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WEATHER RADARS AND WIND FARMS – WORKING TOGETHER FOR MUTUAL BENEFIT

Richard. J. Vogt*, Timothy D. Crum, J. Rex Reed, Charles A. Ray, and Joe N. Chrisman
NEXRAD Radar Operations Center, Norman, Oklahoma

Robert D. Palmer, Brad Isom, and John T. Snow
University of Oklahoma, Norman, Oklahoma

Donald W. Burgess
University of Oklahoma/Cooperative Institute for Mesoscale Meteorological Studies
Norman, Oklahoma

Mark S. Paese
NOAA's National Weather Service Headquarters, Silver Spring, Maryland

1. Introduction

The Nation's weather services and the wind energy industry share several common goals including enhancing the Nation's economy and the quality of life for its citizens. One of the key tools weather forecasters use in preparing forecasts and severe weather warnings is the Nation's network of weather surveillance radars. The federal government installed the network in 1990 – 1997; soon after, the wind energy industry began to deploy a new generation of large wind turbines around the country. Over the last decade, operators of weather surveillance radars have become increasingly aware of the interaction between individual weather radars and nearby (<100 km) wind farms (Vogt et al 2007). Experience has shown that when wind farms are located "close" to weather radars, the towers and rotating turbine blades can negatively impact radar data quality and degrade the performance of critical weather detection algorithms that use these data.

In this paper we will focus on wind turbine interaction with the Weather Surveillance Radar-1988 Doppler (WSR-88D) radar. These radars are the product of the Next Generation Weather Radar (NEXRAD) Program, a joint effort of the Departments of Commerce (DOC), Defense (DOD), and Transportation (DOT) – the NEXRAD tri-agencies. We will refer to the WSR-88D as the "NEXRAD", which is a common name for these radars.

This paper has several purposes:

- Inform the wind energy industry of the mission and location of the NEXRAD radars;
- Provide the wind energy industry basic information on how NEXRAD radars work and how wind farms can impact the NEXRAD radars; and
- Inform the wind energy industry of the NEXRAD Program's desire to work in a collaborative and non-interfering manner.

2. NEXRAD Overview

a. NEXRAD Program Overview

To meet the Nation's need for detailed weather surveillance, NEXRAD radars have been installed at 159 operational and 8 support locations across the United States (Fig. 1) and select

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*Corresponding author contact information: Richard J. Vogt, NEXRAD Radar Operations Center, 1200 Westheimer Drive, Norman, OK 73069; email: Richard.J.Vogt@noaa.gov

overseas sites. These radars scan the atmosphere continuously and provide real-time display of products that have enabled weather forecasters to improve the detection of and give greater advanced warning for tornadoes, flash floods, and other severe weather events. For example, since the establishment of the NEXRAD network, the average warning lead time for tornadoes has increased from 5 minutes to 13 minutes. A recent independent analysis indicates the network of NEXRAD radars has reduced the number of deaths due to tornadoes by 45% annually and the number of injuries due to tornadoes by 40% annually (Simmons and Sutter 2005) since their installation.

NEXRAD data are also key for the safe and efficient operation of the National Airspace System. Beginning in 2002, data from weather surveillance radars (the NEXRAD network) have been displayed on the operational screens of Federal Aviation Administration (FAA) air traffic controllers. Furthermore, relatively new technology now provides for near real-time display of NEXRAD products in the cockpits of some private and commercial aircraft during flight.

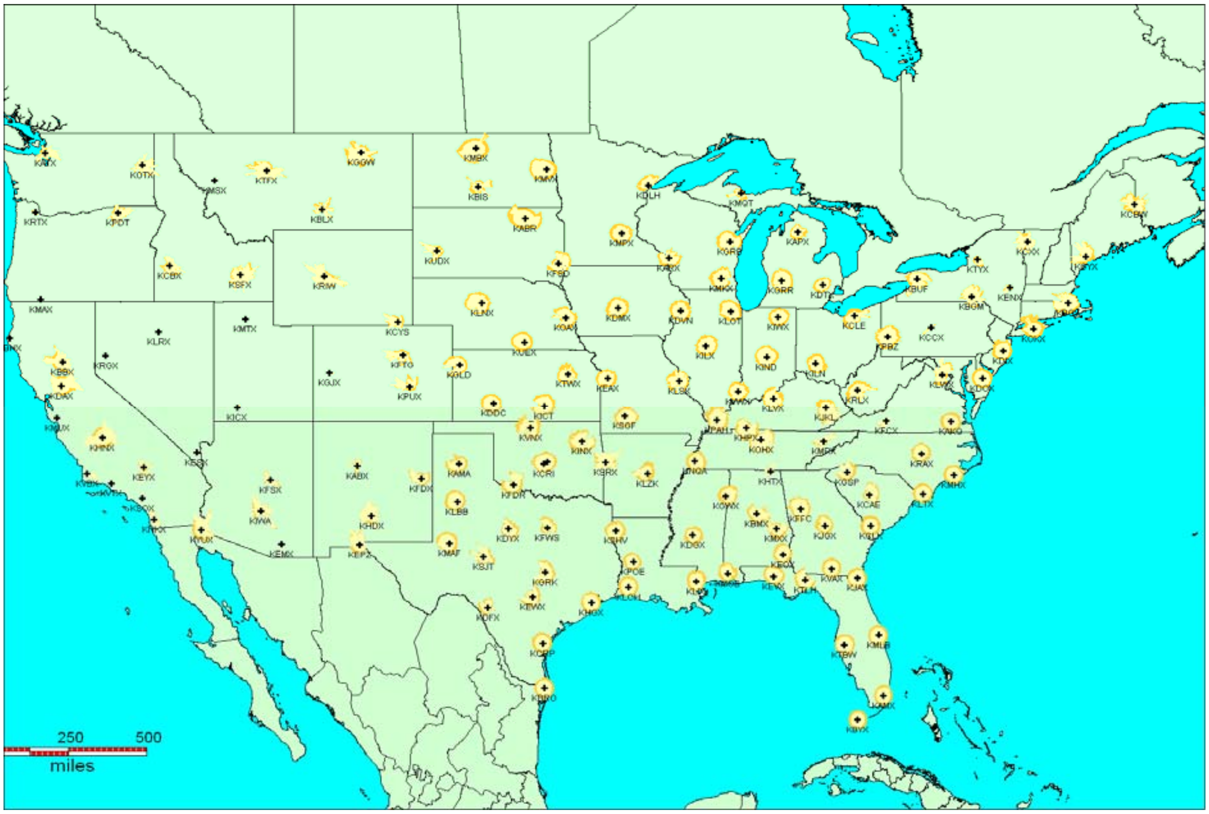


Fig. 1. A map of the 142 NEXRAD radar locations in the contiguous United States. The shaded areas around the radars show where the radar-line-of-sight for each radar is within 425 ft of the ground (yellow shading) and 650 ft of the ground (burnt orange shading). These heights were selected as representative of typical wind turbine heights today and projected for the near future. (Note: this drawing should be used for illustration purposes only. Please consult with the NEXRAD Radar Operations Center (http://www.roc.noaa.gov/Feedback/) for a detailed analysis when wind farm details are known.) See Figs. 4 and 9 for close up examples.

b. NEXRAD System Overview

NEXRAD radars collect, process, and distribute high-resolution and high-accuracy reflectivity, mean radial velocity, and spectrum width (a measure of the variability of radial velocities in the resolution volume) data. (The latter two quantities are the Doppler capability the NEXRAD provided on a national scale for the first time.) The radar estimates of these quantities are based on radio frequency energy returned from precipitation and other reflectors/scatterers (e.g., insects, birds). In addition, because of the system's high sensitivity, measurements of these quantities are typically obtained even in optically clear air. From these data, computer-processed algorithms generate a suite of meteorological and hydrological analysis products. When combined with the user's meteorological knowledge of storm structure and internal processes, these products provide crucial guidance for time-critical decisions that must be made by forecasters, air traffic controllers, and meteorological observers (e.g., emergency managers). Output from these algorithms are vital ingredients for providing short-term forecasts and precise warnings of short-lived, small-scale events such as tornadoes, wind shear, downbursts, and for evaluating the potential threat of devastating floods and other phenomena. The general public may access the data from these network radars from private meteorology companies and the Internet (e.g., http://radar.weather.gov/).

The NEXRAD radars acquire and process Doppler weather radar data using a system that transmits, receives, and processes radio frequency energy in the S-band (10.0 - 11.1 cm wavelength, 2700 - 3000 MHz). The radars' klystron transmitter normally transmits with a nominal peak power output of 750 kW. The NEXRAD uses a parabolic antenna with a diameter of 8.5 m (28 ft), an antenna main lobe one-way 3 dB beam width of approximately 0.95°, and a first side lobe 29 dB below the main lobe. The receiver enables the NEXRAD to detect signals as low as -8 dBZ_e at 50 km.

The NEXRAD radars provide mean radial velocity data and spectrum width data to a range of 230 km (124 nm) with a spatial resolution of 0.25 km and a data resolution of 0.5 ms^{-1}. Reflectivity data have a spatial resolution of 1 km (upgraded to 0.25 km in June 2008) and a data resolution of 0.5 dBZ_e to a range of 460 km (248 nm).

The NEXRAD radars operate continuously. The antenna scans its environment in predefined sequences of 360° azimuthal sweeps at various elevations between 0.5° and 19.5° to collect information for the common mission goals of the NEXRAD agencies. A completed multiple elevation sequence of azimuthal sweeps is called a "volume scan." These scans require 4.5 to 10 minutes to complete. Further information about the NEXRAD radars and their operation is available (Crum and Alberty 1993; Federal Meteorological Handbook No. 11, Parts A – D).

c. NEXRAD Radar Beam Characteristics

There are two important beam characteristics that impact a radar's ability to "see" targets. The first characteristic is beam width. The radar beam width can be considered analogous to the beam of light coming from a flash light. Most of the energy of the flashlight, just as with the radar, is in the beam of light/radar beam, but wider than a line from the center of the beam. Radar beam width is defined as the distance between the half-power points. The half-power points correspond to where the radio frequency energy of the beam is one-half (3 dB down) what it is at its center. The anular separation of the half-power points is fixed, so as the beam propagates from the radar, the beam width increases. For NEXRAD, at 60 nm from the radar the beam is approximately 1 nm wide. Precise location, elevation, and tower height of individual radars may be obtained by contacting the NEXRAD Radar Operations Center (http://www.roc.noaa.gov/Feedback/).

The second important beam characteristic is its propagation path (radar-line-of sight). The path of the energy a radar emits (i.e., the beam) depends upon atmospheric density. Density differences are caused by variations in pressure, temperature and moisture. In a “Standard Atmosphere” the radar beam takes a path that is approximately 4/3 of the Earth’s radius. This bending is called “refraction.” In Fig. 2a, the beam depicted is the radar-line-of-sight for a standard propagation event. As illustrated, even with standard propagation, the radar-line-of-sight enables a radar to see over the optical horizon. In cases where there is a rapid decrease in temperature with height (usually in the heat of summer afternoons), the radar beam can sometimes bend upward from the standard atmosphere case. This situation is called “subrefraction” and is shown in Fig. 2b. In these cases, ground-based targets normally seen by the radar are not seen. In cases of an increase in temperature with height, commonly associated with light winds during the night or after a cold front passes, the beam can be bent down toward the ground more rapidly than in the standard atmosphere. This situation is called “super refraction” and is shown in Fig. 2c. An extreme case of super refraction is “ducting” as seen in Fig. 2d. In super refraction and ducting situations, an increased number of ground-based targets are seen by the radar – some often at large distances from the radar.

Considering the above definition of radar-line-of-sight in a standard atmosphere for a NEXRAD, we can draw maps of the areas around NEXRAD radars where wind towers with turbine blade tips within 425 ft of the ground and 625 ft of the ground will be within the NEXRAD radars’ line-of-sight (Figs. 1, 4, and 9). The formula for calculating the center of the radar beam height, beam width, and beam top and bottom heights as a function of range from a radar can be found at: http://www.wdtb.noaa.gov/tools/misc/beamwidth/index.htm.

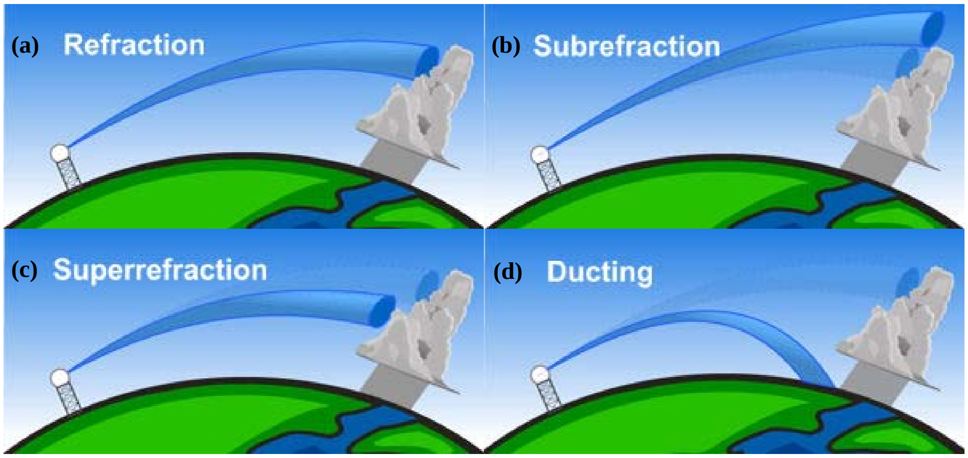
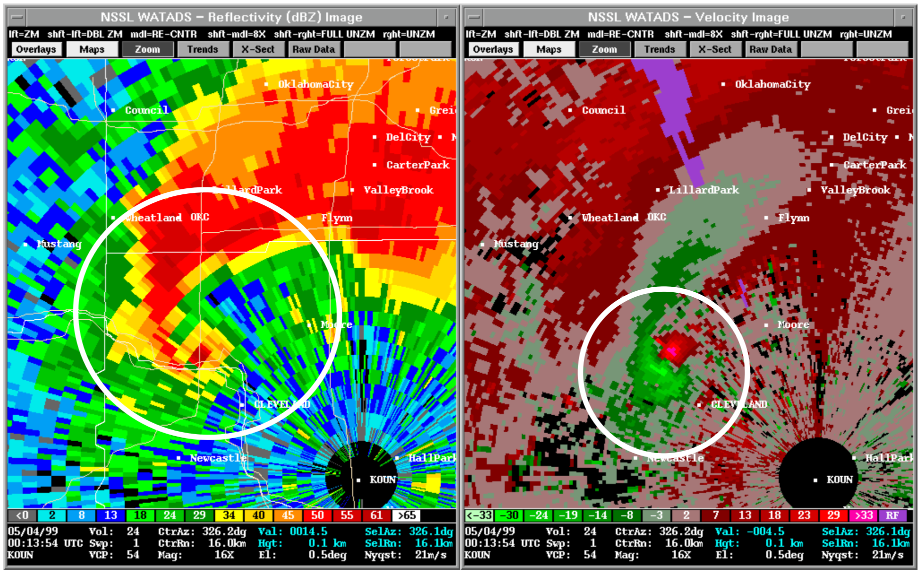


Fig. 2. A depiction of the radar beam width increasing as the beam travels from the radar and the paths the radar beam can take in varying atmospheric conditions.
(a) Normal refraction represents the beam path in a standard atmosphere and approximates a 4/3 Earth radius.
(b) A subrefraction situation where the beam path is elevated above that of the standard atmosphere.
(c) A superrefraction situation where the beam path is bent below that of the standard atmosphere.
(d) Ducting of the radar beam is an extreme case of superrefraction where the radar beam can strike the ground/ground-based targets a long distance from the radar.

d. NEXRAD Products

The NEXRAD produces products at the end of each individual azimuthal sweep as well as at the conclusion of each completed volume scan. Fig. 3 is an example of reflectivity and radial velocity data collected at the same elevation angle and time. The NEXRAD also has a suite of radar algorithms which provide output designed to reduce the workload on the radar operator and provide early automated indications of possible tornadoes, severe weather, or flash flooding.



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00:13:54 UTC  Swp:    1   CtrRn:  16.0km  Hgt:     0.1 km  SelRn:  16.1km
KOUN            VCP:   54   Mag:       16X  El:      0.5deg  Nyqst:  21m/s
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05/04/99        Vol:   24   CtrAz: 326.2dg  Val: -004.5      SelAz: 326.1dg
00:13:54 UTC  Swp:    1   CtrRn:  16.0km  Hgt:     0.1 km  SelRn:  16.1km
KOUN            VCP:   54   Mag:       16X  El:      0.5deg  Nyqst:  21m/s
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Fig. 3. Data collect during the 0.5 ° elevation angle scan by a NEXRAD in Norman, OK on 3 May 1999. At the time of data collection a powerful tornado was on the ground northwest of the radar. The reflectivity data (left) shows the characteristic "hook" shape of a tornado (inside the white circle). The Doppler radial velocity (right) are color coded such that winds flowing toward the radar (the black circle annotated by "KOUN") are green and winds flowing away from the radar are red. The counter-clockwise circulation of the tornado is represented by the bright green colors next to the bright red colors (inside the white circle).

d. NEXRAD Data Users

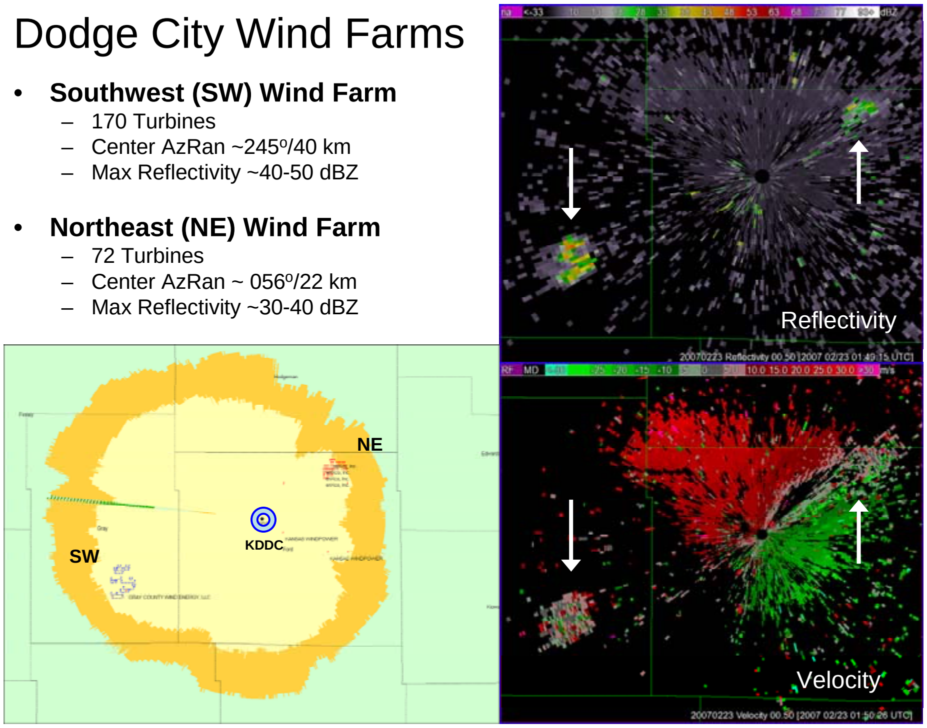
Users of NEXRAD data are numerous and diverse. National Weather Service (NWS) and DOD weather forecasters use these data in preparing forecasts and warnings for tornadoes and severe weather. These forecasts and warnings provide life-saving information to the public, support military operations, and information to resource protection decision makers. NEXRAD data are now displayed in real time on FAA air traffic controllers' screens for airspace management and safety of flight. The NWS teams with local emergency managers to ensure warnings for tornadoes, severe weather, and flash flooding are disseminated to the public. The emergency managers rely on the radar data for making final warning decisions and updating the public on the status of severe weather events.

The private sector weather industry has grown greatly in the last decade, due in part to its use of real-time NEXRAD data. The industry provides value-added products tailored to their clients' needs. Individuals make better informed decisions on daily activities, their safety, and how to protect resources by using real-time NEXRAD data. Television broadcasters rely on both their own weather surveillance radars and data collected from the NEXRAD network to inform their viewers of evolving weather conditions.

3. How Wind Energy Farms Can Impact NEXRAD Data and Products

Return energy from wind farms within the radar-line-of-sight impact the basic measurements of the radars: Power Return (Mean Reflectivity), Mean Radial Velocity, and Spectrum Width. This is illustrated by the situation of two wind farms within line-of-sight of the Dodge City, KS

NEXRAD (KDDC) in Fig. 4. A several-month radar return climatology for KDDC reveals that the radar returns are impacted 86% of the time for the Southwest Wind Farm and 97% of the time for the Northeast Wind Farm. Non-detection periods are associated with calm winds (wind farm returns removed by the clutter filter in these cases) and radar beam sub-refraction (beam energy going above blade-tip height).



Dodge City Wind Farms

- **Southwest (SW) Wind Farm**
  - 170 Turbines
  - Center AzRan ~245º/40 km
  - Max Reflectivity ~40-50 dBZ
- **Northeast (NE) Wind Farm**
  - 72 Turbines
  - Center AzRan ~ 056º/22 km
  - Max Reflectivity ~30-40 dBZ

Fig. 4. Dodge City, KS NEXRAD (KDDC) reflectivity (upper right) and mean radial velocity (lower right) imagery showing two wind farms within line-sight-of the radar. Information on the wind farms is in the upper left and beam geometry relative to blade-tip height is in the lower left (as in Fig. 1).

Returns are seen both during clear-air situations (Fig. 4) and precipitation events (Fig. 5). Wind Farm returns in clear air can negatively impact detection of fronts and other boundaries and hamper observation of convective initiation.

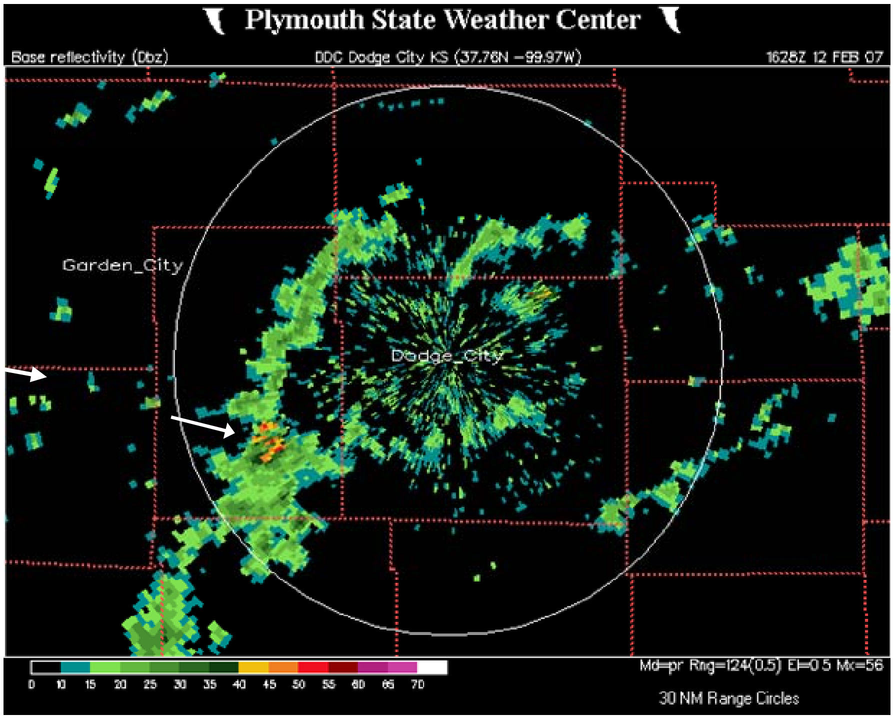


Fig. 5. Dodge City, KS NEXRAD reflectivity at 1628 Universal Time Coordinated (UTC) on 12 February 2007. The Southwest Wind Farm return superimposed on a line of rain showers (point of arrow) results in a doubling of the reflectivity data from ~25 dBZ to ~50 dBZ, falsely suggesting the strong reflectivity of a thunderstorm with possible hail when no thunderstorm existed. (This image was obtained from the Plymouth State University website (http://vortex.plymouth.edu.))

Wind farm returns during precipitation events have serious operational impacts. Weak rain showers can be mistakenly identified as strong thunderstorms (Fig. 5) and large regions of velocity data can be disturbed (aliased into an incorrect velocity measurement interval) and erroneously displayed over areas much larger than the wind farm itself (Fig. 6). Both conditions lead to loss of important data and possible incorrect decision making. Misidentification of rain showers as strong thunderstorms (as in Fig. 5) can lead to major aviation problems because of needless and expensive rerouting of commercial aircraft to avoid the supposed thunderstorms.

The worst operational impacts occur during severe convective storms and heavy rainfall. When life-threatening events occur, weather forecasters must quickly make crucial warning decisions. For these decisions, they rely on correctly displayed radar data and algorithm output. Both missed events and generation of false-alarm warnings are taken very seriously because of the negative impact they have on the whole warning system (emergency managers, the television and radio media, and all users of the warnings, including private-sector weather vendors and the general public). An example of a Mesocyclone Algorithm (tornado warning precursor) false alarm is shown in Fig. 7. Examples of false heavy precipitation accumulation and other negative impacts are shown in Fig. 8.

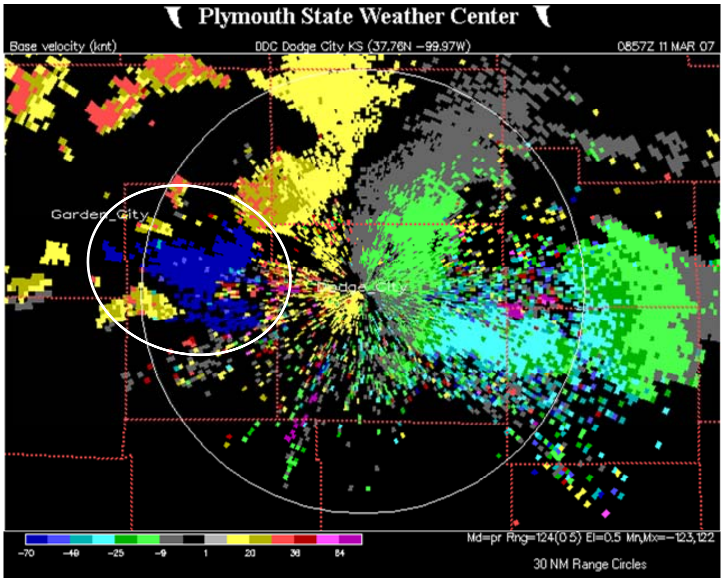


Fig. 6. Dodge City, KS NEXRAD (KDDC) mean radial velocity for 0857 UTC on 11 March 2007. Note the circled region where the indicated velocity is strong inbound (dark blue) when the real velocity was outbound (yellow and red). The velocity estimation error was caused by radar return from the Southwest Wind Farm. (This image was obtained from the Plymouth State University website (http://vortex.plymouth.edu.))

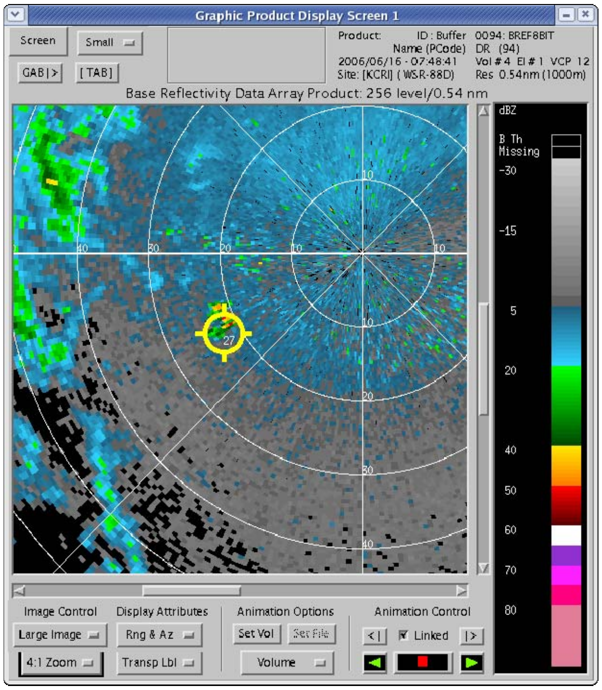

Product: ID : Buffer 0094: BREF8BIT
Name (PCode) DR (94)
2006/06/16 - 07:48:41 Vol # 4 El # 1 VCP 12
Site: [KCRI] (WSR-88D) Res 0.54nm (1000m)
Base Reflectivity Data Array Product: 256 level/0.54 nm

Fig. 7. Dodge City, KS NEXRAD (KDDC) reflectivity for 0748 UTC on 16 June 2006. The yellow circle is a radar algorithm-detected Mesocyclone which in this case is false. The yellow circle overlays radar returns from the Southwest Wind Farm. If forecasters believed the false algorithm detection, a tornado warning might have been issued. The real rain shower and thunderstorm returns are all west of the Southwest Wind Farm and were non-severe at this time. Northeast Wind Farm returns are not seen because that wind farm was not in existence when this data was collected.

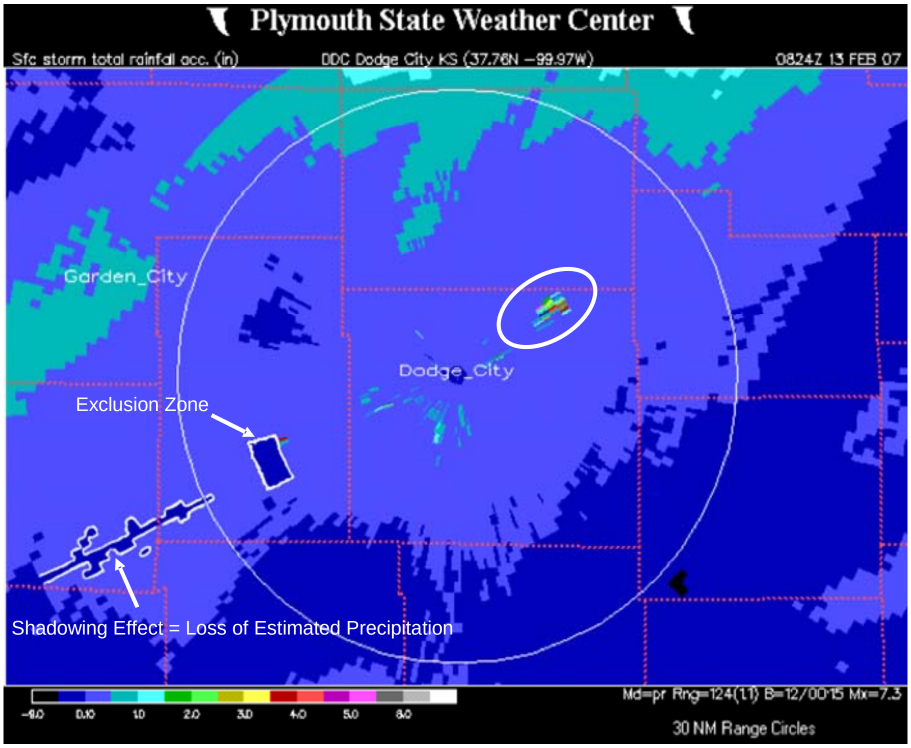


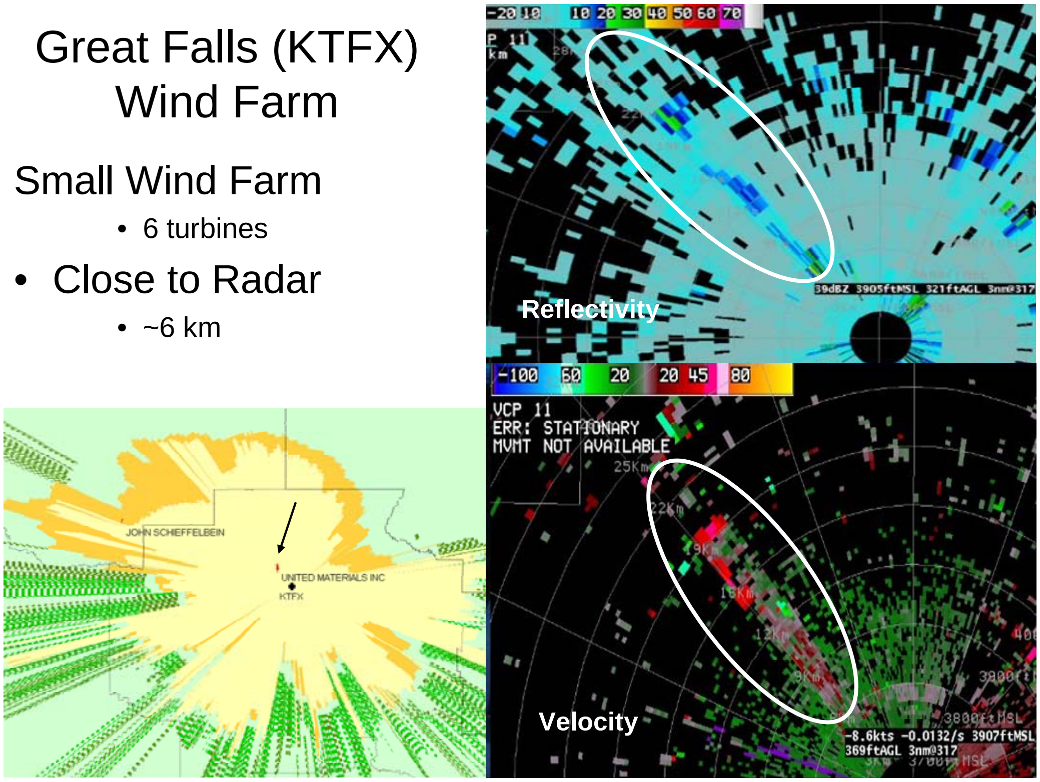
Fig. 8. Dodge City, KS NEXRAD (KDDC) Precipitation Accumulation Algorithm output for 0824 UTC for 13 February 2007. The Northeast Wind Farm (ellipse) has a false accumulation of 7.3 inches of rain within a broad region of 0.1-0.5 inch accumulations. If forecasters believed the 7.3 inch accumulation, a flash flood warning might have been issued. The Southwest Wind Farm false accumulation is masked by a radar operator-entered exclusion zone (which prevents radar-estimated precipitation accumulations from being calculated). Beam attenuation/blockage caused by the wind farm results in false reductions in the precipitation amounts (downrange from the wind farm). (This image was obtained from the Plymouth State University website (http://vortex.plymouth.edu.)

Wind farms at very close range to NEXRAD radars produce additional operational problems. An example is the wind farm near the Great Falls, MT NEXRAD (KTFX) in Fig. 9. Although there are only 6 towers/turbines, their close proximity to the radar produces strong and "multi-path" energy back-scatter, both from the main beam and the beam side lobes. Multi-path echoes are produced when transmitted energy scatters back and forth several times between the towers/turbines before returning back to the radar. The resulting velocity field from this complex energy scattering process erroneously places return from the wind farm as much as 60 km down range from the farm and over an azimuth interval wider than the farm. Large areas of contaminated reflectivity and velocity are produced, which in turn, contaminate NEXRAD algorithm output.

Based on our investigation and experience, we have identified the following impacts wind farms can have on NEXRAD data and forecast/warning operations:

- False or anomalously large radar-estimated precipitation amounts due to reflection from towers/turbines;
- False low radar-estimated precipitation amounts due to radar beam blockage;
- False echoes downrange from wind farms;
- Anomalously large reflectivity values due to reflection from towers/turbines;
- False storm identification due to reflection from towers/turbines;
- Incorrect velocity values due to turbine interference;

- Incorrect wind velocity profiles; and
- Potential blockage of low-level tornado/severe weather signatures due to blockage from towers/turbines.



Great Falls (KTFX) Wind Farm

Small Wind Farm
- 6 turbines

- Close to Radar
  - ~6 km

Fig. 9. Wind Farm near Great Falls, MT NEXRAD (KTFX). This small wind farm (only 6 turbines) is located very close to the radar (~6 km; lower left). Erroneous areas of reflectivity (upper right) and mean radial velocity (lower right) are seen down range along the radials that intersect the wind farm (in the ellipses). These false returns obscure real weather returns and can impact warning and forecast decisions.

4. NEXRAD Program Efforts to Mitigate Wind Farm Impacts

The NEXRAD Program is taking a multi-prong approach to mitigate the impacts of wind farms on NEXRAD data, products, and operations. We are evaluating impacts of existing wind farms; evaluating wind farm mitigation and "work around" practices for meteorologists; and exploring advanced signal processing techniques to reduce wind turbine contamination.

a. Understanding Impacts on Weather Radars and Operations

As discussed in Section 3, we are learning about wind farm impacts on radars and weather forecast office operations where the radars and wind farms already co-exist. Based on this information, we are developing training materials on how to identify, mitigate, and work around impacts during forecast and warning operations.

b. Comparison between Weather Surveillance and Air Surveillance Radars

Even though weather surveillance radars and air surveillance radars (ASRs) must both deal with beam width and beam propagation issues, their targets of interest and signal processing are much different. Therefore, any wind turbine clutter mitigation techniques that may be applicable to one type of radar will likely not be useable in the other type of system. The ASRs look for large, hard, singular targets (aircraft) and process the data to mitigate weak environmental returns. In contrast, weather surveillance radars are designed to sample small, weak and diffuse returns (e.g., water droplets, aerosols, atmospheric particulates) and perform signal processing to remove or mitigate strong, single targets. This requirement to remove strong return while retaining weak, diffuse return is especially troublesome when, due to beam broadening and beam propagation, the radar beam intersects large, strong ground-based targets. Furthermore, weather radars have greater sensitivity (lower noise floor) and the returned signals are processed differently than in ASRs.

In order to reduce the strong, singular targets “seen” by the radar, NEXRAD has a clutter filter algorithm that removes clutter/ground targets/non-meteorological targets. A basic premise of the NEXRAD clutter filter algorithm is that a clutter target has no motion (zero instantaneous velocity). However, as we will discuss later, when the NEXRAD “sees” a wind farm, the turbines are usually in motion and therefore have a nonzero velocity. Hence, the NEXRAD clutter filter algorithm does not remove the returns of the wind farms in most situations.

c. Experimental Signal Processing Techniques

In collaboration with the University of Oklahoma, the NEXRAD Radar Operations Center is evaluating possible mitigation schemes of wind turbine clutter (WTC) on the WSR-88D radar. With the recent Open Radar Data Acquisition (ORDA) upgrade to the WSR-88D network, the possibility of implementing real-time, advanced signal processing algorithms is being explored. The processing capability of the ORDA allows the calculation of the Doppler spectrum, which is defined as the *power weighted distribution of radial velocities within the resolution volume of the radar* (Doviak and Zrnic, 1993). The resolution volume is defined by the pulse length and the antenna beamwidth of the radar and can be on the order of hundreds of meters in range and several kilometers in azimuth. Given that the azimuthal size of the resolution volume increases with range, it is expected that the resulting Doppler spectra can exhibit a variety of functional forms. For example, the Doppler spectrum from ground clutter is well known to have a large peak at zero radial velocity, since the ground clutter has no motion. Bird echoes can show two distinct peaks in the spectrum due to the opposing motion of the beating wings (Wilczak et al. 1995). The focus of this section is to provide examples of the unique spectral characteristics of wind turbine clutter and to introduce methods that may be exploited to mitigate the WTC and estimate the spectral moments of the weather echo.

(1) Spatial Continuity of Doppler Spectra

Though the physical size of the resolution volume can vary over a large range depending on the distance from the radar, it must remain small enough to maintain a high-resolution map of the large-scale weather features. The left panel of Fig. 10 provides a depiction of the radar resolution volume with wind turbines within the volume. The right panel shows the WSR-88D Doppler spectra of a resolution volume containing only one wind turbine. This spectrum was sampled over a four second sampling period and shows distinctive characteristics of the blade motion over time. It is important to note that during actual radar operation, each resolution volume is only sampled for a fraction of a second (approximately 1/20th of a second) and each volume will likely contain multiple wind turbines, complicating the problem. As is apparent, even given the extremely long sampling period in this example, it is difficult to predict the exact shape of the spectrum at any given time because there is no synchronization between the blade rotation and the radar time-on-target. Nevertheless, the supporting towers of the turbine are predictable given that they are stationary and have a corresponding zero Doppler velocity. Current clutter filtering techniques are capable of removing the tower component quite effectively but the blade motion remains problematic.

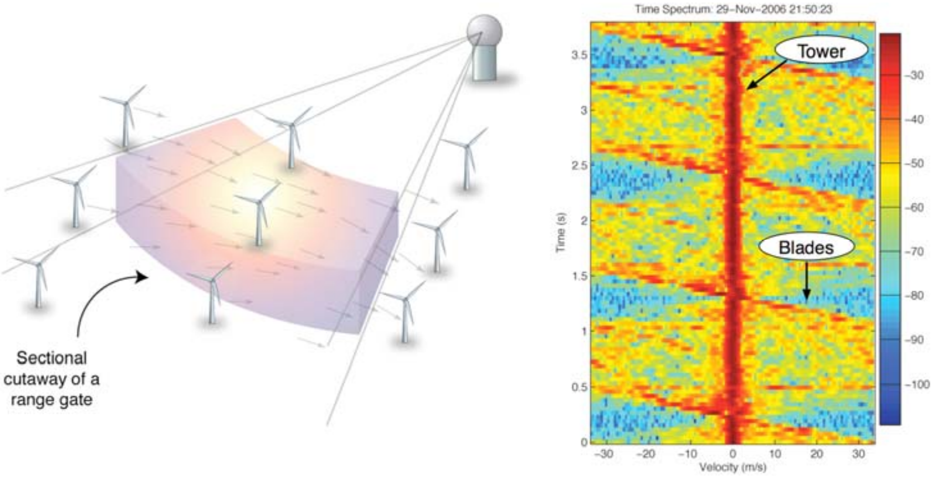


Fig. 10. Schematic diagram of a radar resolution volume containing a single turbine. Also shown is the evolution in time of the spectral content of such a resolution volume. Note the tower structure has zero Doppler velocity and the blades can be detected at a wide range of velocities depending on the time of observation.

The most difficult task in WTC mitigation is removal of the blade components without distorting or removing the desired weather signal. An example of mixed wind turbine clutter and weather Doppler spectrum over many range gates is shown in Fig. 11. In this case, the Doppler spectra are shown as a function of range from the radar. The zero-Doppler tower is clearly visible and can be used as an indicator of the wind farm over 37-44 km. The velocities of the spectrum contaminated by the moving blades vary with range illustrating the variability of wind turbine clutter. It is also important to note the range continuity of the weather signature given that atmospheric echoes will not typically change characteristics significantly over short range spans. Certain techniques to mitigate WTC can exploit this fact by estimating the weather signal in contaminated regions via regions of clean weather signals. Interpolation is one such technique.

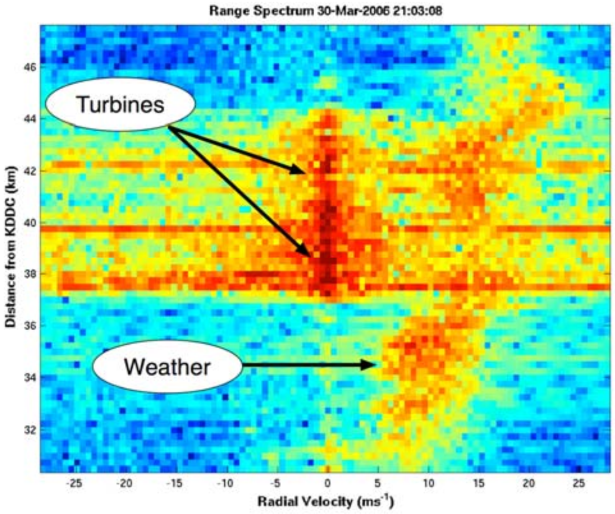


Fig. 11. Evolution in range of the Doppler spectrum taken from the Dodge City, KS NEXRAD (KDDC) on March 30, 2006. The wind turbines are present from approximately 37 to 44 km. The weather signal is visible and has a positive radial velocity. The weather signal does not change substantially over the ranges shown here implying strong spatial continuity.

(2) Three-Dimensional Multiquadric Interpolation

Any interpolation technique relies on the presence of *good* data that have not been contaminated by an undesired signal to estimate the signal at an unknown or contaminated location. For the case of wind turbine clutter, an uncontaminated range neighboring the wind farm can be considered *good* data and can be used to estimate the weather signal in ranges containing one or more wind turbines. This assumption is based on the strong spatial continuity of the natural environment (weather) over a short distance.

One technique historically employed for geo-spatial interpolation is called the *multiquadric* method (Franke, 1982). This technique can be implemented in any number of dimensions and is appropriate given the three-dimensional, continuous structure of weather signals. An example of the implementation of the multiquadric method on data taken from KDDC on March 30, 2006 is shown in Fig. 12. Information regarding the exact locations of the wind turbines was essential in the implementation of this algorithm as it allows for the maximum quantity of *good* data. The wind turbine clutter, outlined in red, is significantly reduced after the application of the three-dimensional interpolation scheme applied to the spectral moments. Some of the weather data embedded within the wind turbine clutter section appear to have been recovered. However, interpolation schemes actually loose information and resolution and are not the technique of choice for most applications.

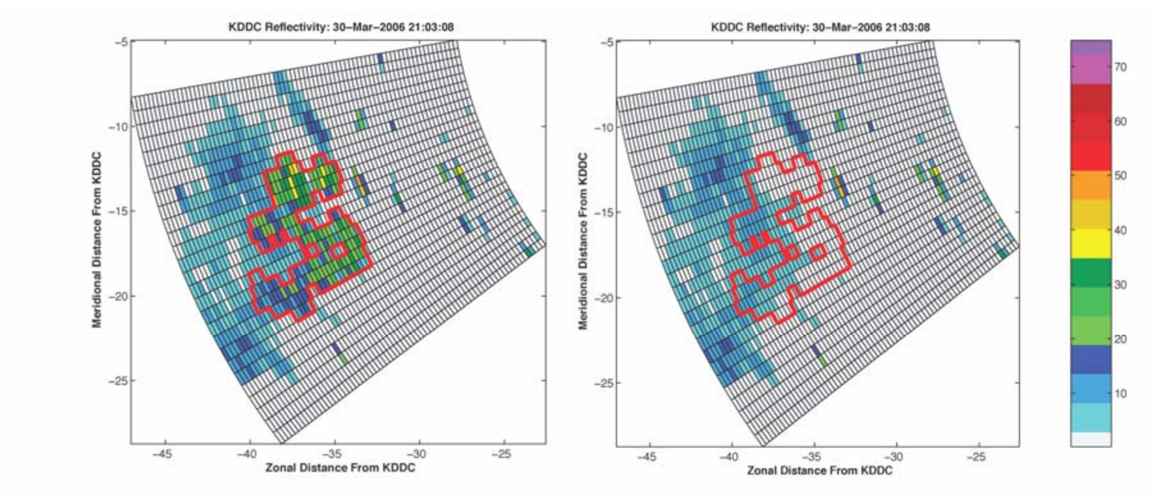


Fig. 12: Real-data demonstration of the three-dimensional multiquadric interpolation technique. The wind farm is outlined in red. The wind farm before applying the multiquadric method is shown in the left panel and the result of the interpolation scheme is shown in the right. It should be emphasized that some of the weather information appears to be recovered but is actually lost by the processing.

(3) Limitations of Mitigation Schemes

The interpolation method described in the previous section assumes that the area surrounding the wind turbine clutter region is a *good* representation of the contaminated area. However, severe weather signals can have significant gradients in both the reflectivity and velocity fields reducing the validity of such an assumption. The application of the interpolation technique eliminates any contaminated data, including the real weather data hidden within the WTC region, and replaces it with estimated data. As a result, the area containing the wind farm is no longer a true representation of the weather echoes within that region but is a function of the surrounding data. More sophisticated algorithms and further research is necessary in order to evaluate the possibility of recovering the true weather signal. Until such a technique is developed, however, a cooperative effort between the wind power industry and the NWS on wind farm siting is the best solution for mitigation of the negative impact of wind farms on weather radar.

d. Wind Farm Siting Collaboration

The Department of Commerce/National Oceanic and Atmospheric Administration is collaborating with other Federal departments and agencies to facilitate communications and the exchange of information related to the planning and siting of wind turbines and the operations of mission critical Federal systems. This coordination among Federal Departments such as Commerce, Energy, Transportation, Defense, Homeland Security, Agriculture, and Interior is paramount to ensure that adequate processes and tools are in place to improve wind siting collaboration. This group has created a one-stop shopping information center – located at: http://www.eere.energy.gov/windandhydro/federalwindsiting/ - for all interested parties to access when planning for wind energy facilities. This will further enable the wind energy industry to consider optimal locations, while not impacting critical agency mission area operations.

5. How We Can Work Together

There are actions the weather radar community and wind energy industry can take that will help meet their common goal of supporting the Nation. The NEXRAD Program would like to participate in public forums and future wind industry conferences to provide information on NEXRAD radar operations. The sharing of information between the NEXRAD Program and the wind energy industry will improve communications and reduce siting coordination problems. The NEXRAD Program has developed a web site: http://www.osf.noaa.gov/windfarm/windfarm_index.asp. The web site provides information on wind farm interactions with the NEXRAD radar. Further, collaborative efforts among Federal departments and agencies will provide an across-the-board exchange of information with the wind energy industry.

Similar to a finding in the 2006 report to Congress on the impacts of wind farms on air surveillance radars (DOD 2006) and a report published in Canada (RABC and CANWEA 2006), experience to date indicates that wind turbines located in the radar-line-of-sight can adversely impact the ability of NEXRAD radars to provide optimum information to weather radar users. The NEXRAD Program believes the best mitigation technique is to avoid locating wind turbines in the radar-line-of-sight of a NEXRAD. This strategy may be achieved by distance, terrain masking, or terrain relief and requires case-by-case analysis.

The NEXRAD Radar Operations Center is willing to assist wind farm developers in determining the potential wind farm impacts and siting alternatives. While the NEXRAD Program has begun to learn about proposed wind farms via the Federal Interdepartmental Radio Advisory Committee (IRAC), this represents a subset of the wind farms being planned. It also appears the timing of these notifications to the IRAC is after the wind energy industry has already invested considerable time and money in developing plans for the wind farms. The NEXRAD Program would prefer the wind energy industry provide information on planned projects, new or expansions, to the NEXRAD Program in advance. This will enable us to estimate the potential impacts on nearby NEXRAD radars and offer suggestions on how to mitigate impacts (e.g., terrain masking, orientation of structures).

REFERENCES

Crum, T. D. and R. L. Alberty, 1993: The WSR-88D and the WSR-88D Operational Support Facility. *Bull. Amer. Meteor. Soc.*, **74**, 1669-1687.

Department of Defense, 2006: Report to the Congressional Defense Committees, The Effect of Windmill Farms on Military Readiness, 62 pp.

Doviak, R.J. and Zrnic, D.S. Doppler Radar and Weather Observations. Dover Publications Inc, Mineola, NY. 1993.

Franke, R. Scattered Data Interpolation: Tests of Some Methods. *Mathematics of Computation*, Volume 38, Number 157. January 1982.

Joint Radio Advisory Board of Canada (RABC) Canadian Wind Energy Association (CANWEA), 2006: Technical information on the assessment of the potential impact of wind turbines on radio communication, radar and seismoacoustic systems, Final Draft 1.1, 21 pp. Publication 2006.08.14.

Federal Meteorological Handbook No. 11, Parts A – D available at: http://www.roc.noaa.gov/FMH_11/default.asp

Simmons, K. M. and D. Sutter, 2005: WSR-88D Radar, Tornado Warnings and Tornado Casualties. Wea Forecasting, **20**, 301-310.

Vogt, R. J., J. R. Reed, T. Crum, J. T. Snow, R. Palmer, B. Isom, and D. W. Burgess, 2007: Impacts of Wind Farms on WSR-88D Operations and Policy Considerations. Preprints, *23rd Int. Conf. on Interactive Information Processing Systems (IIPS) for Meteorology,* *Oceanography, and Hydrology,* San Antonio, TX, Amer. Meteor. Soc., Paper 5B.7.

Wilczak et al. Contamination of Wind Profiler Data by Migrating Birds: Characteristics of Corrupted Data and Potential Solutions. *Journal of Atmospheric and Oceanic Technology*. Volume 12, Number 3. June 1995.

Web sites that offer additional information concerning the NEXRAD, radar meteorology, and wind energy include:

American Wind Energy Association: http://www.awea.org/
Atmospheric Radar Research Center: http://arrc.ou.edu/
Department of Energy Wind & Hydropower Technologies Program:
http://www1.eere.energy.gov/windandhydro/
Federal Aviation Administration Obstruction Evaluation/Airport Space Analysis (OE/AAA):
https://www.oeaaa.faa.gov/oeaaa/external/portal.jsp
Federal Meteorological Handbook No. 11: http://www.roc.noaa.gov/FMH_11/default.asp
NEXRAD Radar Operations Center Wind Farm Information:
http://www.roc.noaa.gov/windfarm/windfarm_index.asp
NEXRAD Radar Operations Center: http://www.roc.noaa.gov/
Real-time NEXRAD Imagery: http://radar.weather.gov/
Weather Radar Information: http://www.srh.noaa.gov/jetstream/remote/doppler.htm