

RESEARCH ARTICLE

Quantifying range- and topographical biases in weather surveillance radar measures of migratory bird activity

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Abstract

Weather radar systems have become a central tool in the study of nocturnal bird migration. Yet, while studies have sought to validate weather radar data through comparison to other sampling techniques, few have explicitly examined the impact of range and topographical blockage on sampling detection—critical dimensions that can bias broader inferences. Here, we assess these biases with relation to the Cheyenne, WY Next Generation Weather Radar (NEXRAD) site, one of the large-scale radars in a network of 160 weather surveillance stations based in the United States. We compared local density measures collected using a mobile, vertically looking radar with reflectivity from the NEXRAD station in the corresponding area. Both mean nightly migration activity and within night migration activity between NEXRAD and the mobile radar were strongly correlated ($r = 0.85$ and 0.70 , respectively), but this relationship degraded with both increasing distance and beam blockage. Range-corrected NEXRAD reflectivity was a stronger predictor of observed mobile radar densities than uncorrected reflectivity at the mean nightly scale, suggesting that current range correction methods are somewhat effective at correcting for this bias. At the within night temporal scale, corrected and uncorrected reflectivity models performed similarly up to 65 km, but beyond this distance, uncorrected reflectivity became a stronger predictor than range-corrected reflectivity, suggesting range limitations to these corrections. Together, our findings further validate weather radar as an ornithological tool, but also highlight and quantify potential sampling biases.

Introduction

The vast majority of bird migration occurs at night and cannot be directly observed (Larkin & Szafoni, 2008; McLaren et al., 2018). Ornithologists have attempted to overcome this challenge using various monitoring techniques, including moon watching (Liechti et al., 1995; Nisbet & Drury, 1969), acoustic monitoring (Evans & Mellinger, 1999), and the deployment of tracking devices on individual birds to monitor migration behavior (McKinnon & Love, 2018; Robinson et al., 2010). One approach that has become central in characterizing nocturnal migration activity, and more broadly throughout aerocology, is the use of weather surveillance radar

(Shamoun-Baranes et al., 2021). Radar has been used for more than 75 years for the study of migratory birds (Gauthreaux Jr., 1970; Lack & Varley, 1945). Enhanced data access and the integration of machine learning, however, has led to a resurgence in the past decade in its use for quantifying movement of nocturnal migrants and driving predictions of where and when large migration events will occur across the continental United States (Van Doren & Horton, 2018). More broadly, radar-driven models are being used in a growing number of applications at multiple spatiotemporal scales including identifying key stopover locations (Cohen et al., 2021; Guo et al., 2023), estimating migratory bird exposure to anthropogenic light (Horton et al., 2019; Weissaupt

et al., 2022), monitoring and forecasting nocturnal migration events (Horton et al., 2021; Kranstauber et al., 2022; Shi et al., 2023; Van Doren & Horton, 2018), and identifying phenological shifts (Deng et al., 2022; Haest, Stepanian, et al., 2021).

Given its increasingly prominent role in shaping our understanding of nocturnal bird migration, it is vital to identify and account for potential spatial and temporal biases in weather radar datasets. Cross-validation studies can be used to determine these biases and inform methods that account or correct for biases, such as range, blockage, and clutter contamination (Buler & Diehl, 2009; Van Doren et al., 2023). Studies have found that time-referenced line-transect surveys estimates of bird observations (Dokter et al., 2013) and visual bird migration counts (Schmidt et al., 2017) correspond well to radar reflectivity. As radar technology has progressed and dedicated bird radars, which are designed specifically to study avian activity, have become available, studies have compared across radar types, both validating weather radar as an ecological tool and illuminating the nuances of each radar system. For example, Dokter et al. (2010) used reference data collected by an X-band radar to validate an automated method for estimating real-time bird density altitude profiles from weather radar data. Gauthreaux et al. (2019) found that seasonal trends in L-band and S-band weather radars bird activity estimates were correlated, but suggested that this relationship was weakened by periods of low migration activity and differences in coverage volume and resolution. Nilsson et al. (2018) compared the observations across four different radar systems and found that weather radar measures of nightly migration intensity across a season correlated with high-resolution, vertically directed radars, particularly under clear sky conditions and at high altitudes. Together, cross-validation studies generally confirm that measures of avian biomass in the atmosphere correlate across different radar types, demonstrating the promise of weather surveillance systems as an ecological tool.

However, given these radar networks are designed to study weather conditions, there are inherent limitations for their use in aeroecology. For example, stations across the Next Generation Weather Radar (NEXRAD) system, a network of 160 weather surveillance stations based in the United States (Crum & Albery, 1993), tend to be located at high elevation and thus may miss biological targets that reside beneath the radar's sampling pattern. Additionally, NEXRAD also has considerable spatial coverage gaps for biological use. These gaps are particularly pronounced across the Western flyways of the continental United States, where radars are less densely distributed. In recognition of this potential bias, range-corrective methods have been developed to

account for the rising radar beam height that occurs with increasing range from the radar (Kranstauber et al., 2020). These methods seek to normalize detection probabilities of in-flight migrants and have been applied in practice to improve estimates of avian activity (Hoekstra et al., 2024; Horton et al., 2023). Yet, the limitations of these corrective measures have yet to be validated across various ranges.

Further, because the electromagnetic pulses emitted by radar can be blocked by landscape features, they are prone to missing aerial activity shaded by topographic blockage, such as mountains in high elevation regions. Based on estimates from clutter masking techniques (Buler et al., 2012), more than half of NEXRAD stations show some degree of blockage with this issue being more pronounced in the western continental United States. This combination of sparse NEXRAD radars and beam blockage due to topography leave the NEXRAD system potentially incapable of detecting important migration corridors in the western United States. Radar has also been used at increasingly varied temporal scales, ranging from analyses of within-night variation in migration activity (Horton et al., 2016), to mean nightly estimate comparisons (Nilsson et al., 2018), and even to seasonal estimates of stopover intensity (Guo et al., 2024). Given the temporal variation in NEXRAD-based studies, it may also be important to understand how these relationships change with temporal resolution.

We employed a high-precision, mobile X-band radar system designed to quantify animal movements in the lower atmosphere to address these limitations and enable filling spatial gaps in NEXRAD-based predictions across the continental United States. We compared migration intensity measured across two different, but complementary radar systems: the BirdScan MR1 and NEXRAD. More specifically, we collected data with the BirdScan MR1 at varying distances and elevations from the NEXRAD station in Cheyenne, WY, to quantify the relationship between these measurements and test how it varied with (1) the distance from the NEXRAD station and (2) beam blockage. We compared these relationships at the nightly and within-night temporal range, and with range-corrected and uncorrected NEXRAD data to understand how they are impacted by temporal resolution and the degree to which current range-correction efforts are affected. We predicted that NEXRAD measures of reflectivity would be less correlated with BirdScan MR1 measures of density as both distance and topographical blockage increased. Additionally, we predicted that relationships would be stronger at the nightly temporal scale and when range-corrections were applied.

Materials and Methods

Study system

The NEXRAD station in Cheyenne, WY (41.15° N, 104.80° W; hereafter referred to by NEXRAD station code “KCYS”) monitors the atmosphere across large portions of southeastern Wyoming and northern Colorado (Fig. 1). The landscape of northeastern Colorado and southern Wyoming is dominated by a mix of rangeland and shortgrass prairie, which is relatively flat, whereas the foothills of the Rocky Mountains begin in north central Colorado. The region ranges from semi-arid plains to mid-elevation forests. Weather surveillance radar estimates of avian migration across the western United States, are likely prone to error (Ruth et al., 2012) and landscapes such as the one covered by the KCYS station

remains ripe for testing the assumptions embedded in these methodologies.

Data collection with the BirdScan MR1

We collected nocturnal migration data with the BirdScan MR1, a vertically directed, mobile, 25 kW X-band (9.4 GHz, 3.2 cm wavelength) pulse radar system designed to monitor and quantify aerial animal movements (Haest et al., 2024; Swiss Birdradar, 2022; Zaugg et al., 2008). We used the short-pulse, antenna-rotating setting, which emits electromagnetic pulses with a pulse length of 81 ns and shot frequency of about 1800 Hz. The pulses reflect off objects in the airspace and produce backscatter up to about 1500 m, depending on the size of the object (Schmid et al., 2019; Weisshaupt et al., 2023). The temporal variation of the returned backscatter is then

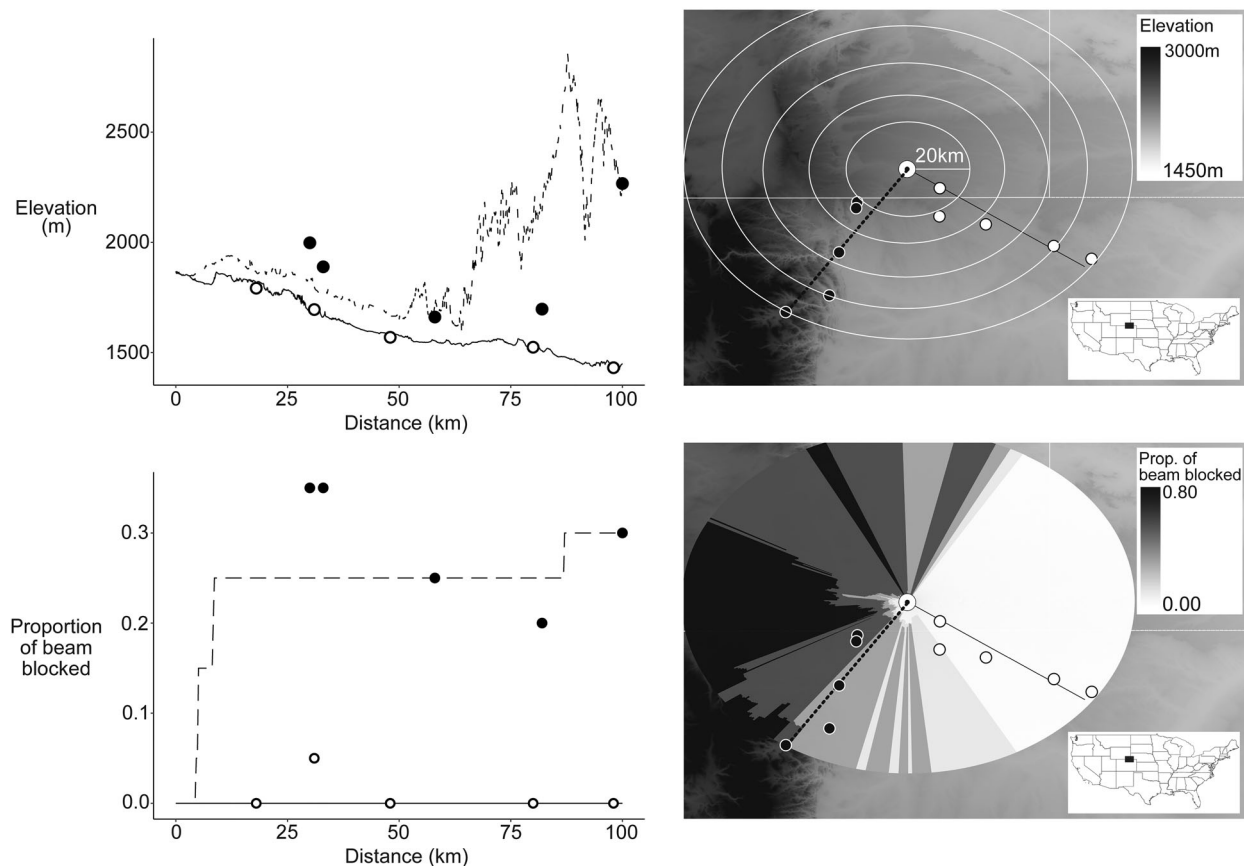


Figure 1. Overview of radar sampling design radiating out from the KCYS weather surveillance radar in Cheyenne, WY as a focal validation site. Sites were selected to span a wide range of elevations and distances from the KCYS radar station (left), with sites mapped out over concentric circles increasing their radii in increments of 20 km (top right). Sites ran along flat (solid line) and elevated (dotted line) transects, one of which extended southeast into the plains of central Colorado (white points) and the other extended southwest into the foothills of the Rocky Mountains (black points) (right). Note that transect elevation profiles were taken along the straight radial line, whereas site locations were selected by accessibility and were not directly on transects.

used to classify objects into bird types (unidentified, swift, passerine, wader, or flock), aerial insects, or precipitation based on echo features such as flight patterns, wingbeat frequency, and the radar cross section, which is a metric of target size (Haest, Schmid, et al., 2021; Schmid et al., 2019; Zaugg et al., 2008).

During spring migration (April 1–May 31) in 2022 and 2023, we collected bird migration data along two 100-km linear transects, both of which began at the KCYS station and included five data collection sites located at varying distances (~20–100 km) from the starting point of the transect for a total of 10 sites (Fig. 1). To collect data across a diversity of topographies, one transect extended southeast into the relatively flat landscape of the Eastern Plains of Colorado and the other transect extended southwest into the foothills of the Rocky Mountain. We collected data at each site for two to three nights between civil twilights throughout each spring migration season. Visits were randomized with a random number generator, such that the order of site selection varied across both seasons.

We used the *birdscanR* R package (Haest et al., 2023) to extract and process measures of bird migration activity from the BirdScan MR1 in R (R Core Team, 2022). We used the *computeDensity()* function to calculate the density of targets flying in all directions within an altitudinal range of 25–1500 m throughout the night for each 20-min period at each of the sampling sites, sum these values vertically across altitudinal bins, and filter out non-avian data to calculate migratory bird density (birds/km²).

Downloading and processing NEXRAD data

We used data from NEXRAD as a comparison point for estimated migration densities. The NEXRAD network is jointly operated by the National Weather Service, the Federal Aviation Administration, and the US Air Force. NEXRAD data are publicly accessible through Amazon Web Services (2023). Radar reflectivity (η) is a measure of the returned power from atmospheric activity, which can be used to estimate biomass within a volume of air (Chilson et al., 2012). This radar product is commonly filtered to remove non-biological clutter and corrected to account for range bias (Buler & Diehl, 2009). To understand the degree to which range-corrections improve the accuracy of NEXRAD estimates, we compared the migration density estimates derived from BirdScan MR1 to both the uncorrected and range-corrected radar reflectivity.

We downloaded level-II (NWS WSR-88D National Level II) radar scans to characterize migratory activity from local sunset to sunrise from April 1 to May 31 of 2022 and 2023. We used the *bioRad* R package to extract,

process, and convert radar reflectivity factor (Z) into radar reflectivity (η), which is a more biologically relevant variable (Chilson et al., 2012). We extracted data from the KCYS radar for each night of interest from scans at elevation angles ranging from 0° to 4.5° and calculated the mean reflectivity over 20-min sampling periods. We used the “*apply_mistnet*” function to filter out precipitation (Lin et al., 2019). To account for the NEXRAD station sampling an increasing height above ground level with increasing distance from the radar (Buler & Diehl, 2009), we compiled scans into vertical profiles of reflectivity and calculated the expected reflectivity at each pixel in each planned position indicator (PPI) using the “*integrate_to_ppi*” function in *bioRad* (Kranstauber et al., 2020). We omitted PPI pixels with a range adjustment factor (R) greater than 10 from our averaging. For uncorrected rasters, we summed the reflectivity values from our scans across elevation angles. Lastly, we changed the reflectivity values to 0 for volumes that were labeled as precipitation by MistNet for both corrected and uncorrected data. We used this process to output one range-corrected raster of migratory activity and one uncorrected raster of migratory activity. For each night that was sampled with the BirdScan MR1, we extracted reflectivity values within a 2-km buffer of each sampling site from both the corrected and uncorrected rasters at a spatial resolution of approximately 0.0095 degrees in both latitude and longitude and averaged them into a temporal resolution of 20-min periods. We used these data to summarize mean nightly reflectivity at each site.

Covariate calculation, model-building, and assessment

To assess the effects of sampling range, elevation, and beam blockage on the relationship between Birdscan MR1 traffic rates and NEXRAD reflectivity, we included them as covariates in our models. For range, we calculated the distance between survey points and the KCYS station using the *geosphere* package in R (Hijmans, 2022). To calculate elevation, we downloaded elevation raster data from the USGS GIS Data Download Application (United States Geological Survey, 2023) and extracted values at our sampling locations. To calculate blockage, we used the *geosphere* R package to produce a raster of the proportion of beam blockage with a beam angle of 0.5 degrees around the KCYS station following the methodology from Buler and Diehl (2009) and extracted the values at each of our points. Elevation and beam blockage were highly collinear ($r = 0.75$), so we removed elevation as a predictor. We scaled and centered beam blockage and distance to avoid numerical instability. To ensure that unequal migration activity across sites and sample size

reduction from range adjustment factor filtering were not driving our results, we used a one-way analysis of variance to compare the mean nightly bird migration densities and the number of removed cells across our sites.

We assessed relationships between BirdScan densities and NEXRAD reflectivity at two temporal scales. We calculated the mean values of each radar system for each sampling night to capture nightly variation and used mean values of our 20-min sampling periods to capture within-night variation. Additionally, we built sets of models with both range-corrected and uncorrected NEXRAD reflectivity values. For both temporal scales, we square root transformed NEXRAD reflectivity and BirdScan densities to account for zero-inflation.

We calculated the Pearson's correlation coefficient between BirdScan densities and NEXRAD reflectivity, before and after filtering out insect detections. To test our hypothesis that both distance and blockage effect the relationship between BirdScan MR1 density and NEXRAD reflectivity, we used the *lme4* R package to fit a series of linear models and linear mixed models (Bates et al., 2015). For all models, we treated BirdScan MR1 density as our response variable predicted by NEXRAD reflectivity. Each model set included: (1) a null model, which included NEXRAD reflectivity as the sole fixed predictor, (2) a model that added two separate interactive terms for distance and NEXRAD reflectivity, and blockage and NEXRAD reflectivity to the null model, and (3) a model that added a three-way interactive term between distance, blockage, and NEXRAD reflectivity to the null model. For within-night variation models, we also included date as a random categorical intercept variable for each model set, with date corresponding to a full night from sunset to sunrise (i.e., including the morning of the following date).

We performed likelihood ratio tests (Tredennick et al., 2021) to assess whether or not the effects of distance and blockage had a significant effect on the relationship between BirdScan MR1 density and NEXRAD reflectivity relative to the null models. We used adjusted R^2 values to assess the relative performance between linear model sets and among linear models in the same set (Nakagawa & Schielzeth, 2013). We used conditional R^2 values to assess linear mixed model performance because we were interested in the full explanatory power of the model and the random effect of date is fundamental to how migration density data are structured.

Lastly, to better understand the role of vertical sampling in the biases we examined, we compared the vertical profiles of migration activity across both radar systems. To do this, we used the elevation of each sampling site to convert BirdScan measurements to altitude (above sea level). We then summed BirdScan 20-min sample

densities into 100-m vertical bins, calculated those densities as proportions of the entire sampling space, and aligned them with the altitudinal bins of our NEXRAD vertical profiles of reflectivity. We then calculated the correlation coefficient for all sites across each altitudinal bin.

Results

Throughout our two spring migration seasons, we recorded over 1,587,000 birds using the BirdScan MR1 across 44 nights of sampling. The mean density during sampling was 2.53 birds/km², with a minimum density of 0 and a maximum density of 43.84. Within our sample periods, the mean nightly density of migrating birds as measured by the BirdScan MR1 did not significantly differ across sites ($F(9, 33) = 1.06$, $P = 0.414$). The mean number of cells removed from precipitation and range adjustment factor filtering did differ by site ($F(9, 795) = 13.41$, $P < 0.05$), however pairwise comparisons through Tukey's HSD tests revealed that these differences were, predictably, driven by our most blocked site and not by distance (Table S1). In total, we were able to compare 803 20-min sampling periods across our 10 sites.

Mean nightly models

Before filtering out insects from BirdScan density values, NEXRAD reflectivity was weakly correlated at the mean nightly scale (corrected: $r = 0.37$; uncorrected: $r = 0.38$). Upon applying an insect filter (Haest et al., 2023), NEXRAD reflectivity was more strongly correlated with BirdScan densities (corrected: $r = 0.85$; uncorrected: $r = 0.71$).

Consistent with correlation coefficients, models that included range-corrected NEXRAD reflectivity calculated as a nightly mean consistently outperformed uncorrected NEXRAD reflectivity models (Table 1). The model with two separate interactive terms for distance and NEXRAD reflectivity, and blockage and NEXRAD reflectivity had the highest adjusted R^2 (0.76) (Fig. 2). The likelihood ratio test revealed that this model did provide a slight improvement to fit relative to the null model ($F(41, 37) = 2.571$, $P = 0.054$). The intercept for this model was significantly larger than zero ($\beta = 8.699$, $SE = 1.483$, $t = 5.865$, $P < 0.01$) and range-corrected NEXRAD reflectivity was a significant predictor, with a positive relationship to BirdScan density ($\beta = 1.185$, $SE = 0.115$, $t = 10.34$, $P < 0.001$). We include a model summary in Table S2.

Within night models

Before filtering out insects from BirdScan density values, NEXRAD reflectivity was, again, weakly correlated at the within-night scale (corrected: $r = 0.31$; uncorrected:

Table 1. Summary of the adjusted R^2 values for six linear models used to characterize the relationship between mean nightly measures of BirdScan MR1 migration densities (birds/km²) and NEXRAD reflectivity (cm²/km²).

Model	Adjusted R^2
BirdScan $\sim$ NEXRAD _{corrected} + block*NEXRAD _{corrected} + dist*NEXRAD _{corrected}	0.758
BirdScan $\sim$ NEXRAD _{corrected} + block*dist*NEXRAD _{corrected}	0.748
BirdScan $\sim$ NEXRAD _{corrected}	0.721
BirdScan $\sim$ NEXRAD _{uncorrected} + block*NEXRAD _{uncorrected} + dist*NEXRAD _{uncorrected}	0.692
BirdScan $\sim$ NEXRAD _{uncorrected} + block*dist*NEXRAD _{uncorrected}	0.686
BirdScan $\sim$ NEXRAD _{uncorrected}	0.497

Note: We include the model formula with its corresponding adjusted R^2 .

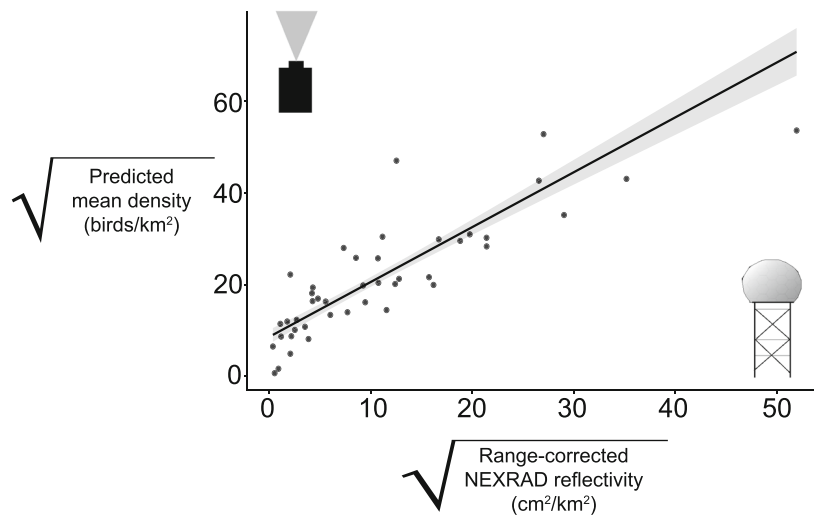


Figure 2. Mean nightly bird density (birds/km²) as predicted by nightly range-corrected NEXRAD reflectivity (cm²/km²) from best-supported linear model. Shaded gray area denotes standard error and data points represent the observed values from the dataset used to develop the model from a dataset of 44 nights of field sampling.

$r = 0.25$). Upon applying an insect filter, NEXRAD reflectivity was more strongly correlated with BirdScan densities (corrected: $r = 0.70$; uncorrected: $r = 0.64$).

In contrast to nightly means, the uncorrected NEXRAD reflectivity model set outperformed range-corrected model sets when data were analyzed within nights (Table 2). The three-way interactive term between distance, blockage, and NEXRAD reflectivity model explained the most variance for both corrected and uncorrected reflectivity, with the uncorrected model providing the highest R^2 value ($R^2_{\text{marginal}} = 0.36$; $R^2_{\text{conditional}} = 0.67$). The likelihood ratio test revealed that this model provided significantly better fit relative to the null model ($\chi^2(6) = 29.22$, $P < 0.01$). The intercept for this model was significantly larger than zero ($\beta = 15.140$, $SE = 1.469$, $t = 10.30$, $P < 0.01$). Uncorrected NEXRAD reflectivity was a significant predictor, with a positive relationship to BirdScan density ($\beta = 0.557$, $SE = 0.057$, $t = 9.813$, $P < 0.01$). Additionally, the interactive term for blockage and NEXRAD

reflectivity was a negative predictor of BirdScan density (blockage: $\beta = -0.317$, $SE = 0.069$, $t = -4.581$, $P < 0.01$) (Fig. 3). The three-way interactive term between distance, blockage, and NEXRAD reflectivity was also a negative predictor of BirdScan density ($\beta = -0.309$, $SE = 0.068$, $t = -4.507$, $P < 0.01$). Distance on its own as a non-interactive predictor had a positive relationship with BirdScan density ($\beta = 4.569$, $SE = 1.491$, $t = 3.068$, $P < 0.01$). We include a full model summary in Table S3.

To further explore the discrepancy between correlation coefficient and linear mixed models results with respect to the relative performance of range-corrected and uncorrected NEXRAD model sets, we built subsequent three-way interaction models with subsets of data within 30, 45, 65, 85 km and calculated the conditional R^2 values for each model. We chose this model structure because it performed best with the full dataset for both range-corrected and uncorrected model sets. Models performed similarly within 65 km, with range-corrected

Table 2. Summary of model performance for six linear mixed models used to characterize the relationship between within night measures of BirdScan MR1 migration densities (birds/km²) and NEXRAD reflectivity (cm²/km²) in 20-min intervals.

Model	R ² marginal	R ² conditional
BirdScan ~ NEXRAD _{uncorrected} + block*dist*NEXRAD _{uncorrected} + (1 date)	0.364	0.674
BirdScan ~ NEXRAD _{uncorrected} + (1 date)	0.361	0.667
BirdScan ~ NEXRAD _{uncorrected} + block*NEXRAD _{uncorrected} + dist*NEXRAD _{uncorrected} + (1 date)	0.370	0.651
BirdScan ~ NEXRAD _{corrected} + block*dist*NEXRAD _{corrected} + (1 date)	0.354	0.646
BirdScan ~ NEXRAD _{corrected} + block*NEXRAD _{corrected} + dist*NEXRAD _{corrected} + (1 date)	0.359	0.629
BirdScan ~ NEXRAD _{corrected} + (1 date)	0.341	0.591

Note: We include the model formula with its corresponding marginal R² and conditional R² values.

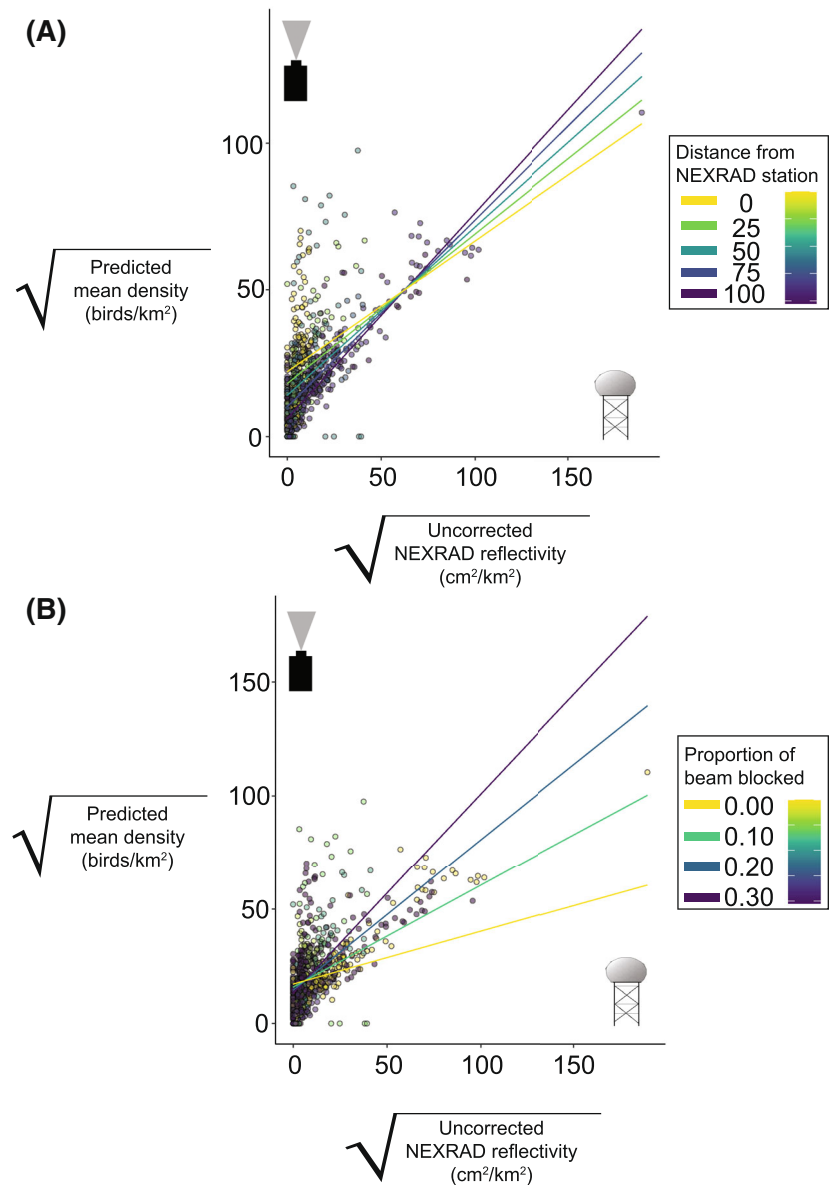


Figure 3. (A) Within night, mean bird migration density (birds/km²) as predicted by uncorrected NEXRAD reflectivity (cm²/km²) in 20-min sampling periods from best-supported linear mixed model. Line color is used to denote predictions at varying distances from the KCYS NEXRAD station at mean beam blockage (0 when scaled) (A) and given varying proportions of beam blockage at mean distance from the station (B). Observed data points are plotted with color denoting distance and blockage as continuous variables.

Table 3. Summary of deviance explained for linear mixed models used to characterize the relationship between within night measures of BirdScan MR1 migration densities (birds/km²) and NEXRAD reflectivity (cm²/km²) in 20-min intervals.

Model: <i>BirdScan</i> ~ <i>NEXRAD</i> + <i>block*dist*NEXRAD</i> + (1 <i>date</i>)		
Maximum distance (km)	Conditional R^2	
	Range-corrected	Uncorrected
30	0.844	0.841
45	0.848	0.846
65	0.745	0.742
85	0.682	0.703
100	0.646	0.674

Note: Models were built with a consistent model formula, but with subsets with varying maximum distances between the radar systems.

models providing slight enhancements to performance ($R^2 \pm 0.004$). However, beyond 65 km this pattern was reversed, with uncorrected models outperforming range-corrected models (Table 3).

Across all sites, we compared the vertical profiles at altitudes ranging from 1900 to 2900 m above sea level. The vertical profiles of each radar system were most correlated at low altitudes and became decoupled at the highest altitudes (Table S4), ranging from 0.68 to 0.08, respectively (mean = 0.394, SD $\pm$ 0.189).

Discussion

As weather radar surveillance systems continue to expand their role in aeroecology, it is crucial that we understand the potential sampling biases and limitations associated with these data (Bauer et al., 2019). We conducted a field-based ground-truthing experiment that quantifies the effects of range and topographical blockage on the NEXRAD system's ability to estimate bird migration activity. At both the nightly and within-night temporal scale, we found that NEXRAD reflectivity was highly correlated with measures of local density. We also found evidence to suggest that these reflectivity measures become less reliable with both increasing distance and beam blockage (Table S3). However, we also found that uncorrected data are a better predictor of migration density than range-corrected data beyond a range of 65 km at the within-night temporal scale, highlighting the spatiotemporal limitations of current range correction methods.

Our finding that NEXRAD reflectivity correlates strongly with local measures of density adds to a growing body of literature demonstrating relatively consistent metrics of migration across different monitoring systems (Dokter et al., 2011; Gauthreaux et al., 2019; Nilsson et al., 2018). The high level of correlation between

weather radar and a dedicated bird radar monitoring system at multiple spatial and temporal scales is encouraging and supports assertions that radar systems can be used as a reliable tool for studying birds aloft (Kelly & Stepanian, 2020). On the whole, our results provide support for the continued use of NEXRAD-derived estimates of bird migration activity (Van Doren & Horton, 2018).

Beyond this overall support, our study design allowed us to explore nuances in how this relationship changes as a function of both range and blockage. With respect to range, our results support the long-held notion that bird detection is negatively impacted by distance as a result of increasing beam height (Buler & Diehl, 2009). This effect has long been recognized and our finding that models that included distance outperform null models emphasize the importance of accounting for range when sampling from stationary weather radars (Schmaljohann et al., 2008). To this end, we found that models with corrected data outperformed models with uncorrected data at the mean nightly scale, suggesting that current range correction measures are somewhat effective at reducing this bias (Dokter et al., 2019). Radar systems remained correlated at the within night scale as well, reinforcing the findings of Nilsson et al. (2018), which found that BirdScan and weather surveillance radars correlated well at a range of 20 km. Within 65 km, corrected and uncorrected models performed similarly. However, beyond this range, within night uncorrected models outperformed range-corrected models. This may suggest that current range-correction measures, which are applied increasingly across the radar aeroecology community (Hoekstra et al., 2024; Horton et al., 2023), may be limited beyond this spatial scale and temporal resolution. Given the relatively limited scope of our study design, it is not clear how generalizable our results are to the entire NEXRAD system. We suggest that future study designs collecting data at finer distance steps may be able to explore this relationship more closely.

In addition to range, our finding that beam blockage was a negative predictor of migration activity is particularly notable given that the proportion of beam blockage across our study sites ranged between 0.00 and 0.30, which does not represent the full range of blockage exhibited by sites in more mountainous regions (Buler & Dawson, 2014). This could suggest that beam blockage may be a significant factor even at low levels and raises the possibility that we may be underestimating its importance. Further, we found a significant interaction between distance and blockage, which may suggest that corrective measures should incorporate both sources of bias. Our study not only serves as a primary step in quantifying their effects at varying distances within a specific NEXRAD site coverage area, but also demonstrates a

methodology with the potential to fine-tune existing range correction measures and inform the development of beam blockage corrective measures.

Temporally, we found that NEXRAD was a consistently stronger predictor of BirdScan densities at the nightly scale than the within-night scale, suggesting that increased temporal scale introduces additional variation. Many comparisons between radar systems have focused on metrics of nightly migration (Dokter et al., 2011; Nilsson et al., 2018). We find it encouraging that, even at the 20-min scale, both radar systems remained relatively well correlated. However, particularly as we expand the usage of NEXRAD data in aeroecology (Bauer et al., 2019, 2024), we recommend that additional work should be done to understand the potential tradeoffs of using weather radar at fine temporal scales.

To this end, we also note several aspects of our study that we could not fully explore but may serve as important areas for future research. Although it was not the explicit goal of this study, it is notable that NEXRAD reflectivity was much more strongly correlated with BirdScan densities upon filtering out insects. This finding reinforces the fundamental differences between these two radar systems. While BirdScan radars are able to detect individuals within its sampling range, NEXRAD provides a measure of total reflected energy within a sampling volume. Thus, as suggested by Stepanian et al. (2016), significantly more insects would be needed to equate to the same reflector size of a bird. Additionally, as noted above, we explored the effects of distance in 20 km steps and beam blockage of up to 0.30. Given we found effects at rather rough scales, we suggest that future studies at more detailed levels could further refine the relationships we describe. Relatedly, we found that vertical profiles between each radar system were most correlated at low altitudes across our sites. While this is consistent with previous work (Nilsson et al., 2018), we show that it remains supported across a much broader range of distances. However, direct comparisons of vertical profiles remain challenging, as the BirdScan profiles we calculated are site specific and NEXRAD profiles are much more general. Studies that explicitly study the relationship between these profiles could be valuable in explaining the mechanisms that drive range- and blockage-induced biases.

Finally, due to the pulsed nature of bird migration and the bulk of migration activity occurring across only a few nights (Van Doren & Horton, 2018), we recognize that our field campaign may have been limited in its ability to capture the range of migration activity at each site. This natural tradeoff of collecting data across multiple sites within a season may limit our ability to assess spatial variation separately from variation between nights. Studies that have collected ground-truthing data with a

dedicated bird radar at a single site for a full migration season have been vital to advancing our knowledge of the biases across different radar systems (Nilsson et al., 2018) and we suggest that taking this approach in the western United States would offer further insight into the range and blockage biases we present here.

To our knowledge, we provide the first natural experiment that explicitly explores the effect of range and beam blockage on detection using two complementary radar systems. In essence, our results validate the use of the NEXRAD weather surveillance system as a tool for studying nocturnal bird migration and emphasize the importance of existing analysis techniques, such as range-correction. Moreover, these findings highlight the limitations of current analysis techniques, particularly with respect to distance. We suggest that further validation research in mountainous regions, such as the western United States, will serve to refine NEXRAD as a tool in aeroecology research.

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Data availability statement

All code and data used in this study are publicly available on GitHub at https://github.com/Migfjim1/jimenez_et_al_RSEC_birdscan. The repository includes all code and a link to the data necessary to reproduce the analyses are provided. For questions regarding the data or code, please contact the corresponding author directly at migfjimenez@gmail.com.

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Supporting Information

Additional supporting information may be found online in the Supporting Information section at the end of the article.

Table S1. Summary of the number of PPI pixels with a range adjustment factor (R) greater than 10, which were removed from the raster output of NEXRAD reflectivity as part of data processing. Mean, median, and standard deviation of the number of removed pixels are summarized by site.

Table S2. Summary of the best supported linear model fit to the mean nightly of migration activity BirdScan MR1 and NEXRAD datasets. This model included the mean nightly BirdScan MR1 measures of density (birds/km²) as a response variable. Mean nightly NEXRAD range-corrected reflectivity (cm²/km²) was included as a fixed predictor. The percentage of beam blockage and the distance of the BirdScan MR1 from the NEXRAD station were also included as fixed predictors with an interaction with NEXRAD range-corrected reflectivity.

Table S3. Summary of the best supported linear mixed model fit to within night migration activity of BirdScan MR1 and NEXRAD datasets. This model included the mean BirdScan MR1 measures of density (birds/km²) in 20-min intervals as a response variable. Mean NEXRAD uncorrected reflectivity (cm²/km²) within the same interval was included as a fixed predictor, and the percentage of beam blockage and the distance of the BirdScan MR1 from the NEXRAD station were included as a three-way interaction with reflectivity. Date was included as a random intercept.

Table S4. Correlation coefficient summary between the proportion of migration activity between BirdScan MR1 and NEXRAD radar systems. The densities of each radar system were subset into 100m bins and calculated as a proportion of total activity across all altitudes. Densities were summarized into 20-min periods as a unit of within-night comparison.