The following supplement accompanies the article

Estimating the distribution and relative density of satellite-tagged loggerhead sea turtles using geostatistical mixed effects models

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Data processing and estimation of Argos location error

Argos assigns each estimated location to one of seven location classes (LC), which are based on decreasing levels of accuracy (LC 3, 2, 1, 0, A, B, and Z; Table S1). While CLS-Argos does provide an estimated error radius for the four most accurate location classes (LC 3-0), error estimates are not provided for LC A and B, which are typically the two LC most commonly-reported (Costa et al. 2010). Additionally, reported errors are assumed to be isotropic, which is not typically the case due to the polar orbit of Argos satellites (Costa et al. 2010; Witt et al. 2010; McClintock et al. 2015). Rather than relying on the default provided error estimates for track reconstruction (see below), we generated empirical estimates of error by directly comparing Argos- and GPS-derived locations reported from 110 turtles tagged with Sea Mammal Research Unit Satellite Relay Data Loggers with Fastloc GPS (Costa et al. 2010; Witt et al. 2010; Hoenner et al. 2012).

Prior to estimating Argos error, both Argos- and GPS-reported locations were filtered to remove obviously erroneous locations. Invalid Argos locations (LC Z) and those exceeding the maximum reasonable speed threshold (2 ms^{-1}; specified prior to tag deployment) were removed, as well as any remaining locations with duplicate time stamps. GPS data were filtered following standard guidelines for marine animal tracking (Witt et al. 2010; Dujon et al. 2014). GPS locations based on transmissions from less than five satellites were discarded prior to analysis, along with any remaining locations with residual errors greater than 30 (Witt et al. 2010). In several instances GPS locations were transmitted far beyond the expected tag life (approximately 120 days) at very infrequent intervals. These “spotty” locations were discarded to ensure that GPS positions were representative of the highly-accurate position estimates typical of functional GPS. The first twenty-four hours of data collected from each turtle were also discarded to mitigate the effect of aberrant post-tagging behavior (TEWG 2009). All data processing was conducted in R statistical software (R Core Team 2016).

For each turtle, Argos-derived location estimates were matched to GPS locations reported within one minute of each other. The minimum straight-line location error (in meters) was estimated as the isotropic Vincenty ellipsoid great circle distance between each matched Argos-GPS location using the R package “geosphere” (Hijmans 2015). Location data were then re-projected into an oblique Mercator center projection centered on 35°00'00.0"N 75°00'00.0"W using the R package “rgdal” (Bivand et al. 2015), and the error in the easting (longitude) and northing (latitude) direction calculated in meters. GPS locations were assumed accurate enough to represent the animal’s true location (Witt et al. 2010). A preliminary analysis that investigated the impact of accounting for additional GPS error on track reconstructions confirmed the validity of this assumption (M. Winton unpubl. data).

The relative accuracy of unfiltered Argos locations was in broad agreement with those reported by CLS-Argos (Table S1), though the errors associated with LC 0 were comparable, and in many cases higher, that those associated with LC A (Tables S1 & S2; Figure S1). Several preliminary analyses were conducted to determine the best way to represent geolocation errors. Correlation between errors in the latitudinal and longitudinal direction was assessed for each LC based on the Kendall rank correlation test (Sokal and Rohlf 1995). Normality of error distributions was assessed using the Shapiro-Wilk test in the R package "MVN" (Korkmaz et al. 2014), as well as graphically via visual inspection of Q-Q plots. Significance for all tests was based on the standard of 0.05. For all LCs, there was no evidence to suggest that errors in the latitudinal and longitudinal direction were correlated (Table S3). However, there was evidence to suggest that the assumption of normally distributed errors was inappropriate (Shapiro-Wilk's normality test; $p < 0.001$ for all LC; Table S4). However, given the additional computation time required to fit non-Gaussian errors (Albertsen et al. 2015) and our interest in broad-scale rather than fine-scale trends, we chose to fit mean-zero Gaussian error distributions to observed errors for each LC to allow for more efficient track reconstructions Table S5).

Track reconstruction

Track reconstructions for individual turtles were based on a continuous-time correlated random walk model (Johnson et al. 2008; Albertsen et al. 2015). Briefly, the model describes the movement process as a function of the instantaneous velocity of the animal at time t, which is described by the Ornstein-Uhlenbeck process:

$$v_{c,t} = \gamma_c + e^{-\beta_c \Delta_t}\left[v_{c,t-1} - \gamma_c\right] + \varepsilon_{c,t}$$

where γ_c is the mean long-term velocity, or drift, in the latitudinal (c = 1) or longitudinal (c = 2) direction, and β is a parameter describing the autocorrelation in velocities. Here, Δ_t is the time interval between locations, and $\varepsilon_{c,t}$ is a random error term, which follows a zero mean Gaussian distribution with variance equal to $\sigma_c^2(1 - e^{-2\beta_c \Delta_t})/2\beta_c$, where the parameter σ controls the overall variability in velocity. Large values of γ and β imply directional persistence with little variability from the path; low values indicate no directional preference and a widely varying path (Johnson et al. 2008).

To reconstruct the animal's actual movement trajectory, the velocity process is integrated over to obtain the location process:

$$\mu_{c,t} = \mu_{c,t-1} + \frac{v_{c,t-1}\left(1 - e^{-\beta_c \Delta_t}\right)}{\beta_c} + \zeta_{c,t}$$

where $\mu_{c,t}$ is the latitudinal or longitudinal coordinate at time t, and $\zeta_{c,t}$ is a random error term that follows a zero mean Gaussian distribution with variance equal to:

$$V\left(\zeta_{c,t}\right) = \frac{\sigma_c^2}{\beta_c^2}\left(\Delta_t - \frac{2\left(1 - e^{-\beta_c \Delta_t}\right)}{\beta_c} + \frac{1 - e^{-2\beta_c \Delta_t}}{2\beta_c}\right)$$

The joint distribution of $\varepsilon_{c,t}$ and $\zeta_{c,t}$ is given by a bivariate Gaussian distribution with covariance equal to:

$$\mathrm{Cov}(\varepsilon_{c,t}, \zeta_{c,t}) = \frac{\sigma_c^2}{2\beta_c^2}(1 - 2e^{-\beta_c \Delta_t} + e^{-2\beta_c \Delta_t})$$

Finally, the error in position estimates is related to the unobservable true location ($y_{c,t}$) via the observation error equation:

$$y_{c,t} = \mu_{c,t} + \epsilon_{c,t}$$

where $\epsilon_{c,t}$ is the geolocation error term associated with each reported location. Error for each location class was estimated as described above. Prior to fitting, all location coordinates were re-projected into oblique Mercator center projection centered on 35°00'00.0"N 75°00'00.0"W using the R package "rgdal" (Bivand et al. 2015). Models were fitted to location data using functions modified from those provided by Albertsen al. (2015) in the software Template Model Builder (Kristensen et al. 2016).

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Tables and Figures

Table S1. Estimated Argos location class (LC) error based on GPS locations transmitted from the same satellite tag. Error was measured (in meters) as the great circle distance between Argos and GPS locations transmitted within one minute of each other. Error estimates provided by CLS-Argos (which correspond to one standard deviation of the estimated location error; CLS-Argos 2015) are also included for comparison.

		Estimated error (m)					
LC	***n***	**Mean**	**Median**	**Minimum**	**Maximum**	**Standard deviation**	**Argos estimated error**
3	233	371	270	15	2572	330	< 250
2	506	723	577	13	3807	562	250 – 500
1	840	1418	1085	18	10089	1222	500 – 1500
0	678	3006	2041	101	28437	3266	> 1500
A	1401	2708	1682	49	41986	3315	NA
B	3884	3477	2402	32	72565	4051	NA

Table S2. Estimated Argos location class (LC) errors based on comparison with GPS locations reported from the same individual turtle within one minute. Error was measured (in meters) as the distance between Argos and GPS locations reported within one minute of each other in the (a) latitudinal and (b) longitudinal directions.

a) Latitudinal error

LC	*n*	Estimated error (m)				
		Mean	**Median**	**Minimum**	**Maximum**	**Standard deviation**
3	233	65	68	-1695	1661	302
2	506	106	79	-2124	3702	504
1	840	115	74	-4415	5152	996
0	678	126	114	-11838	14345	2112
A	1401	58	96	-22694	22204	2298
B	3884	150	78	-19531	59148	3106

b) Longitudinal error

LC	*n*	Estimated error (m)				
		Mean	**Median**	**Minimum**	**Maximum**	**Standard deviation**
3	233	-34	-24	-1964	2250	388
2	506	-12	-25	-2398	2774	758
1	840	14	-17	-6003	10062	1582
0	678	-104	-57	-27095	28311	3902
A	1401	-37	-29	-39354	27666	3610
B	3884	-45	-60	-39804	68684	4339

Table S3. Kendall's rank test results for correlation between Argos location errors in the latitudinal and longitudinal directions.

Location Class	*n*	τ	*t*	*p*
3	233	-0.065	-1.480	0.139
2	506	-0.041	-1.365	0.172
1	840	0.014	0.599	0.549
0	678	-0.006	-0.218	0.827
A	1401	-0.032	-1.815	0.070
B	3884	-0.013	-1.182	0.237

Table S4. Shapiro-Wilk's normality test results for Argos location class errors.

Location Class	*n*	*Latitude*		*Longitude*	
		w	*p*	*w*	*p*
3	233	0.898	**< 0.001**	0.914	**< 0.001**
2	506	0.934	**< 0.001**	0.977	**< 0.001**
1	840	0.944	**< 0.001**	0.946	**< 0.001**
0	678	0.860	**< 0.001**	0.862	**< 0.001**
A	1401	0.756	**< 0.001**	0.819	**< 0.001**
B	3884	0.759	**< 0.001**	0.795	**< 0.001**

Table S5. Maximum likelihood estimates of the standard deviation (σ) of a mean-zero normal distribution fitted to latitudinal and longitudinal components of Argos location class (LC) error in meters. The standard error of the estimate is indicated in parentheses.

LC	*Latitude* σ	*Longitude* σ
3	308.2 (14.3)	389.0 (18.0)
2	514.2 (16.2)	757.3 (23.8)
1	1001.8 (24.4)	1580.6 (38.6)
0	2113.9 (57.4)	3900.5 (105.9)
A	2298.0 (43.4)	3609.3 (68.2)
B	3109.0 (35.3)	4339.1 (49.2)

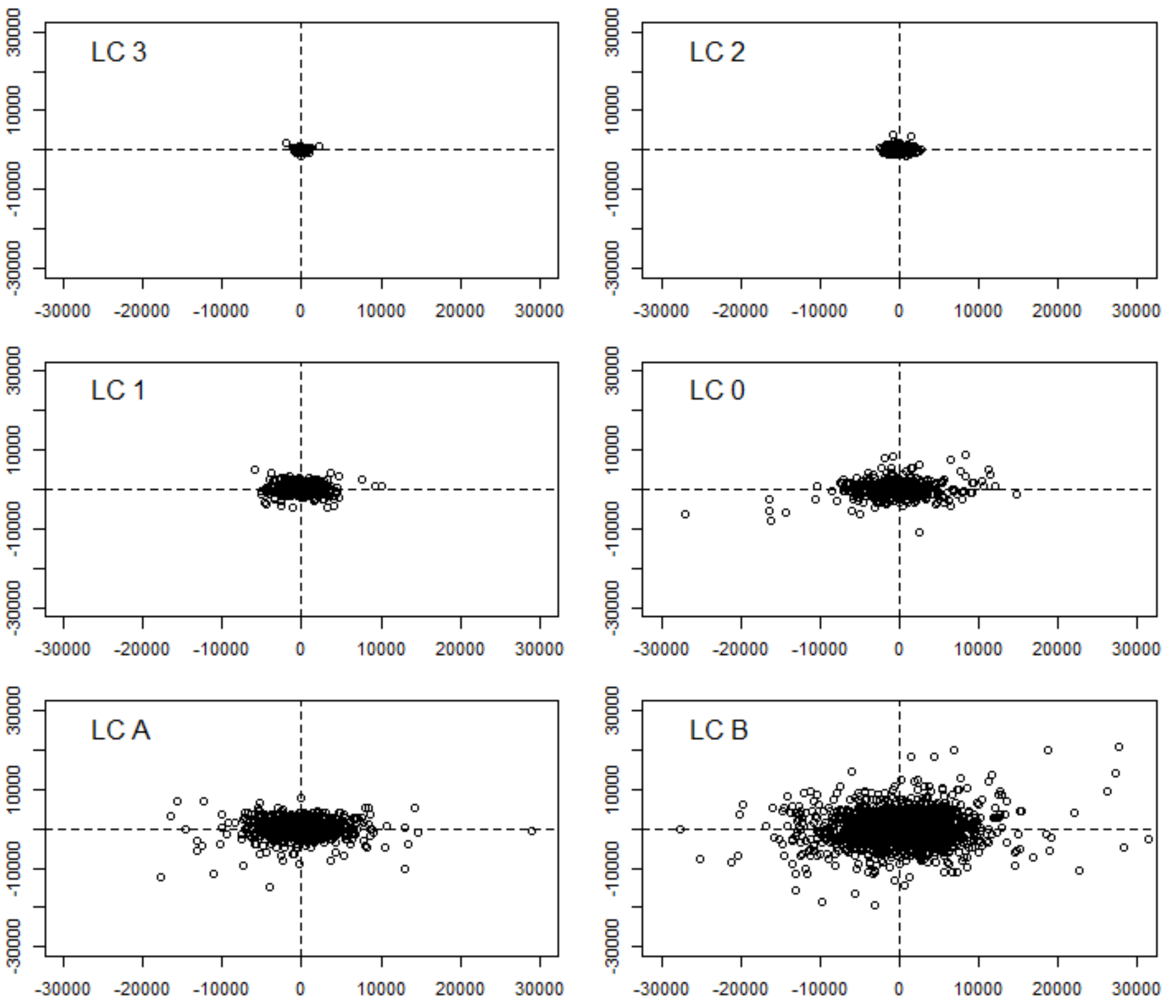

Figure S1. Estimated error associated with each of six Argos-derived location classes (LC 3, 2, 1, 0, A and B) in meters. Plots were standardized to one window size to illustrate differences in the magnitude of error between location classes. Several outliers for LC 0 and LC B are excluded by the bounds.