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Locating Bird Roosts with Doppler Radar

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ABSTRACT: Roosting birds of certain species can be agricultural pests, hazards to aircraft on takeoff and landing, and a purported health hazard. Locating roosts of pest bird species and estimating the numbers of birds using them is time-consuming field work, especially when use of different roosts changes seasonally. Since the middle of the previous century, radar has been used to observe early morning bird echoes, then called “ring angels”. Today, large Doppler radars designed for meteorological work can routinely observe bird roosts, even when birds fly at treetop height. Radar images can often locate all roosts within a certain distance from the radar and can provide an indication of the number of birds using each roost and the general location of their food sources. Single images from the lowest tilt angle (lowest elevation) of different radars show roosts in several areas of the country, and successive scans of a research radar across an area becomes an animated picture of the detailed spatial behavior of birds leaving the roost. Applying a computer image recognition technique, the Hough Transform, to single radar-derived images of bird roosts results in objective numerical estimates of roost location and other data. Data are shown comparing ground-truth visual counts of European starling and brown-headed cowbird departures with such quantitative radar-derived data. The radar correctly estimated the central tendency of flight speed of the birds (20 m/sec), time of morning flight (mean 13.2 min past civil sunrise), and roost location (modal error about 2 km). Sometimes (5.1% of identifications) the algorithm found a “roost” that could not be located by field observers; occasionally there were other sources of confusing echo such as vehicles or migrating birds.

KEY WORDS: algorithm, bat, bird, crow, Doppler, Hough transform, pest, radar, roost, starling

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INTRODUCTION

Organized movements of birds flying to and from roosts were studied with meteorological radar as early as 1957 (Eastwood *et al.* 1962, Harper 1959), quickly establishing the seasonal nature of roost occupation, the low height of roosting flights, and the dramatic synchronization of morning departure vs. the more subtle patterning of evening return to the roost (Blokpoel and Desfosses 1970). In fall and winter in North America, roosts of 10^5 birds are common and roosts of 10^7 birds are documented. Such concentrations of birds are a hazard to aviation (Seubert and Meanly 1974), consumers of food-crop grain (Whitehead *et al.* 1995), and a nuisance in inhabited areas (Marzluff *et al.* 2001). Large roosts disrupt the functioning of computer methods to identify hazardous weather, such as a microburst algorithm designed for aviation safety (Larkin 1991). Even small roosts can be problems. For instance, a civilian aircraft incident at Peachtree-Dekalb in Georgia involved a roost with 3,000 European starlings (*Sturnus vulgaris*, EUST).

Some species are more amenable to observation with radar than others (Ansoorge *et al.* 1992). The most prominent roosting species in North America are collectively referred to as “blackbirds”. Depending on time of year and other factors, they roost and often depart together and have similar behavior (Caccamise and Fischl 1985, Caccamise *et al.* 1983). The European starling (Summers and Feare 1995) is the most numerous of the “blackbirds” in this project. Its characteristic flight speed (ca. 20 m/sec; Eastwood 1967) and roosting behavior are typical of those of other “blackbirds.”

Other important North American roosting species are American crow (*Corvus brachyrhynchos*, AMCR; Caccamise *et al.* 1997, Gorenzel and Salmon 1995), American robin (*Turdus migratorius*), brown-headed

cowbird (*Molothrus ater*, BHCO), purple martin (*Progne subis*; Russell and Gauthreaux 1996), and several species of herons and egrets. Traditional roosts estimated to comprise 10^5 crows (Black 1941, p. 92) or 3.5×10^6 robins (Graber *et al.* 1971, p. 10) are recorded in the Midwest. A roost of 7×10^5 AMCR at Danville, IL was visible on the CHILL radar (see below), but the echoes from these crows were sometimes difficult to distinguish from those from nearby “blackbird” roosts.

METHODS

Ground Truth

Field observers using binoculars and still cameras searched out bird roosts in Illinois. Visual species identification of thousands of widely scattered, intermingled BHCO and EUST was sometimes difficult in pre-dawn conditions, but distinguishing these species had no effect on the radar analysis. During morning departures, observers recorded, when possible, numbers in a group, directions, times to the nearest second, and, paths leaving the roost. Also, whenever possible the numbers, times, and directions of departure of birds from roosts were recorded each morning when radar data were taken. These data were used in estimating the relationship of radar data to number of birds. Roosts that could not be observed simultaneously with radar observations were sometimes counted beforehand (e.g., on the evening before radar observations were conducted) and recounted on subsequent mornings or evenings; stable counts indicated a traditional roost where the location and size were considered verified.

Because ringlike patterns of dispersing roosting birds are distorted by wind, radar and field observations were scheduled for low wind conditions. However, incorrect or vague forecasts provided the inevitable opportunities

for testing the algorithm in moderate wind.

Little effort was spent gathering quantitative data on birds returning to roosts in late afternoon. One reason is that an artifact in the form of rush hour traffic is common in cold weather around dusk. A noteworthy instance of confusion between bird and vehicle echoes occurred at 1615 CST on 3 Nov 1989, when observers in the field recorded a large flock of “blackbirds” of mixed species that flew directly above the center line of the northbound part of divided Illinois Highway 51 for a distance of at least 6 km, from Interstate 72 into and past the center of Decatur. From the birds’ point of view, they were probably using the road as a convenient route among the city’s structures and possibly as a leading line for navigation. From the point of view of weather radar, their echoes would have been mixed with or obscured by traffic. Vehicular traffic is present but generally much less common in the near-dawn time frame of departure from roosts. Another reason for concentrating on morning, as opposed to evening roost movements, is that evening return movements to a roost do not provide a clear spatio-temporal pattern (Clergeau 1990, Harper 1959, Tye 1993).

Radar Data

Radar data were taken with the CHILL (Brunkow *et al.* 2000, Peltier 1989), an S-band Doppler research radar located in Savoy, Illinois that was originally developed by the Universities of Chicago and Illinois, hence the acronym. This radar, and the data it produced, was similar to the current National Weather Service WSR-88D Nexrad (Crum *et al.* 1993, Diehl and Larkin 2005, Gauthreaux and Belser 2003). Other data were obtained from the similar FL-2 radar. The radar-derived map location, echo strength (reflectivity), and radial speed (Doppler velocity) of echoing objects were used. (Technically, echoes from roughly planar dispersed groups of birds are neither isolated scatterers of microwave radiation [point targets] nor diffuse volume scatterers, but such distinctions are not important for this paper.) Only the lowest elevation (closest to the horizon) was used, and one revolution of the radar (sweep) was analyzed at a time, independently of any other radar data. Therefore, the computer program described below (Roosting Birds Algorithm) ignored information about the sweep-to-sweep movement of echoes of birds. It relied entirely on static spatial and Doppler information from individual sweeps, and on the traditional nature of roosts that change size and location only slowly on a week-to-week basis.

Computation of civil sunrise was used to restrict the invocation of the algorithm to the time of day just before and just after dawn, local time. Given latitude, longitude, and day of year (1-366), this computation estimated time of sunrise in decimal hours since 0000Z by a standard method (U.S. Naval Observatory 1990).

Algorithm

A Roosting Birds Algorithm (Larkin 1994) locates the largest and most easily visible roost and then successively smaller and less visible roosts. Sweeps are processed in

Cartesian coordinates. A Hough transform (Illingworth and Kittler 1988) relying on circles, $r^2 = (x - a)^2 + (y - a)^2$, was selected to recognize echoes of birds departing roosts; in still air, the pulsed departures of the birds describe arcs of concentric circles, whose center is the location of the roost and whose maximum diameter is the distance to which the birds fly before alighting and beginning the day’s feeding and other activities. The method is illustrated graphically using actual data in Figure 4 in Larkin and Quine (1989) and is fully described in (Larkin 1994).

Several aspects of the biology of roosting birds substantially increase the rate of success of the transform and enormously increase its efficiency. Increased efficiency results from the transform not wasting a lot of time finding circles that are biologically implausible. Birds fly at characteristic air speed and they fly straight, greatly restricting the possible directions in which the algorithm has to search for roosts. (Variability in winds necessitates setting moderate limits on these directions.)

Because the Hough transform takes place in a finite, bounded plane, the method will favor roost centers located near the middle of the plane (in this case, near the radar). The problem is stochastic and occurs even when working with completely random, ideal data on a bounded plane. It is overcome by a further modification of the Hough transform that, instead of using the Hough transform itself, uses difference between accumulations of normal-velocity data and accumulations of reversed-velocity data. This modification to use “anti-birds” to remove the effect of the finite plane’s boundary, is described in (Larkin 1990). The algorithm also searches for the largest possible circle describing every roost; this procedure is efficient because flying animals departing a given roost often generate concentric circles whose origin is that one roost. The final radius, the maximum of the outward edge of the most populous circle, is computed from the 98th percentile of the radar echoes in that circle.

Accuracy of localization of roosts was measured as the linear geographical distance between the actual location of a roost, as noted in field observations and the computed location of the roost center from the radar data.

The algorithm outputs files suitable for later analysis by statistical packages. In addition, it optionally shows its operation graphically on a color display by drawing the center of the each roost over the data and the diameter of its circle under the data. The “center” of a roost denotes a single Cartesian location used for the geographic coordinates of the roost. In reality, any roost has some spatial extent and a large roost covers several hectares, but we require one characteristic location. In practice, the distinction is not important.

TESTS OF THE ALGORITHM

Artificial and Special Data

Artificial computer-produced “sweeps” with velocity values generated by vector algebra, and arranged in single or concentric circles, yielded centers correctly located within the spatial resolution of the algorithm and radii equal to that of the artificial circle or of the largest artificial concentric circle. Fields of randomly spaced

echoes with randomly assigned velocities yielded no roosts when the anti-bird portion of the algorithm was operating. An interesting test sweep from the FL-2 radar in North Dakota, composed of insects concentrated in distinct and dense rings around thunderstorm outflows, also correctly resulted in no roosts being located. Thus, the use of artificial and special data proved the mathematical correctness of the algorithm.

Tests for Extraneous Targets using Doppler Velocity

Target speeds in the general region of +20 m/sec (positive = away from the roost) for EUST and “blackbirds” represent the plurality of the echoing cells; these are likely to be birds departing the roost. However, many factors introduce variation in measured air speed. The birds fly low, adding ground clutter with low Doppler velocity. Variation in direction of travel of individual scatterers (e.g., birds) in the radar pulse volume, even if all fly at identical speed, reduce measured Doppler velocity. Some moving echoes (vehicles, railroad trains, and other birds such as pigeons) are not roosting birds. Not all the birds are EUST and BHCO (although the majority are), and we have no evidence that even EUST maintain perfect speed constancy. Algorithm malfunctions could generate errors, as could multiple distinct roosts lumped together by the algorithm (see below). Finally, any undetected wind at the height and geographical position of departing birds will change the mean flight speed. Nevertheless, 2,493 of 5,561 cells in this analysis (45%) lay within ± 5 m/sec of 19 m/sec, the air speed of EUST and BHCO (out of a range of -40 to +40 m/sec). (A value slightly below 20 m/sec is expected due to the action of the Central Limit Theorem on non-bird echoes.)

In spite of the many sources of variation, the clear peak in the distribution where expected is strong validation of the algorithm’s ability to selectively and accurately locate birds departing from roosts near dawn. Furthermore, it is worth considering estimated ground speed as a possible automated, day-to-day operational measure of the biological validity of a roost. For instance, it could be used on a day-to-day basis, along with the distance between putative roosts, to decide when to acknowledge a new roost location as a known bird roost, providing that the seasonal species mix making up the roosts near a given WSR-88D can be predicted.

Other Considerations

Intuitively, a circle that is speckled with a few echoes should contain fewer departing birds than a circle that is densely filled. Such a sparsely filled circle should represent a roost with fewer birds or perhaps a dispersal movement just beginning or nearly completed. In testing the algorithm, sometimes it became apparent that sparse circles were false positive roosts. Measures of “sparse” include blackbird-equivalents km^2 and Coverage, or bird echo cells km^2 . Figure 1 plots these measures against each other for $N = 49$ roost locations; it shows that false positives are indeed much more common in sparse roosts, measured either way, but also that Coverage is the better discriminator of false positives from actual roosts.

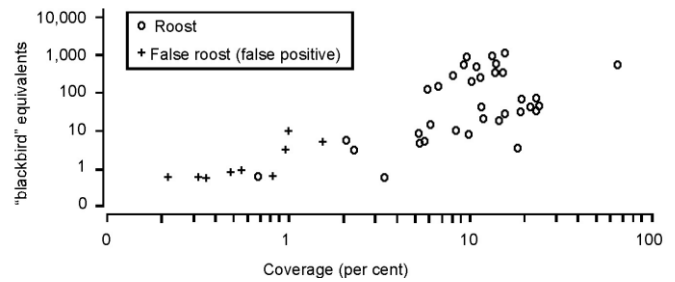


Figure 1. Circles (putative roost departures) show positive correlation between the proportion of the area that has bird echo (horizontal axis) and the calculated number of birds in the area (vertical axis). False positive roost identifications (plus signs) are all sparse.

Roosts must be located sufficiently accurately to match them to the same roosts over time, and to properly position the radius of the circle describing the departing birds, so that their reflectivity and other characteristics may be accurately measured. Figure 2 shows most roosts were correctly located within 4 km. The largest value, at error = 13.1 km, was taken from the FL-2 radar located at Huntsville, Alabama in July 1986, when the radar was heavily dotted with echoes from migrating birds or insects, causing the algorithm to function poorly.

Computation time of the Roosting Birds Algorithm is not a significant factor on a modern computer running only a few times per day. It was 5 to 80 minutes on a slow (ca. 3 SpecMarcs) computer. Several optimizing steps are described in Larkin (1994).

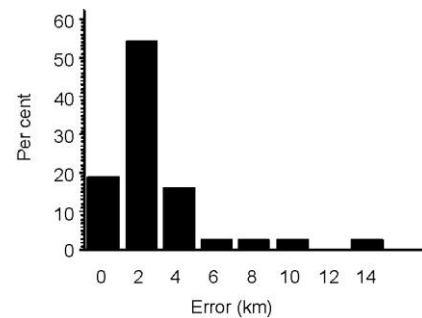


Figure 2. Distance between the center of each roost measured two ways, by observers in the field and by the Roosting Birds Algorithm using radar data. 5.1% of the radar-located “roosts” were not in fact bird roosts (see text).

RESULTS

False Positives

Circle centers that were located by the algorithm, but that corresponded to no known roosts, comprised 5.1% of the algorithm-located “roosts”. The mean number of actual roosts per full sweep found by the algorithm was 2.1 in a 14,000- km^2 area. Assuming that if 2 WSR-88D sweeps occur during roost departures, then the 2.1 roosts that would be located in each sweep would likely be the same roosts, totaling 2.1 roosts/day. Therefore, if the false positive rate of 5.1% is a reasonable estimate, we

expect a false positive on about 1 of each 20 sweeps at a given WSR-88D radar, or every 10 days. Although this rate is low, we may conclude that even if the actual rate may be higher, there is a negligible chance of random false positive roost centers close to one another on successive days. Therefore, the algorithm may generate occasional incorrect candidates for roosts, but they will not persist over days and thus will be dropped. Another argument is that in cold weather, rural roosts are over-dispersed (in the spatial sense, not the statistical sense) in available habitat. Therefore, the algorithm's success in finding a sizeable, stable roost in a certain location is to some extent itself an argument that other roosts do not exist nearby.

Reflectivity and Counting Birds

The CHILL radar reliably registered echoes from flying birds at their common height roughly twice that of trees. When birds headed into strong wind in open country, they commonly flew as low as 1 m above ground level and gave much weaker radar echoes, if any, on CHILL.

With some exceptions, more radar echo (reflectivity) represents larger birds or more birds of a given size (Larkin 2005). Total reflectivity (amount of radar echo, roughly but not linearly proportional to biomass of departing birds) is computed by summing each echo cell within the circle, modified for the infrequent case in which two neighboring roosts have overlapping areas. Because species of birds vary in size (Table 1), we use a "blackbird-equivalent", defined as one EUST, or the equivalent number of different-sized birds that would produce equivalent S-band radar cross-section to one EUST. Variation in mass of birds across a season (Peach *et al.* 1992) is not accounted for in this relationship. One AMCR is 2 blackbird-equivalents (Figure 5 in Vaughn 1985). Relating observed $\log(N)$ to total reflectivity expressed in logarithmic units of dBZ (Doviak and Zrnic 1993) over a range of 5.8×10^2 to 1.0×10^5 blackbird-equivalents gave: $\log_{10} N = 2.51 + 0.048 \times \text{Total Reflectivity}$, which is significant at $p = 0.03$.

Table 1. Masses of common roosting birds; male and female masses averaged (from Dunning 1992).

Species	Mass (g)
American crow	448
American robin	77
European starling	82
Red-winged blackbird	53
Common grackle	114
Brown-headed cowbird	44

Departure Times

Departure times of roosting birds are shown in Table 2 for "blackbirds". AMCRs departed earlier than blackbirds. Times of first and last departures from roosts were extracted from the notes in addition to times of peak departures; they confirmed our rule of thumb for field work that the 30 minutes before civil sunrise is the time of maximum departure activity (see also Russell and Gauthreaux 1999).

Table 2. Departure time (min) from roosts, relative to civil sunrise.

	First	Peak	Last
N	23.0	25.0	17.0
Mean	27.0	13.2	-2.2
S.D.	12.8	11.0	15.2

Birds depart from a large roost in pulses that place cumulatively more birds in the air surrounding the roost, spread steadily in radius, and finally disappear as they reach a certain maximum radius. On 7 December 1982, the rapid CHILL sector scan mode provided roost departure data at close intervals to permit detailed examination of the important algorithm outputs as a function of time during departure. The results from N = 17 runs of the algorithm during the main departure period from this date are shown with the times of successive sweeps in Figure 3. Reflectivity climbs to an asymptote at about 105 birds, not steadily but as three successive pulses departing the roost. The calculated roost center, on the other hand, remained steady very close to the actual stand of evergreens in which the birds roosted. The radius of the outermost circle climbs smoothly (Figure 4), except when the first pulse dissipates at about 0651 and the second pulse begins to dissipate at about 0656. The slope of the long, smooth rise in radius from 0643 to 0650 is 23 m/sec, close to the 20.6 m/sec winter departure speeds previously reported by Eastwood (1967). These time series indicate the algorithm measures output values correctly for a large roost on a calm morning.

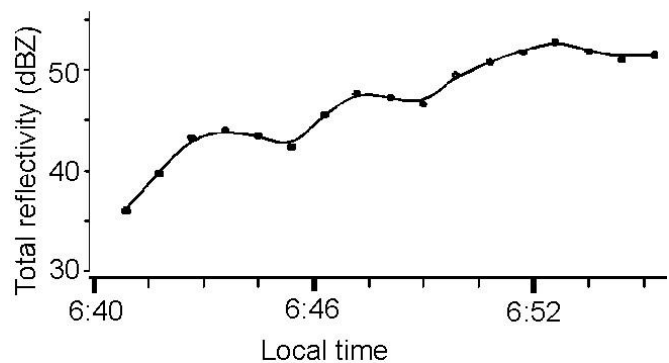


Figure 3. Temporal progression of the amount of radar echo returned from birds departing a roost on the north side of Champaign, IL on 7 December 1982. Successive "waves" of birds departed from a small evergreen wood lot and overflowed mainly bare fields of row-crop agriculture. After some 20 minutes, birds in the air became thinly dispersed and eventually landed on the ground, beginning to reduce the over echo from flying birds. Reflectivity is given in dBZ, a logarithmic scale.

DISCUSSION

Algorithm Performance

Performance of the Roosting Bird Algorithm was verified on blackbirds (mainly EUST) with research radars similar to the National Weather Service WSR-88D. Given suitable topography without obstructions to the

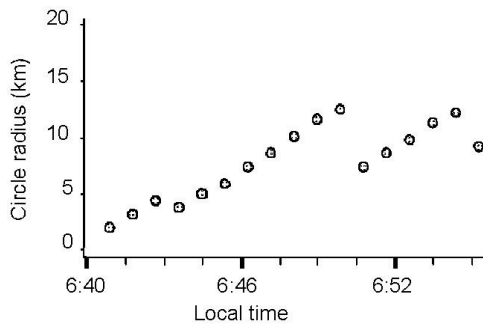


Figure 4. Time axis and source data same as the preceding figure but showing the expanding radius of circles resulting successive waves of birds recognized by the Hough transform.

radar beam, locations of roosts, numbers of birds in each roost, and time of the morning emergence were obtained from the automatically-processed radar data. If this computer program were to operate on a daily basis, the seasonal occupation of roosts could be monitored, and occasional false roosts would probably not be confused with actual stable roosts. In the case of the short-distance migrants studied here, individual birds probably change over a season's roost occupation; the radar can monitor populations but not individuals.

Finding roosts is accomplished much easier by following groups of birds returning to the roost in late afternoon than by observing in the morning. What was not immediately obvious but soon became clear, was that the field biologist's customary approach of finding the birds, then studying them on radar, was inefficient. Radar did a better job. A few minutes on a calm morning observing the real-time color display of a weather radar usually revealed the locations (within a few km) of several or many roosts of varying sizes; the subsequent field work of documenting the exact location of the roosts then could be accomplished quickly, even by observers with minimal field skills.

Clusters of 2-3 "roosts" can coexist within several km of one another in roosting habitat that is spatially dispersed yet patchy, such as urban areas. It is not obvious that it is inappropriate to regard such a cluster of roosts as ecologically one roost that is spread out because the habitat is patchy. In such cases, the algorithm usually incorporates the 2-3 roosts into one large circle with its center often lying close to one of the constituent roosts. It is clear neither whether this behavior is an "error" on the part of the algorithm, nor, if it were, whether anything could be done computationally to correct the "error". The phenomenon of clusters of roosts or roosts in flux is an example of wild birds behaving as they wish; fortunately, when the algorithm encounters this situation it "fails" in such a graceful fashion as to function nearly normally.

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