CHARACTERIZATION AND MITIGATION OF WIND TURBINE CLUTTER ON THE WSR-88D NETWORK

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Abstract

Wind power technology has been well-established for many years and the benefits are widely known in terms of the importance of renewable energy sources. However, the recent increase in the number of wind farms within the United States as well as an increase in the number of turbines per farm has prompted studies of their impact on weather radar operations near these facilities. In addition to the rapid growth of the number of wind farms, increases in wind turbine size have also had an impact on the complexity of the problem. Individual wind turbines can exceed overall heights of 130 m with blade lengths of 40 m, which can rotate at 17 RPM creating tip velocities near 70 $\mathrm{m\,s^{-1}}$. Due to the motion of blades, current ground clutter mitigation techniques, such as notch filtering and the currently employed GMAP algorithm, fail to significantly mitigate the effect of the wind farms on WSR-88D radar products. In this work, we will examine the Doppler spectral content of the wind turbine clutter (WTC) signal in detail for two WSR-88D locations known to experience WTC. The Dodge City, Kansas, WSR-88D radar is located 35 km from a large wind farm comprised of 170 large wind turbines. The Great Falls, Montana, radar is only 6 km from 6 wind turbines, providing an example of inter-turbine scatter and multi-trip echoes. For both radar sites, extensive Level-I time-series data were collected during two field campaigns organized by the National Weather Service's Radar Operations Center (ROC). These data were analyzed using conventional periodogram-based spectral estimation techniques revealing the unique spectral content of the WTC. It will be shown that depending upon the wind turbine orientation, in comparison to the beam of the radar, the Doppler spectrum can exhibit an extremely wide velocity content. Given the expected tip velocity and the typical aliasing velocity of the WSR-88D, the WTC can be spread over all Doppler velocities. Therefore, the WTC signal is not significantly affected by conventional clutter filtering schemes. This work will also propose signal processing techniques to mitigate WTC, which make use of the spatial continuity (moments and spectra) of the weather signal and knowledge of the fixed locations of the wind turbines.

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1. INTRODUCTION

1.1. The Rise of Wind Power

With the rising cost of oil and the now accepted threat of global warming, the wind power industry has become one of the most promising solutions to the aforementioned dilemmas. By examining the increase of wind power capacity just within the United States over the past decade (Figure 1), it becomes clear that wind power is a fast-growing industry. Some of the most wind-rich regions of the United States are located in the Great Plains states [American Wind Energy Association, 2007]. Due to the large areas of unpopulated land in this region, it is feasible for wind power companies to build wind farms that are comprised of 100 or more individual wind turbines. Current wind turbine designs call for blade tip heights in excess of 120 m.

1.2. Impact of Wind Farms

Weather surveillance radars like the United States' NEXRAD network are entirely capable of removing interference from ground clutter targets so long as they are stationary. The WSR-88D currently employs a Gaussian Model Adaptive Processing (GMAP) filter developed by SIGMET Inc. to mitigate the effects of ground clutter [Siggia and Passarelli, 2005]. While the wind turbine tower is a stationary structure, the turbine blades are not, and there are currently no techniques to remove

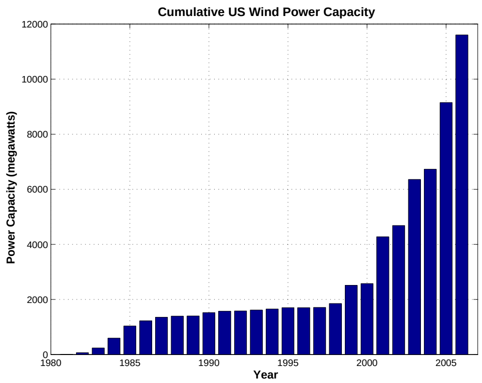


Figure 1: The total wind power capacity within the United States from 1980 to 2006. The cumulative power has increased by more than six times over the past decade alone [American Wind Energy Association, 2007].

such interference targets. Two examples of WTC effects on Level-II data are shown in Figure 2. The two images

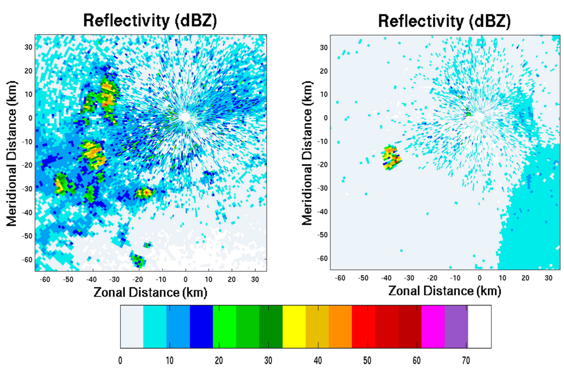


Figure 2: Level-II PPI plots of radar reflectivity from KDDC. The data shown here were taken on two separate days, August 5, 2005 on the left and June 19, 2005 on the right. A clear air reflectivity image of the KDDC coverage region is shown on the right. The same region is shown on the left but with some precipitating cells. It is difficult to distinguish the WTC from the weather in this case. The Level-II data have been filtered by GMAP.

are from two different dates, August 4, 2005 on the left and June 19, 2005 on the right. The right image is a clear air scan of the wind farm region. It is difficult to distinguish between the small storms and the WTC for the left image. Radar products produced from the reflectivity measurements, like rainfall rates and precipitation totals, are affected by any form of non-weather contamination [Doviak and Zrnic, 1993].

NOAA and OU have collaborated in an effort to remove the effects of WTC from radar products through spectral processing techniques (see `http://arrc.ou.edu` for more information). Two field experiments at NEXRAD sites have been completed and the results of these missions are discussed in the next section. A technique to mask the effects of WTC has been developed and is described in Section 3. Summary remarks are provided in the conclusions.

2. CHARACTERIZATION

Efforts to characterize WTC are not limited to the United States. Qinetiq, a United Kingdom company has performed detailed tests and created detailed models of wind turbine effects on aviation radar signals [Poupart, 2003]. Experiments conducted by OU and the ROC in 2006 were primarily focused on the WTC effect on the WSR-88D radar network. A description of the experiments and discussion are provided in the following section.

2.1. WSR-88D Experiments

Two NEXRAD sites within the CONUS were chosen as experiment locations due to their proximity to wind farms and the consistency with which they detect WTC. Dodge City, Kansas is near a large wind farm comprised of 170 wind turbines. Great Falls, Montana is located only 6 km from 6 large wind turbines. Both sites are troubled by WTC on a daily basis.

2.1.1) KDDC Experiment

The experiment performed with the KDDC NEXRAD radar, March 30-31, 2006, had three goals: gather several hours of Level-I data in normal operating mode, gather data in spotlight mode, and perform an RHI scan. The term *spotlight* is used to describe a radar data collection mode where the radar dish is stationary. That is, the radar simply collects a large contiguous set of time-series datum for a single azimuth and elevation angle. This allows for a detailed examination of the spectral characteristics of the WTC signal. The RHI scan was completed to examine the impact of WTC on the WSR-88D sidelobes. The normal operation mode scans were collected for testing any mitigation algorithms. It was discovered through the RHI scan that only the turbine tower affects the WSR-88D sidelobes and as such, normal filtering techniques can remove any WTC detected through the sidelobes. The impact of the blades is minimal in the WSR-88D sidelobes. The results from the remaining two experiments are discussed next.

2.1.2) KDDC Results

As shown in Figure 2, the WTC reflectivity resembles normal precipitation. A closer look at the WTC region as seen from KDDC is shown in Figure 3(a). The wind farm region, outlined in red, is easily seen. Figure 3(a) was generated through a modified version of GMAP which we will call OUGMAP. The frequency domain provides another view of the WTC signal. The temporal evolution of the WTC Doppler spectra is shown in Figure 3(b). Notice that the signal from the tower is prominent at zero Doppler velocity and the blades appear as *flashes* at regular intervals. The Qinetiq study speculates that these *flashes* appear anytime a blade passes vertical (either up or down); this occurs 6 times per rotation for three-blade turbines [Poupart, 2003]. The Dodge City, Kansas wind turbines have a fixed rotation rate of 28.5 RPM, which translates to almost two full rotations in the 4 second time interval shown in Figure 3(b). Note that there are 12 *flashes* visible in this image, which would be expected given the three-blade turbines used on this wind farm.

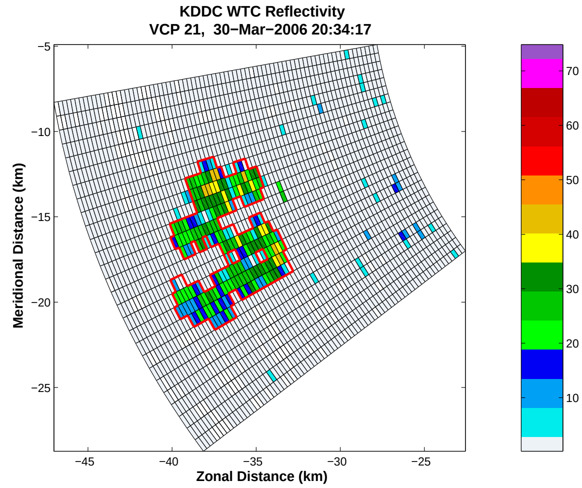
2.1.3) KTFX Experiment

The experiment performed at the KTFX NEXRAD in Great Falls, Montana occurred November 28- December 1, 2006. The goals of this experiment were much the same as the KDDC experiment with the addition of two: examine the effects of any inter-turbine scatter and determine if multi-trip echoes were present in the radar data. The results of this experiment are discussed in the next section.

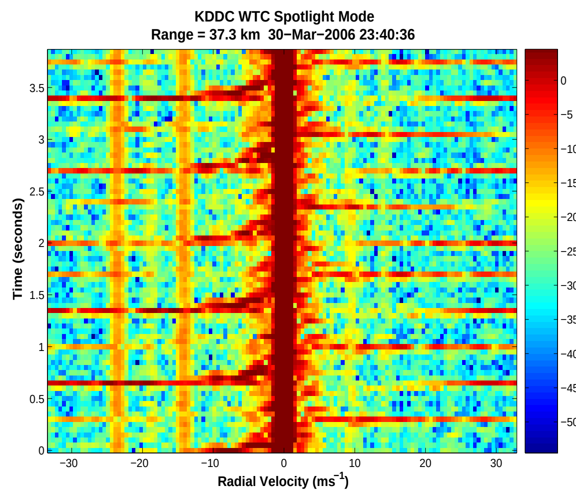
2.1.4) KTFX Results

As with the KDDC results, the OUGMAP filtered WTC reflectivity is shown in Figure 4(a). Notice that the clutter filtering leaves only a few gates contaminated with WTC (again outlined in red). The proximity of the turbines to the radar allows for a much more detailed view of the WTC spectra. The Doppler spectrum evolution in Figure 4(b) appears to show more detail in the blade motion. This is likely due to the contribution of portions of the blade that have lower return power at greater distances.

Some other interesting effects of WTC can be seen in the PPI plot of Figure 5. Inter-turbine scatter can be

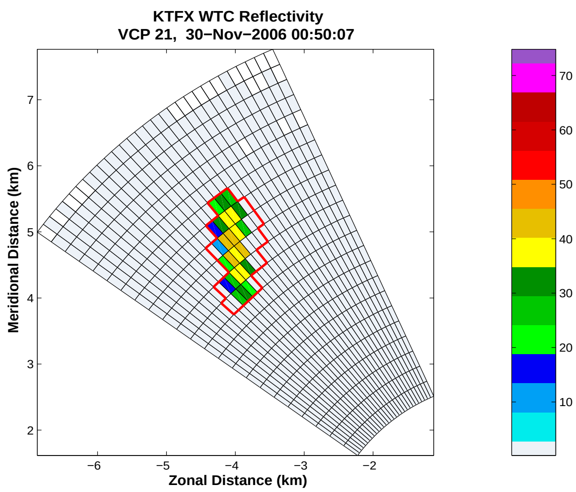


(a)

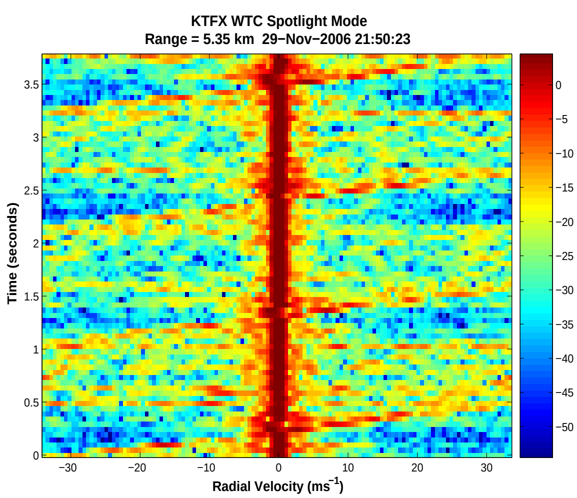


(b)

Figure 3: Two methods of data visualization from the KDDC experiment. During the KDDC WTC experiment, data were collected in standard operating modes as well as an unconventional spotlight mode. The 0.5°VCP 21 scan filtered with OUGMAP is shown in (a) with the wind farm region outlined in red. Four seconds of data collected in spotlight mode are shown in (b). The tower is visible at zero velocity while the blades appear as the regularly spaced *flashes*.



(a)



(b)

Figure 4: Same as Figure 3 but taken at KTFX. More of the blades' motion is visible in the spectra (b) due to the proximity of the turbines to the radar.

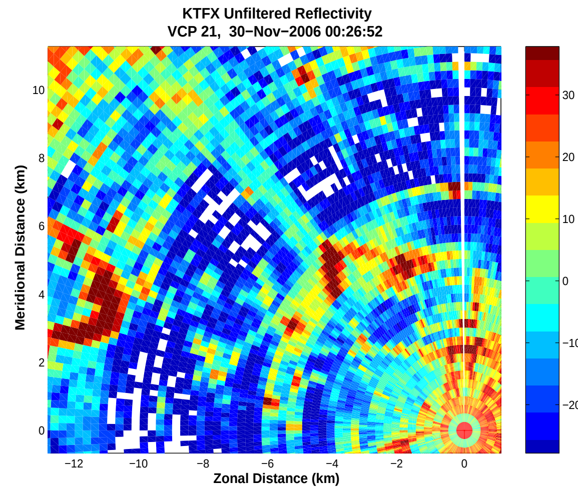


Figure 5: Multi-scatter and multi-trip effects in unfiltered KTFX data. Inter-turbine scatter can be seen in (a) as the *shadow* of higher reflectivity down range from the wind farm. Multi-trip echoes are seen as the area of higher reflectivity exactly twice the radial distance from the radar to the wind farm. The color mapping for this image was altered from the standard for clarity.

seen as a shadow down range of the wind turbines in Figure 5. Multi-trip echoes can be seen as another area of high reflectivity exactly twice the radial distance from the radar as the wind farm.

3. MITIGATION

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 large-scale weather features. The Doppler spectra of a WSR-88D resolution volume containing only one wind turbine is shown in Figure 4(b). 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. Cur-

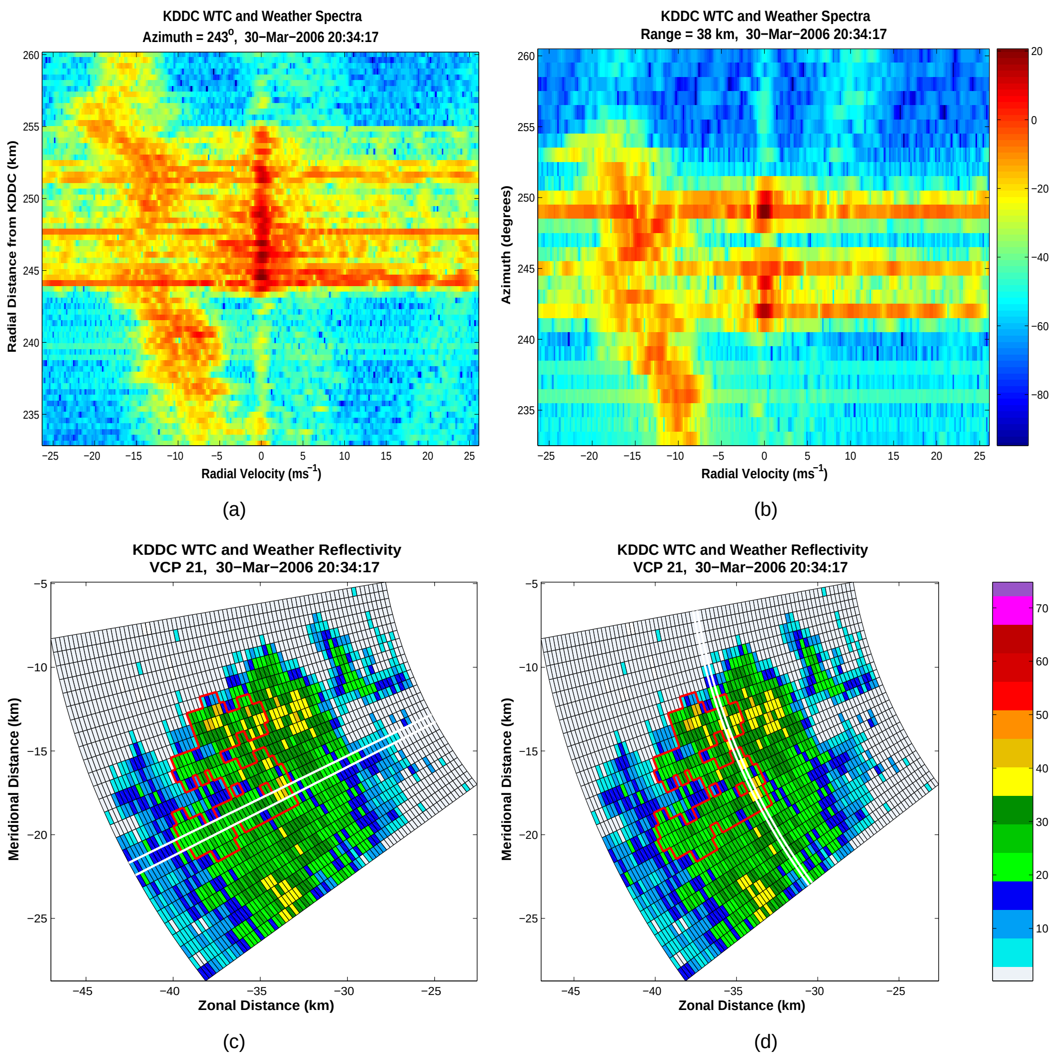


Figure 6: Spectral view of WTC and weather versus range and azimuth. The interpolation technique is well suited for WTC due to the strong spatial continuity of weather. As shown in (a) and (b), the weather signal changes little over approximately 10 kilometers in range and azimuth. Thus the data surrounding the wind farm are appropriate as input for the interpolation algorithm. The regions from which (a) and (b) were created are highlighted white in (c) and (d).

rent clutter filtering techniques are capable of removing the tower component quite effectively but the blade motion remains problematic.

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 Figure 6(a). A similar plot of WTC and weather spectra are shown over a set of azimuth angles for a fixed range in Figure 6(b). The zero-Doppler tower is clearly visible and can be used as an indicator of the wind farm over 37-44 km and azimuth angles 240-250°. 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.

3.1. 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 WTC, 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 Figure 7. 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 each spectral bin at each range and azimuth. *Good* data for this case were taken from the area surrounding the wind farm, as well as the fourth, fifth, and sixth elevation cuts. The first and third cuts were ignored as they are range scans and are less useful for Doppler spectrum cancelation. 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.

Another way to evaluate the interpolation scheme is to view the spectra after the application of the multiquadric method. A OUGMAP has been applied to the original WTC and weather Doppler spectra and the results of this procedure are shown in Figure 8(a). The black dots represent the velocity estimations for the spectra. The red numbers on the right axis indicate the region considered to be affected by WTC and where the multiquadric interpolation was performed. The interpolation results are shown in Figure 8(b). Notice that the velocity estimates after interpolation exhibit more spatial continuity.

Similar results from the KTFX data are shown in Figure 9. Due to the proximity of the turbines to the radar, the WTC effects are seen at high elevation angles. Also, the WTC region is much smaller than that encountered at KDDC. For these reasons, a two-dimensional multiquadric interpolation using only the first elevation angle is appropriate.

4. CONCLUSIONS

This study has shown that WTC has an undeniable effect on NEXRAD weather surveillance radars. It has also been discovered that the WTC Doppler spectrum is unique and unpredictable making it difficult to remove using spectral processing techniques while retaining the desired weather signal. Alternative methods like multiquadric interpolation were explored as a means to replace contaminated data with estimations of the true weather signal and were shown to be quite effective. Additional testing of the multiquadric interpolation algorithm must be performed to fully evaluate the effects on the statistical proportion of the moment estimates and other radar products.

5. ACKNOWLEDGMENTS

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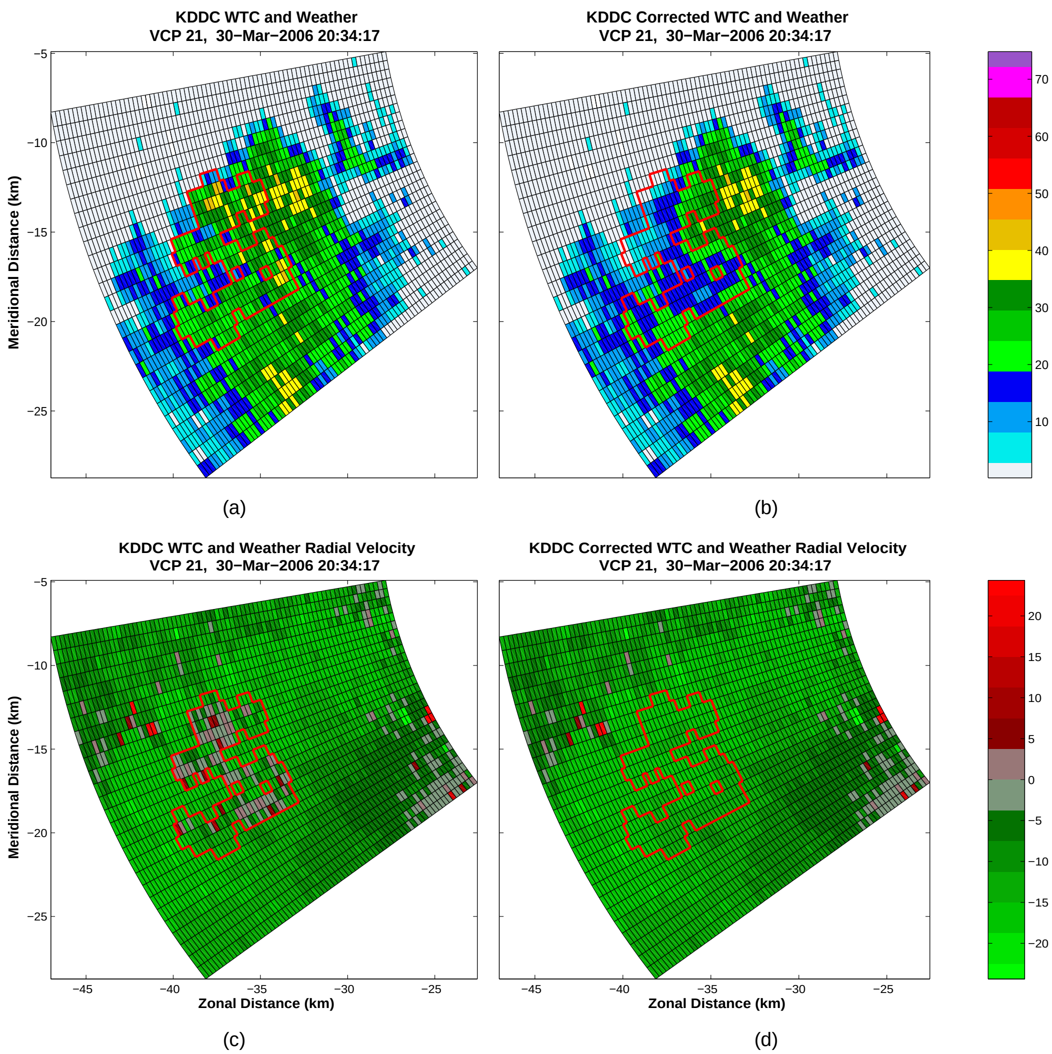
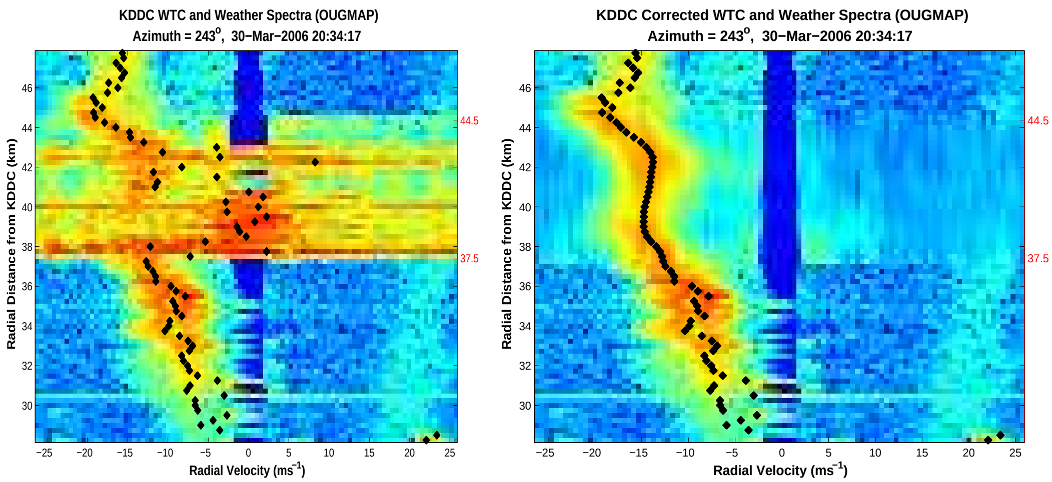


Figure 7: The KDDC reflectivity and radial velocity plots before and after interpolation. The WTC and weather reflectivity and velocity PPI plots filtered with OUGMAP are shown in (a) and (c). The results of the three-dimensional multiquadric interpolation are shown in (b) and (d). The interpolation region is outlined in red.



(a) (b)

Figure 8: The WTC and weather spectrum versus range before and after interpolation. OUGMAP has been applied to the data shown in (a) and the results of the interpolation are shown in (b). The black dots represent the estimated radial velocity of each spectra. The red markers on the right axis denote the region of interpolation.

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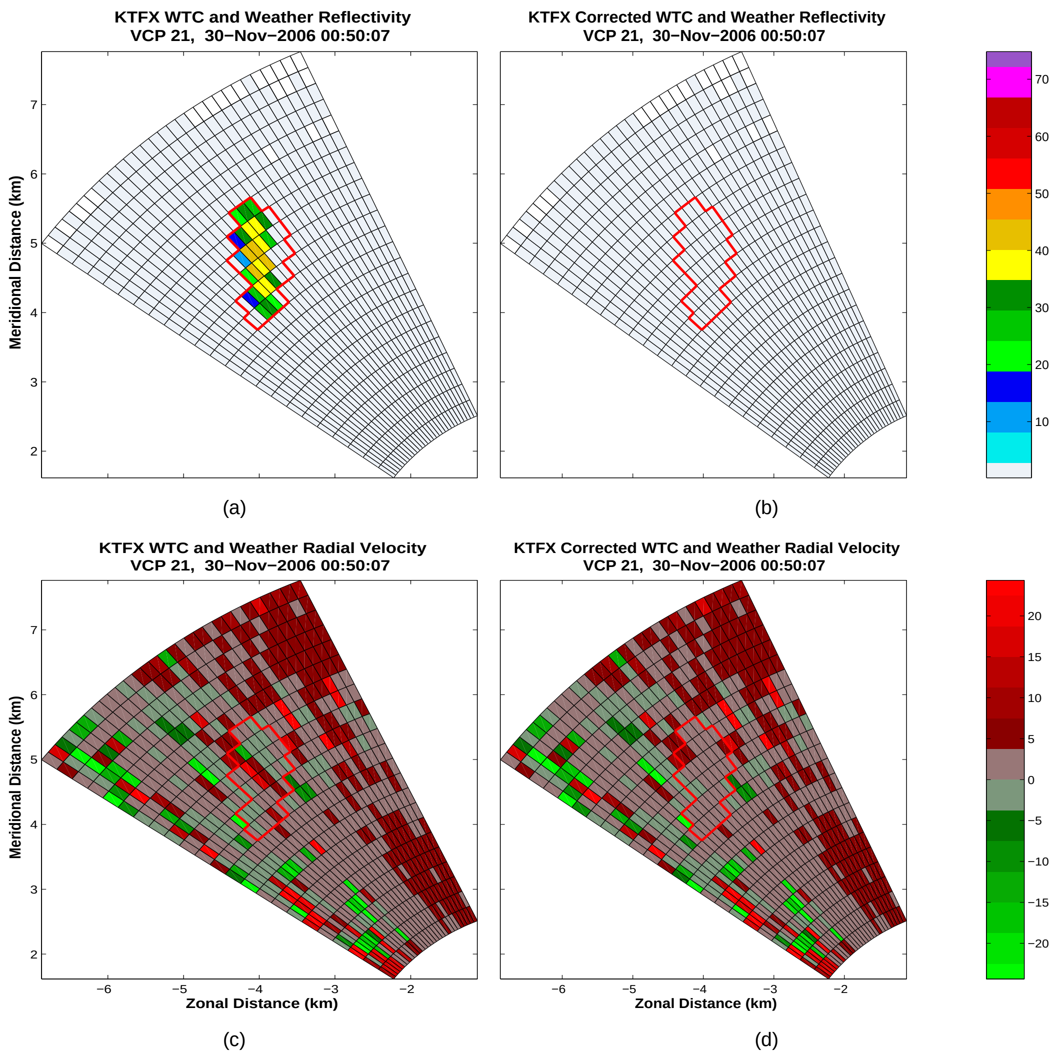

Figure 9: Same as Figure 7 but for KTFX. The WTC and weather reflectivity and velocity PPI plots filtered with OUGMAP are shown in (a) and (c). The results of the 2-D multiquadric interpolation are shown in (b) and (d). The interpolation region is outlined in red.