9.4 WIND TURBINE CLUTTER MITIGATION USING RANGE-DOPPLER DOMAIN SIGNAL PROCESSING METHOD

Feng Nai[1,2] *, Robert Palmer[1,3], Sebastian Torres[1,4]
[1] *Atmospheric Radar Research Center, University of Oklahoma, Norman, OK*
[2] *School of Electrical and Computer Engineering, University of Oklahoma, Norman, OK*
[3] *School of Meteorology, University of Oklahoma, Norman, OK*
[4] *CIMMS, University of Oklahoma, NOAA/National Severe Storms Laboratory, Norman, OK*

1. INTRODUCTION

Wind is considered a "green" source of energy which is renewable. After the initial cost to install the wind turbines and the necessary transmission infrastructure, only routine maintenance is required throughout the life time of a turbine. This reduces the long-term cost of wind energy. Considering the uncertain supply and the increasing price of fossil fuels, wind energy is being pushed as a premier source of energy for the future. A report published by the Department of Energy in 2008 detailed a scenario where 20% of the Nation's energy will be generated through wind power by 2030 (Department of Energy 2008). The projected growth of wind power required to achieve such scenario is shown in Figure 1. While there are many positive outcomes from the growth of wind energy, the negative effects of the expansion of wind farms cannot be ignored. One such negative impact is the interference caused by the wind turbines on radar systems, especially weather radars. Such interference is generally referred to as wind turbine clutter (WTC).

Wind turbine clutter returns are very similar to weather signals and are difficult to distinguish on a plan position indicator (PPI) plot. One example of such confusion is illustrated in Figure 2. Human operators can usually identify WTC because the signal does not move in time, but it is much more difficult for automatic algorithms to identify such contamination. Without mitigating the WTC, three important parameters that describe the weather signal–the power, the radial velocity, and the spectrum width of the return signal are all biased. Other algorithms such as the quantitative precipitation estimation that use these parameters will be biased as well (Vogt et al. 2007). Tornado detection algorithms also have the potential to generate false detections and cause forecasting problems (Vogt et al. 2007).

Recently, several mitigation schemes have been proposed. One such proposition is to use materials that have low radar cross-section to construct the blades of the wind turbine (Cornwall 2007). However, the cost of implementation may be prohibitive. Two mitigation techniques have been developed to help reduce the effect of WTC on weather radars. The first technique applies a non-linear median filter to spotlight data to remove the contamination (Isom et al. 2009). But to collect spotlight data requires a dwell time on the order of seconds, which is not practical in operational radar. The second technique uses neighboring non-contaminated data to interpolate over the contaminated data (Isom et al. 2009). However, the interpolation method is not satisfactory because it reduces the resolution of the radar data and could potentially mask important details of the weather signals.

To achieve good mitigation, the first step is to detect where the WTC contamination occurs. The simple solution of flagging data from every known wind farm location as contaminated is not satisfactory because anomalous propagation and multi-path effects can cause WTC to occur outside the known wind farm locations. There are also conditions under which the wind turbine is not operational and the data are not contaminated. To account for the variable conditions, an automatic WTC detection algo-

* *Corresponding author address*: Feng Nai, Atmospheric Radar Research Center and School of Electrical and Computer Engineering, 120 David Boren Dr., Suite 4630, Norman, OK 73072-7307; *e-mail: Feng.Nai-1@ou.edu.*

rithm was developed (Hood et al. 2010). This algorithm combines several spectral and temporal features of WTC spectrum in a fuzzy logic engine to detect the presence of WTC.

In this paper, we propose a new signal processing algorithm that uses the range-Doppler spectrum to mitigate the effects of WTC. This algorithm treats the range-Doppler spectrum as an image and seeks to use features of this image to separate weather signals from WTC.

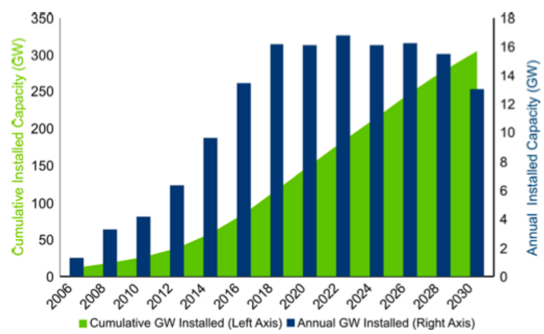

Figure 1. Required growth to reach the goal of 20% wind power by 2030 (Department of Energy 2008).

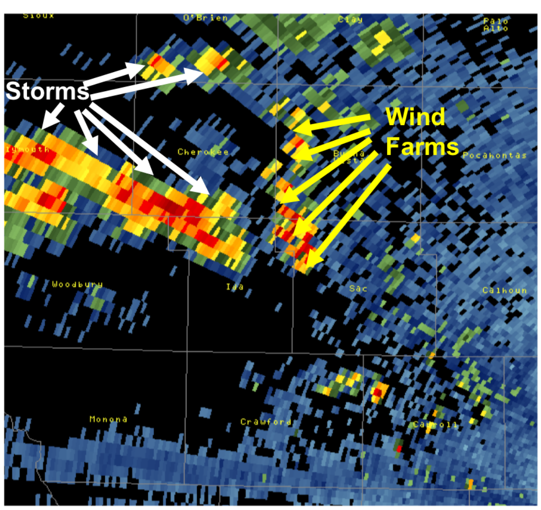

Figure 2. Similar radar returns of storms and WTC on a PPI plot. Image courtesy of the Radar Operation Center, Application Branch.

2. MOTIVATION FOR RANGE-DOPPLER SPECTRUM

The ideal mitigation algorithm would operate on a gate-by-gate basis. However, due to the non-stationary nature of WTC signal, it is very difficult to remove WTC while preserving weather information simultaneously. As shown in Figure 3, wind turbine clutter have three major components: tower, hub, and flash contamination. The tower contamination is the ground clutter return from the tower of the turbines. It is stationary and relatively easy to remove with standard ground clutter filters. The hub contamination is a slowly oscillating signal around 0 m/s. However it is wide enough that a standard ground clutter filter cannot remove it completely. The flash contamination is caused by the rotating blades. The highest tip velocity seen by the radar occurs when the blade rotation plane is parallel to the radar beam and the blade is in the vertical position. Constructive interference of the reflected wave also generates a large radar cross section (Gallardo-Hernando et al. 2011). These combined factors result in the strong flash contamination. Figure 3 shows the Doppler spectrum of WTC changing as a function of time. The non-stationary nature of the contamination makes it very difficult to design a frequency domain filter to remove all WTC while preserving weather information. As a result of this difficulty, we propose to use range-Doppler spectrum instead of a single gate Doppler spectrum to perform mitigation.

3. ADVANTAGES OF RANGE-DOPPLER SPECTRUM

The range-Doppler spectrum is a plot of Doppler spectra for a set of contiguous range gates as a 2-dimensional image. It is denoted $S(r, v)$ and is a function of range r and Doppler velocity v. The range-Doppler spectrum concept is not new and has been used extensively by the wind profiling community (Merrit 1995; Wilfong et al. 1993). One example of the range-Doppler spectrum is shown in Figure 4, where the horizontal axis is Doppler velocity, the vertical axis is range, and the color scale corresponds to the signal power. This is different from Figure 3 because it is not showing the time evolution of the conguishing features, we can hope to classify each pixel in the range-Doppler spectrum into three categories: weather pixels, including the overlapped region of weather and WTC, WTC-only pixels, and noise-only pixels. After successfully identifying the frequency bins that contain the WTC contamination, we can remove them and estimate the weather spectral moments using the remaining weather pixels as done in NIMA (Morse et al. 2002).

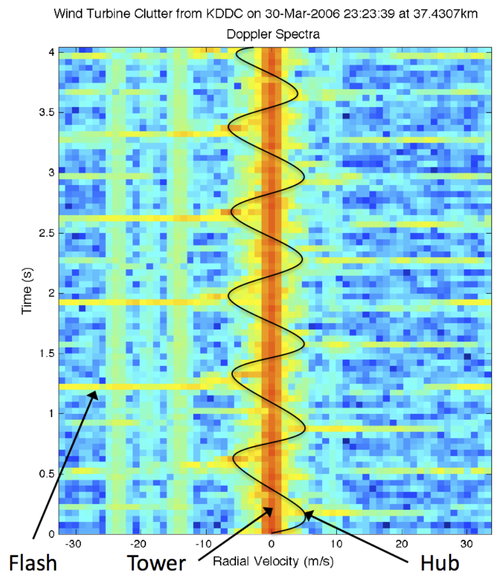

Figure 3. WTC has three types of contamination, tower, hub, and flash. As time evolves, the type of contamination changes and the signal is non-stationary.

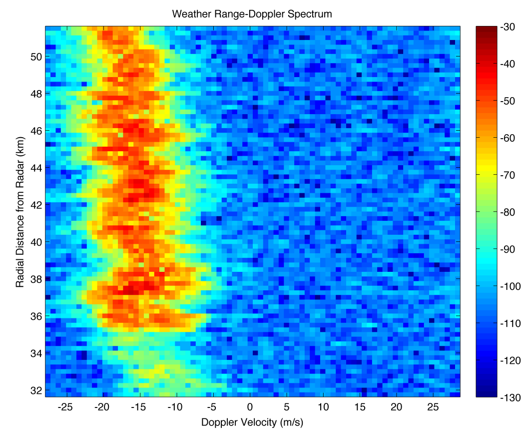

Figure 4. Weather signals is continuous in range and relatively narrow in frequency.

tamination. Rather it is a snap shot of the WTC contamination. The contaminated range-Doppler spectrum in constructed by adding weather signal time series with WTC time series, which allows us to control the level of contamination and gives us the ground truth to evaluate the performance of the technique.

The main advantage of the range-Doppler spectrum is that it includes spatial information that are valuable to our mitigation technique. Comparing Figure 4 to Figure 5 shows two major distinctions between the weather and WTC signals in the range-Doppler spectrum. First, the weather signal is continuous in range, meaning the radial velocity and spectrum width from gate to gate is relatively constant. When WTC contamination occurs, the continuity of weather signals in range is disrupted and we observe a large jump in power level per frequency bin. Secondly, the weather signal is relatively narrow in frequency while the WTC signal is extremely wide in frequency. By focusing on these two distin-

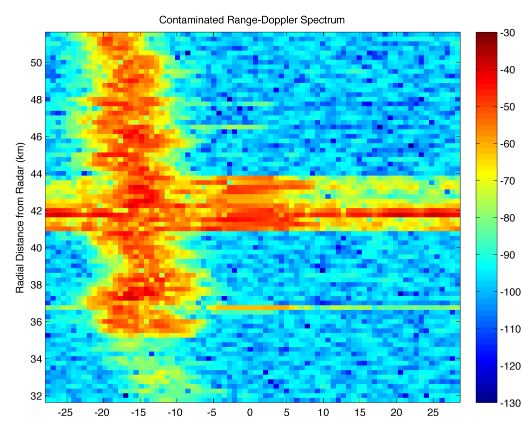

Figure 5. WTC signals is discontinuous in range and relatively wide in frequency.

4. CLASSIFICATION OF PIXELS

To classify the pixels in the range-Doppler spectrum, we focus on classifying the pixels of WTC contamination at the edge of the transition from non-contaminated gate to contaminated gate. This transition has two characteristics: a jump in power level and wide spread in frequency. We model the jump as a step edge and calculate the power ratio on each side of the edge for each frequency bin. Power ratio is defined by

$$PR(r,v) = \frac{10log_{10}(S(r,v))}{10log_{10}(S(r_{ref},v))} \quad (1)$$

where r_{ref} is the closest non-contaminated range gate to the range gate under processing. Ideally the ratio would be 1 on both sides of the edge while significantly lower at the transition edge. The local minimum in power ratio should correspond to the WTC pixels. The left panel of Figure 6 shows one example of such transition edge and the right panel shows the power ratio of this transition edge. There are four types of transitions occurring: noise to noise, weather to weather, WTC to WTC, and noise to WTC. The first three types of transitions are relatively smooth and produce power ratios close to 1. The transition from noise to WTC has a large jump discontinuity and produces power ratios close to 0.5. As predicted, the local minima correspond well to the WTC pixels. By identifying the local minimua in power ratio in the range direction, we can determine the location of the weather in the contaminated gate. To capture the spread in frequency, we count the number of pixels that are horizontally connected while satisfying the jump condition. By setting a length threshold we can eliminate false edges that result from spectral estimation variance and edges corresponding to transition from noise to weather.

After processing the edge and identifying the WTC pixels, we temporarily remove the processed gates from the spectrum and repeat the procedure to identify and process the next contaminated gate. After all range gates are processed, we estimate the weather spectral moments from the remaining weather pixels. Since only gates that contain contamination are changed in this procedure, the moment estimates of non-contaminated gates are not biased by applying this technique. The mitigation result is shown in Figure 7. Our technique improved the radial velocity estimates in the contaminated gates and the non-contaminated gates are not modified.

5. CONCLUSIONS AND FUTURE WORK

The growth of wind energy will increase the occurrence of WTC contamination in weather radars. An automated detection and mitigation algorithm is highly desirable to ensure the quality of the moment data that will be used in other automated algorithms such as quantitative precipitation estimation and tornado detection. Gate-by-gate mitigation is difficult due to the non-stationarity of WTC. Using the range-Doppler spectrum, we incorporate range information into our mitigating technique. Focusing on the discontinuity in range and wide spread in frequency of the WTC contamination, we can recover the weather signal in the contaminated gates and improve our moment estimation by using only the recovered signal.

Currently the technique performs well on strong contamination that fit the step-edge model. However, its performance degrades as contamination weakens and forms ramp edges instead of step edges. To make our technique more robust, we need to build another model to fit weak contamination. Also we would like to include a wide range of weather phenomena in our study to more fully evaluate our technique.

6. ACKNOWLEDGEMENTS

The U.S. Department of Homeland Security (DHS) is acknowledged as the sponsor of this work, under a ”work for others” arrangement, issued under the prime contract for research, development, test, and evaluation services between the U.S. Department of Homeland Security and the National Severe Storms Laboratory.

References

Cornwall, J. M., 2007: Mitigation of Wind Turbine Effects on FAA and Military Radars. Adapted from Jason report JSR-07-126, by A. Despain et al.

Department of Energy, 2008: 20% Wind Energy by 2030. Report from the Energy Efficiency and Renewable Energy.

Gallardo-Hernando, B., J. Munoz-Ferreras, F. Perez-Martinez, and F. Aguado-Encabo, 2011: Wind turbine clutter observations and theoretical validation for meteorological radar applications. *Radar, Sonar Navigation, IET*, **5**, 111 –117.

Hood, K., S. Torres, and R. Palmer, 2010: Automatic detection of wind turbine clutter for weather radars. *Journal of Atmospheric and Oceanic Technology*, **27**, 1868–1880.

Isom, B. M., R. D. Palmer, G. S. Secrest, R. D. Rhoton, D. Saxion, T. L. Allmon, J. Reed, T. Crum, and R. Vogt, 2009: Detailed observations of wind turbine clutter with scanning weather radars. *Journal of Atmospheric and Oceanic Technology*, **26**, 894–910.

Merrit, D. A., 1995: A statistical averaging method for wind profiler doppler spectra. *Journal of Atmospheric and Oceanic Technology*, **12**, 985–995.

Morse, C. S., R. K. Goodrich, and L. B. Cornman, 2002: The nima method for improved moment estimation from doppler spectra. *Journal of Atmospheric and Oceanic Technology*, **19**, 274–295.

Vogt, R. J., J. 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. *23rd Conference on IIPS*, San Antonio, TX, January 17.

Wilfong, T. L., S. A. Smith, and R. L. Creasy, 1993: High temporal resolution velocity estimates from a wind profiler. *Journal of Spacecraft and Rockets*, **30**, 348–354.

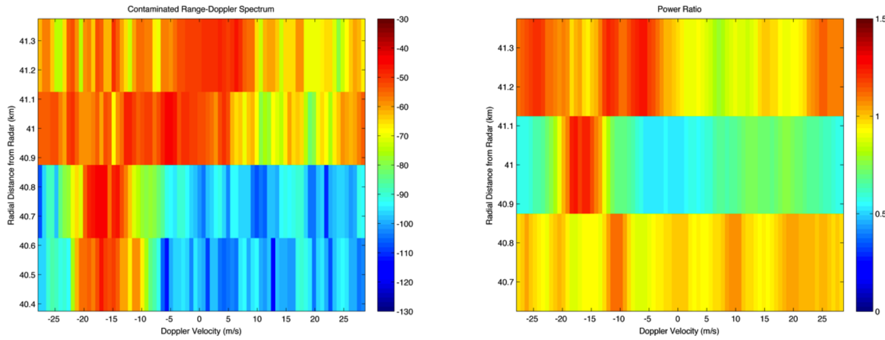

Figure 6. Left panel shows contaminated spectra zoomed in to focus on the transition edge from non-contaminated gate to contaminated gate. Right panel shows the power ratio of the three transitions. A local minimum in range direction occurs at the pixels with WTC contamination.

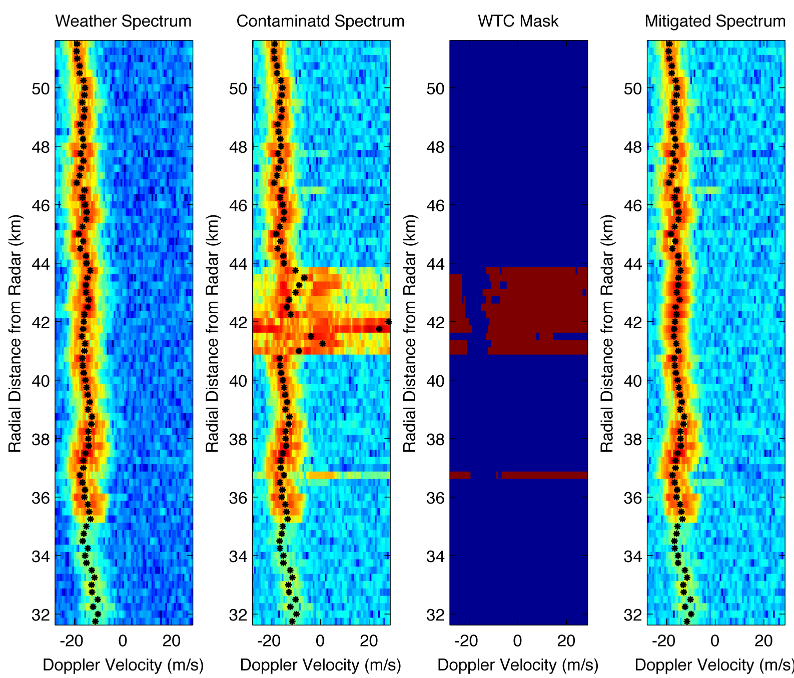

Figure 7. Left panel shows the original weather spectra. The left middle panel show the contaminated spectra. The middle right panel shows the pixels that are identified as WTC in red. The right panel shows the mitigated spectra. The black dots correspond to the estimated Doppler velocity.