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Supplementary material

Appendix 1: Materials and methods

Geolocator analysis

Clock drift
Clock drift describes the offset of the internal clock (device) compared to the real time after a certain time period, in the case of a geolocator between start and end of measurement. Clock drift affects all sunrise and sunset measurements sequentially and thus, longitude estimates will drift linearly over time. Latitude estimates are negligibly affected due to the small difference in shifting sunrise and sunset times within the same day. Clock drift varies according to electronic components but can also vary between individual geolocators with same clock components due to production tolerance and exposure to different temperatures. For practical reasons, clock drift in geolocators is assumed to occur continuously at a constant rate.

In raw geolocator data clock drift can be easily calculated by comparing the internal device time and real time when data are downloaded. However, in cases when the devices had stopped recording before data download or the internal time stamp is obviously incorrect, clock drift can be calculated post-download in different ways.

A: for complete data set with known start and end points

Calculate longitude positions using a common sun elevation angle (for instance for civil twilight or sun rise/set). Compare the calculated longitude at the end of measurement with the real longitude at this site (i.e. the recapture site). If the difference is larger than geolocator accuracy (see Lisovski et al. 2012b) the data set is affected by clock drift. To determine the degree of drift calculate the expected sun rise /set time for a particular day at the focal site (applying the same sun elevation angle as for the geolcoator data) and compare this expected sun rise time with the measured sun rise from the geolocator data. The difference gives the summed clock drift across the complete data set you should correct for.

B: incomplete data set with light intensity records ending before a known site is reached

This approach is based on the resulting linear shift of longitude with time of a focal site when sun set / sun rise records are clock drift affected. Because we know for sure that birds are present during the breeding phase for at least 7-15 days after deployment, we first calculated longitudinal positions for this period using a best-guess sun elevation angle and plotting the longitude data over time. If these data are affected by clock drift the longitude during this stationary period will drift continuously in one direction (the slope of a linear regression would differ from zero). Next, an estimated clock drift is added to the data, longitudes are recalculated based on these corrected data and if there are no directional changes in longitude anymore (the slope of a linear regression would be zero), clock drift is adequately corrected for.

Clock-drift was noticeable (>1 min) only in SOI-GDL2 geolocators. For two geolocators with known start and end points (IDs 3gs, 3je) method A was used. Using method B allowed us to calculate and linearly correct clock-drift also for two SOI-GDL2 geolocators that stopped working before the birds were recaptured (IDs 3pg, 3ox). After these corrections we inspected wintering longitudes over time (Fig. 4) for signs of remaining clock drift problems. Since the wintering period is expected to be stationary in pied flycatchers, longitudes are also expected to drift continuously into one direction during winter if data are still affected by clock drift. The data revealed no continuous clock drift problems in most birds. Only geolocator data of bird (ID 3pg) seemed, when inspecting figure 4, to have remaining clock drift problems. To guarantee that this did not affect our conclusions and results with respect to wintering site longitudes and migratory connectivity, we made a post-hoc estimate of the clock drift for this geolocator using method B, but now performing this correction relative to a wintering period (10 Oct to 28 March). This yielded a median longitude at the nonbreeding ground of -13.0°, which was a negligible difference (i.e. westward shift of 0.2°) compared with our previous estimate (both during the core wintering period, without day length filtering) and much smaller than average geolocation accuracy.

Geolocation accuracy and precision are presented in Table A1 of Appendix 2 for two breeding seasons, i.e. 1) from deployment until the onset of autumn migration (i.e. breeding, moult), 2) from arrival at the breeding site until geolocators were taken off, if data were available for this period. The observed differences in accuracy, SEA (latitude) and precision (latitude, longitude) of median breeding positions between the breeding seasons may have been caused by small-scale post-breeding movements, and/or changes in the habitat, behaviour, geolocator sensitively, weather and the amount of data (i.e. days) available.

Filtering of transition data

Light data were filtered to extract twilight events. We allowed a minimum dark period of respectively four hours in the light intensity data to remove most shading events around dusk and dawn. Glitches (lighting events) were removed manually. Extreme outliers from the resultant transition file were removed using a Loess-function in R (package GeoLight 1.03, Lisovski et al. 2012a). Twilight events were considered outliers when the residual from the local polynomial regression line of sunset and sunrise time exceeded 4 times the interquartile range (i.e. k=4). In addition to this standardized filtering procedure, we also applied day-length filtering to the wintering period (see methods in the main text).

Calibration procedures for latitude

We identified SEAs corresponding to the threshold values separately for the breeding period and the wintering period. The breeding SEA was calculated over the period when a bird was at a known (i.e. breeding) location from the moment of deployment until departure for migration ('in-habitat-on-bird calibration'). Using this SEA, we described breeding latitude accuracy by comparing the known position in the breeding habitat with the median geolocation position. The accuracy was on average 10.3 km for latitude (range 6-18) across all geolocators when calculated over the period from deployment until the onset of autumn migration. We used the median position rather than the mean in all analyses to predict locations, since the median was a more accurate predictor of known locations (data not shown) and the median is less sensitive to outliers than the mean. For non-breeding, we used a Hill-Ekstrom calibration procedure (on day-length filtered data in winter), which aims to find the SEA where variance in latitudinal positions is minimized during the stationary period of interest (Lisovski et al. 2012b). SEAs in winter differed strongly between geolocator type: ranging from -3.9° to +3.4° across all geolocators in day-length filtered data (but also light sensors and scales to record light intensity differed among geolocator types). The Hill-Ekstrom calibration was clearly not successful for three birds where the recorded wintering period did not include equinox periods, i.e. GeoLight had problems to find the local minimum in latitude variance across a range of sun angles. The resultant SEAs led to wintering sites where the 25-75% quartiles were entirely in sea or outside the known wintering range. In these cases we choose SEAs that forced the median wintering latitude to fall closer to the known wintering range (i.e. UK: SEA=-1; one FI bird: SEA=3), to allow visualisation in figure 1.

We were able to compare accuracy of the two calibration methods for late winter (Feb-May 2011) in a pied flycatcher deployed with an OU-Cornell geolocator in open woodland savannah habitat in Ghana. This gives an indication on how successful Hill-Ekstrom calibration procedures can be in describing pied flycatcher wintering locations in West-Africa. We described the accuracy as the average differences of the known position (deployment location) to the median calculated position in the remaining wintering phase, using Hill-Ekstrom (HE) and the on-bird-in-habitat calibration (IH). Both the HE- and the IH-calibration appeared good estimators of the known wintering latitude and longitude (calibration period: from deployment until departure, i.e. Feb-May). The HE-calibration resulted in an accuracy of 23km (0.21°, SEA=-2.3) compared to the 85km (0.76°, SEA=-2.6) for IH-calibration, expressed as the difference between the median wintering position relative to known wintering location. This difference between the two methods became smaller when mean positions rather than medians were used (IH: 14km, HE: 24km). The accuracy of median longitude was 28km (0.25°) for this geolocator, over the same period (for mean: 26km, 0.23°). Our attempt to perform a similar comparison of both methods for the breeding period was not successful, given many errors in the HE-calibration during the breeding period, i.e. GeoLight had problems to find the local minimum in latitude variance across a range of sun angles.

All calibration procedures needed to estimate latitude were done in the R-package GeoLight (Lisovski et al. 2012a).

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References

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Lisovski, S., Hewson, C. M., Klaassen, R. H. G., Korner-Nievergelt, F., Kristensen, M. W. and Hahn, S. 2012b. Geolocation by light: accuracy and precision affected by environmental factors. - Methods Ecol. Evol. 3: 603–612.

Appendix 2: Supplementary figures and tables

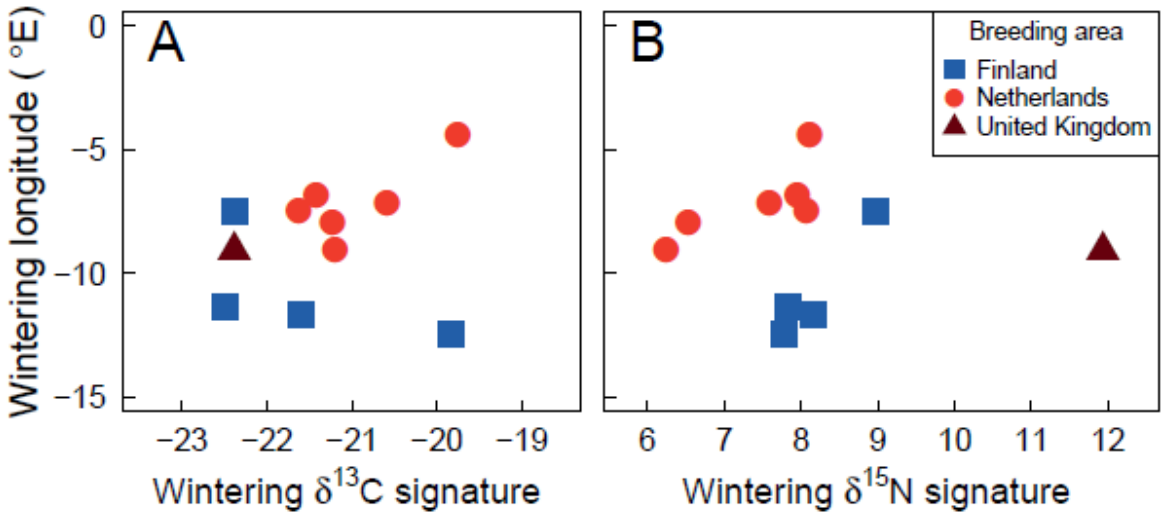

Figure A1. Wintering longitude in relation to wintering stable isotopic signatures of pied flycatchers. Between-individual variation in wintering longitude (median position) as explained by A) $\delta^{13}C$ and B) $\delta^{15}N$ (in ‰) in tertial feathers moulted in the same winter. For Norwegian birds, no feathers were collected.

Table A1. Overview of geolocation positioning, accuracy and precision during the breeding season for pied flycatcher males originating from four European breeding areas. In addition, geolocation positioning and accuracy is given for a pied flycatcher deployed with a geolocator at the wintering grounds (that stopped working soon after wintering departure). Data are shown for two breeding seasons, i.e.1) from deployment until departure in year *t*, and 2) from arrival at the breeding grounds until recapture in year *t+1*. SEA = Sun Elevation Angle used to calculate positions as inferred via in-habitat calibration for the period described, with N indicating the maximum number of days of that period for each geolocator. In one geolocator (ID 15) the in-habitat calibration for latitude in period 2 appeared very unsuccessful (shown in *italics*).

1) Period from deployment until departure

		Longitude °				Latitude °					
ID	**Tag type**	**Known location**	**Median**	**Precision Q1-Q3**	**Accuracy ° / km**	**Known location**	**Median**	**Precision Q1-Q3**	**Accuracy ° / km**	**SEA**	**N**
Finland											
3gs	SOI-GDL2	22.15	23.26	21.0 – 25.5	1.11 / 61	60.05	60.00	56.8 – 62.1	0.05 / 6	1.2	55
3ox	SOI-GDL2	22.15	24.23	21.9 – 27.7	2.08 / 115	60.05	59.97	45.6 – 65.4	0.08 / 9	4.9	53
3pg	SOI-GDL2	22.15	16.23	13.3 – 21.3	5.92 / 325	60.43	60.34	54.5 – 63.3	0.09 / 10	5.6	54
3je	SOI-GDL2	22.15	21.38	18.2 – 24.5	0.77 / 43	60.05	59.94	54.9 – 63.0	0.11 / 13	5.0	70
Norway											
2935	Intigeo-W50	10.63	9.34	7.8 – 10.8	1.29 / 72	59.98	59.90	58.3 – 60.7	0.08 / 9	-2.2	57
Netherlands											
30	OU-Cornell	6.43	6.59	5.4 – 7.9	0.16 / 11	52.82	52.74	50.7 – 54.1	0.08 / 9	0.7	49
36	OU-Cornell	6.43	5.66	4.1 – 7.4	0.77 / 51	52.82	52.74	51.2 – 54.2	0.08 / 9	-0.3	59
40	OU-Cornell	6.43	6.38	5.0 – 7.4	0.06 / 4	52.82	52.75	51.1 – 53.7	0.07 / 8	-1.8	56
b17	OU-Cornell	6.42	5.28	3.6 – 6.9	1.14 / 77	52.82	52.75	49.4 – 54.9	0.07 / 8	0.0	59
201	OU-Cornell	6.43	5.80	4.7 – 6.8	0.63 / 42	52.82	52.73	51.1 – 53.9	0.09 / 10	-1.7	67
207	OU-Cornell	6.42	4.43	3.1 – 6.9	1.99 / 134	52.82	52.73	51.1 – 54.0	0.09 / 10	-1.0	54
233	OU-Cornell	6.43	6.21	5.3 – 7.4	0.22 / 15	52.82	52.73	51.7 – 53.6	0.08 / 9	-1.9	59
England											
8	MK6540C	-3.73	-3.91	-6.6 – -1.6	0.18 / 12	50.59	50.45	46.5 – 54.6	0.15 / 16	4.0	70
15	MK6540C	-3.72	-4.21	-9.6 – -0.6	0.49 / 35	50.59	50.43	38.7 – 58.0	0.17 / 18	8.6	61
Ghana											
5	OU-Cornell	-1.74	-1.99		0.25 / 28	7.96	7.20		0.76 / 85	-2.6	85

Table A1. Continued.

2) Period from arrival at the breeding grounds until recapture

ID	Tag type	Longitude °				Latitude °					
		Known location	Median	Precision Q1-Q3	Accuracy ° / km	Known location	Median	Precision Q1-Q3	Accuracy ° / km	SEA	N
Finland											
3gs	SOI-GDL2	22.15	23.05	21.3 – 26.5	0.90 / 50	60.05	59.93	54.4 – 61.5	0.12 / 13	4.3	11
3ox	SOI-GDL2	22.15				60.05					
3pg	SOI-GDL2	22.15				60.43					
3je	SOI-GDL2	22.15	21.89	19.2 – 24.4	0.26 / 14	60.05	59.97	57.1 – 61.9	0.08 / 9	2.1	18
Norway											
2935	Intigeo-W50	10.63				59.98					
Netherlands											
30	OU-Cornell	6.43				52.82					
36	OU-Cornell	6.43	5.12	4.6 – 6.1	1.30 / 88	52.82	52.72	52.6 – 53.2	0.10 / 11	-2.4	9
40	OU-Cornell	6.43	6.97	5.6 – 7.7	0.53 / 36	52.82	52.68	48.2 – 54.8	0.14 / 16	-0.6	1
b17	OU-Cornell	6.42				52.82					
201	OU-Cornell	6.43				52.82					
207	OU-Cornell	6.42	5.26	3.9 – 6.5	1.17 / 79	52.82	52.74	49.7 – 54.3	0.08 / 9	-0.7	30
233	OU-Cornell	6.43	7.06	6.8 – 7.8	0.62 / 42	52.82	52.69	50.1 – 53.3	0.13 / 14	-3.0	5
England											
8	MK6540C	-3.73	-5.30	-10.0 – -3.5	1.57 / 111	50.59	50.39	42.2 – 55.0	0.20 / 23	3.6	9
15	MK6540C	-3.72	-2.97	-4.5 – -0.8	0.75 / 53	50.59	*25.66*	*-11.3 – 68.4*	*0.75 / 53*	*9.4*	16

Table A2. Overview of geolocation median positions and precision (quartile range Q1-Q3) for pied flycatcher males at their wintering grounds calculated for different periods (core and whole winter) with day length filtering (A) and without day length filtering (B). ‘Core winter period’ is from 15 November-15 February. ‘Whole winter period’ starts with winter arrival until the start of spring migration. All positions in a window of 15 days at each side of the equinox were removed. SEA = Sun Elevation Angle used to calculate positions, as inferred via Hill-Ekstrom (HE) calibration over the whole winter. () indicate that arbitrary SEAs were used for calculations, i.e. in case the HE-procedure was unsuccessful. In all these cases, longitudes median and Q1-Q3 were unaffected. In addition, geolocation precision by in-habitat (IH) calibration is given for a pied flycatcher deployed with a geolocator at the wintering grounds.

A) With day length filter

		Core winter period				Whole winter period					
		Longitude °		Latitude °		Longitude °		Latitude °		SEA	Clock drift (min)
ID	Tag type	Median	Precision Q1-Q3	Median	Precision Q1-Q3	Median	Precision Q1-Q3	Median	Precision Q1-Q3		
Finland											
3gs	SOI-GDL2	-7.51	-8.7 – -6.6	7.27	5.5 – 9.0	-7.06	-8.3 – -6.3	7.77	4.6 – 10.8	2.6	48
3ox	SOI-GDL2	-11.32	-12.7 – -9.8	15.55 (10.98)	13.3 (8.5) – 18.5 (13.4)	-10.70	-12.2 – -9.5	15.28 (9.89)	12.8 (7.6) – 18.4 (12.8)	1.2 (3)	35
3pg	SOI-GDL2	-12.45	-13.5 – -11.9	10.14	8.7 – 11.7	-12.14	-13.6 – -10.9	10.39	8.4 – 14.7	0.2	35
3je	SOI-GDL2	-11.63	-13.1 – -10.1	16.97	11.8 – 18.8	-12.19	-13.6 – -10.6	16.05	9.2 – 22.9	1.2	30
Norway											
2935	Intigeo-W50	-14.19	-14.4 – -13.7	11.09	10.1 – 12.3	-14.04	-14.4 – -13.5	11.40	10.2 – 13.6	-3.0	< 1
Netherlands											
30	OU-Cornell					-7.97	-8.6 – -7.0	12.25	8.2 – 15.6	-1.6	
36	OU-Cornell	-4.43	-4.8 – -4.2	6.18	4.5 – 7.5	-4.58	-5.0 – -4.2	6.18	3.7 – 7.9	-2.9	< 1
40	OU-Cornell	-7.44	-7.9 – -7.0	10.77	10.0 – 11.9	-7.39	-7.9 – -7.0	10.65	9.7 – 11.9	-3.9	< 1
b17	OU-Cornell					-6.84	-7.4 – -6.1	11.24	1.6 – 13.2	-2.0	
201	OU-Cornell					-9.05	-9.5 – -8.8	10.67	9.0 – 13.6	-2.9	
207	OU-Cornell	-6.25	-6.6 – -5.8	6.56	5.2 – 7.2	-6.46	-7.1 – -6.0	6.59	4.8 – 7.8	-2.1	< 1
233	OU-Cornell	-7.12	-7.4 – -6.5	6.58	5.6 – 7.9	-6.57	-7.2 – -5.8	6.34	4.8 – 7.8	-3.3	< 1
England											
8	MK6540C	-9.09	-9.7 – -8.5	-1.03 (11.18)	-2.7 (9.4) – 0.7 (12.8)	-9.00	-9.7 – -8.4	-1.00 (12.79)	-2.6 (10.4) – 0.9 (16.4)	3.4 (-1)	< 1
15	MK6540C	-9.06	-9.7 – -8.5	-1.64 (4.44)	-5.5 (2.5) – 0.5 (6.1)	-9.17	-9.9 – -8.4	-1.39 (4.96)	-6.5 (2.0) – 2.4 (10.4)	1.2 (-1)	< 1

Table A2. Continued.

B) Without day length filter

		Core winter period				**Whole winter period**					
		Longitude °		**Latitude °**		**Longitude °**		**Latitude °**		**SEA**	**Clock drift (min)**
ID	**Tag type**	**Median**	**Precision Q1-Q3**	**Median**	**Precision Q1-Q3**	**Median**	**Precision Q1-Q3**	**Median**	**Precision Q1-Q3**		
Finland											
3gs	SOI-GDL2	-7.53	-9.1 – -6.3	5.95	2.1 – 10.7	-7.17	-8.8 – -5.6	5.23	0.0 – 11.1	4.4	48
3ox	SOI-GDL2	-11.94	-14.3 – -9.7	24.32	20.0 – 29.8	-11.09	-13.4 – -9.2	25.28	20.0 – 30.8	-0.4	35
3pg	SOI-GDL2	-12.75	-13.9 – -11.9	11.56	9.0 – 15.7	-12.22	-13.9 – -10.9	12.05	8.0 – 17.8	0.6	35
3je	SOI-GDL2	-11.68	-14.2 – -10.1	17.43	13.3 – 24.2	-12.82	-14.8 – -10.9	17.56	11.7 – 25.3	2.0	30
Norway											
2935	Intigeo-W50	-14.39	-14.9 – -13.9	11.07	9.7 – 13.0	-14.01	-14.6 – -13.5	11.44	9.7 – 14.2	-2.6	< 1
Netherlands											
30	OU-Cornell					-7.96	-8.9 – -6.8	12.31	9.2 – 22.1	-1.0	
36	OU-Cornell	-4.28	-4.8 – -3.9	5.94	4.4 – 7.6	-4.56	-5.1 – -4.0	6.28	3.9 – 9.1	-2.4	< 1
40	OU-Cornell	-7.80	-8.4 – -7.2	9.74	8.2 – 11.3	-7.66	-8.1 – -7.1	9.52	7.4 – 11.4	-3.1	< 1
b17	OU-Cornell					-6.53	-7.4 – -6.0	20.18	11.5 – 21.4	-1.0	
201	OU-Cornell					-9.23	-10.0 – -8.7	7.92	4.2 – 14.0	-1.5	
207	OU-Cornell	-6.13	-6.7 – -5.6	9.12	7.8 – 10.9	-6.44	-7.1 – -5.8	9.77	7.6 – 12.4	-2.1	< 1
233	OU-Cornell	-6.86	-7.3 – -5.8	7.56	6.0 – 8.8	-6.47	-7.2 – -5.7	7.56	5.8 – 9.4	-3.2	< 1
England											
8	MK6540C	-9.35	-10.3 – -8.4	-3.20	-6.1 – -0.7	-9.11	-10.2 – -8.0	-3.19	-6.6 – 0.9	4.9	< 1
15	MK6540C	-8.94	-9.7 – -8.1	-4.17	-7.2 – -1.3	-9.07	-10.0 – -7.9	-3.70	-8.8 – 2.5	3.0	< 1
Ghana											
5	OU-Cornell					-1.99	-2.7 – -1.4	8.17	4.0 – 12.5	-2.3 HE	
5	OU-Cornell					-1.99	-2.7 – -1.4	7.20	3.0 – 12.0	-2.6 IH	