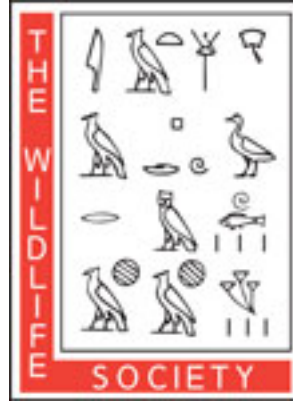


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# SOME SOURCES OF BIAS AND SAMPLING ERROR IN RADIO TRIANGULATION

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**Abstract:** Data were collected when transmitters and receivers were at known locations. One method used to determine the direction of the transmitters, called the "loudest-signal method," had an overall bias of 0.2° and a sampling error of 3.9°. A 2nd method, called the "null-average method," had an overall bias of -2.9° and a sampling error of 1.1°. Biases of the different factors for the "null-average method" differed significantly. Factors examined were: observers, days, receivers, distance between transmitters and receivers, and transmitters. None of these had significantly different biases when the "loudest-signal method" was used. Error arcs can be drawn about averaged readings. The intersection of 2 or more error arcs forms an error polygon. The probability that a transmitter is within the intersection of those arcs is the product of the individual probabilities.

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As part of a radio-tracking study of coyotes (*Canis latrans*) on the U.S. Department of Energy Hanford Reservation, I attempted to determine the degree to which bias and sampling error affected locations obtained by radio triangulation. The Hanford Reservation is described elsewhere (Springer 1979).

Few investigators who have used radio triangulation have reported on the bias and sampling error involved. Often it was assumed that locations obtained by triangulation were exact (e.g., Ables 1969, Seidensticker et al. 1970, Chesness 1973). Studies in which errors were considered often omitted information on how to compensate for these errors (Verts 1963, Sargeant et al. 1965, Storm 1965). Some investigators explained how the errors were applied to the data, but did not provide statistics such as confidence limits to the location estimations (Cochran and Lord 1963, Tester et al. 1964, Hanson et al. 1969, Hawkins and Montgomery 1969, Dunstan 1972, Gipson and Sealander 1972).

At any given moment, the location of an animal is effectively a point on a map. Perhaps for that reason, animal locations determined by radio triangulation often

have been treated as discrete points. However, Heezen and Tester (1967) pointed out that the error in radio-determined locations has area. The area of error about each location point was termed an "error polygon." Error polygons should be identified to aid in estimating home range size. If a home range were delineated by the minimum area method (Mohr 1947), a common procedure, the size of that home range could be miscalculated unless the error polygons were included in the calculations.

A 2nd reason for estimating the size, shape, and sampling error of error polygons is to aid in determining animal activity patterns. One frequently used method is to measure distances between 2 locations over a specified time interval. There are instances when no movement occurred or when actual distance moved is small when compared to the size of the error polygons. Overlapped error polygons would indicate that no detectable movement had occurred at some specified level of statistical significance. When error polygons are disregarded, the data might suggest movement when there was none and activity patterns that do not exist.

Deviations from a true transmitter location can result from several factors. In

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simplest form, the  $i$ th triangulation reading,  $x_i$ , can be considered the sum of the true location,  $\mu$ , the bias, and the  $i$ th sampling error,  $e_i$ ; that is,

$$x_i = \mu + \text{bias} + e_i. \quad (1)$$

(Another value that could be a separate component of  $x_i$  is measurement error, that is error in reading the direction indicated on the compass rose. In this study I assumed that such error was extremely small and was included within the sampling error,  $e_i$ .) The  $e_i$  values are assumed to be normally distributed about zero, to have homogeneous variances, and to be independent. Although the bias is considered a constant in this model, it can be affected by various factors (e.g., among individual observers). The purpose of this research was to determine the magnitude of such effects.

It is obvious that the expected value of  $(x_i - \mu)$  is the bias in this model. Further, the distribution of the sampling error may vary from that usually postulated, as above. Bias and sampling error are independent components of the model, and the latter is influenced by sample size while the former is not.

By determining the sampling error of a triangulation reading, it becomes possible to place confidence limits on a single reading or the average of several readings. Utilizing an estimate of the variance of the  $e_i$  and assumptions concerning the distribution of the  $e_i$ , confidence limits can be computed. A location obtained by triangulation will be defined as the intersection of 2 or more error arcs formed by the confidence limits (Fig. 1). The resulting intersection of the arcs will delineate an error polygon (Heezen and Tester 1967). If the confidence limits about any given reading are broad, the resulting error polygon will be large. Therefore, 1 goal of this study was to find

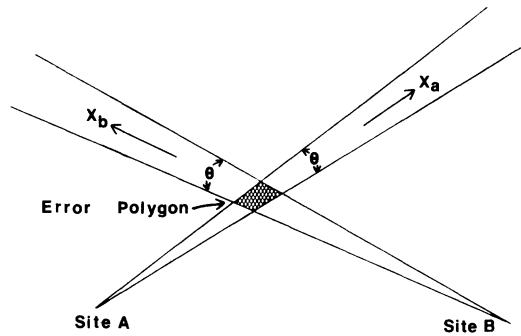


Fig. 1. Example of location obtained by radio triangulation. Sites A and B are the 2 sites from which readings were taken.  $X_a$  is the reading obtained at site A.  $X_b$  is the reading obtained at site B. The angle  $\theta$  is equal to  $\pm$  the total error (bias + sampling error) about each reading, and forms the error arc. The intersection of the error arcs forms the error polygon.

ways to reduce the confidence limits, e.g., by increasing the number of readings, or utilizing different observers to reduce sampling error.

Another purpose of this study was to arrive at some estimate of the bias that could be used to adjust readings, as well as an estimate of the error variance to be used in estimating sample size for a desired confidence limit. Situations that resulted in high error variance were identified.

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## MATERIALS AND METHODS

This investigation involved 3 experiments designed to determine bias and sampling errors associated with receivers, transmitters, days, observers, distances between transmitter and receiver, and also the methods used in taking readings. The radio equipment was tuned to approximately 151 MHz. The 4 transmitters were constructed at Cedar Creek Biotelemetry Laboratories, Bethel, Minnesota. Transmitters #1 and #2 were fixed in collars to be placed on coyotes, and were like those described previously (Springer 1976). Transmitters #3 and #4 were the same as those described by Fitzner and Fitzner (1977) for use on Swainson's hawks (*Buteo swainsoni*). Transmitters #1 and #2 were taped to 0.91-m lengths of lath pushed into the ground so that the transmitters remained upright and about 0.6 m off the ground, as they would be on a coyote. Transmitters #3 and #4 were taped to the limb of a tree in an upright position, as they would be on a hawk.

Two receivers were used, always with earphones. Model LTS receiver made by Dav-tron (Minneapolis, Minnesota) was described previously (Springer 1976), and the Cedar Creek receiver has been described by Tester and Siniff (1976). The receiver antenna was an 11-element yagi, with a 366-cm boom, and a reflector element 102 cm long. The antenna had a 13-db forward gain, and a front-to-back ratio of 28 db. It was attached to a 215-cm galvanized steel mast that passed through a compass rose on a 100-cm high platform. The platform was attached to the bed of a pickup truck. A pointer attached to the antenna mast indicated the

direction toward which the front of the antenna pointed.

*Loudest Signal Method.*—In this method the observer turned the antenna until the signal seemed loudest. The observer always began each reading with the antenna pointed away from the test transmitters, and did not look at the compass rose or the antenna until after a decision as to the direction was made.

*Null-Average Method.*—This method required the observer to turn the antenna away from the test transmitter until no signal could be heard. He then turned the antenna back toward the transmitter until he barely heard the signal. This direction was noted, and the process was repeated to the other side of the test transmitter. The observer never looked at the antenna or the compass rose until he heard the signal. The 2 directions the observer thus obtained were null points. Because the reception pattern of a yagi antenna resembles a figure 8, the average of the 2 null points should be the direction to the transmitter.

In both methods 10 readings were made for each test situation. After each experiment was completed, the true direction to the test transmitter was determined. The difference between each reading and the true direction was then calculated. Any error associated with mapping true directions was assumed to be negligible.

*Experiments.*—Experiment A was conducted on 12 April 1976 by R. E. Fitzner and me. We used all 4 transmitters and placed them 0.5 km from the Cedar Creek receiver. Experiment B was conducted on 13 April 1976, by myself. I used transmitters #1 and #2, placed 1.6 km away from the Cedar Creek receiver at first, and then at 3.2 km. Experiment C was conducted on 27 April by R. Olson and me. We used transmitters #1 and #2

placed 1.6 km from both the Cedar Creek receiver and the Dav-tron receiver. In all 3 experiments both the loudest-signal method and the null-average method were used.

**Analysis.**—Results for each experiment were separated so that loudest-signal data could be analyzed separately from null-average data. To these 6 sets of data I added 2 more, composed of my results from experiments B and C at 1.6 km, for the purpose of comparing data from different days. The data in each of the 8 sets were subjected to Bartlett's test of homogeneity of variance (Snedecor and Cochran 1967:296). Analyses of variance were also performed to determine if there were statistically significant differences among treatment means. For example, in comparing 2 observers, 1 and 2, the model becomes

$$x_{1i} = \mu + \text{bias}_1 + e_{1i}, \quad (2)$$

and

$$x_{2i} = \mu + \text{bias}_2 + e_{2i} \quad (3)$$

$$(i = 1, \dots, n)$$

for the 2 observers, respectively. Consequently

$$\bar{x}_1 = \mu + \text{bias}_1 + \bar{e}_1, \quad (4)$$

$$\bar{x}_2 = \mu + \text{bias}_2 + \bar{e}_2, \quad (5)$$

$$\bar{x}_1 - \bar{x}_2 = (\mu + \text{bias}_1 + \bar{e}_1) - (\mu + \text{bias}_2 + \bar{e}_2), \quad (6)$$

and

$$\bar{x}_1 - \bar{x}_2 = (\text{bias}_1 - \text{bias}_2) + (\bar{e}_1 - \bar{e}_2). \quad (7)$$

Further, the expected value ( $E$ ) of the difference between means is

$$E(\bar{x}_1 - \bar{x}_2) = \text{bias}_1 - \text{bias}_2, \quad (8)$$

as it was assumed that

$$E(e_{1i}) = E(e_{2i}) = 0. \quad (9)$$

Therefore, any statistically significant differences between treatment means

would indicate that the bias between treatments differed, where a treatment would be receivers, transmitters, days, etc.

## RESULTS AND DISCUSSION

### Bias and Sampling Error

Estimations of bias and sampling error were obtained from the analyses of the data gathered in experiments A, B, and C. Tables showing the data and analyses are shown in Springer (1977).

The factor that showed the greatest influence on readings was the method used. Table 1 shows the sampling error, represented by the pooled standard deviation ( $s_p$ ), and it shows the bias. The overall average bias for the loudest-signal method was  $0.2^\circ$ , and the total pooled standard deviation was  $3.9^\circ$ . This is a sharp contrast to the average bias of  $-2.9^\circ$  from the null-average method, and the overall pooled standard deviation of  $1.1^\circ$ . The null-average method bias was significantly different from 0, while the loudest-signal method was not. Variances for the 2 methods were different ( $P < 0.005$ ) in each of the 3 experiments, and the loudest-signal method showed a consistently higher variance. Though the relatively small standard deviation of the null-average method appears attractive, the large bias associated with this method made it unattractive for practical application. The bias proved to be too unpredictable from experiment to experiment, and even within experiments. In every analysis of variance for the null-average method the treatment means (biases) differed ( $P < 0.005$  or  $P < 0.02$ ). Furthermore, there frequently were significant interactions between factors, e.g., observers-distance, or transmitter-receiver. For these reasons, the null-average method was deemed unsat-

Table 1. Method bias ( $\bar{x} - \mu$ ) and sampling error (pooled standard deviation) in degrees, comparing the loudest-signal method (LS) and the null-average method (NA). Data combined from experiments A, B, and C.

Method	Experiment	N	$\bar{x} - \mu$	$s_p$ (df)
LS	A	80	1.3*	4.5** (72)
LS	B	40	-0.7	2.9** (36)
LS	C	80	-0.5*	3.7** (72)
NA	A	80	-1.1*	1.4** (72)
NA	B	40	-0.5	0.9** (36)
NA	C	80	-6.0*	1.0** (72)

\* Different ( $P < 0.01$ ) from bias for the other method in the same experiment.  
\*\* Different ( $P < 0.05$ ) from sampling error for the other method in the same experiment.

isfactory for field use. Further results and discussion will be limited to the loudest-signal method.

The 2nd factor examined was the observer. Table 2 shows bias and sampling error of the 3 observers. There were no statistically significant differences among the observer means, which averaged 0.4°, with a pooled standard deviation of 4.1°.

No statistically significant differences between days were found (Table 3). The average bias was -0.3°, and the pooled standard deviation was 3.2°.

The 2 receivers used were quite different in design, yet no statistically significant differences were found. As can be seen in Table 4, the Cedar Creek receiver had slightly less bias and slightly less sampling error. The average bias for the 2 receivers was -0.5° and the pooled standard deviation was 3.7°.

Table 2. Observer bias ( $\bar{x} - \mu$ ) and sampling error (pooled standard deviation) in degrees, based on loudest-signal method. Data for observer I from experiments A and C. Data for observer II from experiment A only. Data for observer III from experiment C only.

Observer	N	$\bar{x} - \mu$	$s_p$ (df)
I	80	0.2	4.3 (72)
II	40	2.2	4.3 (36)
III	40	-1.0	3.6 (36)

Table 3. Day bias ( $\bar{x} - \mu$ ) and sampling error (pooled standard deviation) in degrees, based on loudest-signal method. Data from experiments B and C, but only those collected by the author with the Cedar Creek receiver at 1.6 km.

Date	N	$\bar{x} - \mu$	$s_p$ (df)
13 Apr	20	-0.2	2.9 (18)
27 Apr	20	-0.3	3.5 (18)

The 5th factor examined was distance between transmitter and receivers. Table 5 shows the bias and sampling error associated with distances of 0.5, 1.6, and 3.2 km. Though no statistically significant differences were found among distances, there was a significant transmitter-distance interaction ( $P < 0.05$ ). This shows that while 1 transmitter has less variance at a short distance than it has at a long distance, a 2nd transmitter will have more variance at a short distance than it has at a long distance. Though these differences were observed and resulted in a statistically significant interaction, the actual differences were small. However, when one is using transmitters in the field, one would be safer to assume the worst case: that the largest variance observed at a given distance applied to every transmitter at that distance. The trend evident from Table 5 is that bias is unaffected by distance (overall average of 0.2°), though the standard deviation tends to decrease with increased distance. This phenomenon was noted before (Springer 1976).

The results shown in Table 6 compiled from all 3 experiments show no signifi-

Table 4. Receiver bias ( $\bar{x} - \mu$ ) and sampling error (pooled standard deviation) in degrees, based on the loudest-signal method. Data from experiment C.

Receiver	N	$\bar{x} - \mu$	$s_p$ (df)
Dav-tron	40	-0.6	4.3 (36)
Cedar Creek	40	-0.4	3.0 (36)



**Table 5.** Distance bias ( $\bar{x} - \mu$ ) and sampling error (pooled standard deviation) in degrees, based on the loudest-signal method. Data for 0.5 km from experiment A only. Data for 1.6 km from experiments B and C. Data for 3.2 km from experiment B only.

Distance (km)	<i>N</i>	$\bar{x} - \mu$	<i>s<sub>p</sub></i> (df)
0.5	80	1.3	4.5 (72)
1.6	100	-0.3	3.6 (90)
3.2	20	-1.7	2.9 (18)

**Table 6.** Transmitter bias ( $\bar{x} - \mu$ ) and sampling error (pooled standard deviation) in degrees, based on loudest-signal method. Data for transmitters #1 and #2 are combined from experiments A, B, and C. Data for transmitters #3 and #4 are from experiment A only.

Transmitter	<i>N</i>	$\bar{x} - \mu$	<i>s<sub>p</sub></i> (df)
1	80	-0.4	3.4 (72)
2	80	0.4	4.3 (72)
3	20	1.3	3.6 (18)
4	20	1.7	4.3 (18)

cant differences among the 4 transmitters. However, the analysis of variance for experiment A showed an observer-transmitter interaction ( $P < 0.01$ ). This shows the importance of testing each observer involved in radio-tracking experiments, and testing them under a number of situations.

Future studies in which radiotelemetry is employed should devote some pilot effort to identify the factors that might affect bias and sampling error. The researchers should test these factors and determine the magnitude of the bias and sampling error, and then design an experiment with these results in mind.

### Confidence Limits and Error Arcs

After determining bias and sampling error, my purpose was to set confidence limits on any given reading or average of readings. Because the bias was small and not significantly different from zero, it was dropped from equations (1) and (4), giving

$$x_i = \mu + e_i, \quad (10)$$

and for an average of several readings

$$\bar{x} = \mu + \bar{e}. \quad (11)$$

A confidence limit for  $\bar{x}$  was made using the formula

$$L_{(0.95)} = 2s/\sqrt{n}, \quad (12)$$

where  $L_{(0.95)}$  is the approximated limit of

the error with a 95% probability of containing the true value,  $\mu$ . The assumption is made that the pooled standard deviation from the overall experiment, such as the one described here, is an estimator of the standard deviation of the  $n$  readings used to compute  $\bar{x}$ . Hence,  $s$  in equation (12) comes from an appropriate test situation with a relatively large number of readings (more than 28 df). The value  $n$  in equation (12) is independent of  $s$ , but is used to compute the standard error of  $\bar{x}$ ,  $s/\sqrt{n}$ . The multiplier of the standard error has been approximated by the value 2 since the  $t$ -distribution approaches the standard normal with 28 or more df.

The error limit will simply equal the pooled standard deviation if 4 observations are involved, so that the 95% confidence limit becomes

$$\bar{x} - s_p < \mu < \bar{x} + s_p. \quad (13)$$

The confidence limit can be drawn as an error arc, with the receiver site as the origin, with  $\bar{x} - s_p$  as one ray, and  $\bar{x} + s_p$  as the other ray (Fig. 1). The error arc thus formed has a 95% probability of containing  $\mu$ , and hence the animal that carries the radio transmitter.

If  $s_p$  differs significantly as distance between transmitters and receivers varies, then the use of error arcs based on only 1 given distance would not be appropriate. Either a number of  $s_p$  values should be determined for various dis-

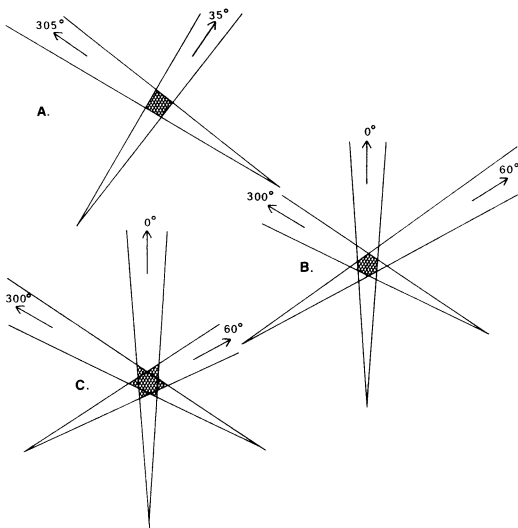


Fig. 2. Error arcs forming error polygons. (A) Polygon formed by 2 arcs has a 90% probability of containing animal. (B) Intersection of 3 arcs has a 86% probability of containing animal. (C) Polygon formed by combining all intersections of 2 or 3 arcs has a 99% probability of containing animal.

tances, or the greatest  $s_p$  value should be used.

Using equation (12) a researcher could use a lower probability level, reducing the confidence limits by using the  $t$  value at this different level in place of 2 in equation (12). Thus, I could have had  $L = 2.5^\circ$  by lowering the confidence limit to 90%, and using  $t_{0.10} = 1.7$  (for an experiment with 28 or more df),  $s_p = 2.9$ , and  $n = 4$ .

Error Polygons

The intersection of 2 or more error arcs forms an error polygon. The problem then becomes one of determining the probability that this error polygon contains the transmitter, hence the animal. The probabilities of being enclosed by 1 or more independent error arcs are individual terms of the binomial

$$(P + Q)^n. \tag{14}$$

If  $P_n$  were the probability that the animal was within the  $n$ th arc, then  $Q_n = (1 - P_n)$  would be the probability that the animal was outside the  $n$ th arc. If the researcher were to use 2 independent error arcs with equal probabilities, he would be interested in the 1st term of the expression

$$P^2 + 2PQ + Q^2, \tag{15}$$

because  $P^2$  is the probability that the animal is within both arcs. Using 95% confidence limits, as I have suggested,  $P^2 = 0.9025$ ; thus there would be a 90% probability that the error polygon so delineated contained the animal (Fig. 2A).

Were 3 arcs used, as in Figs. 2B and 2C, then equation (14) expands to become:

$$P^3 + 3P^2Q + 3PQ^2 + Q^3, \tag{16}$$

where  $P^3$  is the probability that the animal is within all 3 arcs, hence within the intersection,  $3P^2Q$  is the probability that the animal is outside 1 arc but within the other 2,  $3PQ^2$  is the probability the the animal is outside 2 arcs but within the 3rd, and  $Q^3$  is the probability that the animal is outside all 3 arcs.

The error polygon one might usually consider is the intersection of all 3 arcs, as shown in Fig. 2B. If each error arc had a 95% confidence limit, then this polygon would have an 86% probability of containing the animal, about 4% lower than had only 2 arcs been used. This may seem paradoxical, but note that the area of the polygon in Fig. 2B is less than in Fig. 2A; in fact the particular polygon in Fig. 2B is about 13% smaller than the polygon in Fig. 2A. Though this reduction depends on the positions from which the 3 arcs originate, an error polygon formed by 3 arcs can obviously be no larger than the polygon formed by 2 arcs. A further consideration is that if all the area included by at least 2 error arcs were added to the intersection of the 3 arcs



(Fig. 2C) this polygon would have a 99% probability of containing the animal ( $P^3 + 3P^2Q$ ). The calculated area of the polygon in Fig. 2C is about 90% larger than that of the polygon in Fig. 2B. Some researchers may accept the larger error area for increased probability of locating the animal.

The size of an error polygon will depend on the distance between the transmitting animal and the receiver, the width of the confidence limits, and finally the intersect angle of the readings or averaged readings. The shorter the distance between the animal and the receiver, the narrower will be the error arc in terms of distance, provided the degree of error does not increase. My results indicated that sampling error at 0.5 km is larger in total degrees than the sampling error at 1.6 km ( $s_p = 4.5^\circ$  and  $3.6^\circ$ , respectively). However, the width of the error arc at 0.5 km with  $\pm 4.5^\circ$  is only 75 m. The width of the error arc at 1.6 km with  $\pm 3.6^\circ$  is 195 m. An error polygon formed by 2 1.6-km error arcs would have an area more than 6 times larger than one formed by 2 0.5-km error arcs, if the error arcs had the above confidence limits, and if the readings for which the areas were drawn intersected at right angles.

For 2 error arcs, the arrangement that will yield the smallest error polygon is where the readings for which the arcs are drawn intersect at right angles as in Fig. 2A, and as indicated by Heezen and Tester (1967). For 3 error arcs, the ideal arrangement is where the readings intersect at  $60^\circ$  angles, as in Figs. 2B and 2C.

With a mobile receiving unit in the field, these ideal arrangements can seldom be met. Small error polygons could be achieved by the following precautions. First, average several readings so that the confidence limits of the error arcs can be narrowed. Second, the distance

between the animal and the receiver should be kept as short as possible without affecting the animal's normal movement patterns. Third, the angles between reading sites should be within  $45^\circ$  and  $135^\circ$ , and as near the ideal as possible. Complying with these recommendations will usually require 3 different reading sites per animal location.

## Home Range and Activity Patterns

Once locations are plotted as error polygons with shape, size, and a probability of containing the true location, the animal's home range and activity patterns can be estimated. Though there are many ways to delineate an animal's home range, the minimum area method (MAM) described by Mohr (1947) is 1 of the most common techniques.

How this method could be applied to locations obtained by triangulation is illustrated in Fig. 3A. In this example there are 7 locations represented by error polygons, each of which has a 99% probability of containing the true location. An asterisk shows the center of activity (CA). The largest possible home range is delineated by applying MAM to the point in each error polygon that is farthest from the CA. Note that locations #4 and #7 are not used in forming the maximum boundary. The smallest possible home range is delineated by applying MAM to the point of each error polygon closest to the CA. Note that locations #3 and #5 are not used. The 2 areas thus obtained are the upper and lower limits to the estimate of home range size.

Activity patterns are usually measurements of distance between 2 consecutive locations, assuming the time intervals remain the same. How this concept should be applied to triangulation data is illustrated in Fig. 3B. For instance, to find the distance traveled between the 1st and

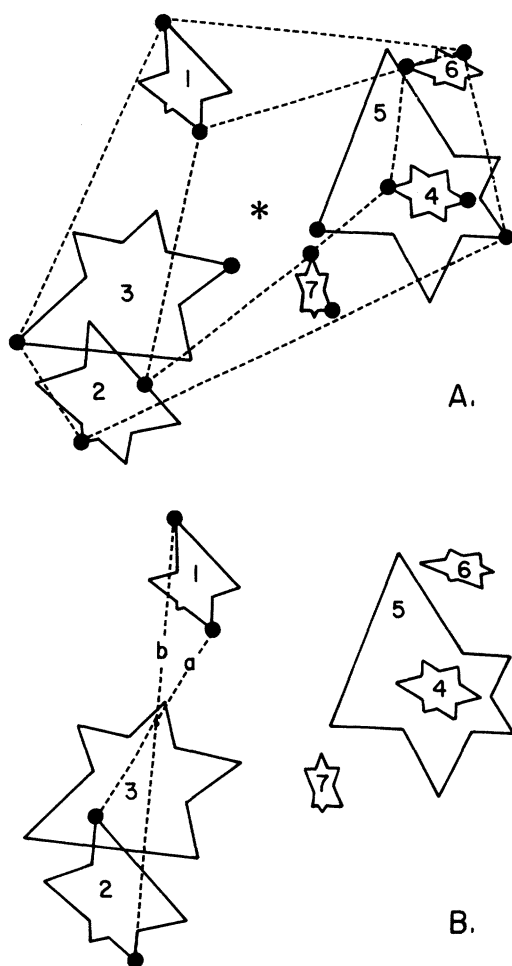


Fig. 3. Error polygons representing 7 estimated locations of an animal. (A) Maximum and minimum home range determined by the minimum area method. (B) Determination of the shortest and longest possible distance moved between the 1st and 2nd locations.

2nd locations, one should first calculate the greatest possible distance traveled, represented by line segment a. Then calculate the shortest possible distance, line segment b. These 2 distances give the upper and lower limits to the distance traveled, at the 99% confidence level. When consecutive location error polygons overlap, as between the 2nd and 3rd locations and the 4th and 5th locations,

one must conclude that at the 99% confidence level one could not detect measurable movement.

When doing calculations such as these, it would be preferable to use error polygons with equal probabilities. If unequal probabilities are used, then one must base conclusions on the lower probability level.

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