Utilizing Radar Measured Velocity Fields to Forecast Turbine Wind Speeds

James B. Duncan Jr.[1], Brian D., Hirth[1], John L. Schroeder[2]

[1]*National Wind Institute, Texas Tech University, Lubbock, TX, USA*
[2]*Department of Geosciences, Texas Tech University, Lubbock, TX, USA*

Wind turbines almost exclusively operate in a reactive state. In most cases, a parcel of air may entirely pass through the rotor sweep before the turbine's control system even attempts to adapt. Given a wind turbine typically has no knowledge of the upstream flow conditions, a snapshot of the approaching wind field could provide for improved turbine performance through a reduction of structural loads and increased energy capture. Although information of the near-upstream flow conditions has been examined through the use of nacelle mounted LIDAR (Light detection and ranging) systems (e.g. Bossanyi et al. 2014; Mikkelsen et al. 2013; Schlipf et al. 2011), employing three-dimensional wind field maps derived from scanning instruments to provide an extended wind speed forecast for individual turbine locations has never been investigated.

Utilizing Texas Tech University's Ka-band Doppler radar systems, researchers have demonstrated the ability to derive three-dimensional wind field maps of the complex flows and wake structures surrounding an individual turbine (Hirth and Schroeder 2013) as well as within wind plants (Hirth et al. 2015). While only the radial component of the wind may be derived from a single radar (or LIDAR) system, a dual-Doppler scanning strategy allows for the extraction of the full horizontal velocity vector and construction of horizontal wind field map as shown in Figure 1.

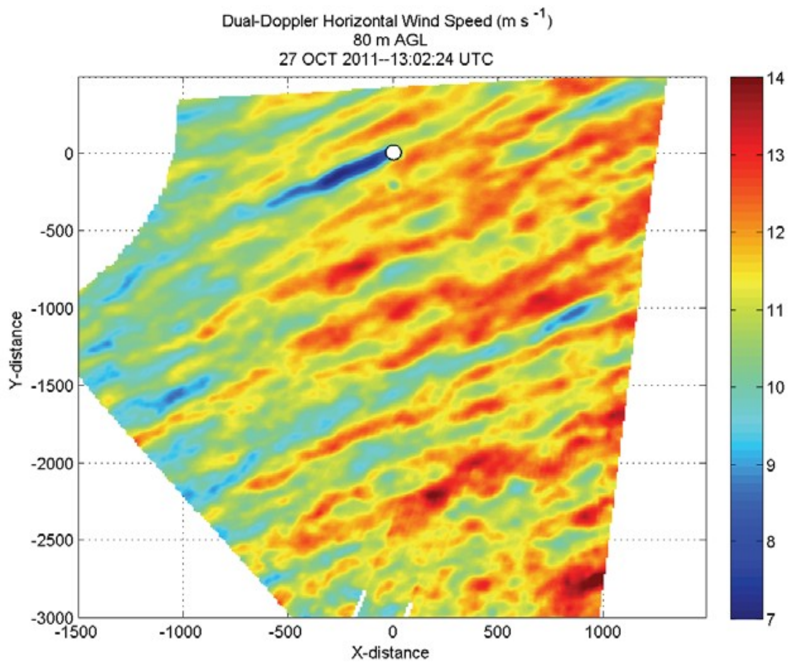

Figure 1. Dual-Doppler horizontal wind speed (m/s) synthesis at 80 m AGL for a single volume ending at 13:02:24 UTC on 27 October 2011.

Whereas nacelle mounted LIDAR systems predominantly sample wind speeds in the near-upstream region of the turbine, radars have the ability to provide wind speed and direction measurements over a much larger domain with the temporal resolution necessary to resolve and track wind features relevant to wind turbine controls. The acquired information allows for the attempted prediction of turbine inflow wind speed and direction one minute or more in advance. The acquired measurements adjacent to a farm also provide an opportunity to identify and track regional scaled weather phenomena (e.g. fronts, outflow boundaries, etc.) before they arrive onsite.

The data used for this investigation were collected surrounding a single utility scale turbine on 27 October 2011. Details of the deployment, radar scanning strategies employed and analysis domain used can be found in Hirth and Schroeder (2013). Dual-Doppler volumes over a three dimensional grid with 10-m horizontal and vertical grid spacing were constructed approximately every 45 s. In order to forecast wind speeds to the turbine's position, the following methods were applied. Given a radar volume, a governing wind direction was calculated at 1D upstream of the turbine. This governing wind direction was an average of the wind directions across the rotor swept area and was calculated at 1D upstream to mitigate the effects of ground clutter associated with the turbine rotor on the adjacent wind field. Conventional wisdom might lead one to use this governing wind direction to project the upstream flow field from the turbine's location to obtain a preview of the incoming wind. However, in order to minimize the error in forecasted wind speed estimates, this wind direction alone cannot be the only consideration.

Organized coherent structures are embedded within the turbulent flow-fields of the atmospheric boundary layer. One structure type, referred to as near-surface streaks, are elongated areas of enhanced/reduced wind speeds (Traumner et al. 2015), and have been shown using full-scale radar measurements to be skewed to the left of the wind direction (e.g. Lorsolo et al. 2008; Marathe 2014). While generally aligned with the prevailing wind direction, these streak features do not passively advect with the mean flow field. To examine the variation between projected and actual streak motion, a four-minute period of wind speed data was analyzed. Beginning with an initial radar volume scan, two streak features of enhanced wind speed were isolated. To derive the projected advection, an area average wind direction and speed representative of the features were calculated. Using this vector and the amount of time until the completion of the volume scan, a forecasted position of the feature was generated. For this initial work, the advection of the features was based upon visual inspection of the wind field map at the end of each volume. Shown in Figure 2, the true advection of the feature lagged the forecasted position and was several degrees to the left of the projected advection according to the governing wind speed and direction from the prior volume scan. For this four-minute span, variation in advection ranged from 2.6° - 8.3° to the left of projected motion.

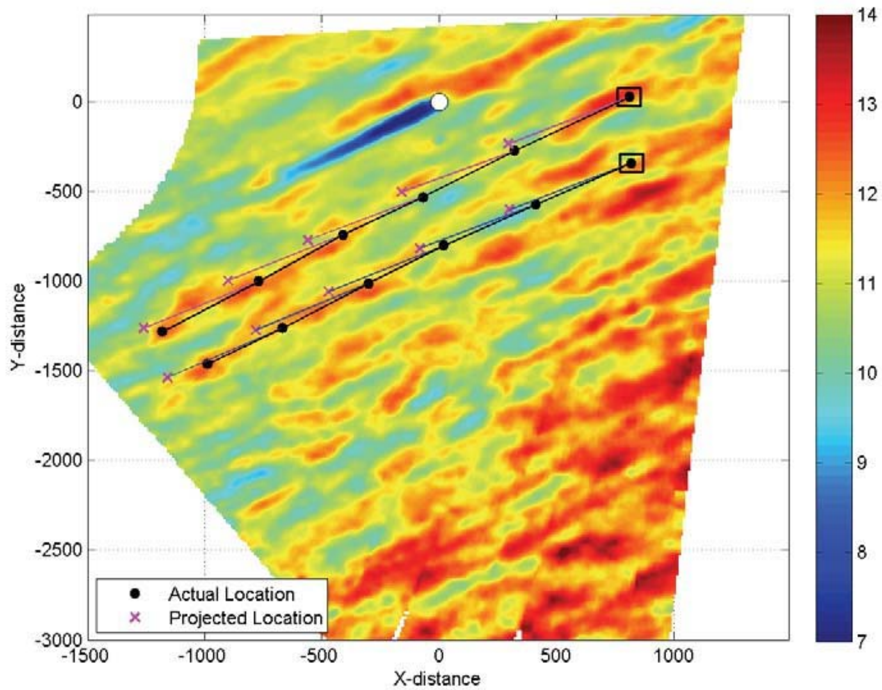

Figure 2. Dual-Doppler horizontal wind speed (m/s) synthesis at 80 m AGL for a single volume ending at 12:59:26 on 27 October 2011 demonstrating actual streak motion (circle) versus projected motion (cross) based upon the governing wind speed and direction determined using five consecutive dual-Doppler volume scans between 12:55:31 – 12:59:26 UTC.

With knowledge regarding the advection of near-surface streaks, a directional offset was applied to the upstream look-angle to obtain the best estimate of the future-forecasted wind speeds at the turbine location. To generate a future-forecasted time series, wind speeds at hub height were analyzed at distances between 1-10 D upstream of the turbine at intervals of approximately 10.5 m. Given the wind speed associated with each feature, a time offset was derived denoted as the time it would take for that feature to reach the turbine. Assuming that the wind speed magnitude of the feature did not vary with time, a forecasted wind velocity time series may be generated based upon a future time of arrival.

To verify these estimates, projected wind speeds are compared to data from the nacelle mounted 3-cup anemometer. The performance of the radar derived future-forecasted wind speeds for one sample volume scan are displayed in Figure 3. Analysis of the sample horizontal wind field map allows for the projection of wind speeds, which averaged on a 3-second time scale for the duration of 44 seconds, yields a RMSE value of 0.199 m/s. When expanding to a 10-second averaging window, the RMSE value decreases to 0.124 m/s.

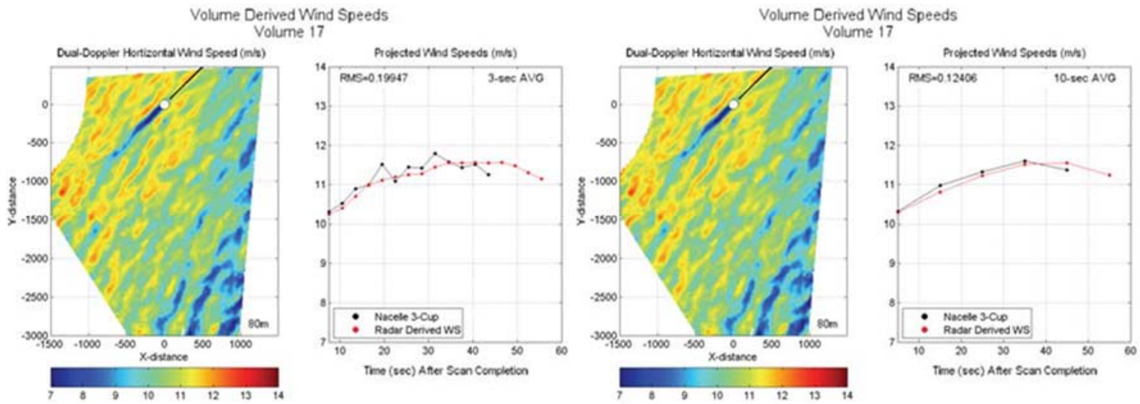

Figure 3. Comparison of nacelle mounted 3-cup anemometer (black) to future-forecasted radar derived wind speeds (red) according to 3-sec (left) and 10-sec (right) averaging times.

Preliminary results demonstrate the ability to predict future conditions at the turbine leveraging radar-derived dual-Doppler horizontal wind field maps. Unique to employing this method is the ability to accurately forecast wind speeds upwards of a minute or more in advance from the turbine. If sub-minute radar volume revisits are available, as they were in this case, another snapshot preview of the wind field can be collected and further integrated into the real-time prediction system. The coordinated deployment of multiple specialized Doppler radar systems and associated dual-Doppler synthesis techniques can provide the foundational information to construct proactively responding turbine control systems yielding a reduction in structural loads and an increase in power output. Elevating the radars to hub height could reduce the time to collect hub height information by an order of magnitude and further enhance the method.

ACKNOWELDGEMENTS:

The use of radar technology to document wind plant complex flows occurred with support from the United States Department of Energy Congressionally Directed Project: Great Plains Wind Power Test Facility (DE-FG-06-GO86092). This specific research is funded through support from the National Science Foundation: Building the Foundation for Smart Wind Farms through First-Order Controls Opportunities based on Real-Time Observations of Complex Flows (CBET-1336935).

REFERENCES:

Bossanyi, E. A., A. Kumar, and O. Hugues-Salas, 2014: Wind turbine control applications of turbine-mounted LIDAR. *J. Phys.: Conf. Ser.*, **555**, 012011.

Hirth, B. D. and J. L. Schroeder, 2013: Documenting wind speed and power deficits behind a utility-scale wind turbine. *J. Appl. Meteor. Climatol.,* **52**, 39-46.

Hirth, B. D., J. L. Schroeder, W. S. Gunter, and J. G. Guynes, 2015: Coupling Doppler radar-derived wind maps with operational turbine data to document wind farm complex flows. *Wind Energ*y, **18**, 529-540.

Lorsolo, S., J. L. Schroeder, P. Dodge, and F. Marks, 2008: An observational study of hurricane boundary layer small-scale coherent structures. *Mon. Wea. Rev.*, **136**, 2871-2893.

Marathe, N. 2014: Investigation of power performances and wakes of wind turbines under yawed flow. Dissertation, Texas Tech University, 141 pp.

Mikkelsen, T., N. and Couauthors, 2013: A spinner-integrated wind lidar for enhanced wind turbine control. *Wind Energy*, **16**, 625-643.

Schlipf, D., J. Anger, S. Kapp, O. Bischoff, M. Hofsäß, A. Rettenmeier, and M. Kühn, 2011: Prospects of optimization of energy production by lidar assisted control of wind turbines. *Proc. European Wind Energy Conference and Exhibition*, EWEA, Brussels, 14-17 2011.

Träumner, K., T. Damian, C. Stawiarski, and A. Wieser, 2015: Turbulent structures and coherence in the atmospheric surface layer. *Bound.-Layer Meteor.*, **154**, 1-25.