IDENTIFYING AND MITIGATING ERRORS IN SATELLITE TELEMETRY OF POLAR BEARS

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Abstract: Satellite radiotelemetry is a useful method of tracking movements of animals that travel long distances or inhabit remote areas. However, the logistical constraints that encourage the use of satellite telemetry also inhibit efforts to assess accuracy of the resulting data. To investigate effectiveness of methods that might be used to improve the reliability of these data, we compared 3 sets of criteria designed to select the most plausible locations of polar bears (*Ursus maritimus*) that were tracked using satellite radiotelemetry in the Bering, Chukchi, East Siberian, Laptev, and Kara seas during 1988–93. We also evaluated several indices of location accuracy. Our results suggested that, although indices could provide information useful in evaluating location accuracy, no index or set of criteria was sufficient to identify all the implausible locations. Thus, it was necessary to examine the data and make subjective decisions about which locations to accept or reject. However, by using a formal set of selection criteria, we simplified the task of evaluating locations and ensured that decisions were made consistently. This approach also enabled us to evaluate biases that may be introduced by the criteria used to identify location errors. For our study, the best set of selection criteria comprised: (1) rejecting locations for which the distance to the nearest other point from the same day was >50 km; (2) determining the highest accuracy code (NLOC) for a particular day and rejecting locations from that day with lesser values; and (3) from the remaining locations for each day, selecting the location closest to the location chosen for the previous transmission period. Although our selection criteria seemed unlikely to bias studies of habitat use or geographic distribution, basing selection decisions on distances between points might bias studies of movement rates or distances. It is unlikely that any set of criteria will be best for all situations; to make efficient use of data and minimize bias, these rules must be tailored to specific study objectives.

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Studies of animal movements often rely on data obtained through radiotelemetry. With most tracking systems, errors in determining an animal's position usually are constrained within limits defined by study area boundaries or the capabilities of transmitters and receivers. In addition, an observer often is present when data are collected, so that unlikely data points can be identified as they are obtained. However, conventional very-high-frequency (VHF) transmitters may be impractical for tracking movements of animals that travel long distances or inhabit remote areas. The development of satellite telemetry has provided a means of studying movements of these species (Fancy et al. 1988). However, the logistical constraints that encourage the use of satellite telemetry also inhibit efforts to assess accuracy of the resulting data. For example, it often is impractical to obtain visual sightings to confirm satellite locations. To date, most studies that have used satellite telemetry were concerned with large-scale movement patterns and either considered location errors to be negligible within the scale of the study (e.g., Craighead and Craighead 1987) or used some unspecified and probably subjective criteria to remove locations thought to be implausible. Although a few studies, notably those of Keating and colleagues (Keating and Key 1990, Keating et al. 1991, Keating 1994), have examined the suitability of satellite telemetry for studies at a finer scale, there is as yet no widely accepted technique for evaluating and screening data obtained through satellite telemetry.

To investigate methods of improving the reliability of data from satellite radiotelemetry, we evaluated 5 indices for their ability to select the most plausible locations of polar bears (*Ursus maritimus*) that were tracked using satellite radiotelemetry during 1988–93. We compared the effectiveness of the indices at distinguishing plausible from implausible locations when used individually and in 2 combinations. The magnitude of errors that are deemed acceptable will vary depending on the goals and resolution of a particular study. Because polar bears commonly travel long distances over short periods (Garner et al. 1990, 1994), we decided to accept location errors of ≤100 km. Thus, our objective was to compare criteria for choosing 1 location/day for each animal. Our basis for evaluating these criteria was the likelihood that errors >100 km would be excluded and that locations with greater accuracy would be retained.

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METHODS

Polar bears were captured in U.S. territory near St. Lawrence Island and along the northwest coast of Alaska and in Russian territory near Wrangel Island, the southeastern East Siberian Sea, eastern Kara Sea, and western Laptev Sea using tranquilizer darts fired from low-flying helicopters (Garner et al. 1990, 1994). Adult female bears were equipped with collars containing transmitters programmed to transmit for 6 hours every 3 days (transmitters sometimes operated for longer or shorter periods than specified). Positions of transmitters were determined by satellites using the Argos Data Collection and Location System (Argos) as described by Fancy et al. (1988), Garner et al. (1988), and Harris et al. (1990). The system used 2–3 satellites in polar orbit, each making approximately 14 revolutions/day (Argos 1988). Individual transmitters were located ≤15 times/day, depending on performance of the transmitters and the altitude of satellite overpasses relative to the horizon.

Locations provided by Argos were determined using the Doppler shift of radio signals received by satellites passing overhead. This method produced 2 possible points for each location: 1 presumably was correct, and the other was the mirror image on the opposite side of the satellite path (Argos 1988). Under standard processing service, Argos determined which of the possible points was correct based on the transmitter's previous locations and the earth's rotation (Harris et al. 1990). However, we obtained both sets of coordinates and performed this selection ourselves by choosing the location closest to the previous selection. Accuracy of locations may be affected by the number of messages received during an overpass, transmitter frequency stability, and the angle between satellite, transmitter, and horizon (Argos 1988). Argos provided an index of accuracy (NLOC) for each location based on these criteria. Values ranged from 0 (low accuracy) to 3 (high accuracy). Argos (1988) reported that the standard deviations of repeated locations of stationary transmitters were 1,000, 350, and 150 m for NLOC values of 1, 2, or 3, respectively. According to Keating et al. (1991), these standard deviations suggest that 68% of locations with NLOC values of 1, 2, or 3 would be ≤1,510, 528, and 226 m, respectively, from the transmitter's true position. Estimates of accuracy and precision were not available for locations receiving an NLOC value of 0, but we included these because they accounted for approximately 50% of the data obtained for polar bears.

Identification of Implausible Locations

Because the transmitters were deployed over a large, remote area, we could not determine actual positions of transmitters. Instead, we used the following plausibility criteria to indicate an implausible location:

1. Two vectors ≥250 km formed by locations from 3 consecutive transmission periods.
2. Two vectors ≥100 km with the angle between them <20 degrees, formed by locations from 3 consecutive periods.
3. Rate of travel ≥100 km/day and time since previous location ≥1 day.

These criteria were based on 4 assumptions. First, sequential locations of a single bear were expected to be serially correlated. Second, location errors were expected to be random deviations from a transmitter's true position; thus, errors rarely should have occurred close together. These 2 assumptions suggested that sequential locations that were close together were more likely to be correct than locations that were widely separated. Third, we assumed that bears were unlikely to travel long distances and then immediately return to where they started; thus, when 3 locations formed a narrow angle with long legs, ≥1 of the locations was likely to be an error. Finally, we assumed that bears were unlikely to move ≥100 km/day for periods of >1 day. Combining a minimum time interval with the maximum rate of movement allowed us to include short, rapid movements of bears as well as errors <100 km from locations obtained over short time intervals.

Error Mitigation

We define error mitigation as the process of applying rules to decide which locations to exclude. We use the term mitigation to acknowledge that any set of rules is likely to include some erroneous locations and to exclude some true locations; thus, locations are not positively identified as errors or non-errors. However, an effective mitigation technique will exclude most or all of the large errors and retain as much accurate data as possible. We evaluated 5 indices of location accuracy for possible use in mitigation procedures: NLOC, number of locations obtained/day (NDAY), distance to the closest other point from the same day (DPOINT), the greater of the standard deviations of the x and y coordinates of locations obtained within a day (STD), and the index proposed by Keating (1994:415):

$$\xi = \left(\frac{V_1 + V_2}{2}\right)\left(\frac{\min[V_1, V_2]}{\max[V_1, V_2]}\right)\left(\frac{1 + \cos\beta}{2}\right)$$

where V_1 and V_2 are the lengths of the vectors leading to and away from a location, respectively, and ß is the angle between them.

Evaluation of Mitigation Procedures

Our original database consisted of 68,000 locations of 143 bears that were monitored from January 1988 through December 1993. From these, we selected a baseline data set for each bear consisting of 1 location for each day that the bear was located. The location chosen was that closest to the location selected for the previous transmission period. We then plotted these data using Arc/Info (Environ. Systems Res. Inst., Redlands, Calif.) and examined the locations using the plausibility criteria. When suspect points were indicated, we made subjective decisions regarding which locations were plausible and which were implausible based on the bear's assumed route of travel indicated by previous and subsequent locations. We then compared mean values of the 5 indices between plausible and implausible locations. To determine the effect of setting threshold values of the indices, we examined distributions of the proportions of locations with index values below (NLOC and NDAY) or above (STD and Keating's index) various limits. These distributions indicated the proportion of observations that would be eliminated if a particular index value were used as a threshold.

We then examined the effectiveness of 2 selection procedures using combinations of indices. Both procedures selected locations from the original set of 68,000 points. For the first procedure (NLOC), we determined the highest NLOC index for each day and deleted all locations with lower values. Then, from the remainder, the location closest to the selection for the previous transmission period was selected. For the second procedure (50 km+NLOC), we added the threshold values of DPOINT ≤ 50 and NDAY ≥ 2. That is, we determined the distance from each location to the nearest other location obtained during the same day, excluded all points for which this distance was >50 km and those from days when only 1 location was obtained, and then repeated the NLOC procedure. We chose these thresholds because, when used individually, they removed most implausible locations while retaining approximately 90% of plausible locations (see Results). However, many other thresholds and combinations might be used instead.

Again, locations selected by each of the mitigation procedures were plotted for each bear, the plots were examined using the plausibility criteria, and subjective decisions were made regarding which locations were implausible. We then compared the numbers of implausible locations that were identified in the data sets after using each procedure. We also attempted to identify the circumstances that caused the implausible locations to be selected and determine if the selection procedures were selecting implausible locations when plausible locations were available.

RESULTS

The baseline data set included a total of 15,505 locations, representing every bear–day combination for which ≥1 location was obtained. Of these, 302 (1.9%) were identified as implausible. Mean values of every index differed significantly between implausible and plausible locations (*t*-tests, $P < 0.0001$; Table 1). However, for all indices, frequency distributions overlapped broadly between plausible and implausible locations. Most (98.3%) implausible locations had NLOC = 0. However, eliminating all locations with NLOC = 0 would have deleted 58.5% of the plausible locations from the baseline data set (Table 2). The other indices all had threshold values that would eliminate >50% of implausible locations while retaining ≥90% of plausible locations (Tables 3, 4, 5, and 6).

The NLOC procedure also selected 15,505 locations, of which 299 (1.9%) were implausible. Using the 50 km+NLOC procedure, 12,847 locations were selected (17.1% fewer than under the baseline and NLOC procedures), of which 10 (0.1%) were identified as implausible. The proportion of implausible locations remaining in the data after using the 50 km+NLOC procedure was significantly less ($\chi^2 = 228.83$, $P < 0.0001$) than with the baseline and NLOC procedures, but there was no difference ($\chi^2 = 0.015$, $P = 0.90$) between the baseline and NLOC procedures. Most (69.2%) of the implausible locations for the baseline and NLOC procedures were obtained on days when only 1 location was available. The 50 km+NLOC procedure eliminated these by requiring ≥2 locations within a day; this requirement alone would remove 10.6% of the plausible locations from the data selected by the baseline procedure.

Most of the implausible locations were obtained on days when none of the available locations seemed likely to be correct; thus, these errors were not due to the criteria of the procedures (89, 91, and 70% of implausible locations for the baseline, NLOC, and 50 km+NLOC procedures, respectively). However, on some occasions the selection criteria did not select the most plausible of the available locations. The closest location was not the most plausible for 15 and 2 occasions for the baseline and NLOC procedures, respectively (5.0 and 0.7% of implausible locations). The location with the highest NLOC was not

Table 1. Comparison of indices of location quality between plausible and implausible satellite locations of polar bears in the western Arctic, 1988–93.

	Plausible		Implausible					
Index	Mean	*n*	Mean	*n*	Var[a]	t^b	df	*P*
NLOC[c]	0.54	15,203	0.02	302	0.0094	55.6805	800	<0.0001
NDAY[d]	4.44	15,203	1.65	302	0.0822	33.9878	337	<0.0001
DPOINT[e]	18.09	13,589	385.97	93	67.9642	5.4127	92	<0.0001
STD[f]	8.14	13,589	100.77	93	15.4125	6.0098	92	<0.0001
Keating's[g]	11.50	14,959	84.40	283	6.3326	11.5115	282	<0.0001

[a] Pooled variance calculated according to Steele and Torrie (1980:106).
[b] *t*-test for samples with unequal variances (Steele and Torrie 1980:106).
[c] Argos location accuracy code.
[d] Number of locations reported for the day.
[e] Distance (in meters) to the closest point from the same day, excluding days with only 1 location.
[f] Maximum of standard deviations of the *x* and *y* coordinates (in meters) of locations from the same day, excluding days with only 1 location.
[g] Index proposed by Keating (1994), excluding first and last locations of each animal.

Table 2. Distributions of implausible and plausible locations according to values of the Argos accuracy code (NLOC) from satellite radiotracking of polar bears in the western Arctic, 1988–93. Percents of locations with lesser values of NLOC are the percents of locations that would be removed if a particular value of NLOC were used as a minimum acceptable value.

	Implausible			Plausible		
NLOC	*n*	%	% lesser	*n*	%	% lesser
0	297	98.3	0.0	8,895	58.5	0.0
1	5	1.7	98.3	4,582	30.1	58.5
2	0	0.0	100.0	1,544	10.2	88.7
3	0	0.0	100.0	182	1.2	98.8

Table 3. Distributions of implausible and plausible locations according to number of locations obtained/day (NDAY) from satellite radiotracking of polar bears in the western Arctic, 1988–93. Percents of locations with lesser values of NDAY are the percents of locations that would be removed if a particular value of NDAY were used as a minimum acceptable value.

	Implausible			Plausible		
NDAY	*n*	%	% lesser	*n*	%	% lesser
1	209	69.2	0.0	1,614	10.6	0.0
2	53	17.6	69.2	1,913	12.6	10.6
3	17	5.6	86.8	2,222	14.6	23.2
4	10	3.3	92.4	2,765	18.2	37.8
5	1	0.3	95.7	2,015	13.3	56.0
6	6	2.0	96.0	1,592	10.5	69.3
7	2	0.7	98.0	1,370	9.0	79.7
8	1	0.3	98.7	967	6.4	88.7
9	2	0.7	99.0	411	2.7	95.1
10	1	0.3	99.7	157	1.0	97.8
11	0	0.0	100.0	76	0.5	98.8
12	0	0.0	100.0	60	0.4	99.3
13	0	0.0	100.0	18	0.1	99.7
14	0	0.0	100.0	19	0.1	99.8
15	0	0.0	100.0	4	<0.1	>99.9

Table 4. Distributions of implausible and plausible locations according to distance to the nearest location obtained on the same day (DPOINT). Data are from satellite radiotracking of polar bears in the western Arctic, 1988–93. Percents of locations with greater distances are the percents of locations that would be removed if a particular distance were used as a maximum acceptable value.

DPOINT category[a]	Implausible			Plausible		
	n	%	% greater	*n*	%	% greater
10	3	3.2	96.8	9,026	66.4	33.6
20	1	1.1	95.7	1,779	13.1	20.5
30	0	0.0	95.7	845	6.2	14.3
40	0	0.0	95.7	466	3.4	10.8
50	3	3.2	92.5	350	2.6	8.3
60	2	2.2	90.3	225	1.7	6.6
70	2	2.2	88.2	168	1.2	5.4
80	5	5.4	82.8	122	0.9	4.5
90	3	3.2	79.6	93	0.7	3.8
100	2	2.2	77.4	78	0.6	3.2
>100	72	77.4	0.0	437	3.2	0.0

[a] Values listed for DPOINT are the maximum values of adjacent 10-point categories, except for the >100-point category.

Table 5. Distributions of implausible and plausible locations according to maximum values of the standard deviations of the *x* and *y* coordinates (STD) of locations from satellite radiotracking of polar bears in the western Arctic, 1988–93. Percents of locations with greater standard deviations are the percents of locations that would be removed if a particular value of STD were used as a maximum acceptable value.

STD category[a]	Implausible			Plausible		
	n	%	% greater	*n*	%	% greater
10	45	48.4	51.6	11,422	84.1	15.9
20	0	0.0	51.6	804	5.9	10.0
30	1	1.1	50.5	396	2.9	7.1
40	1	1.1	49.5	251	1.9	5.3
50	0	0.0	49.5	164	1.2	4.1
60	4	4.3	45.2	92	0.7	3.4
70	1	1.1	44.1	93	0.7	2.7
80	2	2.2	41.9	70	0.5	2.2
90	5	5.4	36.5	48	0.4	1.8
100	0	0.0	36.5	43	0.3	1.5
110	2	2.2	34.4	30	0.2	1.3
120	2	2.2	32.2	21	0.2	1.1
130	2	2.2	30.1	26	0.2	0.9
140	1	1.1	29.0	15	0.1	0.8
150	2	2.2	26.9	19	0.1	0.7
>150	25	26.9	0.0	95	0.7	0.0

[a] Values listed for STD are the maximum values of adjacent 10-km categories, except for the >150-km category.

the most plausible on 13 (4.3%) and 1 (10.0%) occasions for the NLOC and 50 km+NLOC procedures, respectively. Finally, selecting only locations with another location within 50 km evidently caused 2 (20.0%) implausible selections for the 50 km+NLOC procedure. Selecting locations based on the previous location might cause errors to be perpetuated (i.e., if an erroneous location was selected, then the following locations also might be selected erroneously). However, this evidently occurred on only 18 (6.0%) and 12 (4.0%) occasions for the baseline and NLOC procedures, respectively, and never for the 50 km+NLOC procedure. No apparent errors were perpetuated for >1 additional location.

DISCUSSION

Although the indices we examined all provided information that was useful in evaluating potential accuracy

Table 6. Distributions of implausible and plausible locations according to values of Keating's (1994) index. Data are from satellite radiotracking of polar bears in the western Arctic, 1988–93. Percents of locations with greater values of the index are the percents of locations that would be removed if a particular value of the index were used as a maximum acceptable value.

Index	Implausible			Plausible		
category[a]	*n*	%	% greater	*n*	%	% greater
10	58	20.5	79.5	9,724	65.0	35.0
20	27	9.5	70.0	2,393	16.0	19.0
30	22	7.8	62.2	1,235	8.3	10.7
40	26	9.2	53.0	685	4.6	6.2
50	13	4.6	48.4	372	2.5	3.7
60	7	2.5	45.9	214	1.4	2.2
70	15	5.3	40.6	143	1.0	1.3
80	15	5.3	35.3	75	0.5	0.8
90	11	3.9	31.4	46	0.3	0.5
100	7	2.5	29.0	29	0.2	0.3
110	7	2.5	26.5	15	0.1	0.2
120	6	2.1	24.4	6	<0.1	0.1
130	7	2.5	21.9	11	<0.1	<0.1
140	5	1.8	20.1	4	<0.1	<0.1
150	8	2.8	17.3	3	<0.1	<0.1
160	7	2.5	14.8	2	<0.1	<0.1
170	3	1.1	13.8	1	<0.1	<0.1
180	1	0.4	13.4	1	<0.1	0.0
190	5	1.8	11.7	0	0.0	0.0
200	3	1.1	10.6	0	0.0	0.0
>200	30	10.6	0.0	0	0.0	0.0

[a] Values listed for the index are maximum values of adjacent categories with increments of 10, except for the >200 category.

of locations, none were sufficient, either alone or in combination with the others, to exclude all implausible locations while not excluding an undesirably large number of the other locations. Similarly, the error mitigation procedures we examined all allowed some large apparent errors to remain in the selected data sets. Thus, some additional filtering was necessary. Choosing locations with the greatest value of NLOC within a day showed little improvement over simply selecting the location closest to the previous selection (NLOC procedure vs. baseline). However, the combination of requiring ≥2 locations ≤50 km apart and selecting the greatest NLOC value showed significant improvement relative to the amount of plausible data that was lost. Also, our plausibility criteria could not indicate which specific locations were likely to be errors and so could not be used as a mitigation procedure. This was because some conditions that caused the plausibility criteria to be met were the result of an implausible previous or subsequent location. For example, an unusually long movement leading to a location may be the result of an error in the previous location. Thus, it was necessary to examine the set of locations after applying the plausibility criteria, to decide subjectively which locations were implausible.

Keating (1994) recommended a threshold of 1.5 for his index to identify potential errors in telemetry data from bighorn sheep (*Ovis canadensis*), a relatively sedentary species. This threshold should not be expected to apply to a species that routinely makes long, irregular movements, but the index does provide a convenient method to quantify the spatial relationships among consecutive points and can be useful in a subjective analysis. Also, an upper threshold for the index could be used with our baseline and NLOC procedures. For example, a threshold of 40 would have eliminated 53% of the implausible locations and only 6.2% of the plausible locations in the baseline data set. However, for the polar bear data, our 50 km+NLOC procedure was a more efficient mitigation method. Compared to the baseline and NLOC procedures, the 50 km+NLOC procedure reduced the number of implausible locations by 97% while reducing sample size by only 17%. To remove as many implausible locations using Keating's index alone would have required eliminating locations with index values ≤0.2 and would have removed 89.3% of the plausible locations.

In the absence of confirming data, the plausibility of an animal's movements may be difficult to assess, especially when movements may be affected by outside influences. For example, the sea ice inhabited by polar bears moves in response to wind and ocean currents. Movements of bears that are traveling on moving ice may be accelerated or reduced, depending on the bears' direction of travel. This might cause movement patterns that would seem unlikely in areas where the substrate does not move. Thus, we made subjective decisions regarding what movements we would consider to be implausible, and what level of accuracy we would accept. These decisions must be tailored to fit the circumstances of a particular study.

CONCLUSIONS

To make best use of data from satellite telemetry it is necessary to balance the competing demands of eliminating errors and retaining as much accurate data as possible. This can be especially difficult for wide-ranging species such as polar bears, because unusual movements may be difficult to identify. All of the parameters we examined overlapped between plausible and implausible locations; however, all provided information that could be used in a subjective analysis. In any case, use of mitigation procedures based on characteristics of the data points themselves may introduce bias into the resulting data sets. Furthermore, the type and amount of bias will depend on the analysis that will be conducted. For example, selecting the point with the shortest distance to the previous point might be acceptable for studies of habitat use or geographic distribution, but this method might underestimate average distances traveled and rates of movement between periods. Thus, no single mitigation procedure will be appropriate for every type of analysis. However, using a formal set of plausibility criteria simplifies the task of evaluating locations, ensures that decisions are made consistently, and facilitates evaluating the effect of biases that may be introduced. We recommend that studies using satellite telemetry include a thorough consideration of location accuracy and the effects of methods used to identify potential errors.

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