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**Project Title:** Development of a High-Resolution Virtual Wind Simulator for Optimal Design of Wind Energy Projects

**Contract Number:** RD3-42 **Milestone Number:** 4 **Report Date:** 04/01/11

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**Congressional District:** (Corporate office) Minnesota 5th

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# MILESTONE REPORT

## Executive Summary:

This project aims at developing a '*Virtual Wind Simulator*' (VWS) for the prediction of atmospheric boundary layer flow and its interactions with wind turbines and wind farms. The use of the simulator will assist in the improved design of potential wind energy projects by providing more accurate predictions of local and wind turbulence at site and turbine levels. Additionally, the VWS will help increase the level of wind energy utilization and reduce the cost of energy production.

Computational Fluid Dynamics (CFD) methods are used in this project to develop a computational framework for conducting high-resolution simulations of wind turbulence at the meso and micro scales. In particular, the Large-Eddy Simulation (LES) technique will allow for accurate simulations of the turbulent flow at spatial resolutions as small as one to ten meters, and temporal resolutions of just a few seconds. Parameterizations for wind turbine forces will also be developed in the LES framework. In addition, three-dimensional, time-evolving flow fields obtained from LES at any location within a potential wind farm site could then be used as the inflow condition for even more detailed simulations of the turbulent flow around the blades of specific wind turbines using a hybrid Reynolds-Averaged Navier-Stokes (RANS)/LES technique. The SAFL computational models will be coupled to macro-scale regional models to develop a powerful multi-scale computational tool, the VWS. The VWS will integrate the latest advancements in computational fluid dynamics research and provide reliable, high-resolution descriptions of wind turbulence across the entire range of scales that are relevant to wind power production. This information will provide objective, scientifically based criteria that can be used by wind energy project developers for the site-specific, optimal selection and placement (micro-siting) of wind turbines.

As planned, during this reporting period (quarter) activities have been carried out that address the following objectives:

*(a)* Development of a multi-scale computational fluid dynamics (CFD) framework for accurate simulation of high-resolution wind and turbulence fields and their effects on wind turbine operation and energy output.

*(b)* Validation of the proposed *Virtual Wind Simulator* using high-resolution wind and turbulence measurements collected in an atmospheric boundary layer wind tunnel. Specifically, wind farm performance under different layouts is under study. Fundamental physics is being extracted from both CFD and experiments.

*Project funding provided by customers of Xcel Energy through a grant from the Renewable Development Fund.*

**Technical Progress:**

We have made substantial progress in Task 1, Task 2 and Task 4. The progress made in the three tasks is discussed below.

## Task 1. Development of the *Virtual Wind Simulator* for high-resolution simulations of wind, turbulence and their effect on energy production

Progress has continued on the development and testing of the Virtual Wind Simulator. Our current efforts are focused on the wind farm performance under different layouts. An actuator disk model is implemented in the CURVIB code for wind farm simulation.

In actuator disk model, the rotor is represented by uniformly distributed body forces on a disk. Hence, the Navier-Stokes equation with a body force for rotor model reads as,

$$\frac{\partial u_i}{\partial t} + \frac{\partial u_i u_j}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left((\nu + \nu_t)\frac{\partial u_i}{\partial x_j}\right) + f_i.$$

The total force of acting on the flow from a wind turbine in the streamwise direction is calculated using the following expression

$$F_t = -\frac{1}{2}\rho C_T'(U_d)^2\frac{\pi}{4}d^2$$

where $C_T' = \frac{C_T}{(1-a)^2}$ , $U_d = (1-a)U_\infty$ is the velocity on the disc, and $d$ is the diameter of the disk. The $a$ is the axial induction factor and $C_T = 4a(1-a)$ which is from the one-dimensional momentum theory. In general the disk grids don't coincide with background grids. Discrete delta functions are used to transfer quantities between the disk grids ($g_t$) and background grids ($g_b$) as shown below

$$U_d(X) = \sum_{x \in g_b} u\delta_h(x - X)V(x).$$

$$f_t(x) = \sum_{X \in g_t} F_t \delta_h(x - X) A(X)$$

where $\delta_h(x - X)$ is the discrete delta function, $V(x)$ is the volume of background grid and $A(X)$ is the area of the disk surface grid. The discrete delta function used in the present work can guarantee the total force and total torque applied on the background grids are the same as that on the disk.

Both aligned wind farm and staggered wind farm are simulated using the CURVIB method with actuator disk model. 16 turbines are used in the present simulation. The layouts of the turbines are show as in Fig. 1. Periodic boundary conditions are used in streamwise (x) and spanwise (y) directions. Slip boundary condition is used at the top and wall model is used at the bottom wall. The Reynolds number based on the bulk velocity and the diameter of the disk is 36000, which is nearly the same as that of the wind tunnel experiments. The axial induction factor $a$ equals 0.07 which is estimated from the experiment. Fig. 2 shows the mean velocity profiles. It can be seen that the velocity in the wind turbine region is lower in staggered wind farm than that in the aligned wind farm. Fig. 3 shows the extracted power density from aligned wind farm and staggered wind farm. The extracted power density is defined as $P_k = \left( \frac{P}{\rho S_x S_y} \right)_k$, where $S_x = 5d, S_y = 4d$ are the spaces of wind farm in streamwise and spanwise directions respectively. Comparing the time-averaged extracted power density, we can see that the staggered wind farm is more efficient than aligned wind farm. Fig. 4 shows the turbulence intensity of the streamwise velocity components. Both of the figures show that the turbulence exists in the top regions of the wind turbines for this induction factor. By comparison, we can see that the staggered wind farm generates less turbulence than that from aligned wind farm. Fig. 5 shows the contour of the instantaneous streamwise velocity. We can see that there are high speed streaks in the aligned wind farm, which means the wind energy is not effectively exacted by the aligned wind turbines. And it may be also one of the reasons for the large turbulence intensities in the aligned wind farm. For staggered wind farm, we also can see the high speed spots, but they are very small. In all, this study shows that staggered wind farm can extract more energy from the wind and has lower turbulence intensity at the same time; and the numerical results agree well with the experiments results.

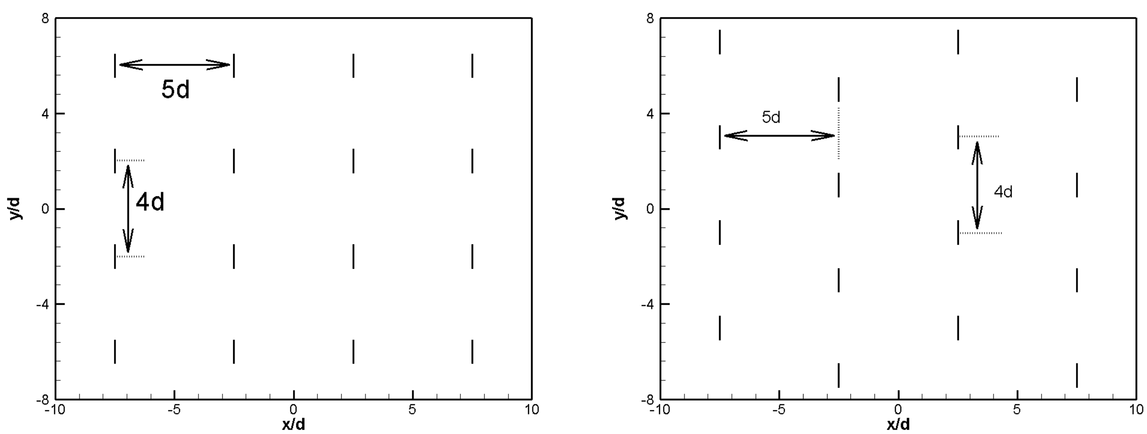


**Fig. 1.** Layouts for the aligned wind farm (left) and staggered wind farm (right).

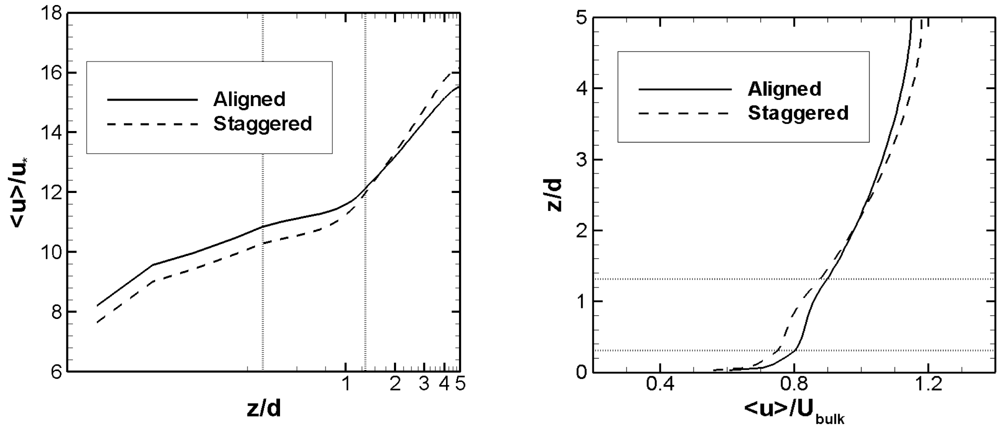


**Fig. 2**. Mean velocity profiles. Left: normalized by the total friction velocity (considering both frictions from the wind turbines and the wall); Right: normalized by the bulk velocity.

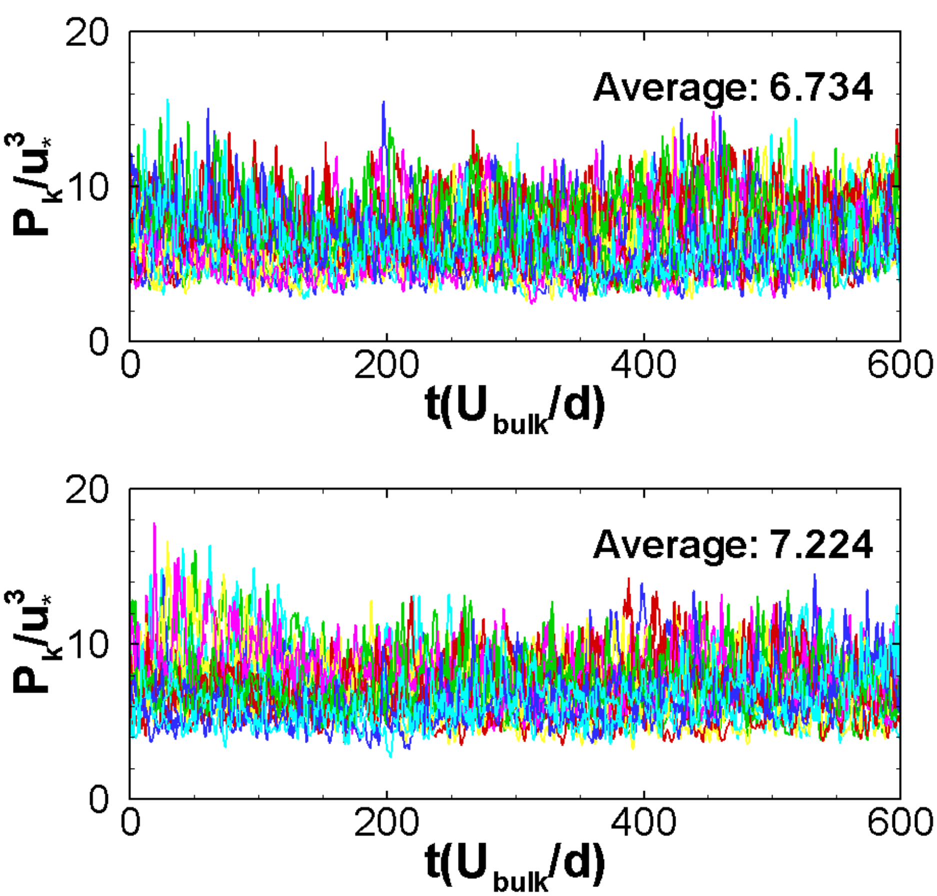


**Fig. 3.** Extracted power density. Upper: aligned wind farm; Lower: staggered wind farm.

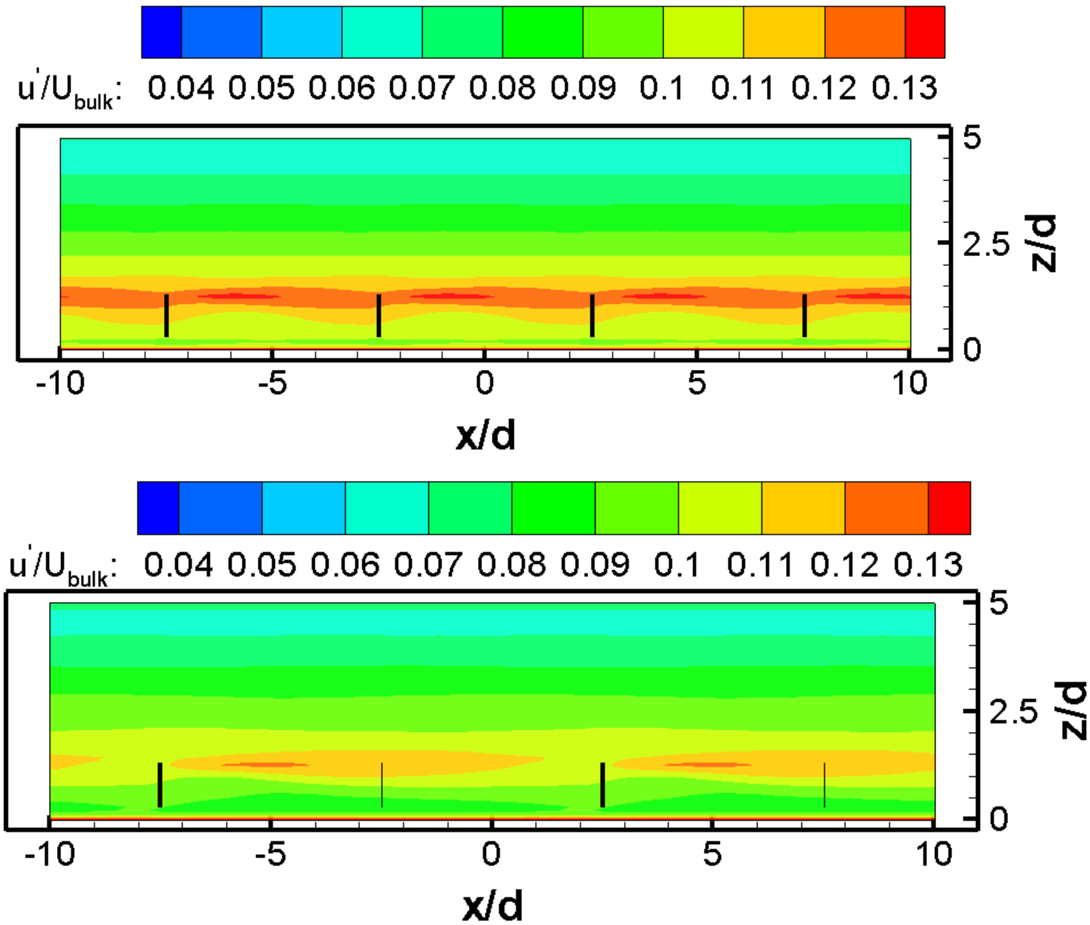


**Fig. 4.** Turbulence intensity. Upper: aligned wind farm; Lower: staggered wind farm.

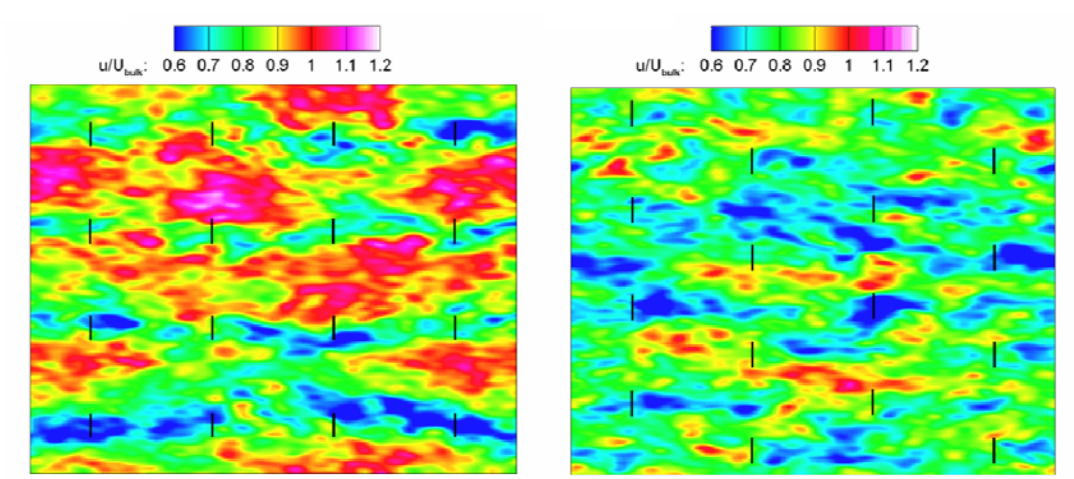


**Fig. 5.** Contour of the instantaneous streamwise velocity. Left: aligned wind farm; Right: staggered wind farm.

**Task 2. Validation of the *Virtual Wind Simulator* using wind tunnel measurements**

## Wind tunnel experiments

Progress has continued on the fundamental understanding of the turbulent flow properties around wind turbines. In particular, wind tunnel experiment has been performed to quantify the Reynolds number dependence of turbulence statistics in the wake of a model wind turbine. A wind turbine was placed in a boundary layer flow developed over a smooth surface under thermally neutral conditions. Experiments considered Reynolds numbers, based on the turbine rotor diameter and the velocity at hub height, ranging from $Re = 1.66\times10^4$ to $1.73\times10^5$. Results suggest that main flow statistics (mean velocity, turbulence intensity, kinematic shear stress and velocity skewness) become independent of Reynolds number starting from $Re \approx 9.3\times10^4$. In general, stronger Reynolds number dependence was observed in the near wake region where the flow is strongly affected by the aerodynamics of the wind turbine blades. In contrast, in the far wake region, where the boundary layer flow starts to modulate the dynamics of the wake, main statistics showed weak Reynolds dependence.

These results will allow us to extrapolate wind tunnel and CFD simulations, which often are conducted at lower Reynolds numbers, to full scale conditions. In particular, these findings motivate us to improve existing parameterizations for wind turbine wakes (e.g., velocity deficit, wake expansion, turbulence intensity) under neutral conditions and the predictive capabilities of atmospheric LES models.

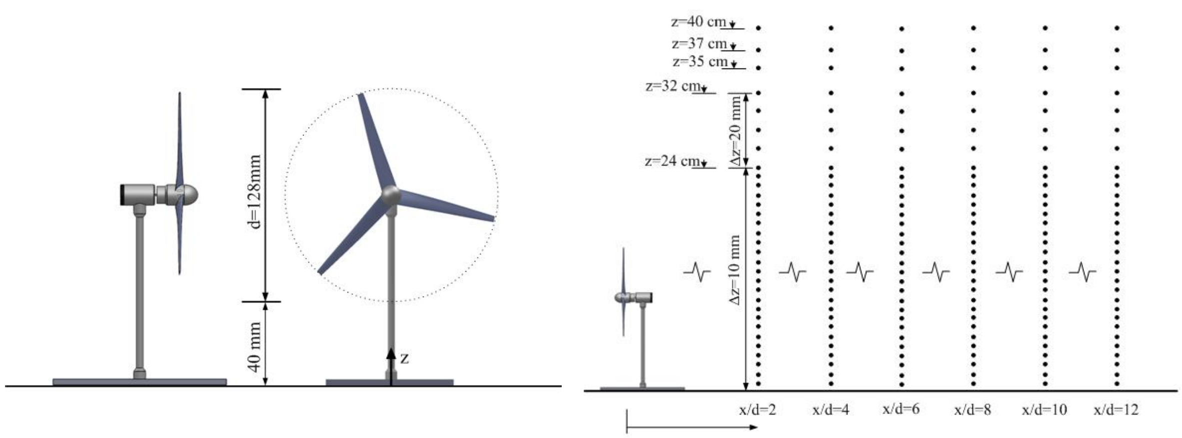


**Fig. 6**. Experimental set-up. Left: front and top views of the miniature wind turbine, right: measurement locations.

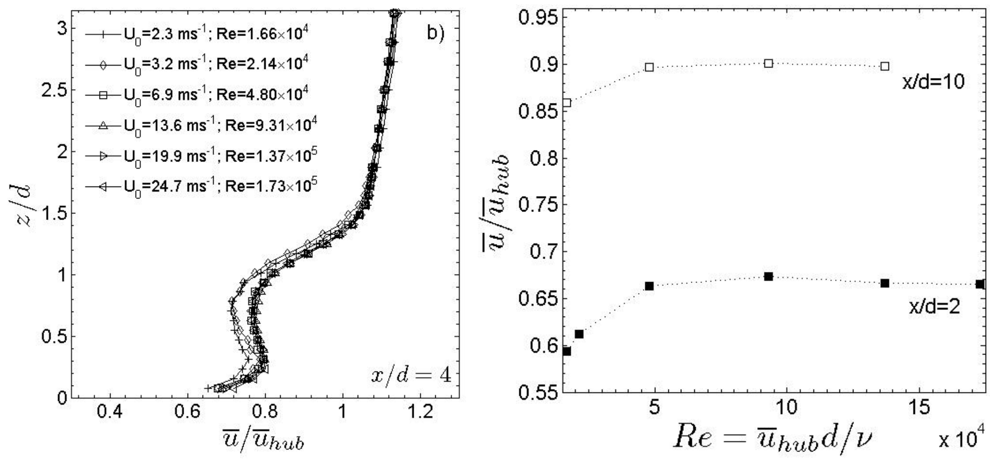


**Fig. 7**. Left: normalized velocity distribution at x/d=4; right: Normalized velocity two rotor diameters downwind of the wind turbine at hub height for different Reynolds numbers.

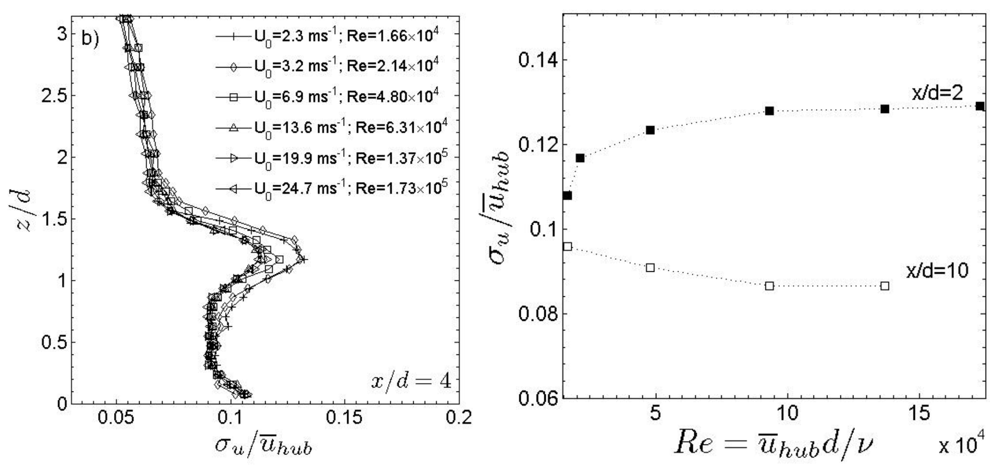


**Fig. 8**. Left: Turbulence intensity distribution at x/d=4; right: Turbulence intensity two rotor diameters downwind of the wind turbine at hub height for different Reynolds numbers.

**Task 4. Virtual wind simulator Application (Wind Assessment at Undeveloped Site with Complex Terrain)**

## Field experiments

Field measurements are under way to obtain data to validate the computational models in a real-life wind farm. The measurements are carried out in collaboration with our partners from WindLogics, Inc. and Barr Engineering. During the past three months, WindLogics have been collecting measurements from the sodar atop the bluff near Prairie Island. The sodar was deployed to the site in late December and has been operating since then.

On December 27, 2010, one Triton SODAR, owned by WindLogics Inc., was deployed at the Prairie Island bluff location just east of County Road 18 on the Minnesota side of the Mississippi River. Mariah Resources was contracted for the deployment, and Mariah worked with the Prairie Island Community to plow snow and prepare the site prior to the SODAR deployment. The SODAR has been collecting data at the bluff site since that time. As of April 11, 2011, there have been 105 days of data collection. The SODAR provides a bluff top measurement of wind that will complement the valley level measurements from the ASC SODAR (owned by Barr Engineering) that was deployed near the Prairie Island Casino at an earlier date. Additionally, Barr Engineering has a meteorological tower near their SODAR at the casino.

When data collection is complete, WindLogics will work with Barr Engineering and the University of Minnesota to identify particular cases to study for high resolution modeling work. A summary of the data collected so far is included in Figs. 9 and 10.

These activities fall under Task 4, subtask 4.1 in the original proposal.

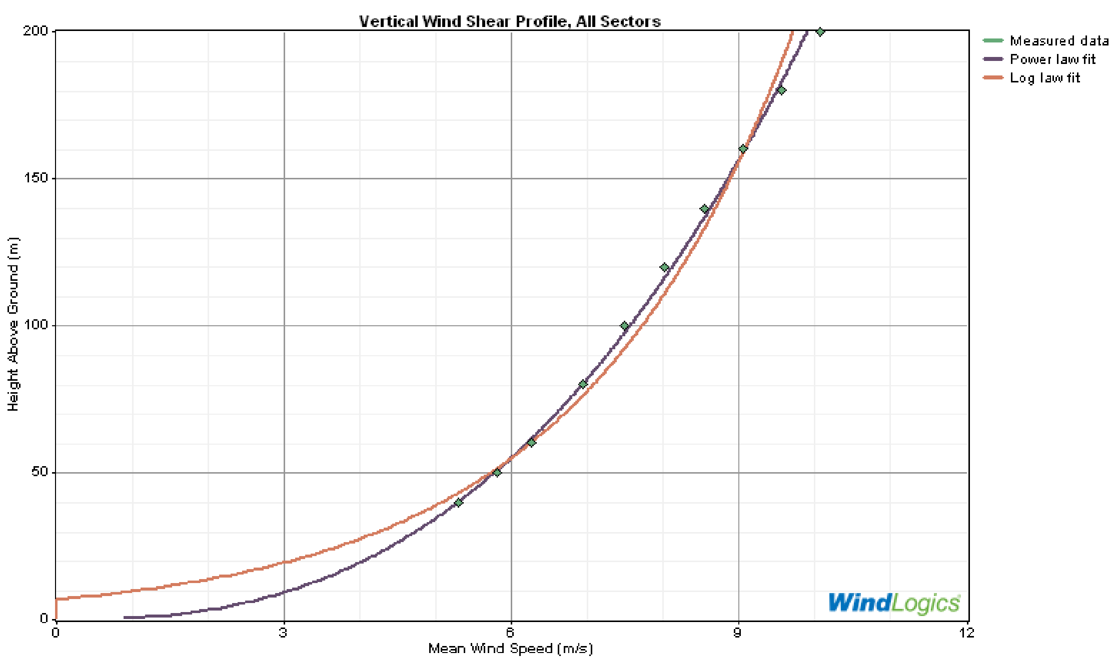


**Fig. 9.** Wind profile analysis for the SODAR data collected from the Prairie Island bluff site.

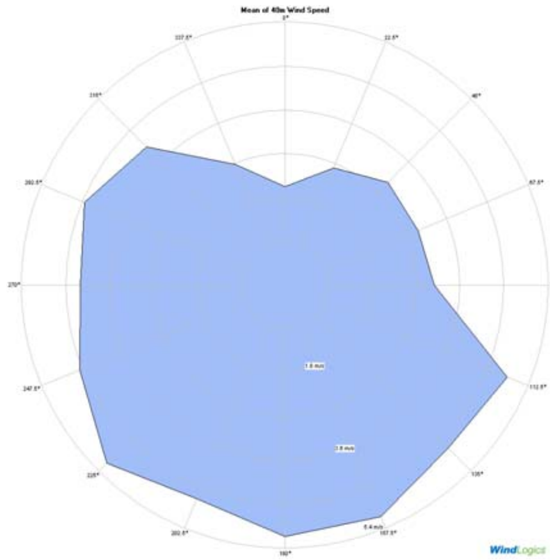


**Fig. 10.** Wind rose at 40 meters above ground level for the SODAR data collected from the Prairie Island bluff site.

Throughout the fourth quarter 2010, and first quarter 2011 Barr continued to monitor and QA/QC data from equipment deployed at the “complex terrain” site at Prairie Island, near Red Wing, Minnesota. The equipment is deployed on property owned by the Prairie Island Indian Community, at sites selected in cooperation with the PI Indian Community.

These data were collected throughout the quarter from the following equipment:

- Conventional anemometry installed on the 50-meter meteorological tower located at a site near the Prairie Island Casino;
- An ASC Sodar unit that is deployed next to the meteorological tower; and
- A WindLogics Triton Sodar unit located at a site on the Mississippi River bluff. (This site is also owned by the Prairie Island Indian Community.) Barr deployed the Triton Sodar unit at the bluff site in December, 2010, but WindLogics is collecting and analyzing these data.

In December, 2010, Barr also installed CSAT3 sonic anemometers on the meteorological tower near the Casino at Prairie Island. Data collection from these CSAT3 anemometers is expected to begin next quarter in conjunction with other data collected at the site.

**Additional Milestones:**

Work is in progress towards Milestone 5.

**Project Status:**

The project is ahead of schedule due to the fact that work on the project started before the contract was finalized.

**Appendix:**
**List publications**

**Papers in Refereed Journals**

1. Chamorro, L.P., Arndt, REA and Sotiropoulos F. 'Turbulent flow properties around a staggered wind farm'. *Boundary- Layer Meteorology*. *Under Review.*
2. Chamorro, L.P., Arndt, REA and Sotiropoulos F. 'Reynolds number dependence of turbulence statistics in the wake of wind turbines'. *Wind Energy*. *Under Review.*
3. Chamorro, L.P., Arndt, REA and Sotiropoulos F. 'Non-uniform velocity distribution e ect on the Betz limit' *to be submitted (Wind Energy)*
4. Chamorro, L.P., and F. Porté-Agel, 2010. 'Thermal stability and boundary-layer effects on wind turbine wakes. A wind tunnel study'. *Boundary-Layer Meteorology*, 136: 489-513.
5. Lu, H., and F. Porté-Agel, 2010. 'A modulated subgrid-scale model for large-eddy simulation: Application to a neutral atmospheric boundary layer'. *Physics of Fluids*, 22(1):015109.
6. Wu, Y.-T., and F. Porté-Agel, 2011. 'Large-eddy simulation of wind-turbine wakes: Evaluation of turbine parameterizations'. *Boundary-Layer Meteorology*, 138:345–366.
7. Chamorro, L.P., and F. Porté-Agel, 2009. 'A wind tunnel investigation of wind turbines wakes: Boundary-layer turbulence and surface roughness effects'. *Boundary-Layer Meteorology*, 132: 129-149.

**Conference Presentations**

1. Chamorro, L.P., R.E.A. Arndt and F. Sotiropoulos, 2011. 'Turbulence patterns around a large wind farm. 49th AIAA Aerospace Sciences Meeting, Orlando, Florida.
2. Chamorro, L.P., R.E.A. Arndt and F. Sotiropoulos, 2010. 'Turbulence characteristics around a staggered wind farm configuration. A wind tunnel study'. American Physical Society Meeting. Minneapolis, Long Beach, CA.
3. Porté-Agel, F., Y.-T. Wu, and H. Lu, 2009. 'Large-eddy simulation of wind-turbine wakes'. American Physical Society Meeting. Minneapolis, MN.
4. Chamorro, L.P., and F. Porté-Agel, 2009. 'A wind tunnel investigation of wind turbine wakes'. American Physical Society Meeting. Minneapolis, MN.
5. Porté-Agel, F., F. Sotiropoulos, R. Conzemius, L. Chamorro, Y.-T. Wu, S. Behara, H. Lu, 2009. 'Development of a high-resolution Virtual Wind Simulator for optimal design of wind energy projects'. E3 -Energy, Economic and Environmental- Conference. Minneapolis, MN.
6 Porté-Agel, F., Y.-T. Wu, Y.-T.., H. Lu, 2009. 'Parameterization of turbulent fluxes and wind-turbine forces in large-eddy simulation'. European Geophysical Union. Vienna.
7. Chamorro, L.P., and F. Porté-Agel, 2009. 'A wind tunnel investigation of wind turbine wakes: Boundary-layer turbulence and surface roughness effects'. European Geophysical Union. Vienna.
8. Wu, Y.-T.., H. Lu, and F. Porté-Agel, 2008. 'Large-eddy simulation of wind-turbine wakes'. American Geophysical Union. San Francisco, CA.
9. Chamorro, L.P., and F. Porté-Agel, 2008. 'A wind tunnel investigation of wind turbine wakes: Boundary-layer turbulence and surface roughness effects'. American Geophysical Union. San Francisco, CA.
10. Porté-Agel, F., F. Sotiropoulos, R. Conzemius, L. Chamorro, Y.-T. Wu, S. Behara, H. Lu, 2008. 'Development of a high-resolution Virtual Wind Simulator for optimal design of wind energy projects'. E3 -Energy, Economic and Environmental- Conference. Minneapolis, MN.