2018

Efficacy of Avian Radar Systems for Tracking Birds on the Airfield of a Large International Airport

Adam C. Phillips
USDA APHIS Wildlife Services

Siddhartha Majumdar
University of Illinois at Urbana-Champaign

Brian E. Washburn
APHIS, brian.e.washburn@aphis.usda.gov

David Mayer
University of Illinois at Urbana-Champaign

Ryan M. Swearingin
USDA APHIS Wildlife Services

See next page for additional authors

Authors
Adam C. Phillips, Siddhartha Majumdar, Brian E. Washburn, David Mayer, Ryan M. Swearingin, Edwin E. Herricks, Travis L. Guerrant, Scott F. Beckerman, and Craig K. Pullins

Wildlife Society Bulletin 42(3):467–477; 2018; DOI: 10.1002/wsb.910

Original Article

Efficacy of Avian Radar Systems for Tracking Birds on the Airfield of a Large International Airport

ADAM C. PHILLIPS, *U.S. Department of Agriculture, Animal and Plant Health Inspection Service, Wildlife Services, 3430 Constitution Drive, Suite 121, Springfield, IL 62711, USA*

SIDDHARTHA MAJUMDAR, *University of Illinois at Urbana-Champaign, 205 N Mathews Avenue, Urbana, IL 61801, USA*

BRIAN E. WASHBURN,[1] *U.S. Department of Agriculture, Animal and Plant Health Inspection Service, Wildlife Services, National Wildlife Research Center, 6100 Columbus Avenue, Sandusky, OH 44870, USA*

DAVID MAYER, *University of Illinois at Urbana-Champaign, 205 N Mathews Avenue, Urbana, IL 61801, USA*

RYAN M. SWEARINGIN,[2] *U.S. Department of Agriculture, Animal and Plant Health Inspection Service, Wildlife Services, 3430 Constitution Drive, Suite 121, Springfield, IL 62711, USA*

EDWIN E. HERRICKS, *University of Illinois at Urbana-Champaign, 205 N Mathews Avenue, Urbana, IL 61801, USA*

TRAVIS L. GUERRANT, *U.S. Department of Agriculture, Animal and Plant Health Inspection Service, Wildlife Services, 3430 Constitution Drive, Suite 121, Springfield, IL 62711, USA*

SCOTT F. BECKERMAN, *U.S. Department of Agriculture, Animal and Plant Health Inspection Service, Wildlife Services, 3430 Constitution Drive, Suite 121, Springfield, IL 62711, USA*

CRAIG K. PULLINS, *U.S. Department of Agriculture, Animal and Plant Health Inspection Service, Wildlife Services, O'Hare International Airport, AMC Building, Room 421, Chicago, IL 60666, USA*

ABSTRACT Avian radar technologies have the potential to serve an important role in the quantification of bird movements and determining patterns of bird use in areas where human–wildlife conflicts might occur (e.g., airports, wind-energy facilities). However, capabilities and limitations of these technologies are relatively unknown and ground-truthing studies are needed to help wildlife managers understand the biological meaning of radar information. We evaluated the efficacy of 3 X-band marine radar sensors for tracking birds and flocks of birds observed on the airfield at Chicago's O'Hare International Airport, USA, during March 2011–November 2012. We used specific information regarding field observations of birds or flocks to determine how frequently the 3 radar sensors provided corresponding tracks of these avian targets. In addition, we examined various factors to determine if they had any influence on the frequency of correspondence between visual observations and radar tracks. Of the 972 sightings of individual birds (49%) or flocks of birds (51%) by observers on the airfield that had the potential to be observed by the radar, 143 (15%) were tracked by $\geq$1 radar sensor. All confirmed tracks of individual birds or flocks were $\leq$4.8 km from these radars. Among the 3 radar sensors, larger bodied bird species, bird/flocks flying at higher altitudes, and bird/flocks closer to the radars increased the ability of those units to track avian targets. This study provides new information regarding the performance of radar systems for tracking birds on the airfield of one of the largest and busiest airports in the world. Published 2018. This article is a U.S. Government work and is in the public domain in the USA.

KEY WORDS airports, airport wildlife management, avian radar systems, birds, human–wildlife conflicts, wildlife strikes.

Radar technologies have been used to track bird movements for many decades (Lack and Varley 1945, Eastwood 1967). Military and civilian radar systems and networks have been used in many studies to examine movement patterns of numerous bird species in a variety of environments (Cooper et al. 1991, Hamer et al. 1995, Bertram et al. 1999, Deng and Frederick 2001, Gauthreaux and Schmidt 2013). In recent years, advances in information technology and automated processing of large digital data sets have led to the development of several commercially available avian radar systems. These are essentially marine radar systems with customized antennae, transceivers, and processing software designed for tracking individual or groups of birds to a distance of up to 20 km (12.4 mi) from the radar (Beason et al. 2013, Gauthreaux and Schmidt 2013). There is considerable interest in using avian radar systems to gain ornithological information associated with contemporary

Received: 31 August 2017; Accepted: 2 July 2018
Published: 21 September 2018

[1]*E-mail: brian.e.washburn@aphis.usda.gov*
[2]*Present Address: Illinois Department of Natural Resources, Springfield, IL 62711, USA.*

human–wildlife conflicts, including bird mortalities associated with wind-energy development (Harmata et al. 1999, Desholm and Kahlert 2005, Krijgsveld et al. 2009, May et al. 2017) and human safety concerns associated with wildlife–aircraft collisions (wildlife strikes [van Belle et al. 2007, Coates et al. 2011, Gerringer et al. 2016]).

Wildlife strikes (of which 96% involve birds) pose increasing risks and economic losses to aviation worldwide (Dolbeer et al. 2016). Annual economic losses from such strikes with civil aircraft are conservatively estimated to exceed US$1.2 billion worldwide and US$690 million in the United States alone (Allan 2002, Dolbeer et al. 2016). Methods of detecting the presence of, and trends in, wildlife hazardous to aviation within the airport environment are essential for the deployment of effective management techniques to reduce hazardous wildlife in and around airports (DeVault et al. 2013).

Avian radar systems might be effective in providing information regarding bird activity on a continual basis during both diurnal and nocturnal periods (Brand et al. 2011, Coates et al. 2011, Beason et al. 2013). Such information could be used in real-time to notify air traffic controllers and, consequently, aircraft of potential bird hazards; allow for the timely deployment of airport personnel to disperse or remove the hazard; and provide spatial and temporal trends in hazardous wildlife activity (Federal Aviation Administration 2010, Nohara et al. 2011, Beason et al. 2013, Gauthreaux and Schmidt 2013). Although avian radar systems have many apparent advantages, many aspects of the new technology remain poorly understood and relatively unevaluated (Gauthreaux and Schmidt 2013).

Few published studies have investigated the ability of radar to detect avian targets and what factors may influence target tracking, particularly within actual airport environments. The Integration and Validation of Avian Radar Project provided estimates of the proportion of radar tracks that were actual birds, as confirmed by field observers (Brand et al. 2011). Of 2,632 tracked radar targets that were potentially birds, an average of 62% (range = 34–77%) were confirmed to be birds by ground observers. Gerringer et al. (2016) evaluated the ability of a commercially available radar (i.e., Merlin Aircraft Birdstrike Avoidance Radar™; DeTect, Inc., Panama City, FL, USA) to track avian targets near an airport. These researchers reported that the avian radar detected and tracked single, large bird targets <30% of the time, whereas flocks of large birds were detected and tracked 40–80% of the time. Clearly, further evaluations of the efficacy of avian radar systems for detecting and tracking birds/bird flocks on or near civil airports and military airfields are needed.

We used an evaluation approach similar to Dokter et al. (2013), in that we used 2 independent data sets, one of ground-based field observations of individual birds and bird flocks and the other a set of radar tracks, to determine the proportion of related observations between the 2 methods. Our objectives were to 1) investigate the ability of commercially produced avian radar systems to track birds in a large, complex airport environment, and 2) determine which variables influenced the ability of these radars to track avian targets.

STUDY AREA

Data collection took place at Chicago's O'Hare International Airport (ORD) in Chicago, Illinois, USA, from March of 2011 through November of 2012. The airport (41°58′43″N, 87°54′17″W) was operated by the Chicago Department of Aviation and encompassed approximately 2,950 ha (Chicago Department of Aviation 2014). In 2010, there were >67 million passengers and 882,612 aircraft operations at the airport, making ORD one of the largest and busiest civilian airports in the world (McMillen 2004, Airports Council International 2011).

The airport property consisted of a variety of land covers, including pavement–buildings (1,281 ha), grasslands (1,375 ha), areas under construction (232 ha), and forest–shrublands (24.7 ha). In addition, numerous water features (e.g., retention ponds) and drainage areas were distributed throughout the ORD airfield (Chicago Department of Aviation 2014). These vegetation types typically attract many types of wildlife that were hazardous to aviation safety, most notably raptors (e.g., hawks and owls), gulls, and waterfowl. Mean annual precipitation at the study area was 930 mm/year, with 56% typically falling as snow during October–April (Calsyn et al. 2012). Average daily temperatures were 22.2° C during summer and −4.1° C during winter.

METHODS

Avian Radar Systems

Our study used Accipiter® avian radar (AR) units acquired from Accipiter Radar Technologies, Inc. (ARTI; Fonthill, ON, Canada). These radars consisted of a Furuno® 8252 X-band marine radar (Foruno Electric Company Ltd., Nishinomiya City, Japan). One radar sensor, designated as avian radar 1 (AR1) was equipped with a parabolic dish antennae set at 2° above the horizon. The second radar sensor was equipped with a parabolic dish set at 4° (AR2-1), and the third sensor's parabolic dish was set at 8° above the horizon (AR2-2). The altitude setting of these sensors allowed for more altitudinal coverages (Fig. 1). The 3 radar sensors were mounted on top of 2 portable radar trailers (i.e., 2 sensors on one trailer and the third sensor on the second trailer), elevating them approximately 2.5 m above the ground. Each dish antenna was set to rotate at 24 revolutions/minute (~1 rotation/2.5 s). The radar sensors operated almost continuously during March 2011–November 2012, except for short periods of time when equipment maintenance and repair was necessary. The AR1 and AR2-2 radar sensors were operated in short pulse mode (<1 μs), whereas the AR2-1 was in long pulse mode (>1 μs; which increases range of detection) for the duration of the study. According to the radar company that provided the units, individual large birds, and bird flocks are detected out to distances of 11 km from the radars (Weber et al. 2005).

Prior to the beginning of data collection, a team from the University of Illinois Center for Excellence in Aviation Technology and ARTI came to ORD to assist us in identifying the optimal location for the radars. The team investigated 21 potential locations and selected the final

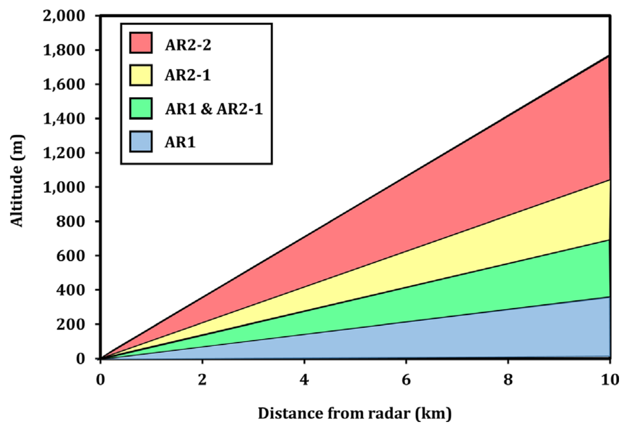

Figure 1. Graphical representation of the beam geometry of the AR1, AR2-1, and AR2-2 radar sensors used during a study at Chicago's O'Hare International Airport, Chicago, Illinois, USA, during March 2011–November 2012.

location based on local clutter environments, coverage of nearby runways, and availability of utilities necessary to operate the systems. The radar trailers were located next to each other on the northwestern side of the airfield (41.993163, −87.934061; Fig. 2).

The radars used Tracker.exe Software® (Version 6.7.7.7; Accipiter Radar Technologies, Inc., Fonthill, ON, Canada) to identify and display radar targets. A filter was installed to censor echoes that were traveling faster than a speed of 40 m/s (~90 miles/hr) to exclude fixed- and rotary-wing aircraft. When the radar received an echo from a potential avian target, it was recorded as a plot. If that same echo was recorded on the next 3 antenna revolutions, the plot was then recorded as a track, assigned an identifier, and the target was tracked until an echo was no longer detected. Information collected from such echoes included: time of observation (GMT), distance from radar (m), speed of target (m/s), heading of target (°), and altitude above ground level (m AGL). Radar plots and tracks were simultaneously displayed on a screen in the radar trailers and automatically saved onto a computer hard drive for subsequent analyses.

Airfield Bird Observations

We conducted field observations of birds on the ORD airfield during March 2011–November 2012. Wildlife Services' biologists and specialists (hereafter, "observers") recorded information related to birds that were observed at altitudes that should have been visible to the radars. Prior to data collection, observers were trained on estimating altitude

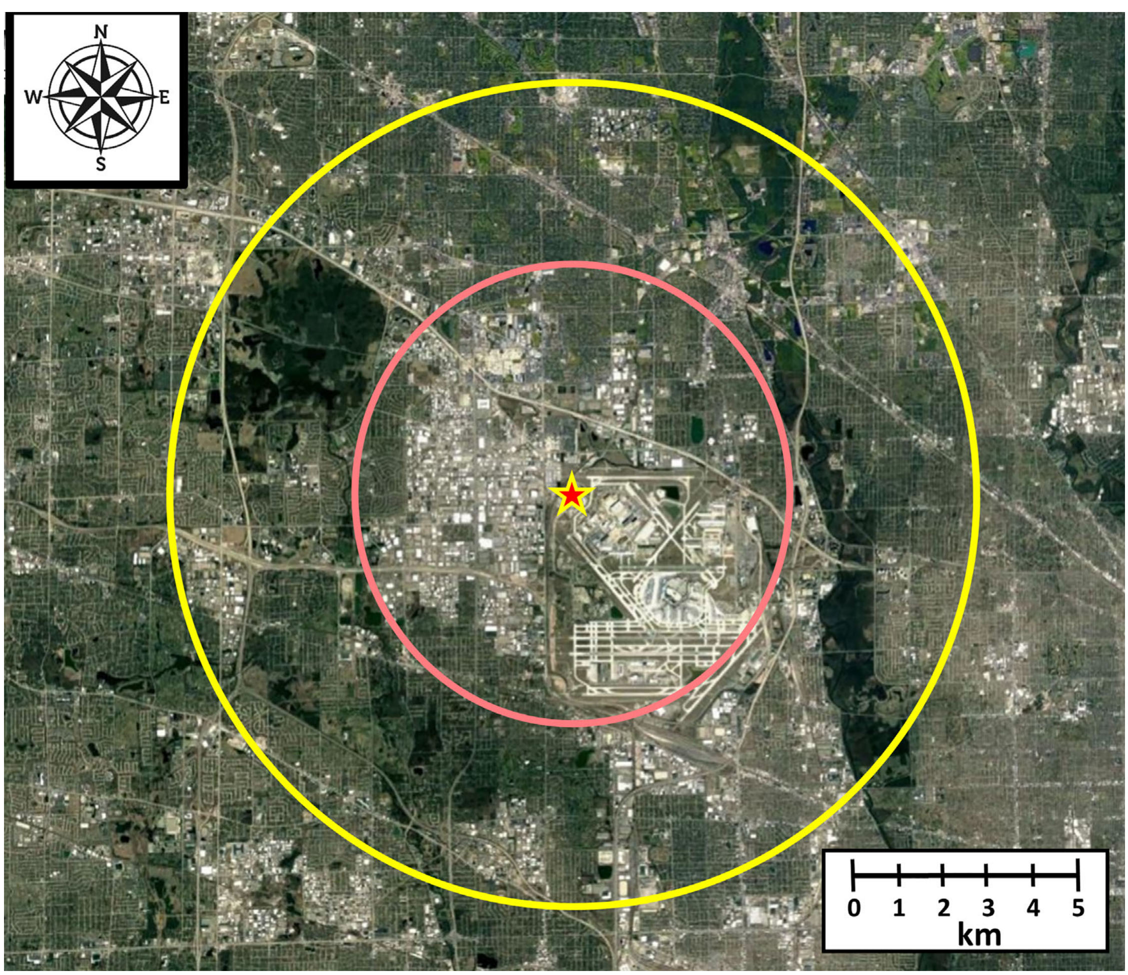

Figure 2. Location of the 3 radar sensors (designated by a star) in relation to the airfield at Chicago's O'Hare International Airport, Chicago, Illinois, USA. The circular lines represent an area around the radars with a 5-km radius (denoted in pink) and an area with a 10-km radius (denoted in yellow) during March 2011–November 2012.

and distance to an individual bird or flock of birds (i.e., $\geq$2 birds). Observers were taken into the area where avian targets would be tracked and determined the distance and altitude of landmarks on or near the airfield. Observers used these landmarks in the estimation of the altitude and distance (from observer) of birds and flocks. To obtain accurate time information, observers used atomic watches that synched to the atomic clock in Fort Collins, Colorado, USA, via radio signals. Observers used rangefinders for distance to a bird or flock (i.e., range) estimation, and binoculars to assist with bird species identification.

Observers determined whether the bird or flock was at an altitude that could be observed by the radars and also if the bird or flock was in the area long enough to create a track. A track was not created until the fourth echo detection, and the dish rotates once every 2.5 s; therefore, an avian target must be in the radar beam for $\geq$10 s to create a track. Observations were recorded for any birds or flocks of birds that met these criteria.

During the course of their normal wildlife-hazard-management activities, when an observer identified a bird or flock that should have been visible to the radars, data related to the observation were collected for that target. These data included date, observation start and end time (to the nearest s), Global Positioning System location of observer, species of bird(s), number of birds (i.e., flock size), estimated bird or flock altitude (m), estimated bird or flock heading (°), bearing to bird or flock from the observer (°), estimated distance to the bird or flock (m), and current weather conditions. Observers entered all data into an electronic database and censored any incomplete or suspicious accounts.

Comparison of Airfield Bird Observations and Radar Tracks

We processed radar data obtained from the digital radar processor at ORD using the Trackdataviewer.exe® software to produce data files in a comma-separated values (CSV) format for further analyses. We compared radar and observer data using a stepwise filtering script written with Program R (R Core Team 2015). This script greatly reduced the time needed to conduct the analyses, allowed buffers to be built into some parameters, and reduced the potential for human error. We conducted quality control efforts to ensure the script was functioning correctly. When building the script that Program R would use to associate radar and observational data, we built several buffers to address any bias associated with observer error. For example, the program analyzed radar data from 10 s before to 10 s after each airfield bird observation. An observer field of view of $\pm 30°$ was established around the estimated bearing from the observer to account for observer error related to estimating the location of the bird or flock. We used a buffer of $\pm 45°$ to account for potential inaccuracies in the estimation of the target's heading. In cases where the bird or flock was located directly overhead of the observer, we included all radar tracks within 100 m of the observer. Based on these buffers, Program R produced a figure that displayed the observer location, the observer's field of view, and any radar tracks that were in the area simultaneously with each bird or flock observation. We excluded any airfield bird observations (and the corresponding radar data) that occurred during precipitation events (e.g., rain, snow) from the data set prior to analysis because radar systems are unable to track birds during such events as a result of precipitation-induced clutter (Saxton and Hopkins 1951, Gauthreaux and Schmidt 2013).

We filtered radar data based on time, observer field of view, target heading, and range from observer to search for potential radar data matches with observer data. When compared with observational data, we classified radar tracks as either "NO_MATCH" (coded as 0) for instances in which an observer reported a bird or flock of birds that could have potentially been tracked by radar but no radar data were correlated to that observation, or "MATCH" (coded as 1) in which a radar track (presumed to be the avian target) was tracked within the buffers of the field observation. We then saved these data as CSV files that could be reviewed for quality assurance.

Statistical Analyses

Radar tracks (matching) was a binary response variable, with 0 representing instances in which an observer reported a bird or flock of birds that could have potentially been tracked by radar but no radar data were correlated with that observation and 1 representing a radar track (presumed to be the avian target) that was tracked within the buffers of the field observation. We developed a set of candidate models and then ranked those models using Akaike's Information Criterion adjusted for small sample size (AIC_c; Burnham and Anderson 2002). We used binomial logistic regression in Program R Version 3.2.1 (R Core Team 2015) to model radar tracks (matching) as a function of 4 fixed factors: Flock Size (i.e., the no. of birds), Altitude (i.e., the estimated flight altitude of the bird or flock), Distance (i.e., the estimated distance of the bird or flock from the radar unit), and Month (i.e., the month of the observation). We built regression models only for the species with >200 field observations (i.e., red-tailed hawks [*Buteo jamaicensis*] and Canada geese [*Branta canadensis*]) and for all species combined. We built logistic regression models for each of the 3 radar sensors independently. We considered models with $\Delta AIC_c \leq 2$ to be competing candidate models (Burnham and Anderson 2002). We used model-averaging techniques using the R package AICcmodavg (Mazerolle 2015) to generate model-averaged parameter estimates for all models that had an $AIC_c < 10$ from the top model (Symonds and Moussaili 2011). We developed effect plots for variables that were important in influencing the performance of the AR1, AR2-1, and AR2-2 radars for red-tailed hawks, Canada geese, and all birds (combined) independently (Fox 2003).

RESULTS

Observers on the airfield made 1,052 observations of birds or flocks of birds that were in a location that had the potential to be "matched" with a radar track from one or more of the radars. We removed 80 of these bird or flock observations because they occurred during precipitation events. In addition, bird observations were removed that occurred when one of the radar systems or sensors was not working (e.g., it was being repaired), which resulted in 959, 946, and 870 bird or flock observations that could have been tracked by the AR1 radar sensor, the AR2-1 radar sensor, and the AR2-2 radar sensor, respectively. There were 972 bird or flock observations that could have been tracked by ≥1 of the radar sensors. Bird or flock observations were located at distances of 0.1 to 9.2 km from these radars.

Twenty-eight different bird species were present within the 972 bird or flock airfield observations. Red-tailed hawk, Canada goose, and mallard (*Anas platyrhynchos*) were the most frequently observed bird species, accounting for approximately two-thirds of the total bird or flock observations (Table 1). Overall, 476 (49%) of these observations involved single birds, whereas 496 (51%) involved a flock of ≥2 birds. Across species, the average flock size per observation was 23 birds. Looking specifically at the species most observed, red-tailed hawks were observed as single birds in 90% of observations, whereas Canada geese and mallards were most often observed in flocks (91% and 92%, respectively).

Overall Radar Performance

Of the 972 bird or flock observations from the airfield that should have been visible to the radar sensors, 143 of these bird movements were tracked by ≥1 of the radar sensors (15%; Table 1). Overall, 12% of individual birds and 17% of bird flocks that were observed in the field were successfully tracked by ≥1 of the radar sensors. Confirmed tracks of bird or flocks were from 0.1 km to 4.8 km from the radars. When we considered each of the radar sensors independently, the AR1 radar sensor had twice as many confirmed tracks of bird or flocks when compared with the AR2-1 and AR2-2 sensors (Table 1). The majority of the birds observed, as well as those tracked by the radar sensors, were medium to large in body size (Table 1). Bird species influenced the tracking rates provided by the radars. Red-tailed hawks were tracked by ≥1 the radar sensors 16% of the times they were observed, Canada geese were tracked 26% of the times they were observed, and mallards were tracked 4% of the times they were observed (Table 1). Other field observations were distributed among the remaining 26 bird species and tracking rates by the radar sensors ranged from 0% to 13%.

Factors Influencing AR1 Performance (2°)

The AR1 radar was a parabolic dish antennae set at 2° above the horizon. Factors influencing the percentage of tracking events, where bird or flocks were tracked by the AR1 unit, varied among the bird species being observed. When we considered only red-tailed hawks, the top-ranked model (with Akaike weight $[w_i] = 0.38$) included distance as the only important factor that influenced the performance of the AR1 radar (Table 2). The nearest competing model (with w_i of 0.19) also included distance and was within <2 ΔAIC_c units of the top model. As distance of the hawk or hawks from the AR1 unit increased, the percentage of successful tracking events decreased (Table 3 and Fig. 3). For Canada geese, the top-ranked model (with $w_i = 0.45$) included flock size as the only important factor that influenced the performance of the AR1 radar (Table 2). The larger the goose flock size the greater percentage of successful tracking events (Table 3 and Fig. 3). When all birds combined were examined, the top-ranked model (with $w_i = 0.32$) included distance and flock size as important factors that influenced the performance of the AR1 radar (Table 2). The nearest 2 competing models (with w_i of 0.19 and 0.19) also included one or both of these variables and were within approximately 1 ΔAIC_c unit from the top model. The radar was more successful at making corresponding radar tracks with larger flocks of birds that were closer to the radar (Table 3 and Fig. 3).

Table 1. The number (and percentage) of field observations of a bird or flocks of birds that corresponded to a radar observation, by species, during a study at the Chicago (IL) O'Hare International Airport, Chicago, Illinois, USA, during March 2011–November 2012. Samples sizes are presented in parenthesis after each species.

	Radar sensor			
Species	**AR1**	**AR2-1**	**AR2-2**	**Any radar (≥1)**
Red-tailed hawk (*Buteo jamaicensis*; $n = 305$)	40 (13.1%)	15 (5.0%)	15 (5.0%)	50 (16.4%)
Canada goose (*Branta canadensis*; $n = 237$)	45 (19.0%)	25 (10.5%)	23 (9.7%)	61 (25.7%)
Mallard (*Anas platyrhynchos*; $n = 83$)	2 (2.4%)	0 (0.0%)	1 (1.2%)	3 (3.6%)
European starling (*Sturnus vulgaris*; $n = 67$)	8 (11.9%)	2 (3.0%)	4 (6.0%)	9 (13.4%)
Great blue heron (*Ardea herodias*; $n = 67$)	7 (10.4%)	1 (1.5%)	2 (3.0%)	7 (10.4%)
Ring-billed gull (*Larus delawarensis*; $n = 47$)	1 (2.1%)	0 (0.0%)	0 (0.0%)	1 (2.1%)
Rock pigeon (*Columba livia*; $n = 35$)	3 (8.6%)	0 (0.0%)	0 (0.0%)	3 (8.6%)
Great egret (*Ardea alba*; $n = 23$)	0 (0.0%)	1 (4.3%)	0 (0.0%)	1 (4.3%)
Killdeer (*Charadrius vociferus*; $n = 21$)	0 (0.0%)	0 (0.0%)	0 (0.0%)	0 (0.0%)
Other birds combined[a] ($n = 87$)	4 (4.6%)	1 (1.1%)	4 (4.6%)	8 (9.2%)
All species combined ($n = 972$)	120 (12.3%)	45 (4.6%)	49 (5.0%)	143 (14.7%)

[a] Other birds included: American crow (*Corvus brachyrhynchos*; $n = 1$), American kestrel (*Falco sparverius*; $n = 19$), barn swallow (*Hirundo rustica*; $n = 13$), cliff swallow (*Petrochelidon pyrrhonota*; $n = 1$), double-crested cormorant (*Phalacrocorax auritus*; $n = 11$), green heron (*Butorides virescens*; $n = 2$), herring gull (*Larus smithsonianus*; $n = 2$), house sparrow (*Passer domesticus*; $n = 1$), lesser scaup (*Aythya affinis*; $n = 2$), mixed flock (>1 species flying together; $n = 6$), mourning dove (*Zenaida macroura*; $n = 9$), osprey (*Pandion haliaetus*; $n = 1$), peregrine falcon (*Falco peregrinus*; $n = 1$), rough-legged hawk (*Buteo lagopus*; $n = 5$), red-winged blackbird (*Agelaius phoeniceus*; $n = 3$), sandhill crane (*Grus canadensis*; $n = 1$), short-eared owl (*Asio flammeus*; $n = 1$), snow bunting (*Plectrophenax nivalis*; $n = 1$), tree swallow (*Tachycineta bicolor*; $n = 1$), turkey vulture (*Cathartes aura*; $n = 5$), and unknown species ($n = 1$).

Table 2. Top-ranked logistic regression models of 2 bird species (red-tailed hawk and Canada goose) and all bird species (combined) among 3 radar sensors (AR1, AR2-1, and AR2-2), ranked by Akaike's Information Criterion adjusted for small sample size (AIC_c), predicting radar track (matching with visual observations of birds or flocks) during a study at the Chicago (IL) O'Hare International Airport, Chicago, Illinois, USA, during March 2011–November 2012.

Model[a]	K[b]	LL[c]	AIC_c[d]	$\triangle AIC_c$[e]	w_i[f]	Cumulative AIC_c weight
AR1 radar						
Red-tailed hawk						
Distance	2	−112.16	228.37	0.00	0.38	0.38
Distance + Month	3	−111.80	229.69	1.32	0.19	0.57
Canada goose						
Flock size + Distance	3	−105.51	217.12	0.00	0.45	0.45
All species combined						
Flock size + Distance	3	−331.00	668.04	0.00	0.32	0.32
Flock size + Altitude + Distance	4	−330.54	669.12	1.08	0.19	0.51
Distance	2	−332.55	669.12	1.09	0.19	0.70
AR2–1 radar						
Red-tailed hawk						
Distance	2	−56.74	117.52	0.00	0.39	0.31
Flock size + Month	3	−56.44	118.96	1.44	0.15	0.46
Distance + Month	3	−56.71	119.50	1.98	0.11	0.57
Canada goose						
Altitude + Distance + Month	4	−61.61	131.40	0.00	0.59	0.59
Flock size + Altitude + Distance + Month	5	−61.12	132.51	1.11	0.34	0.93
All species combined						
Altitude + Distance + Month	4	−166.24	340.52	0.00	0.42	0.42
Distance + Month	3	−167.30	340.63	0.11	0.40	0.81
Flock size + Altitude + Distance + Month	5	−166.17	342.41	1.89	0.16	0.98
AR2–2 radar						
Red-tailed hawk						
Distance	3	−74.95	99.94	0.00	0.33	0.33
Flock size + Distance	3	−47.43	100.96	1.02	0.20	0.52
Altitude + Distance	3	−47.74	101.57	1.63	0.14	0.66
Distance + Month	3	−47.75	101.59	1.65	0.14	0.81
Canada goose						
Altitude + Distance + Month	4	−58.54	125.28	0.00	0.32	0.32
Flock size + Altitude + Distance + Month	5	−57.80	125.88	0.61	0.23	0.55
Altitude + Distance	3	−60.29	126.69	1.41	0.16	0.71
Flock size + Altitude + Distance	4	−59.25	126.69	1.41	0.16	0.87
All species combined						
Distance + Month	3	−168.92	343.86	0.00	0.23	0.23
Altitude + Distance + Month	4	−167.94	343.92	0.06	0.23	0.46
Altitude + Distance	3	−169.37	344.77	0.91	0.15	0.61
Distance	2	−170.45	344.90	1.04	0.14	0.75
Flock size + Altitude + Distance + Month	5	−167.61	345.29	1.42	0.11	0.86

[a] Radar system × species × model parameter(s).
[b] No. parameters in model.
[c] LL, log likelihood.
[d] Akaike's Information Criterion adjusted for small sample sizes.
[e] Difference in AIC_c compared with lowest AIC_c model.
[f] Model weight.

Factors Influencing AR2-1 Performance (4°)

The AR2-1 radar was a parabolic dish antennae set at 4° above the horizon. As with the AR1 unit, factors influencing the percentage of tracking events, where bird or flocks were tracked by the AR2-1 radar, varied among the bird species being observed. For red-tailed hawks, the top-ranked model (with $w_i = 0.39$) included distance as the only important factor that influenced the performance of the AR2-1 radar (Table 2). The nearest 2 competing models (with w_i of 0.15 and 0.11) were within <2 ΔAIC_c units of the top-ranked model, one of which included distance. However, upon review of the model-averaged parameter estimates, it would appear that no variables had a significant effect on the tracking ability of the AR2-1 unit (Table 2 and Fig. 3). When considering Canada geese, the top-ranked model (with $w_i = 0.59$) included 3 variables (altitude, distance, and month) as important factors that influenced the performance of the AR1 radar (Table 2). The nearest competing model (with w_i of 0.34) also included these 3 variables and was within <2 ΔAIC_c units of the top-ranked model. Canada geese flying at higher altitudes were tracked more frequently by the AR2-1 radar, as were geese that were closer to the radar unit (Table 3 and Fig. 3). During January and February, the tracking ability of the AR2-1 appears to be much greater (33–50% of the visually observed single goose or goose flocks had corresponding radar tracks from that radar sensor) compared with the rest of the year (≤15%). When we considered all bird species combined, the top-ranked model (with $w_i = 0.42$) included 3 variables (altitude, distance, and month) as important factors that influenced the performance of the AR1 radar (Table 2). The nearest 2 competing models (with w_i of 0.40 and 0.16) also included these 2 or 3 of these

Table 3. Model-averaged parameter estimates with unconditional standard errors (SE) and 95% confidence intervals (LCL, UCL) for radar track (matching with visual observations of birds or flocks) during a study at Chicago's O'Hare International Airport, Chicago, Illinois, USA, during March 2011–November 2012.

Parameter[a]	Estimate	SE	LCL	UCL
AR1 radar unit				
Red-tailed hawk				
Intercept	−0.93	0.36	−2.11	1.18
Distance	−0.44	0.17	−0.77	−0.11
Canada goose				
Intercept	−1.31	0.42	−2.13	0.82
Flock size	0.02	0.01	0.01	0.04
All species combined				
Intercept	−1.66	0.22	−2.09	0.43
Distance	−0.18	0.08	−0.35	−0.02
AR2–1 radar unit				
Red-tailed hawk				
Intercept	−1.95	0.54	−3.00	1.06
Canada goose				
Intercept	0.65	0.87	−1.06	1.71
Altitude	0.01	0.01	0.00	0.03
Distance	−0.68	0.22	−1.12	−0.25
Month	−0.24	0.08	−0.39	−0.09
All species combined				
Intercept	−0.55	0.57	−1.67	1.12
Distance	−0.43	0.15	−0.72	−0.14
Month	−0.20	0.06	−0.32	−0.09
AR2–2 radar unit				
Red-tailed hawk				
Intercept	−0.86	0.60	−2.04	1.18
Distance	−1.21	0.41	−2.02	−0.4
Canada goose				
Intercept	0.70	0.94	−1.14	1.84
Altitude	0.01	0.01	0.00	0.02
Distance	−0.95	0.26	−1.46	−0.44
All species combined				
Intercept	−0.32	0.60	−1.50	1.18
Distance	−0.79	0.17	−1.13	−0.46

[a] Radar system × species × model parameter(s).

same variables and were within <2 ΔAIC_c units of the top-ranked model. However, upon review of the model-averaged parameter estimates, it would appear that distance was the only variable that had a significant effect on the tracking ability of the AR2-1 unit (Table 2 and Fig. 3).

Factors Influencing AR2-2 Performance (8°)

The AR2-2 radar was a parabolic dish antennae set at 8° above the horizon. Distance and altitude were the factors influencing the percentage of events where bird or flocks were tracked by the AR2-2 radar. When we considered only red-tailed hawks, the top-ranked model (with $w_i = 0.33$) included distance as the only important factor that influenced the performance of the AR2-2 radar (Table 2). The nearest 3 competing models (with w_i of 0.20, 0.14, and 0.14) were within <2 ΔAIC_c units of the top-ranked model; all of them included distance. As distance from the AR2-2 radar increased, the proportion of successful tracking events decreased (Table 2 and Fig. 3). For Canada geese, the top-ranked model (with $w_i = 0.32$) included 3 variables (altitude, distance, and month) as important factors that influenced the performance of the AR2-2 radar (Table 2). The nearest 3 competing models (with w_i of 0.23, 0.16, and 0.16) also included these 2 or 3 of these same variables and were within <2 ΔAIC_c units of the top-ranked model. A single Canada goose, and Canada goose flocks at higher altitudes, were tracked more frequently by the AR2-2 radar, as were geese that were closer to the radar unit (Table 2 and Fig. 3). When we considered all bird species combined, the top-ranked model (with $w_i = 0.23$) included 2 variables (distance and month) as important factors that influenced the performance of the AR2-2 radar (Table 2). The nearest 4 competing models (with w_i of 0.23, 0.15, 0.14, and 0.11) also included these same 2 variables and were within <2 ΔAIC_c units of the top model. However, upon review of the model-averaged parameter estimates, it would appear that distance was the only variable that had an effect on the tracking ability of the AR2-2 unit (Table 2 and Fig. 3).

DISCUSSION

The relative species composition of the field observation data set (and consequently the tracking data set provided by the radars) was representative of the avian community at ORD. Red-tailed hawks and Canada geese were the most commonly observed birds, and their abundance and relative large body mass (average of ~1.1 kg from red-tailed hawks [Preston and Beane 2009]; average of ~4.5 kg for Canada geese [Mowbray et al. 2002]) makes them a high risk for damaging bird strikes (Dolbeer and Wright 2009; DeVault et al. 2011, 2016). During 1990–2015, red-tailed hawks and Canada geese accounted for >US$155 million in reported costs, 92,325 hr of aircraft downtime, and were involved in 1,104 collisions with aircraft that resulted in damage (Dolbeer et al. 2016). In addition, the relatively large body mass of these 2 species also increases the ability of radar systems to detect them because of their relatively larger radar cross-section (Nohara et al. 2011).

Overall, the radar tracking rates for birds or flocks observed on the airfield were lower than we had expected based on the findings of other studies (Brand et al. 2011, Dokter et al. 2013, Gerringer et al. 2016). Airports are complex environments, with many objects (other than birds) in the air and many obstacles on the ground (e.g., terrain, terminal buildings, navigational aids) that can degrade the ability of a radar to track avian targets. Although other evaluations of avian radar performance were conducted within airport environments, the airfield at ORD is considerably larger (in area) and contains much more activity (e.g., ground vehicles and aircraft movements) than other airfields referenced in previous radar studies. We suspect the greater level of ground-level complexity resulted in more clutter interference and consequently lower tracking performance at the large, international airport. In addition, other studies focused all tracking evaluations upon a single trajectory of the radar beam, whereas this study encompassed the entire area of potential radar coverage (i.e., 360° around the radar sensors).

Our results demonstrate that the distance an individual bird or bird flock is from the radar unit has a strong influence on whether or not the radar sensor tracks that bird. Although the radar sensors we used were capable of tracking birds at relatively long distances (e.g., 4 km to 6 km from the radar sensor), these systems performed better

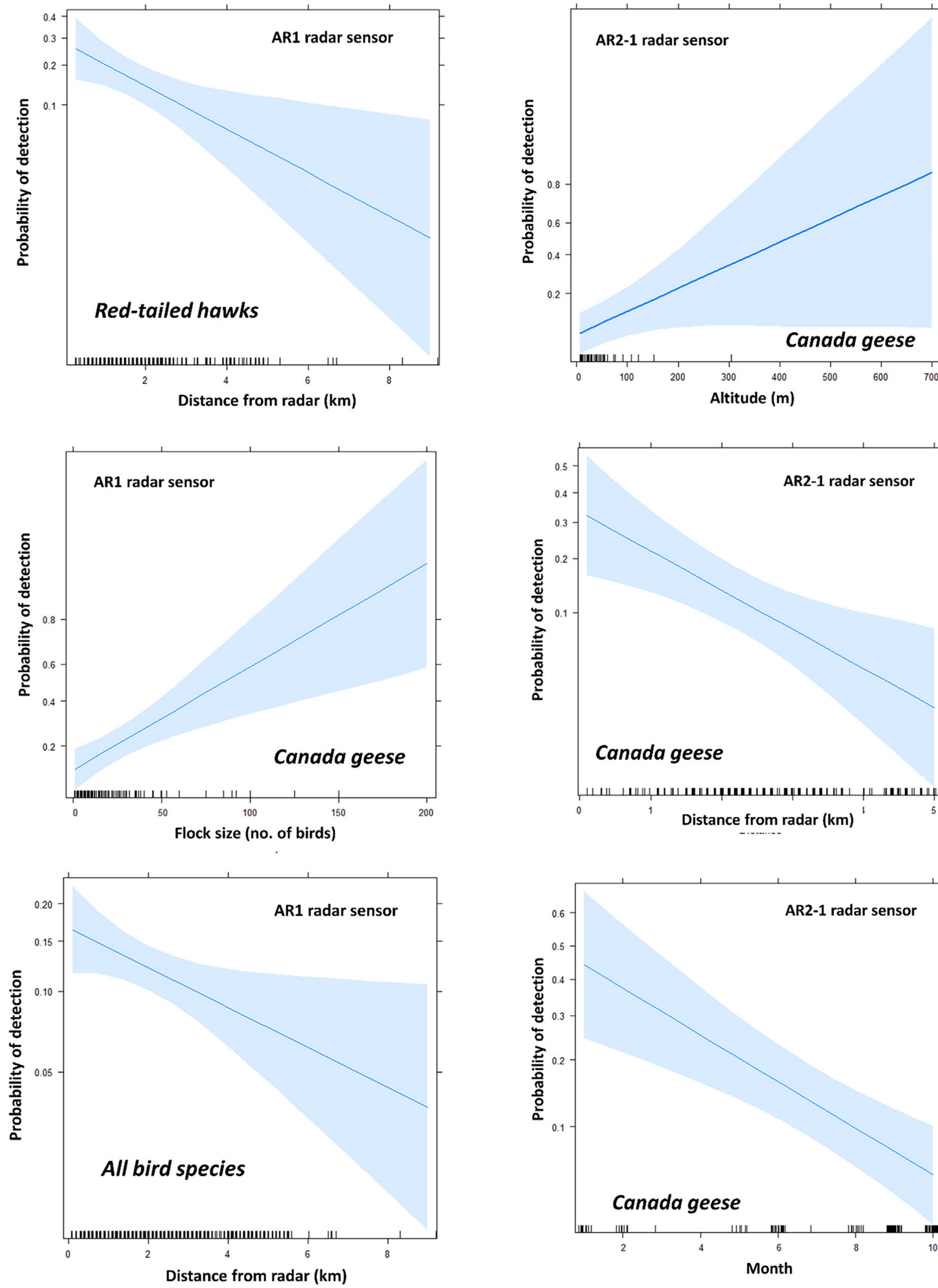

Figure 3. Effects plots for variables found to be important in influencing the performance of the AR1, AR2-1, and AR2-2 radars for red-tailed hawks, Canada geese, and all bird species (combined) during a study at Chicago's O'Hare International Airport, Chicago, Illinois, USA, during March 2011–November 2012.

when the bird or bird flock was closer (e.g., <2 km) to the radars. The AR1 radar sensor (set at 2° above the horizon) lost efficacy (i.e., was less likely to detect the observed bird[s]) when the bird or flock was ≥4 km from the radar, where the efficacy of the AR2-1 and AR2-2 radar sensors declined when the bird or flock was only ≥2 km from the radar. This finding might be due to beam geometry and the flight characteristics of birds at ORD. When the antenna is

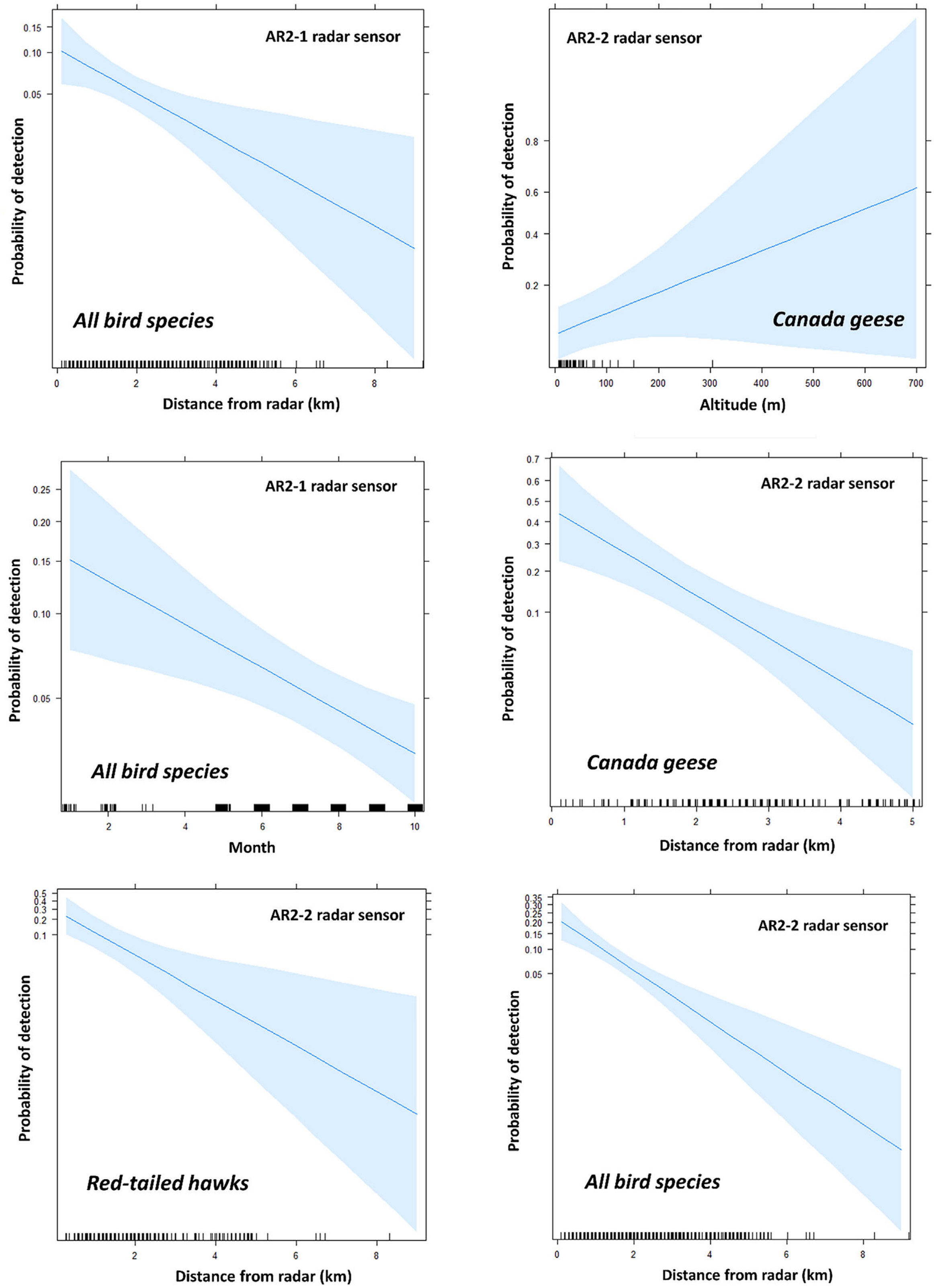

Figure 3. Cont. Effects plots for variables found to be important in influencing the performance of the AR1, AR2-1, and AR2-2 radars for red-tailed hawks, Canada geese, and all bird species (combined) during a study at Chicago's O'Hare International Airport, Chicago, Illinois, USA, during March 2011–November 2012.

set to 4° or 8°, the beam increases in altitude rapidly as it gets farther from the radar sensor. If birds typically fly at altitudes below the 4° and 8° radar beams, they would only be tracked when they are close to the sensor and intersect the beam at altitude. Gerringer et al. (2016) found that the efficacy of the radar system they evaluated decreased considerably when birds were >3.7 km from the radar. Similarly, in their evaluation of a different radar system in a marine environment, Dokter et al. (2013) reported its operational range for single waterbirds was 1.5 km from the radar unit. Based on the findings of these studies, we found similar results to the distance limitations of our radar systems in an airport environment.

Although the AR1 radar sensor's performance was not related to the flight altitude of the observed birds and flocks, this factor was very influential on the other 2 radar sensors (set at 4° and 8° above the horizon). We found that these 2 radar sensors were much more effective at tracking birds when their flight altitudes were >100 m (328 feet) above the ground. Poorer performance of these radars at flight altitudes below 100 m is likely due to beam geometry (that is birds need to fly higher into the radar beam for good tracking) and the fact that radars have difficulty in distinguishing avian targets from the background interference from ground clutter (Brand et al. 2011, Dokter et al. 2013). Given the complexity of the physical environment at ORD, we suspect ground clutter was an even more challenging factor during this study relative to other environments.

As mentioned earlier, it appeared that the AR2-1 radar confirmed field observations at a greater rate during January and February. One potential explanation for this could be the small sample sizes ($n = 9$ each month) during the winter compared with the autumn migration period ($n = 72$ in Sep and $n = 83$ in Oct).

MANAGEMENT IMPLICATIONS

Our study demonstrates that the efficacy of the 3 different radar sensors for tracking individual birds and bird flocks was influenced by several factors, including target altitude and distance from the radars. Wildlife managers intending to use avian radar to detect and track birds would likely find the best application of this tool by ensuring the radar system is located within 4 km of the landscape, habitat, or suspected bird movement corridor of interest. Additional well-designed scientific evaluations of these radar systems—as well as other commercially available avian radars—in a variety of physical environments (e.g., coastal locations, mountainous areas) is essential for fully understating and evaluating the use of avian radar systems (Federal Aviation Administration 2010) as part of integrated wildlife-damage-management programs to reduce the risk of bird–aircraft collisions and increase human safety.

ACKNOWLEDGMENTS

We thank the Federal Aviation Administration (FAA); the U.S. Department of Agriculture, Wildlife Services; and the University of Illinois at Urbana-Champaign for funding and support. Opinions expressed in this manuscript do not necessarily reflect current FAA policy decisions governing the control of wildlife on or near airports. In particular, we thank G. Martinelli, M. Rice, A. Spencer, J. Wisdom, and C. Mello for assistance in the field. In addition, the City of Chicago (Chicago's O'Hare International Airport) provided study site access and logistical support. We thank T. L. DeVault, Associate Editor Frank Thompson III, and 2 anonymous reviewers for their efforts to improve this manuscript.

LITERATURE CITED

Airports Council International. 2011. Passenger traffic 2010 final. Airports Council International, Montréal, Québec, Canada. http://www.aci.aero/Data'Centre/Annual-Traffic-Data/Passengers/2010-final. Accessed 2 Aug 2016.

Allan, J. 2002. The costs of bird strikes and bird strike prevention. Pages 147–155 *in* L. Clark, editor. Proceedings of the National Wildlife Research Center symposium. Human conflicts with wildlife: economic considerations. U.S. Department of Agriculture, National Wildlife Research Center, Fort Collins, Colorado, USA.

Beason, R. C., T. J. Nohara, and P. Weber. 2013. Beware the Boojum: caveats and strengths of avian radar. Human-Wildlife Interactions 7:16–46.

Bertram, D. F., L. Cowen, and A. E. Burger. 1999. Use of radar for monitoring colonial burrow-nesting seabirds. Journal of Field Ornithology 70:145–157.

Brand, M., G. Key, E. Herricks, R. King, J. T. Nohara, S. Gauthreaux Jr., M. Begier, C. Bowser, R. Beason, J. Swift, M. Klope, H. Griese, and C. Dotur. 2011. Integration and Validation of Avian Radars (IVAR). Environmental Security Technology Certification Program Final Report for Project SI—2000723. SPAWAR Systems Center-Pacific, San Diego, California, USA.

Burnham, K. P., and D. R. Anderson. 2002. Model selection and multimodel inference: a practical information-theoretic approach. Second edition. Springer, New York, New York, USA.

Calsyn, D. E., L. P. Reinhardt, K. A. Ryan, and J. L. Wollenweber. 2012. Soil survey of Cook County, Illinois. U.S. Department of Agriculture, Natural Resources Conservation Service, Washington, D.C., USA.

Chicago Department of Aviation. 2014. Chicago O'Hare International Airport wildlife hazard management plan. City of Chicago, Department of Aviation, Chicago O'Hare International Airport, Illinois, USA.

Coates, P. S., M. L. Casazza, B. J. Halstead, J. P. Fleskes, and J. A. Laughlin. 2011. Using avian radar to examine relationships among avian activity, bird strikes, and meteorological factors. Human-Wildlife Conflicts 5:249–268.

Cooper, B. A., R. H. Day, R. J. Ritchie, and C. L. Cranor. 1991. An improved marine radar system for studies of bird migration. Journal of Field Ornithology 62:367–377.

Deng, J., and P. Frederick. 2001. Nocturnal flight behavior of waterbirds in close proximity to a transmission power line in the Florida Everglades. Waterbirds 24:419–424.

Desholm, M., and J. Kahlert. 2005. Avian collision risk at an offshore wind farm. Biology Letters 1:296–298.

DeVault, T. L., J. L. Belant, B. F. Blackwell, and T. W. Seamans. 2011. Interspecific variation in wildlife hazards to aircraft: implications for airport wildlife management. Wildlife Society Bulletin 35:394–402.

DeVault, T. L., B. F. Blackwell, and J. L. Belant, editors. 2013. Wildlife in airport environments: preventing animal-aircraft collisions through science-based management. Johns Hopkins University Press, Baltimore, Maryland, USA.

DeVault, T. L., B. F. Blackwell, T. W. Seamans, and J. L. Belant. 2016. Identification of off airport interspecific avian hazards to aircraft. Journal of Wildlife Management 80:746–752.

Dokter, A. M., M. J. Baptist, B. J. Ens, K. L. Krijgsveld, and E. Emiel van Loon. 2013. Bird radar validation in the field by time-referenced line-transect surveys. PLoS ONE 8(9):e74129.

Dolbeer, R. A., and S. E. Wright. 2009. Safety management systems: how useful will the FAA National Wildlife Strike Database be? Human-Wildlife Conflicts 3:167–178.

Dolbeer, R. A., S. E. Wright, J. R. Weller, and M. J. Begier. 2016. Wildlife strikes to civilian aircraft in the United States 1990–2015. Federal Aviation Administration, Wildlife Aircraft Strike Database Serial Report Number 22. U.S. Department of Transportation, Federal Aviation Administration, Airport Safety, Washington, D.C., USA.

Eastwood, E. 1967. Radar ornithology. Meuthuen, London, England, United Kingdom.

Federal Aviation Administration. 2010. Airport avian radar systems. Advisory Circular 150/5200-25. U.S. Federal Aviation Administration, Washington, D.C., USA.

Fox, J. 2003. Effects displays in R for generalized linear models. Journal of Statistical Software 8:1–27.

Gauthreaux, S. A., Jr., and P. M. Schmidt. 2013. Application of radar technology to monitor hazardous birds at airports. Pages 141–151 *in* T. L. DeVault, B. F. Blackwell, and J. L. Belant, editors. Wildlife in airport environments: preventing animal–aircraft collisions through science-based management. Johns Hopkins University Press, Baltimore, Maryland, USA.

Gerringer, M. B., S. L. Lima, and T. L. DeVault. 2016. Evaluation of an avian radar system in a Midwestern landscape. Wildlife Society Bulletin 40:150–159.

Hamer, T. E., B. A. Cooper, and C. J. Ralph. 1995. Use of radar to study the movements of marbled murrelets at inland sites. Northwestern Naturalist 76:73–78.

Harmata, A. R., K. M. Podruzny, J. R. Zelenak, and M. L. Morrison. 1999. Using marine surveillance radar to study bird movements and impact assessment. Wildlife Society Bulletin 24:44–52.

Krijgsveld, K. L., K. Akershock, F. Schenk, F. Djik, and S. Dirksen. 2009. Collision risk of birds with modern large wind turbines. Ardea 97:357–366.

Lack, D., and G. C. Varley. 1945. Detection of birds by radar. Nature 156:446.

May, R., Y. Steinheim, R. Kvaløy, R. Vang, and F. Hannssen. 2017. Performance test of an off-the-shelf automated radar tracking system. Ecology and Evolution 7:5930–5938.

Mazerolle, M. J. 2015. AICcmodaveg: model selection and mulitmodel inference based on (Q)AIC(c), R package version 2. 0-3. Available at http://CRAN.R-project.org/package=AICcmodavg/. Accessed 15 Jun 2016.

McMillen, D. P. 2004. Airport expansions and property values: the case of Chicago's O'Hare Airport. Journal of Urban Economics 55:627–640.

Mowbray, T. B., C. R. Ely, J. S. Sedinger, and R. E. Trost. 2002. Canada goose (*Branta canadensis*). Account 682 *in* A. Poole and F. Gill, editors. The birds of North America. The Academy of Natural Sciences, Philadelphia, Pennsylvania; and The American Ornithologists' Union, Washington, D.C., USA.

Nohara, T. J., R. C. Beason, and P. Weber. 2011. Using radar cross-section to enhance situational awareness tools for airport avian radars. Human-Wildlife Interactions 5:210–217.

Preston, C. R., and R. D. Beane. 2009. Red-tailed hawk (*Buteo jamaicensis*). Account 682 *in* A. Poole and F. Gill, editors. The birds of North America. The Academy of Natural Sciences, Philadelphia, Pennsylvania; and The American Ornithologists' Union, Washington, D.C., USA.

R Core Team. 2015. R: a language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria. http://www.R-project.org/. Accessed 6 Jan 2017.

Saxton, J. A., and H. G. Hopkins. 1951. Some adverse influences of meteorological factors on marine navigational radar. Proceedings of the IEE—Part III: Radio and Communication Engineering 98:26–36.

Symonds, M. R. E., and A. Moussaili. 2011. A brief guide to model selection, multimodel inference, and model averaging in behavioural ecology using Akaike's information criterion. Behavioral Ecology and Sociobiology 65:13–21.

van Belle, J. V., J. Shamoun-Baranes, E. V. Loon, and W. Bouten. 2007. An operational model predicting autumn bird migration intensities for flight safety. Journal of Applied Ecology 44:864–874.

Weber, P., T. J. Nohara, and S. Gauthreaux. 2005. Affordable, real-time 3-D avian radar networks for centralized North American bird advisory systems. Proceedings Bird Strike Committee USA/Canada https://digitalcommons.unl.edu/birdstrike2005/. Accessed 13 Mar 2017.

Associate Editor: Thompson.