The AMTA host for the two conferences in India was Prof. O. P. N. Calla, Director of the International Centre for Radio Science in Jodhpur. He was helpful and very hospitable throughout. In fact, the meetings were run with much ceremony and with special recognitions for each of the speakers.

Dr. Janse van Rensburg summarized his first visit to India, "I found the people to be very friendly and welcoming and I had a good time." In fact, all AMTA speakers enjoyed the India experience and look forward to a return visit!

For more information on ATMS, visit http://www.atms.org.

Also, planning for the 2008 AMTA Regional Conference in Los Angeles is under way for the summer of 2008. We'll notify everyone in the AMTA Corner when we have the date, but head over to http://www.amta.org to get the latest information. Enjoy the spring!

This Month's Contribution

This month's paper is from Brian M. Kent, PhD, Kueichien C. Hill, PhD, Alan Buterbaugh, and Greg Zelinski, Capt USAF with the Air Force Research Laboratory at Wright-Patterson AFB and Robert Hawley, Lisa Cravens, Tri-Van, Christopher Vogel, and Thomas Coveyou from ATK Mission Systems Group, in Dayton, Ohio. The paper is entitled "Dynamic Radar Cross Section and Radar Doppler Measurements of Commercial General Electric Windmill Power Turbines Part 1: Predicted and Measured Radar Signatures." The research examines the radar cross section signature of various windmills over time, with both the dynamic RCS and the radar Doppler signatures measured. The measurements were then compared with modeled data results to verify the windmill models created. The problem with such large, moving metallic devices such as windmills is the potential interference such structures present to an array of civilian air-traffic-control radars. A recent study by the Undersecretary of Defense for Space and Sensor Technology acknowledged the potential performance impact wind turbines introduce when located within line of site of air-traffic-control or air-route radars. We hope you enjoy their contribution to the AMTA Corner.

Feedback and Contact Information

We're proud to be the AMTA Corner Associate Editors, and we wish to thank all those who contribute to its success, especially our authors who allow us to publish their papers in the AMTA Corner. In particular, AMTA extends our gratitude to Ross Stone for giving us the opportunity to contribute this column to this prestigious *Magazine*. If you wish to reference other previous AMTA publications, AMTA members can do so through our online archive at http://www.amta.org. If you are not a member, $50.00 and a few mouse clicks will get you registered as a member today! With the AMTA Corner, we're certainly open to feedback as to how we're doing. We can be e-mailed at stephen.schneider@wpafb.af.mil or jeff.kemp@gtri.gatech.edu. Until next time!

Dynamic Radar Cross Section and Radar Doppler Measurements of Commercial General Electric Windmill Power Turbines Part 1: Predicted and Measured Radar Signatures

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Abstract

Commercial windmill-driven power turbines ("wind turbines") are expanding in popularity and use in the commercial power industry, since they can generate significant electricity without using fuel or emitting carbon-dioxide "greenhouse gas." In-country and near-off-shore wind turbines are becoming more common on the European continent. The United States has recently set long-term goals to generate 10% of national electric power using renewable sources. In order to make such turbines efficient, current 1.5 MW wind-turbine towers and rotors are very large, with blades exceeding 67 m in diameter, and tower heights exceeding 55 m. Newer 4.5 MW designs are expected to be even larger. The problem with such large, moving, metallic devices is the potential interference such structures present to an array of civilian air-traffic-control radars. A recent study by the Undersecretary of Defense for Space and Sensor Technology acknowledged the potential performance impact wind turbines introduce when located 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 that the interference issues could be credibly studied. This paper, the first of two parts, will discuss the calibrated RCS measurement of the turbines, and compare this data (with its uncertainty) to modeled data.

Keywords: Doppler measurements; spectral analysis; radar cross sections; mobile diagnostic measurements

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. This paper will discuss the signature measurements and prediction portion, while Part 2 [2] will discuss the Doppler measurements and predictions.

Wind-turbine power is becoming increasingly popular in both Europe and the United States. Individual wind-turbine generators can produce ~1.5 MW of clean and renewable energy, without increasing carbon emissions or degrading the environment. Since future power requirements for the US and Europe require the creation of many gigawatts of electric generating capacity, large-area installations of wind turbines, called "wind farms," are being planned and installed throughout the world. Despite obvious energy-independence and greenhouse-gas benefits, wind farms also introduce a potentially significant clutter problem for civilian and military radar systems, if individual windmills are within the radar's line of sight. The purpose of this measurement campaign is to carefully predict and measure the radar signature (or radar cross section) and Doppler signature of typical GE wind turbines as installed in the field. By recording relevant calibrated in-phase and quadrature (*I*, *Q*) signature data, various air-traffic and military radar manufacturers can accurately assess the impact of wind-turbine clutter on specific military and civilian radar models.

2. Description of a Single GE Windmill Power Turbine

The targets for this test were the General Electric (GE) wind turbines, located on the Fenner Wind Farm in Fenner, New York. Each wind turbine consisted 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 was 3.78 m at the base and 2.59 m at the top. The length of each blade was 34.4 m. The total height of the wind turbine (tower and blades) was 100 m. A photo of a representative wind turbine is shown in Figure 1, along with the dimensions of the pertinent components. Note that the blades rotated nominally between 5 rpm and 22 rpm, and the windmill was designed to point automatically into the wind. This meant that they were constantly changing direction and speed, depending on the time-dependent eddies and flows of wind over the complex local terrain. The speed of the tips of the blades approached high subsonic speeds at the highest rotation rates, meaning that the turbines could produce significant Doppler returns.

3. CEM Windmill RCS Prediction Methods

The overall scope of this project required us to assess the ability to theoretically model the windmill tower design, and to assess if accurate computational electromagnetics (CEM) tools could be used to assess windmill designs with sufficient confidence to assess their RF environment impacts prior to building and field testing. Although the theoretical models required field tests to validate, the hope was that the CEM analysis would produce results of sufficient fidelity to reduce the future need for windmill field testing. In addition, we needed an assessment of the accuracy and timeliness of CEM predictions, and we needed to validate predic-

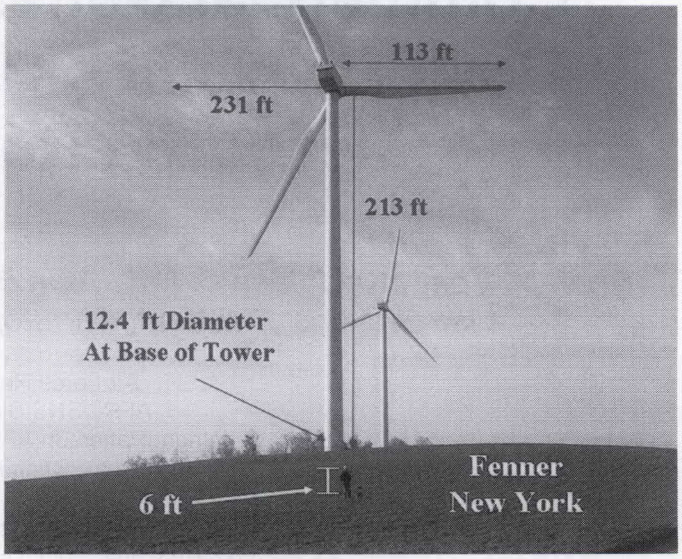


Figure 1. The GE 1.5 MW windmill power turbine.

tions with available measured data taken in the four main radar bands (L, S, C, X). Since windmills vary over time, we needed to do calculations for a variety of turbine incident or yaw angles (azimuth) and elevation angles.

Given the sheer size of these windmills, we also had to address the required geometric fidelity, and the density of the computational meshes. We also needed to know how detailed the geometry needed to be, and whether we had to calculate the entire structure plus blades, or whether we could break the problem up into smaller subsections.

The first order of business was to obtain the geometry from General Electric, who graciously supplied AFRL with a series of `STEP` and `IGES` files for all the windmill component parts. We then employed *ACAD* [2], a CAD/mesh-generation tool that is capable of producing high-precision, high-quality meshes suitable for detailed CEM simulations. Since we were interested in frequencies from 1.3-9.7 GHz, the overall geometry of the windmill required the rendering of over 403,655 facets for our finest grid rendering. Table 1 shows the overall facet size of the various components of the windmill. Figures 2 and 3 show a visual comparison, with the final *ACAD* geometry compared to the actual GE windmill geometry. As can be seen in Figure 4, the geometric rendering was quite remarkable. However, we do need to point out some very important differences between the real system and the model. First, the blades of real windmills are mostly thick fiberglass, with a small lightning-diverter rod running up their length. The *ACAD* rendering was for a perfectly conducting blade. Second, we modeled the blades assuming that the blades do not flex during movements. In fact, the blades move in both pitch and vibrate during normal generating operations.

The CEM Analysis relied on *X-Patch*, a well-known RCS prediction tool [3] that was ideally suited for this job. While *X-Patch* RCS calculations included the effect of all the blades and tower interactions, we know that *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.

It must be kept in mind that the windmill was electrically "very large" in wavelengths, even at the lowest frequencies. At 1.5 GHz, the tower was 325λ tall, and each GE 34a blade was 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 multiple bounces, sampling rates needed to be at least twice the Nyquist sampling rate. Since blade RPM could cause a significant change in Doppler frequency, and since there was 120° symmetry with this geometry, the number of computer runs needed to calculate the RCS and Doppler was phenomenal! Of course, the computational time was dependent on the electrical size of the windmill. At L band, RCS calculations required 4,800 angles at seven minutes per run on a supercomputer to complete. To make the same RCS computation at X band for each 0.005° 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]. We will compare the calculated RCS plots with measurements after describing the RCS measurement setup.

Table 1. The windmill facet density with *ACAD*.

	Number of Facets		
	Mesh 1 (Coarse)	Mesh 2 (Medium)	Mesh 3 (Fine)
Nose cone	2,641	7,293	15,543
Hub & blades	56,586	140,514	279,284
Nacelle	18,774	45,588	86,098
Tower (fixed mesh)	22,730	22,730	22,730
Total	100,731	216,125	403,655

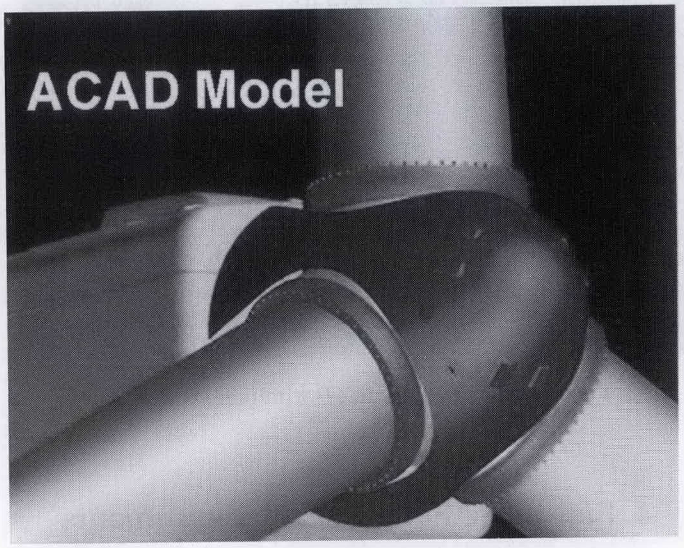


Figure 2. A close-up of the *ACAD* model of the windmill.

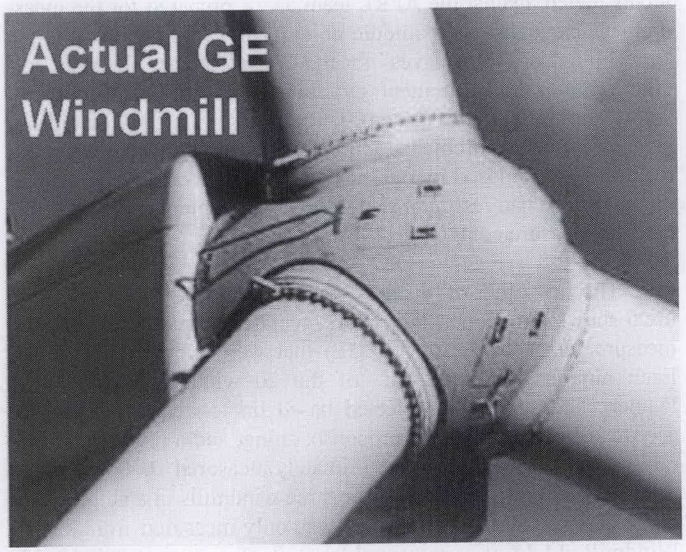


Figure 3. A close-up of the GE windmill.

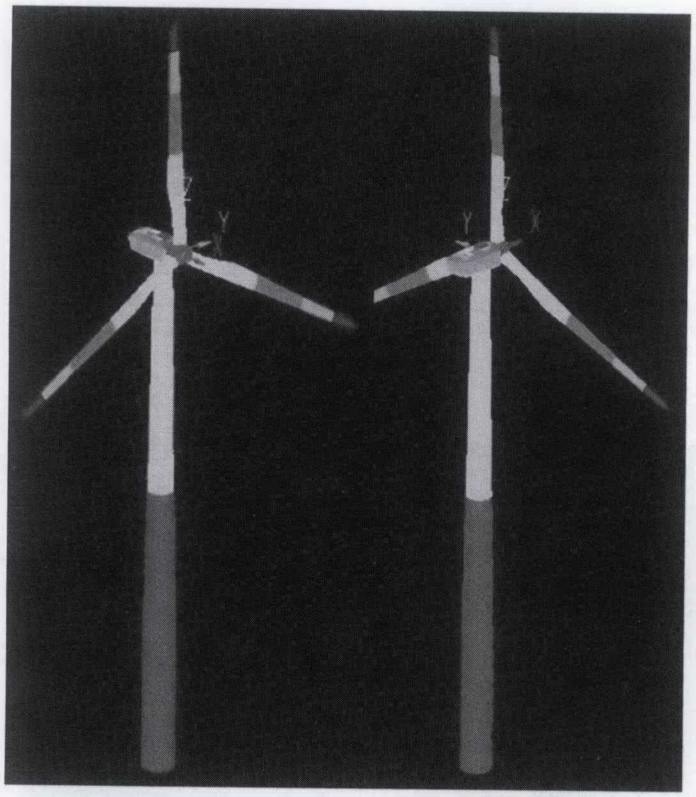


Figure 4. The overall *ACAD* windmill geometry.

4. Full-Scale Field RCS Measurements

Figure 5 shows the conceptual diagram for the windmill RCS and Doppler measurement setup. As we studied the problem in preparation for the measurement, we recognized that the measurement of RCS and Doppler from windmills was not a trivial undertaking. Table 2 shows the specific OUSD measurement requirements levied against the AFRL team as we prepared for the measurement campaign. The middle column in Table 2 represents the "thresholds" or "must haves" for the measurements. The right column outlines "measurement requirements," and the "stoplight" colors show if we met (green), partially met (yellow), or did not meet (red) the requirements. On balance, we met all the threshold requirements imposed by our customer, a remarkable achievement given that we had *less than two full months* to prepare for and execute the measurements.

The first order of business was to perform a site survey. Figure 6 shows the Fenner, New York, wind-farm map, and the three measurement sites (2, 6, and GE) that were ultimately selected. Each number represents one of the 20 windmills installed at Fenner. The sites were selected based on topology, land-owner access (all were on private property), siting, and a diversity of terrain. Of the 20 windmills, we ultimately measured 10 single windmills, as well as groups of two or three windmills in a single radar range cell. Windmill #2 (WM 2) was only measured from site 6. Windmills 14-18 were measured from site 2, and windmills 10, 12, 18, 19, and 20 were measured from site "GE." We acquired topology information and (later) GPS coordinate information for every physical feature and windmill that played into the overall measurement uncertainty.

At first glance, the sheer size and signature would make the windmill measurement appear relatively easy. When we explored the problem in depth, we realized a number of serious technical issues that had to be worked. These included, but were not limited to, terrain variations, wind and weather variations, radar-antenna siting, multi-bounce (between windmills), unintentional interference from legal spectrum users, calibration, and field probing. Each issue was addressed in turn, and these are described briefly below.

4.1 MDL Configuration

The AFRL Mobile Diagnostic Laboratory (MDL) was specifically configured to accomplish this test. Figure 7 shows a close-up of the exterior antenna and bore-sighted video camera.

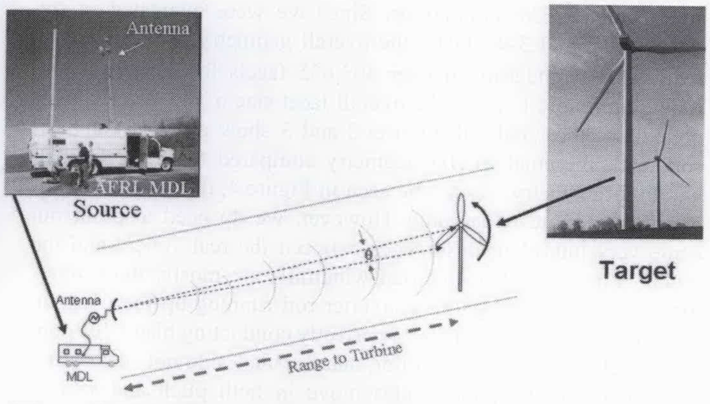


Figure 5. The AFRL Mobile Diagnostic Laboratory experimental setup for windmill measurements.

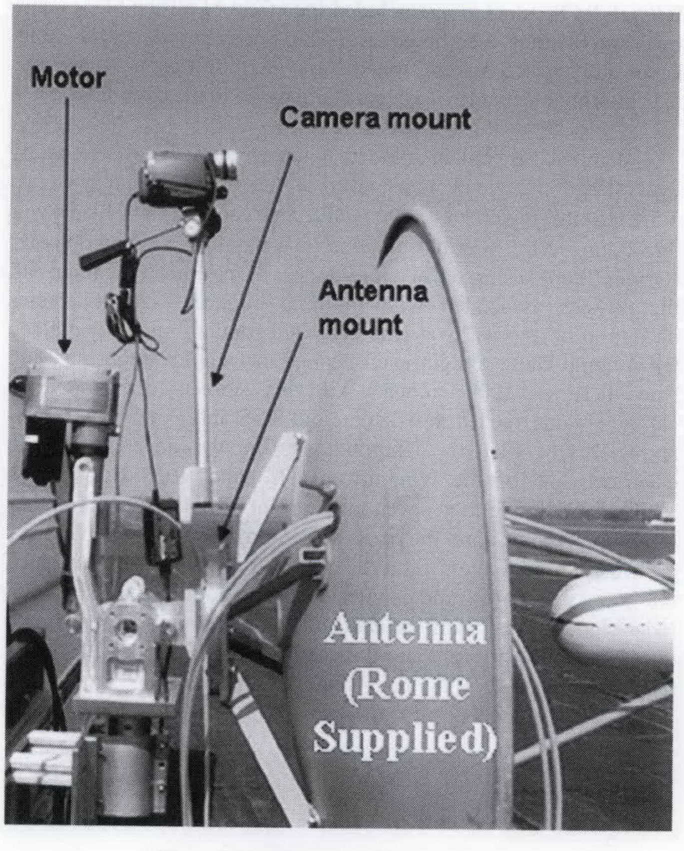
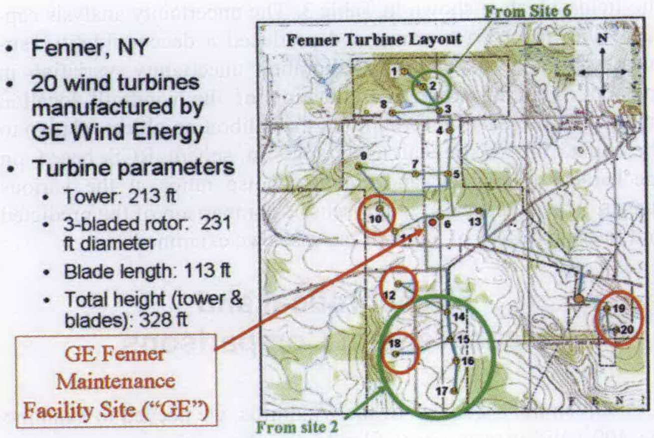


Figure 7. A close-up of the antenna.



- Fenner, NY
- 20 wind turbines manufactured by GE Wind Energy
- Turbine parameters
  - Tower: 213 ft
  - 3-bladed rotor: 231 ft diameter
  - Blade length: 113 ft
  - Total height (tower & blades): 328 ft

Figure 6. The RCS measurement locations, Fenner, NY.

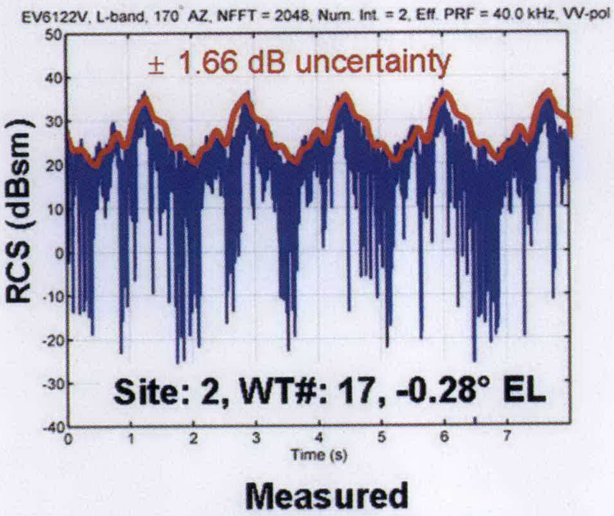


Figure 11a. The measured RCS of the GE windmill (170° yaw, 0° elevation, 1.5 GHz, 12.7 rpm, VV polarization).

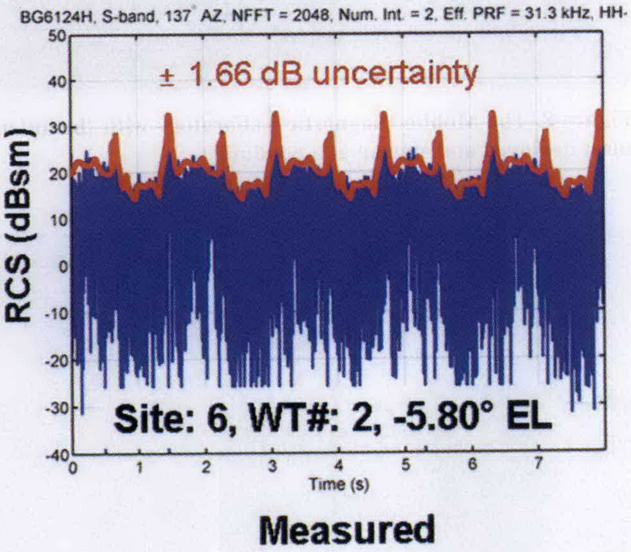


Figure 12a. The measured RCS of the GE windmill (137° yaw, –5° elevation, 3.6 GHz, 12.7 rpm, HH polarization).

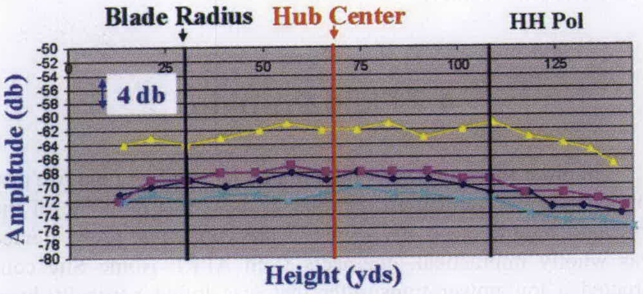


Figure 9. The Site 2 relative 1 way field probe (yellow: L band, cyan: S band, light blue: X band, dark blue: C band).

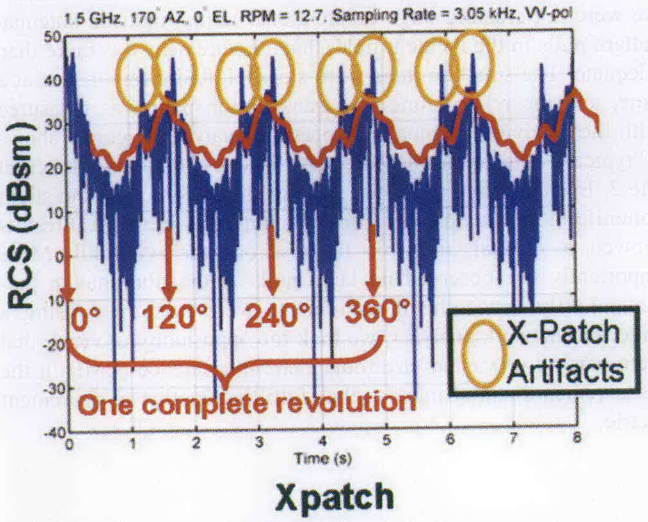


Figure 11b. The predicted RCS of the GE windmill (170° yaw, 0° elevation, 1.5 GHz, 12.7 rpm, VV polarization).

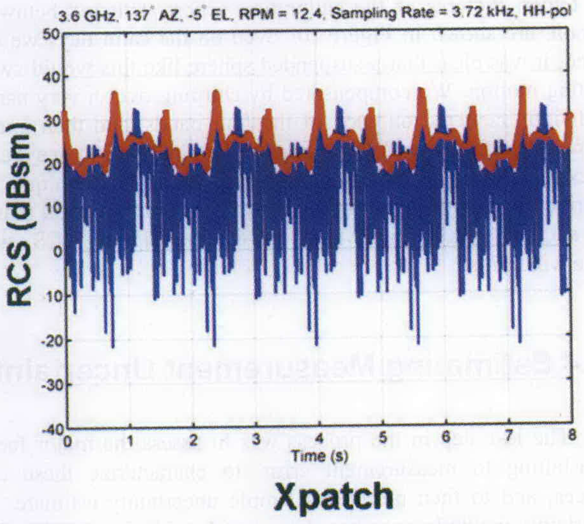


Figure 12b. The predicted RCS of the GE windmill (137° yaw, –5°elevation, 3.6 GHz, 12.7 rpm, HH polarization).

Figure 8 shows the Mobile Diagnostic Laboratory mast deployed to its nominal 6.1 m target height The antenna was aimed at the hub of the windmills by adjusting the mast azimuth with a "periscope" mount, and in elevation by using a pan/tilt slaved camera mount under computer control.

4.2 Field Probing

In order to estimate the variation in the incident field, we performed a crude vertical field probe in the principle plane of the antenna/windmill geometry. Since a precision field-probe device was wholly impractical, engineers from AFRL Rome Site constructed a low-power transmitter that was lofted vertically by a tethered helium balloon. We used a spectrum analyzer to act as a one-way receiver. Since the windmill owners were very concerned about the balloon tether being lofted in the vicinity of the windmill, we were asked to set up our field probes some distance in front of the windmills. Since the purpose of the field probe was to assure we were not creating large unintentional terrain-induced antenna-pattern nulls in the incident field, this measurement was more than adequate. The small emitters were slowly lofted a few inches at a time, and the relative one-way transmission path was measured with the receiving antenna and spectrum analyzer. Figure 9 shows a "typical" field probe measurement for one polarization taken at site 2. Even accounting for the sway of the balloon, and the slight nonuniform antenna pattern from the emitters, these typical results showed a gradual, null-free taper across the windmill. More importantly, we observed no large nulls in the illumination patterns. Lastly, since the measurements were performed using a wideband network analyzer, we took the opportunity to verify that there was no unwanted electromagnetic interference (EMI) in the measurement band of interest, thus fulfilling another measurement metric.

4.3 Calibration

Another important factor in the windmill measurement was radar calibration. Once again, given the restrictions of working in an operational windmill environment, we decided to calibrate by lofting a precision sphere with another, smaller, helium balloon and tether. Pictures of the calibration sphere, tethered below the balloon, are shown in Figure 10. Even on the calm days we calibrated, it was clear that a suspended sphere like this would swing, creating motion. We compensated by chirping over a very narrow bandwidth, centered on each of the four bands, and then imaged and removed the sphere's swinging motion. In doing so, we created an extremely stable calibration object. The full technique was described in a 2006 AMTA paper [5]. The results created reasonable and stable calibration values for use in assigning RCS values to the windmills.

4.4 Estimating Measurement Uncertainty

The last step in the process was to assess the major factors contributing to measurement error, to characterize these error sources, and to then produce a simple uncertainty estimate. The uncertainty methods were based on ANSI-Z-540 [6], NISTR 5019 [7], and summarized by Welsh et al. [8]. Using this methodology, we produced an estimate of the overall measurement uncertainty in the field, which is shown in Table 3. The uncertainty analysis captured the major error terms, and produced a decent fidelity estimate. The analysis included calibration uncertainty, variation in incident field, uncertainty of position of the windmill location relative to the radar, uncertainty of the calibration object relative to the radar, the theoretical uncertainty in sphere RCS based on mechanical tolerances, and signal-to-noise ratios at the various ranges. The next section will discuss a comparison of the predicted and measured RCS of a few of the cases we examined.

5. Theoretical and Measurement Comparisons

Given the sheer size of the windmills, we needed to examine the 409 valid measurement files to correlate a few measurements

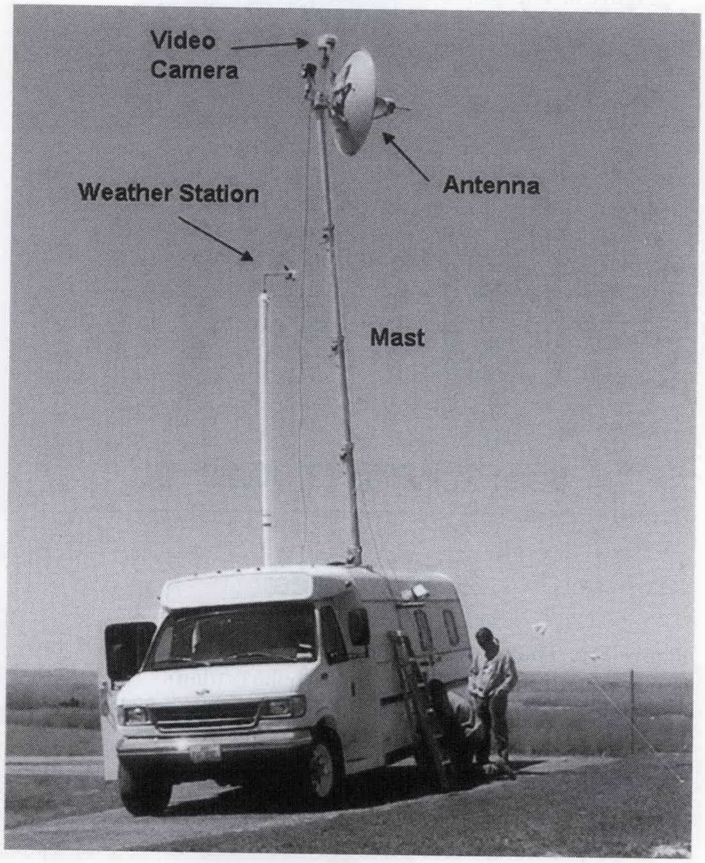


Figure 8. The Mobile Diagnostic Laboratory with the antenna mast deployed and staring at a windmill.

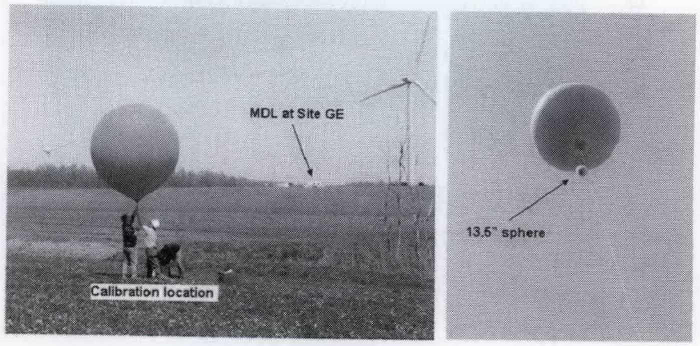
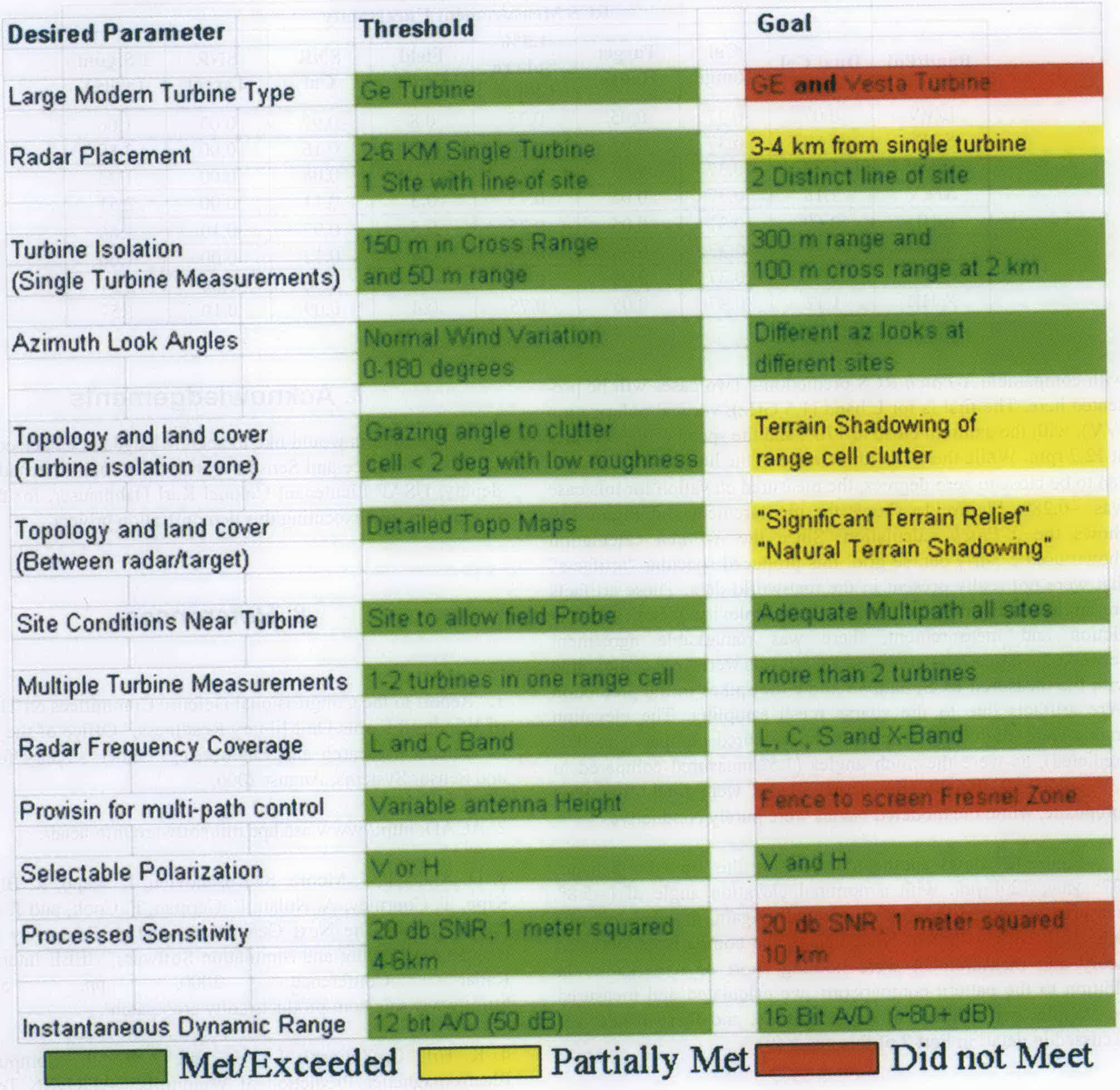


Figure 10. (l) The calibration balloon prior to launch and (r) a lofted balloon with the 14 in sphere.

Table 2. The RCS/Doppler measurement requirements.



Desired Parameter	Threshold	Goal
Large Modern Turbine Type	🟩 Ge Turbine	🟥 GE **and** Vesta Turbine
Radar Placement	🟩 2-6 KM Single Turbine 1 Site with line-of site	🟨 3-4 km from single turbine 🟩 2 Distinct line of site
Turbine Isolation (Single Turbine Measurements)	🟩 150 m in Cross Range and 50 m range	🟩 300 m range and 100 m cross range at 2 km
Azimuth Look Angles	🟩 Normal Wind Variation 0-180 degrees	🟩 Different az looks at different sites
Topology and land cover (Turbine isolation zone)	🟩 Grazing angle to clutter cell < 2 deg with low roughness	🟨 Terrain Shadowing of range cell clutter
Topology and land cover (Between radar/target)	🟩 Detailed Topo Maps	🟨 "Significant Terrain Relief" "Natural Terrain Shadowing"
Site Conditions Near Turbine	🟩 Site to allow field Probe	🟩 Adequate Multipath all sites
Multiple Turbine Measurements	🟩 1-2 turbines in one range cell	🟩 more than 2 turbines
Radar Frequency Coverage	🟩 L and C Band	🟩 L, C, S and X-Band
Provisin for multi-path control	🟩 Variable antenna Height	🟥 Fence to screen Fresnel Zone
Selectable Polarization	🟩 V or H	🟩 V and H
Processed Sensitivity	🟩 20 db SNR, 1 meter squared 4-6km	🟥 20 db SNR, 1 meter squared 10 km
Instantaneous Dynamic Range	🟩 12 bit A/D (50 dB)	🟩 16 Bit A/D (~80+ dB)

🟩 Met/Exceeded 🟨 Partially Met 🟥 Did not Meet

Table 3. An RSS assessment of measurement uncertainty.

	RCS Measurement Uncertainty							
Band/Pol	**Dual Cal**	**Cal Range**	**Target Range**	**1.5% Sphere Ellipse**	**Field Taper**	**SNR Cal**	**SNR Target**	**1 Sigma (±dB)**
L/VV	0.07	0.37	0.05	0.75	0.8	0.97	0.03	1.66
S/VV	2.57	0.37	0.05	0.75	0.25	0.16	0.00	2.89
C/VV	1.33	0.37	0.05	0.75	0.35	0.08	0.00	1.73
X/VV	2.18	0.37	0.05	0.75	0.3	0.11	0.00	2.51
L/HH	0.60	0.37	0.05	0.75	0.5	0.97	0.10	1.66
S/HH	1.12	0.37	0.05	0.75	0.6	0.12	0.00	1.66
C/HH	1.87	0.37	0.05	0.75	0.7	0.06	0.00	2.37
X/HH	1.12	0.37	0.05	0.75	0.4	0.09	0.10	1.57

with comparable *X-Patch* RCS predictions. Two cases will be presented here. The first is for L band (1.5 GHz), vertical polarization (VV), with the azimuth close to 170°, and the speed of the turbines at 12.7 rpm. While the elevation relative to the hub center was chosen to be close to zero degrees, the measured elevation for this case was −0.28°. Figure 11a shows the measurement and Figure 11b shows the *X-Patch* calculation. Since the *X-Patch* calculation shown used a fairly course grid, this produced specular "artifacts" that were not really present in the real-world data. These artifacts are circled in Figure 11b. Despite the complexity of both the prediction and measurement, there was remarkable agreement between the cases. The predicted RCS levels were very comparable with the measured RCS, and we know the spikes in the prediction were artifacts due to the coarse mesh sampling. The elevation angles were slightly different (0.28° measured compared to 0.0° predicted), as were the pitch angles (1.5° measured compared to 0.0° predicted). Finally, the actual blades were thick fiberglass composite, while the modeled blades were purely conductive.

Figure 12 shows another comparison, this time for S band, 137° yaw, 12.4 rpm, with a nominal elevation angle of (−5.8° measured compared to −5.0° predicted). Again, the *X-Patch* artifacts were clearly shown. Nonetheless, the comparisons between theory and measurement were nothing short of remarkable. In addition to the pattern comparisons, we calculated and measured the Doppler performance of the windmills, and these results are discussed in detail in Part 2 of this paper [9].

6. Summary

This paper explored the ability to theoretically model the RCS performance of a large commercial-windmill electric generator. In addition, we described a measurement campaign that captured RCS measurements of actual windmills under field conditions. These measurements required many measurement innovations, and the accuracy of the data were estimated by an uncertainty analysis. In the end, the measurements and predictions were incredibly consistent, and gave us confidence that the modeling and measurement work accurately captured the real-world radar-scattering characteristics of these large windmill generators. While this paper was limited to a few cases, additional data exist that cover a wide range of turbine-viewing yaw angles, as well as different frequencies and polarizations from L, S, C, and X bands.

7. Acknowledgements

The authors would like to acknowledge the Undersecretary of Defense for Space and Sensors System, Dr. John Stubstad, and his deputy, USAF Lieutenant Colonel Karl Dahlhauser, for their help in planning and executing this demonstration project.

8. References

1. "Report to the Congressional Defense Committees on The Effect of Windmill Farms On Military Readiness," Office of the Director of Defense Research and Engineering, Undersecretary for Space and Sensor Systems, August 2006.

2. ACAD: http://www.asc.hpc.mil/software/info/acad/.

3. D. Andersh, J. Moore, S. Kosanovich, R. Kapp, R. Bhalla, R. Kipp, T. Courtney, A. Nolan, F. German, F. Cook, and J. Hughes, "XPATCH 4: The Next Generation in High Frequency Electromagnetic Modeling and Simulation Software," IEEE International Radar Conference 2000, pp. 844-849; http://www.saic.com/products/software/xpatch/.

4. K. Hill, G. Zelinski, T. Van, and C. Vogel, "Computational Electromagnetics Prediction of Windmills," AFRL/SN Technical Report CEM-0701, July 2007.

5. Brian M. Kent, Alan Buterbaugh, Thomas Coveyou, Robert Hawley, and Byron M. Welsh, "The RCS Calibration Uncertainty of Balloon Tethered Spheres," Antenna Measurement Technique Symposium, Austin, TX, October 2004, pp. 302-306.

6. B. M. Kent, T. Hestilow, and B. Melson, "ANSI Z-540/ISO25 Certification of the AFRL and Atlantic Test Range RCS Measurement Facilities – Range and Reviewers Perspectives, Part 1," Antenna Measurement Techniques Associations, Philadelphia, PA, October 2000.

7. R. C. Wittman, M. H. Francis, L. A. Muth, and R. R. Lewis, "Proposed RCS Uncertainty Analysis for RCS Measurements," NISTR 5019, National Institute of Standards and Technology, January 1994.

8. Byron Welsh, William Muller, William Forster, Brian M. Kent, and Dan Turner, "Update on the Air Force Research Laboratory Advanced Compact Range Calibration Uncertainty Analysis," Antenna Measurement Techniques Symposium, October 2003, Irvine CA, pp. 3-8.

9. B. M. Kent, A. Buterbaugh, K. C. Hill, G. Zelinski, R. Hawley, L. Cravens, T. Van, C. Vogel, and T. Coveyou, "Dynamic Radar Cross Section and Radar Doppler Measurements of Commercial General Electric Windmill Power Turbines Part 2 – Predicted and Measured Doppler Signatures," AMTA 2007 Symposium, St. Louis, MO.