Dynamic Radar Cross Section and Radar Doppler Measurements of Commercial General Electric Windmill Power Turbines
Part 2 – Predicted and Measured Doppler Signatures

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ABSTRACT

Commercial windmill driven power turbines ("Wind Turbines") are expanding in popularity and use in the by the Undersecretary of Defense for Space and Sensor Technology acknowledged the potential performance impact wind turbines introduce when sited within line of site of air traffic control or air route radars. [1]. In the Spring of 2006, the Air Force Research Laboratory embarked on a rigorous measurement and prediction program to provide credible data to national decision makers on the magnitude of the signatures, so the interference issues could be credibly studied. This paper, the second of two parts, will discuss the calibrated Doppler measurement of the turbines and compare this data to modeled Doppler data. In addition, hypothetical modeling and simulation results will be shown to illustrate how a windmill can cause spurious and dropped tracks as a business class corporate jet signature is "flown" through windfarm radar clutter.

Keywords: Doppler Spectra, Radar Cross Section, Mobile Diagnostic Measurements

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1. Introduction

This two-part paper summarizes an Office of Undersecretary of Defense sponsored Radar Signature and Doppler measurement and prediction campaign [1] for large, energy producing wind turbines manufactured by the General Electric Corporation. Part 1 discussed the signature measurements including the site setup, radar calibration, field probing, measurement uncertainty and the RCS prediction modeling. This paper, Part 2, discusses the Doppler aspects of the Air force Research Laboratory Mobile Diagnostics Laboratory, MDL, measurements and X-Patch prediction data [2,3].

2. Description of Single GE Windmill Power Turbine

The targets for this test are the General Electric (GE) wind turbines located on the Fenner Wind Farm in Fenner, New York. Each wind turbine consists of a 2.13 m deep concrete foundation, a 64.9 m tall tubular steel tower, a 70.4 m diameter, three-bladed rotor connected to a gearbox and generator, and an electronic control unit to monitor and operate the system. The diameter of the tower is 3.78 m at the base and 2.59 m at the top. The length of each blade is 34.4 m. The total height of the wind turbine (tower and blades) is 100 m. A photo of a representative Wind Turbine is shown in Figure 1 along with dimensions of the pertinent components (US units).

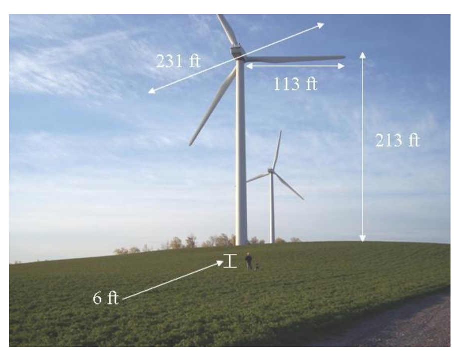

Figure 1 GE 1.5 MW Windmill Power Turbine

The windmill is designed to point automatically into the wind, meaning the windmill is constantly changing direction relative to the MDL collection radar as the prevailing wind direction changes. Throughout the two-week Fenner, NY deployment the turbine blades had a nominal rotation range of 12.4 rpm or less. We also had two days were the winds were too weak to start the turbine rotation. At the beginning of the Fenner deployment, the prevailing winds were predominantly from the SW direction and had changed to a predominately NE direction at the end of the deployment.

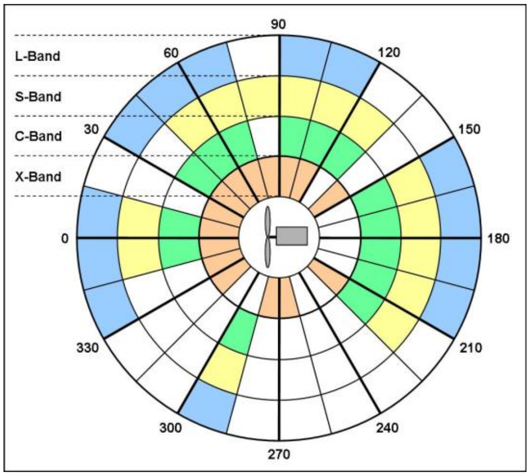

Figure 2 Turbine Yaw Sectors Measured by the MDL

This fortunate change in wind direction, along with the four different MDL deployment locations at the Fenner Wind Farm site, allowed us to collect scattering measurements of the windmills at a large number of different observation angles. A color coded data collection matrix of the Yaw sector measured is shown in Figure 2. Colored sectors indicate observation angles where at least one valid data collection occurred. This matrix corresponds to the Vertical co-polarization data collections. A similar chart was also developed for the Horizontal co-polarization data collections. Note the front Yaw sector (270° to 0° to 90°) is with the turbine blades located in front of the windmill support tower and observation from the rear Yaw sectors will have the support tower in front of the turbine blades. For the rear Yaw sectors measurements we would expect some portions of the Doppler spectra to be shadowed by the very large support tower as the turbine blades rotate through a 360 degrees rotation.

3. Data Collection for Doppler Processing

All of the scattering collection measurements were collected at one of the four discrete frequencies in the L-, S-, C-, and X-band for a 30-second time duration. The maximum rotation speed of the GE windmills is around 22 rpm. During the initial radar timing setup we observed the nominal rotation rate to be 12 rpm. Using this observation we decided that for each data collection we would collect three, nearly identical back-to-back data sets of 30 second duration each. The first collection used a two pulse-to-pulse phase coherent integration, followed by a four-pulse integration data collection and then an eight-pulse integration collection. The higher integration count provides a 3-dB noise reduction for each doubling of integrated pulses. At the higher integration numbers it is possible to under-sample the received signal for high windmill rotation rates. Doppler processing of an under sampled signal would result in spectral aliasing which is not desirable. By always collecting the windmill scattering at 2, 4, and 8 integrations we were assured the data would be adequately sampled for Doppler processing. As it turned out the windmill rotation speed remained at or below 12 rpm and even the 8-integration data set adequately sampled. An additional benefit of this collection procedure is that it gave us a total of 90 seconds of almost continuous data for each data collection point.

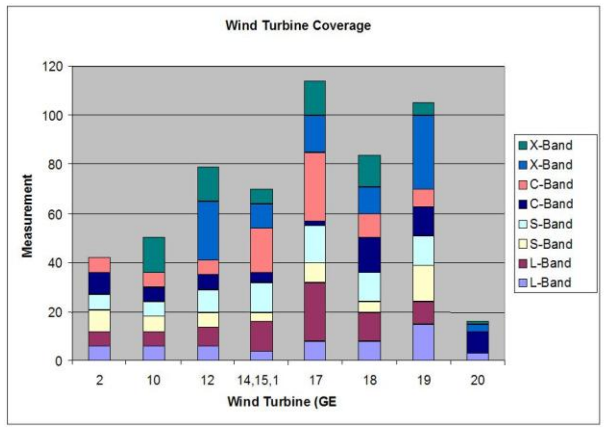

Figure 3 Valid Data sets Collected by Band, pol, and Wind Turbine Number

Over 400 valid data files were collected during two-week Fenner deployment. A histogram of the number of data collection by band, polarization and wind turbine number is given in Figure 3. This large and diverse data set gave us more than ample data to evaluate the Doppler spectra phenomenology and to compare against the X-Patch modeled data sets [3].

4. Doppler Spectra Processing

Processing of the four hundred data files was a very labor-intensive task that where individual calibration constants had to be determined for each frequency, polarization, windmill, and MDL location site [5]. At the time of the data collection and for the two-month time period afterwards we did not have access to the GE metric data Yaw angle offsets from true North. In other words, we did not have absolute "truth" of the yaw angle relative to geometric north. Since we did not have the offset constants, we and had to rely on the Doppler measurement data to estimate the individual Yaw angles. In July 06, after the initial test, a separate surveying team was sent back to Fenner, NY to measure the Yaw angle offsets of the individual windmills. In the end, the measured offsets were less than 1 degree from our estimate from the Doppler data!

The general data processing procedure is shown in Figure 4. Here the raw I/Q radar data is calibrated using the procedures described in Part 1 of this paper [5]. The calibration operation scales the data to account for range to the target and the radar response as a function of frequency and polarization. Calibration provides data in units of RCS in dBsm for the RCS vs. Time format.

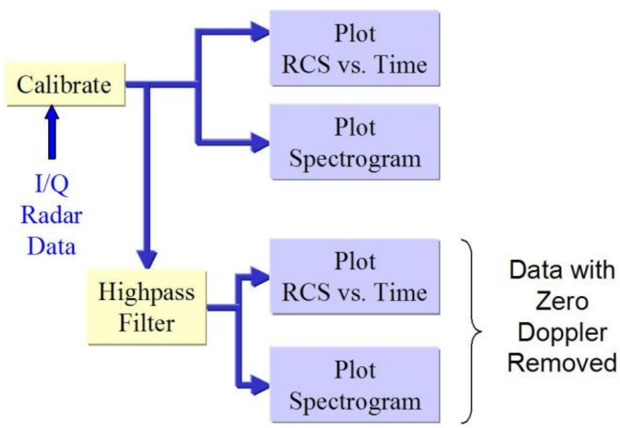

Figure 4 Calibration and Scattering Processing

The target data is processed in two formats. One is RCS vs. Time and the second is a Spectrogram plot with time on the X-axis, Doppler frequency on the Y-axis and intensity in color in the third dimension. In addition both formats were delivered with and without the Zero Doppler Processing, ZDP. Since the intent of this program was too examine windmill Doppler spectra scattering, all of the Spectrogram plots have the zero Doppler component removed with the ZDP filter.

The high pass filter removes the portion of the target response that is either stationary or has no significant range rate with respect to the radar position. The effect of this filter produces the Zero Doppler plots shown in Figures 5 and 6. For the ZDP displayed plots, the zero Doppler components were removed using a filter customized for this data set. This filter is a simple, high pass digital filter utilizing a 4096 tap, equal-ripple response with less than 0.1 dB

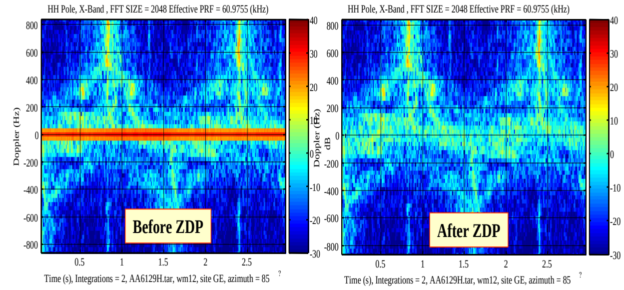

Figure 5 Spectrogram With and Without ZDP

A Spectrograms with and without Zero Doppler Processing are given in Figure 5. As shown in the figure the scattering spectra are identical in frequency and magnitude for all spectra outside the ZDP notch frequency. It should be noted that RCS is defined to include the stationary components (Zero Doppler) a high pass filtering of the RCS data invalidates the units of dBsm since a component of the total RCS signature is removed. The authors of this paper fully understand that the RCS after ZDP is not true RCS, but it is a true RCS level of the turbine rotating components and target multi-bounce effects. Without ZDP the stationary tower dominates the scattering and little information can be gleaned from the time domain data plots. A spectral plot of the time of a Fourier Transformed data set with and without ZDP is shown in Figure 5. As shown in the figure the magnitude and spectra of the windmill Doppler return is unperturbed outside the narrowband clutter notch frequency.

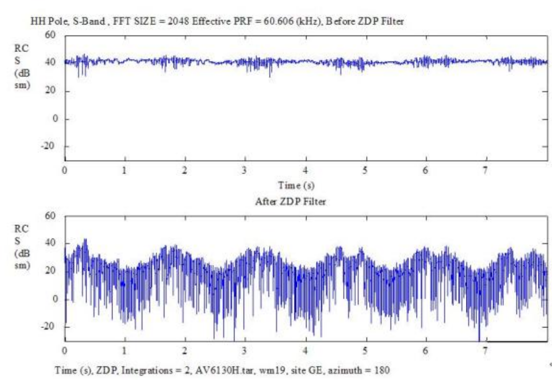

Figure 6 Scattering With and Without ZDP

A Spectrogram of the time varying signal is generated using the procedure illustrated in Figure 7. In the Spectrogram display targets with a positive spectra are approach the measurement radar and a negative spectra indicates a target that is moving away from the radar.

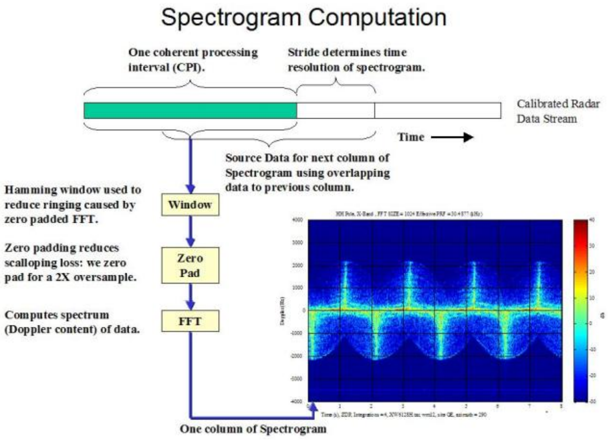

Figure 7 Spectrogram Processing

5. Interpretation of Doppler Spectra

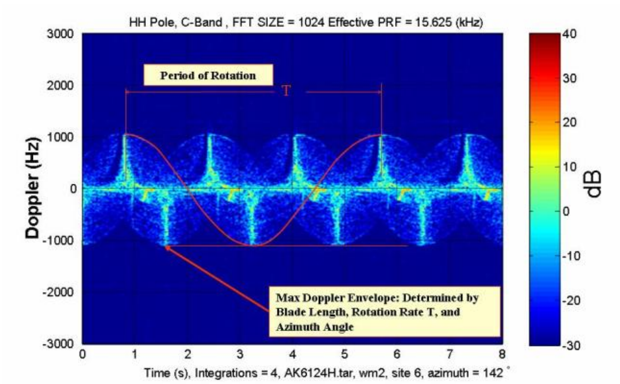

Figure 8 Windmill Rotation Rate and Yaw Orientation

Figure 8 illustrates the C-Band, HH polarization, Doppler spectra for Windmill 2 as viewed from the MDL Site 6 location. Several observations can be easily identified from the transformed data. First the specular blade flashes form the individual blades are clearly identified in the plot. The red sinusoidal trace shown in the figure corresponds to a 360 degree rotation of one of the three turbine blades. In this figure the positive Doppler correspond to the turbine blade rotating toward the MDL radar and the negative Doppler corresponds to an increasing range rate or the blades moving away from the radar. The period of rotation is readily determined from this periodic specular flash, additionally the orientation (Yaw angle) of the windmill towards the MDL collection radar can be calculated from the spectrogram. For this calculation the max Doppler spectra envelop corresponds to the turbine blade tip scattering and is proportional to the cosine of the Yaw angle of the windmill. At the Fenner site we did not have access to the GE metric data and relied on the blade rotation rate and Doppler envelope to determine the Yaw angles. The correct Yaw angles obtained in July 06 and were found to be within a 1 degree of our calculated values!

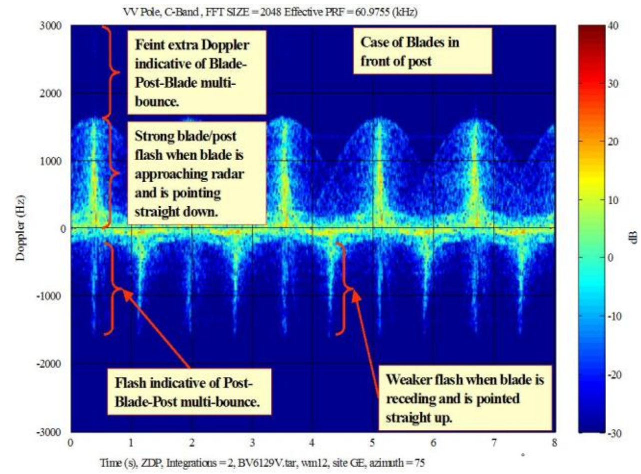

Figure 9 Doppler Scattering Phenomenology

The Spectrogram in Figure 9 highlights additional scattering phenomenology that can deduced from the measured data. Multi-bounce, blade-post-blade, scattering is shown at Doppler frequencies greater than the blade Doppler scattering. In Figure 9 the turbine blades are in front of the support tower and no tower shadowing is observed. In Figure 8 the windmill tower is located in front of the turbine blades. Shadowing of the blade by the tower is observed to the left of the positive Doppler specular flashes shown in the spectrogram.

The following observations should be noted when examining the spectrogram plots:

- Doppler is proportional to the range rate of the scattering mechanism that generates it.
- Multi-path can have a range rate that is different than the range rate between the blade and the radar.
- A multi-bounce that hits the blade, the post, back to the blade, then back to the radar can have a Doppler of twice that of the blade itself.
- A multi-bounce that hits the post, the blade, back to the post, then back to the radar can have a Doppler that is the opposite of the blade itself.
- Blades rotate in a clockwise fashion when the windmill is facing the radar (0° Yaw).
- When windmills are facing away from the radar the shadow location indicates which quadrant the windmill is facing.

5. Comparison of Measured and Predicted Doppler Spectra

Our CEM analysis relied on ACAD modeling and X-Patch scattering prediction. Part I of this joint paper provides a description of the ACAD and X-patch modeling [2,3,5]. While the X-patch RCS calculations included the effect of all the blades and tower interactions, we know X-Patch does not model traveling waves and surface waves. Nonetheless, we didn't expect these latter scattering mechanisms to contribute much to the overall RCS. The X-Patch simulation was also complicated by the number of elevation angles required for comparison to the measured data collections. The elevation angle from the MDL to the windmills was different for each windmill. This elevation varied from 0.6 to 5.8 degrees.

Keep in mind that the windmill is electrically "very large" in wavelengths, even at the lowest frequencies. At 1.5 GHz, the tower is 325 λ tall, and each GE 34a blade is 325λ long. The RCS calculations thus required a supercomputer (Origin 3900) using 64 or more nodes to execute. To capture all the physics associated with multi-bounces, sampling rates need to be at least twice the Nyquist sampling rate. Since blade RPM can cause significant change in Doppler Frequency, and since there is 120 degree symmetry with this geometry, the number of computer runs needed to calculate the RCS and Doppler is phenomenal! Of course, the computational time is dependent on the electrical size of the windmill. At L-Band, RCS calculations required 4,800 angles at 7 minutes per run on a supercomputer to complete. To make the same RCS computation at X-band for each 0.005 degrees of rotation required 24,000 runs with an average of 4.8 hours per run! At the conclusion of the output processes, both radar signature calculations and Doppler Spectrograms were produced. [4].

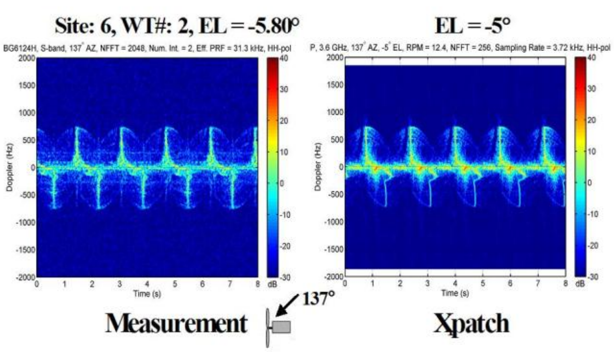

Figure 10 Spectrogram S-Band, 12.4 RPM, 137 degree Az, HH Pol

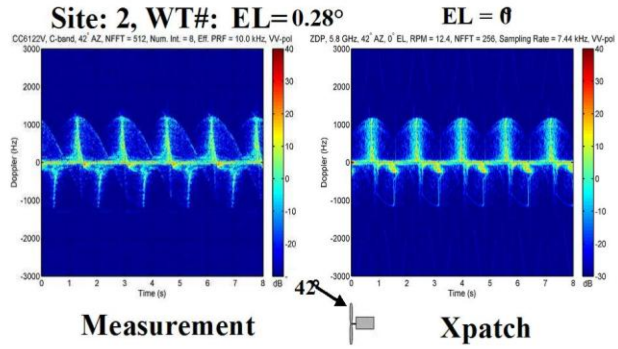

Figure 11 Spectrogram C-Band, 12.4 RPM, 42 degree Az, VV pol

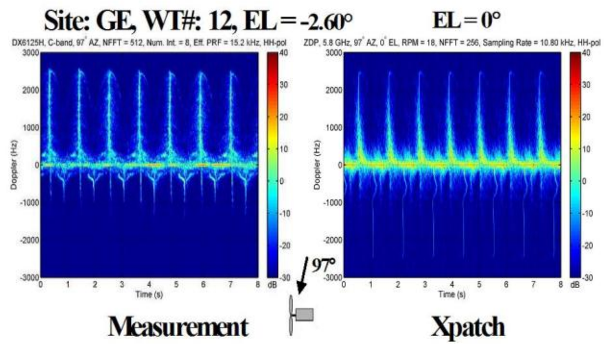

Figure 12 Spectrogram C-Band, 18 RPM, 97 degree Az, HH pol

Figures 10 to 12 provide a side-by-side comparison of the measured RF data with the X-Patch predictions. The Spectrograms include both S- and C-band and both HH and VV polarization. Figures 11 and 12 have a 12.4 rpm rotation rate and Figure 12 is with a 18 rpm rotation rate. Comparison of the measured and predicted data shows that we can successful model the windmill RCS and successfully model the Doppler signature.

6. Hypothetical Aircraft Track Ambiguity

Our last tasks was to relate windmill Doppler values to other air vehicles and their velocities. Figure 13 illustrates the measured Doppler from the windmill blades for each of the four RF bands measured. Note the apparent velocity of the large turbine blades can be as high as 160 mph. The maximum Doppler value varies from a low value where the blade rotation is orthogonal to the position of the measurement radar to a high value where the blades are rotating in the plane of maximum range rate change.

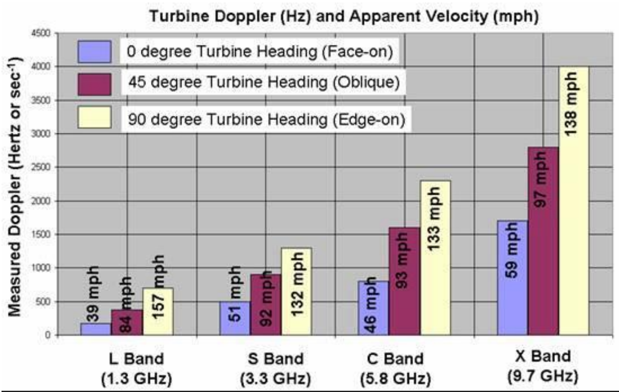

Figure 13 Apparent Velocity of Turbine Blades

Our final task in this study was to demonstrate in a hypothetical sense how an aircraft flying past a single windmill would appear to a radar operator. For this simulation we embedded a commercial business jet signature into the measured Doppler signature and fed this simulated-measured data set into a simple moving target detector. Note there is no intent to model any particular radar or radar-processing scheme; we are simply trying to show a comparison of the Doppler scattering of a commercial business jet to the windmill Doppler. The results of this simulation are shown in Figure 14.

The top plot in

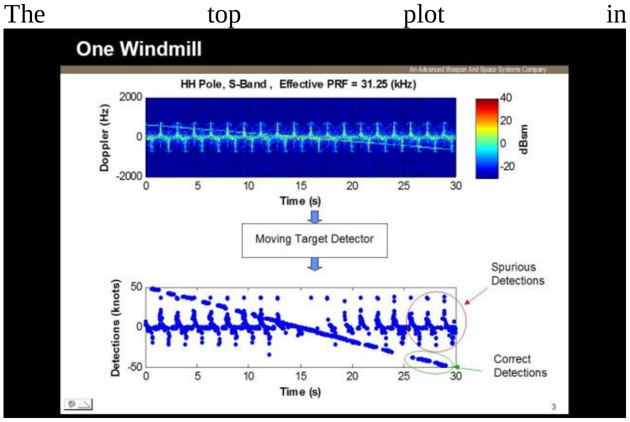

Figure 14 shows a representative spectrogram of a windmill with the embedded aircraft Doppler return. The bottom plot illustrates one type of track display available to a radar operator. As shown in the figure as a number of spurious detections could be encounter when the target's Doppler is relatively close to the windmill scattered Doppler signature.

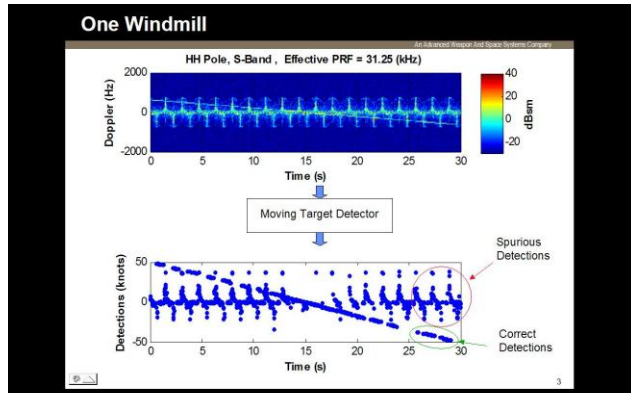

Figure 14 Hypothetical Aircraft Track with Windmill

6. Summary

This paper examined RCS and Doppler spectra of large electrical power generation wind turbines collected with the AFRL/MDL at Fenner, NY. A comparison of theoretically modeled Doppler signatures using an X-Patch computer model was made to using a small subset of the MDL field measurement data set. A radar simulation of a commercial business jet signature embedded into a measured windmill data file was also presented. While this paper limited to a few comparisons over 400 L-, S-, C-, and X-band data files at varying Yaw and elevation angles were collected by the MDL during the two-week deployment to Fenner, NY.

7. References

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8. Acknowledgements

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