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COMPARATIVE ACCURACY OF AERIAL AND GROUND TELEMETRY LOCATIONS OF FORAGING RAPTORS[1]

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Abstract. Widely ranging raptors are difficult to radio-track from fixed locations on the ground; therefore, we investigated the feasibility of tracking Prairie Falcons (*Falco mexicanus*) from a Cessna 182 airplane outfitted with a belly-mounted, rotary, H-antenna. Locations were estimated by flying directly over the signal's source, and recorded with an on-board global positioning system. Location estimates of stationary and mobile beacons derived from aerial tracking were more accurate than locations derived from triangulation by 4–6 ground-based trackers ($\bar{x}$ 95% confidence ellipses: aerial = 112 ha, ground = 875 ha). Aerial accuracy was not influenced by mobility of a beacon and was similar for two observers. However, because falcons spend a majority of their time in proximity of their aerie, most aerial fixes were close to the nest site. This resulted in significant underestimates of falcon foraging ranges, especially for breeding males.

Key words: Home range; Prairie Falcon; radio-telemetry; Idaho; foraging; Falco mexicanus; *movement.*

INTRODUCTION

Aerial radio-tracking using conventional wing-mounted antennas has been used extensively to locate and observe large, conspicuous animals or monitor the general location of less conspicuous animals (Mech 1983, Kenward 1987, White and Garrott 1990, Kuyt 1992). Locations obtained during aerial tracking are often used without ground verification (Garrott et al. 1987, Fuller et al. 1988) and exact error ellipses associated with point estimates are rarely reported. Precise error estimates are needed before aerial locations can be combined with or compared to locations derived by triangulation techniques with known errors, or used in assessments of habitat selection which are sensitive to location error (Nams 1989, Samuel and Kenow 1992). Precise estimates of transmitter locations can be obtained (Hoskinson 1976, Gilmer et al. 1981, Garrott et al. 1987), but this involves a lengthy flight procedure which can reduce the number of fixes obtained and increase expenses.

Herein, we determine the accuracy and efficiency of locating stationary and mobile beacons from an airplane using a rotary, belly-mounted antenna. Moreover, we begin to understand some of the biases associated with aerial tracking by comparing location estimates of free-ranging Prairie Falcons (*Falco mexicanus*) in the Snake River Birds of Prey Area (SRBOPA) determined by both aerial and ground-based tracking.

METHODS

FIELD PROCEDURES

This study was conducted in the SRBOPA (see U.S. Department of the Interior 1979 for habitat characteristics) from January to August 1992. We divided this area into six tracking zones ranging in size from 70–120 km^2; size being determined by our ability to detect transmitter signals within the area. The test of ground-tracking accuracy occurred from 23 January to 25 March, and involved estimating the location of stationary and mobile transmitters ("beacons") at 134 and 25 sites, respectively. Stationary beacon sites were evenly distributed, approximately 2 km apart, across the six tracking zones. At each site, we raised beacons to four heights (1 m, 3 m, 10 m, 30 m) in random order, using helium balloons or a kite. Mobile beacons were attached to a vehicle's antenna and driven throughout a zone at approximately 30 mph. Two trucks were used in mobile tests to reduce the tracker's ability to directly observe the beacon. We marked each beacon site and used a Trimble Pathfinder Global Positioning System (GPS) unit to determine the site's location.

We conducted ground tracking accuracy tests using four to six radio-trackers taking simultaneous bearings from different receiver sites within each of the six zones. Receiver sites were stra-

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tegically positioned on high points along the perimeter of the zone, allowing simultaneous bearings taken on transmitters to cross at approximately right angles, thereby minimizing triangulation error (White and Garrott 1990). If high points were unavailable at important locations within the zone, we used towers consisting of 5 m sections of 3.75 cm pvc pipe mounted on portable tripods or permanent support posts. Trackers used ATS scanning receivers, four-element Yagi antennas and hand-held compasses to take bearings (see Marzluff et al. 1991 for details of field tracking methods).

We used a Cessna 182 airplane outfitted with a rotary H-antenna suspended 0.3 m below the belly of the plane (for schematics of antenna design and mounting see Carrel 1972; available from authors) to estimate the locations of 60 stationary and 11 mobile beacons placed approximately 1 m above the ground. We detected beacons randomly as we flew, using an ATS scanning receiver and aircraft headphones. Once a signal was detected, we rotated the antenna to obtain maximum reception and indicated to the pilot the angular direction of the signal from the present course. We continued this process, generally crossing a straight course with shallow angles, until the signal was received with equal strength from either side. As signal strength continued to increase, we judged when we had passed over the beacon and instantaneously recorded our position using a Garmin GPS 100. We then verified the fix by rotating the antenna 180° to confirm that the signal was stronger behind the plane. Trackers sat in the back seat and were blind to the location of stationary and mobile beacons.

Prairie Falcons were tracked throughout the breeding season (April–August) by ground and aerial crews. Tracking procedures were as described above, however the actual locations of the falcons were not known. Ground crews tracked nearly every day during this time, but aerial crews only tracked on eight days.

QUANTIFICATION OF TRACKING ACCURACY

We calculated three sources of error for location estimates derived from aerial and ground-based tracking: (1) the linear distance between the location estimate and the GPS-measured location of a beacon, (2) the precision of this estimate, and (3) the size of the average 95% confidence ellipse (or circle) around each point estimate. Ground-based bearings were analyzed using Lenth's (1981) maximum likelihood estimator to determine a point estimate of location and an associated 95% confidence ellipse. No bearings were taken during aerial tracking; the data obtained were a sample of distances between estimated and known locations of beacons. The mean of the difference between estimated and actual locations was the linear estimate of error (mean error). Tracking precision, a measure of estimation variability, can then be calculated as the standard deviation (SD) of this sample (White and Garrott 1990). A 95% confidence circle can be determined around each point estimate from aerial tracking by centering a circle with radius (1.96) X (mean error SD) at the point estimate (White and Garrott 1990).

COMPARISON OF AERIAL AND GROUND-BASED TRACKING

Error estimates using locations of mobile and stationary beacons at 1m for both aerial and ground-based tracking were compared using standard one-way analysis of variance and *t*-tests. Tukey's HSD multiple range test was used to perform pair-wise comparisons between ground-based tracking tests of beacons at different heights because of unequal sample sizes (Wilkinson 1989).

We conducted aerial and ground-based tracking on the same days, but we did not track the same falcon simultaneously. Aerial and ground estimates were paired post hoc using a variety of criteria, the most restrictive case using aerial and ground fixes taken on the same day within 1 hr of each other. We created three less restrictive cases by pairing aerial locations with ground locations taken: (1) on the same day at any time, (2) within 1 hr and ±3 days and (3) any time ±3 days. The travel distance from the aerie to the location estimate was calculated and the samples of matched aerial and ground travel distances were compared using standard paired *t*-tests. When more than one ground fix was taken during the specified time interval around an aerial location, we used the average travel distance from those locations to compare with the travel distance calculated from the aerial fix.

RESULTS

DETERMINATION OF ACCURACY

Aerial Tracking. Estimates of the locations of transmitters were very accurate from the airplane. The average distance between estimated and actual locations of 71 beacons was 409 m. This mean error had an associated tracking precision (SD) of 304 m which resulted in a 95% confidence circle of 112 ha around each point estimate (using a circle with radius = 1.96 × SD).

Mean error was not influenced by the mobility of the beacon or the individual estimating the beacon's location. Differences in estimated and actual locations of 11 mobile beacons were similar to differences for 60 stationary beacons ($\bar{x}_{\text{mobile}} = 472$ m, SD = 458 m; $\bar{x}_{\text{stationary}} = 397$ m, SD = 271; $t = 0.76$, $P = 0.45$). The mean error associated with 34 location estimates by one observer was similar to the error associated with 37 estimates by the other observer ($\bar{x}_{\text{observer 1}} = 387$ m, SD = 339 m; $\bar{x}_{\text{observer 2}} = 428$ m, SD = 272; $t = 0.56$, $P = 0.58$).

Ground Tracking. Location estimates determined by triangulation from ground positions were influenced by the beacon's height above the ground and whether or not it was mobile. The average 95% confidence ellipse for all ground estimates was 541 ha ($n = 221$, SD = 630 ha). However, ellipse size varied significantly with beacon height and mobility (Fig. 1A; $F_{4,216} = 5.1$, $P = 0.001$). The average distance between actual and estimated locations was 1,826 m ($n = 223$). This was associated with a tracking precision (SD) of 2,382 m. Linear differences between actual and estimated locations varied with beacon height and mobility (Fig. 1B; $F_{4,218} = 2.7$, $P = 0.03$), in large part because the percentage of trackers that were able to contribute a bearing to a triangulation attempt varied with beacon height and mobility (Fig. 1C; $F_{4,511} = 36.7$, $P < 0.001$).

Aerial Versus Ground Tracking. Location estimates determined by aerial tracking were consistently more accurate than those determined by ground tracking. The average confidence ellipse size was 4.8× smaller for aerial estimates than ground estimates. Average confidence ellipse size for stationary and mobile beacons determined by aerial and ground tracking differed significantly (Fig. 1A; t-tests comparing ground tracking mean to a constant equal to the aerial mean: 1 m high, stationary beacons, $t = 4.08$, 24 df, $P < 0.001$; 1 m high, mobile beacons, $t = 3.53$, 24 df, $P < 0.002$). The average linear distance error was 4.5× smaller for aerial estimates than ground estimates. The mean errors associated with stationary beacons 1 m above the ground were significantly different between aerial and ground estimates (Fig. 1B; $F_{1,83} = 22.5$, $P < 0.001$). Comparisons of mean errors between aerial and ground estimates of mobile beacon locations were not significant (Fig. 1B; $F_{1,34} = 3.2$, $P = 0.08$). Aerial location estimates were also more consistent than ground estimates; the SD associated with aerial estimates was 7.8× smaller than the SD for ground estimates. The reduction in accuracy associated with all ground positions not receiving a beacon's signal was not evident in the air as every signal was received (Fig. 1C).

TRAVEL DISTANCES OF PRAIRIE FALCONS DETERMINED BY AERIAL AND GROUND TRACKING

We rarely were unable to get a location estimate once a bird's signal was received and we received every bird's signal on nearly every flight. On average, one location estimate was obtained every 5.2 min of tracking ($n = 143$).

We rarely obtained location estimates during ground-based tracking of falcons inside the canyon near their nests (13.8% of 87 male locations and 11.9% of 59 female locations were within 1,826 m of their nest; 1,826 m was the average linear error in beacon tests). However, we were able to pick up falcon transmitters anywhere in the study area from the air, and because falcons spend a high percentage of time near the aerie (60–73% for females depending on stage of nesting, 39–44% for males; Marzluff et al. 1992), many location estimates from the air were of falcons near their nest sites (40.6% of 96 male locations and 53.7% of 82 female locations were within 409 m of their nest; 409 m is the average linear error associated with aerial tracking). Differences in the proportion of location estimates near aeries depended upon the method of tracking employed (males: $X^2_{(1)} = 16.4$, $P < 0.001$; females: $X^2_{(1)} = 26.0$, $P < 0.001$).

Travel distances from the aerie were shorter for locations determined by aerial tracking than for locations determined by ground tracking. This result was stronger for males than for females, and especially pronounced among birds successfully fledging offspring (Figs. 2, 3). Location estimates for failed breeders, especially males, determined by aerial tracking were similar to the locations determined by ground tracking (note lack of significant differences in Table 1). The greatest difference between ground and aerial fixes occurred when pairs of location estimates came

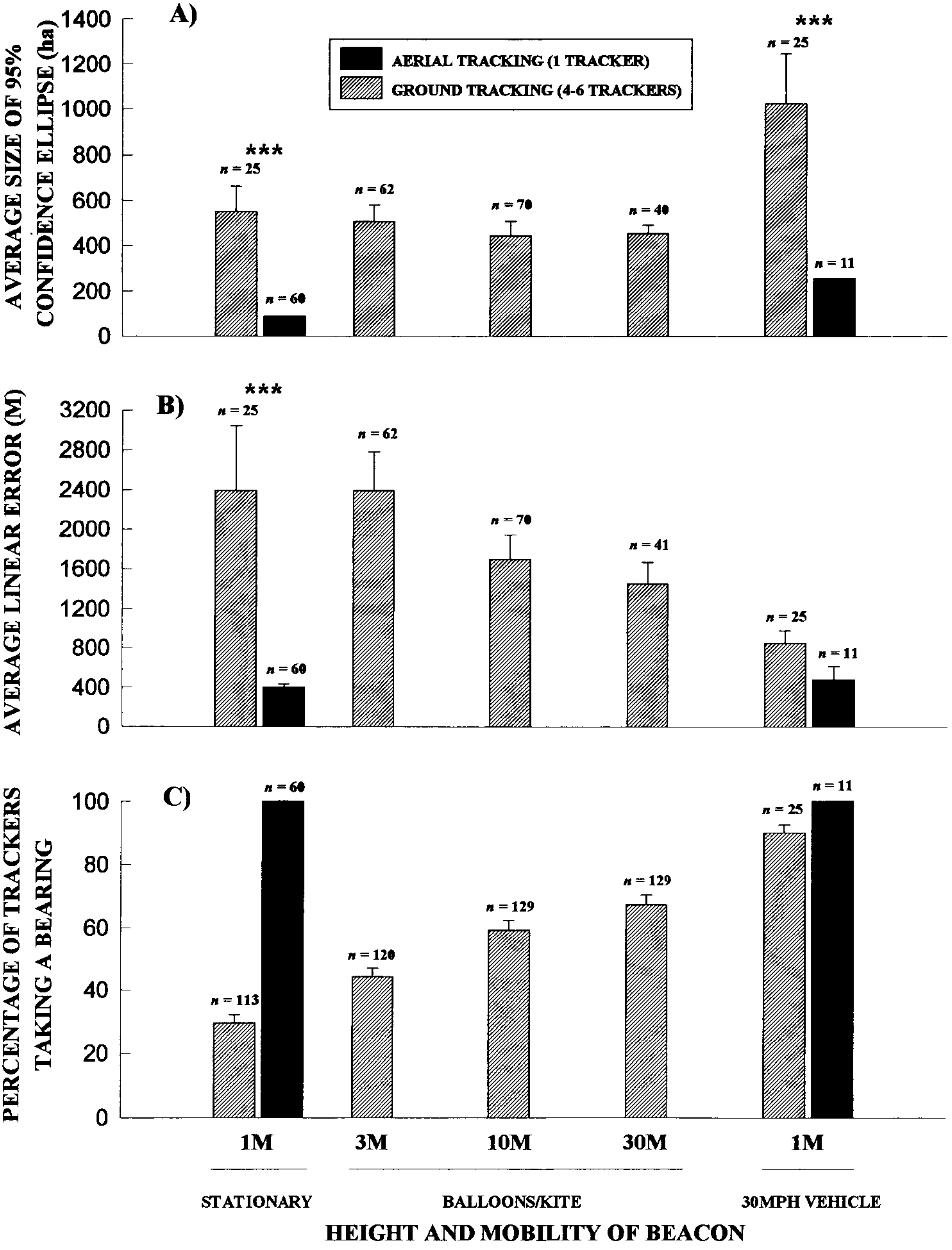

FIGURE 1. Comparison of measures of precision (A) and accuracy (B) associated with location estimates of beacons, and ability to detect signals from beacons (C), during ground-based tracking and aerial tracking. Beacons were placed on stationary posts (1 m height), attached to balloons or kites (3– 30 m heights) or attached to a vehicle driven approximately 30 mph (1 m height). Average values are indicated by the top to the bars. Error bars are + 1 SE. Samples sizes are given above the bars. Significant differences between ground and aerial tracking precision and accuracy are indicated by asterisks (*** = $P < 0.001$).

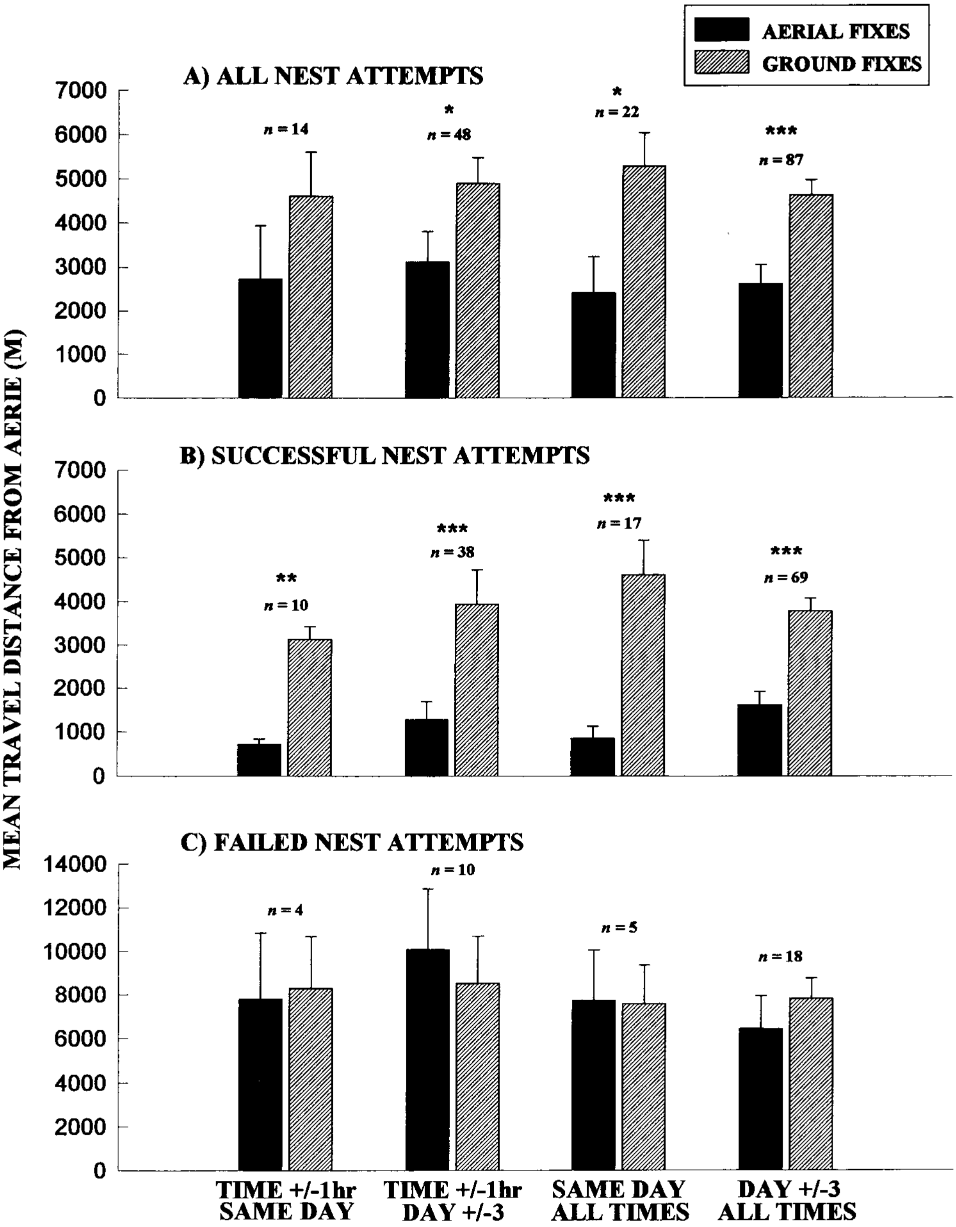

FIGURE 2. Average travel distances of male Prairie Falcons from aeries (+1 SE) calculated from location estimates made during ground-based and aerial tracking. Distances calculated for all nesting attempts (A), successful nesting attempts (B) and unsuccessful attempts (C) are plotted separately. Sample sizes (*n*) indicated above bars are numbers of distances, each of which could have come from 1 of 30 falcons. Significant differences between aerial and ground-based fixes are indicated with asterisks (* = $P < 0.05$; ** = $P < 0.01$; *** = $P < 0.001$). Distances calculated from locations estimated from the ground versus air were compared if they were taken: (1) on the same day within 1 hr of each other, (2) within 1 hr, but up to three days apart, (3) on the same day at any time, and (4) at any time, and up to three days apart.

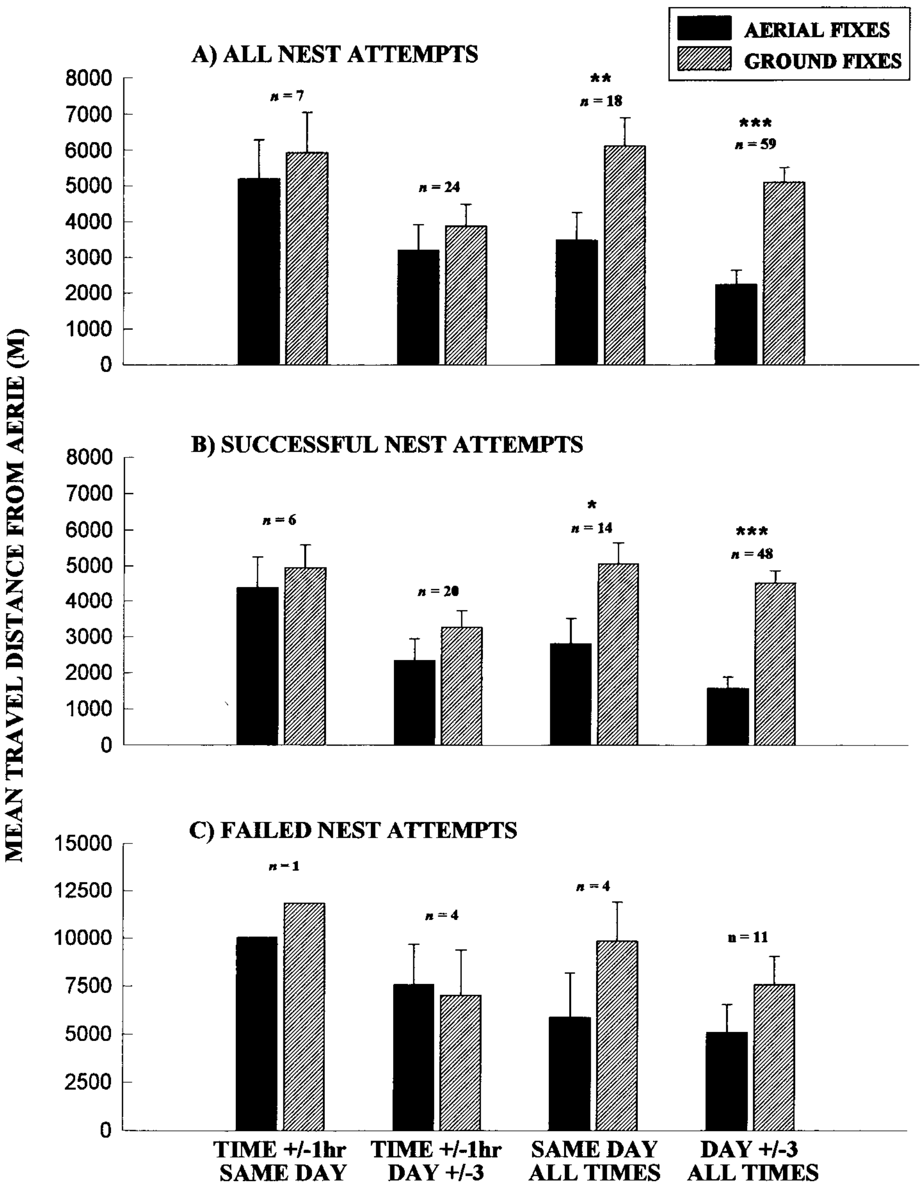

FIGURE 3. Average travel distances of female Prairie Falcons from aeries (+1 SE) calculated from location estimates made during ground-based and aerial tracking. See the legend for Figure 2 for details.

from disparate times (sample sizes were also largest for these comparisons). However, the trend for travel distances of successful breeders, especially males, to be underestimated by aerial tracking was evident regardless of which pairs of ground and aerial fixes were compared.

DISCUSSION

The use of a single, rotary antenna enabled us to quickly and accurately home in on an animal and pass over it. This antenna system is preferable to more commonly used fixed antenna arrays (e.g., Gilmer et al. 1981) because fewer sharp turns are necessary thereby reducing stress placed on the plane and trackers (Carrel 1972), and there is no need to take bearings from the plane to the animal. It also reduced the amount of time required to obtain a fix relative to the results and procedures reported by Hoskinson (1976) and Gilmer et al. (1981).

TABLE 1. Statistical comparison between prairie falcon travel distances from the aerie determined by aerial and ground-based radio tracking. Table entries, from top to bottom, are mean difference (ground travel distance − aerial travel distance, in meters), paired *t*-test *t* value, and probability of *t* value. Travel distances were paired in 4 ways as defined in METHODS. Sample sizes are given in Figures 2,3.

Reproductive status and sex of falcons		Time ± 1 hr		All times	
		Same day	Day ± 3	Same day	Day ± 3
Successful females	$\bar{x}$ =	573	927	2,264	2,958
	t =	0.64	1.6	2.2	6.1
	P =	0.55	0.13	0.05	<0.001
Unsuccessful females	$\bar{x}$ =	—	-545	3,989	2,455
	t =	—	0.48	1.8	2.0
	P =	—	0.66	0.17	0.07
Successful males	$\bar{x}$ =	2,424	2,658	3,763	2,178
	t =	3.8	4.6	4.4	5.5
	P =	0.004	<0.001	<0.001	<0.001
Unsuccessful males	$\bar{x}$ =	499	-1,572	-113	1,382
	t =	0.12	0.57	0.03	0.85
	P =	0.92	0.58	0.98	0.41

Error associated with aerial tracking arises because trackers obtain an equally strong signal just before they pass over the transmitter, when they are directly over it, and just as they pass it. This error could be reduced by slowing airspeed (Hoskinson 1976) or lowering the flight level so that more subtle changes in signal strength as the transmitter is approached could be detected. This would be practical when stationary or slowly moving animals are the subject of study. However, it was impractical in our situation because of the fast travel speeds of Prairie Falcons. Slower airspeed would probably result in fewer aerial fixes being taken on flying falcons or greater error in those fixes, and lower flying level may cause falcons to flush and thereby bias location estimates.

If the aim of a study is to document the ranging habits of radio-tagged individuals, then the distribution of location estimates from aerial tracking may be biased. If locations are obtained each time an individual is encountered, as we did, then the distribution of locations will be influenced by the amount of time an individual spends at each site. For example, breeding birds, such as Prairie Falcons and other species, spend a substantial percentage of their time close to their nest (Dunstan et al. 1978, White and Nelson 1991, Marzluff et al. 1991), therefore most location estimates will also be close to the nest. This may not be a problem if a home range weighted by the time spent throughout the range is desired. However, management considerations are often dependent upon an understanding of an animal's foraging range away from a nest (Squires et al. 1993) and aerial tracking will underestimate this type of range unless a large number of estimates are obtained or if locations near the nest are excluded from analysis. This bias may not exist for animals that are not closely tied to a central location such as a nest which suggests that aerial tracking may be especially well suited to studies of non-breeders, failed breeders, or wintering animals.

One must be aware of the suite of factors potentially influencing the study animals' travels to determine the potential biases that aerial tracking may introduce into a study. Prevailing weather, prey abundance and distribution, time of day, and the presence or absence of predators and competitors may all influence an animal's travel habits and bias estimates of spatial use. Once the factors influencing travel are realized, then aerial tracking may be timed to coincide with peak activity periods which should reduce the bias associated with obtaining a preponderance of fixes near a center of activity outside the foraging range.

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