redundant distance' filter (MRD), which simply retains locations based on spatial redundancy between consecutive locations; (ii) the 'distance angle rate' filter (DAR), which retains spatially redundant locations and locations that pass movement rate and turning angle tests; and (iii) the 'hybrid' filter (HYB), which optimally combines the MRD and DAR results by extracting DAR outcomes only during migration periods and combines them with all MRD outcomes. When a user applies the DAF in Movebank, a new attribute called 'algorithm marked outlier' is added to the data set and the value 'true' is assigned to all filtered locations. The outlier attribute can be entirely removed at any time, and the DAF reapplied using a different method or different thresholds. Any filtering decision can be manually overruled on a case-by-case basis using tabular- and map-based interfaces. User-defined parameters that are required or optional for the DAF are denoted henceforth in capital letters and further described in Table S1.

### *Maximum redundant distance filter*

The MRD filter retains locations that have near-consecutive locations within a user-defined distance threshold. The premise for the MRD filter is that errors of consecutive Argos locations are independent. Each processing step by the algorithm considers the distances between three consecutive locations A, B and C and marks them as either mrd_retained or mrd_filtered. If any of the vectors AB, BC or AC are shorter than the user-defined parameter MAXREDUN, then the respective vector endpoints are marked as mrd_retained. The user also prescribes which LCs are exempt to filtering. In practice, any location with an LC greater than or equal to KEEP_LC will be unconditionally retained. All remaining points are marked as mrd_filtered unless they were previously marked mrd_retained. The user also prescribes how an animal's last location will be treated. If KEEPLAST = 1 (true), then the last location of a track is always marked mrd_retained, otherwise, it must pass the MRD criteria.

In the next processing step, locations B, C and D are considered and so on until the end of the track. A slight variation occurs if the user-defined parameter SKIPLOC is set to 1. In this case and if location B was marked as mrd_filtered, then location B is skipped in the next step and C, D and E are considered instead of B, C and D.

### *Distance, angle and rate filter*

The DAR filter identifies implausible locations based on unrealistic movement rates or the fact that a majority of tenuous Argos locations indicate that an animal moved a substantial distance and then returned, resulting in a tracking path that goes 'out-and-back'.

Each processing step in the algorithm considers four consecutive locations A, B, C and D around a focal location B that will be marked as either dar_retained or dar_filtered. Five tests are evaluated sequentially based on distances between locations, for example, distAB; tracking velocities between locations, for example, rateAB; the internal angle between AB and BC denoted by alpha; and the minimum allowed angle minAlpha, determined as −25 + RATECOEF*ln(min(distAB, distBC)). The user prescribes thresholds for MAXREDUN, MINRATE, RATECOEF and KEEP_LC. MINRATE should reflect an upper bound of sustainable movement rate over a period of hours, including potential assistance by winds or currents. Larger values for RATECOEF will be less tolerant of acute turning angles; choices are typically between 15 and 25. The five sequential tests that evaluate location B are as follows: (1) if distance (A,B) < MAXREDUN, then retain; (2) if LC $\geq$ KEEP_LC, then retain; (3) if alpha < minAlpha, then filter; (4) if rateAB > MINRATE, then filter; and (5) if rateBC > MINRATE and distAB + distBD > distAC + distCD, then filter.

If the condition for any test is fulfilled, all subsequent tests are skipped. If none of the conditions are fulfilled, the location is retained. If the user has specified R_ONLY = 1 (rate only), then test 3 is not conducted. In the next processing step, locations B, C, D and E are considered and so on until the end of the track. The filtering procedure is repeated five times, each time only keeping locations marked as dar_retained for the next iteration. In the last iteration, test 5 is simplified to test 5a: if rateBC > MINRATE, then filter.

Rationale behind test 3: the condition is designed to detect improbable tracking paths that go 'out-and-back'. The weighting factor ln(min (distAB,distBC)) in the calculation of the minimum allowed angle minAlpha reflects the assumption that the farther an animal moves, the less likely it is to have immediately returned back towards the originating locale. Rationale behind test 4: if rateAB is implausibly high, then location B is filtered. Rationale behind test 5: if rateBC is implausibly high, then it becomes ambiguous whether location B or location C is implausible (test 5a). If the cumulative distance from A to D via B is greater than the cumulative distance from A to D via C, then location B is considered more implausible and filtered (test 5b). Otherwise, location B is retained, and it is left to the next processing step to filter location C or not. The DAR strategy is iterated 5 times because filtering a location may create implausible tracking velocities or suspicious angles that need to be re-evaluated by a subsequent iteration. In the last iteration, the cumulative distance test is skipped (test 5b) to exclude any remaining vectors longer than MAXREDUN with implausible movement rates.

### *Hybrid filter*

The HYB filter was developed for avian tracking data characterized by periods of relatively sedentary behaviour (nesting, moulting, staging, etc.) interspersed with rapid and directional movement (migration). First, locations that passed the MRD filter are unconditionally retained as 'anchor points'. Then, any chronologically intervening migration locations that passed the DAR filter are judged to determine whether they conform with directional movement when compared to the vector formed by their preceding and subsequent MRD anchor locations.

This step in the algorithm considers two consecutive locations $x_0$ and $x_n$ that have passed the MRD filter and the temporally intervening locations $x_1$, …, $x_{n-1}$ that have uniquely passed the DAR filter. HYB algorithm only retains an intervening DAR location $x_i$ if the containing sequence $x_0$, $x_1$,…, $x_{n-1}$, $x_n$ qualifies as a 'migration event' and if $x_i$ passes a composite directionality test. The sequence $x_0$, $x_1$, …, $x_{n-1}$, $x_n$ is considered a migration event if the distance between $x_0$ and $x_n$ exceeds XMIGRATE*MAXREDUN.

If a migration event is determined, the following tests are performed separately for all intervening locations $x_i$ in $\{x_1, …, x_{n-1}\}$. First, the distance between $x_0$ and $x_{n-1}$ must be less than the distance between $x_0$ and $x_n$ + XOVERRUN*MAXREDUN. If true, three more tests are performed. Test 1 (directional deviation): the heading of the vector $x_0-x_i$ must be within ± XDIRECT degrees of the heading of the vector $x_0-x_n$. Test 2 (angular deviation): the angle formed by $x_0-x_i-x_n$ must exceed XANGLE degrees. Test 3 (distance deviation): the length of $x_0-x_i-x_n$ must not exceed the length of $x_0-x_n$ by more than XPERCENT percentage. Location $x_i$ is retained by the HYB filter if it passes a user-defined number of the three directionality tests, depending on the LC of location $x_i$. If the LC of $x_i$ is B or Z, then a user-prescribed number of tests (TEST_BZ) need to be passed. If the LC of $x_i$ is A or better, TEST_0A tests need to be passed.

### *'Best of Day' subset*

The 'Best of Day' option creates a subset of the retained locations by choosing the 'best-quality' location per Greenwich Mean Time (GMT) day or per PTT duty cycle. Locations are grouped by GMT day if the user defines PICKDAY = 1. Otherwise, groups are defined by a time interval in which consecutive locations are less than MINOFFH hours apart. The user prescribes MINOFFH to be slightly larger than the PTT's maximum on-period (in hours). If the PTT's on-period is greater than its off-period, the ability to discriminate between duty cycles is not possible, and PICKDAY = 1 should be used.

The 'best-quality' location within each group is chosen based on variables in the DIAG data. The location with the best LC will be chosen. Tie-breaking depends on the user's choice of RANKMETH (1, 2, or 3) in which the following hierarchy of DIAG variables is used to rank the tied locations within a group: (1) LC, IQX, IQY, NBMES; (2) LC, IQX, NBMES, IQY; and (3) LC, NBMES.

### PERFORMANCE OF THE DAF

Two avian tracking studies contributed data for quantifying performance of the DAF. One study co-led by the United Nations Food and Agriculture Organization and US Geological Survey tracked 252 individual waterfowl in Asia and Africa during 2006–2011. This multinational study contributed data from nine duck species ($n$ = 128 individuals), two goose species ($n$ = 114) and one swan species ($n$ = 10). Data include 92,579 Argos Doppler locations collected on 24,847 animal-tracking days. Most locations (68·6%) were obtained from bar-headed geese (*Anser indicus*, $n$ = 96) and ruddy shelducks (*Tadorna ferruginea*, $n$ = 45). The second study monitors California condors (*Gymnogyps californianus*) and is led by a consortium of conservation partners, including the US Fish and Wildlife Service, National Park Service and the Ventana Wildlife Society. The condor study contributed 207,655 Argos Doppler locations from 62 individuals collected on 30,048 animal-tracking days. Both studies used Argos-linked GPS PTTs manufactured by Microwave Telemetry Inc. (Columbia, MD, USA) that were harnessed onto waterfowl and wing-clipped on condors. Waterfowl PTTs typically had seasonal duty cycles that ranged from 2 to 6 h on and 1–2 days off, while condor PTTs typically transmitted for 4–5 h daily. All Argos locations were estimated by CLS using the least-squares method (see Discussion).

Argos DIAG tracking data for each bird were filtered with the DAF using the HYB method. Before filtering, location-long/location-lat was chosen between the primary and alternate locations using the Movebank algorithm described above. DAF was independently applied four times, each prescribing a different MAXREDUN threshold: 15, 10, 5 and 2 km. All other user-defined parameters were held constant for each run: MINRATE = 80 km $h^{-1}$ (condors) and 100 km $h^{-1}$ (waterfowl), KEEP_LC = 1, KEEPLAST = 0, SKIPLOC = 0, RATECOEF = 25, R_ONLY = 0, XMIGRATE = 2, XOVERRUN = 2, XDIRECT = 20°, XANGLE = 150°, XPERCENT = 20%, TESTP_0A = 2, TESTP_BZ = 3 and RANKMETH = 2. To quantify Argos location accuracy for tracking data obtained from free-ranging birds before and after filtering with the DAF, Argos Doppler locations within ±5 min of a GPS location were extracted ($n$ = 21,044) and compared with the GPS location.

## Results

Argos location estimates of free-ranging birds exhibited a wide spread of errors that were generally consistent with their assignment to LCs (Fig. 1a). The 68th error percentiles for LCs 3, 2 and 1 were 0·4, 1·0 and 2·5 km, respectively (Table 2), notably worse than the error estimates of 0·25, 0·5 and 1·5 km documented by CLS (Table 1). The 68th error percentiles of unfiltered LC 0, A, B and Z locations were 10·4, 8·1, 30·5 and 30·3 km, respectively. Roughly 25–30% of the unfiltered class A and 0 locations and 50–60% of the class B and Z locations had errors >10 km (Fig. 1a). A greater proportion of LC A locations had errors <10 km compared with class 0, but the relationship switched for errors >15 km.

Argos location errors had a longitudinal bias that was evident regardless of error magnitude (Fig. 2), as has been found in previous studies (Keating, Brewster & Key 1991; Hays *et al.* 2001; Vincent *et al.* 2002; Costa *et al.* 2010; Witt *et al.* 2010) and reported by CLS (2011). Longitudinal error exceeded latitudinal error in 88% of LC Z locations and 65–70% of all other locations.

Douglas Argos-filter strives to exclude locations with large errors while retaining those with small errors, and MAXREDUN is the most influential user-defined parameter that governs omission and commission filtering error rates. Prescribing MAXREDUN = 15 km was effective in excluding most of the more erroneous locations (Fig. 1b), with 95% of the retained locations having <21 km error (Table 2). Furthermore, omission-filtering errors were minimal, that is, few locations with modest error (<10 km) were excluded (Fig. 1b).

Reducing MAXREDUN produced outputs with greater overall accuracy, but with fewer locations (Table 2). For example, prescribing MAXREDUN = 5 km retained only 61% and 41% of the LC A and Z locations, respectively (Table 2), but their accuracy was generally commensurate with LC 1 (Fig. 1c). Among retained locations of LCs 0 and B, 95% had errors <13 km. However, using MAXREDUN = 5 km to improve accuracy among the retained locations was accompanied by greater levels of omission error. About 50% of the excluded LC 0 locations had errors <10 km and similarly for 35%, 20% and 15% of the LC A, B and Z locations, respectively (Fig. 1c).

The Movebank algorithm that selected between the two Argos location solutions overruled the primary location in favour of the alternate location in 3% ($n$ = 624) of the data records. The Movebank algorithm was robust because incorrect choices by Argos typically cause location errors in the order of hundreds of kilometres (Fig. 3) and because the

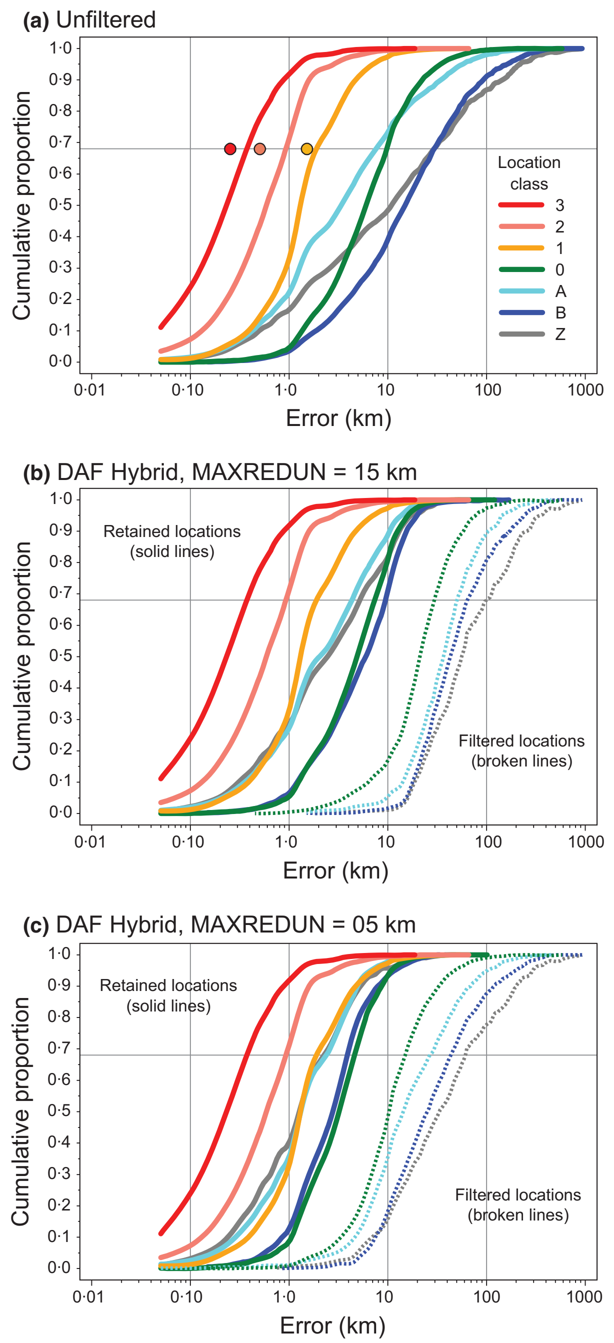


**Fig. 1.** Cumulative Argos location error distributions among seven location classes (LCs) before (a) and after filtering with the Douglas Argos-filter (DAF) hybrid algorithm using a spatial redundancy threshold of 15 km (b) and 5 km (c). Data from free-ranging birds. Location classes 3, 2 and 1 were exempt from filtering; hence, their lines are static in all three panels. Results were averaged within error bins for plotting. Horizontal reference line denotes 68th percentile. Three dots (top panel) denote upper ranges of the Collecte Localisation Satellites (CLS)-estimated error radii (Table 1) for LC 3, 2 and 1. Note the *x*-axis is log scale.

Movebank algorithm had information about the full track and thus the animal's destination, which CLS did not have. Incorrect choices by Argos were most common among LC Z (25%), but occurred even for standard LCs (3, 2 and 1) (Fig. 3). Of the 624 records for which the alternate location was chosen, 62%, 53%, 39% and 27% were ultimately retained by the DAF (HYB method) when MAXREDUN was prescribed as 15, 10, 5 and 2 km, respectively.

**Table 2.** Argos Doppler location errors before and after filtering with the Douglas Argos-filter (DAF) algorithm, expressed as the 68th, 95th and 99th error percentiles and root mean square errors (RMSE) among seven Argos LCs (location classes)

| | Error (km) | | | | | |
|---|---|---|---|---|---|---|
| Location class | 68% | 95% | 99% | RMSE | *n* | % Retained |
| Unfiltered data | | | | | | |
| 3 | 0·4 | 1·5 | 3·9 | 1·0 | 1110 | |
| 2 | 1·0 | 3·3 | 8·0 | 2·5 | 2324 | |
| 1 | 2·5 | 7·6 | 16·6 | 4·3 | 3424 | |
| 0 | 10·4 | 35·8 | 78·1 | 21·3 | 8686 | |
| A | 8·1 | 59·6 | 139·7 | 33·0 | 2053 | |
| B | 30·5 | 163·2 | 334·4 | 74·4 | 2525 | |
| Z | 30·3 | 220·2 | 577·5 | 112·5 | 922 | |
| DAF Hybrid, MAXREDUN = 15 km | | | | | | |
| 0 | 7·9 | 17·2 | 28·0 | 9·1 | 7070 | 81 |
| A | 4·8 | 15·0 | 25·0 | 7·4 | 1672 | 81 |
| B | 10·0 | 20·9 | 33·6 | 13·0 | 1362 | 54 |
| Z | 5·9 | 18·6 | 33·5 | 9·1 | 540 | 59 |
| DAF Hybrid, MAXREDUN = 10 km | | | | | | |
| 0 | 6·8 | 15·1 | 23·1 | 7·8 | 6118 | 70 |
| A | 4·1 | 11·3 | 19·0 | 5·7 | 1534 | 75 |
| B | 7·6 | 18·0 | 28·8 | 11·5 | 1096 | 43 |
| Z | 4·7 | 14·8 | 30·9 | 7·2 | 488 | 53 |
| DAF Hybrid, MAXREDUN = 05 km | | | | | | |
| 0 | 5·1 | 11·9 | 19·7 | 6·3 | 4011 | 46 |
| A | 2·9 | 7·0 | 15·5 | 4·2 | 1248 | 61 |
| B | 4·3 | 13·0 | 23·4 | 6·2 | 701 | 28 |
| Z | 2·8 | 8·8 | 26·6 | 5·2 | 375 | 41 |
| DAF Hybrid, MAXREDUN = 02 km | | | | | | |
| 0 | 4·6 | 12·6 | 21·1 | 6·4 | 2061 | 24 |
| A | 1·7 | 5·8 | 14·7 | 3·6 | 830 | 40 |
| B | 2·8 | 9·5 | 21·3 | 5·2 | 326 | 13 |
| Z | 1·4 | 4·8 | 16·7 | 3·3 | 253 | 27 |

Filtering results were obtained using the DAF hybrid option, executed with four different user-prescribed redundant distance thresholds (MAXREDUN). Filtering was applied to the lower-quality Argos LCs only (0, A, B and Z). Data obtained from free-ranging birds wearing Argos-linked global positioning system (GPS) receivers for pairs of Argos and GPS locations that were <5 min apart. Raw data provided in Data S1.

## Discussion

Although higher-accuracy GPS tags are increasingly popular, the lighter-weight Argos PTTs remain the only option for tracking small animals over large distances and are the source of large amounts of existing data, so improving the quality of those locations remains a priority. Our study builds on a growing body of literature documenting Argos location errors of free-ranging animals when compared to concurrent GPS data (Soutullo *et al*. 2007; Hazel 2009; Kuhn *et al*. 2009; Costa *et al*. 2010; Witt *et al*. 2010). Our sample size ($n = 21{,}044$) is the largest published to date and the first to robustly quantify data from free-ranging birds; see Soutullo *et al*. (2007) for

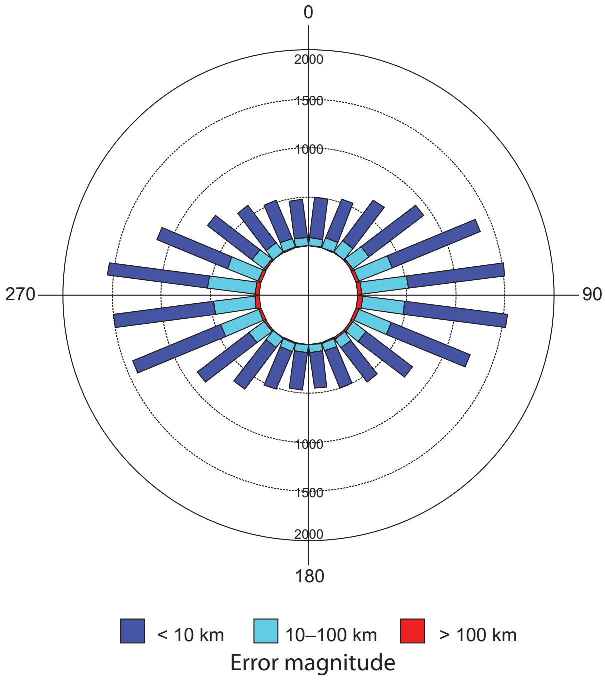


**Fig. 2.** Circular histogram showing counts of unfiltered Argos locations of free-ranging birds ($n$ = 21,044) with respect to the error azimuth (from the 'true' global positioning system (GPS) location), partitioned by three intervals of error magnitude.

$n$ = 96. Errors among our unfiltered Argos locations (Table 2) were consistent with those obtained by other animal tracking investigations: (i) standard LCs (3, 2 and 1) possess errors greater than those reported by Argos; (ii) errors for lower-quality LCs (0, A, B and Z) are highly variable; (iii) a majority of locations are of lower-quality LCs; (iv) LC A has smaller 1-sigma errors than LC 0; and (v) errors are biased longitudinally (Fig. 2).

Few animal tracking studies can exclude all low-quality Argos LCs without eliminating potentially important biological information. The primary goal of the DAF is to moderate the error distribution among LCs 0, A, B and Z so that higher-quality locations within these classes can be used for data analysis. MRD is a robust filtering strategy for relatively slow-moving animals for which there is a high probability of obtaining consecutive locations that are within a threshold of spatial redundancy (MAXREDUN). This probability is influenced by PTT duty cycles, the frequency of satellite overpasses and species' behaviour. The underlying strategy assumes that accurate locations obtained during a period when the animal has moved little will cross-validate one another.

Some species have movement behaviours that markedly reduce probability of obtaining consecutive locations at the same locale. DAR method is generally more appropriate than MRD for species such as marine turtles and marine mammals. However, MAXREDUN remains important to the DAR because consecutive locations that are within MAXREDUN distance will be retained by virtue of spatial redundancy – regardless of movement rates or turning angles. With MAXREDUN = 5 km, DAR method is similar to the Argos filtering approach developed by Freitas *et al.* (2008). DAR method is more robust for slower-moving animals because MINRATE becomes more effective in discriminating

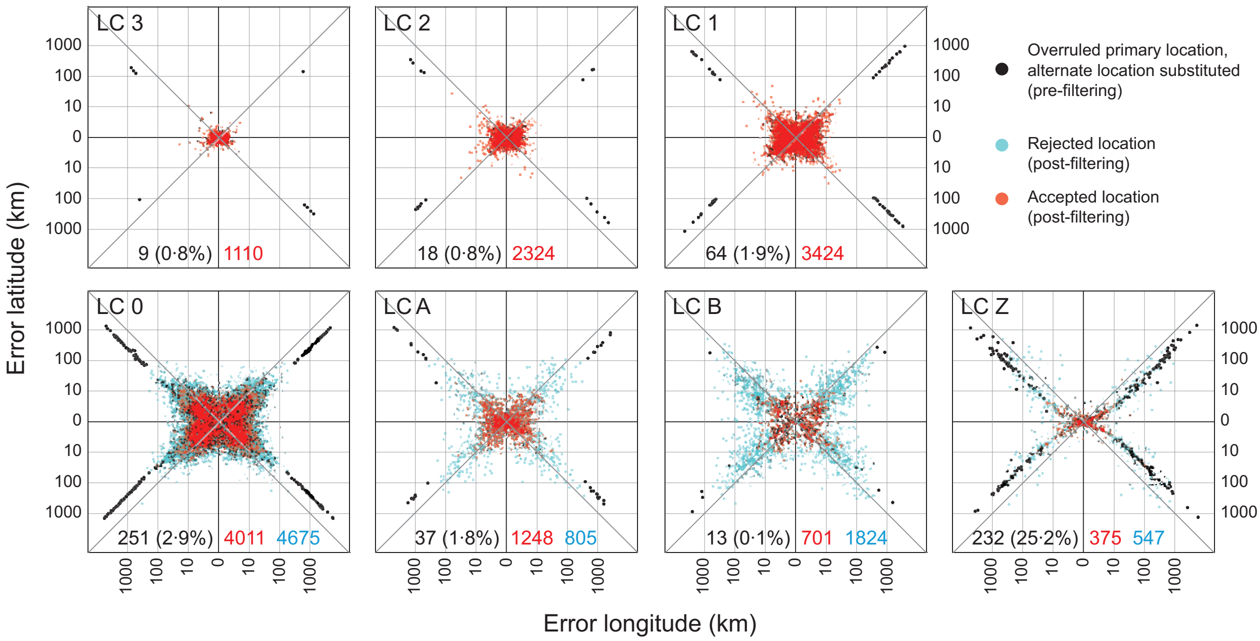


**Fig. 3.** Latitude and longitude errors of free-ranging birds among seven Argos location classes (LCs). Black dots show primary locations that were overruled in favour of their alternate locations before filtering. Then, accepted (red) and rejected (blue) locations were classified with the Douglas Argos-filter algorithm using the hybrid method and a 5-km redundant distance threshold (MAXREDUN). Location classes 3, 2 and 1 were exempt from filtering. Sample sizes at the bottom of each panel are colour-coded as per the legend. Diagonal reference lines highlight that errors are not strictly isotropic. Note log scales for both axes.

implausible locations. Commission filtering errors are more probable with the DAR method (compared with MRD), however, because it is not uncommon to obtain sequences of poor-accuracy locations that are temporally separated in a manner that precludes implausible movement rates and spatially dispersed in manner that precludes acute turning angles. The DAR method tends to retain more locations with less overall accuracy compared with the MRD method.

Hybrid method was developed for animals that intermittently move relatively great distances with high speed, such as migratory birds. MRD method is robust when an animal is sedentary, but performs poorly when an animal moves quickly because the probability of acquiring spatially redundant locations is greatly reduced. Hence, movements retained by the DAR method are merged with the MRD output, but only if the movement was far enough to qualify as a 'migration event'. The user can optionally require that DAR movements pass directionality tests for membership in the HYB output; if directionality tests are inappropriate for the species, the tests can be disabled by setting XOVERRUN = 1000, XDIRECT = 180, XANGLE = 0 and XPERCENT = 1000.

Although the uniquely DAR-filtered locations are typically a minority (<5%) of the HYB output for avian tracks, they are sometimes key to biological interpretations because of their role in establishing migratory routes. A spatially isolated low-quality location during a migration event may pass criteria for membership in the HYB output, but this alone does not certify its individual accuracy. Multiple low-quality locations with sufficient temporal frequency (such as during a PTT duty cycle) are necessary to confidently position an animal along its migratory route, and multiple positions (i.e. short duty cycles or continuous tracking) are needed to render full representation of the route (Lonergan, Fedak & McConnel 2009).

Douglas Argos-filter should be applied in a manner congruent with the intended spatial scale of data interpretation. Liberal filtering strategies are recommended for ascertaining broad-scale migration routes and generalized stopover locales and for estimating movement chronologies by virtue of retaining more locations. Continental-scale analyses of migration can tolerate more location error than local-scale analyses of habitat use or home range (Hays *et al.* 2001; Bradshaw, Sims & Hays 2007). Prescribing a liberal MAXREDUN threshold (e.g. 15 km) is strategic for broad-scale analyses because extreme outliers are excluded with few omission errors (Fig. 1b).

Local-scale analyses of Argos animal tracking data are challenged by the magnitude of locational errors. Aggressively constraining errors with the DAF is accomplished by conservatively prescribing MAXREDUN (e.g. 2 or 5 km) to minimize inclusion of unsuitable locations. Reducing MAXREDUN retains fewer locations, but they possess higher collective accuracy (Table 2). However, an upper range in the post-filtering error distribution will persist (Table 2), and local-scale interpretations should be tempered accordingly.

All three filtering methods are compatible with any PTT duty cycle regime. Duty cycles are pre-programmed to balance PTT energy limitations with study objectives, but to the extent possible, minimizing the duty cycle off-time is desirable because judging or estimating an animal's true path of movement is adversely impacted by long periods of PTT inactivity (Lonergan, Fedak & McConnel 2009).

Applications of state-space movement models have pioneered new methods to statistically address locational error, estimate locations at regular time intervals and make inferences about animal behaviour (Jonsen, Flemming & Myers 2005; Johnson *et al.* 2008; Patterson *et al.* 2008; Winship *et al.* 2012). However, before applying a state-space model to Argos tracking data, outlier locations should be excluded, especially if the model uses a Kalman filter which assumes Gaussian error distribution (Patterson *et al.* 2008; Royer & Lutcavage 2008).

**Table 3.** Comparison between the CLS Kalman filter (KF) and the Douglas Argos-filter algorithm (DAF) hybrid method

| | Mean error (km) | | | Std. dev. error (km) | | | Number of locations | | |
|---|---|---|---|---|---|---|---|---|---|
| Lopez & Malardé (2011) | LS | KF | Δ (%) | LS | KF | Δ (%) | LS | KF | Δ (%) |
| Marabou stork | 3·31 | 2·96 | −10 | 3·68 | 3·18 | −14 | 431 | 466 | +8 |
| Geese | 5·97 | 4·64 | −22 | 8·67 | 5·53 | −36 | 4289 | 5263 | +23 |
| This study, threshold 15 km | LS | DAF-15 | Δ (%) | LS | DAF-15 | Δ (%) | LS | DAF-15 | Δ (%) |
| Waterfowl | 8·86 | 3·15 | −64 | 15·79 | 3·38 | −79 | 4794 | 4034 | −16 |
| Condors | 7·22 | 4·00 | −45 | 9·28 | 3·75 | −60 | 15,328 | 12,928 | −16 |
| This study, threshold 5 km | LS | DAF-05 | Δ (%) | LS | DAF-05 | Δ (%) | LS | DAF-05 | Δ (%) |
| Waterfowl | 8·86 | 1·82 | −79 | 15·79 | 1·67 | −89 | 4794 | 3228 | −36 |
| Condors | 7·22 | 2·42 | −66 | 9·28 | 2·16 | −77 | 15,328 | 9590 | −37 |

Following Lopez & Malardé (2011), all locations of quality class Z were removed, and one-message KF locations were removed. Then, the mean and variance of location errors were calculated from values below the 95th percentile of the error distribution for each algorithm. Percentage change (Δ) is relative to the unfiltered Doppler locations derived with the traditional least-squares (LS) algorithm. Values from Lopez & Malardé (2011) were extracted from their Tables II, IV and V. Results for the DAF are presented for two redundant distance (MAXREDUN) thresholds: 15 km (DAF-15) and 5 km (DAF-05).

Not only can the DAF fulfil such a prerequisite, we provide raw data for all error estimates ($n = 21,044$) to facilitate derivations of Argos LC error structures (Data S1).

The condor and waterfowl Argos locations were estimated with a least-squares method that CLS has used since inception of Argos. In March 2011, CLS introduced a new location algorithm that is formulated under a state-space representation with Kalman filtering and interacting movement models (Lopez & Malardé 2011). Presently, Argos users choose between the traditional least-squares method and the new Kalman filtering method. We compared performance of the DAF in the same manner that Lopez & Malardé (2011) compared the Kalman Filter to the least-squares method for avian tracking data (Table 3). The Kalman method is capable of deriving more locations, providing error estimates for locations among all LCs and estimating locations based on satellite passes that obtain only one message – all notable advantages over the least-squares method (Lopez & Malardé 2011). Nonetheless, the DAF algorithm achieved greater overall accuracy and better precision (lower standard deviation) compared with the Kalman filter for avian tracking data, most notably when MAXREDUN was prescribed conservatively (Table 3). Strengths and weaknesses of obtaining Argos locations estimated with CLS' new Kalman method vs. the traditional least-squares method (post-filtering) have yet to be thoroughly investigated. The least-squares method continues to be used and is the source of nearly three decades of past animal tracking data. The DAF provides a robust, flexible and freely available method for improving the quality of these data sets for a wide range of species and study objectives.

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## Supporting Information

**Data S1.** Comma-delimited ASCII data file of error estimates for 21,044 Argos locations of free-ranging waterfowl and condors based on concurrent ( < 5 min) GPS locations.

**Table S1**. Annotated descriptions of the required and optional user-defined parameters for the Douglas Argos-filter Algorithm.