

## A simple new algorithm to filter marine mammal Argos locations

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### ABSTRACT

During recent decades satellite telemetry using the Argos system has been used extensively to track many species of marine mammals. However, the aquatic behavior of most of these species results in a high number of locations with low or unknown accuracy. Argos data are often filtered to reduce the noise produced by these locations, typically by removing data points requiring unrealistic swimming speeds. Unfortunately, this method excludes a considerable number of good-quality locations that have high traveling speeds that are the result of two locations being taken very close in time. We present an alternative algorithm, based on swimming speed, distance between successive locations, and turning angles. This new filter was tested on 67 tracks from nine different marine mammal species: ringed, bearded, gray, harbor, southern elephant, and Antarctic fur seals, walruses, belugas, and narwhals. The algorithm removed similar percentages of low-quality locations (Argos location classes [LC] B and A) compared to a filter based solely on swimming speed, but preserved significantly higher percentages of good-quality positions (mean  $\pm$  SE% of locations removed was  $4.1 \pm 0.8\%$  *vs.*  $12.6 \pm 1.2\%$  for LC 3;  $6.8 \pm 0.6\%$  *vs.*  $15.7 \pm 0.9\%$  for LC 2; and  $11.4 \pm 0.7\%$  *vs.*  $21.0 \pm 0.9\%$  for LC 1). The new filter was also more effective at removing unlikely, conspicuous deviations from the track's path, resulting in fewer locations being registered on land and a significant reduction in home range size, when using the Minimum Convex Polygon method, which is sensitive to outliers.

Key words: cetaceans, location class accuracy, location errors, path filter, pinnipeds, satellite telemetry.

During the last two decades the Argos satellite telemetry system has been used extensively to document movement patterns, and other behavioral data, for many marine mammal species. The system uses transmitters (known as PTTs—platform terminal transmitters) that are attached to animals, which send radio signals (uplinks) to polar-orbiting satellites. At least four uplinks are required to estimate a location with known accuracy (Argos 1996). The limited amount of time spent at the water surface (or on land) by marine mammals can severely restrict the number of uplinks received on each satellite's overpass and therefore result in a high proportion of locations with low or unknown accuracy. Argos locations are classified in different location quality classes (LCs); accuracy decreases in the following order: 3, 2, 1, 0, A, B, and Z. LCs 3, 2, 1, and 0 have estimated accuracies of 150, 350, 1,000, and >1,000 m. LCs A, B, and Z are based on less than four successive uplinks and have no estimated location accuracy. LC A locations are based on three uplinks. LC B locations are based on two uplinks and LC Z are points for which the location process failed. The accuracies reported by Argos generally agree with the location errors obtained from recent location-assessment studies conducted on captive and free-ranging marine mammals, though LC A locations were found in practice to have accuracies similar to LC 1 (Vincent *et al.* 2002, White and Sjöberg 2002).

Location data produced by Argos are often filtered to deal with the low accuracies of some locations, typically by removing locations requiring unrealistic swimming speeds for a given species. The algorithm presented by McConnell *et al.* (1992a) is often used for this purpose. A modification of this algorithm was presented by Austin *et al.* (2003), which calculates swim speed at three separate stages resulting in the retention of more locations compared to the McConnell *et al.* filter. These filters provide tremendous improvements in the visual fit of the tracks, but have the disadvantage of removing good-quality locations for which high swimming speeds are a result of locations being taken very close in time. Locations can also be filtered based on the angle and distance between locations, as suggested by Keating (1994). Such an approach is based on the reasoning that erroneous locations are more likely when data indicate a single, relatively large movement, followed by an immediate return to a point near the original track line (Keating 1994). Problems do arise when two or more erroneous locations are obtained successively. In this case a broader angle in the changed direction of the track can be formed and thus the locations will not be removed. On the other hand, this approach can lead to the removal of real locations that are a result of short-term movements that are not confirmed by the direction of the previous and next locations (Keating 1994). These difficulties are likely to be reduced if the track is previously filtered using another parameter such as swimming speed.

The option of simply removing all locations of low quality (LCs 0, A, B, and Z) seems an obvious solution, but in the case of marine mammals, it is very data costly because the percentage of such locations is typically higher than 50% and sometimes as high as 90% (see McConnell and Fedak 1996, Goulet *et al.* 1999; Table 1). On the other hand, retaining all good-quality locations (LC 1, 2, and 3), independently of other parameters, is also not desirable because Argos accuracy estimates are not absolute values. They are based on a 68% probability that these locations are within these distances, which implies that they can be much less accurate (Stewart *et al.* 1989, McConnell *et al.* 1992b).

A different approach to dealing with low-quality locations is to produce new tracks, taking into account the LCs accuracies, using smoothing algorithms (Thompson *et al.* 2003) or state-space models (Jonsen *et al.* 2003, 2005). These methodologies are not dealt with further in this study.

Table 1. Number of tracks and locations of each species analyzed in the present study. Number and percentage of locations with location class (LC) lower than 1 is also given.

Species	No. animals (tracks)	No. locations per track (min.–max.)	No. locations (total)	No. locations with LC < 1	% locations with LC < 1
Ringed seals	11	678–3,079	20,115	17,426	87
Bearded seals	13	344–5,575	33,123	27,670	84
Southern elephant seals	2	1,525–2,998	4,523	4,185	93
Walruses	9	1,110–2,240	13,355	11,394	85
Belugas	12	685–4,779	22,675	15,727	69
Narwhals	2	326–386	712	607	85
Harbor seals	6	1,040–2,695	11,359	9,357	82
Gray seals	6	749–2,326	8,746	7,161	82
Antarctic fur seals	6	731–995	5,154	3,561	69
Total	67	326–5,575	119,762	97,088	81

The present study presents a new track-filtering algorithm that aims to minimize the loss of good-quality locations during the filtering process. This new filter was tested on 67 tracks from nine different marine mammal species, including both nomadic foragers and Central Place (CP) foragers; the latter being characterized by returning to familiar locations on land after their foraging trips.

## MATERIALS AND METHODS

An algorithm for filtering Argos locations was developed using R software (R Development Core Team 2007). It is based on the traveling speed of the tracked animal, distance between successive locations, and turning angle. This filter, called hereafter the SDA-filter (Speed-Distance-Angle-filter) is available within the R package “argosfilter” (function `sdafilter`) at <http://cran.r-project.org>. The first step in the filtering process consists of removing all locations with LC Z. Subsequently, it excludes all locations requiring swimming speeds ( $V_i$ ) higher than the threshold defined for the species (2 m/s for example), in accordance with the filter developed by McConnell *et al.* (1992a), unless these positions are located less than 5 km from the previous location. If they are, then they are retained. This additional factor enables retention of good-quality positions for which high swim speeds are merely an artifact resulting from positions being recorded very close to each other in time. Without this condition, a location taken 1 min after the previous location would have to be located within 120 m from that location in order to be within the speed limit. A chosen limit of 5 km allows for the retention of two locations taken close to each other in time (up to approximately 42 min apart). In a worse-case scenario, when an animal does not move at all between two closely timed locations, the maximum error associated with the second location will be 5 km (assuming that the first location is correct).

The final step in the filtering process excludes all locations requiring turning angles ( $TA_i$ ) higher than a given threshold. The higher the turning angle and distance to an apparently deviant location, the less likely it is that the corresponding location represents a real movement. In this study we chose to remove all locations requiring turning angles higher than  $165^\circ$ , if the track leading to them was longer than 2,500 m

and also all locations requiring turning angles higher than  $155^\circ$ , if the track leading to them was longer than 5,000 m. These values were chosen empirically, based on the measurement of the angles and lengths of the most conspicuous, abrupt deviations from the principal path of the animal's track. We judge that these are likely to be erroneous locations. Different criteria might be more appropriate for other data sets and therefore exploratory analysis of tracks is highly recommended after the first steps of the filtering process. The *sdafilter* function (in the R package *argosfilter*) allows one to see filtered tracks prior to the last step to enable such analysis.

In order to calculate the swimming speed ( $V_i$ ) associated with each position  $i$ , the following formula presented by McConnell *et al.* (1992a) was used:

$$V_i = \sqrt{\frac{1}{4} \sum_{j=-2, j \neq 0}^{j=2} (v_{i,j+i})^2} \quad (1)$$

where  $v_{i,j}$  is the traveling speed between consecutive locations  $i$  and  $j$  (calculated by dividing the distance by the time spent traveling between these locations). When applying the above formula to a set of locations, since  $V_i$  calculates the root mean square of the speeds between location  $i$  and the previous, second previous, next and second next location, high swimming speeds can be obtained for points that are adjacent to outlier locations. Therefore, when the algorithm is run for a set of locations, only the peaks in  $V_i$  (that are above the defined maximum speed) are removed. Other locations are retained even if they are above the speed limit. Swimming speeds  $V_i$  are then recalculated  $n$  times until all locations are below the speed threshold.

Distance between two locations  $i$  and  $j$  can be calculated using spherical trigonometry, assuming a spherical earth (see Zwillinger 2003), using the following relationship:

$$D_{i,j} = \frac{60}{1852} \times \frac{180}{\pi} \times \arccos(\sin(rlat_i) \times \sin(rlat_j) + \cos(rlat_j) \times \cos(rlat_i) \times \cos(rlon)) \quad (2)$$

Here,  $\pi$  is 3.141593,  $rlat_i$  is the latitude of location  $i$  in radians,  $rlat_j$  is the latitude of location  $j$  in radians, and  $rlon$  is the difference between the longitudes of locations  $j$  and  $i$ , in radians.  $D_{i,j}$  in the above formula is given in meters.

The angle or bearing  $B_{i,j}$  between two geographical locations  $i$  and  $j$  can also be calculated using spherical trigonometry, using the following relationship:

$$B_{i,j} = \frac{180}{\pi} \times \arccos\left(\frac{\sin(rlat_j) - \sin(rlat_i) \times \cos(rd_{i,j})}{\sin(rd_{i,j}) \times \cos(rlat_i)}\right) \quad (3)$$

Note that if  $\sin(rlon) < 0$ :

$$B_{i,j} = 360 - \left(\frac{180}{\pi} \times \arccos\left(\frac{\sin(rlat_j) - \sin(rlat_i) \times \cos(rd_{i,j})}{\sin(rd_{i,j}) \times \cos(rlat_i)}\right)\right) \quad (4)$$

In the above formulas  $B_{i,j}$  is given in degrees,  $\pi$ ,  $rlat_i$ , and  $rlat_j$  are the same as in formula 2 and  $rd_{i,j}$  is:

$$rd_{i,j} = \frac{D_{i,j}}{60} \times \frac{\pi}{180} \quad (5)$$

The turning angle  $TA_i$  at a given position  $i$  was calculated as the absolute angle between the bearing to the current location  $i$  and the bearing to the next location ( $i + 1$ ):

$$TA_i = |B_{i-1,i} - B_{i,i+1}| \quad (6)$$

If  $|B_{i-1,i} - B_{i,i+1}| > 180$ , then

$$TA_i = 360 - |B_{i-1,i} - B_{i,i+1}| \quad (7)$$

Sixty-seven paths from nine different marine mammal species were run through the SDA-filter to test its performance (see Table 1): ringed seals, *Pusa hispida* ( $n = 11$ ); bearded seals, *Erignathus barbatus* ( $n = 13$ ); southern elephant seals, *Mirounga leonina* ( $n = 2$ ); walruses, *Odobenus rosmarus* ( $n = 9$ ); belugas, *Delphinapterus leucas* ( $n = 12$ ); narwhals, *Monodon monoceros* ( $n = 2$ ); harbor seals, *Phoca vitulina* ( $n = 6$ ); gray seals, *Halichoerus grypus* ( $n = 6$ ); and Antarctic fur seals, *Arctocephalus gazella* ( $n = 6$ ). The first six species are typically nomadic foragers while the last three are generally CP foragers. SDA-filter results were compared with those acquired running the same data through the McConnell *et al.* (1992a) filter, which is based solely on swimming speed (hereafter referred to as the S-filter). Note that the two first and two last locations of the tracks, where  $V_i$  is unknown, were excluded by both filters. Nonparametric tests (Kruskal–Wallis test) were used to compare the number of locations removed by the different filters.

In order to investigate differences in home range size resulting from locations being processed *via* different filters, monthly home ranges were calculated from the filtered tracks of one of the species (walruses;  $n = 9$ ). Home ranges were calculated using R software (package *adehabitat*), using both the 100% Minimum Convex Polygon method (Mohr 1947) and the kernel method (Worton 1989). Kernel home ranges were estimated using the same smoothing parameter ( $b = 3,000$ ) for both filters and for all months ( $n = 84$ ). The 95% kernel contour was used as home range. Home range sizes (areas) obtained from the two filtering processes were compared using one-way ANOVA. Areas were log-transformed to achieve normality and stabilize the variances. Normality was checked graphically (through histograms and q–q plots) and using the Kolmogorov–Smirnov test. Homogeneity of variances was verified using Fligner–Killeen and Bartlett tests. Unless stated otherwise, all values in the results are reported as mean  $\pm$  SE. The statistical significance level was set at  $P < 0.05$ .

## RESULTS

The tracks contained 119,762 locations (326–5,575 locations per track). For the different species, 69%–93% of the locations had an LC equal to or lower than 0 (Table 1). For the 67 tracks analyzed the SDA-filter removed an average of only  $4.1 \pm 0.8\%$  of the LC 3 locations, compared with  $12.6 \pm 1.2\%$  removed by the S-filter (Table 2). This difference was statistically significant (see Kruskal–Wallis rank sum test in Table 2). Additionally, significantly smaller percentages of LC 2 locations ( $6.8 \pm 0.6\%$  *vs.*  $15.7 \pm 0.9\%$ ) and LC 1 locations ( $11.4 \pm 0.7\%$  *vs.*  $21.0 \pm 0.9\%$ )

*Table 2.* Mean percentage (and SE) of Argos locations of various location classes (LC) removed by the S-filter and by the SDA-filter from the tracks analyzed in this study ( $n = 67$ ). Kruskal–Wallis test statistics ( $\chi^2$ ), testing for differences between the percentages of locations removed by the two filters are also presented, together with the degrees of freedom (df) and significance level ( $P$ ) of the tests.

LC	S-filter		SDA-filter		$\chi^2$	df	$P$
	Mean	SE	Mean	SE			
3	12.6	1.2	4.1	0.8	41.18	1	<0.001
2	15.7	0.9	6.8	0.6	48.47	1	<0.001
1	21.0	0.9	11.4	0.7	53.75	1	<0.001
0	36.0	1.2	32.5	1.1	4.63	1	0.031
A	28.8	1.2	25.9	1.1	2.08	1	0.149
B	41.7	1.2	44.3	1.1	2.47	1	0.116
Z	57.2	1.7	100.0	0.0	35.62	1	<0.001

were removed by the SDA filter compared to the S-filter (Table 2). The total number and percentage of locations removed for each species by the filters are presented in Table 3. No differences were found in the performance of the SDA-filter (the percentage of good locations removed) between CP foragers (harbor seals, gray seals, and Antarctic fur seals) and nomadic foragers (Kruskal–Wallis rank sum test—LC 3 locations:  $\chi^2 = 0.068$ ,  $df = 1$ ,  $P = 0.794$ ; LC 2 locations:  $\chi^2 = 0.267$ ,  $df = 1$ ,  $P = 0.606$ ; LC 1 locations:  $\chi^2 = 0.594$ ,  $df = 1$ ,  $P = 0.441$ ).

The SDA-filter removed all Z locations, as defined in the algorithm. It removed approximately the same percentage of LCs B and A locations (Table 2), and slightly fewer LC 0 locations (Table 2).

Both filters removed the majority of the most unlikely locations (see examples in Fig. 1), but the SDA-filter also removed additional unlikely deviations in the track, resulting in the retention of more high-quality positions and relatively few positions over land in the final track (see Fig. 1). The removal of such additional deviations from the tracks also resulted in significantly smaller MCP home ranges when using the SDA-filter (mean area was  $13,420 \pm 2,221$  km<sup>2</sup> when using the SDA-filter *vs.*  $21,917 \pm 3,312$  km<sup>2</sup> when using the S-filter; ANOVA:  $F_{1,166} = 10.69$ ,  $P = 0.001$ ). However, no significant differences were found between the 95% kernel home ranges obtained by the two filters (mean area =  $43,655 \pm 12,039$  km<sup>2</sup> when using the SDA filter *vs.*  $40,342 \pm 9,102$  km<sup>2</sup> when using the S-filter; ANOVA:  $F_{1,166} = 1.63$ ,  $P = 0.204$ ).

## DISCUSSION

Errors generated by low-accuracy locations generally have little importance when plotting long-range movements of animals. However, these errors can have serious implications when more fine-scaled movements are considered and when other determinations are attempted, such as calculations of traveling speed (Hays *et al.* 2001), determination of home ranges (*e.g.*, Austin *et al.* 2003, this study), and analysis of other movement and habitat-use parameters. They can also negatively influence the interpretation of other measurements collected by the transmitters, such as the position of dives or oceanographic data records. The location where these sorts of measurements

Table 3. Number and percentage of Argos locations of various location classes (LCs 3, 2, 1, 0, A, B, and Z) removed from the tracks of each species by the S-filter and the SDA-filter.

Species	S-filter							SDA-filter								
	3	2	1	0	A	B	Z	Total	3	2	1	0	A	B	Z	Total
<i>n</i> removed																
Ringed seals	56	133	327	419	1,309	4,907	234	7,385	13	36	135	316	878	4,634	352	6,364
Bearded seals	104	260	629	1,013	1,890	6,753	1,256	11,905	10	56	228	810	1,502	6,720	2,372	11,698
Southern elephant seals	1	7	19	159	294	705	446	1,631	0	6	28	234	393	817	742	2,220
Walrus	42	94	162	211	543	2,404	253	3,709	7	39	77	203	544	3,340	470	4,680
Belugas	129	454	1,307	2,259	2,031	3,303	—	9,483	30	180	621	1,808	1,666	3,018	—	7,323
Narwhals	2	9	29	91	63	174	—	368	2	6	21	86	60	181	—	356
Harbor seals	42	80	193	306	626	2,531	228	4,006	13	35	122	321	653	2,870	378	4,392
Gray seals	13	37	93	135	420	1,344	59	2,101	5	26	64	135	482	1,735	96	2,543
Antarctic fur seals	14	38	116	151	230	746	1	1,296	9	24	77	159	219	829	2	1,319
% removed																
Ringed seals	13	17	22	38	27	44	66	37	3	5	9	28	18	42	100	32
Bearded seals	11	15	23	38	30	41	53	36	1	3	8	31	24	41	100	35
Southern elephant seals	3	9	8	23	27	43	60	36	0	8	12	34	36	49	100	49
Walrus	9	14	19	35	24	30	54	28	2	6	9	33	24	42	100	35
Belugas	23	24	29	49	43	51	—	42	5	9	14	39	36	47	—	32
Narwhals	29	33	41	55	45	58	—	52	29	22	30	52	43	60	—	50
Harbor seals	12	12	20	34	26	44	60	36	4	5	12	36	27	50	100	39
Gray seals	4	7	12	20	20	32	61	24	2	5	8	20	22	41	100	29
Antarctic fur seals	5	9	13	25	22	39	50	25	3	6	9	26	21	43	100	26

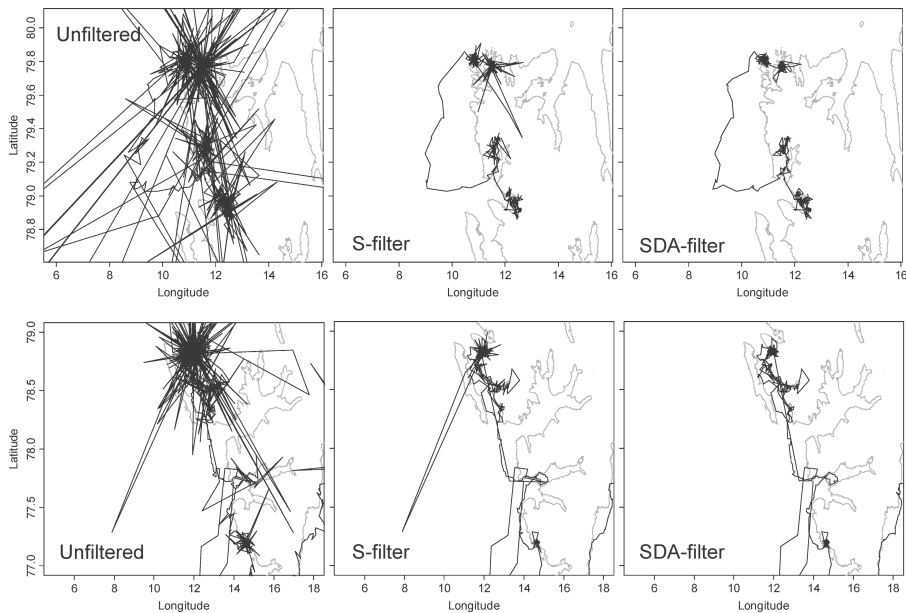


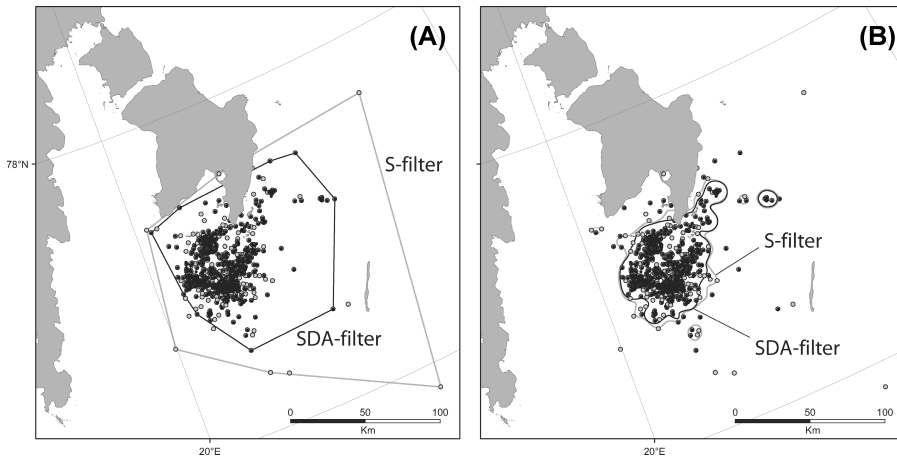
Figure 1. Track of a bearded seal *Erignathus barbatus* (upper panels) and track of a ringed seal *Pusa hispida* (lower panels) before and after applying the S-filter and the SDA-filter to the original Argos data.

were made is estimated *via* interpolation from the Argos locations. Thus, inaccuracies in the track are problematic. The higher percentage of good-quality locations preserved by the SDA-filter should provide more accurate results when interpolating the location of such data-sampling events and when analyzing small-scale movements in general. Both the S-filter and the SDA-filter successfully remove the majority of the most unlikely locations from the tracks (see Fig. 1). Estimates of home range by the MCP method are extremely sensitive to outlier locations. Because some evident outliers were still retained by the S-filter, significantly larger MCP home ranges were obtained when this filter was used. In contrast, the kernel method takes into consideration the density of data points and therefore the 95% kernel contour area is not affected as much by the presence of outliers (see example in Fig. 2).

In the present study, the preservation of good-quality locations by the SDA-filter was evident both for nomadic and CP foragers. The identification of conspicuous deviations from the track is however easier in tracks of nomadic foragers, especially when they perform long-distance, directional movements. CP foragers' tracks sometimes appear to be more erratic, and it can be more difficult to distinguish between short-term movements and erroneous deviations from the paths when exploring the data visually. In such cases, it can therefore be more difficult to define the turning angle limits to use in the filter.

In most studies, it is not possible to compare the filtering results with the real locations of animals. However, the number of locations retained within each LC and a visual analysis of the resulting track can provide an indication of the performance of the algorithm used to reduce inaccuracies in the path. The present filter, by removing





*Figure 2.* Locations filtered by the S-filter (gray) and SDA-filter (black) for one of the walrus tracks analyzed in this study. Panel A shows the 100% Minimum Convex Polygons (MCP) created from those locations, while Panel B shows the 95% kernel contours for the same locations.

sudden, unlikely deviations from the track, generally resulted in fewer locations being positioned on land (that must have actually been at sea or along the coast). Such incorrect on-land positions can be frequent in coastal areas, even after tracks have been filtered or modeled. The incorporation of a condition in the filtering algorithm to exclude locations on land is however not recommended, since this can result in paths being asymmetrically skewed offshore (for example for an animal traveling parallel to a coast or using a coastal area for a long period of time). Depending on the type of analysis the filtered data are being used for, the on-land positions can be manually removed post-filtering where this is desirable. The speeds measured by the present algorithm were measured using linear distances. However, in some cases, the transit between two locations would require circumnavigation of islands or peninsulas. Post-filtering, manual control of those situations is needed. Automation of this sort of correction should be a point of improvement in future developments of filters.

The present algorithm is implemented in R software and is freely available online, but it can be written in a diversity of other languages, including in macros within Excel (Microsoft Corporation). The parameters used in the SDA-filter can also be used in the online tool STAT (Coyne and Godley 2005), which was developed for sea turtles. This tool enables filtering Argos locations based on a number of options, including traveling speeds, LC, turning angles and times and distances between successive locations. Similar to marine mammal data, sea turtle tracking data are often dominated by low-accuracy locations (Plotkin 1998), and hence the filtering parameters developed in the present study can be useful to be included in studies on such species.

In summary, the present filter retained higher proportions of good-quality locations in relation to a filter based solely on swimming speed. It also removed additionally conspicuous deviations from the track, even when the speed to such locations was feasible, resulting in fewer at-sea/coast locations being registered as being on land

and in significantly smaller home ranges when applying the MCP method that is extremely sensitive to outlier locations. Although the automatic removal of such additional outliers is important, the preservation of good-quality data is the main advantage of the filter, especially when small-scale analyses of the tracking data are desired.

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