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# WEATHER RADARS AND WIND FARMS – WORKING TOGETHER FOR MUTUAL BENEFIT

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## 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. This paper and accompanying poster have much of interest to the wind energy industry, including information on: Next Generation Weather Radar (NEXRAD) systems; how wind farms can impact NEXRAD data and impair life-saving severe weather warnings; how wind generator electronics can be negatively impacted by NEXRAD radars; NEXRAD Program efforts to support wind energy industry siting decisions; and how the wind energy industry can collaborate with the NEXRAD Program to reduce impacts on weather radars.

One of the key tools weather forecasters use in preparing forecasts and severe weather warnings is the Nation's network of weather radars (NEXRAD). In recent years, operators of NEXRAD systems have become increasingly aware of the interaction between weather radars and wind farms. Experience has shown that when wind farms are located in a NEXRAD radar beam/radar line of sight (RLOS), the towers and especially rotating turbine blades can adversely impact radar data quality and the performance of severe weather detection algorithms. Just as the wind energy industry is investing in wind farm planning and construction, the federal government invested over $1.4B on the NEXRAD network and operates and maintains the network of radars to ensure the best possible protection of life and property.

The potential for wind farm interference with the NEXRAD network will likely increase with the anticipated large growth in wind energy projects. This increased likelihood is due to not only the explosive growth of the number of wind farms, but also to the larger number of turbines in wind farms and use of taller turbines (which can cause impacts on radars at a greater distance). Furthermore, the wind industry tends to favor the same relatively high, unobstructed terrain and proximity to population centers where weather radars are located.

The best approach to avoid interference and have a mutually beneficial co-existence is for increased collaboration between the NEXRAD Program and the wind energy industry. Earlier and more frequent exchange of information with developers will enable better siting decisions earlier in the planning process while the costs for accommodation are relatively lower.

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## 2. NEXRAD Overview

a. NEXRAD Program Overview

To meet the Nation's need for detailed weather radar data, NEXRAD radars have been installed at 159 operational locations across the contiguous United States (Fig. 1), Alaska, Hawaii, Puerto Rico, and select overseas sites. (Developers can obtain the location and elevation of individual radars by contacting the NEXRAD Radar Operations Center (http://www.roc.noaa.gov/Feedback/)). These radars, also known as the Weather Surveillance Radar-1988 Doppler (WSR-88D), have enabled National Weather Service (NWS) and DOD weather forecasters to improve the detection of and provide greater advanced warning for tornadoes, flash floods, and other severe weather events. These forecasts and warnings provide life-saving information to the public, support military operations, and inform resource protection decision makers. NEXRAD data are also key for the safe and efficient operation of the National Airspace System - NEXRAD data are displayed on Federal Aviation Administration (FAA) air traffic controllers' screens and sent directly to many airborne aircraft. The private sector weather industry has grown greatly in the last decade, due in part to the availability of and use of 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.

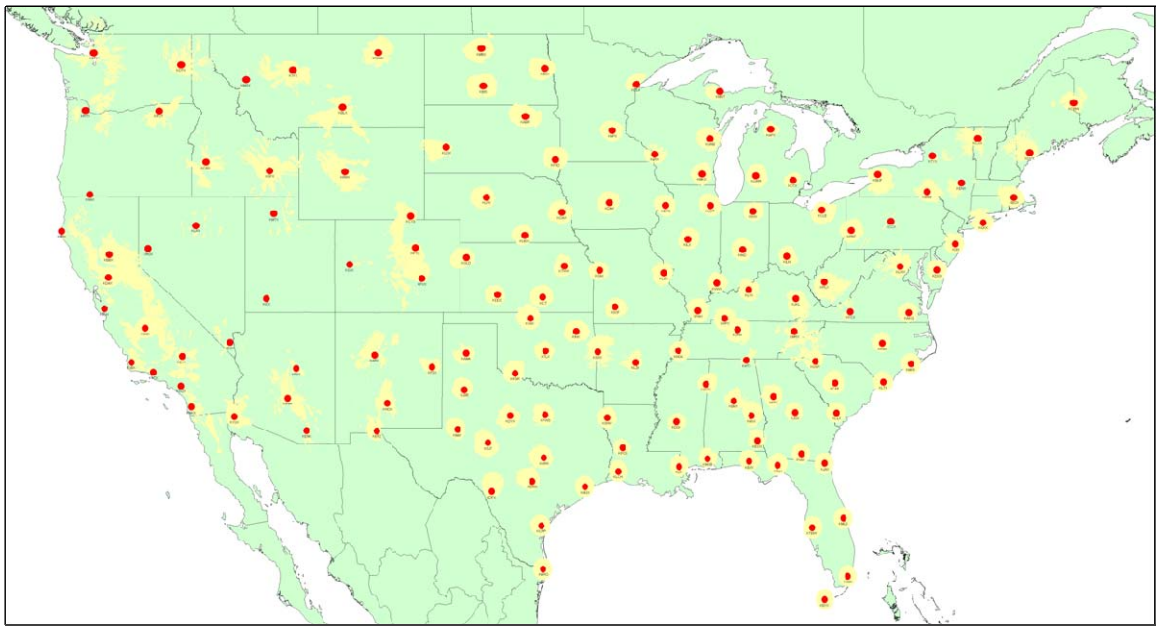

Fig. 1. A map of the 142 NEXRAD radar locations in the contiguous United States. The yellow shaded areas around the radars show where the radar line of sight is within 200 m (656 ft) of the ground. This height was selected as representative of projected wind turbine heights for the near future. Areas within 10 statute miles of each radar are indicated in red. Wind turbines in the 10 mile area could be impacted by the radar and likely will have significant impacts on the radar. (This drawing should be used for illustration purposes only.) Data from this map will be incorporated into a "NEXRAD Tool," similar to the "Long Range Radar Tool," on the FAA OE/AAA web site (https://www.oeaaa.faa.gov/oeaaa/external/portal.jsp) by summer 2008. See Section 4 for a description of the areas depicted on the map.

b. NEXRAD System Overview

The NEXRAD radars transmit radio frequency energy with a nominal peak power output of 750 kW. The radars automatically scan the atmosphere in pre-defined patterns from $0.5^{o}$ to $19.5^{o}$ elevation above the horizon, then process and distribute reflectivity, mean radial velocity, and spectrum width (a measure of the variability of radial velocities in the resolution volume) data. The radar estimates of these quantities are based on radio frequency energy returned from precipitation and other reflectors/scatterers (e.g., insects, birds, wind turbine blades). From these data, computer-processed algorithms generate a suite of

meteorological and hydrological analysis products. 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, floods, and other phenomena. The general public may access the radar data from private meteorology companies and the Internet (e.g., http://radar.weather.gov/). Further information about the NEXRAD radars and their operation is available (Federal Meteorological Handbook No. 11, Parts A – D; http://www.roc.noaa.gov/FMH_11/default.asp).

The NEXRAD has a clutter filter algorithm to remove clutter/ground targets/non-meteorological targets. Since NEXRAD is scanning the atmosphere for small-scale atmospheric motions indicating severe weather, a fundamental premise of this algorithm is that a clutter target has no motion (zero instantaneous velocity). However, when the NEXRAD "sees" a wind farm, the turbine blades are usually in motion and therefore have a nonzero velocity. Hence, the NEXRAD clutter filter algorithm does not remove the returns of the turbine blades in most situations. Furthermore, NEXRAD is designed with a very high sensitivity and low noise floor in order to detect weather signatures at long range. This makes NEXRAD particularly vulnerable to wind turbine blades in the radar line of sight (RLOS).

c. NEXRAD Radar Beam/Radar Line of Sight Characteristics

There are two important beam characteristics that define a radar's ability to "see" targets: (1) beam width or RLOS; and (2) beam propagation path/bending/refraction. The radar beam width/RLOS (Fig. 2a) can be considered analogous to the beam of light from a flash light. Most of the energy of the flashlight, just as with the radar, is in the beam of light (radar beam/RLOS). As the beam propagates from the radar, the beam width increases. For NEXRAD, at 60 miles from the radar the beam width/RLOS is approximately 1 mile wide. In a "Standard Atmosphere" the radar beam takes a path that is approximately 4/3 of the Earth's radius. In Fig. 2b, the beam width/RLOS for a standard propagation event is depicted. The intersection of wind turbine blades with the beam width/RLOS in a Standard Atmosphere is the benchmark the NEXRAD Program uses for requesting further consultation with developers to mitigate the potential impact of the wind farm on the nearby NEXRAD(s).

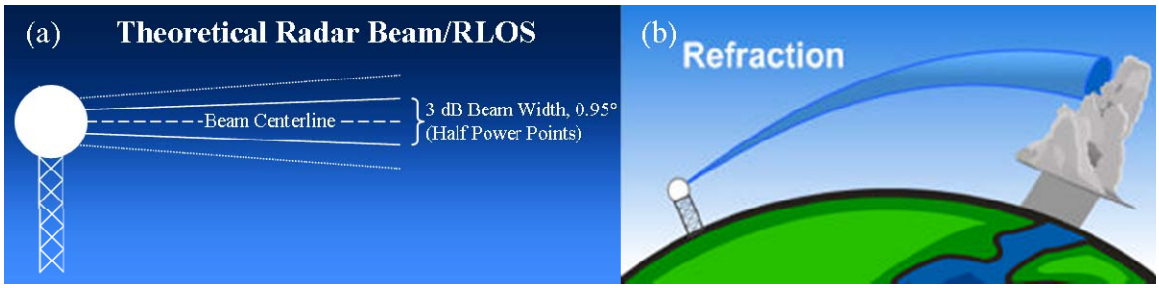


Fig. 2. (a) A depiction of the radar beam width/RLOS increasing as the beam travels from the radar. The lowest tilt of the radar is 0.5°. (b) A depiction of the path the radar beam takes in a Standard Atmosphere and approximates a 4/3 Earth radius, which is different than the optical line of sight.

## 3. Wind Farms and NEXRAD

a. How Wind Farms Can Impact NEXRAD Data and Users

Reflected energy from wind farms within the NEXRAD RLOS negatively impacts the radar data and products. This is illustrated by the situation of two wind farms within line of sight of the Dodge City, KS NEXRAD (KDDC) in Fig. 3.

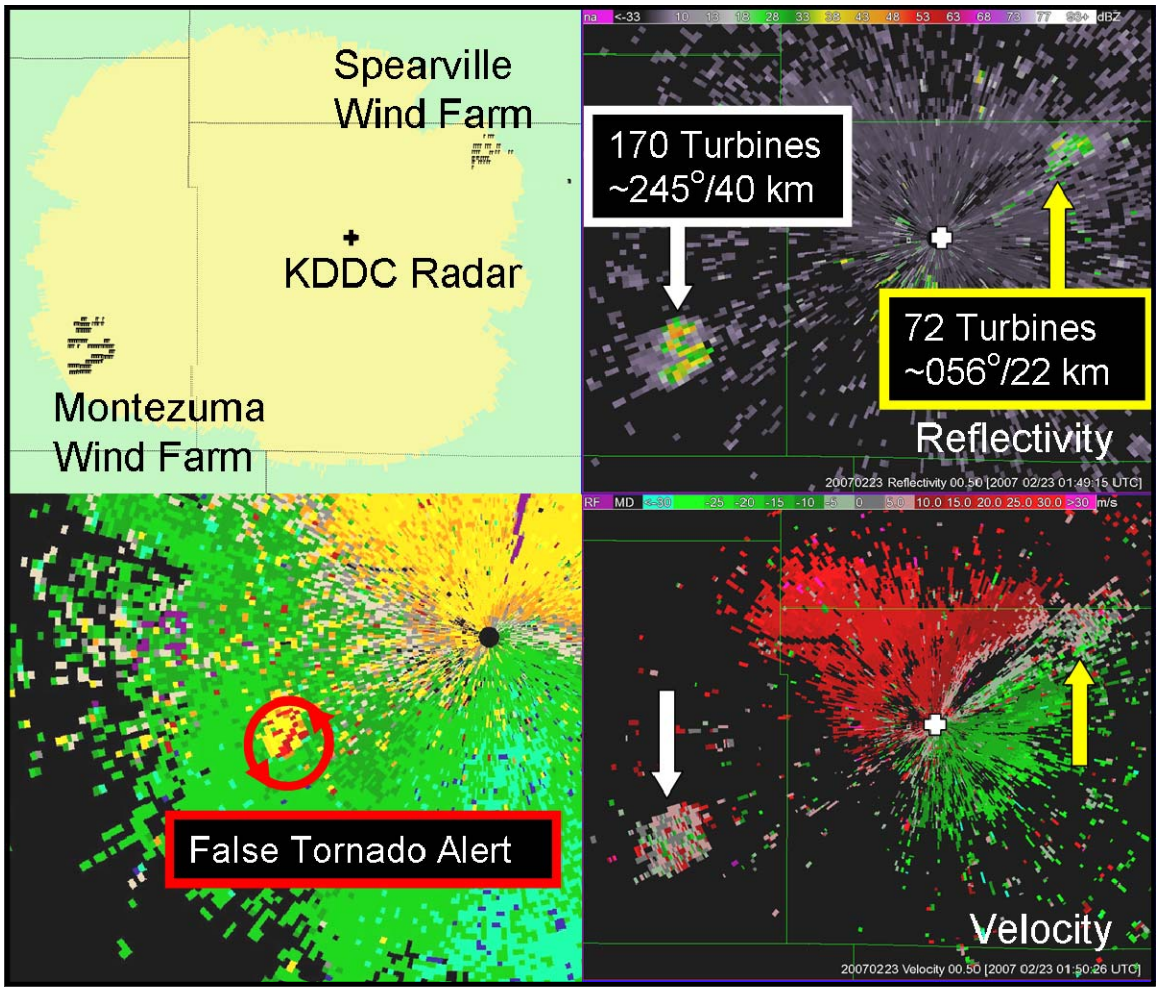


Fig. 3. Dodge City, KS NEXRAD (KDDC) reflectivity (upper right) and mean radial velocity (lower right) imagery for 0150 UTC on 23 Feb 2007 showing two wind farms within the RLOS. The yellow area in the upper left image depicts areas where the radar line of sight is within 130 m of the ground (differs from the 200 m area shown in Fig. 1). The reflectivity and velocity values are anomalous and can confuse users. The lower left panel shows the effects of the wind farm to the southwest whose influence has resulted in a false tornado alert generated by the NEXRAD algorithms.

Reflected energy from turbine blades can be difficult to discriminate from actual weather returns. Wind farm returns during precipitation events can have serious operational impacts. Weak rain showers can be mistakenly identified as strong thunderstorms and large regions of velocity data can be disturbed and erroneously displayed over areas much larger than the wind farm itself. Both conditions can distract users or reduce their situational awareness particularly during hazardous/severe weather events and potentially leading to incorrect decision making. Misidentification by FAA controllers and pilots of rain showers as strong thunderstorms can lead to needless and expensive rerouting of aircraft to avoid the implied thunderstorms.

The worst operational impacts occur during life-threatening events, such as severe thunderstorms and heavy rainfall. Weather forecasters rely on correctly displayed radar data and algorithm output to make quick warning decisions during rapidly evolving severe weather events. Both missed events and generation of false-alarm warnings are taken very seriously because of the negative impact they have on the entire warning system (emergency managers, the television and radio media, and all users of the warnings, including private-sector weather vendors and the general public).

Based on our investigation and experience, we have identified the following impacts wind farms can have on NEXRAD data and users:

- Anomalously large reflectivity values;
- False, low- or anomalously-large radar-estimated precipitation amounts or storms;
- False echoes downrange from wind farms;
- Incorrect velocity estimates; and
- Potential missed low-level tornado/severe weather signatures due to blockage from towers/turbines or anomalous signatures.

b. Differences between NEXRAD and Air Surveillance Radars

Even though weather surveillance radars and air surveillance radars (ASRs) operate on similar principles, their targets of interest and signal processing are significantly different. Therefore, any ASR-wind turbine clutter mitigation techniques may not be useable in the other type of system. ASRs look for large, hard, point targets (aircraft) and process the data to mitigate weak environmental returns. In contrast, weather surveillance radars are designed to sample small, weak and distributed returns (e.g., water droplets, aerosols, atmospheric particulates) and perform signal processing to remove or mitigate strong, point targets.

## 4. Upcoming NEXRAD Tool on FAA OE/AAA Web Site

The Federal Aviation Administration (FAA) Obstruction Evaluation/Airport Airspace Analysis (OE/AAA) web site (https://www.oeaaa.faa.gov/oeaaa/external/portal.jsp) has a Long Range Radar Tool where developers can obtain an initial evaluation of the potential impacts on Air Defense and Homeland Security radars. This pre-screening tool was instituted to assist wind farm developers in their initial siting process. In the summer of 2008 the FAA OE/AAA web site will add a NEXRAD Radar Tool where developers can obtain a similar initial evaluation of the potential impacts on NEXRAD radars. As with the Long Range Radar Tool, the NEXRAD Radar Tool will have a Green/Yellow/Red legend, defined as follows:

GREEN: "Minimal to no impact to WSR-88D weather radar operations. Aeronautical study required. National Telecommunications & Information Administration (NTIA) notification strongly advised." Rationale: Even though the wind farm development may not penetrate the NEXRAD RLOS for the Standard Atmosphere, during non-Standard Atmosphere conditions, the wind farms can impact NEXRAD imagery and algorithm products. The NEXAD Program wants developers to be more aware of potential impacts in advance.

YELLOW: "Impact likely to WSR-88D weather radar operations. Turbines likely in radar line of sight. Aeronautical study required. NTIA notification strongly advised." Rationale: The NEXRAD Program wants developers to be aware of impacts in advance. Please see Section 5 for information on potential and observed impacts.

RED: "Impact highly likely to WSR-88D weather radar operations and wind turbine electronics. Turbines likely in radar line of sight. Aeronautical study required. NTIA notification strongly advised." Rationale: (1) Turbine nacelle electronics within the RLOS and within 10 statue miles of the NEXRAD may require cable shielding to avoid interference to turbine electronics from the radar. (2) Within 1 km and within the RLOS the turbine reflection of the NEXRAD transmitted energy can destroy the NEXRAD receiver, or can prevent the radar beam from properly forming. (3) Within 600 ft and within the NEXRAD RLOS, microwave energy levels at the turbines could exceed the threshold of 1.0 $mW/cm^2$ for public exposure or 5.0 $mW/cm^2$ for occupational exposure**.**

## 5. NEXRAD Program Analyses of Potential Wind Farm Impacts

Based on planned wind farm development information we receive from developers directly and from the NTIA, the NEXRAD Radar Operations Center (ROC) provides a case-by-case analysis of potential wind farm impacts on NEXRAD data and forecast/warning operations. In the last 2 years, the ROC has

provided over 225 individual analyses, well short of the number of wind farms in the planning stage. It is vitally important for developers to consult the NEXRAD Tool on the FAA OE/AAA web site and submit all proposals through the NTIA as soon as practical. We are working with the NTIA to develop a more efficient proposal submission process. Some developers have found Comsearch or other support organizations as a convenient vehicle for sending proposals to the NTIA.

Figure 4 depicts an example of the primary categories of wind farm analysis requests/replies. Proposal X is clearly out of the RLOS, would have minimal to no impact on the radar. Proposal Y would have potentially some to moderate impacts on the radar if turbines were built in the western portion of the proposal area. The NEXRAD Program would seek to consult with the developer to determine if most/all wind turbines could be located in the eastern portion of the proposed area. Proposal Z would potentially have large impacts on the radar. The NEXRAD Program would seek to consult with the developer to determine if there is flexibility to consider impact mitigation techniques as described in Section 6 and to ensure the developers are aware of potential impact on forecast/warning operations. Proposal W would have potentially serious impacts on the turbines and the NEXRADs for the portion of the proposal in the red area. The NEXRAD Program would seek to consult with the developer to ensure they are aware of the likely impact on forecast/warning operations, the NEXRAD system, and the wind turbines/personnel.

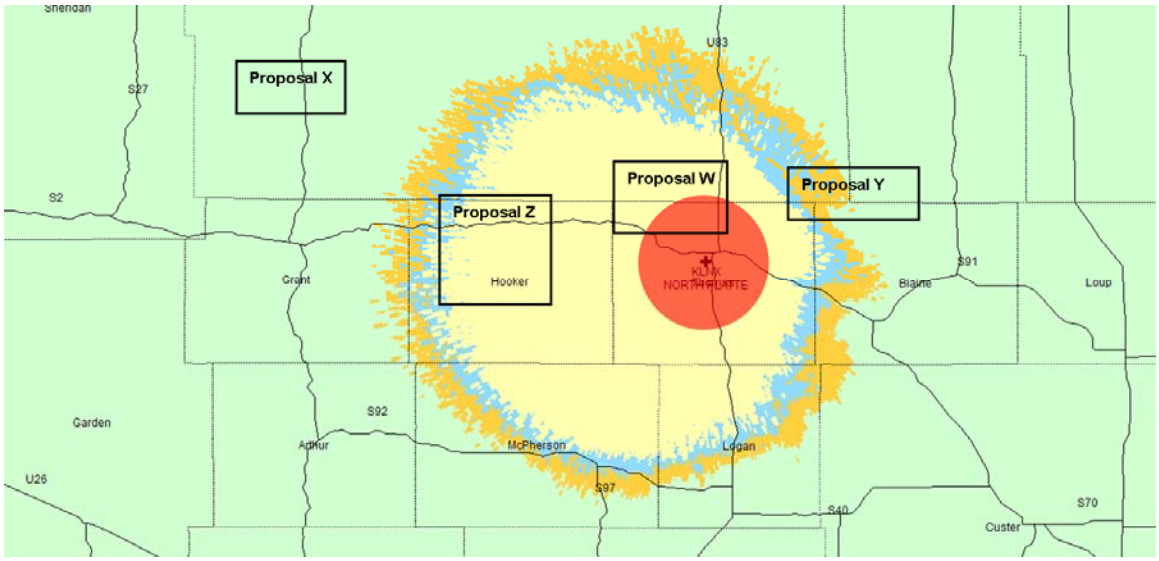


Fig. 4. An example radar line of sight (RLOS) map generated by the NEXRAD ROC for a wind farm analysis. Four hypothetical proposals: W, X, Y, and Z as described in the text are shown. Note that this RLOS map has three values (130, 160, and 200 m above ground) rather than the one value (200 m above ground) in Fig. 1.

## 6. NEXRAD Program Efforts to Mitigate Wind Farm Impacts

The best mitigation technique is to avoid locating wind turbines in the RLOS of a NEXRAD. This strategy may be achieved by distance, terrain masking, or terrain relief. Mitigation of impacts if turbines are in the RLOS can be achieved by reducing the number of turbines in RLOS and the degree of blade penetration into the RLOS, greater separation from the radar, or through selective turbine siting; e.g., to reduce the azimuthal extent of the turbines with respect to the radar. Each situation requires case-by-case analysis.

The NEXRAD Program has taken a multi-prong approach to mitigate the impacts of wind farms on NEXRAD data, products, and operations.

a. Understanding Impacts on Weather Radars and Operations

We continue to learn 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 for radar operators and weather forecasters on how to identify, mitigate, and partially work around wind turbine impacts during forecast and warning operations. In the absence of predictive

modeling software, we are also learning how observed impacts at one site can apply to similar proposals for evaluation.

b. Supporting Experimental Signal Processing Technique Research

In collaboration with the Atmospheric Radar Research Center (ARRC) at the University of Oklahoma, the ROC is evaluating possible mitigation schemes of wind turbine clutter on NEXRADs. A brief summary of the work will be provided here. For further details, see related WINDPOWER2008 poster and paper: *Wind Turbine Clutter Characterization and Mitigation on Federal Weather Radars (NEXRAD).*

The NEXRAD has a flexible, open architecture signal processor which enables potentially relatively-low cost and rapid implementation of improvements in signal processing techniques. Success of this research could depend on partnering with other federal agencies and/or the wind energy industry. In addition, sharing of wind turbine telemetry data with the NEXRAD Program may prove beneficial for future research and possible operational implementation of mitigation techniques.

As a temporary work around, the ARRC is investigating whether interpolating and "nowcasting" radar data can reduce the wind turbine impacts on NEXRAD algorithms for common weather scenarios. However, this technique does not eliminate the turbine impacts on the NEXRAD base data on which many NWS forecasters rely for final warning decision making. This technique relies on the presence of uncontaminated or *good* data to estimate the signal at a contaminated location, thus favorable wind turbine placement may be a helpful mitigation technique.

Research at the ARRC is underway that incorporates more sophisticated signal/array processing techniques with the goal of recovering the underlying weather information from the turbine-corrupted signal. In addition to algorithm research, innovative radar designs, such as adaptive phased array antennas, are being explored to determine if they can mitigate impacts from wind turbine clutter. Knowledge-based techniques, which would exploit information (blade phase, rotation speed, pointing direction, etc.) from the wind turbines, are being conceived which could take place in a controlled laboratory setting or during field campaigns with collaborative wind farm operators. In order for progress to be made, however, appropriate and sufficient funding sources must be identified. The potential exists for a possible solution to this difficult problem, but further research is needed.

## 7. How We Can Work Together

a. What the NEXRAD Program Has Recently Done.
- Participated in 2008 AWEA Siting workshop and WINDPOWER2007 and 2008;
- Significantly refined ROC analysis process to generate more objective measures on impacts to radars and turbines;
- Worked with some developers to mitigate impacts on both the radar and proposed wind farm turbines (possible interference to turbine electronics from radar energy);
- Continued funding mitigation research; and
- Maintained/Updated Wind Farm Interaction section of our web page, http://www.osf.noaa.gov/windfarm/windfarm_index.asp, provides information on wind farm interactions with the NEXRAD radar

b. What the NEXRAD Program Plans To Do.
- Implement "NEXRAD Tool" on FAA OE/AAA web site to help developers with one-stop analysis and planning;
- Continue funding mitigation research;
- Continue outreach to learn more about the wind energy industry and inform the industry about NEXRAD, seek mitigation funding, and strengthen partnerships; and
- Engage other government agencies to support/fund mitigation research

c. What the Wind Energy Industry Can Do.
- Visit http://www.roc.noaa.gov/windfarm/windfarm_index.asp, to learn more about wind farm interactions with the NEXRAD radar;

- Use new "NEXRAD Tool" on OE/AAA web site to work with us early in the planning process to better site turbines when in proximity to a NEXRAD radar;
- Earlier and consistent notifications through the NTIA; and
- Partner with government, R&D labs, universities to fund impact studies/develop mitigation strategies

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 Radar Operations Center is willing to assist wind farm developers in determining the potential wind farm impacts on radars, potential impacts on turbines from radars, and siting alternatives. While the NEXRAD Program has learned about many proposed wind farms via the NTIA, this represents a small subset of the wind farms being planned. It also appears the timing of these notifications is after the wind energy developers have already invested considerable time and money in planning wind farm projects. Advance information on new planned projects, or expansions, would enable impact analysis and siting consultation earlier in the project lifecycle, potentially avoiding costly project changes. The NEXRAD Program and NTIA are sensitive to the proprietary nature of data shared by the wind energy industry early in the project planning stage, and will protect this information to the extent allowed by federal law.

Awareness and early consultation by wind project developers with the NEXRAD Program is essential to minimizing project risk and operational conflicts with the Nation's weather radar network and NOAA's NWS severe weather warning program. Research tools and evaluation processes are in place to facilitate early consultation. We urge wind project developers to take advantage of this consultation to arrive at mutually beneficial siting decisions.

## SELECTED REFERENCES

Isom, B. M. R. Palmer, G. Secrest, R. Rhoton, D. Saxion, J. Reed, T. Crum and R. Vogt, 2008: Wind Turbine Clutter Characterization and Mitigation on Federal Weather Radars (NEXRAD). Poster, *American Wind Energy Association WINDPOWER 2008*, Houston, TX.

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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 Airspace Analysis (OE/AAA): https://www.oeaaa.faa.gov/oeaaa/external/portal.jsp
One-stop federal information center: http://www.eere.energy.gov/windandhydro/federalwindsiting/
NEXRAD Radar Operations Center Wind Farm Information: http://www.roc.noaa.gov/windfarm/windfarm_index.asp
National Telecommunications Information Administration: http://www.ntia.doc.gov/
Real-time NEXRAD Imagery: http://radar.weather.gov/
A one-stop federal information center when planning wind energy facilities: http://www.eere.energy.gov/windandhydro/federalwindsiting/.