AN ALTERNATIVE INDEX OF SATELLITE TELEMETRY LOCATION ERROR

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Abstract: Existing indices of satellite telemetry error offer objective standards for censoring poor locations, but have drawbacks. Examining distances and relative directions between consecutive satellite telemetry locations, I developed an alternative error index, ξ, and compared its performance with that of the location quality index, *NQ* (Serv. Argos 1988). In controlled tests, ξ was more ($P \leq 0.005$) effective for improving precision than was a threshold of $NQ > 1$. The ξ index also conferred greater control over the trade off between sample size and precision, making ξ more cost-effective than *NQ*. Performances of ξ and *NQ* were otherwise comparable. In field tests with bighorn sheep (*Ovis canadensis*), rejecting locations where $\xi \geq 1.5$ km reduced ($P < 0.001$) longitudinal dispersion, the predominant error component. Longitudinal dispersion for these locations was less ($P = 0.025$) than for locations where $NQ > 1$ and 63% fewer data were censored, so that the extent of animals' movements was better indicated by using ξ rather than *NQ*. Because use of ξ may lead to underestimating the number of long-range, short-term forays (especially when the frequency of forays is high relative to sampling frequency), potential bias should be considered before using ξ. Nonetheless, ξ should be a useful alternative to *NQ* in many animal-tracking studies.

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Although satellite telemetry is well suited to tracking animals' gross movements (Craighead and Craighead 1987, Fancy et al. 1988, Harris et al. 1990), it suffers from imprecision (Keating et al. 1991). Three indices of satellite telemetry error have been used to objectively censor locations and, thereby, improve precision: location quality (*NQ*) (Serv. Argos 1988), standard deviation (Clark 1989), and maximum satellite pass height (Harris et al. 1990). Of these, maximum satellite pass height is cost prohibitive (Harris et al. 1990), while Clark's (1989) 3-standard-deviation criterion relies on the untenable assumption that the distribution of locations is circular bivariate normal. Only *NQ* is widely used to index satellite telemetry error.

Location quality is determined from 6 criteria (Table 1) and is reported for every location by Service Argos (Landover, Md.). Unfortunately, few medium or high quality locations ($NQ > 1$) are achieved in most animal-tracking studies (Stewart et al. 1989, Harris et al. 1990), so that use of *NQ* typically leads to rejecting a high proportion of animal-tracking data. Moreover, individual *NQ*1 (Table 1) locations often are more accurate than ostensibly higher quality locations (Keating et al. 1991), so that use of *NQ* may lead to censoring many otherwise suitable locations.

Because existing indices of satellite telemetry error are, to varying degrees, unsatisfactory for animal-tracking data, I developed an alternative error index, ξ, and compared it with *NQ*. Comparisons focused on 2 aspects of index performance: effectiveness for improving precision and accuracy, and cost effectiveness.

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METHODS

The Index

To develop an alternative error index, I reasoned that large errors are more likely when

Table 1. Criteria for assigning location quality indices (*NQ*) to calculated satellite telemetry locations (Serv. Argos 1988, Clark 1989).

Location quality	Criteria
*NQ*3	>4 messages received by satellite, pass duration >420 sec, internal consistency <0.15 Hz, 5° < DT[a] < 18°, quality control on oscillator drift, and unambiguous solution.
*NQ*2	>4 messages received by satellite, pass duration >420 sec, internal consistency <1.5 Hz, 1.5° < DT < 24°, quality control on oscillator drift, and unambiguous solution.
*NQ*1	≥4 messages received by satellite, pass duration >240 sec, internal consistency <1.5 Hz, 1.5° < DT < 24°, and 1 test to determine correct solution.
*NQ*0	≥2 messages received by satellite.

[a] DT = angular distance from satellite ground track.

data indicate a single, relatively large movement, followed by an immediate return to a point near the origin. Conversely, large errors should be less likely when data indicate localized movements, movements in unrelated directions, or successive movements in the same direction. These patterns can be distinguished from as few as 3 consecutive locations, from which the magnitudes of 2 vectors (V_1 and V_2) and the smallest angle (β) formed by the vectors can be calculated (Fig. 1). Larger errors should be indicated when V_1 and V_2 are large ($[V_1 + V_2]/2 \rightarrow \infty$) and equal ($V_1/V_2 \rightarrow 1$), and when $\beta \rightarrow 0°$. Thus, I formulated the index as

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

where $\min(V_1, V_2)$ and $\max(V_1, V_2)$ are the smaller and larger, respectively, of V_1 and V_2. When $V_1 = V_2$ and $\beta = 0°$, ξ becomes an estimate of the error (i.e., $\xi = [V_1 + V_2]/2$). Conversely, $\xi \rightarrow 0$ as $\min(V_1, V_2)/\max(V_1, V_2) \rightarrow 0$ (indicating that the animal did not return to the point of origin) or as $\beta \rightarrow 180°$ (indicating successive movements away from the point of origin). I compared performances of ξ and *NQ* in controlled and field tests.

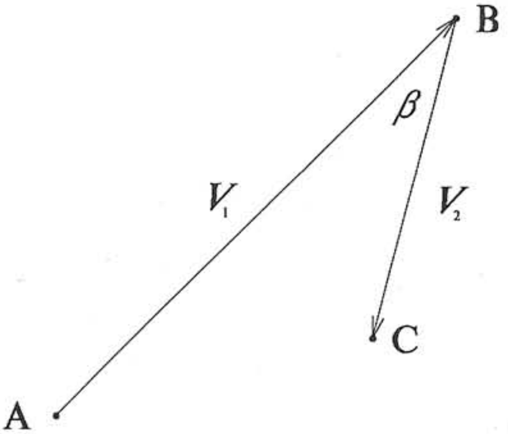

Fig. 1. Parameters used in calculating the satellite telemetry error index, ξ. Three consecutive locations (A, B, and C), the vectors (V_1 and V_2) formed by those locations, and the minimum angle (β) formed by the vectors are shown. The index is calculated as

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

where $\min(V_1, V_2)$ and $\max(V_1, V_2)$ are the minimum and maximum of V_1 and V_2, respectively.

Controlled Tests

Ten Telonics platform transmitter terminals (PTTs) (Model ST-3, Telonics, Inc., Mesa, Ariz.) were deployed in 2 phases. In phase 1, I placed PTTs in a circle (radius = 2 m) around a second-order National Geodetic Survey marker near Scalplock Lookout, Glacier National Park, Montana. Given National Geodetic Survey standards (D. R. Doyle, Natl. Geodetic Surv., pers. commun.), I considered horizontal and vertical controls for the site accurate to within ±0.1 m. When calculating observed location errors, I assumed PTTs were directly on the survey marker, as the 2 m difference was considered trivial. In phase 2, I placed the same PTTs on domestic dogs, horses, and mules confined to 6 areas with radii <20 m. I disregarded data collected when animals were indoors or removed from test sites. I surveyed site locations using a Pathfinder II® Global Positioning System (Trimble Navig., Sunnyvale, Calif.) in autonomous mode. Position dilutions of precision values were <6, so that survey errors were estimated to be <10 m for horizontal controls and <15 m for vertical controls (A. E. Jasumback, U.S. For. Serv. Missoula Tech. Dev. Cent., Mont., pers. commun.). Elevation for 1 of the 6 sites was estimated from survey data for a nearby site and was assumed to be within 20 m of the true elevation. Test sites for phases 1 and 2 were within 48°1′ and 48°31′N and 113°33′ and 114°15′W.

Service Argos reports coordinates for satellite telemetry locations as latitudes and longitudes, referenced to the World Geodetic System 1984 ellipsoid. I converted these to North American Datum 1927 equivalents, then to Universal Transverse Mercator (UTM) coordinates, using NADCON4 (Dewhurst 1989) and UTMS (Carlson and Vincenty 1989) software. I comparably converted surveyed coordinates of the Scalplock Lookout site and of domestic animals before calculating telemetry errors.

Service Argos assigned and reported NQ values. Using UTM coordinates, I calculated ξ (1) for all but the first and last locations of each PTT, using all possible triads of successive locations. For example, given 4 successive locations (ABCD) of a single PTT, I calculated ξ using ABC and BCD, yielding ξ-values for locations B and C. I did not consider locations where $NQ = 0$ because such locations were not calculated during phase 1. Also, they are imprecise (Keating et al. 1991) and, typically, are not used in studies where precision is a concern (i.e., in studies where use of error indices is likely). I tested 3 null hypotheses comparing the performances of ξ and NQ.

Null Hypothesis 1.—Error indices ξ and NQ are equally effective for improving precision of satellite telemetry locations. Applying thresholds of $NQ > 1$ and $NQ = 3$ to phase 1 and phase 2 data, I generated 4 subsamples of locations. I then derived equal-sized subsamples from the same datasets using ξ rather than NQ to censor locations. To test null hypothesis 1, I compared the log-normal mean errors of the equal-sized subsamples for equality using a 2-sample t-test. I used log-normal mean error to indicate precision because satellite telemetry errors were approximately log-normally distributed (Keating et al. 1991).

Null Hypothesis 2.—Subsamples derived using ξ and NQ are equally biased. Because only the magnitude (not the direction) of the bias is relevant for comparing the performances of ξ and NQ, I measured bias as the magnitude (r_B) of the mean vector, given by

$$r_B = \sqrt{\bar{x}^2 + \bar{y}^2}, \qquad (2)$$

where $\bar{x}$ and $\bar{y}$ are the mean errors along the east-west and north-south axes, respectively (Batschelet 1981). To test null hypothesis 2, I calculated differences (D) between the biases of the equal-sized subsamples described above and compared them with distributions of differences expected under the null hypothesis that $D = 0$. I used a bootstrap procedure (Manly 1991) to estimate the expected distribution of differences for each pair of equal-sized subsamples. Two bootstrap samples were drawn, 1 from each of the equal-sized subsamples. Bootstrap estimates of bias ($\hat{r}_B$) were then calculated (2) and the expected difference (D^*) was estimated as $D^* = \hat{r}_{B,\xi} - \hat{r}_{B,NQ} - D$. I calculated 1,000 D^*-values for each pair of equal-sized subsamples and estimated the probability that $|D^*| \geq |D|$ from the resulting distributions. This analysis excluded 1 pair of equal-sized subsamples because subsamples were too small ($n = 2$) to support bootstrap procedures.

Null Hypothesis 3.—Indices ξ and NQ are equally cost-effective for improving precision of satellite telemetry locations. Cost effectiveness (CE) equals the change in precision per location censored. Because precision is inversely related to the log-normal mean of the absolute errors ($\bar{r}_{ln}$), CE may be calculated as

$$CE = -\frac{d\bar{r}_{ln}}{dn_c}, \qquad (3)$$

where n_c is the number of locations censored. To estimate CE, I first estimated the relationship between $\bar{r}_{ln}$ and n_c by repeatedly recalculating log-normal mean error as locations with successively smaller apparent errors (smaller ξ, larger NQ) were excluded. I repeated this process 4 times, using first ξ, then NQ, to censor phase 1 and phase 2 data. To allow comparisons between datasets, I then standardized $\bar{r}_{ln}$ and n_c; n_c was expressed as a proportion (n_p) of the uncensored sample size, and $\bar{r}_{ln}$ as a proportion ($\bar{r}_p$) of the uncensored log-normal mean error. I then estimated relationships between $\bar{r}_p$ and n_p using stepwise polynomial regression, which yielded third- and second-order models for the ξ- and NQ-derived subsamples, respectively. For phase 2 data, the resulting model for NQ was unreasonable, probably due to the small number ($n = 3$) and particular position of data points used to fit the curve. Therefore, I used nonlinear regression to fit these data to a model of the general form $\bar{r}_p = 1 + b_0 n_p + b_1 n_p^{b_2}$, where b_0, b_1, and b_2 were regression coefficients. I selected this model to be realistic and to portray performance of NQ in the best light, so that any conclusion of a relative advantage of ξ over NQ would be conservative. Finally, I estimated cost effectiveness (3) from the modeled relationships and compared patterns of cost effectiveness for ξ and NQ graphically.

Field Tests

I used satellite telemetry locations of 2 free-ranging bighorn sheep collared on the Mount Altyn winter range in the Many Glacier Valley, Glacier National Park, Montana (48°47′N, 113°40′W). Both were adult females, trapped during December 1987–April 1988, fitted with PTTs (Telonics ST-3), and tracked for about 1 year. Locations for which $NQ = 0$ were not calculated. The area occupied by the sheep was characterized by precipitous peaks and glaciated valleys. Elevations ranged from 1,463 to 3,052 m. Because location calculations assumed PTTs were at sea level, locations were corrected for elevation-induced errors (Keating, unpubl. data) before calculating ξ. I recorded visual observations of collared animals primarily during spring and summer 1988. I also recorded visual observations of adult females associated with collared animals. These females were individually identifiable from unique horn characteristics.

To test efficacy of ξ, I rejected bighorn locations where $\xi \geq 1.5$ km. Because actual errors were unknown, the resulting picture of bighorn movements was compared with visual observations and with hypothesized changes in the dispersion of telemetry locations. Reduced longitudinal dispersion was hypothesized because satellite telemetry errors tend to be greater in the east–west direction (Clark 1989, Keating et al. 1991). To determine if the reduction in longitudinal variance was statistically significant, I used randomization methods (Manly 1991) to test the null hypothesis that the longitudinal variance of the ξ-derived subsample was greater than or equal to the longitudinal variance of 5,000 equal-sized subsamples that were drawn randomly (without replacement) from the pool of bighorn locations. I compared performances of ξ and NQ, using Levene's test (Conover et al. 1981), to evaluate the null hypothesis that the longitudinal variance of the ξ-derived subsample was greater than or equal to the longitudinal variance of the NQ-derived subsample. Finally, I used Levene's test to evaluate the null hypothesis that the longitudinal variances of the ξ-derived subsample and the visual locations were equal.

I primarily used SYSTAT and SYGRAPH (Wilkinson 1988*a*,*b*) software. Significance was assumed at $\alpha = 0.05$. Except where otherwise indicated, transformations and parametric and nonparametric tests were applied according to Zar (1984).

RESULTS

Controlled Tests

I rejected the null hypothesis that ξ and NQ were equally effective indices for improving precision. Although there were no differences between precisions of equal-sized subsamples generated using ξ and those generated using a threshold of $NQ = 3$, ξ yielded more precise subsamples than did a threshold of $NQ > 1$ (Table 2). There were no differences, however, between biases of the ξ- and NQ-derived subsamples (Table 3).

I also rejected the hypothesis that ξ and NQ were equally cost effective. The index ξ was most cost effective when <30% of the data were rejected, whereas NQ was most cost effective only when larger proportions of data were rejected (Fig. 2). Also, cost effectiveness for ξ was positive regardless of the proportion of locations rejected. For phase 2, cost effectiveness of NQ was negative until >80% of the data were rejected (Fig. 2).

Field Tests

I calculated ξ for 875 locations of 2 bighorn sheep. Because both animals used the same seasonal ranges, data were pooled. One extreme outlier (location error ≈7,400 km) likely resulted from selecting the wrong solution to the location algorithm (each location calculation has 2 possible solutions and Service Argos uses results from consecutive passes to choose between them). This outlier was excluded from analyses because it caused efficacies of both indices to be overstated.

Rejecting locations where $\xi \geq 1.5$ km reduced longitudinal dispersion of locations (SD = 2.045 vs. 2.486 km, $P < 0.001$) and improved the fit with visual observations (Fig. 3). However, dispersion for the ξ-derived subsample was still greater than for visual observations (SD = 2.045 vs. 1.204; $F = 49.453$; 1, 771 df; $P < 0.001$). Sample size declined 31%. In contrast, sample size declined 99% when restricted to high quality ($NQ3$) locations and 84% when restricted to medium and high quality ($NQ > 1$) locations. Being cost prohibitive, a threshold of $NQ = 3$ was not considered further. Thresholds of $NQ > 1$ and $\xi < 1.5$ km yielded subsamples with identical longitudinal ranges (299.947 km $\leq$

Table 2. Tests of the null hypothesis that error indices ξ and *NQ* were equally effective for improving precision of satellite telemetry locations. Thresholds indicate the criteria (Table 1) used to censor satellite telemetry locations in the *NQ*-derived subsamples. Threshold values for ξ varied, but were selected to yield subsamples of equal size (n). A t-statistic was used to test the null hypothesis that $\bar{r}_{\ln,\xi} = \bar{r}_{\ln,NQ}$.

		Log-normal mean error[a]					
Threshold	n	$\bar{r}_{\ln,\xi}$	SE	$\bar{r}_{\ln,NQ}$	SE	t	P
Phase 1							
$NQ = 3$	129	5.522	0.088	5.428	0.090	0.749	0.455
$NQ > 1$	411	5.717	0.044	6.025	0.057	−4.283	0.000
All	776	6.331	0.040	6.331	0.040	NA	NA
Phase 2							
$NQ = 3$	2	6.857	0.773	6.141	0.484	0.785	0.515
$NQ > 1$	22	6.375	0.122	7.000	0.171	−2.975	0.005
All	114	6.821	0.090	6.821	0.090	NA	NA

[a] ln(error + 1), where error is in m.

UTM easting ≤ 312.948 km), but longitudinal variance of the ξ-derived subsample was smaller (SD = 2.045 vs. 2.366 km; $F = 5.029$; 1, 734 df; $P = 0.025$).

Because 63% fewer data were rejected by using ξ rather than *NQ*, the full extent of the animals' movements was better indicated. This was evidenced by 35 locations in the ξ-derived subsample, which suggested that the animals' home ranges extended up to 2.1 km farther south than was indicated by locations where $NQ > 1$ (Fig. 3). Two lines of reasoning suggested that these movements were real, although they could not be confirmed by visual observations. First, I calculated the latitudinal difference between the southernmost location in the *NQ*-derived subsample and each of the 35 locations in question. Comparing the distribution of these differences with the distribution of random latitudinal errors associated with *NQ*1 locations (as calculated from the phase 1 data), I concluded that system error could not account for observed discrepancies (Mann-Whitney $U = 4{,}331.5$; 35, 365 df, $P = 0.002$). The fact that I observed no similar discrepancy for the northern extent of the animals' home ranges further supported this finding. Second, visual observations confirmed that the area in question was used by other adult female bighorns during the same period (late summer), and that these same females commonly associated with the collared animals on adjacent spring and summer ranges. Because seasonal movements by bighorn sheep are traditional and are learned from conspecifics, particularly those of the same sex (Geist 1971), these observations make it likely that collared animals also used the area in question.

DISCUSSION

Although ξ and *NQ* are objective, nonparametric indices of satellite telemetry error, they are otherwise dissimilar. The index *NQ* explicitly considers only select determinants of location error and, being an ordinal index, offers limited control over the trade off between sample size and precision. The index ξ implicitly integrates effects of all determinants of error and, being a ratio-scale index, confers great con-

Table 3. Tests of the null hypothesis that error indices ξ and *NQ* yielded equally biased subsamples of satellite telemetry locations. Thresholds indicate the criteria (Table 1) used to censor satellite telemetry locations in the *NQ*-derived subsamples. Threshold values for ξ varied, but were selected to yield subsamples of equal size (n). *P*-values indicate the 2-tailed probability that $r_{B,\xi} - r_{B,NQ} = 0$ and, like estimates of SE, were calculated from 1,000 bootstrap samples each.

		Magnitude of bias				
Threshold	n	$r_{B,\xi}$	SE	$r_{B,NQ}$	SE	P
Phase 1						
$NQ = 3$	129	93.724	42.665	38.181	15.434	0.244
$NQ > 1$	411	40.178	9.208	65.110	16.229	0.461
Phase 2						
$NQ > 1$	22	305.682	70.399	580.448	180.420	0.289

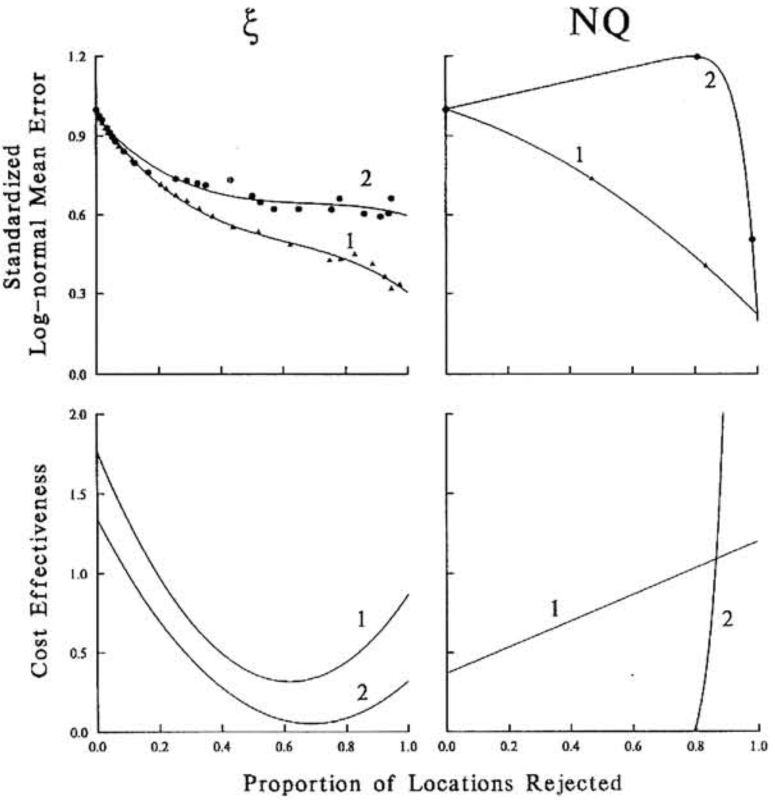

Fig. 2. Log-normal mean satellite telemetry error and cost effectiveness of censoring locations as functions of the proportion of the sample rejected, where locations with the largest apparent errors were censored first. Results obtained using patterns of consecutive locations (ξ) to index errors are compared with those obtained using Service Argos' index of location quality (*NQ*). Curves 1 and 2 show regression results for data from 10 transmitters placed at a National Geodetic Survey marker (phase 1) and then on domestic animals at known locations (phase 2), respectively.

trol over the trade off between sample size and precision. Comparisons indicated that such differences do not affect location accuracy, but do translate into disparities in precision and cost effectiveness.

Precision tended to be higher when ξ, rather than a threshold of $NQ > 1$, was used to censor locations. In controlled tests, use of ξ reduced log-normal mean error by 7–10%. When back transformed to express log-normal mean error in meters, the reduction was 36–46%. In field tests, the longitudinal variance of the ξ-derived subsample (as measured by SD) was 18% smaller, even though fewer data were censored. Because satellite telemetry errors are predominantly longitudinal (Clark 1989, Keating et al. 1991), this reduced longitudinal variance was consistent with the hypothesis that the ξ-derived subsample was more precise. Precision was not different when ξ was compared with a threshold of $NQ = 3$. However, too few *NQ*3 locations usually are achieved in animal-tracking studies (Stewart et al. 1989, Harris et al. 1990, this study) to make it practical to limit analyses to such data. Thus, it is the comparison between ξ and a threshold of $NQ > 1$ that is most relevant to wildlife research.

The index ξ also was more cost effective than was *NQ*. In controlled tests, ξ yielded most of the potential increase in precision when <30–40% of the locations were censored, whereas cost effectiveness for *NQ* remained low until much larger proportions of the data were rejected. In the most extreme example, cost effectiveness for *NQ* was negative until >80% of the locations had been censored. Results from field tests also supported the conclusion that ξ was the more cost-effective index: 63% fewer locations were censored using ξ, yet precision was greater than for the *NQ*-derived subsample.

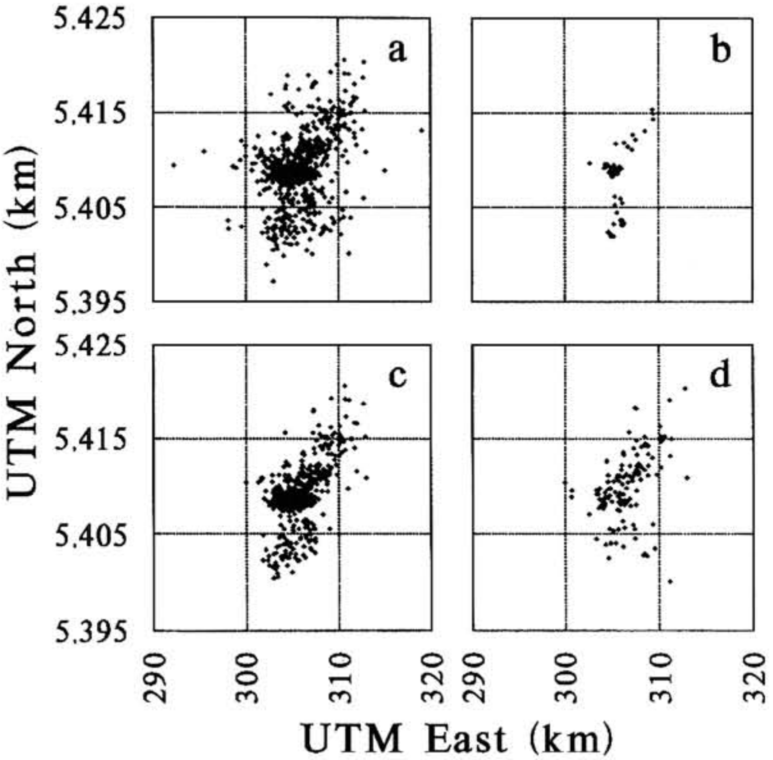

Fig. 3. Dispersions of (a) 875 satellite telemetry locations for 2 bighorn sheep, (b) visual observations of the 2 radio-collared animals, (c) the 600 locations where $\xi < 1.5$ km, and (d) the 136 medium and high quality ($NQ > 1$) locations. Locations are referenced to zone 12 of the Universal Transverse Mercator (UTM) coordinate system.

The relatively low cost effectiveness of *NQ* was probably due to 2 factors. First, because this study was dominated by *NQ*1 locations, it was not possible to use *NQ* to censor fewer than 47–84% of the data, thereby ensuring that cost was high regardless of effectiveness. Second, substantial overlap existed among error distributions associated with different *NQ* values (Fig. 4), so that *NQ* was a reliable index of precision only for relatively large samples. This likely accounted for phase 2 results, whereby 81% of the locations were censored yet the log-normal mean error of the remaining 22 locations increased 2.6% (nearly 20% for the back-transformed data) (Table 2). Both factors suggest that cost effectiveness for *NQ* might exceed that of ξ in studies achieving higher proportions and larger absolute numbers of *NQ*2 or *NQ*3 locations. However, high proportions of such locations appear to be atypical of animal-tracking studies. In 12 wildlife studies summarized by Harris et al. (1990:13), *NQ*1 locations comprised 42–92% ($\bar{x} = 0.67 \pm 0.04$ SE) of the data.

Although it offers important advantages, use of ξ entails assumptions that may bias results. By using 3 consecutive locations to index error, I assumed that extreme movements were not real unless confirmed by the preceding or subsequent location. Clearly, a second corroborative location will not always be obtained before an animal departs to a new area or returns to a location near its point of origin. Use of ξ should, therefore, lead to underestimating the frequency of long-range, short-term movements. The degree to which such movements are underestimated should depend upon sampling frequency and an animal's movement patterns. Short-term movements should be most seriously underestimated when sampling frequency is low and for individuals making frequent, long-range forays from 1, or between 2, activity centers. Little bias is expected when the frequency of large movements is low relative to sampling frequency, as it was for bighorns in this study. Before using ξ to censor locations, one should weigh the potential for bias against the alternatives of either using *NQ* or relying on uncensored data.

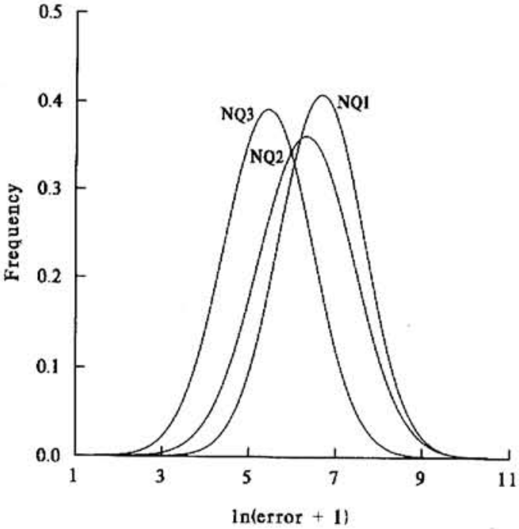

Fig. 4. Estimated distributions of log-transformed satellite telemetry errors associated with the different location qualities (*NQ*-values; Table 1) assigned by Service Argos. Distributions were calculated from estimates (Keating et al. 1991) of lognormal means and standard deviations of satellite telemetry errors associated with each *NQ*-value, and suggest that *NQ* is not a reliable index of satellite telemetry error for small samples. Errors were originally calculated in meters.

Selection of a threshold value for ξ is a subjective exercise that will be influenced by individual requirements for precision and sample size. Because precision and sample size are influenced by many factors (Harris et al. 1990, Keating et al. 1991), firm guidelines cannot be expected. However, workers should anticipate the trade offs exemplified in this study. When I rejected 31% of the bighorn sheep data, sampling frequency declined from 1.1 to 0.8 locations/PTT/day and cost per location increased 38%. In return, censoring yielded a more precise dataset, eliminating many locations from clearly unsuitable habitats such as lakes and deep forests. This enabled more confident identification of seasonal ranges and specific migration routes among them (Keating, unpubl. data). Although such trade offs must be weighed on a case-by-case basis, it appears that ξ may be usefully and broadly applied to improve the precision and, hence, the interpretability of satellite telemetry data.

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