Public Service Commission of Wisconsin
& The Statewide Energy Efficiency and Renewables Administration

Environmental and Economic Research and Development Program

Final Report
July 2008

A Landscape Scale Decision Support Tool for Monitoring Bird and Bat Migration Across Wisconsin

Prepared by:

Manuel Suarez, US Geological Survey
Patricia Heglund – US Fish and Wildlife Service
Robert Kratt, Media Specialist – US Geological Survey
Eileen Kirsch, U.S. Geological Survey

This report in whole is the property of the State of Wisconsin, Public Service Commission of Wisconsin, and was funded through the FOCUS ON ENERGY program.

Executive Summary

Location: The Upper Mississippi River Region, primarily focusing on stations in Wisconsin but also includes Nexrad stations in Illinois, Iowa, Michigan, and Minnesota.

Objective of research

This project was initiated to begin addressing the uestion, "Are there patterns in timing, location, and direction among migrating landbirds?" that have been at the forefront of discussion with our Federal, State, and County partners with regard to siting wind energy projects. Our goal was to explore the use of Nexrad weather data to see if examining 5 or more years' worth of data would provide us with a sense of the general timing, movement patterns and habitat use by migrating landbirds.

How Nexrad Works

Next-generation Radar, or Nexrad, is the colloquial term for Weather Surveillance Radar-1998 Doppler (WSR-88D), the system of over 150 long-range weather monitoring radars operated by NOAA, the DoD, and the FAA. The primary purpose of the network is to allow meteorologists to forecast significant weather events to protect the people of the United States. However, the radars detect not only meteorological events, but also particulate (e.g. smoke and dust) and biological (e.g. birds, bats, and insects) events as well. The concept of long-range radar biology then, is to identify, observe, and study the biological signals present in the radar data.

A traditional radar system emits radio waves, either continuously or in pulses, and measures the time it takes to receive that energy reflected from a target (e.g. rain drop, bird, etc.). From this, the range to the target can be determined. Doppler radar systems can also measure the radial velocity of a target relative to the station by measuring the frequency shift of the return signal. Due to the “Doppler Effect”, objects moving toward the radar cause an increase in frequency (shorter wavelength or “blue-shift”), while objects moving away from the radar return a lower frequency (longer wavelength or “red-shift”).

Why We Chose to Investigate the Use of Nexrad to Study Migration

A strength of the Nexrad system is its nationwide distribution with 154 stations across the United States with many of these stations located in the Midwestern US. Given the broad spatial coverage (for migrating birds, each station has an effective range of about 80 miles from the center of each station) and dense temporal coverage (signals have been collected every 5-10 minutes since the early to mid 1990s), Nexrad provides a unique potential to study avian migration on a regional or national scale.

It is important to note that it is time- and technologically-challenging to amass large amounts of Nexrad data. Each Nexrad station produces hundreds of volume scans per day and the amount of data to sort through and identify biological phenomenon is staggering. We believe there is potential in monitoring migration from a landscape scale and compiling data from multiple years to look for patterns in timing and movements to help communities, managers, and agencies evaluate proposed siting of wind energy projects. We developed this product as a means to more quickly visualize potential patterns in the Nexrad data and also provide supporting data for more in-depth investigation and analysis.

Caveats

There are limitations inherent in using Nexrad, however. First and foremost is that National or Statewide coverage is not complete. Where radar stations do not exist, there will be gaps in our knowledge about bird movements and timing. Nor can a tool developed for landscape scale assessment provide highly detailed information at the individual site scale. The value in the creation of a landscape scale animation is in its ability to help us hone in on areas that will require more detailed investigation and to look for patterns of timing and movement over time across Wisconsin.

Methods

Examining migration timing, looking for stopover locations, and evidence of possible pathways over multiple years and over any significant amount of space and time is difficult and computationally intensive. The first step is to capture and download the massive amount of data from all the radar stations in Wisconsin and specific sites in the surrounding states. We downloaded approximately a terabyte of data from the National Climate Data Center to create a dataset and visualization tool that could be used by scientists interested in exploring timing and movement patterns as detected by Nexrad. Then we used the data and supporting Flash software to create an animation viewer that would allow a user to visually inspect the data in a number of ways; from a single year and time period, or up to four seasons simultaneously. Six years of Nexrad data were downloaded and used to create animations during the peaks of spring and fall migration (April-May, September-October).

Results/Accomplishments

The animation tool is complete and users can select up to four months (April or May 2002 to 2007 or September or October 2002 to 2007) for concurrent display. Once a particular time frame is selected users can then analyze the raw data for more information with regard to weather patterns, explicit stop over locations, timing of exodus and fall out, etc. For researchers who are interested in conducting additional analyses on the data we recommend that you contact the lead author to obtain the full dataset.

Examples of Interesting Findings

While the scope of this project did not include in-depth analyses of the data, there are a few items that surfaced during the development of the tool and will require further attention. For example, under the 4-year viewer, we have noted lower activity in the Marquette, MI radar station relative to the stations along the Wisconsin border of Lake Michigan. There may be something blocking the radar at the Marquette site, or birds that follow the Lake Michigan shoreline may be taking a different pathway once they arrive at the Upper Peninsula of Michigan. We also observed progressions of movement from south to north in the spring data and from north to south in the fall data and this can be looked at more closely in terms of timing of movements. Lastly, when looking at individual years and months in the single –viewer mode, there are a few locations that repeatedly display high intensity returns, which suggest these might be stop over areas. Further investigation over multiple years and smaller scales is needed to confirm this.

Management Implications

Results from this work can be used in a variety of ways by managers and by researchers who are interested in the timing and patterns of migration events. The animation is a useful visualization of migration across a large landscape but the real value is in the data supporting the animation. We have developed the code necessary to partially automate the ordering and downloading process and can provide managers and scientists with the code (for those wishing to download data for a different time period or for additional years) as well as up to 6 years of daily Nexrad scenes during peak months for landbird migration.

Abstract

Migratory birds and bats face many challenges as they traverse the airspace between wintering and breeding grounds. Among these challenges are tall structures, including wind turbines and communication towers that are being erected or proposed across the United States and off shore. Complicating factors include the knowledge that birds and bats migrate at night and are therefore very difficult to track over long distances. In particular, neotropical migrant birds and bats tend to have small body sizes and therefore are too small to wear radio transmitters with enough capacity to monitor for long distances and long periods of time. Indeed, few tools exist for deciphering the migratory habits of volant species, but incorporating the use of radar to better understand migration movements and habitat use patterns, holds promise. Nexrad Weather Surveillance Radar (WSR-88D) is increasingly viewed as a potentially valuable resource in the study of bird and bat migration (Gauthreaux and Belser 1998b, 2003; Diehl et al. 2003; Diehl and Larkin 2005). The NOAA National Climatic Data Center (NCDC) archives WSR-88D data and makes it freely available through their website. We captured 6 years of data from the Nexrad WSR-88D sites located in Wisconsin (and in neighboring states) by generating time-series mosaics of the radar products. The animations allow the viewer to identify and summarize timing, stop over locations, and general pathways of movement

across Wisconsin where Nexrad coverage exists. Only by understanding the behavior and phenology of migrating birds and bats can we hope to minimize the impact of wind power generation projects on those populations. We are providing Wisconsin resource managers with a tool to help them better understand where and when large numbers of birds and bats are most vulnerable to development and operation of wind power generators. With this tool, managers can then better target site specific evaluations as individual projects arise as well as work preemptively with industry managers to select or avoid specific sites for future projects. Perhaps most importantly, managers and scientists can use the data for additional summarization of migration events. This report addresses the **Siting of Renewable Energy Projects: Wind energy** concern of the Wisconsin Focus on Energy: Environmental Research Program. The recent workshop entitled: "Applying radar technology to migratory bird and bat conservation and management: strengthening and expanding a collaborative effort" held October 23-26, 2006, in Albuquerque, New Mexico, identified the need of resource managers for decision support tools with regard to wind energy development as a high priority for future work.

1. Introduction

Migratory birds face many challenges in the landscapes they traverse and the habitats they use. Like Neotropical migratory birds, several bat species undertake long-distance migrations and are of conservation concern due to declining numbers. Wind turbines and communications towers pose hazards to birds and bats in flight. Both federal and state agencies are under increasing pressure to evaluate proposed energy projects in terms of their effects on volant wildlife yet, few tools exist to decipher migratory travels. Radar-based studies, however, show much promise for increasing our ability to map migratory pathways, to identify important stopover locations, and to monitor in-flight behavior. The U.S. Geological Survey recently convened a workshop: "Applying radar technology to migratory bird and bat conservation and management: strengthening and expanding a collaborative effort" in Albuquerque, New Mexico, October 23-26, 2006, that highlighted priorities for management oriented research. At this workshop priorities were established for both research scientists and resource managers. Among these priorities was the need to develop the capability to evaluate migration over time and space to help resource managers better understand the timing, pathways, and stopover characteristics of migrants across landscapes. Large scale patterns can then be used to inform and target more site-specific studies. Understanding how migrants use airspace will help guide human use of that same airspace.

Wind power projects, communication towers and other tall structures, known to cause bird and bat mortality are being erected or proposed at several locations in Wisconsin. By 2012, it is projected that more than 155,000 turbines will dot the U.S. landscape. For example, areas immediately adjacent to Horicon Marsh and the Neda mine, located in Dodge and Fond du Lac Counties, are situated along the Niagara Escarpment, a limestone rock shelf that runs from central Wisconsin to Niagara Falls, New York. The Niagara Escarpment provides a reliable source of sustained winds and holds great potential for wind energy development. The Neda mine hosts the largest known bat hibernaculum in the Midwest with as many as 400,000 bats wintering in the mine each year. Horicon Marsh is the largest freshwater cattail marsh in the United States. This marsh is renowned for its migrant flocks of Canada geese but it is also home to more than 260 other kinds of birds. Horicon Marsh is both a state wildlife area and national wildlife refuge and has been designated as a "Wetland of International Importance" and a "Globally Important Bird Area." Horicon Marsh is also listed on the National Register of Historic Places by the State Historical Society of Wisconsin in association with the U.S. Department of the Interior. The Marsh is also a unit of the National Ice Age Scientific Reserve. Land Managers working at the junctures of where wind development potential and important wildlife resources collide have been frustrated by the lack of information available on migration in this and other areas of the State.

Several site specific studies are currently under way to assess bird and bat movements. The problem with these studies is that development has already been proposed and often these studies, due to cost and time constraints, do not provide a comprehensive evaluation of the wildlife resources that may use the associated airspace. By providing a landscape and longer term view of how and when birds and bats are moving across the State we believe that resource managers can work with energy developers to take a preemptive approach to wind power generation project planning. We captured 6 years of data from the Nexrad WSR-88D sites located in Wisconsin and generated time-series mosaics (animations) of the radar products. Only by understanding the behavior and phenology of migrating birds and bats can we hope to minimize the effects of wind power generation projects on those populations. Through this report and our associated Long-range Surveillance Radar Biology Viewer, we are providing Wisconsin resource managers with a decision support tool to help them better understand where and when large numbers of birds and bats are most vulnerable to development. With this tool to help identify candidate locations and/or dates of migration, managers can more closely examine the mid-level data with regard to more specific locations as individual projects arise.

2. Long-range Surveillance Radar Biology

Next-generation Radar, or Nexrad, is the colloquial term for Weather Surveillance Radar-1998 Doppler (WSR-88D), the system of long-range weather monitoring radars operated by NOAA, the DoD, and the FAA (Figure 1). The primary purpose of the network is to allow meteorologists to forecast significant weather events to protect the people of the United States. The radars detect not only meteorological targets and effects, but particulate (e.g. smoke and dust) and biological (e.g. birds, bats, and insects) ones as well. The concept of long-range radar biology then, is to identify, observe, and study the biological signals present in the radar data.

A traditional radar system emits radio waves, either continuously or in pulses, and measures the time it takes to receive that energy reflected from a target. From this, the range to the target can be determined (Figure 2). Doppler radar systems have the further capacity to measure the radial velocity of a reflector relative to the emitter by measuring the frequency of the return signal. Due to the "Doppler Effect", objects moving toward the radar cause an increase in frequency (shorter wavelength or "blue-shift"), while objects moving away from the radar return a lower frequency (longer wavelength or "red-shift") (Figure 3). A third moment of reflectivity, known as Spectrum Width, measures the variability of velocities within a pulse volume.

The Nexrad systems are pulsed, S-band radars. Until recently –and for all the data reported here—the radars had a main lobe beam width of approximately 1° and sampled with one degree resolution in azimuth and a range resolution of 1,000m for reflectivity, 250m for velocity.[1]

The WSR-88D has two operational modes, Clean Air and Precipitation, each with a number of scanning strategies or Volume Coverage Patterns (VCP). Precipitation Mode is used when significant weather echoes are either present or anticipated. The VCPs for

[1] During the spring of 2008, the Nexrad network began a transition to upgraded specifications, called "super-resolution", which improves azimuthal resolution to 0.5° and range resolution to 250m for all three moments.

this mode consists of between 9 to 14 elevation angles and complete one full 360° volume scan in 4.2 to 6 minutes (Figure 4). This rapid update cycle along with the many elevation angles give meteorologists important temporal and vertical structure information needed to forecast the weather. In Clean Air mode the radar scans only at the 5 lowest angles, and takes 10 minutes to complete a full volume scan (Figure 5). The benefit, however, is that it provides much better signal-to noise ratio thus can detect objects with much lower reflectivity. This mode is ideally suited to detecting biological targets.

Due to the curvature of the earth, the altitude of the radar beam increases as it travels away from the radar unit. The result is that beyond a certain range, ~130km (~80 miles), the radar beam has typically gone above the level of migrating birds (Figure 6). This causes gaps in coverage between many radar stations in the network.

3. Processing

3.1. Data Acquisition

One of the most ambitious aspects of the current work was the collection and assembly of over 1TB (Terabyte, 2^{40} or ~10^{12} bytes) of raw Level-II Nexrad data. At the data rate available to us for much of the data acquisition period (1.5Mbps), this would have taken over two months of continuous downloading. Between unreliable connections, system downtime and discontinuous ordering, it took roughly six months to retrieve all the data

The NCDC hosts the world's largest archive of climate data, much of which is available free of charge via internet ordering and download. However, while the online ordering system, HAS (Hierarchical Data Storage System (HDSS) Access System), provides easy access to Level II Nexrad data, it is not well suited to large data orders. By default, it lists all 150+ stations when the user may only be interested in a handful (see Figure 7a). It becomes extremely tedious and error-prone to select individual stations from such a list with each order. To simplify the ordering process, a Greasemonkey script was written for the Mozilla Firefox web browser to display only the relevant stations, the dates of interest, and assign an e-mail address to which to send a completion/pick-up notice (Figure 7b).

The ordering form allows a maximum 10 stations for 7 days be requested at a time, but is limited to ~4.6GB (5×10^9 bytes) per order[2], which practically-speaking amounts to only 2-3 stations of Level II data for that period of time.

When the data is ready for pickup from the NCDC FTP server, an e-mail is sent to the address listed in the ordering form. Given the number of individual orders required to reach or target data quantity, a (python) script was written to check the e-mail account

[2] This has recently changed to 31 days for 10 stations, but since the volume cap has not changed, this does not practically increase the ordering limit, in fact since super-resolution data is more voluminous, one station for one week to 10 days is a more likely figure.

for new notification messages. When a new data order was available, the script would parse it's location on the server from the e-mail, connect to the server, and download the data. Once the data was successfully downloaded, the notification e-mail was deleted from the mail server.

3.2. Animation

The principal product of this work was a set of time-series animations of Nexrad weather radar, which include biological signals. Target discrimination, that is separating biological from non-biological signals, is an active area of research [Gauthreaux 2008] including some work that the authors are associated with [Mead *et al* 2008]. At the outset of this project, there was cautious optimism that the latter would have been developed enough to incorporate. As it stands, an experienced eye is often relied upon as the primary classifier. So though the automated classifier is not yet available, some of the data collected for this project are being used to train those algorithms and will provide a good test-bed for its application.

Generating the animations is a multi-step process and several of the intermediate datasets have been maintained for future analysis. First, however, a bit of pre-processing was required. Since all Nexrad stations operate independently depending on local conditions, the frequency and timing of data acquisitions period can vary from four to ten minutes. The first step was to extract individual raw data files from their archived, TAR (Tape Archive), format taking the nearest scan to consistent ten-minute interval.

The NCDC has developed a software tool, NOAA's Weather and Climate Toolkit (formerly known as Java Nexrad Tools) to read raw Level-II Nexrad data and export it into a variety of GIS formats. The software does not currently have the ability to display data from multiple radar sites simultaneously; however, working with its author and the NCDC we were allowed access to the source code in order to implement multi-site mosaics. The mosaics were exported to moderate-resolution floating-point TIF (Tagged Image Format) images, which are good for analysis in a GIS environment, but not amenable to animation. The TIFs were then scaled to a byte range, given a color-scale, and converted to the PNG (Portable Network Graphics) image format. The PNGs were then cropped, resized and encoded to Flash Video using an AviSynth script and Adobe Flash CS3 Video Encoder. A custom animation viewer was developed and is described in the next section (details below). The animated day/night view of earth was also created using AviSynth based on a sequence of images generated by Xplanet.

3.3. Calendar

Another exploratory tool developed was to summarize the animations as a calendar snapshot at a particular time, e.g. 2AM local time (Figure 8). From this we can quickly observe migratory activity for nocturnal migrants over the course of a season and compare and contrast across years or between fall and spring.

3.4. Velocity

To take advantage of the Doppler capability of the WSR-88D, an effort was made to estimate the true direction and velocity of migration by combining radiosonde, i.e. weather balloon, observations with Nexrad radial velocity information. Browning and Wexler [1968] developed an approach to estimating target ground velocity based on the radial velocity determined by Doppler radar. This approach forms the basis of the Velocity-Azimuth Display (VAD), a quantity distributed by the NWS in their Nexrad Level III product giving wind velocity (speed and direction) as a function of altitude. It is known that the speed and direction of winds aloft can be contaminated by the presence of birds in the airspace by combining the velocity signal of the birds' powered flight with passive (wind-carried) particles [Wilczak 1995, Gauthreaux 1998a]. Gauthreaux and others [Gauthreaux 2003; Diehl *et al* 2003] have estimated true direction and speed of avian targets by subtracting the wind velocity determined by the radiosonde from the velocity determined from Nexrad. Difficulties in this approach are that radiosondes are not released at all Nexrad stations, and they are only released twice per day (00 and 12UTC). Following the method described by Diehl [2006], we were able to estimate the direction and velocity of migration, though we only completed processing for 2007 and only for the four sites with both Nexrad and radiosonde. The preliminary results presented in Figure 9 for the evening of September 26, 2007 at 2AM CDT are striking in their precisely southward (heading of 180°) direction, especially for Davenport, IA (KDVN) and Green Bay, WI (KGRB). The next step in this analysis would be to aggregate the results from each site over groups of days to test the variability of direction over the migratory period. Further, it may be informative to interpolate radiosondes between stations, or use historically modeled atmospheres such as, NARR (North American Regional Reanalysis) to estimate velocities at other stations.

4. Long-range Surveillance Radar Biology Viewer

The large-scale radar biology video player is designed to provide access to a selection of composite videos of weather radar in the Upper Midwest. This prototype application contains sequences of weather radar from April through May and September through October for the years 2002-2007. The video player includes a single viewer that provides enhanced playback controls to access specific observations/events; a dual viewer that incorporates radar animations alongside an earth view with concurrent day/night information; and a quad viewer that allows simultaneous playback for up to four separate radar animations. Each animation includes data layers that may be viewed or turned off, including relief (physical geography), state borders, and large rivers. The application also contains a related overview section which illustrates several common biological patterns found in the videos.

4.1. Objective

The intent of developing a specialized Nexrad animation viewer was to incorporate several features available in neither typical media players nor scientific/geographic visualization packages. First, the ability to display the radar data as a layer on top of a variety of background images and vector layers was an important priority as it allows the user to view the information in varying contexts, e.g. relative to topography, rivers, land cover, public lands, etc. This was considered a *must-have* but the implications of this are far-reaching as it requires that the animation layer include transparency, or an *alpha*-channel, which will be described in detail later. Second, we also wanted the ability to view synchronized animations from multiple years (or months) simultaneously. This gives the observer an indication of the variability of migration from year to year and the significance of weather events in birds' decision to rest or continue [Richardson 1978, Danhardt *et al* 2001].

Another feature which is found in some media players, though its functionality is highly dependent on the type of media, is the ability to "scrub" through a video; that is, to manually control the direction and speed of playback. Finally, it was also decided that the ability to run the Viewer as a web application, while not critical, would be nice to have.

Geographic visualization products, e.g. Google Earth and Unidata's Integrated Data Viewer (IDV), on the other hand can readily handle multiple layers, and even a limited capacity to display time-series animations. Their general approach to the latter however, is to sequence a series of still images. This is suitable to short time series, but considerably less so for series containing thousands, perhaps tens-of-thousands of frames.

The ability to synchronize playback of multiple video streams is typically reserved for professional video production packages. So in the end, it was decided that what was needed was a custom application which combines features of media players, geographic visualization packages, and video production software.

4.2. Approach

Given all the features to be implemented, the first step was to decide what programming language, framework, or environment offered the best option given our resources. Given the need for alpha-transparency in the video, this immediately narrowed the choice of possible video codecs and containers. The decision came down to writing an application to handle Apple QuickTime files with the Animation codec, or Adobe Flash Video with the On2 VP6.2 codec. Each has advantages and disadvantages, but ultimately developing an application for the latter with Adobe Flash or Flex would provide the best chance for a successful implementation.

4.3. Result

The Long-range Surveillance Radar Biology (LSRB) Viewer, is a stand-alone, interactive viewer for Nexrad animations of the peak migratory periods from 2002-2007 for the state of Wisconsin. The first tab presents a single animation and a sliding menu from which to choose the desired month for playback. When given a moment to buffer data, the animation is responsive and scrubbing works, adequately though not perfectly. Similarly, the second tab show playback of a single month synchronized with an image of the globe showing the transition between day and night. This was to be the primary display, however due to the synchronized animation the performance of scrubbing playback fell far short of our expectations. We strongly believe this is a limitation of our Flash implementation. Similarly, synchronization of multiple Nexrad animations on the third tab performs poorly when scrubbed. Finally an instructional page describes some of the common biological signals in Nexrad imagery.

4.4. Conclusions and Observations

While the overall performance of the application fell short of our initial vision, it remains a useful approach to investigating periods of strong avian migratory activity. The data collected for the project has already been shared with other researchers interested in issues of habitat conservation in the face of wind power development. The ability to gain a visual overview of such a large dataset by condensing it to less than 1% of its original size is also a promising development. Due to the nature of the codec used, that compression ratio could be improved another order of magnitude or more at the expense of frame-by-frame manipulations (e.g. scrubbing).

A number of added capabilities are under consideration should development continue. Ideally, the viewer would serve as a visual browser through which specific scenes or time periods could be selected for in-depth analysis.

Acknowledgments

We thank Wisconsin's Focus on Energy and the Environmental Research Program for funding this effort and Steve Ansari and Stephen DelGreco of the NOAA NCDC for their help with –and access to—the source code for the Java Nexrad Tools before it was publicly available.

References

HDSS Access System: http://hurricane.ncdc.noaa.gov/pls/plhas/has.dsselect

Browning, K. A., and R. Wexler. 1968. The determination of kinematic properties of a wind field using Doppler radar. Journal of Applied Meteorology 7:105-113.

Danhardt, J., and A. Lindstrom. 2001. Optimal departure decisions of songbirds from an experimental stopover site and the significance of weather. *Animal Behaviour* 62, no. 2 (August): 235-243.

Diehl, R. H., R. P. Larkin, and J. E. Black. 2003. Radar Observations of Bird Migration Over the Great Lakes. *The Auk* 120, no. 2: 278-290.

Diehl, R.H., and R.P Larkin. 2005. Introduction to the WSR-88D (NEXRAD) for ornithological research. in Ralph, C.J. and Rich, T.D., eds., Bird conservation implementation and integration in the Americas, Proceedings of the Third International Partners in Flight Conference, v. 2: Albany, Calif., USDA Forest Service, Pacific Southwest Research Station, General Technical Report PSW–GTR–191, p. 876–888.

Diehl, R.H., J. Gu, and D. Ali. 2005. Improving ground speed and direction estimation for biological target discrimination on surveillance radar. Published abstract. Personal communication.

Gauthreaux, Sidney A., John W. Livingston, and Carroll G. Belser. 2008. Detection and discrimination of fauna in the aerosphere using Doppler weather surveillance radar. Integr. Comp. Biol. (May 8): icn021. doi:10.1093/icb/icn021.

Gauthreaux, S. A., Jr., C. G. Belser, and D. Van Blaricom. 2003. Using a network of WSR-88D weather surveillance radars to define patterns of bird migration at large spatial scales. Pages 335–346 *in* P. Berthold, E. Gwinner, and E. Sonnenschein, editors. Avian Migration.

Gauthreaux Jr, S. A., D. S. Mizrahi, and C. G. Belser. 1998a. Bird Migration and Bias of WSR-88D Wind Estimates. *Weather and Forecasting* 13, no. 2: 465-481.

Gauthreaux, Jr., S.A., and C.G. Belser. 1998b, Displays of bird movements on the WSR-88D—patterns and quantification. Weather and Forecasting. v. 13, p. 453–464.

Mead, R., J. Paxton, and R.S. Sojda. 2008. Identifying Biological Echoes in Radar Scans Using Machine Learning. pages 1758-1765 in: Sànchez-Marrè, M., J. Béjar, J. Comas, A. Rizzoli and G. Guariso, eds. Proceedings of the Fourth Biennial Meeting of the International Congress on Environmental Modelling and Software: Integrating Sciences and Information Technology for Environmental Assessment and Decision Making. Barcelona, Catalonia.

Richardson, W. J. 1978. Timing and Amount of Bird Migration in Relation to Weather: A Review. *Oikos* 30, no. 2, Current Bird Migration Research. Proceedings of a Symposium at Falsterbo, Sweden, 3-8 October, 1977: 224-272.

Wilczak, J. M., R. G. Strauch, F. M. Ralph, et al. 1995. Contamination of Wind Profiler Data by Migrating Birds: Characteristics of Corrupted Data and Potential Solutions. Journal of Atmospheric and Oceanic Technology 12, no. 3: 449-467.

Software Used

NOAA's Weather and Climate Toolkit: http://www.ncdc.noaa.gov/oa/wct/

Mozilla Firefox: http://www.mozilla.com

Greasemonkey Add-on: https://addons.mozilla.org/en-US/firefox/addon/748

Greasemonkey Homepage: http://www.greasespot.net/

AviSynth: http://avisynth.org

Xplanet: http://xplanet.sourceforge.net/

Adobe CS3 Production Premium

Acronym Dictionary

Codec – encoder-decoder

DoD – Department of Defense

FAA – Federal Aviation Administration

GIS – Geographic Information System

HDSS – Hierarchical Data Storage System

HAS – HDSS Access System

LSRB – Long-range Surveillance Radar Biology

Mbps – Megabits per second

NARR – North American Regional Re-analysis

NCDC – National Climatic Data Center

NOAA – National Oceanic and Atmospheric Administration

NWS – National Weather Service

PNG – Portable Network Graphics

TAR – Tape Archive

TB - Terabyte

TIF – Tagged Image Format

WSR-88D – Weather Surveillance Radar 1988 Doppler

VCP – Volume Coverage Pattern

Figures

Figure 1 – The Nexrad network with range bubbles of 80km (green), 120km (yellow) and 200km (red).

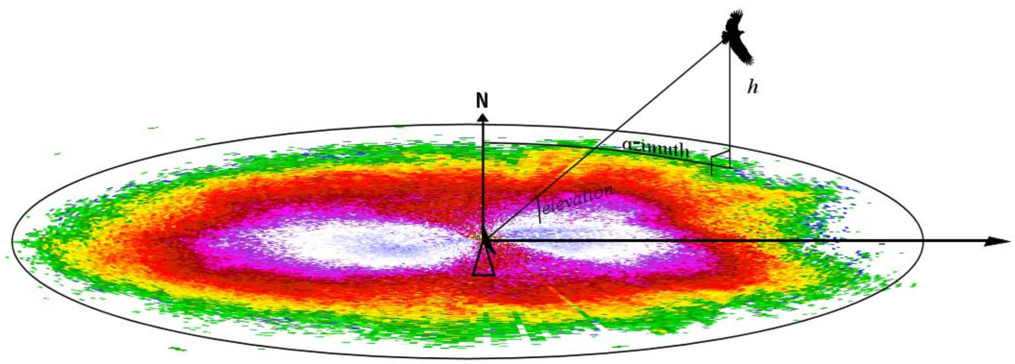

Figure 2 – Radar reflectivity measures the amount of energy returned from a target relative to the energy emitted.

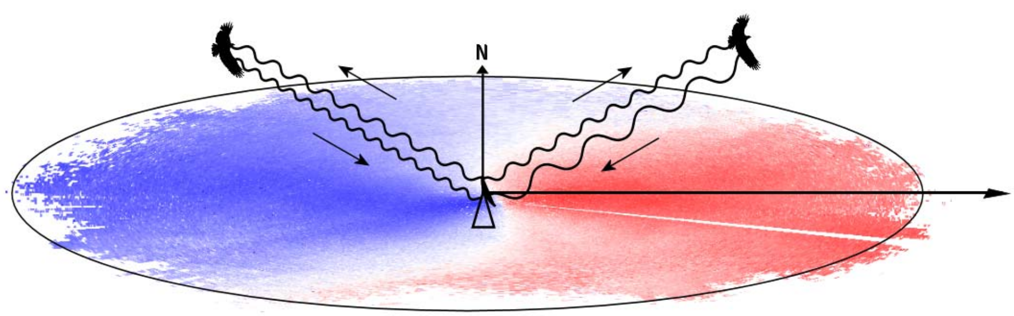

Figure 3 – Doppler radar can measure a target's radial velocity, i.e. the component of a target's velocity toward (blue) or away from (red) the station.

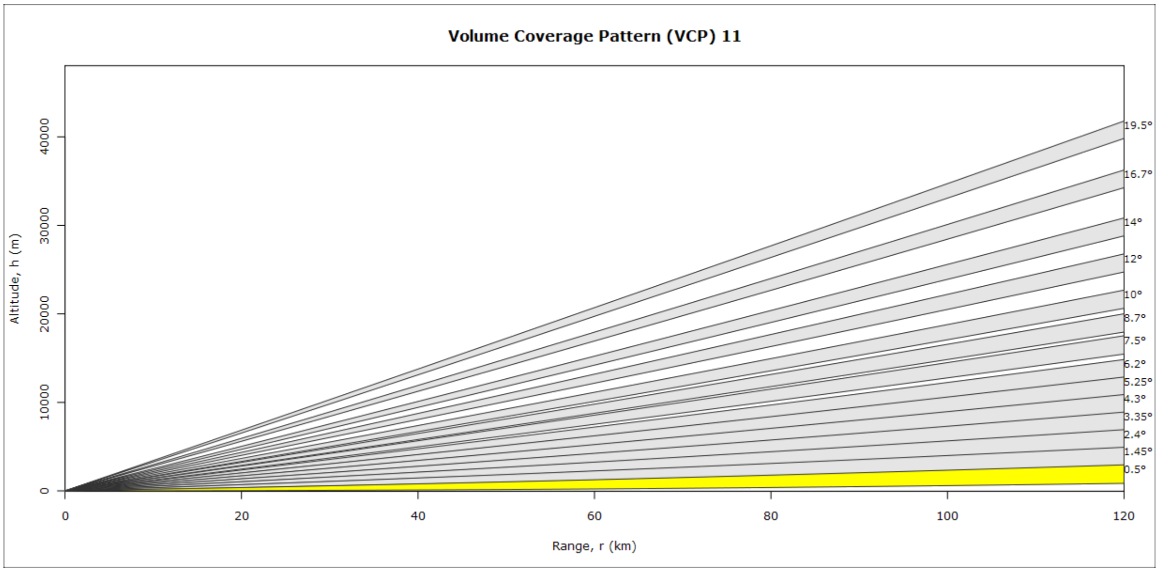

Figure 4 – Precipitation mode VCP's scan with a frequency of 4 to 6 minutes.

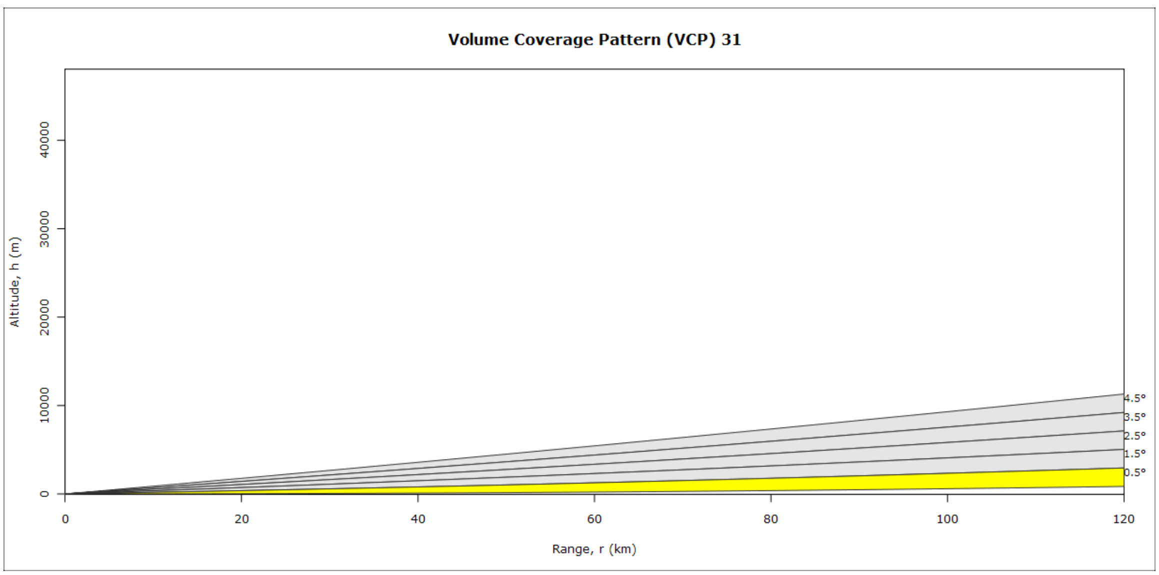

Figure 5 – Clean Air mode VCP's only scan only the lowest elevation angles every 6-10 minutes, but with a greater degree of sensitivity.

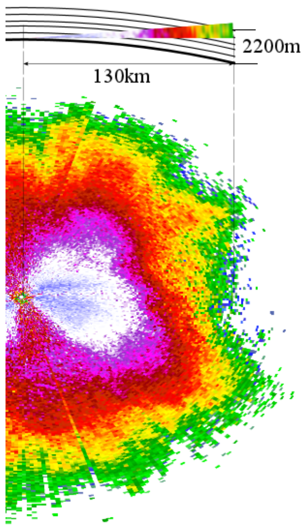

Figure 6 – As the radar beam travels away from the station, Earth's curvature causes the beam to travel at an increasing altitude above ground.

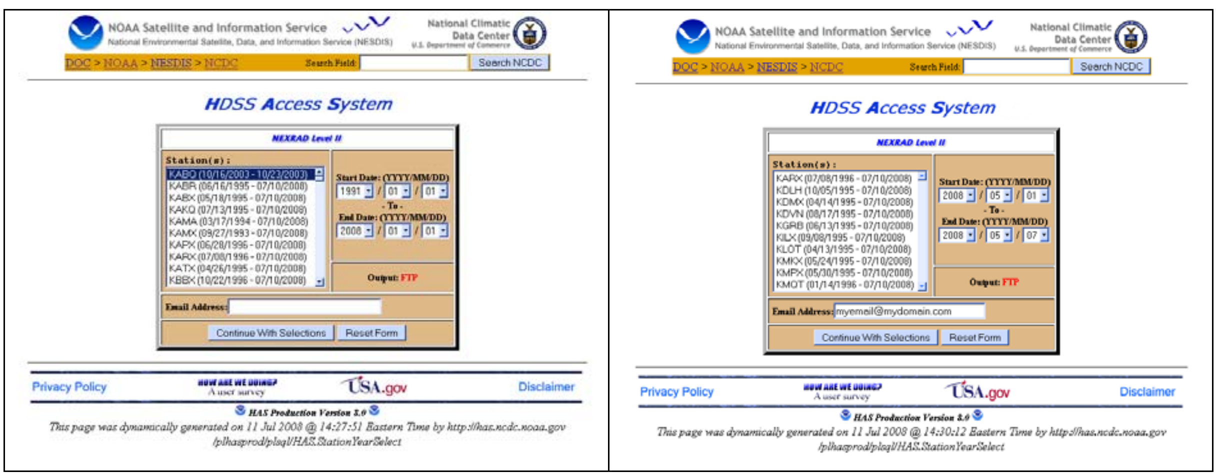

Figure 7 – The HAS ordering system displays all Nexrad stations, which make submitting multiple requests for a limited subset of sites tedious and error-prone. Using a Greasemonkey script for the Mozilla Firefox web browser, the fields presented can be limited to only those of interest, and the date range and email address can be pre-filled.

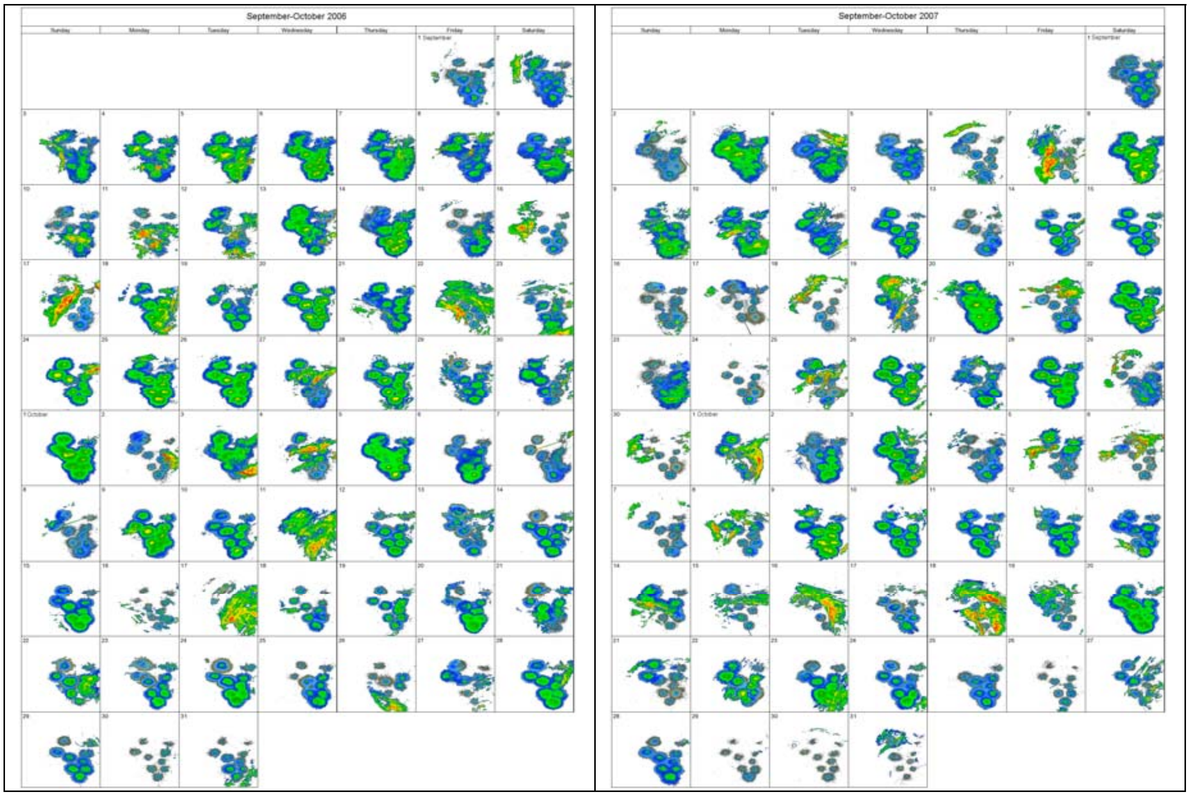

Figure 8 – Viewing Nexrad reflectivity as a calendar allows for a quick visual comparison of the timing and intensity of migration between years.

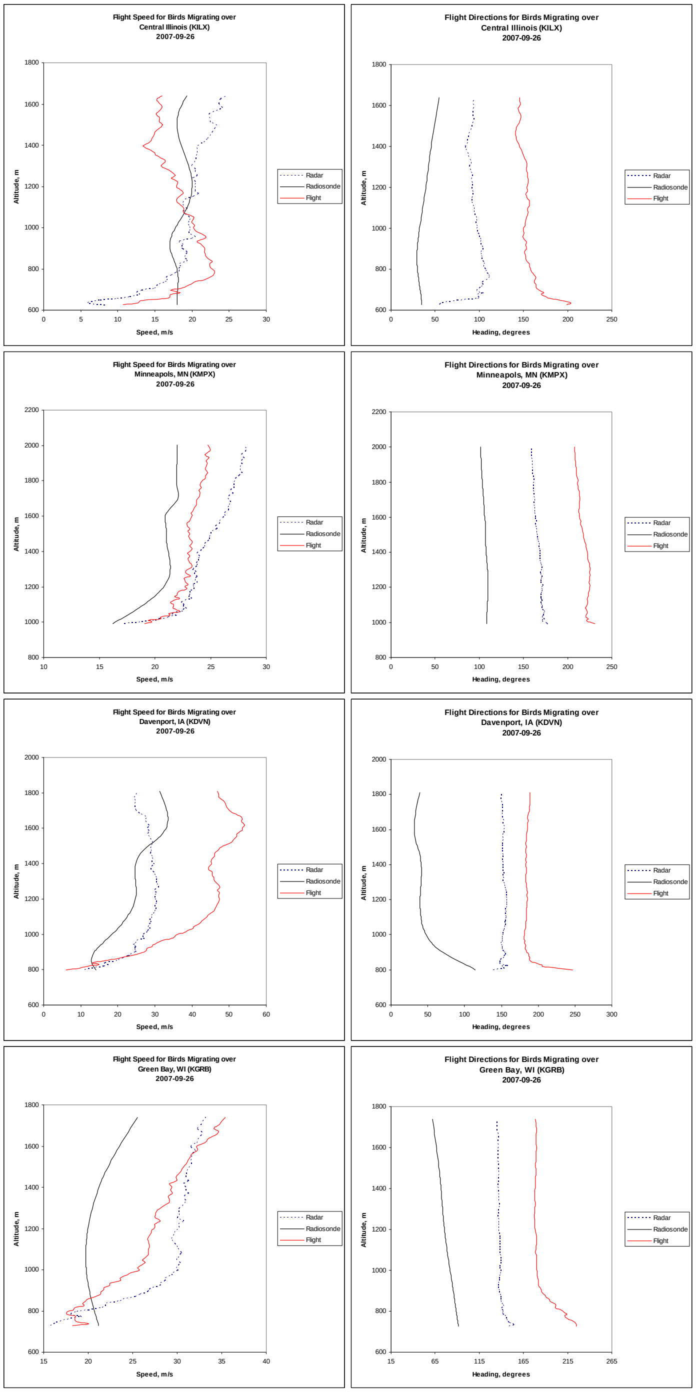

Figure 9 – Combining Doppler velocity with (nearly) coincident radiosonde observations, the speed and direction of migration can be estimated.