6B.4 AN UPDATE ON POLICY CONSIDERATIONS OF WIND FARM IMPACTS ON WSR-88D OPERATIONS

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1. BACKGROUND

The use of wind turbines in the United States to generate electricity continues to grow rapidly (http://www.awea.org/projects/) (Fig. 1). For example, in its 3rd Quarter 2007 Market Report, the American Wind Energy Association (AWEA) estimated a total of 4,000 MW of new wind-generated electricity capacity would be brought on line in 2007 (http://www.awea.org/). In order to meet a national goal of wind generation supplying up to 20% of U.S. electricity consumption by 2020, over 250,000 additional wind turbines must be installed.

New wind farms sometimes have over 100 wind turbines with blade-tip heights over 140 m (458 ft) above ground level (AGL). Greater blade-tip heights are expected in the near future. As the number and height of wind turbines increase, there is growing potential for turbines to be constructed close to weather radars and so interfere with radar performance. Optimum locations for weather (and other) radars and for wind turbines are often the same – relatively high, unobstructed terrain. The geographic distribution of turbine locations favors certain locations – further increasing the potential for wind turbines to be built in close proximity to radars (Fig. 2).

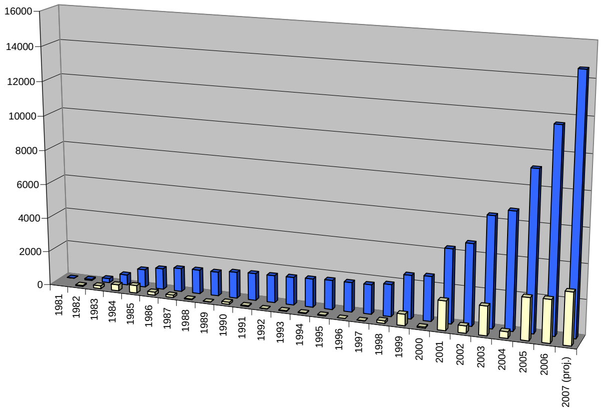

Fig. 1. Annual U. S. wind power capacity (MW), net annual increase (yellow bars) and cumulative capacity (blue bars) from 1981 through 2007 (projected). (American Wind Energy Association 2007)

Fig. 2. Locations of new wind power projects built in 2006 (red) and being built in 2007 (blue and open circles). (American Wind Energy Association 2007)

Nearly all wind farms installed before 2006 did not include consideration of their potential impact on weather radars. Permitting for wind farm construction is generally done at a local level. The federal government has no regulatory authority

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over wind turbine construction on private property. The Federal Aviation Administration is notified of structures over 200 ft tall and determines if the structures are a hazard to aviation via Obstruction Evaluation/Airport Airspace Analysis (OE/AAA) (Title 14 of the Code of Federal Regulations CFR Part 77), but does not consider possible weather radar interference.

In September 2006 the Department of Defense (DoD) reported to Congress (DoD 2006) on the impact of wind turbine installations on military readiness and air surveillance radars. The primary finding in the report was that to preclude adverse impacts on defense radars, developers should avoid locating wind turbines in the radar line of sight (RLOS). This can be achieved by distance, terrain masking, or terrain relief. This approach requires a case-by-case analysis. The report deferred to the National Oceanic and Atmospheric Administration's (NOAA's) National Weather Service (NWS) to address impacts on weather radars.

Data from the national network of Weather Surveillance Radar-1988, Doppler (WSR-88D) systems are a key component in the decision-making processes of issuing weather forecasts and severe weather warnings, and supporting the National Airspace System. Experience has shown that when wind turbines are within the WSR-88D's RLOS (defined as the cone of the half-power points, approximately 1 degree in width), spurious signals returned by the turbine towers and the rotating blades can negatively impact radar data quality and degrade the performance of radar algorithms.

This paper updates the paper presented at the 2007 IIPS Conference (Vogt et al 2007). This paper provides: updated examples of wind farm impacts on WSR-88D base products and algorithms; the WSR-88D Radar Operations Center (ROC) outreach efforts to the wind energy industry; ROC efforts to mitigate wind farm impacts on WSR-88D radar data quality; and plans to continue to work with the wind energy industry to mitigate the impacts of wind farms on WSR-88D systems.

2. IMPACTS OF WIND FARMS ON WSR-88D SYSTEMS

Wind farms within RLOS of WSR-88D radars have several potential impacts (Burgess et al 2008). First, false reflectivities and areas of disturbed mean radial velocity and spectrum width data may appear in base data displays. Partial beam blockage can occur for larger wind farms and those that extend further into the radar beam. These artifacts can confuse forecasters and other radar data users. Second, erroneous base data can affect radar algorithms. Most often encountered are anomalous precipitation accumulations, but another important source of error is false detection and inaccuracies in mesocyclone and tornado detection algorithms. False turbulence detection algorithm signatures arise from disturbed spectrum width regions. Wind farms at "extremely close" ranges to radars have all the impacts listed above and additional ones. Inter-turbine scatter and multi-trip/multi-path echoes expand wind-farm-related radar returns to extended ranges down radial from the real wind farm echo regions. In some cases, these regions of erroneous data can extend down radial for 40 km or further. In such cases, the disturbed areas are large enough to cause additional forecaster confusion and to affect forecasts and radar data (particularly Velocity Azimuth Display Wind Profile) assimilations into numerical models. Finally, if large wind farms were to exist in the near field (that is, within 183 m (600 ft) of radars, full beam blockage and damage to electronic components to both radars and turbines might occur.

Examples of how wind farms appear on operational WSR-88Ds are shown in Figs. 3 - 6. These and other examples are available at: http://www.roc.noaa.gov/windfarm/windfarm_impacts.asp.

In collaboration with the University of Oklahoma/Cooperative Institute for Mesoscale Meteorological Studies, the ROC is evaluating operational impacts of select current wind turbine installations on the data and products produced by the WSR-88D network as well as subsequent impact to weather forecast and warning performance.

Wind turbine clutter has not yet become a major negative impact on forecast operations. However, with more and larger wind turbine installations coming on line in the near future, experience gained to date suggests that negative impacts should be anticipated -- some sufficient to compromise the ability of radar data users to perform their missions.

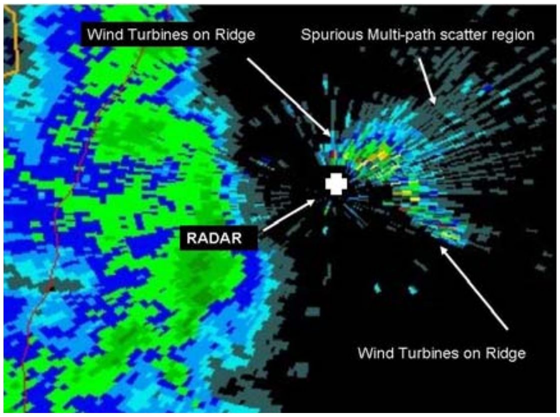

Fig. 3. A 0.5 degree scan Reflectivity product from the Fort Drum, NY WSR-88D (KTYX) on March 10, 2007 at 1234 GMT. A wind farm is approximately 6 - 14 km north through east-southeast of the radar (see annotations). The stronger echoes (e.g., red, yellow, and green pixels) begin along the leading edge of the wind farm and extend downrange due to multi-path and inter-turbine scattering of the radar beam. The echoes west of the radar are from an approaching area of rain. Without the wind farm, the echoes to the north - east of the radar would not be present.

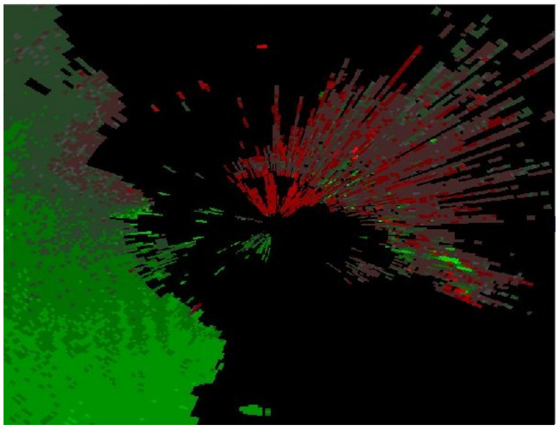

Fig. 4. A 0.5 degree scan Mean Radial Velocity product from the Fort Drum, NY WSR-88D (KYTX) corresponding to the time of the image in Fig. 3. Red colors indicate outbound velocities and green colors indicate inbound velocities. The radar interaction with the wind farm has created the anomalous velocity data north – east of the radar as shown in Fig. 3. Note the anomalous and more “chaotic” wind velocities depicted down range of the wind farm in comparison with the velocities in the “real weather” data west of the radar. These echoes could confuse data users or radar meteorological algorithms.

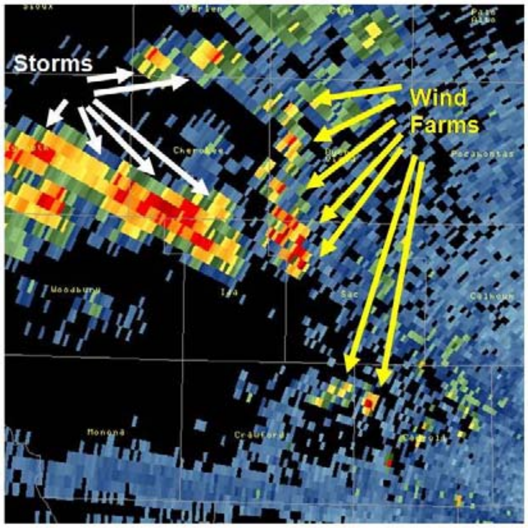

Fig. 5. This Reflectivity image (0.5 degree scan) from the Des Moines, IA WSR-88D (KDMX) on July 19, 2007 at 0236 GMT shows how it can be difficult to distinguish high radar reflectivity returns (yellow and red pixels) due to wind turbines from strong storm returns (see annotations). The wind farms vary in distance from approximately 115 km to 160 km from the WSR-88D. In this case an emergency manager, monitoring the severe weather situation using the Des Moines WSR-88D, mentioned confusion as the storm moved into their area of responsibility.

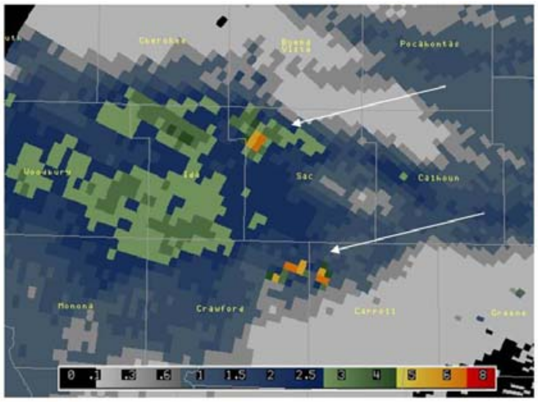

Fig. 6. This radar-estimated Storm Total Precipitation accumulation product from the Des Moines, IA WSR-88D on July 19, 2007 at 0512 GMT includes the period of time and storms shown in Fig. 5. Erroneous 5+ inch radar-estimated Storm Total Precipitation accumulations (indicated by the yellow arrows) are due to wind farms northwest of the WSR-88D. The anomalous accumulations make estimates of the amount of rainfall over an area/river basin more difficult to determine.

3. MITIGATION ACTIONS TAKEN

a. Outreach to Wind Energy Industry

Weather radar operators began reporting radar – wind farm/turbine interactions early in this decade. In 2006, the NOAA/NWS and the ROC, on behalf of the Next Generation Weather Radar (NEXRAD) Program, began systematic efforts to investigate these interactions. These efforts included:

(1) Participating in a federal interagency working group charged with finding ways to improve collaboration with the wind energy industry;
(2) Exploring potential interference mitigation approaches; and
(3) Increasing communication with the wind energy industry.

In addition, the ROC began receiving voluntary notifications from wind farm developers (now received via the National Telecommunications Information Administration) of their intentions to build wind farms at specific locations. The ROC analyzes whether the proposed wind turbines would intercept the RLOS of a WSR-88D on a case-by-case basis. The NEXRAD Program has adopted the RLOS as a bench mark for seeking further discussions with developers to determine if alternative siting strategies (e.g., relocation, terrain masking, and/or a more optimum deployment pattern with respect to reducing radar interference) could reduce the potential impact of wind turbines on radar performance. Since mid-2006, the ROC has completed over 140 analyses of proposed wind farm deployments. About 15% of proposed wind farms have been potentially in the RLOS of a WSR-88D. Some of these analyses have resulted in further discussions with the developers who in turn have been able to modify their siting plans to reduce the impact of the new wind farm on the nearby WSR-88D.

During 2007 the ROC has taken the following actions to work with other federal agencies and the wind energy industry to promote co-existence of WSR-88Ds and wind farms with minimal interference:

(1) Participated, in the 2007 AMS IIPS conference (Vogt et al 2007); the 2007 AMS International Radar Conference (Isom et al 2007) and a presentation on wind farm impacts by Don Burgess.
(2) Participated, via poster and a paper, in the June 2007 AWEA WINDPOWER 2007 conference (Vogt et al 2007(2)). This generated new awareness, interest, and questions from the wind energy industry and established contacts for further discussions.
(3) Began working with the FAA to add a NEXRAD “toolkit” on the FAA OE/AAA web site (https://www.oeaaa.faa.gov/oeaaa/external/portal.jsp). This addition will enable developers to ascertain, early in their planning process, potential wind farm impacts on WSR-88D systems in a manner similar to DoD/Department of Homeland Security (DHS) long-range radars.
(4) Established a portion of the ROC web page (http://www.roc.noaa.gov) entitled “Wind Farm Interaction.” The page has information on the WSR-88D, maps of the RLOS for each WSR-88D in the CONUS, and examples of radar-wind turbine impacts on the WSR-88D and imagery of wind farms as seen by operational WSR-88Ds. The page has been visited by developers, WSR-88D operators, and WSR-88D data users.
(5) Exchanged information with other federal agencies operating radars, such as the DoD/DHS Long-Range Radar Joint Program Office.
(6) Hosted a Department of Energy (DOE)-led technical interchange meeting of federal government and private industry members to discuss mitigation tools and potential strategies for increasing the sophistication of the tools.
(7) Participated in a DOE-organized technical interchange meeting to discuss wind farm interaction analysis and mitigation tools in place and planned.
(8) Shared ideas, publications, and radar data with the Air Force Research Laboratory that is working on wind farm impacts on air surveillance radars.
(9) Participated in the January 2008 JASON Winter Study session on radar –wind farm interaction.

b. Experimental Signal Processing Techniques

In addition to the above-listed outreach activities, the ROC continued its collaboration with the University of Oklahoma to evaluate schemes for mitigating wind turbine clutter (WTC) on the

WSR-88D. With the recent Open Radar Data Acquisition (ORDA) upgrade to the WSR-88D network, it is now possible to implement real-time, advanced signal processing algorithms that may greatly reduce the impact of WTC. 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. 7 (at end of text) 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.

The most challenging task in WTC mitigation is removal of the blade components without distorting or removing the desired weather signal. Examples of mixed wind turbine clutter and weather Doppler spectra over many range and azimuth gates are shown in Fig. 8 (at end of text). The Doppler spectra are shown as a function of range from the radar in Fig. 8a, while the spectra are shown as a function of azimuth in Fig. 8b. The turbines show up as extremely large bandwidth (large Doppler spread) signals over 37-44 km and 240-250^{o} for Figs. 8a and 8b, respectively. The dominant 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 spatial continuity of the weather signature given that atmospheric echoes will not typically change characteristics significantly over short distances. 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.

(2) Multiquadric Interpolation and Nowcasting

Any interpolation technique relies on the presence of uncontaminated or *good* data to estimate the signal at an unknown or contaminated location. For the case of wind turbine clutter, an uncontaminated gate neighboring the wind farm can be considered *good* data and can be used to estimate the weather signal in gates 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 (Hardy, 1971). This technique can be implemented in any number of dimensions and is appropriate given the three-dimensional, continuous structure of weather signals. In addition to exploiting the spatial continuity of weather, temporal continuity can be used to further enhance any interpolation scheme. A simple method developed by Rinehart and Garvey (1978) is employed using the current and previous scans to translate *good* data into the WTC region. By calculating the first moment of the two-dimensional cross-correlation between the two images, a motion vector can be determined that regulates the data translation. Following the data translation, interpolated and nowcasted data are optimally combined through least-mean squares criterion.

An example of the implementation of the multiquadric method in conjunction with the simple nowcasting algorithm on data taken from the Dodge City, KS WSR-88D on March 30, 2006 is shown in Fig. 9 (at end of text). 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 black, is significantly reduced after the application of the two-dimensional interpolation and nowcasting hybrid scheme applied to the spectral moments. Some of the weather data embedded within the wind turbine clutter section appears to have been recovered. However, interpolation schemes actually loose information and resolution and are not the technique of choice for most applications.

(3) Limitations of Interpolation 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.

(4) Advanced Signal Processing Research

In addition to interpolation, several true signal/image processing techniques are also being explored. For example, principle component analysis (PCA) is a technique used to reduce the dimensionality of data sets to lower dimensions for analysis. In this experimental application, it is used to retrieve the mean radial velocity of the weather features. The weather feature at approximately 36 km (Fig. 10) was characterized using PCA and 80% of the subspace that spanned this feature was retained. This subspace was then applied to other features within this image to obtain their correlation values to the weather feature test set. These correlation values, along with spatial continuity constraint of the mean radial velocity, were applied to extract the mean radial velocity of the weather structure. The results obtained, as well as the spectrum and radial velocities of the weather and clutter contaminated fields, are shown in Fig. 10 (at end of text). Although very preliminary, more advanced signal processing methods are providing guarded optimism that such approaches may help to extract the weather signal from WTC contamination.

c. Radar Operation and Interpretation

Wind farm interference on radars is a relative term, but the bottom-line metric is the impact the interference has on the operational mission. Forecasters in NOAA/NWS Weather Forecast Offices (WFOs) can learn to recognize wind farm weather radar signatures; reduce impacts somewhat through proper radar configuration; and attempt to accommodate or “work around” the wind farm impacts in their decision process (Burgess et al 2008). For example, forecasters can:

(1) Establish exclusion zones to limit precipitation overestimation or false accumulations. However, exclusion zones only apply to real-time precipitation algorithms and do not remove the contamination from the base data which may be used years later for climatological purposes.
(2) Invoke clutter suppression. This approach only excludes stationary targets and is not effective on clutter arising from turbine blades in motion.
(3) Look at higher elevations to “see over” wind farms. This can result in the loss of low-altitude information crucial in some forecast situations, e.g., onset of a tornado.

Operational forecasters can often distinguish WTC from weather signals using their experience. However, a major concern is the effect of these echoes on automated detection algorithms and users not as experienced or used to the appearance of WTC.

4. PLANNED MITIGATION ACTIONS

The ROC, on behalf of the NEXRAD Program, plans to continue to expand contacts with the wind energy industry in 2008 and beyond to promote earlier and more frequent sharing of information and collaboration. We have accepted an invitation to participate in the February 2008 AWEA Wind Power Project Siting Workshop and have submitted an abstract for consideration for inclusion in the June 2008 AWEA annual meeting, WINDPOWER 2008. We plan to continue to support the University of Oklahoma mitigation research and perform testing of the Multiquadric Interpolation and Nowcasting technique on data sets collected at operational WSR-88D sites to determine the benefit of that approach to mitigating WTC in the radar data. The ROC also plans to support another study at the University of Oklahoma on the impacts of a wind farm on a nearby WSR-88D and WFO forecast and warning operations. We look forward to working with other federal agencies and the private sector to generate a checklist for developers to use while planning a wind farm that will include consideration of potential radar impacts.

5. SUMMARY

The rapidly increasing number of wind farms used to generate electricity is beginning to negatively impact weather surveillance radar data. At present, the operational impacts appear to be minor. However, experiences to date indicate the on-going near-exponential growth in the number of such installations is cause for concern. NOAA's NWS is involved in studying the impacts of wind farms and mitigation opportunities to ensure the network of WSR-88Ds can continue to provide mission-critical support to essential forecast and warning operations.

6. RELATED URLs

WSR-88D Radar Operations Center Wind Farm Interaction:
http://www.roc.noaa.gov/windfarm/windfarm_index.asp

University of Oklahoma Atmospheric Radar Research Center: http://arrc.ou.edu/

Federal Aviation Administration Obstruction Evaluation / Airport Airspace Analysis (OE/AAA):
https://www.oeaaa.faa.gov/oeaaa/external/portal.jsp

7. ACKNOWLEDGMENTS

The support of several people in the ROC has been key in analyzing potential wind farm impacts on operational WSR-88Ds. The authors are particularly appreciative of the efforts of Lynn Allmon, Joe Chrisman, Ron Guenther, Captain John Sandifer, Glenn Secrest, Tony Ray, and Major Jennifer Winslow. Karl Jungbluth, NWS Des Moines, IA WFO, provided the imagery from the Des Moines WSR-88D.

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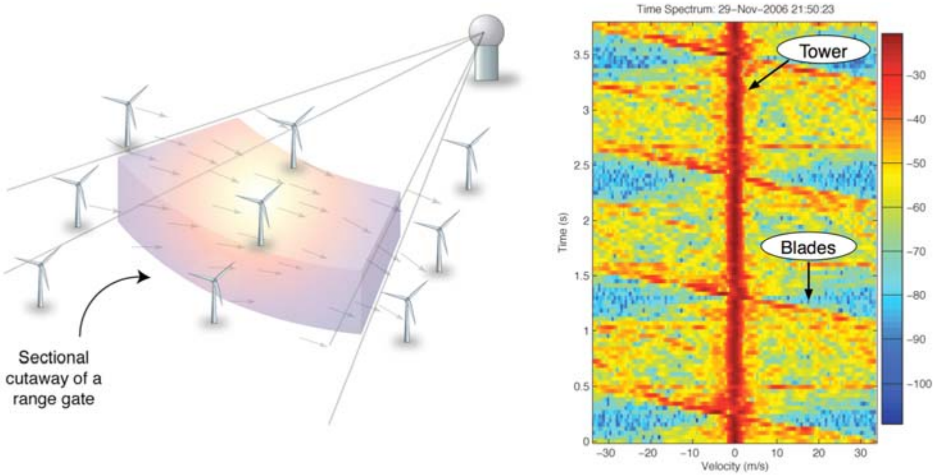

Fig. 7. Schematic diagram of a radar resolution volume containing a single turbine. Also shown is the evolution in time of the spectral content of such a resolution volume. Note the tower structure has zero Doppler velocity and the blades can be detected at a wide range of velocities depending on the time of observation.

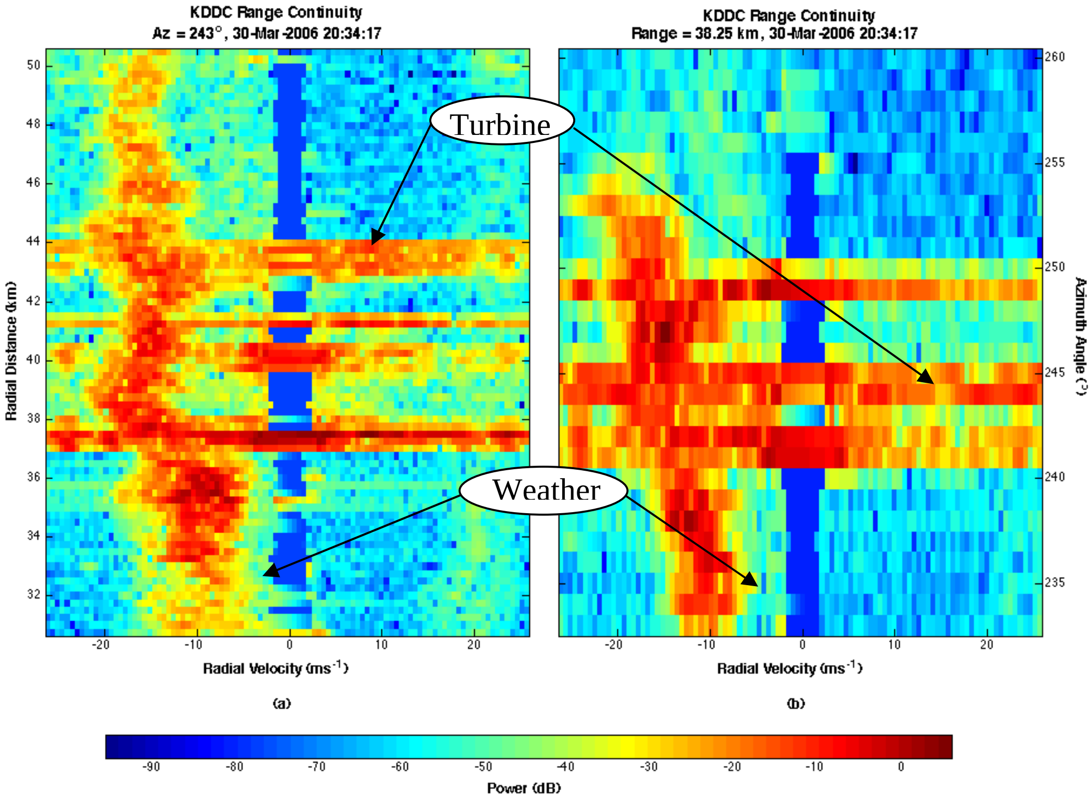

Fig. 8. Evolution in range and azimuth of the Doppler spectrum taken from the Dodge City, KS WSR-88D (KDDC) on March 30, 2006. The wind turbines are present from approximately 37 to 44 km and 240 to 250^o. The weather signal is visible as a negative radial velocity and does not change substantially over the gates shown here implying strong spatial continuity.

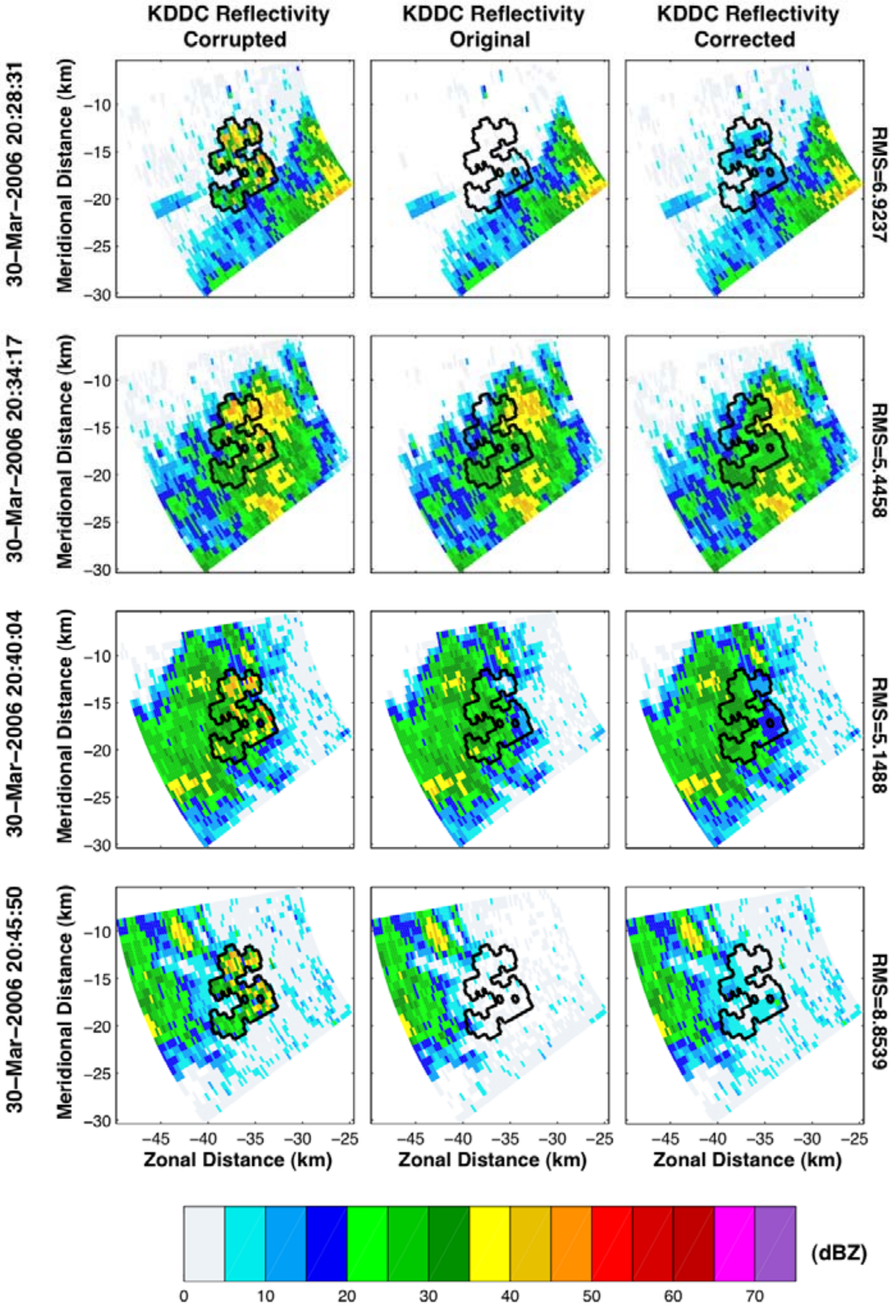

Fig. 9: A demonstration of the two-dimensional multiquadric interpolation-nowcasting hybrid technique. The corrupted, original, and corrected reflectivity images for four consecutive scans are shown in the left, center, and right columns, respectively. RMS error for each time frame is provided to the right.

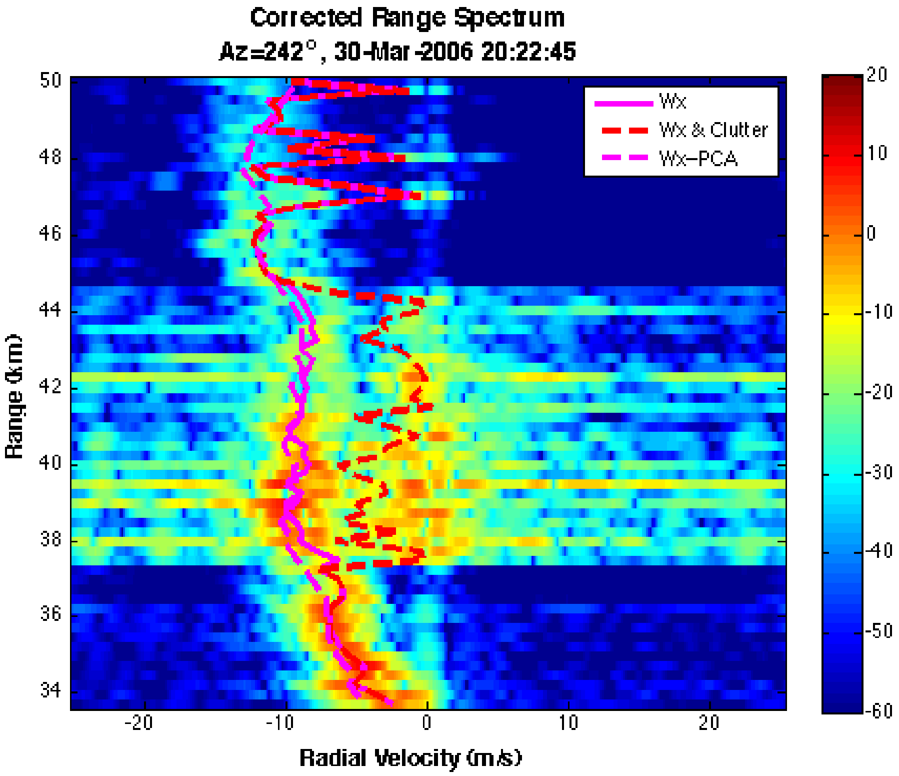

Fig. 10: Mean radial velocity retrieved using principle component analysis. The weather feature at approximately 36 km was used as a test set to obtain the weather subspace. The retrieved correlation values, along with spatial continuity constraint, were applied to retrieve the mean radial velocity of the weather features.