Range-Doppler Domain Signal Processing to Mitigate Wind Turbine Clutter

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***Abstract*— Wind turbines produce clutter signals that can bias estimates of the spectral moments and polarimetric variables of weather signals. These biases can propagate to and negatively influence the output of automatic algorithms, such as severe weather detection and quantitative precipitation estimates. Moreover, existing ground clutter filters are ineffective at removing wind turbine clutter (WTC) contamination because the moving components of the wind turbine produce clutter signals with non-zero Doppler frequency shifts. As the first step in any mitigation scheme, an automatic WTC detection algorithm is necessary and was recently developed by University of Oklahoma and National Severe Storm Laboratory scientists. After successfully detecting the presence of WTC, the goal is to devise signal processing algorithms that mitigate this contamination so that the weather signal can be recovered and used to estimate the spectral moments and polarimetric variables. However, WTC is inherently non-stationary due to the moving wind turbine blades, which makes frequency-domain-filtering based clutter mitigation methods ineffective. In this work, we propose a new signal processing technique to separate the WTC from the weather signal in the range-Doppler domain. This technique exploits the different spatial and spectral characteristics of WTC and weather signals. Real weather signals and WTC data are used to test the effectiveness of the mitigation scheme.**

I. 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 [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).

For single target radar systems, such as the air traffic control radars (ATC), WTC degrades the radar's ability to detect and track an aircraft. The tower of the wind turbine causes ground clutter and decreases the probability of detection for an ATC radar [2]. Moreover, the moving blades result in return signals that have non-zero Doppler velocity, which renders ground clutter filters ineffective. It is known that when an aircraft flies over a wind farm, the automatic tracking algorithms can miss a detection or generate false alarms on the location of the aircraft [3].

For weather radars, the problem is more complicated. WTC returns are very similar to weather signals and are difficult to distinguish on a plan position indicator (PPI) plot. 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 [4]. Tornado detection algorithms also have the potential to generate false detections and cause forecasting problems [4].

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 [5]. However, the cost of implementation may be prohibitive. Perry and Biss [3] proposed to track inhibition algorithms to prevent false detection of aircrafts in wind farms, but such techniques do not solve the problem with weather radars. Two mitigation techniques have been developed to help reduce the effect of WTC on weather radars [6]. The first technique applies a non-linear median filter to spotlight data to remove the contamination [6]. However, collecting spotlight data requires dwell time on the order of seconds, which is much longer than the dwell time used in operational radars. The second technique uses neighboring non-contaminated data to interpolate over the contaminated data [6]. 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 algorithm was developed [7]. 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. Section II will discuss the need for range-Doppler spectrum, Section III will give an overview of the algorithm, and Section IV will show the preliminary results to demonstrate the feasibility of this algorithm, and will comment on future works.

II. Motivation for Range-Doppler Domain

A. Spectral Moments

For weather radar observations, the targets are the hydrometeors inside a resolution volume. The Doppler spectrum $S(v)$, which is a power-weighted distribution of radial velocities, is used to describe the motion of the hydrometeors. For weather signals, $S(v)$ is generally assumed to be Gaussian shaped [8]. If a Gaussian Doppler spectrum is assumed, then three parameters completely describe the spectrum: return signal power, radial velocity, and spectrum width. Return signal power is the zeroth moment of the Doppler spectrum and is related to the intensity of a storm. Radial velocity is the first moment of the Doppler spectrum which describes the mean motion of a storm. Finally spectrum width is the second central moment of the Doppler spectrum which measures the dispersion of radial velocities of the hydrometeors inside the resolution volume. The goal of the mitigation algorithm is to reduce the bias caused by WTC in estimating these three parameters to acceptable levels.

B. Single Gate Mitigation Challenges

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 1, 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

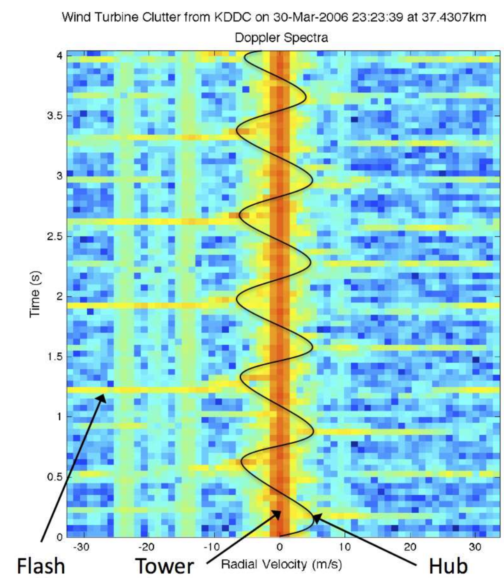

Fig. 1. WTC has three types of contamination, tower, hub, and flash. As time evolves, the type of contamination changes and the signal is non-stationary.

position. Constructive interference of the reflected wave also generates a large radar cross section [9]. These combined factors result in the strong flash contamination. Figure 1 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.

C. Range-Doppler Spectrum

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 velocity v. The range-Doppler spectrum concept has been used extensively by the wind profilling community [10]. One example of the range-Doppler spectrum is shown in Figure 2, 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 1 because it is not showing the time evolution of the contamination. 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.

Comparing the contaminated spectrum in Figure 2(b) with the non-contaminated spectrum in Figure 2(a), we see two major distinctions between the weather and WTC signals in the range-Doppler spectrum. The weather signal is continuous in range, meaning the radial velocity and spectrum width from gate to gate are relatively constant. The WTC contamination

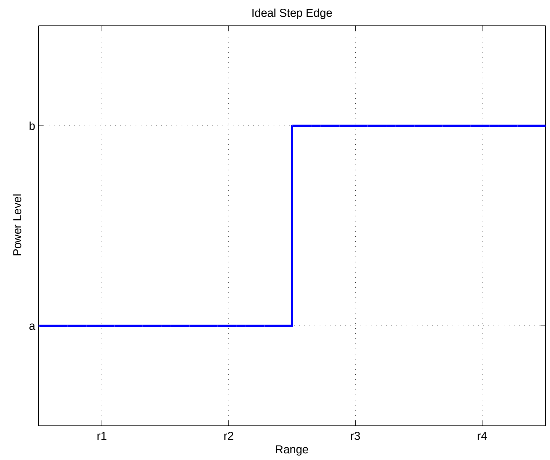

Fig. 3. The ideal step edge used to model the transition from uncontaminated gate to contaminated gate. Range gates r_0, r_1 are uncontaminated while r_2, r_3 are contaminated.

disrupts the continuity of the weather signal and causes a large jump in power level from uncontaminated gate to contaminated gate in each frequency bin without weather signal. The second contrasting feature is the wide spread of the jump in power level. The transition from a gate with no weather to a gate with weather also shows a jump in power level, but this jump is narrow because weather signals are relatively narrow in frequency. The power jump from uncontaminated gate to contaminated gate are much wider. An expert can easily identify which pixel in the image belongs to the weather signal and which pixels belong to WTC. This proposed technique seeks to mimic the expert and classify each pixel as weather (weather only and region where WTC overlaps weather), WTC-only, or noise-only. After classification, the spectral moments for each range gate will be estimated using only the weather pixels as done in NIMA [12].

III. Pixel Classification

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. To capture the power jump, we process each frequency bin individually and model the feature as an ideal step edge as in Figure 3. In the ideal step edge, the power level on both side of the transition are constant while the transition shift power level from a to b. We define a feature caller power ratio given by

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

where $S(r, v)$ is the range-Doppler spectrum, r is the gate under processing, and r_{ref} is a reference gate which is not contaminated. In the ideal model, the power ratio between r_2 and r_1 and the power ratio between r_4 and r_3 both equal to 1, but the power ratio between r_3 and r_2 equals to $\frac{a}{b}$. If we treat the power ratio of each frequency bin as a function of range, we see the step edge will correspond to a local extremum. Figure 4 shows an example of edge transition from non-contaminated gate to contaminated gate. 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. To capture the wide spread of the WTC contamination in frequency, we count the number of pixels that are horizontally connected while satisfying the jump condition. By setting a length threshold we can remove false edges due to spectral estimation variance and noise to 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 5. Our technique improved the radial velocity estimates in the contaminated gates and the non-contaminated gates are not modified.

IV. 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.

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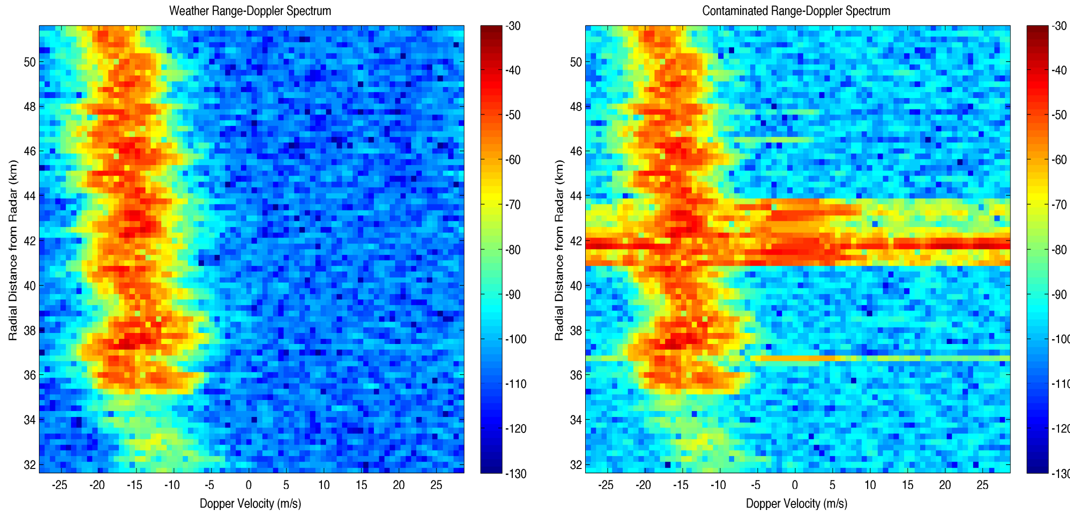
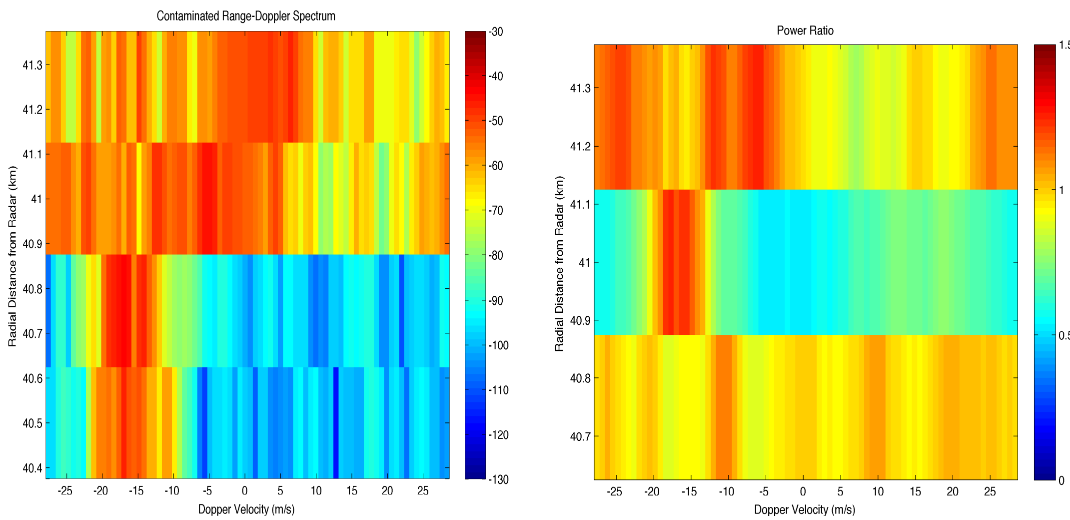


(a) Uncontaminated Spectra (b) Contaminated Spectra

Fig. 2. Comparing the two range-Doppler spectra, it is easy to see that uncontaminated weather signal is relatively narrow in frequency and continuous in range and the WTC contamination causes a discontinuity in range and are extremely wide in frequency.



(a) Range-Doppler Spectrum Edge (b) Power Ratio

Fig. 4. 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.

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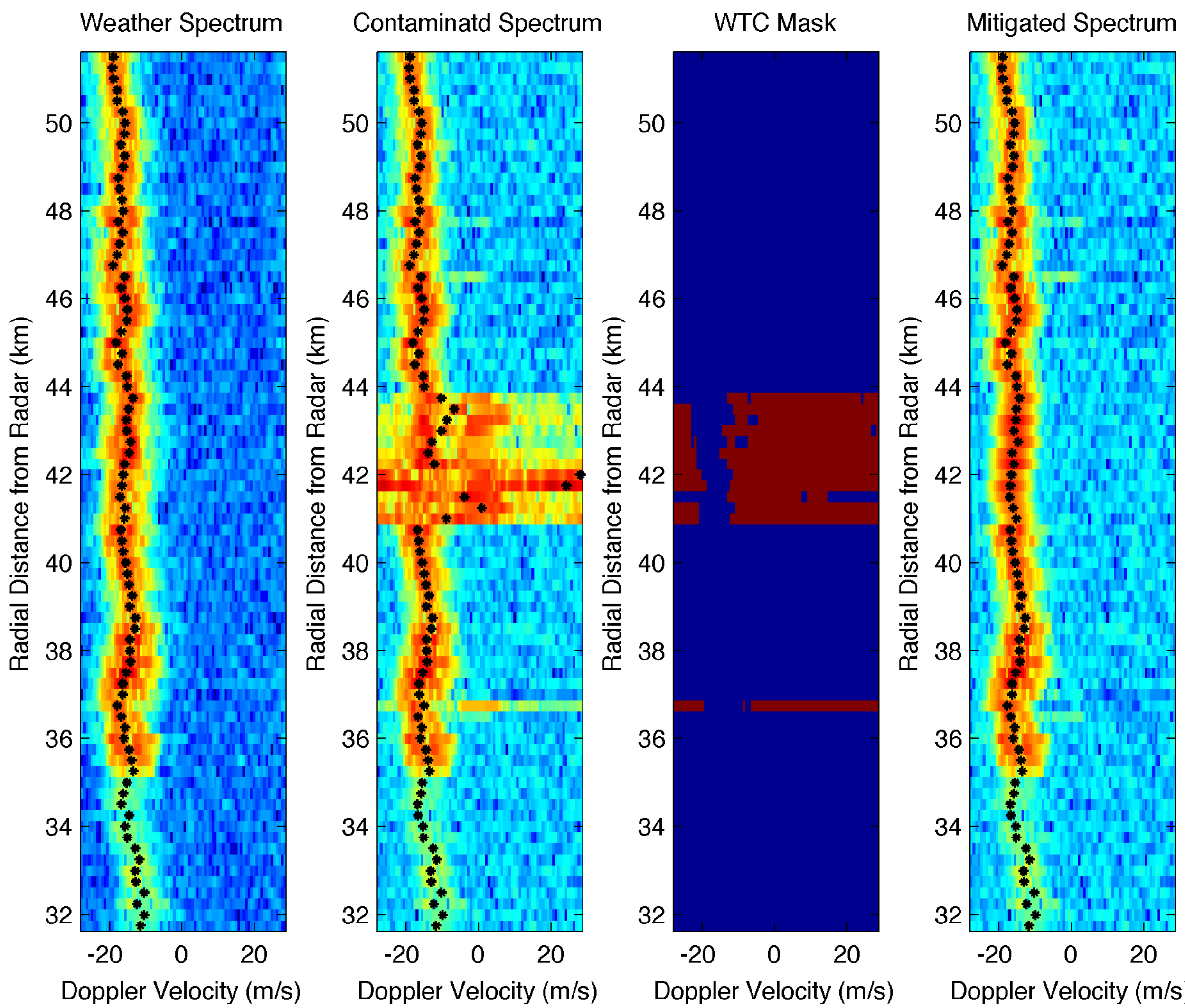

Fig. 5. Left panel shows the original weather spectra. The left middle panel show the contaminated spectra. The middle right panel shows the pixels that are identified as WTC in red. The right panel shows the mitigated spectra. The black dots correspond to the estimated Doppler velocity.