Detecting bird movements with L-band avian radar and S-band dual-polarization Doppler weather radar

Sidney A. Gauthreaux Jr, Ann-Marie Shapiro, Dave Mayer, Barry L. Clark & Edwin E. Herricks

1Department of Civil and Environmental Engineering, Center of Excellence in Airport Technology (CEAT), University of Illinois at Urbana-Champaign, Newmark Civil Engineering Laboratory, MC-250, 205 North Mathews Ave, Urbana, Illinois 61801-2352
2SRC, Inc., 6225 Running Ridge Road, North Syracuse, New York, New York 13212

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Abstract
Marine surveillance radars with X-band (3-cm) and S-band (10-cm) wavelengths not only detect birds but also record return from insects, rain, ground objects and rough seas that often make discrimination of echoes from birds difficult. We compare the density of bird tracks recorded by an L-band (ca. 23-cm wavelength) avian radar at the Dallas/Fort Worth International Airport that does not detect insects and rain with the amount of mean bird reflectivity in resolution cells of a dual-polarization S-band Doppler weather surveillance radar. Radar data files of 1.5° scans gathered near midnight from January through May for the years 2014, 2015 and 2016 were processed by filtering radar resolution cells to retain only those with backscatter differential phase values characteristic of birds flying more or less perpendicular to the radar beam. In general, increases and decreases in the density of bird movements were correlated significantly between the two radars, but the low $R^2$ values confirm that results obtained from one radar cannot be used to make quantitative estimates for the other. A decrease in the mean biomass index of migrating birds from January through May, and the difference in coverage volume and resolution between the two radars likely account for the low $R^2$ values. Each type of radar has advantages and provides important information on bird movements at different spatial scales.

Introduction
Radar ornithology has played an important role in the conservation of migratory birds (Gauthreaux and Belser 2003). Two types of radar have been used extensively to monitor bird movements in the atmosphere. Long-range weather radars have been used to monitor the seasonal movements and roosting departures of birds since the early 1950s in Britain (Harper 1958) and the early 1960s in the United States (Gauthreaux 1970). Small mobile radar units have been used to monitor bird movements at renewable energy sites in an effort to minimize bird injury and mortality from collisions with wind turbines (Kunz et al. 2007; Villegas-Patraca et al. 2014; Tomé et al. 2017) and powerlines and towers (Gauthreaux 1985; Deng and Frederick 2001) and incineration at solar energy plants (Diehl et al. 2016). The radars have also been placed at many airports throughout the world to monitor, warn and alert airport personnel of bird movements that pose a bird-aircraft collision risk (Chen et al. 2012; Beason et al. 2013; Gauthreaux and Schmidt 2013). Most of the small, mobile radars are off-the-shelf or modified marine navigation radars with either X-band (3-cm) or S-band (10-cm) wavelengths. They not only detect individual birds and flocks, but also return from insects, rain, ground objects and rough seas that often make discrimination of echoes from birds difficult. Attempts to eliminate return from non-birds can often eliminate echoes from birds. Radars with longer wavelengths (L-band, 15-cm to 30-cm) are less sensitive to precipitation, and as Schaeffer (1968: page 64) noted ‘L-band radar is exceptionally poor for the detection of small birds and all insects’.

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In an effort to overcome some of the shortcomings of marine navigation radar for studies of bird movements, SRC, Inc. (North Syracuse, New York) in 2009 developed a small, phased-array L-band radar for use at airports to reduce bird/aircraft collisions and improve flight safety—BSTAR™ AVIAN SURVEILLANCE AND WARNING SYSTEM (BSTAR™ ASWS). The radar was designed specifically to detect and track a standard avian target (SAT) according to the requirements of the Advisory Circular of the Federal Aviation Authority (2010, p. 21) with a radar cross section (RCS) of \(-16 \text{ dBm}^2\) and a mass of 0.50 kg (1.1 pound) equivalent to a single crow-sized bird. A BSTAR™ ASWS (Fig. 1) was placed at the Dallas/Fort Worth International Airport (DFW) in October 2011 for monitoring bird movements by airport wildlife management personnel and for validation studies by researchers from the Federal Aviation Administration (FAA)-designated Center of Excellence for Airport Technology (CEAT) at the University of Illinois.

Because the BSTAR™ ASWS at DFW is located within the much larger coverage pattern of the Weather Surveillance Radar-1988 Doppler (WSR-88D) for Dallas/Fort Worth (KFWS) located 45.6 km to the south-west of the airport, and the WSR-88D has been used extensively to monitor bird movements in the United States within the coverage of a single radar (Gauthreaux and Belser 1998, 1999; Gauthreaux et al. 2008), regional clusters of radars (e.g. Diehl et al. 2003; Horton et al. 2016) and the national network of weather radars (Gauthreaux et al. 2003; Kelly and Horton 2016; Van Doren and Horton 2018), we wanted to compare the performance of the two radars with respect to the detection of migrating birds. With the completion of the upgrade of the WSR-88D to dual-polarization in 2013, three new dual-polarization products became available (differential reflectivity, correlation coefficient and differential phase) and these in addition to the three legacy products (base reflectivity, base velocity and spectrum width) can now be used by researchers to distinguish between biological and meteorological scatterers in the atmosphere (Schuur et al. 2003; Tang et al. 2014) and discriminate between return signals from birds and those from insects (Zrnic and Ryzhkov 1998; Zhang et al. 2004, 2005; Jiang et al. 2013; Stepanian et al. 2016).

In this paper we compare the density of tracks of birds recorded by the BSTAR™ ASWS at the Dallas/Fort Worth International Airport with the amount of reflectivity from birds in resolution cells in selected files of the WSR-88D at Dallas/Fort Worth (KFWS) near midnight from January through May for the years 2014, 2015 and 2016. We hypothesize that during the spring migration period the agreement between detections by BSTAR™ ASWS and WSR-88D will be good initially as larger birds (ducks and geese) begin their nocturnal migration, but as the season progresses and the mean radar cross section of migrating birds at night decreases (Dokter et al. 2011), the agreement will become poorer.

Materials and Methods

Bstar™ avian surveillance and warning system

The BSTAR™ ASWS radar has fully coherent Doppler waveforms and processing that suppresses stationary clutter. It was designed to detect single small birds weighing 0.1 kg (L-band radar cross section of approximately 20 cm\(^2\)) out to a range of 3 km, and single crow-sized birds weighing 0.5 kg (L-band radar cross section of approximately 100 cm\(^2\)) out to a range of 10 km over areas of high ground clutter (Fig. 2). Larger birds and dense flocks of smaller birds can be detected at even greater ranges. These ranges are based on theoretical calculations by the developer using the characteristics of the radar, the radar range equation and experimental observations.

The BSTAR™ ASWS and software provide fully automatic 3-dimensional location, tracking and target classification within the coverage volume. The unit has a nonrotating electronically steered antenna that scans through 360° at a rate of 31.5 scans min\(^{-1}\). Although
resolution cells have dimensions of 75 m \times 15^\circ \text{ in azimuth} \times 30^\circ \text{ in elevation above ground level, algorithm processing enables a range accuracy of 10–15 m, an azimuth accuracy of approximately } 2^\circ \text{ and an elevation accuracy of about } 3^\circ. \text{ If more than one scatterer is located within a resolution cell, the scatterer with the highest value of backscatter signal is tracked after being detected in three sequential scans. The BSTAR\textsuperscript{TM}Analyzer Software Suite contains a data management subsystem that continuously captures and indexes all the radar data including: three-dimensional position and velocity of the scatterer, time and biomass. The software generates tracks from detections and classifies tracks as bird, aircraft, ground vehicle or unknown. The classification is based on scatterer velocity, radar cross section and altitude. The software also provides replay and data extraction and analysis capabilities, and generates automatic reports. Because the BSTAR\textsuperscript{TM} ASWS operates at a frequency of 1.2–1.4 GHz (wavelength of about 23 cm), it does not detect rain (Curry 2012), and the design of the system also eliminates interference caused by insects (Schaeffer 1968, p. 64; Richardson 1979).}

BSTAR\textsuperscript{TM} ASWS data for this study consisted of tracks classified as birds throughout a track’s history. Only tracks with more than one update (> three initial detections plus one track point) at altitudes of 304.8 m (1000 ft) and above were included in the analysis. On nights without precipitation in the surveillance area (314 km\textsuperscript{2}) from the beginning of January through the end of May for the years 2014–2016, a 5-minute sample of tracks centered on 06:00 UTC was downloaded from an archive. Seventy samples were gathered in 2014, 59 in 2015 and 44 in 2016. Because the number of tracks passing through the surveillance area of the BSTAR\textsuperscript{TM} ASWS (314 km\textsuperscript{2}) is influenced by the ground speed of the birds, track counts were converted to track densities by dividing track counts by the average ground speeds of the tracks.

In addition to the track density data we also gathered data on the biomass of the tracked scatterers during the 3 years of study. Radar cross sections of tracked scatterers were not available because of security restrictions, but estimates of average biomass were reported in kilograms (kg) for each track. For each nightly sample of tracks a frequency distribution of average biomass ranging from 0 through 3.5 was plotted and descriptive statistics calculated. We selected the mean value and standard deviation of the biomass for each date for analysis of trends for each of the 3 years of study. In an effort to relate bird biomass to radar cross section in cm\textsuperscript{2} for L-band wavelengths, we compiled data from Eastwood (1967, p. 46, 23-cm wavelength), Moon (2002, p. 300, 23-cm wavelength) and Antonucci (1991, p.13, 25-cm wavelength), and these data are included in Table 1 and plotted in Figure 3.
Table 1. Bird biomass and L-band radar cross sections of different types of birds.

| Bird biomass (kg) | Radar cross section (cm²) | Type of bird    | Source ¹ |
|------------------|---------------------------|-----------------|----------|
| 0.1              | 42                        | European Blackbird | a        |
| 0.024            | 2.2                       | Chaffinch       | a        |
| 0.025            | 2.4                       | House Sparrow   | a        |
| 0.2              | 91                        | Lapwing         | a        |
| 0.017            | 1.1                       | European Robin  | a        |
| 0.07             | 22                        | Song Thrush     | a        |
| 0.08             | 29                        | Starling        | a        |
| 0.043            | 8.3                       | European Swift  | a        |
| 0.02             | 1.7                       | Garden Warbler  | a        |
| 0.008            | 0.3                       | Chiffchaff      | a        |
| 0.01             | 0.2                       | Warbler         | b        |
| 0.025            | 1.3                       | Sparrow         | b        |
| 0.075            | 10                        | Starling        | b        |
| 0.2              | 51                        | Follower        | b        |
| 0.5              | 109                       | Pigeon          | b        |
| 0.8              | 88                        | Duck            | b        |
| 1                | 210                       | Swan            | b        |
| 2.02             | 174                       | Eider           | c        |
| 1.48             | 157                       | Brant           | c        |
| 2.63             | 190                       | Lesser Snow Goose | c         |
| 2.68             | 191                       | White-fronted Goose | c       |
| 0.87             | 131                       | Long-tailed Duck | c        |
| 0.95             | 135                       | Pintail         | c        |
| 6.8              | 261                       | Whistling Swan  | c        |
| 3.07             | 200                       | Greater Snow Goose | c         |

¹a (Eastwood 1967, p. 46), b (Moon 2002), c (Antonucci 1991).

WSR-88D

The WSR-88D is a pulse-Doppler, S-band (10.7 cm, 2.8 GHz) weather radar (https://www.roc.noaa.gov/WSR88D/Engineering/NEXRADTechInfo.aspx) with three base products (reflectivity, radial velocity and spectrum width) and three dual-polarization products (differential reflectivity, correlation coefficient and differential phase) that contain information from meteorological and biological scatterers in the atmosphere within a range of coverage of 230 km. The radar has a beam width of approximately 1° and completes several 360° scans at different elevation angles depending on the volume coverage pattern (VCP). VCPs are changed depending on weather conditions (e.g. precipitation in coverage range, clear air). The minimum detectable signal of −113 dBm enables the radar to detect very light precipitation, very small biological scatterers (small insects) and other scatterers (e.g. smoke particles). Radar resolution cells are 0.5° in azimuth after processing, 1° in vertical dimension and 250 m in range.

The University Corporation for Atmospheric Research (UCAR) Image Archive Meteorological Case Study Selection Kit (http://www2.mmm.ucar.edu/imagearchive/) was used to review WSR-88D images of composite reflectivity for the southern plains for the months of January–May for the years 2014–2016 to eliminate dates with extensive precipitation in the surveillance coverage of the WSR-88D at Dallas-Fort Worth, TX (KFWS). For the surviving dates, Level II WSR-88D binary data were downloaded from Amazon Web Services using a custom script developed in R (Version 3.4.4, 15 March 2018) that utilized the aws.s3 package, decompressed, and then unpacked using the NetCDF Tools User Interface package to obtain level II data in NetCDF file format. High-resolution arrays of data were extracted from the NetCDF file, reshaped into data tables. The altitude of each resolution cell was calculated using the beam-width calculator from the National Oceanic and Atmospheric Administration’s National Weather Service site (https://training.weather.gov/wdtd/tools/misc/beamwidth/index.htm) and the R package geosphere: Spherical Trigonometry version 1.5-1. All recorded WSR-88D high-resolution moment tables were aligned by time, azimuth, elevation and range from the radar. This allowed the comparison of values of reflectivity factor (dBZ) of individual resolution cells with associated values of radial velocity, spectrum width and the three dual-polarization variables.

Following the spatial and temporal alignment of the resolution cells, only cells meeting the following criteria were retained: antenna elevation closest to 1.5° (1.2°–1.7°), an altitude of 304.8 m or greater and differential phase values greater than or equal to 0° to eliminate some range folded values below zero. The reflectivity factor (dBZ) in the surviving resolution cells contained biological and any meteorological scatterers present beyond the range of the biological scatterers. These resolution cells were then filtered to eliminate those associated with values of backscatter differential phase characteristic of insect scatterers based on the findings of Zrnic and Ryzhkov (1998) and precipitation based on the findings of Trömel et al. (2013).

Total differential phase (TDP) includes initial system differential phase (ISDP) of the radar, propagation differential phase (PDP) attributable to increases in values as the beam travels through precipitation and backscatter differential phase (BDP) from scatterers in the atmosphere. If sample files have no precipitation, PDP is absent. Initial system differential phase ISDP values are nominally 60° for the WSR-88D, but the value will drift over time, so ISDP values were determined in the middle of each month for each year. When ISDP is removed from TDP, the remaining differential phase is BDP. Based on the findings of Zrnic and Ryzhkov (1998), the maximum value of BDP for insect scatterers is approximately 50°, or 50° above the actual values of ISDP, and
backscatter differential phase of rain is near 0° for S-band radars (Trömel et al. 2013). In an effort to eliminate BDP from insects and any possible remaining precipitation, we filtered the resolution cells to retain only cells with reflectivity factor associated with values of differential phase 50° above the value of the radar’s ISDP and less than or equal to 270°. Filtering to remove insects and return from precipitation also removes reflectivity from birds oriented head-on and tail-on to the radar because the head-on and tail-on values of backscatter differential phase can overlap those produced by insects flying with their body axis oriented perpendicular to the radar beam. The reflectivity factor (dBZ) in the remaining resolution cells was converted to radar equivalent reflectivity factor (Ze) in mm^2/m^3, and Ze was used to calculate total bird reflectivity (η) in cm^2/km^3 (Chilson et al. 2012). To determine the number of birds km^-3, total biological reflectivity in a resolution cell is divided by the radar cross section of a bird (e.g. 12 cm^2), but because we had no information on the radar cross sections of birds aloft, we have chosen to conduct our analyses using mean bird reflectivity (total bird reflectivity divided by the number of remaining reflectivity resolution cells). The above filtering procedures were used to process all sample files from the three years of study. We have not corrected the resulting data for range-dependent biases such as beam filling and non-standard beam refraction (sensu Buler and Diehl 2009 and Chilson et al. 2012). Statistical test were conducted with JMP® Pro 12.2.0 software (SAS Institute, Inc.: Cary, NC).

Results

The seasonal distribution of the density of tracks recorded by the BSTAR™ ASWS and the mean bird reflectivity in resolution cells from the WSR-88D filtered to retain only cells associated with differential phase values of ISDP + 50° through 270° for all three years of study is plotted in Figure 4A and B. The polynomial fit (quadratic, degrees = 2) of the bivariate plot of BSTAR™ ASWS track density by date (Fig. 4A) has an adjusted R^2 = 0.36 (P < 0.0001, n = 173), whereas the polynomial fit (quadratic, degrees = 2) of the bivariate plot of mean bird reflectivity by date (Fig. 4B) has a R^2 = 0.39 (P < 0.0001, n = 173). The Spearman’s test of the covariance between mean bird reflectivity and track density is significant (R = 0.589, P < 0.0001, n = 173), but the low R^2 of the polynomial fit (quadratic, degrees = 2) of the bivariate plot of mean bird reflectivity and track density (R^2 = 0.132, P < 0.0001, n = 173) indicates that the value of one variable cannot be used to predict the value of the other. In all three years the WSR-88D and the BSTAR™ ASWS recorded very little movement in January. The first major peak in track density (75 tracks) from the BSTAR™ ASWS and mean bird reflectivity (93 cm^2/km^3) from the WSR-88D occurred on 16 February 2014. In 2015 the first major movement recorded by the BSTAR™ ASWS had a density of 46 tracks and the WSR-88D had a mean bird reflectivity of 66 cm^2/km^3 on 11 February. The first good movement of birds in 2016 occurred on 14 February 2016 when BSTAR™ ASWS recorded a density of 45 tracks, whereas the WSR-88D recorded a mean bird reflectivity of 52 cm^2/km^3. The highest track densities for the season from BSTAR™ ASWS were 77 on 8 March 2014, 70 on 7 and 29 March and 16 April 2015 and 66 on 18 February 2016. The highest mean bird reflectivity measures recorded for the season by the WSR-88D were 2051 cm^2/km^3 on 4 May 2014, 1989 cm^2/km^3 on 1 May 2015 and 1654 cm^2/km^3 on 4 May 2016. After the middle of April the trend for track density from BSTAR™ ASWS

Figure 3. Relationship between weight (kg) and L-band radar cross section (cm^2) of several types of bird. The data from Eastwood (1967) and Moon (2002) are for a 23-cm wave length and the data from Antonucci (1991) are for a 25-cm wavelength.
decreased, whereas the values of mean bird reflectivity recorded by the WSR-88D increased to a peak in early May and then declined.

The mean biomass index of birds (single or flocks) tracked by BSTAR™ ASWS decreased from January through May (Fig. 5) over the three years of study (slope $= -0.0045$, $R^2 = 0.06$, $P < 0.0006$, $n = 173$). When the seasonal pattern of values of mean biomass was examined by individual year, the plots of mean biomass index by date were significant for the 2014 samples (slope $= -0.0016$, $R^2 = 0.13$, $P < 0.003$, $n = 70$) and the 2015 samples (slope $= -0.0015$, $R^2 = 0.11$, $P = 0.01$, $n = 59$), but the relationship for the 2016 samples was not significant (slope $= 0.0001$, $R^2 = 0.0004$, $P = 0.90$, $n = 44$).

Discussion

The increases and decreases in the patterns of track density from BSTAR™ ASWS and mean bird reflectivity from the WSR-88D are significantly correlated for the three seasons of combined data, however, the low value of $R^2$ for the fit of mean bird reflectivity by track density indicates that the amplitude of change in one variable cannot predict the amplitude of change in the other variable. This is not surprising considering the differences between the two systems. The BSTAR™ ASWS tracks mostly large birds and flocks, and the seasonal changes in the patterns are likely associated with the decreasing trend in the sizes and radar cross sections of the migrating birds as the
season progresses. In our study the mean biomass index of the birds tracked by the BSTAR™ ASWS showed a significant decrease from January through May in 2014 and 2015 but the decrease was not significant for 2016. The seasonal decrease in the average biomass index was approximately 0.2 kg and according to the data in Table 1, this change is equivalent to a change in L-band radar cross section on the order of 51–90 cm². The decrease in the mean biomass of birds tracked by the BSTAR™ ASWS would likely result if birds with large radar cross sections migrated earlier in the season. It is well known that the first spring migratory movements of waterfowl from the Gulf Coast region begin in late January and early February, peak in late February and March and decline markedly in April (Bellrose 1980). Shorebirds migrating in flocks through the Gulf Coast begin in March, increase in numbers until late April and early May and decline by June (Norling et al. 2012). In a study combining weather surveillance radar data and ground based observations of different species of migratory birds (eBird-Cornell Lab of Ornithology), Horton et al. (2018) documented the pattern of a seasonal shift from early, large-bodied, fast-flying migrants to late, small-bodied, slow flying migrants in spring in central North America. A decrease in radar cross sections of migrating birds also has been recorded in Europe where cross section of migrant passerines decreased from 16 to 10 cm² by 0.1 ± 0.04 cm² day⁻¹ in the period mid-March to early May as the abundance of large passerines decreased as spring migration progressed (Dokter et al. 2011).

In our study the decrease in the sizes of migrating birds at night as the season progressed impacted the two radars differently. When the number of smaller birds migrating individually at night increases, the number of resolution cells with bird reflectivity (cm²/km³) in the displays of the WSR-88D increases dramatically, but few of these small birds are tracked by the BSTAR™ ASWS. When this occurs the mean bird reflectivity of resolution cells in the WSR-88D data will be disproportionally higher than the density of tracks recorded by the BSTAR™ ASWS, and this is what we documented in our analysis.

Relatively few studies have used two or more different types of radar to study the movements of biological scatterers in the atmosphere. Most of the comparisons involved radars with 3-cm wavelengths and weather radars with C-band (5-cm) and S-band (10–11 cm) wavelengths. Van Gasteren et al. (2008) compared the observations of migrating birds using a dedicated 3-cm X-band bird tracking radar and a 5-cm wavelength C-band Doppler weather radar in the Netherlands. They found that the total migration intensity reproduced by the vertically integrated reflectivity of the weather radar within the range of 5–25 km showed a good correlation with the observations from the bird radar located 80 km away. They reported that migration intensity measured by the weather radar at a specific 200 m layer could not be matched with bird radar observations and attributed this mismatch to small sample sizes and the distance between both measurement sites.

Buler and Diehl (2009) sampled the vertical distribution of targets near the beginning of nocturnal bird migration with a portable 12-kW surveillance radar with a 3-cm (X-band) wavelength and vertically rotating 20° open-array antenna. They constructed vertical profiles of target density in 26 height intervals of 50 m from 100 to 1400 m above ground level and compared them to vertical profiles of reflectivity (VPR) in 50 m increments of altitude derived by integrating data between the ranges of 5 and 20 km from the WSR-88D radar (KLIX) located 120 km away. The VPR matched the mean observed

![Figure 5. Relationship between mean biomass index (kg) and date for the combined spring seasons of 2014–2016 (173 dates). Standard deviation above the mean is shown.](image-url)
We used the data from an entire 360° above for quantifying bird movements in the atmosphere. They found the altitude profiles recorded by the avian radar closely matched those recorded by the weather radar within the ranges 5–25 km and documented a ‘remarkable correspondence’ between the absolute numbers of birds recorded by both radars.

Nilsson et al. (2018) compared the pattern of nocturnal bird migration movements recorded by four different radar systems at a site in southern Sweden within the range of a C-band weather radar, a vertically-pointing 3-cm ‘BirdScan’ radar, a standard 3-cm marine radar and a 3-cm tracking radar. All the radars except the tracking radar measured the seasonal course of migration well, but estimated mean ground speeds differed among all four radars. Migration intensity agreed reasonably well only between the weather radar and the BirdScan radar, and flight directions recorded by the weather, BirdScan and tracking radars matched well.

The aforementioned studies used a stacked scan technique to generate vertical profiles of reflectivity (VPR) from birds within relatively short ranges from the weather radar (e.g. 5–25 km) to obtain more accurate measures of the altitudinal distribution of bird reflectivity. If one assumes that the density distribution of migrating birds is the same over the entire coverage area of the weather radar (e.g. Dokter et al. 2011) then the VPR measures close to the radar can be applied to the entire surveillance area. However, if the amount of bird reflectivity varies within the surveillance area of the weather radar, the widespread application of the VPR measure will produce erroneous measures of bird reflectivity.

We used a different approach from those discussed above for quantifying bird movements in the atmosphere. We used the data from an entire 360° sweep of the WSR-88D because the values of the reflected signals of several of the WSR-88D radar products change depending on the orientation (aspect) and movement of the scatterer relative to the radar, and we have noted on several occasions variation in the reflectivity factor in different portions of the surveillance area. We filtered resolution cells containing radar reflectivity factor (dBZ) with values of backscatter differential phase that eliminated resolution cells with return from precipitation, nearly all insects, birds oriented head-on and tail-on to the radar and chaff. After filtering with backscatter differential phase, the surviving resolution cells contain birds oriented more or less perpendicular to the beam and display maximum reflectivity factor. When one filters radial velocity data to eliminate return from insects and other wind borne scatterers, birds moving more or less perpendicular to the radar beam will have low or no radial velocities and be eliminated, whereas birds flying more or less parallel to the radar beam will exhibit radial velocities that are true ground speeds.

In our study we have not examined the impact of scatterers not filling the radar beam of the WSR-88D as range increases. We do know that fixed densities of birds will be underestimated somewhat as range increases (Chilson et al. 2012), particularly when most of the radar beam is above the maximum altitude of the movement and relatively few birds are in the bottom of the beam.

The ‘bird radars’ and weather radars used to measure simultaneously bird movements in previous studies readily detect backscatter from insects, bats, birds and precipitation, but in our study the two radar systems we used were very different in that one (L-band unit) did not detect precipitation, insects or single small birds at distances greater than 3 km and the other (S-band) weather radar detected all types of scatterers aloft. Our study demonstrates the advantages and limitations of both radar systems with respect to monitoring bird movements, and there is clearly a role for both types. Small high-resolution, marine-navigation radars with 3- and 10-cm wavelengths can monitor bird movements within a range of 10–12 km and provide greater spatial resolution and better coverage at lower altitudes than weather surveillance radars, but they also detect insects, ground objects and light rain that can produce clutter that potentially obscures return from birds. Larger insects may be classified as birds, and attempts to filter the return from ground clutter often eliminates echoes from birds flying above the clutter. The development of small Doppler avian radars with wavelengths of 3- and 10-cm will enable velocity filtering that will eliminate stationary clutter and help with separation of moving scatterers based on ground speed. Development of dual-polarization capability in these units will generate products that potentially can be used to separate biological and non-biological scatterers and distinguish between backscatter from birds and backscatter from insects.

In our study we used a small radar with 23-cm wavelength that was designed to track single crow-sized and larger birds and flocks within a range of 10 km and individual small birds within a range of 3 km without interference from ground clutter, insects and rain. We used the radar to monitor bird movements within the boundary of a large international airport, but a radar of this type could be used to monitor the movements of raptors and other large birds (e.g. cranes, waterfowl) near wind turbines, transmission lines and tall towers.
In contrast Doppler weather surveillance radar with 5-cm and 10-cm wavelengths can detect and quantify bird movements at ranges well beyond the coverage of small avian radars (Gauthreaux et al. 2008; Dokter et al. 2011, Kelly et al. 2012; Shamoun-Baranes et al. 2014; Nilsson et al. 2018) and provide information on departing concentrations of birds from roost sites (Russell et al. 1998; Kelly et al. 2012) and migration stopover areas (Buler and Dawson 2014) within a range of 150 km. Weather radar with dual-polarization capability enables the separation of signals returned from biological and meteorological scatterers and from birds and insects in the atmosphere (Zrnic and Ryzhkov 1998; Stepanian et al. 2016) and may allow the development of algorithms that can automatically detect and classify different types of biological scatterers aloft at a continent-wide scale.

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