2016

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Gerringer, Michael B.; Lima, Steven L.; and DeVault, Travis L., "Evaluation of an Avian Radar System in a Midwestern Landscape" (2016). *USDA National Wildlife Research Center - Staff Publications*. 1773.
https://digitalcommons.unl.edu/icwdm_usdanwrc/1773

Wildlife Society Bulletin 40(1):150–159; 2016; DOI: 10.1002/wsb.614

Tools and Technology

Evaluation of an Avian Radar System in a Midwestern Landscape

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ABSTRACT Bird strikes in aviation are an increasing threat to both aircraft and human safety. Management efforts have focused largely on the immediate airport environment. Avian radar systems could potentially be useful in assessing bird strike threats at greater distances from the airport, at higher altitudes, and at night, but few studies have been conducted to assess the capabilities of avian radar systems. Thus, our goal was to assess the detection and tracking abilities of a commercially available avian radar system in an airport environment in Indiana, USA, during October 2011–March 2012. Transits by free-flying birds allowed us to assess radar tracking performance as influenced by flock size, altitude, and distance from the radar unit. Most of the single large-bird targets (raptors) observed within 2 nautical miles (NM) of the radar were tracked $\geq$1 time, but such targets were generally tracked <30% of the time observed. Flocks of large birds such as geese (*Branta canadensis*) and cranes (*Grus canadensis*) were nearly always tracked $\geq$1 time, and were generally tracked approximately 40–80% of the time observed, even those several NMs away from the radar unit. Our results suggest that avian radar can be a useful tool for monitoring bird flock activity at airports, but less so for monitoring single large-bird targets such as thermalling raptors. Published 2015. This article is a U.S. Government work and is in the public domain in the USA.

KEY WORDS airport, airport wildlife management, avian radar, bird strike, human–wildlife conflict.

Bird strikes involving aircraft are a serious threat to human safety (DeVault et al. 2013, Dolbeer et al. 2014*b*). The forced landing of U.S. Airways Flight 1549 into the Hudson River after striking a flock of Canada geese (*Branta canadensis*; Marra et al. 2009) was a dramatic example of the consequences of such strikes. Bird–aircraft collisions increased during recent decades due, in part, to increasing air traffic (Dolbeer et al. 2014*b*), quieter aircraft with fewer engines (Burger 1983, Kelly et al. 1999), and increasing populations of large birds (Dolbeer and Eschenfelder 2003, Cleary et al. 2006). Annually there are, on average, approximately 3.7 fatalities/year due to bird collisions with nonmilitary aircraft in the United States, compared with 211 fatalities due to deer (*Odocoileus* spp.)—automobile collisions (Conover et al. 1995). Even so, bird strikes caused the destruction of >210 civil and military aircraft, resulting in >229 deaths worldwide between 1988 and 2000 (Richardson and West 2000). Aircraft bird strikes occur much less frequently than vehicle collisions with wildlife on roads (Conover et al. 1995), but they are costly for the aviation industry in terms of aircraft damage and downtime. In 2013 alone, 11,315 bird strikes were reported in the United States under a voluntary reporting system; 601 strikes resulted in aircraft damage (Dolbeer et al. 2014*b*). Using data from 1999 and 2000, Allan and Orosz (2001) estimated that bird strikes result in an annual cost of >US$1.2 billion for commercial airline carriers worldwide. The U.S. military also suffers significant costs from bird strikes, with U.S. Air Force damages totaling US$33 million annually (Allan and Orosz 2001, Zakrajsek and Bissonette 2005).

The field of airport wildlife management has grown considerably during the past 2 decades in response to the bird strike problem. Most large civil airports and military airfields in the United States now employ full-time wildlife biologists (Dolbeer 2013). Wildlife management efforts (including habitat modification, deterrents, and wildlife relocation and removal; DeVault et al. 2013) have served to reduce wildlife hazards and damaging strikes at airports (Dolbeer 2011), where historically approximately 75% of all strikes occur (Dolbeer 2006). More research is needed to develop methods for reducing bird strikes outside the immediate airport environment, where strikes are more likely to cause aircraft damage, but relatively few effective solutions exist (but see Fernández-Juricic et al. 2011, Blackwell et al. 2012).

Avian radar systems have the promise of providing information on bird activity within several nautical miles

Received: 18 November 2014; Accepted: 21 August 2015
Published: 24 December 2015

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(NM) of an airport, during both night and day (Dolbeer 2006, Beason and Bowser 2009, Brand et al. 2011, Coates et al. 2011). Avian radar systems are typically defined as those capable of automatically detecting and tracking birds around an airfield, at distances of up to 6 NM (11 km), and at altitudes up to 5,000 feet (1,524 m; Beason et al. 2013). (Units of feet and NM are used throughout as per the standards of the aircraft transportation system). Most radar systems are capable of providing real-time estimates of target location, altitude, and speed (Gauthreaux and Schmidt 2013). Thus, avian radar could provide airport personnel with near real-time warnings of bird hazards in the general airport environment (Nohara 2009, Gauthreaux and Schmidt 2013). Yet, despite the potential of avian radars, there is still much uncertainty concerning their detection and tracking performance, as well as how the information gathered by such systems should be used (Weber et al. 2005, Gauthreaux and Schmidt 2013). An Advisory Circular on avian radar (Federal Aviation Administration 2010) recently set forth general guidelines for the use of avian radars for reducing bird strikes, noting that integration plans should be specific to the needs and organizational structure of each airport. Avian radar has also been used to assess avian flight patterns at proposed wind farm sites (Cooper 1996; Gauthreaux and Belser 2003; Krijgsveld et al. 2005, 2011; Drewitt and Langston 2006), during migration (Gauthreaux and Belser 2003, Coates et al. 2011, Bowden et al. 2015), and between roosting and feeding sites (Beason et al. 2013).

The value of avian radars in reducing bird strikes in aviation, and in other applications, will ultimately be determined by ground-truthed studies of their ability to detect and track avian targets. One of the few avian radar evaluation projects conducted to date is the Integration and Validation of Avian Radar Project (Brand et al. 2011). During this project, radar operators relayed target locations to field observers, who confirmed whether or not a bird target was present at that location. Integration and Validation of Avian Radar workers determined that $\geq$58% of the targets being tracked by radar were, in fact, birds. On limited occasions, field observers identified targets for radar technicians to confirm, but such work was hampered by the fact that much of the evaluation work was done with a dish antenna. A dish antenna samples a relatively narrow range of altitudes at a given time, making it difficult for field observers to determine whether a bird was within the radar beam (but see Beason et al. 2010). More recently, Dokter et al. (2013) assessed an avian radar system by linking observed bird targets to radar tracks using transect crossing times as determined by field observers. Their results indicated that approximately 50% of single bird targets were tracked, and that the radar system's tendency to miss birds was dependent on bird mass. Overall, there is still much uncertainty about the efficacy of avian radar systems and thus a need to evaluate their basic detection and tracking performance. Specifically, data are needed regarding the percentage of time that targets are tracked while within the radar beam in order to adequately assess radar tracking performance. Also, few data exist that differentiate tracking performance between single birds and flocks.

Our primary goal was to test the tracking ability of a commercially available avian radar system, as it would be employed by an airport wildlife management team. The radar system tested was the Merlin Aircraft Birdstrike Avoidance Radar (DeTect, Inc., Panama City, FL). We worked in an airport environment to evaluate the radar system's ability to detect and track free-flying raptors and waterbirds as a function of distance, altitude, and flock size. Specifically, we determined 1) the percentage of overall bird transits during which target birds were tracked at least once, and 2) the average percentage of time that birds were tracked out of the total time that they were visible to the field observer and within the radar beam.

STUDY SITE

The field evaluation took place at the Terre Haute International Airport east of Terre Haute, Indiana, USA (39.459°N, 87.303°W). The radar unit was set up at the edge of a level, asphalt tarmac on the northeastern side of the airport. The vertical radar was aligned with a nearby east–west road (Swalls Drive), such that the center of the vertical beam crossed Swalls Drive at approximately 2 NM from the radar unit (Fig. 1). This configuration allowed easy access to both the vertical and horizontal beams from this road out to 4 NM. However, ultimately, there were not enough bird transits across the vertical beam to assess the vertical scanning radar. The Merlin system can operate at ranges >4 NM, but when operating at such ranges, radar data cannot be recorded and saved because the volume of information is too much for the system to process. A technician from DeTect, Inc. worked with us to optimize the radar system for use at the airport. The optimization process included the creation of static clutter maps of the radar testing area. Clutter maps allow the radar system's software to minimize the effects of stable clutter such as that produced by returns from buildings or trees, and were updated as vegetation changed (autumn to spring) over the course of the study.

The Terre Haute International Airport was surrounded primarily by agricultural fields, small forested areas, and grasslands (Fig. 1), and was, thus, typical of airports on the periphery of urban areas in the midwestern United States. The specific area over which we worked (to the east, Fig. 1) provided the lowest clutter environment in the area surrounding the airport, being essentially level (at 600 ft [183 m] above sea level) with <5% forest cover and fewer than 10 one-story buildings. The open agricultural fields, grassland habitat, and abundance of lakes (Fig. 1) within the study site attract a variety of raptors, migrating waterfowl, and resident waterfowl moving among lakes and feeding sites. These large birds present the greatest avian hazards to aircraft (Kelly 1999, Blackwell and Wright 2006, DeVault et al. 2011), and are capable of inflicting significant structural damage (requiring a major repair–replacement of a component or resulting in damage beyond repair; Dolbeer et al. 2014*b*) and rendering aircraft engines inoperable.

METHODS

Radar System

The Merlin System (hereafter, "radar system") consists of a trailer carrying a climate-controlled cabin that houses the computer systems, radar processors, and other equipment, and 2 towers on which the dual-scanning array antennas are mounted. The system (VIN no. 1D9BR2427AP670010; production no. Merlin 56), obtained 16 February 2010, has both a vertical and horizontal scanning solid-state S-band marine-radar-array antenna, each with a power of 0.2 kW and a rotational speed of 24 revolutions/minute (2.5 s/scan). The horizontal scanning radar (HSR) has a stated detection range of 6–8 NM from the radar unit, up to 15,000 feet (4,572 m) above ground level (AGL), and scans 360° with a 24° beam mounted with 7° of upward tilt (DeTect, Inc. 2010). The HSR provides latitude–longitude coordinates (2-dimensional tracking) for each tracked target, as well as estimated target size, speed, heading, and a number of other variables. The vertical scanning radar (VSR) also has a 24° beam width, but with a stated detection range of 3–4 NM and $\geq$10,000 feet ($\geq$3,048 m) AGL (DeTect, Inc. 2010). The differences in the stated detection range between the HSR and VSR are the result of antenna orientation and the typical ranges at which the radars are operated. The VSR provides specific measures of target altitude and distance (among other variables) centered on a single radius away from the radar system.

Study Species and Procedures

Transits of free-flying birds provided the opportunity to test directly how well the avian radar system can track single birds and flocks. We assessed 1) the frequency with which such targets were tracked at a given distance and altitude, and 2) the average percentage of time that targets were tracked while visible to the field observer and within the beam. Key measures of tracking performance were 1) the percentage of overall bird transits during which target birds were tracked at least once, and 2) the average percentage of time that birds were tracked out of the total time that they were visible to the field observer. We focused observations of bird transits on the area along Swalls Drive (Fig. 1), and conducted observations at 0.5-NM increments out to 4 NM from the radar in random order, spending roughly an equal amount of time at each location. Most of the transits took place in low-clutter environments. This study covered the period between 1 October 2011 and 28 March 2012, and thus focused on species wintering in, or migrating through, west-central Indiana.

Our focus was on relatively large birds, including raptors and large flocking waterbirds. Turkey vultures (*Cathartes aura*) and red-tailed hawks (*Buteo jamaicensis*) were observed most frequently. We, thus, selected these 2 species to represent "large thermalling raptors." Red-tailed hawk and turkey vulture strikes together account for 93% of civilian aircraft downtime due to raptor strikes (Cleary et al. 2004, Blackwell and Wright 2006), and 64% of all damaging raptor strikes to U.S. Air Force aircraft (Kelly 1999, Blackwell and Wright 2006). Given that turkey vultures have a greater mass than red-tailed hawks (2,000 g vs. 1,000 g; Dunning 2008), we evaluated tracking performance separately for each species.

We observed 22 large, flocking waterbird species in the study area, but we included in the analysis only those species

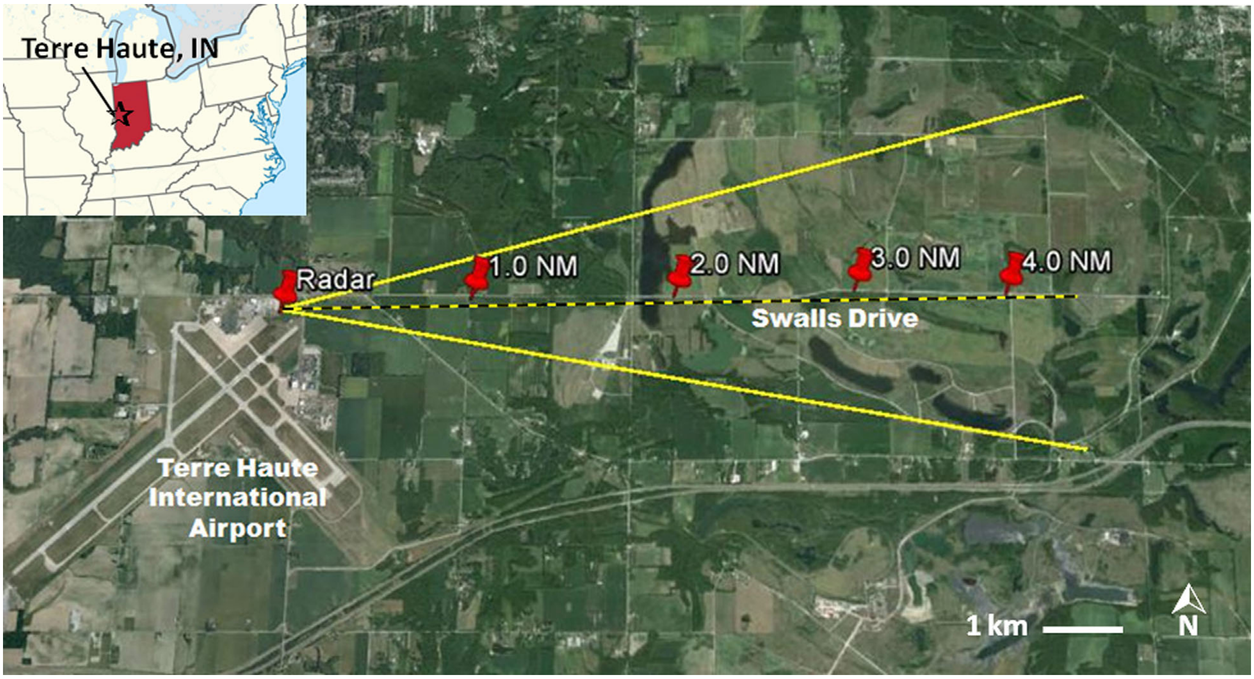

Figure 1. Overview of the study site where we assessed detection and tracking abilities of a commercially available avian radar system in an airport environment in Indiana, USA, during October 2011–March 2012. The Merlin Radar unit and distance increments are marked with a red pin. The dashed black and yellow line represents the center of the vertical beam (86° bearing from north), whereas the solid yellow lines outline the edges of the vertical beam coverage. The horizontal radar covers the entire study site out to 4 nautical miles, but we worked within yellow lines so that both radars could be tested simultaneously.

yielding sufficient sample sizes. These included sandhill cranes (*Grus canadensis*), Canada geese, and ducks (mainly mallards [*Anas platyrhynchos*], ring-necked ducks [*Aythya collaris*], and gadwalls [*Anas strepera*]). These flocking bird species are particularly hazardous to aircraft (DeVault et al. 2011, Dolbeer et al. 2014*a*) and represent the group of birds (waterfowl) that is among one of the most frequently struck groups (Dolbeer et al. 2014*b*). Given that the cranes (3,000–4,800 g; all body mass estimates from Dunning 2008), geese (3,500–4,500 g), and ducks (680–1,250 g) are considerably different in size and behavior, we evaluated tracking performance separately for each.

Turkey vultures and red-tailed hawks observed during the study generally exhibited thermalling (tightly circling) flight behavior. Sandhill crane flocks typically alternated between straight flight patterns and thermal circling or doubling-back to gain altitude. Flocks of Canada geese and ducks were often traveling between roost lakes and agricultural fields, following relatively straight or widely circling trajectories.

Avian Ground-Truthing Protocol

A field observer (M. Gerringer) communicated bird targets to the radar operator, who then confirmed whether or not that bird target was being tracked by the radar (i.e., displayed on the radar computer screen). The field observer also provided the radar operator (who was recording observations) with updates on the location of a bird target every few seconds (see below). After each session, we reviewed the recorded radar tracking data and notes in detail to ensure accuracy and determine the tracking performance for each observed target. This approach addresses errors of omission, or instances in which known birds were not tracked by the radar system. Our focus was on the ability of the radar system to detect known birds, and because the observer undoubtedly missed some potential avian targets, our approach likely overestimated to some extent the true capabilities of the radar system. Errors of commission could not be assessed because potential targets identified by radar can be easily missed by field observers or could be false tracks generated by clutter. Note that we excluded targets that may have been within, or close to, the cone of silence (a conical area directly above the radar site and outside of the scanning range of the radar), which generally means high-flying birds near the radar unit itself. Given the known height of the top of the beam at any given distance from the radar, we could determine whether the target was within the beam or not. It was particularly clear when a flock had entered the cone of silence because a strong track suddenly disappeared from the radar display.

To aid in conveying a bird's location to the radar operator, we divided the study site along Swalls Drive (Fig. 1) into various sectors defined by forest edges, fence rows, roads, and lakes. For each bird or bird flock, the observer updated the location of the target within a given sector every 5–30 s (depending on how quickly the target was moving across the study site) for as long as the target was visible to the field observer. Using the location of a bird target within a sector, the observer could subsequently determine its approximate distance from the radar by using the measuring tool in Google Earth (Google, Inc., Googleplex, Mountain View, CA). An associated estimate of a target altitude was recorded, placing each target within broad altitude classes (above or below 500 ft [approx. 150 m]). These birds were generally at <1,000 feet (<305 m) AGL, and thus within the horizontal radar beam in nearly every instance (given known beam geometry). The field observer did not include avian targets near or below tree-top level, thus excluding targets likely to be missed by the radar.

The observer also recorded notes on species and general behavior (flight direction and flight pattern) for each observed target. If the birds were flying in a flock, the observer recorded the number of individuals and an estimate of inter-bird spacing (dense or loose flock). The observer considered dense flocks to be those in which inter-bird spacing was <5 body lengths, whereas loose flocks had an inter-bird spacing >5 body lengths. Given that nearly all flocks observed were dense, we considered only dense flocks in the analysis. We also excluded from analysis flocks that were <1,200 ± 100 feet (366 ± 30.5 m) apart (as estimated by the field observer) so as to avoid the possibility of the radar system detecting 2 separate flocks as one target. We pooled all acceptable bird transits by species into distance and altitude categories as required to obtain reasonable sample sizes ($n \geq 10$). The observer conducted all bird observations on fair and relatively calm days. During windy conditions, with wind gusts exceeding 30 miles/hr, few birds were in the air, and very few were at altitudes high enough to be detected by radar.

Avian Radar Data Review

In the radar system's software, a detection or "plot" occurs when, during a given radar scan, a radar echo is recognized by the software as a bird-sized target. A track begins when enough detections are generated to initiate a track (detections during 3 out of 4 consecutive scans). A track can include "misses" (nondetections), termed "coasted targets." These coasted targets maintain a tentative track that is determined by the speed and trajectory of the most recent detections. The software allows for up to 2 consecutive misses, which are included as part of the track (displayed on the computer screen as a different color). If a target is missed during 3 consecutive scans, the software terminates that track. The tracking software assigns each track a track identification (in a Microsoft Access database), and so each detection or coasted target that is a part of a given track is labeled under the same track identification (for a detailed discussion of the Merlin radar data and processing, see Krijgsveld et al. 2011).

When a software-tracked target was within 0.2 NM (1,200 ft [366 m]) of the actual bird location, we considered the former to be the bird. This liberal criterion reflects a problem with the radar unit's positioning system, which caused targets to be placed consistently north of their actual location, with the degree of deviation increasing with distance from the radar unit (up to approx. 0.2 NM). We do not attribute this to an inherent problem with the radar system, but rather to a set-up—optimization problem that was not resolved by radar technicians. Nonetheless, the shape of the tracks produced by the radar, target speed, and target altitude closely matched what the field observer saw in the field. Thus, there was rarely any question as to whether a tracked target was the bird in question.

The radar software allows users to select the minimum target size value (no. of pixels in the radar raster image) used by software algorithms to determine what constitutes an avian radar detection. After initial testing, a radar technician from DeTect recommended settings that would optimize the effectiveness of the radar relative to range. Within 2 NM (0–1.9 NM) of the radar unit, we selected a minimum target size (target extent) of 3 pixels for this study, meaning that a target must occupy ≥ 3 pixels in order to be tracked and displayed on the radar computer screen. We selected a more sensitive minimum target size value of 2 pixels (max. sensitivity) for greater distances (2.0–4.0 NM); a setting of 3 pixels resulted in few tracked targets beyond 2 NM. A minimum target size of 2 pixels could not be used within 2 NM, given the resulting number of false tracks produced by ground clutter, making it nearly impossible to distinguish false tracks from real bird targets.

Analysis of Avian Data

The analysis focused only on data collected by the HSR. Winds exceeding 5 mph usually created clutter over a section of trees between 1.1 NM and 1.8 NM from the radar system, so the observer avoided that area when observing bird transits. Also excluded were any cases in which clutter happened to be a significant issue where a bird target was present. Bird transits during rain or snowfall were not included because of confusion from tracks associated with precipitation-induced clutter (Gerringer 2013). The target filter settings could be adjusted to remove rainfall clutter, but doing so also removed many of our targets of interest (especially raptor targets). As a result, the radar could not be used during precipitation events.

We included in this study only targets (single raptors or flocks) well-separated (>1,200 ft [366 m]) from any other targets. This criterion eliminated the possibility of confusing one target for another when multiple bird targets were present. Occasionally, larger flocks were tracked as more than one target. As long as ≥ 1 target (representing a given flock) was being tracked during a given scan, we counted it toward the amount of time that the flock in question was tracked.

We conducted a frame-by-frame analysis of the radar recordings for observed bird tracks. We defined an individual bird transit as the observed passage of a single raptor or waterbird flock across the study site. As mentioned earlier, our measures of tracking performance were 1) the percentage of overall bird transits during which target birds were tracked at least once, and 2) the average percentage of time that birds were tracked out of the total time that they were visible to the field observer. The radar system software allows for up to 2 consecutive misses in a track (see above, which can occur more than once), which we included as time tracked. The time tracked began once enough detections had occurred to generate a track, so the 3 detections required to initiate the track were not counted toward time tracked. We provide each measure of tracking performance as a function of distance and altitude (above or below 500 ft [approx. 150 m]) for single bird targets, and as a function of distance and flock size for flocks. We do not present altitude data for waterbird flocks, given that duck and goose flocks were almost always between approximately 200 and 400 feet (approx. 60–122 m); whereas, cranes were nearly always above 500 feet (approx. 150 m; usually approx. 1,000 ft [305 m]). For single bird targets, we pooled observations in 1-NM increments out to 4 NM. For flocks, we divided distance from the radar unit into near (<2-NM) or far (>2-NM) categories, and flock size categories into either small (2–10 birds), medium (11–29 birds), or large (≥ 30 birds).

We analyzed patterns in the percentage of flights detected at least once using a generalized linear model (binomial with link = logit) in the statistical package R (R Development Core Team 2011). For single raptors as the targets, the dependent variable was whether or not a target was tracked at least once, and the independent variables were altitude, distance, and distance^2. We used the distance^2 variable to account for possible nonlinear relationships between distance and detections. For flocking birds, the independent variables were flock size and distance (distance included only 2 levels; hence, we did not include distance^2 as a variable).

We used a general additive model (GAM) in R (Wood 2006) to analyze patterns in the percentage of time that raptors were tracked as a function of altitude and distance because the many missed targets (zeroes) significantly violated the underlying assumptions of generalized linear models. We set the number of "knots" in the GAM splines (Wood 2006) at $n-1$, where n is the number of levels of distance under consideration. The GAM analysis results in χ^2 statistics with noninteger degrees of freedom as estimated by R via an iterative procedure. We set a criterion of $\alpha = 0.05$ for statistical significance in all tests. The spline function applied only to the distance variable; the use of only 2 levels for the altitude variable precluded the use of a spline function. As such, the results for altitude are expressed via a t-test within the GAM analysis (Wood 2006). We analyzed the percentage of time that flocks were tracked as a function of flock size and distance (both fixed factors) using a generalized linear model rather than a GAM, which reflected the fact that few flock targets were missed. The small number of flock size and distance categories used for pooling flock data also precluded the efficient use of GAM models (Wood 2006).

RESULTS

Single Raptors

We included 189 total turkey vulture transits in the radar evaluation, 96 (51%) of which were tracked by the radar at least once. Within 2 NM at both high and low altitudes, approximately 75–95% of turkey vultures were tracked at least once (Table 1). The percentage tracked at least once beyond 2 NM was 10–39%. The percentage of vultures tracked peaked between 1 NM and 2 NM, and then

Table 1. The percentage of turkey vulture (TUVU) and red-tailed hawk (RTHA) transits in which a bird was tracked at least once by the horizontal scanning radar at an airport environment in Indiana, USA, during October 2011–March 2012. "Low" refers to birds <500 feet above ground level, whereas "high" refers to birds ≥500 feet (≥150 m) above ground level. "NM" is nautical miles. "No obs." is "no observations."

		Percentage of transits with ≥1 track		Sample size (no. of birds)	
Distance (NM)	**Altitude**	**TUVU**	**RTHA**	**TUVU**	**RTHA**
0–1	Low	79	54	29	13
	High	75	100	8	2
1–2	Low	95	No obs.	21	No obs.
	High	81	100	16	3
2–3	Low	36	62	30	13
	High	39	60	38	10
3–4	Low	10	20	29	15
	High	22	27	18	11
Total low				109	41
Total high				80	26
Overall total				189	67

decreased considerably between 2 NM and 3 NM. However, the effect of distance on vulture tracking was not significant (distance: $Z = -0.33$, $P = 0.740$; distance^2: $Z = -1.77$, $P = 0.076$). There was no relationship between altitude and the percent of transits tracked ($Z = -0.059$, $P = 0.950$).

On average, turkey vulture transits were 78 s (SD = 86.9) in length (or 31 radar scans). Overall, vultures were tracked <50% of the time while visible to the field observer (Fig. 2A). The best tracking performance was within 2 NM of the radar. Distance ($\chi^2 = 68.8$, df = 1.24, $P < 0.001$) had a significant effect on tracking performance, but altitude did not ($t = 1.14$, $P = 0.256$). Track lengths for turkey vultures were typically only 2–3 scans (5–7.5 s) on average (Gerringer 2013).

We included 67 total red-tailed hawk transits in the radar evaluation, of which 33 (49%) were tracked by the radar at least once. This measure of performance was relatively high within 2 NM (Table 1; but note the low sample sizes at close range). The effect of distance, however, was not significant (distance: $Z = 1.25$, $P = 0.210$; distance^2: $Z = -1.95$, $P = 0.051$). There also was no obvious trend with altitude ($Z = 0.703$; $P = 0.480$).

The average percentage of time that red-tailed hawks were tracked out of the total time observed was generally <20% (Fig. 2B), except between 1 NM and 2 NM, where it was approximately 45% ($n = 3$ hawks). On average, red-tailed hawk transits were 116 s (SD = 100.6) in length (or 46 radar scans). One hawk was tracked 83% of the time it was observed (at 1.2 NM from the radar). However, even when excluding this well-tracked hawk, average tracking performance between 1 NM and 2 NM was still higher (27%) than that at other ranges. The tendency for tracking performance to peak at intermediate distances from the radar was similar to the trend observed for turkey vultures. The effect of distance on the average percentage of time that red-tailed hawks were tracked was statistically significant ($\chi^2 = 13.32$, df = 1.61, $P = 0.002$), and there was no obvious trend with altitude ($t = 0.06$, $P = 0.550$).

Flocks of Waterbirds

We included 83 total sandhill crane flock transits in the radar evaluation, most of which ($n = 79$; 95%) were tracked at least once. Only a few smaller flocks went completely untracked (Table 2). This tracking performance far exceeded that associated with raptors. Recall that all of these flocks (except for two) were in the high-altitude category (>500 ft; approx. 150 m), typically at approximately 1,000 feet (305 m).

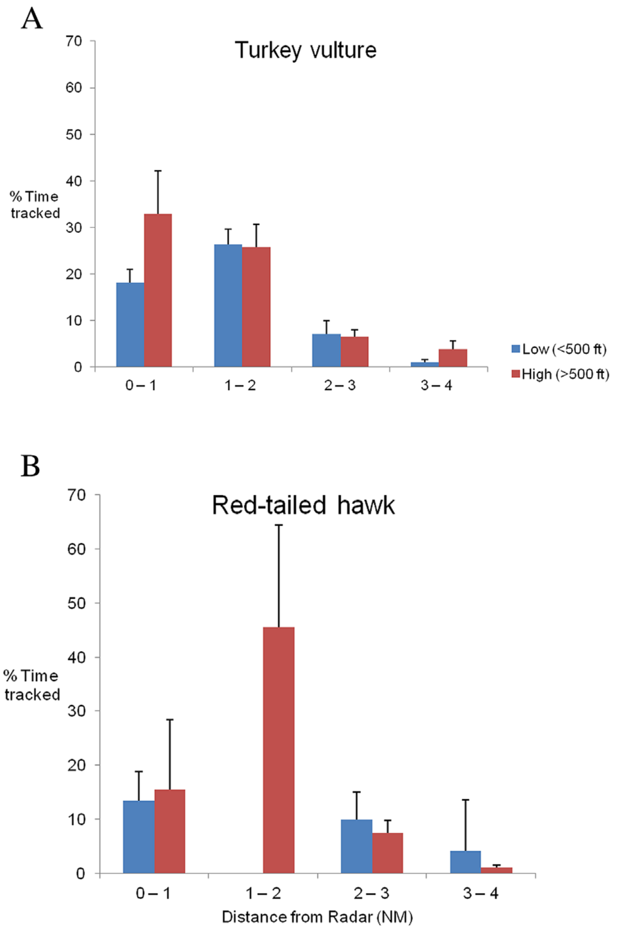

Figure 2. The average percentage of time that single turkey vultures (A) and red-tailed hawks (B) were tracked as a function of distance (nautical miles [NM]) and altitude by the horizontal scanning radar at an airport environment in Indiana, USA, during October 2011–March 2012. Mean values and standard errors are plotted. 500 feet = approximately 150 m.

Table 2. The percentage of sandhill crane (C), Canada goose (G), and duck (D) flock transits that were tracked at least once by the horizontal scanning radar at an airport environment in Indiana, USA, during October 2011–March 2012. "Near" refers to flocks within 2 nautical miles (NM) of the radar unit, whereas "far" refers to flocks >2 NM from the radar.

		Percentage of transits with ≥1 track			Sample size (no. of flocks)		
Flock size	**Distance**	**C**	**D**	**G**	**C**	**D**	**G**
2–10	Near	75	89	57	8	36	7
	Far	75	70	53	8	20	59
11–29	Near	100	100	40	11	25	10
	Far	100	88	83	11	17	18
≥30	Near	100	96	92	18	22	13
	Far	100	100	100	27	14	19
Total near					37	83	30
Total far					46	51	96
Overall total					83	134	126

Crane flocks were tracked 40–80% of the time, on average (Fig. 3A). The average percentage time tracked increased with increasing flock size ($F = 13.66$, df = 2,77, $P < 0.001$), and in all cases greatly exceeded that for single turkey vultures or red-tailed hawks. On average, crane flock transits were 126 s (SD = 80.1) in length (or 50 radar scans). Distance from the radar was not a significant factor ($F = 0.24$, df = 1,77, $P = 0.629$). Typical track lengths were relatively long, especially for large flocks (15–20 scans, or 40–50 s); track lengths for medium flocks were 10–15 scans, and 9–10 scans for small flocks (Gerringer 2013). Note that large flocks of cranes sometimes exceeded 100 individuals.

We included 134 total Canada goose flock transits in the radar evaluation, of which 121 (90%) were tracked by the HSR at least once. This measure increased significantly ($Z = 2.42$, $P = 0.025$) with increasing flock size (Table 2). Distance also had a significant effect ($Z = -2.14$, $P = 0.032$), with somewhat improved tracking closer to the radar unit (<2 NM). Overall, goose flocks were tracked much more often than raptors, but less often than crane flocks.

The average percentage of time that Canada goose flocks were tracked (Fig. 3B) increased with increasing flock size ($F = 20.67$, df = 2,128; $P < 0.001$). There was no clear effect of distance ($F = 1.56$, df = 1,128, $P = 0.214$). On average, goose flock transits were 85 s (SD = 61.4) in length (or 34 radar scans). The average percentage of time tracked was relatively high at 60–70% for the largest flocks, but <50% for smaller flocks. Typical track lengths were 4–6 consecutive scans for small flocks, 10–12 scans for medium flocks, and 9–16 scans for large flocks (Gerringer 2013).

We included 126 total duck flock transits in the radar evaluation, of which 85 (67%) were tracked at least once. The percentage of duck flocks tracked at least once also increased significantly ($Z = 4.11$, $P < 0.001$) with increasing flock size (Table 2). The relationship between this measure and distance from the radar was not significant ($Z = 1.77$, $P = 0.077$), but showed a tendency to increase at greater distances. The trends observed for duck flocks largely matched those for crane and goose flocks, but the ducks were tracked less often than the others, especially in smaller groups.

The average percentage of time that duck flocks were tracked (Fig. 3C) increased with increasing flock size ($F = 19.83$, df = 2,120, $P < 0.001$), and was generally greater farther from the radar ($F = 4.33$, df = 1,120, $P = 0.040$). On average, duck flock transits were 62 s (SD = 39.3) in length

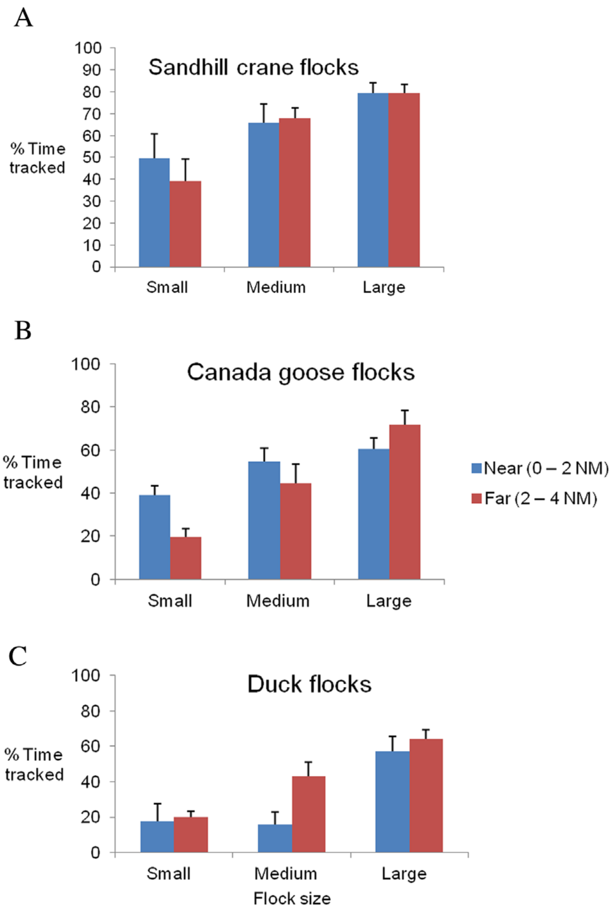

Figure 3. The average percentage of time that sandhill crane (A), Canada goose (B), and duck (C) flocks were tracked by the horizontal scanning radar at an airport environment in Indiana, USA, during October 2011–March 2012 as a function of distance and flock size. Mean values and standard errors are plotted. Flock sizes are define as follows: small (1–10 birds), medium (11–29 birds), and large (≥30 birds). NM, nautical miles.

(or 25 radar scans). Overall, the average percentage of time tracked was lower for duck flocks compared with that for crane and goose flocks (compare with Fig. 3A and B), likely reflecting the smaller body size of ducks. Typical track lengths for duck flocks were lower than those for crane and goose flocks, yet much higher than those for single raptors: 5–7 consecutive scans for small flocks, 6–8 scans for medium flocks, and 9–10 scans for large flocks (Gerringer 2013).

DISCUSSION

Our results demonstrate that the radar system is capable of tracking a large bird at distances out to 4 NM, but such targets were not tracked well (usually <50% of the time that targets were visible to field observers). In a study using a different radar system that employed a dish antenna (narrow beam system), there was a 49% probability that a vulture in the beam was tracked by the system within 3 NM (Beason et al. 2010; calculated using information supplied therein), which is comparable to our results. Work by Dokter et al. (2013) with a third radar system yielded roughly similar results, with a 50% probability of tracking single bird targets (several species of waterbirds) within 0.8 NM (1.5 km) of the radar unit. According to the FAA Advisory Circular on Avian Radar, in a moderate clutter environment (flat airport, no rain), avian radar systems must be capable of detecting a crow (*Corvus brachyrhynchos*) —sized target with a confidence level of 90% up to 1 NM and with a 75% confidence level from 1 NM to 3 NM to meet the requirements for use at commercial airports (Federal Aviation Administration 2010).

Flocks of relatively large birds were clearly more detectable than single raptors, especially Canada geese and sandhill cranes. Compared with single raptor targets, the sizes of targets represented by waterbird flocks are 1) much more likely to be tracked by the radar system, 2) more likely to be tracked at greater distances from the radar unit, and 3) tracked far more reliably. The radar system's greater ability to track flocks undoubtedly reflects the larger radar cross-section of flocks (Beason et al. 2013), which made them detectable well away from the radar unit despite their relatively low altitude. In fact, nearly every sandhill crane and Canada goose flock was tracked at least one time by the HSR, and such flocks were generally tracked 40–80% of the time that they were visible to field observers.

Avian radar has received much attention in recent years, but little work has been conducted to demonstrate how well such systems perform (Weber et al. 2005, Gauthreaux and Schmidt 2013), and peer- reviewed evaluations are rare (but see Beason et al. 2010, Dokter et al. 2013). Our results indicate that the DeTect Merlin avian radar system we tested can be useful for monitoring birds, but the system does not necessarily detect all targets nor does it always track them completely. Although our study evaluated only one of several avian radar systems currently marketed for use in monitoring birds at airports, wind farms, and other locations (Cooper 1996, Gauthreaux and Belser 2003, Gauthreaux and Schmidt 2013), nearly all avian radars share many common components, and a significant level of detection and tracking error is inherent in all of these systems (e.g., Beason et al. 2010, Dokter et al. 2013). Our radar unit was tested at one airport, but the landscape features and clutter environment at the Terre Haute International Airport are typical of many airports across the United States, and representative of airport environments in the midwestern United States. Therefore, we believe that our results are likely representative of other avian radar systems that are currently in use in similar environments.

Our results demonstrate that the radar system we tested is capable of detecting and tracking large flocking birds out to a distance of 4 NM, and likely at greater distances, given that such flocks were often tracked from the moment they entered the 4-NM radar-coverage area until the moment they exited. The HSR could, thus, be a useful tool for airports in assessing the daily movements of large flocking birds, or for airports that lie in the migration pathway of waterfowl species. Avian radar could also be useful for applications in which the desired information can be gained without detecting the majority of avian targets, such as determining the general flight patterns of birds moving through wind farms (Desholm and Kahlert 2005, Fijn et al. 2015), identifying habitat features that serve as bird attractants on and near airports (Martin et al. 2011), and perhaps characterizing bird movement patterns during wildlife hazard assessments at airports (Dolbeer 2013). However, real-time tracking and warnings of single targets such as raptors and other species of concern at wind farms and airports are not likely a feasible option at this time given our results and those in Beason et al. (2010) and Dokter et al. (2013). Further evaluations such as ours will be important for determining the capabilities, limitations, and best uses for avian radars deployed at airports and other areas where bird monitoring is needed.

ACKNOWLEDGMENTS

We thank many people who helped with this project. P. Schmidt laid the early groundwork for the radar evaluation. Our technicians J. Kesner and J. Bodwell operated the radar system with great attention to detail. W. Mitchell provided advice on our statistical analyses. T. West from DeTect, Inc. was instrumental in teaching us how to operate the Merlin System. J. Beasley and the other security personnel at the Terre Haute International Airport helped immensely by securing a location for the radar and allowing access to the airport on a daily basis. The U.S. Federal Aviation Administration (FAA) provided funding and support. Opinions expressed in this study do not necessarily reflect current FAA policy decisions governing the control of wildlife on or near airports. We thank three anonymous reviewers and R. E. Kissell, Jr. for helpful comments on the manuscript.

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Associate Editor: Kissell Jr.