USING A DUAL-POLARIMETRIC WEATHER RADAR SIMULATOR TO INVESTIGATE MICROWAVE BACKSCATTER FROM BIRDS

Phillip B. Chilson[1,2,*], Kara Bolognini[1], Boon Leng Cheong[2], and Jeff Kelly[3,4]

[1] School of Meteorology, University of Oklahoma, Norman, Oklahoma, USA
[2] Atmospheric Radar Research Center, University of Oklahoma, Norman, Oklahoma, USA
[3] Department of Zoology, University of Oklahoma, Norman, Oklahoma, USA
[4] Oklahoma Biological Survey, University of Oklahoma, Norman, Oklahoma, USA

1. INTRODUCTION

Aeroecology, the discipline that embraces and integrates the domains of atmospheric science, ecology, earth science, geography, computational biology, and engineering was aptly named and created to study the effects of the environment on the organisms that reside in and depend on the boundary layer for survival (Kunz et al., 2008). Aeroecology has incredible potential within the realm of radar ornithology. Tracking birds with radar merits attention from all scientific disciplines, but especially from meteorology, aviation, biology, and ecology. The collaboration of these fields in the area of radar ornithology can advance information and technology related to birds and their migration patterns, changing environmental factors and their effects on avian population, migration, and stopover habits.

Another important interdisciplinary focus of radar ornithology is to reduce collisions between birds and commercial aircraft. More effective monitoring of airport space using radar and better bird filtering techniques can lead to help decrease incidents between birds and aircraft. Between 1990 and 2008, over 106,000 incidents were reported of birds striking aircraft, according to the Federal Aviation Administration. A total of 2,780 of these strikes were considered to inflict substantial damage; meaning serious structural damage was incurred as to adversely affect the structural integrity, performance, or flight characteristics of the aircraft (faa.gov-“National Wildlife Strike Database”). With the recent interest and national spotlight on the 15 January 2009 event of U.S. Airways Flight 1549 making an emergency landing in the Hudson River due to a collision with birds, the potential in radar ornithology and its applications has increased dramatically. Improved radar identification techniques and more knowledge about specific locations and migration patterns of birds will allow for airport staff, air traffic controllers, pilots, and radar operators to safely and quickly navigate aircraft out of harms way. Thus commercial aircraft companies could possibly save over $500 million in potential damage costs of bird-related incidents with aircraft each year and, above all, avoid the irreplaceable loss of life (Dolbeer, 2006).

The idea of tracking birds with radar is not a recent development. Radar echoes from birds and insects account for many of the dot angels that were seen on radar displays as far back as the mid-1940s and World War II (Lack and Varley, 1945; Dobson et al., 1968). However, there has been renewed interest in using radar for ornithological research in recent years. It has become much more feasible to perform increasingly sophisticated studies and obtain more detailed data with the 1990 implementation of the WSR-88D Next Generation Radar (NEXRAD) network of radars in the United States and ever-advancing technology (Larkin, 2005).

Prior to Doppler radar many other types of radars were used to detect, monitor, and quantify bird flight, roosting, feeding, and migration patterns in the atmosphere (Dobson et al., 1968). The most popular tracking tools to monitor avian activity include military radars, small tracking radars, and marine radars (Larkin, 2005). Marine radars are the most commonly used radars to track ornithological movements. They are able to measure several parameters of the birds, including speed, track, and position. However, there are limitations to marine radars abilities to detect bird targets. The most serious of these includes a large beam width that dissipates power over a large volume, reducing the range of target detection. Despite the limitations associated with them, marine radars are often the most cost-effective and reliable solution to tracking birds for recreational and educational endeavors (Larkin, 2005).

Since the installation and implementation of the Doppler Weather Surveillance Radar (WSR-88D, or NEXRAD) network in the United States in 1990 (Crum and Alberty, 1993), interest in the academic community in using radar for ornithological research has increased dramatically and a new dimension of research was in-

* *Corresponding author address:* Phillip B. Chilson, University of Oklahoma, School of Meteorology, 120 David L. Boren Blvd., Rm 5900, Norman, OK 73072-7307; e-mail: chilson@ou.edu

troduced (Buler and Diehl, 2009). The most effective way to track and quantify birds and migratory patterns in the United States is through the use of WSR-88D radars. This network of 154 radars is located throughout the United States and is used for a variety of applications, primarily for weather research and analysis. Other worthwhile uses of NEXRAD include aviation and ornithological purposes. Each WSR-88D uses a 10-cm wavelength (S-band) and has a range coverage extending out to 124 nautical miles (Gauthreaux Jr. and Belser, 2003).

Other biological targets in addition to birds, can be detected by radar and in some cases reflect local conditions and/or animal migration. Despite this history of biological use, there remain persistent and significant limitations in using the existing NEXRAD system for biological monitoring. In part, these problems stem from 1) the lack of a robust biological nexus within the radar community, 2) the current limited ability of NEXRAD to reliably discriminate among targets of different taxonomic origins, 3) the manner in which the data are filtered before being released to the public, and 4) a paucity of available funds to adequately explore this topic. In addition to limiting the biological value of radar data, the failure to cleanly separate biological and meteorological targets in existing radar data compromises the quality of weather monitoring and forecasting. In order to confront some of these limitations, we have adopted a modeling approach that allows us to simulate backscatter from biological targets using a virtual weather radar. The simulator provides a platform that allows quasi-realistic interactions of dual-polarimetric microwaves with individual virtual birds placed within the sampling domain and which produce raw (in-phase and quadrature) data streams corresponding to the backscattered radar signals.

2. ARRC WEATHER RADAR SIMULATATOR

The University of Oklahoma (OU) Atmosphere Radar Research Center (ARRC) has developed and maintains a sophisticated weather radar simulator, which can be used to explore the application of a variety of radars for a wide range of meteorological scenarios (Cheong et al., 2008). The ARRC Weather Radar Simulator (AWRS) generates realistic in-phase and quadrature (I & Q) time series radar data as a result of the modeled electromagnetic waves allowed to propagate through the simulated domain and interact with thousands of point targets distributed within the domain. The scattering properties of each point target as well as their velocity components are determined from output data from the Advanced Regional Prediction System (ARPS) developed at the Center for the Analysis and Prediction of Storms (CAPS) at OU (Xue et al., 2003). A radial and angular weighting functions are used to scale the contribution of the scatters to the total signal. The angular weighting function is patterned after a Bessel function based on the simulated antenna shape and size. The range weighting function is approximated using a Gaussian function centered on the desired range.

The spatial and temporal resolution of the ARPS output are typically 25 m and 1 s, respectively. To begin the simulation process, scatterer characteristics are initialized from a known ARPS data set. At the next time step, the scatterer positions are updated according to the wind field as well as their corresponding properties at their new locations. The return signal amplitude and phase from each scatterer is then processed via Monte Carlo integration to calculate time series of the desired meteorological parameters. Moment data from the simulator are calculated from the I & Q time-series data. In addition to simulating conventional weather radars with dish antennas, the AWRS can also operate in a phased array mode or in a dual-polarization mode.

The AWRS has recently been modified to include the effects of backscatter from biological point targets such as birds and bats. In the current version of the simulator, it is possible to model birds of various sizes, aspect ratios, spatial distributions, and flight speeds. There is also a means of accounting for the time varying wing beat frequencies of the virtual birds. The ability to study echoes from the virtual birds under a controlled environment is expected to lead to a better understanding of how radio waves interact with actual birds. Results from the weather radar simulator will ultimately be compared to real dual-polarimetric weather radars operating at C- and S-band. Such a study is particularly timely considering the future polarimetric upgrade of the NEXRAD network.

3. REAL AND SIMULATED RADAR OBSERVATIONS OF PURPLE MARTINS

To demonstrate one application of the AWRS, we consider the departure of purple martins from a roosting site in northeastern Oklahoma. Purple martins are colonial nesters and often assemble in nocturnal roosts, which have been observed to reach numbers of inhabitants larger than 700,000 (Russell et al., 1998). In central and eastern North America, the martins will begin congregating in late June and their numbers will peak in late July to early August. They will have mostly vacated these roosts by late August as they continue along their migratory trek towards southern climes. Typically the purple martins depart their roosting sites in the morning just before sunrise and return in the evening around sundown. During early morning departure, it is common to observe the birds traveling radially outwards from the roost in all cardinal directions (Russell and Gauthreaux Jr., 1998). This behavior can, however, be influenced by weather conditions or the orographic features associated with the roosting site.

One of the popular roosting sites for purple martins is in Tulsa, OK area. Every year during the summer between 100,000 and 250,000 of these birds will take up temporary residence in the downtown area. Their early morning departure can be observed in the radar displays from the WSR-88D KINX (Tulsa, OK), which is only about 40 km from the roosting site. Figure 1 presents an example of a radar display showing echoes (depicted in dBZ) from purple martins as they leave the roost. The image was recorded on August 2, 2009 at about 11:16 UT (06:16 local time). The location of the radar is denoted as "INX". Range rings centered on the roost site and spaced every 2 km have been overlaid on the image for reference. A reference colorbar is not shown, but the light and dark green colors correspond to reflectivity values of about 25 and 30 dBZ, respectively. A second roost can be seen in the image about 14 km south of the radar site. Actually, inspection of the entire radar scan for this time reveals that several martin roosts are located in the vicinity of KINX.

Next we consider the radial velocity data from KINX for the same time as shown in Figure 1. The velocity data are shown in Figure 2. Again, no reference colorbar is provided, but the burnt red and cyan colors prominent around the Tulsa roost correspond to velocity values of approximately 10 m s^{-1} and -10 m s^{-1}, respectively. The pattern apparent in the radial velocity field is indicative of divergent motion, as we would expect. Note that a similar pattern and radial velocity values are associated with the roost located south of the radar.

In order to simulate the departure of the purple martins from their roosting site, we have begun developing several modules, which can be run within the AWRS. A total of N_{birds} birds are originally located at position $x_o + \Delta x_o * \texttt{randn}$, $y_o + \Delta y_o * \texttt{randn}$, and $z_o + \Delta z_o * \texttt{randn}$, where `randn` corresponds to a normally distributed pseudorandom number generator having a standard deviation of one. The values of x, y, and z are all expressed relative to the location of the radar, which is positioned at $(x = 0, y = 0, z = 0)$. The birds leave the roost in a continuous stream over a time interval given by t_{exit}. After this period, all birds will be aloft. The flights of the birds are simulated for N_{steps} with the time interval between each step being dt.

The flight speed and directions of the birds are broken down into radial (horizontal) and vertical components. Each simulated bird departs in a random cardinal direction given by $2\pi * \texttt{rand}$ and is assigned a radial velocity given by $v_r + \Delta v_r * \texttt{randn}$. Here `rand` corresponds to a uniformly distributed pseudorandom number generator. For each subsequent time step, the radial direction for every bird that has left the roost is modified using $\Delta\theta * \texttt{randn}$ and its radial velocity is updated using $v_r + \Delta v_r * \texttt{randn}$. The vertical trajectory of each bird is assumed to follow a track that follows the analytic form given by

$$z(t) = z_{max}\,[1 - \exp(-t/\tau)]. \qquad (1)$$

Consequently, the vertical velocity w can be written as

$$w(t) = z_{max}/\tau\, \exp(-t/\tau). \qquad (2)$$

The values of z_{max} and τ are updated for each time step and for each bird according to $z_{max} = z_o + \Delta z_o * \texttt{randn}$ and $\tau = t_o + \Delta t_o * \texttt{randn}$. Additionally, the calculated value of w can be further adjusted for each bird and for each time step using $w = w + \Delta w * \texttt{randn}$.

Table 1: Parameters used to simulate purple martins leaving a roost. See text.

Symbol	**Description**	**Value**
N_{birds}	Number of birds	10,000
N_{steps}	Number of time steps	310
dt	Time interval per step	1 s
x_o	Initial x position	-40,500 m
y_o	Initial y position	0 m
z_o	Initial z position	0 m
Δx_o	Variation of x_o	100 m
Δy_o	Variation of y_o	100 m
Δz_o	Variation of z_o	0 m
v_r	Radial velocity	10 m s^{-1}
Δv_r	Variation of v_r	5 m s^{-1}
$\Delta\theta$	Variation of θ	15°
t_o	Ascent time constant	50 s
Δt_o	Variation of t_o	5 s
z_o	Max ascent height	450 m
Δz_o	Variation of z_o	100 m
t_{exit}	Duration of exit	180 s
Δw	Variation in w	0.3 m s^{-1}
σ_b	Radar cross-section	15 cm^2
$\Delta\sigma_b$	Variation of σ_b	1 cm^2
R_{asp}	Aspect ratio	0.5
ΔR_{asp}	Variation of R_{asp}	0.1
$\Delta\phi_{scat}$	Variation of ϕ_{scat}	0

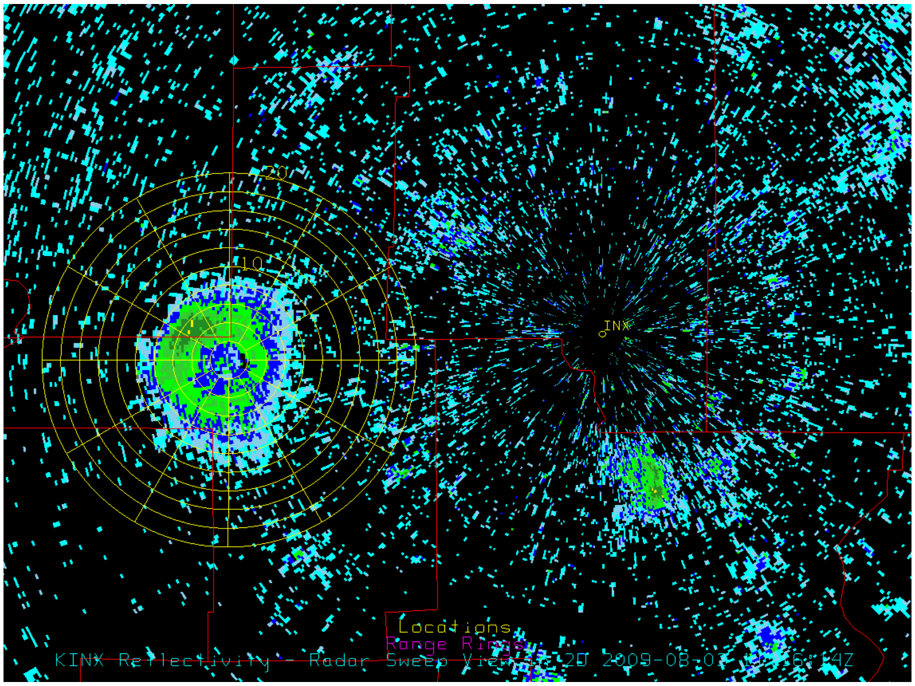

Figure 1: Example of roost rings visible in reflectivity data from KINX near Tulsa, OK. The radar echoes are the result of large numbers of purple martins departing from a roosting site around sunrise.

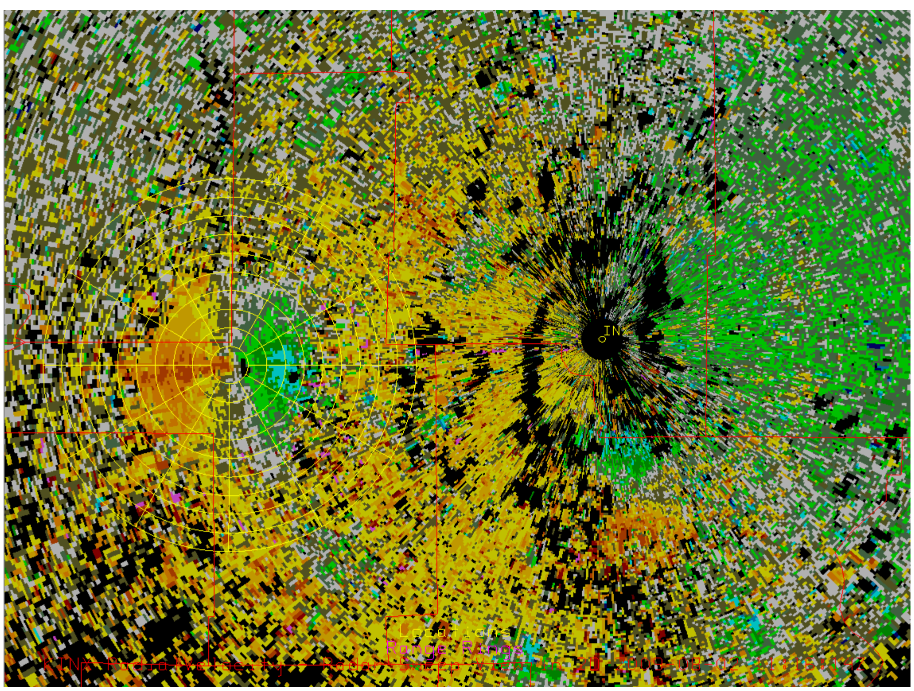

Figure 2: Image of radial velocity data corresponding to results shown in Fig 1.

Next we must consider the scattering properties of the birds. The backscattering characteristics of the birds are determined through assigned radar cross-section (RCS) values. Each bird is given an RCS according to $\sigma_b + \Delta\sigma_b * \texttt{randn}$. Furthermore, the aspect ratio of the birds is assigned using $R_{asp} + \Delta R_{asp} * \texttt{randn}$. These values do not currently change as the simulator time is updated. Finally, a random phase term is associated with the backscatter of each bird. This is meant to simulate wing beats, but is currently set to zero.

The AWRS was configured and run for a case corresponding to purple martins located near the radar site such they could be observed as they left their roost. The parameters for the simulated radar (wavelength, beam width, pulse width, pulse repetition frequency, and so forth) were consistent with those for a WSR-88D. The location of the roost with respect to the radar was similar to that for the Tulsa roost with respect to KINX. Additional parameters used to configure the simulator are given in Table 1. For this run, the weather signal was disabled. That is, only backscatter from the birds is considered.

The primary purpose of this simulation was to ascertain if the scattering physics and the crude model of the birds' flight trajectories used would produce reasonable results. We realize that many refinements will be needed in order to produce realistic roost ring echoes patterns. Bearing that in mind, we next present an example of the spatial distribution of the simulated purple martins during one time step. These data are shown in Figure 3. Note that the scale for the z-axis (representing height above the surface) has been exaggerated with respect to the scales for the horizontal dimensions. The AWRS was configured such that radar data were collected every 10 s. The positions depicted in the figure correspond to the 20th set of radar data or 190 s into the simulation. At this point in time, all of the martins willl have left the roost (from Table 1 we see that $t_{exit} = 180$ s).

The simulated radar image corresponding to the bird locations shown in Figure 3 is presented in Figure 4. Data are for an sector scan with an elevation angle of 0.5°. Time series (I & Q) data are shown in the upper left hand panel for a particular sampling volume. There are 50 points in the time series. The corresponding Doppler spectrum is shown in the upper right hand panel. Also shown with the Doppler spectrum are fits to the data and an estimate of the radial velocity. There are 19 azimuthal scans, each separated by 1°. Additionally, there are 36 range gates separated by 250 m. The range resolution given by the 3-dB points is 235 m (pulse width $\tau = 1.57\mu$s). The middle three panels show the reflectivity (dBZ), radial velocity ($\mathrm{m\,s^{-1}}$), and the spectrum width ($\mathrm{m\,s^{-1}}$) for the horizontal polarization. The data shown in the upper two panels were were collected in the sampling volume denoted by the 'x' mark. The lower three panels are the same as for the middle three, except that data from the vertical polarization are shown.

Similarities between the data shown in Figures 1, 2, and 4 are clearly visible. The annular pattern in the derived radar fields has been reproduced in the simulated data and values of reflectivity and radial velocity also match those observed using KINX. Although not shown for KINX, the spectral width data from the AWRS are also similar to those observed.

For the sake of comparison, a second radar data realization from the AWRS is shown in Fig 5. There are no surprises here. The outer diameter of the annulus is larger (6 km compared to 4 km) and a more distinct 'eye' in the annulus can be seen. It does show that that simulator is capable of producing consistent sequences of data as a function of time.

4. FUTURE DIRECTIONS

In its present state of development, the primary focus has been the modification and testing of the AWRS as a means of realistically simulating radar echoes coming from biological targets such as birds. Early results are encouraging, but we hope to be able to continue these developments. For example, a mechanism to facilitate the effects of wingbeat frequencies for birds has already been envisioned and implemented, but it requires further testing. This will enable us to more accurately model avian flight parameters. Dual polarimetric radar will provide more detailed information concerning targets, and open up a more detailed way to analyze discrete radar signals. The AWRS is already capable of generating dual polarization radar signals, but again, more testing is needed in this area. A sensitivity study could be performed in the future and test how well the proposed formulas work when the radar sampling volume decreases and birds approach close to the radar.

We have begun exploring how bats are seen on weather radar. Similar to birds, when bats leave their dwellings in search for food, they produce ring patterns in the fields of radar products such as reflectivity, radial velocity, and spectrum width. An example of how bats are seen in reflectivity data is shown in Figure 6. These data were collected in Texas using KEWX. As is true for bird observations, when properly adjusted, the reflectivity data can be used to estimate the number densities of the bats.

5. CONCLUSION

The implications of tracking birds with radar are far-reaching. Integrating several science fields into radar ornithology in order to further knowledge and technology in all of the disciplines will be very important in the future. As more ornithologists become interested in using radar to observe and analyze avian migration move-

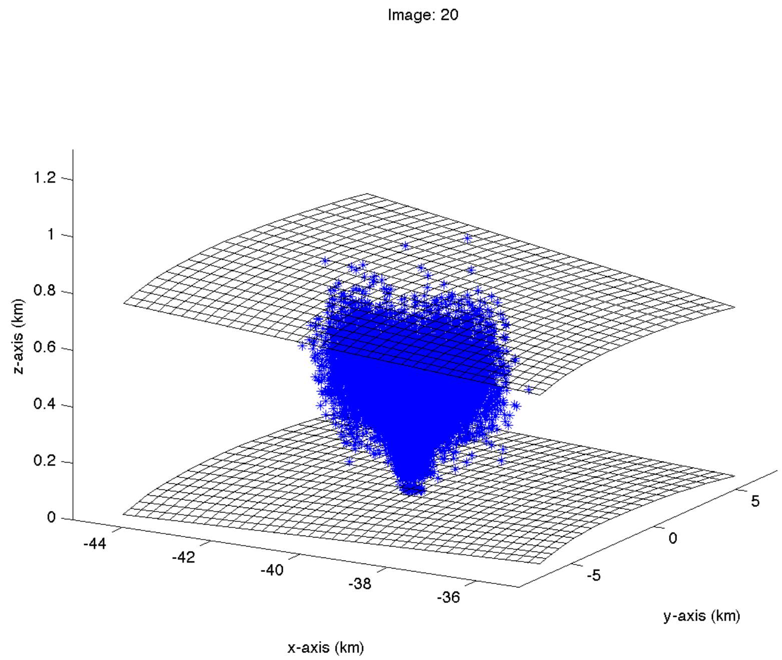

Figure 3: A snapshot of the spatial distribution of the martin locations during one time-step of the simulation run.

ments, more information will be come available with ever-advancing radar technology. With the advance of dual-polarimetric radar on the near horizon, additional information will be extracted from radar data.

Tracking bird migration patterns with radar will give ornithologists a better understanding of how the environment affects migration patterns. Whether global climate change affects spring and autumn migration timing is a very large issue in the ornithological community that could be further researched using radar. Changing environments and food source phenology and optimal breeding time due to global climate change could change fall and spring migration times (Hedenstrom, 2009). Using radar to investigate long-term patterns of migration times would be helpful to ornithologists in assessing the environmental and climatological impact on bird migration times and patterns.

There exists a huge potential for stronger collaboration between biologists and radar researchers. Often the difficulty in forming these collaborations lies in momentum of initially bridging the gap. Tools such as the AWRS and other model based approaches to studying the effects of biological targets on radar can help facilitate cross-fertilization between these fields. Simulation studies will also help us to better understand and interpret the signals recorded by real radars of birds, bats, and bugs.

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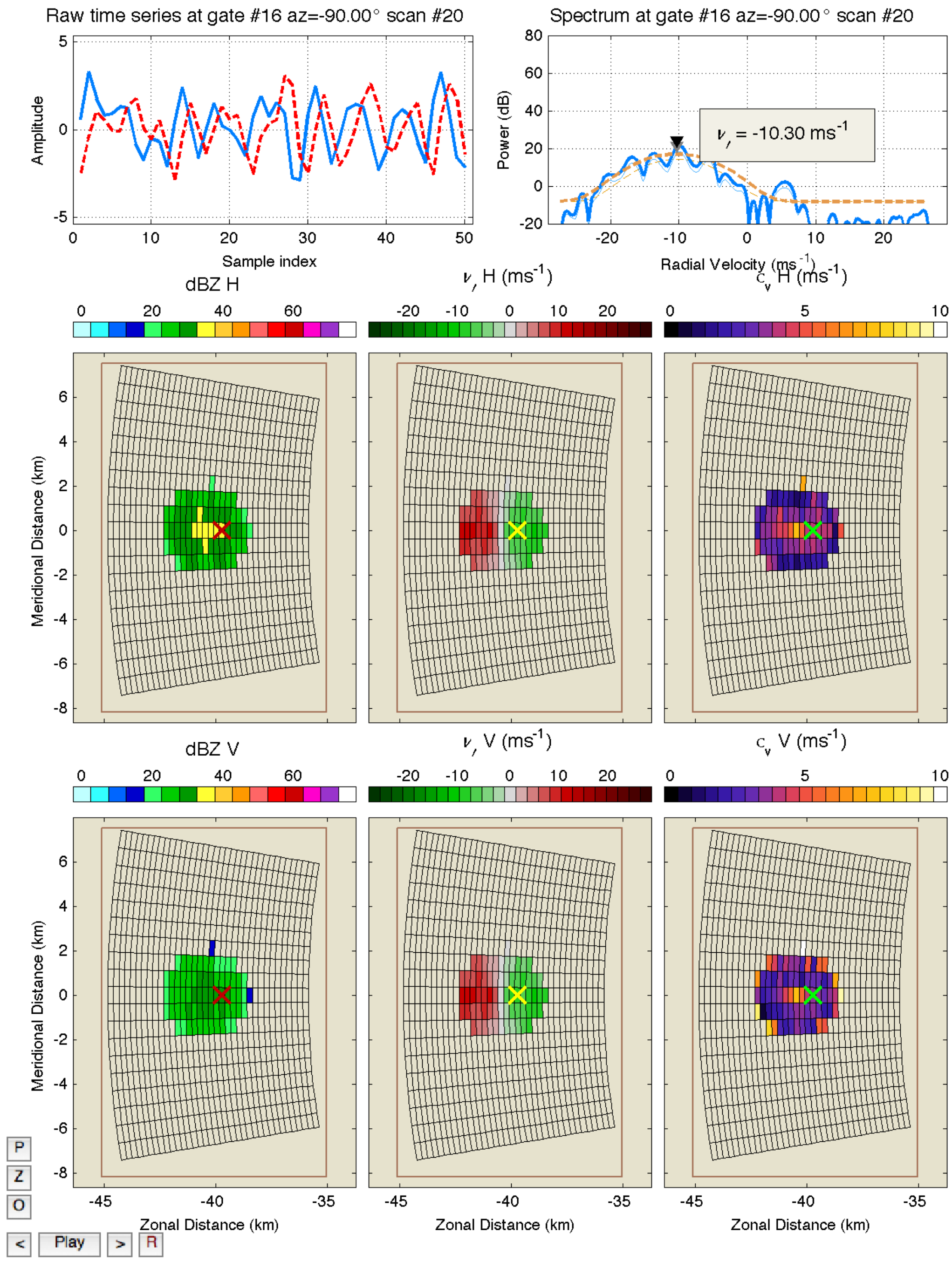

Figure 4: Simulated radar data for the bird positions shown in Fig 3 See text for an explanation of the format.

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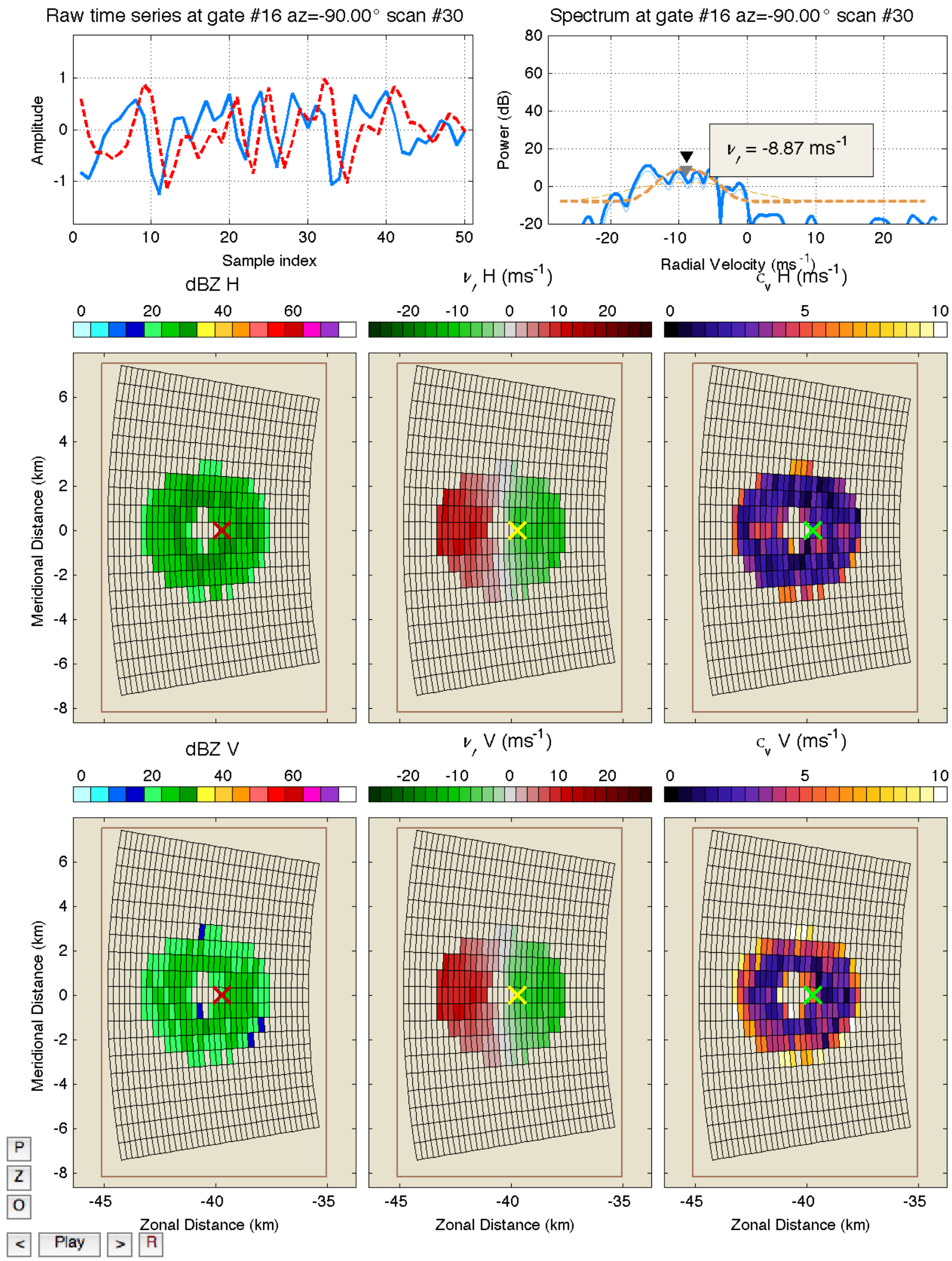

Figure 5: Same as for Fig 4 except the 30th set of radar is shown (310 s into the simulation).

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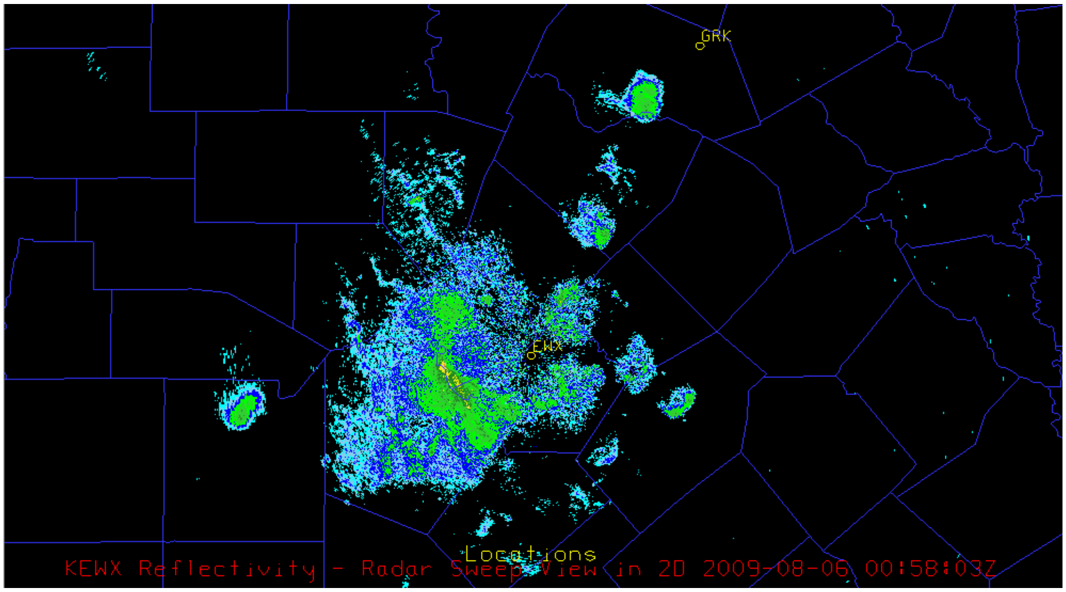

Figure 6: Example of radar echoes from KEWX in Texas caused by bats. Here, the locations of several bat caves can be identified by the plumes of enhanced reflectivity values.

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