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SUPPRESSION OF THE WINDFARM CONTRIBUTION FROM THE ATMOSPHERIC RADAR RETURNS

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ABSTRACT – A methodology for suppression of the returns from wind turbines in weather radar data is presented. The methodology is demonstrated on a data set provided by the Atmospheric Radar Research Center (ARRC) of the University of Oklahoma (OU) and obtained using S-band weather radar. Bootstrapping, spectral phase coherence and time Doppler spectral analysis are used to facilitate the recognition of the wind turbine contributions. These recognized contributions are suppressed in the frequency domain allowing for a recovery of the residual weather signal. This methodology is applicable for any pulse Doppler radar system and is applied to the IQ level data also known as level 1 data.

1. PROBLEM

The U.S. President signed the Energy Bill which called for a decrease in reliance on fossil fuels and an increase in the nation's exploitation of renewable energy with an emphasis on the use of wind turbines. In 2009 wind power made up ~2% of the nation's electricity portfolio. The Department of Energy predicts that with the development of more efficient turbines, wind could provide 20% of U.S. electricity supplies by 2030. The Wind Energy Research and Development Act requires the Secretary of Energy to carry out a program of research and development to improve the energy efficiency and create a demonstration program to measure wind energy performance that includes a full range of wind conditions across the country (govtrack.us, renewableenergyworld.com). The bill authorizes $200 million per year from 2010 through 2014 for these programs. This incentive elucidates why the industrial wind turbine projects are growing at an accelerated pace. Turbines come at a variety of shape, sizes and materials. Larger wind turbines and wind farms negatively impact radars (oeaaa.faa.gov, eere.energy.gov, Brenner et al. 2008, roc.noaa.gov). Industrial wind turbines are impressive structures reaching 150 m in height and having massive blades reaching up to 50 m in length. (thewindpower.net). Examples of wind farms are shown in Figs. 1 and 2a. A 35 m turbine blade during transportation is shown in Fig. 2b to highlight the impressive size of the structure.

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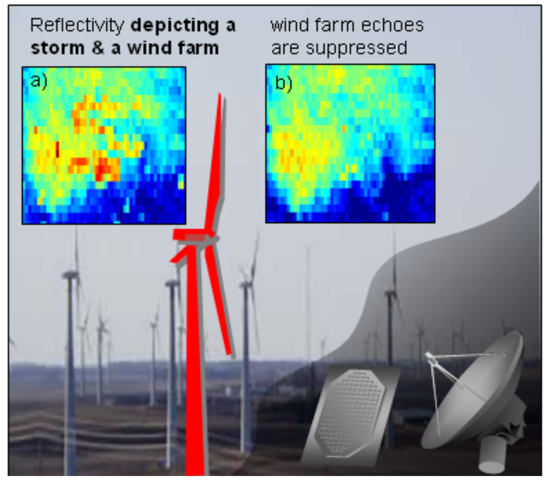

Fig. 1: Weather radars are negatively affected by wind farms. To visually assess the degree of impact, compare images depicting reflectivity from precipitation over a wind farm (a) before suppression and (b) after suppression.

Atmospheric radars such as NEXRAD exemplified in Fig. 2c are located on towers that are about 20 m high (wikipedia.org, www.roc.noaa.gov). The exact height of the tower at any given NEXRAD site depends on the elevation of the site as well as the relative height of the surrounding terrain. A network of 159 of these radars across the U. S. is operated to inform citizens of the changing environment, measure precipitation, support weather forecasts, produce severe storm warnings, and monitor climate. Sophisticated algorithms for ground clutter suppression are used on these radars to improve data quality for scans obtained at low radar beam elevation angles (Chrisman and Ray 2006). These algorithms are based on the fact that ground clutter is stationary and has zero Doppler shift (Doviak and Zrnic 1993). New methodologies are needed to suppress echoes from wind turbines because the motion of rotating turbine blades creates non-zero Doppler shift.

2. SPECTRAL SIGNATURE OF A WIND TURBINE

Wind turbines have very interesting spectral signatures with prominent time dependent features. Spectral signatures of turbines observed on a research radar (in a mode when the radar is continually pointing in one direction) are shown in Fig.3. This type of spectral depiction is referred to as time-Doppler spectra.

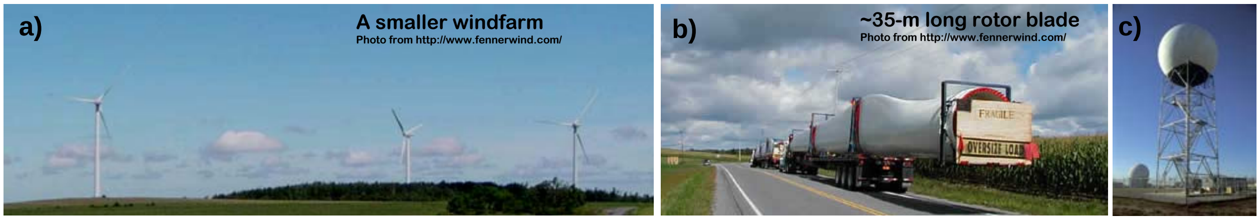

Fig. 2: a) An example of a smaller windfarm shows how turbines tower above the woods into the clouds. b) A photograph of a 35 m turbine blade captured during transportation highlights the impressive size of the structure. c) NEXRAD radar on a 25 m tower is shorter then the blade in (b).

Signatures at zero-Doppler shifts are due to the stationary tower of the wind turbine. The returns from the tower do not pose a significant problem and can be filtered using current NEXRAD clutter filtering algorithms. Signatures with non-zero Doppler shifts in Fig. 3 are from the rotating blades (Isom et al 2009). The returns from the blades are often referred to as blade flashes. Note that NEXRAD is a rotating radar system, therefore, only one time snapshoot (i.e., any one row from image in Fig. 3) of such signatures is detectable on NEXRAD. It is extremely difficult to classify echoes on meteorological and moving-on-the-ground scatterers from only one snapshot of this dynamic signature. The impressive wind turbine structures penetrate into the atmosphere, create obstructions, and produce Doppler shifts that obscure weather echoes.

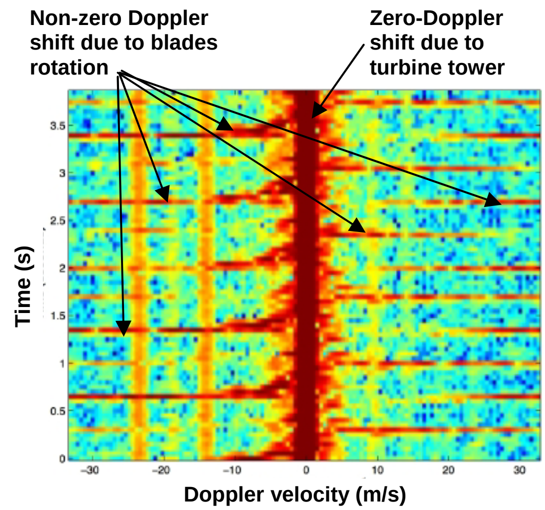

Fig. 3: Example of non-zero Doppler shift due to the rotation of wind turbine blades (*http://arrc.ou.edu/turbine/signal.htm*)

The illustration presented in Fig. 4 shows a weather radar looking at a cloud in the vicinity of a wind turbine. In this situation, the radar detects a mixture of echoes. This mixture may have many components with different velocities: 1) storm motion mean velocity, 2) blade motion toward radar and 3) blade motion away from the radar. The possibility to correctly estimate weather velocity from storm echoes is obliterated by the strong echoes from rotating blades. In some situations, rotating blades may trigger tornado detection algorithms.

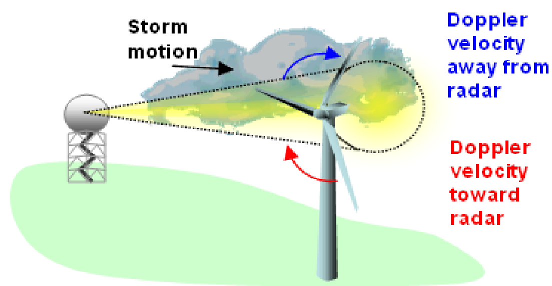

Fig. 4: Illustration depicting turbine penetrating into the radar beam and creating Doppler shifts that obscure the Doppler shift due to storm motion.

Ground clutter maps are used on NEXRAD to facilitate clutter filtering from terrain and man-made ground structures such as buildings, cranes and towers. It is apparent that a special wind-farm-clutter map can be used to facilitate the suppression of echoes from wind farms. An example of such a map is shown in Fig. 5. This map was assessed in the frequency domain in a multistep process that includes thresholding spectral power at zero Doppler, assessing the level of spectral median in regards to spectral floor, and combining the resulting information. Regardless of the availability of the wind-farm-clutter map, the suppression technique was applied throughout the radar coverage in the examples presented in Fig. 6. The use of the map would speed up this process.

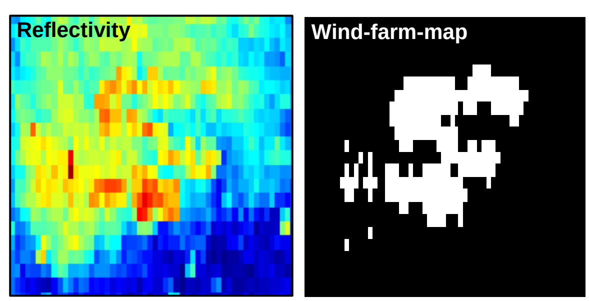

Fig. 5: Reflectivity and a wind-farm clutter map.

3. SOME BACKGROUND INFORMATION AND DEFINITIONS

The proposed suppression technique requires level 1 radar data; also referred to as IQ data. IQ data is a sequence of complex-valued samples containing echoes from one resolution volume observed during the dwell time. The number of IQ samples is generally indicated by the number of pulses transmitted at this dwell.

The proposed suppression is performed on Doppler spectrum. Doppler spectrum is a frequency-domain representation of the signal. Because frequency-domain is a mathematical concept, the true spectrum is not known. Spectrum can be estimated using different parametric and non-parametric methods. For this technique the spectrum is estimated using non-parametric Fourier Transformation. The suppression quality can be evaluated by examining the Range-Doppler spectra, or a collection of spectra at consecutive range locations. Doppler signature is a shape (peak) in the Doppler spectrum that characterizes strength, radial velocity and velocity dispersion of the scattering entity.

Ground clutter Doppler signature, such as echoes from the wind turbine tower, is expected to contribute to the zero-velocity component in the Doppler spectrum. Note that this contribution can be successfully filtered using current clutter filtering techniques. Wind turbine clutter Doppler signature, in addition to zero-Doppler, has contributions from rotating blades and therefore cannot be easily pre-identified for suppression processing.

For accurate filtering, a high resolution spectrum is desirable. Bootstrap is used to artificially increase spectral resolution. Bootstrap in signal processing is a family of statistical methods that can be used to estimate unknown parameters of a signal observed in noise based on a random sample. Bootstrap is used to extend short I/Q sequences obtained at a limited dwell time and to make the sequence suitable for accurate spectral analyses. Bootstrap can be used to improve spectral resolution (additional spectral coefficients that are not interpolations), to improve range resolution (additional spectrum between range gates in range-Doppler), or to improve both.

Another item needed for accurate ground clutter filtering is the high confidence recognition of those spectral components that contributed to clutter. We use spectral phase coherence test to pinpoint spectral coefficients containing contributions from ground clutter. Spectral phase coherence is a differential phase between the coefficients of two spectra obtained from the same I/Q sequence by shifting the sequence (or selecting a series in a pattern of even and odd indexed samples).

After all signal processing mechanisms used in the proposed wind farm clutter suppression solution are presented for readers review, we proceed with the general description of the proposed algorithm. Please note that the exact description of the algorithm is a Lockheed Martin Trade Secret.

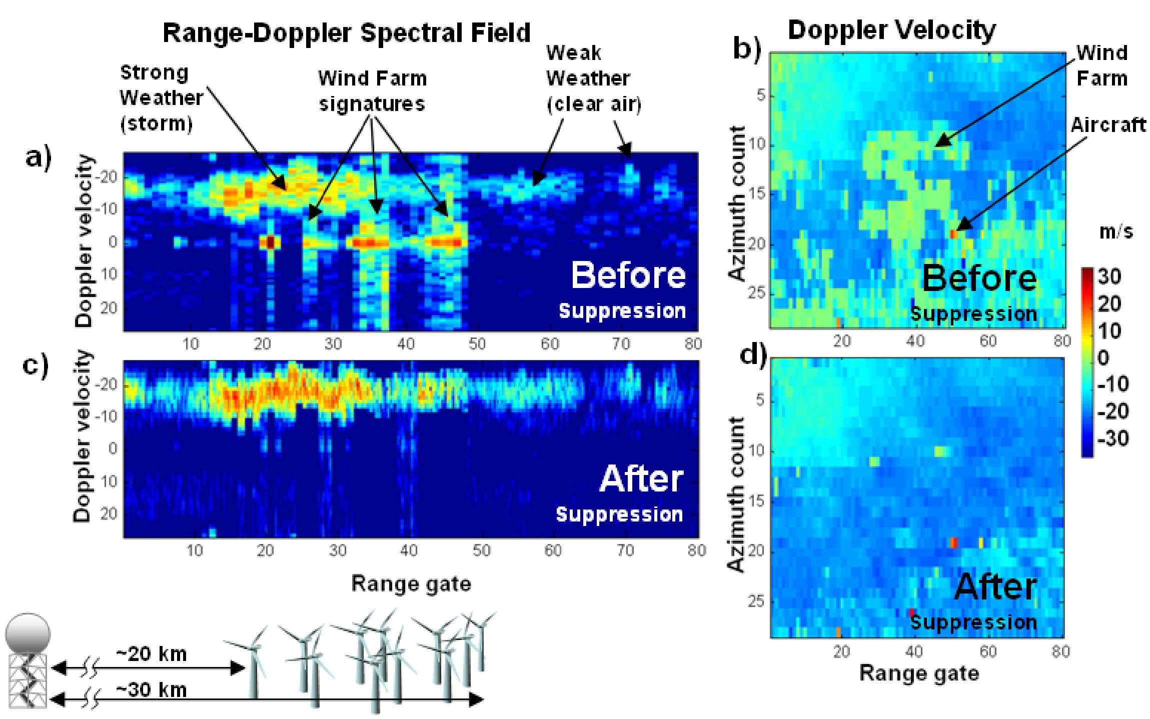

Fig. 6: Range-Doppler spectral fields (a) before and (c) after wind farm clutter suppression, that contribute to Azimuth count 12 of the Doppler velocity fields (b) before and (d) after suppression.

4. SUPPRESSION

It is suggested that a wind-farm-clutter map is used prior to suppression to reduce computational load. However, the algorithm is proven to perform without the wind-farm-clutter map as demonstrated in Fig.6. Suppose, a range location is indicated by the wind-farm-clutter map as containing multi-modal Doppler signatures, then the following spectral analyses are performed:

1. A Hankel matrix on IQ data is produced to set up an analysis of changes in data on a per-pulse basis.
2. Bootstrap is applied to each row of the Hankel matrix.
3. Window weighting function is applied.
4. Fourier transformation of bootstrapped and weighted sequence is performed.
5. Time-Doppler spectral Moving Target Identification processing is applied to remove non moving contributions on per-pulse basis.
6. Signatures in consecutive range resolutions are correlated for all ranges (7) or only for ranges flagged by the wind farm map.
7. Velocity tracking within a resolution range cell is performed and signatures outside of the window centered on the track are uniformly suppressed.
8. The mean velocity value for each resolution volume is estimated

The performance of this algorithm is outstanding, at the cost of computational complexity. Figs. 6a and 6c depict two Range-Doppler fields before and after clutter suppression for comparison. The conventional range-Doppler depiction (Fig. 6a) exposes prominent signatures of windfarm ground clutter indicated by arrows. This cluttered Range-Doppler contributes to the velocity field in Fig. 6b at Azimuth Count 12. The depiction of Range-Doppler after suppression (Fig. 6c) exposes more defined signatures of weather and an increased contrast due to higher resolution. Recall that higher resolution is due to bootstrapping. This uncluttered Range-Doppler contributes to the velocity field in Fig. 6d at Azimuth Count 12. The velocity fields clearly show that the wind farm signature is suppressed and the velocities at the area with weak-weather are less noisy.

5. CONCLUSION

This approach is devised for suppression of non-zero Doppler wind turbine clutter from atmospheric radar returns. This approach is computationally complex and is based on extraction of per-pulse differences in Doppler signatures. Blade flashes from wind turbines are de-correlated from the signature while weather Doppler remains correlated so weather can be tracked and preserved.

AKNOWLEGEMENT

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