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ERROR IN TELEMETRY STUDIES: EFFECTS OF ANIMAL MOVEMENT ON TRIANGULATION

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Abstract: We used Monte Carlo simulations to investigate the effects of animal movement on error of estimated animal locations derived from radio-telemetry triangulation of sequentially obtained bearings. Simulated movements of 0–534 m resulted in up to 10-fold increases in average location error but <10% decreases in location precision when observer-to-animal distances were <1,000 m. Location error and precision were minimally affected by censorship of poor locations with Chi-square goodness-of-fit tests. Location error caused by animal movement can only be eliminated by taking simultaneous bearings.

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Telemetry triangulation is commonly used for obtaining location estimates of animals. The accuracy of a location estimate "is a function of tower locations, the animal's location relative to the towers, and precision of the bearings from the tower to the animal" (White and Garrott 1986:509), where towers refer to the antennas used by observers to obtain bearings. For triangulation from fixed antennas where bearings are obtained simultaneously, an animal has only 1 location relative to the antennas. However, many studies employ a single mobile antenna to sequentially obtain all bearings for a single location estimate. The time delay due to changing

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antenna locations allows for animal movement and, thus, error due to changes in the animal's position. These errors may decrease the ability to detect habitat selection (White and Garrott 1986) or may alter the interpretation of social interactions (Pyrah 1984, Andelt 1985).

Our objective was to simulate the telemetry location process and to understand how animal movements might magnify telemetry location error. By examining animal movements simultaneously with other sources of location error, the relative importance of animal movements in obtaining accurate location estimates can be determined.

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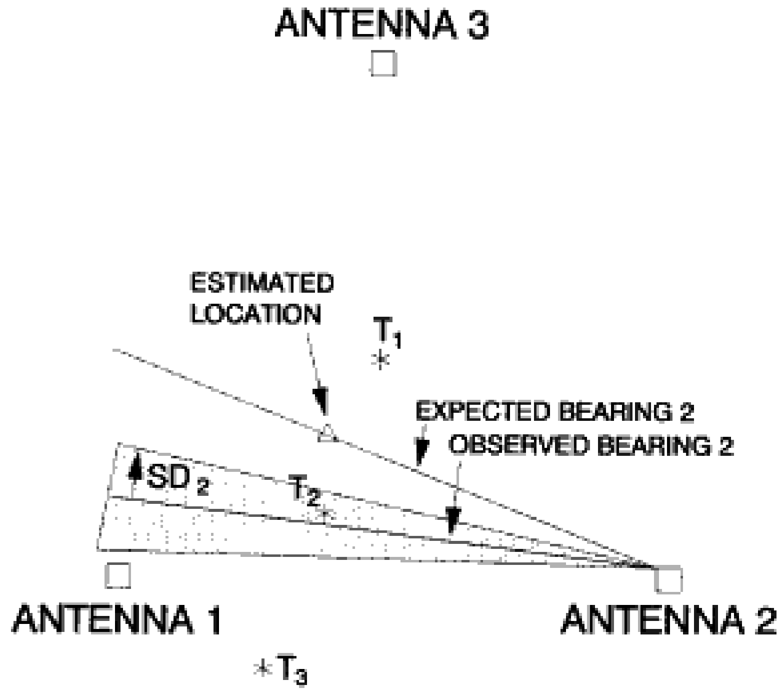

Fig. 1. Location of a simulated animal by triangulation from 3 antennas. T_1, T_2, and T_3 are the animal's true locations when sequentially obtaining bearings from antennas 1, 2, and 3. The location estimate was derived by maximum likelihood estimation (Lenth 1981). For each antenna there was an observed bearing with an associated antenna standard deviation (SD) and an expected bearing.

METHODS

We simulated telemetry locations by triangulation from 3 antennas for a stationary animal and for one moving in randomly chosen directions. All simulations were developed using the SAS program language (SAS Inst., Inc. 1987). Movement rates were selected from a normal distribution with a standard deviation arbitrarily estimated to be 25% of the mean rate. We chose a range of simulated movements to represent studies of large, terrestrial vertebrates. Mean movement rates of 0.6–1.6 km/hour and time delays between 2 consecutive bearings of 3–10 minutes were simulated. These movement rates were similar to those found for breeding coyotes (*Canis latrans*) (Andelt 1985) and territorial roe deer (*Capreolus capreolus*) (Sempere 1980). Although these movement rates were themselves partially based on triangulation of telemetry locations, we feel they were sufficiently accurate for use in our simulation. Direction of movement was randomly selected from a uniform distribution ranging from 0 to 360°. Movement, a product of movement rate and time delay between first and last bearings, ranged from 0 to 534 m.

Estimates of animal locations were generated using Lenth's (1981) maximum likelihood estimator (MLE). When 3 bearings do not intersect at the same point, 3 intersections are created. The MLE method computes an estimate of location that minimizes the distance to all 3 of these intersections. The MLE provides an estimated animal location and a 95% confidence ellipse. We defined 3 true locations: T_1, T_2, and T_3 were, respectively, the simulated animal's true location when the first, second, and third bearings were obtained (Fig. 1). For simultaneously obtained bearings, the animal's true location was a single, stationary position ($T_1 = T_2 = T_3$). Movement during the location process was the distance between T_1 and T_3. Time delays were equal between bearings from antennas 1 and 2 and between antennas 2 and 3. At the beginning of the simulations, antenna-to-animal distances (AAD) were 250, 500, 1,000, and 2,000 m, and antennas were equidistant from the animal and from each other to minimize location error (White 1985). Movement away from this central, equidistant position contributes to location error associated with animal movement.

We simulated antenna standard deviations of 1.5, 3.0, and 5.0° to approximate bearings potentially obtained with high quality vehicle-mounted antennas, low quality vehicle-mounted antennas, and hand-held antennas, respectively. Thus, each iteration of the simulation routine selected a random bearing from a normal distribution with the mean equal to the true bearing and standard deviation equal to 1.5, 3.0, or 5.0°. Mean bearing error was zero degrees. Animal movements were assumed to not affect antenna standard deviation through signal mod-

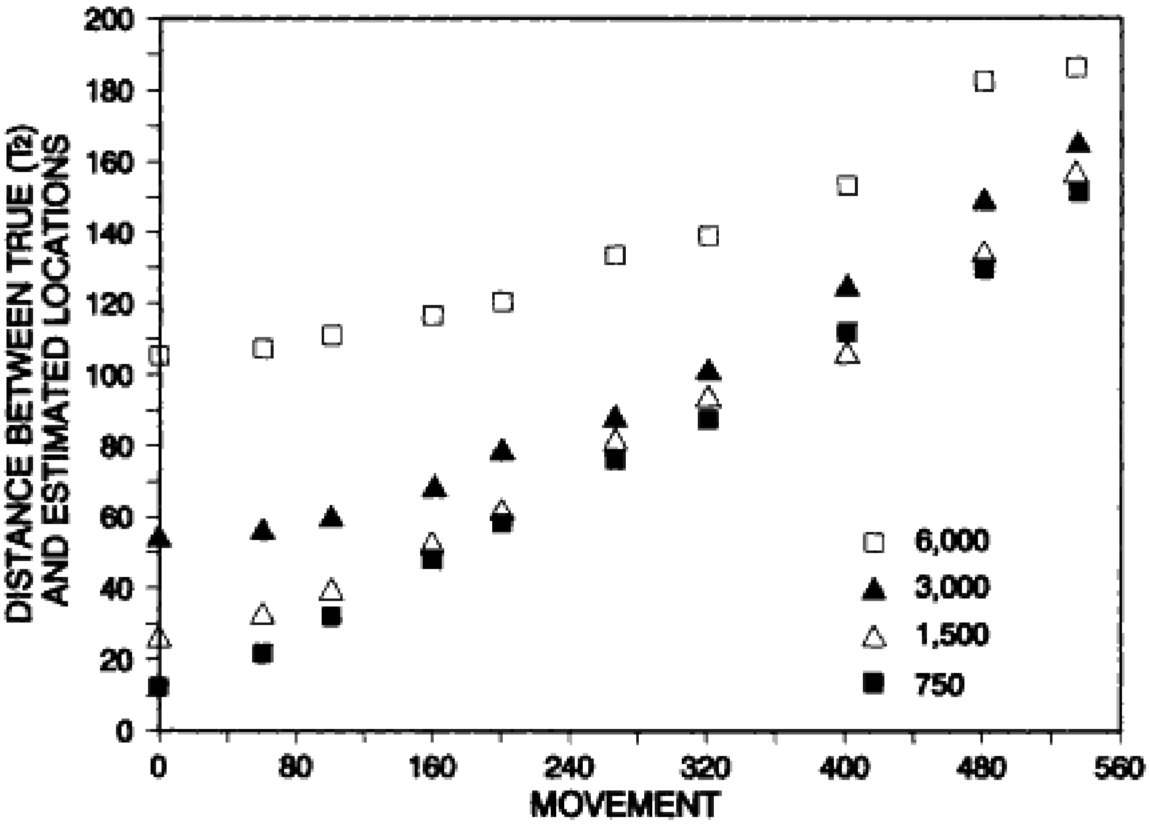

Fig. 2. Location error as represented by the distance between the estimated location and true location of a simulated animal located by triangulation from 3 antennas. Movement (movement rate multiplied by time delay between bearings) represents the linear distance an animal travels during the location process. Antenna standard deviation (SD) represents the accuracy of the antenna used, and AAD is the antenna-to-animal distance at the beginning of the location process. Points represent the product of AAD times antenna standard deviation. Axes are in meters, but any scale may be substituted.

ulation, although Cederlund et al. (1979) and Lee et al. (1985) suspected that this may occur.

Location error, or accuracy, was calculated as the distance between the animal's estimated location and true location(s). The minimum error for all locations of a moving animal was the distance between the estimated location and T_2, the true location when obtaining the second bearing. Due to the particular spatial arrangement of antennas used in our study relative to an animal moving in 1 direction, T_2 was always closest to this location estimate. Subsequent references to error refer to the distance between the estimated location and T_2. Location precision was the confidence ellipse areas (m^2) associated with each location estimate. Prior to analysis, locations were excluded from the data set when any 2 of 3 bearings failed to intersect within a distance of 3 times AAD of all antennas. This situation, representing extreme movements, occurred with the shortest AAD's and fastest movement rates and accounted for <5% of locations in the uncensored data set. Censorship of these locations effectively eliminated nonintersecting bearings that caused irregular behavior of the MLE.

Each unique combination of AAD, movement rate, and antenna standard deviation represented a set of conditions that could influence location error and precision irrespective of animal movements. We therefore simulated each set of conditions with each movement rate 1,000 times. Each set of 1,000 locations was then analyzed with Chi-square goodness-of-fit tests to see if inaccurate locations could be identified and censored to improve average location error. Chi-square goodness-of-fit tests were computed as

$$\chi^2 = \sum_{i=1}^{3} [(\text{Observed bearing } i - \text{Expected bearing } i)/SD_i]^2$$

where i indexes antennas, observed bearing i is the bearing for antenna i, SD_i is the standard deviation for antenna i, and expected bearing i is the bearing from antenna i to the estimated location (Fig. 1). This statistic has only 1 degree of freedom because estimates of the location ($\hat{x}$ and $\hat{y}$ coordinates) are required to compute the expected bearings. Because of the variance associated with obtaining bearings from a given antenna, bearings on a stationary animal will usually intersect close to, but not at, the estimated location. For a moving animal, observed bearings deviate more strongly from the bearing to the estimated location (expected bearing), and thus, result in comparatively larger Chi-square values. Therefore, these test statistics were used to examine if a given location estimate fit the expected distribution of location estimates for a stationary animal at the specified AAD and antenna standard deviation. The AAD and antenna standard deviation both negatively affect location error but are independent of error caused by animal movement. The product of AAD and antenna standard deviation is presented in our figures as a single value to represent this independent source of location error.

RESULTS

In our simulations, location error was on average less than the associated animal movement. The closeness of the estimated location to T_2 (T_2 being the midpoint between T_1 and T_3) accounted for this result. Although location error was less than the actual animal movement, the 2 measures were positively and linearly correlated (Fig. 2). The greater the unidirectional movement during the location process, the greater the location error. The slope of this linear relationship was dependent on AAD and antenna standard deviation values.

Average error increased (Fig. 2) and precision declined with increasing time delay most rapidly when AAD's and antenna standard deviations were smallest. Average error increased 269%, and precision declined 4% for a 160-m movement given AAD = 500 m and 1.5° antenna standard deviation. Average error increased 492%, and precision declined 8% with a 266-m movement. Because both AAD and antenna standard deviation affect location error and precision (White and Garrott 1986), large AAD's and antenna standard deviations "swamp" movement-induced location error and precision. Large AAD's (≥1,000 m) and antenna standard deviations (5°) resulted in ellipse areas of 9–38 ha. Though movement-induced error and reduced precision were negligible under these conditions, the precision of the location estimate was much poorer than with short AAD's and precise antennas.

We rejected location estimates of moving animals most frequently under conditions of short AAD's and precise antennas. With only 60-m movement, >70% of locations were rejected when AAD = 250 m and antenna standard deviation was 1.5° (Fig. 3). As expected, rejection occurred in approximately 5% of locations when no movement occurred, because α was specified at 0.05.

Average error never decreased more than 23% when only locations meeting the Chi-square goodness-of-fit criteria ($P > 0.05$) were used. For a 534-m movement (SD = 1.5°, AAD = 500 m), 93% of the locations were censored with the goodness-of-fit test, but the average error was only reduced by 23% and was still about 10 times the average error for zero time delay. Precision only improved by 20% (the max. for all situations simulated), but this improvement was very slight considering the large proportion of locations censored. Thus, the goodness-of-fit test provided little help in improving the quality of location estimates, even when a large proportion of the data was rejected.

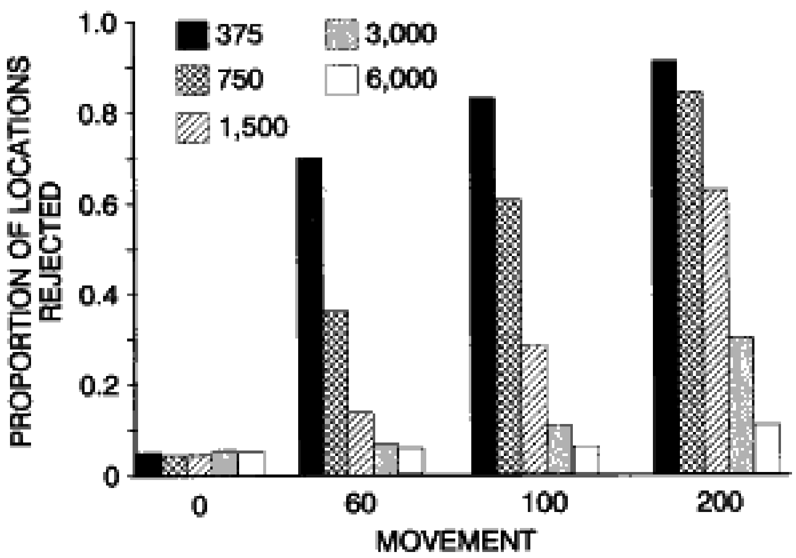

Fig. 3. Proportion of 1,000 location estimates obtained with triangulation from 3 antennas that are rejected using Chi-square goodness-of-fit tests. Movement (movement rate multiplied by time delay between bearings) represents the linear distance an animal travels during the location process. Antenna standard deviation (SD) represents the accuracy of the antenna used, and AAD is the antenna-to-animal distance at the beginning of the location process. Bars represent the product of AAD times antenna standard deviation.

DISCUSSION

Animal movements have been recognized by many investigators as a source of error in telemetry locations (Hupp and Ratti 1983, Loft et al. 1984, Edge and Marcum 1985), but the magnitudes of the errors are rarely addressed. Laundré and Keller (1981) simulated coyote movements by having a person carry a transmitter along a known path at various potential coyote speeds. With 2–4 minutes between bearings they estimated movement-induced errors of ±0.14 km. In many current studies, time delays between bearings are much longer (Edge and Marcum 1985). Investigators are generally aware that animal movements hamper triangulation accuracy and precision, but lack a good assessment of the error caused by movements. To offset these difficulties, investigators have used subjective sampling and data censorship such as sampling only during periods of expected in-activity and/or including only those locations obtained within a "reasonable" amount of time (Andelt 1985, Edge and Marcum 1985).

Animal movements should increase location error when bearings are obtained sequentially. The magnitude of this increase has been assumed to be minimal, as previous investigators have given animal movements scant attention. Indeed, in our simulation, location error was on average less than the associated animal movement (Fig. 2). However, error increased most rapidly with animal movement when using short AAD's and small antenna standard deviations (Fig. 2). Although short AAD's and small antenna standard deviations minimize overall location error, the proportional contribution of animal movement to location error is greatest under these conditions. Yet, investigators purposely create these conditions in studies that require relatively accurate and precise estimates of location to minimize error not associated with animal movement (White 1985). Animal movements therefore exacerbate location error the most where error is least allowable.

The simulated movements in 1 direction during time delays between bearings resulted in larger errors than would occur with more random directional movements, but we believe that our restrictions are more realistic than a model incorporating random movements. Because movement was the variable of interest, any value for either movement rate or time delay between bearings could have been used. Additionally, because error and precision, AAD, and movement were all measured in meters, the axes and legend of Figure 2 can be treated as unitless, making them more generally applicable. Consequently, our results are relevant to all telemetry studies that derive location estimates with triangulation.

Location error was markedly affected by animal movement, but precision was not. The acceptable amount of error and precision depends upon the hypotheses being addressed. Investigators desiring relatively accurate estimates of animal location must account for animal movements. Even small time delays between bearings can significantly decrease accuracy. Simultaneous bearings are highly preferred.

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