Measuring a Utility-Scale Turbine Wake Using the TTUKa Mobile Research Radars

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ABSTRACT

Observations of the wake generated by a single utility-scale turbine and collected by the Texas Tech University Ka-band mobile research radars on 27 October 2011 are introduced. Remotely sensed turbine wake observations using lidar technology have proven effective; however, the presented radar capabilities provide a larger observational footprint and greater along-beam resolution than current scanning lidar systems. Plan-position indicator and range–height indicator scanning techniques are utilized to produce various wake analyses. Preliminary analyses confirm radial velocity and wind speed deficits immediately downwind of the turbine hub to be on the order of 50%. This introduction lays the groundwork for more in-depth analyses of wake structure and evolution using the Texas Tech University Ka-band radar systems, including wake meandering and wake-to-wake interaction in large wind park deployments.

1. Introduction

Understanding the structure and evolution of turbine wakes is essential to properly plan wind farms and estimate wind turbine and farm efficiency. These wakes maintain wind speed deficits from the free streamflow and enhanced turbulence capable of providing higher dynamic loads to downwind turbines. Although only a few observational studies on the impact of turbine wakes exist, initial findings suggest power output decreases for individual wake-influenced turbines can reach 40%. Total power output loss due to wake influences across a large wind farm can be as large as 20% (Barthelmie et al. 2009). The impact of turbine wakes directly relates to appropriate turbine spacing and associated infrastructure costs. Accurately forecasting the expected total power output of a large wind park on short temporal scales requires a full understanding of complex wake interactions within the park itself.

A multitude of numeric simulations (LES, CFD, etc.) has been conducted in an attempt to quantify the structure and effect of turbine wakes. Barthelmie et al. (2009) provides a detailed list of concerns when applying these simulation results to the real atmosphere and full-scale turbine systems. Among other limitations, current numeric simulations are not yet capable of accurately handling the natural variability of atmospheric stability and turbulence as well as complex underlying terrain. The net result is a systematic underprediction of wake losses within a large wind park. Additionally, the computational expense of accurately incorporating turbine and blade geometry into simulations remains large, requiring the employment of simplified approaches that do not exactly represent reality (Sanderse et al. 2011). Despite these limitations, wake modeling efforts are necessary as current observational capabilities are not yet able to provide the spatial and temporal resolution needed to see the full range of scales within a turbine wake in the real atmosphere. However, to validate the simulation

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TABLE 1. Selected technical specifications for the TTUKa radar systems.

Parameter	Specifications
Peak transmit power	212.5 W
Transmit frequency	35 GHz
Wavelength	8.6 mm
Antenna diameter	1.22 m
Half-power beamwidth	0.49°
dBZ_0	−38.5 dBZ
Pulse length	12.5, 20, 30 μs
Range gate spacing	15 m
Pulse repetition frequency	5000–15 000 Hz
Maximum range	10–30 km
Azimuthal (PPI) resolution	0.352°
Elevation (RHI) resolution	0.1°
Horizontal scan speed	24° s^{-1}
Vertical scan speed	6° s^{-1}

FIG. 1. The TTUKa radar deployed for scanning.

results, expansion of existing observational capabilities and coverage is vital.

To date, observational studies of the horizontal influence of turbine wakes are limited to sparse tower measurements and light detection and ranging (lidar) technology. Fixed meteorological tower measurements provide valuable ‘‘ground truth’’ data but are inherently limited in their horizontal and vertical coverage. Lidar utilizes the Doppler effect to obtain a remotely sensed along-beam measurement of the wind velocity vector. The advantages of research-grade lidar systems include their compact size and narrow beamwidths, which are generally less than 0.5 m. Recent full-scale measurements using scanning lidar technology have proven effective when observing wind turbine wakes (Käsler et al. 2010; Pichugina et al. 2011). These measurements have shown the effects of turbine wakes to extend beyond 10–15 rotor diameters (D) downwind. Existing published wake studies indicate that current lidar technology is handcuffed by the inverse relationship between maximum range and along-beam range resolution. This limitation precludes the ability to fully observe wakes of significant length or wake interaction within a large wind park using current lidar technology. The maximum presented along-beam range gate spacing from scanning lidar wake studies is 30 m (Pichugina et al. 2011) using the National Oceanic and Atmospheric Administration (NOAA) High-Resolution Doppler lidar (HRDL; Grund et al. 2001). Research-grade mobile Doppler radar systems provide the opportunity to expand the lidar coverage footprint with increased range resolution while utilizing adaptive scanning strategies. Here, an introduction to using mobile research radar for wake detection and monitoring will be presented.

2. Texas Tech University Ka-band radar

Texas Tech University (TTU) designed and constructed two mobile Ka-band (35 GHz) Doppler radar systems (TTUKa) in 2006. These systems were developed to observe various aspects of the atmospheric boundary layer with a high level of sensitivity and spatial resolution. The TTUKa radars represent the first research-grade mobile Doppler systems to use a nonlinear pulse-compression frequency modulation technique in the Ka band (Weiss et al. 2009). The transmitted signal is generated using a fully coherent traveling wave tube amplifier; thus, no velocity noise (error) is present. The pulse-compression technique allows for accurate radial velocity measurements using a relatively long pulse width while maintaining improved range resolution when compared to traditional radar systems. The half-power beamwidth is 0.49°. The along-beam range gate spacing is 15 m and is a function of modulation bandwidth. Additional technical specifications can be found in Table 1. Each radar is truck mounted (Fig. 1), allowing for mobility to and around a desired scanning location. The radar systems are designed to operate during extreme meteorological environments including thunderstorms and hurricanes. A radome protects the antenna from wind loading, wind-borne debris, hail, and miscellaneous hazards during transit. A hydraulic leveling system levels the radar during deployment and the radar is operated from within the truck cab. Each radar utilizes a Sigmet Radar Video Processor 9 (RVP9) signal processor and is capable of performing sector or full 360° horizontal plan-position indicator (PPI) sweeps (outside of the influence of the truck cab). Vertical range–height indicator (RHI) scanning from 0° to 90° along a single azimuth is also possible. Spatial oversampling is accomplished by collecting data every 0.352° (0.1°) for PPI

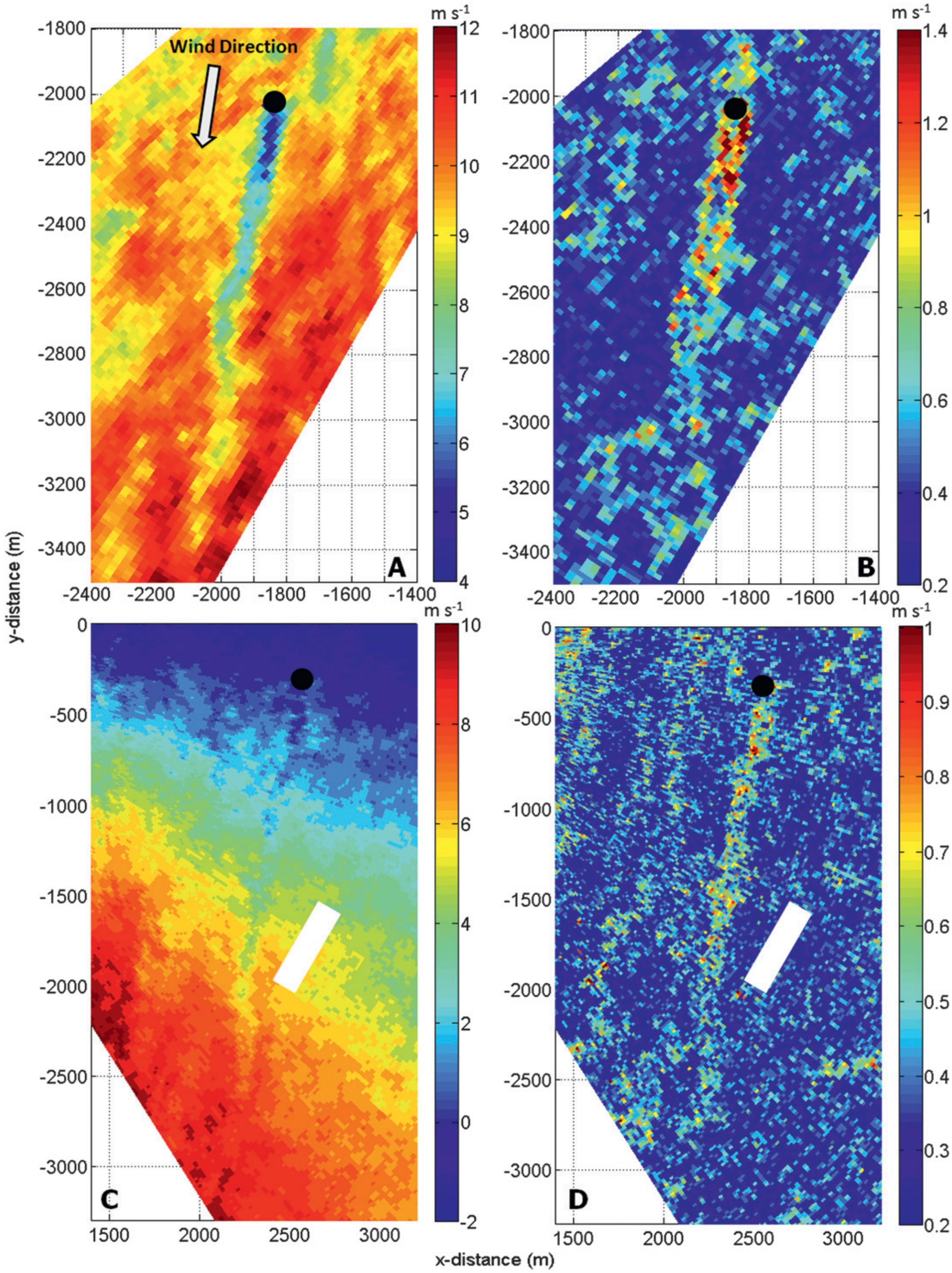

FIG. 2. PPI scans at 1.2° beam elevation of (a) TTUKa1 radial velocity (m s^{-1}), (b) TTUKa1 spectrum width (m s^{-1}), (c) TTUKa2 radial velocity (m s^{-1}), and (d) TTUKa2 spectrum width (m s^{-1}). The location of the turbine is denoted by the black dot. The prevailing wind direction is also shown. An area of ground targets has been removed from the TTUKa2 analyses.

(RHI) scanning strategies. Multiple scanning strategies can be interwoven to satisfy a variety of scanning goals.

The TTUKa radars generally provide continuous radial velocity measurements out to the maximum range when distributed meteorological targets (water droplets, ice crystals, etc.) are present. To date, radial velocity measurements when scanning clear air are often observed, but with intermittent coverage in low relative humidity environments. An antenna upgrade is planned for both radars during the summer of 2012. The antenna diameter will be increased 50% from 1.22 m (4 ft) to 1.83 m (6 ft), reducing the half-power beamwidth from 0.49° to 0.33° and increasing the antenna gain 6 dB. The net result will be an increase in clear-air sensitivity and azimuthal resolution. A limitation of Doppler radar measurements when compared to lidar is the effect of beam spread at large ranges. A beamwidth of 0.49° results in a beam spread of 17.1 m at 2-km range and 85.5 m at 10-km range. Following the scheduled upgrade, a beamwidth of 0.33° will reduce the azimuthal beam spread 33% to 11.5 m and 57.6 m at 2-km and 10-km ranges, respectively.

3. TTUKa wake measurements

On the morning of 27 October 2011, 6 h of radar data were acquired by both TTUKa radars (TTUKa1 and TTUKa2) of the flow surrounding a single utility-scale turbine in West Texas. A pulse length of 12.5 μs was used along with a pulse repetition frequency of 7500 Hz, yielding a maximum range of 20 km. Data were collected during continuous light to moderate rainfall. The turbine hub height was 80 m, where D was 86 m. TTUKa1 was positioned at a distance of 2713 m north–northeast of the turbine. At this bearing, the turbine was oriented closely parallel to the mean wind direction (from the north through northeast) downwind of TTUKa1. TTUKa2 was positioned 2563 m west–northwest of the turbine.

TTUKa1 performed 20° sector scans at an elevation angle of 1.2° for extended periods (>30 min) throughout data collection. This elevation angle was chosen to maximize beam residence within the wake. At the location of the turbine and at 6-km range, the beam height was 56.8 and 125.7 m AGL, respectively. Because beam misalignment with the true wind vector, radial velocity measurements will generally reflect values less than the actual wind speed. For example, a radial velocity measurement will be 1.5% less than the true wind speed for a beam misaligned by 10° and 13.4% for a beam misaligned by 30°. Because of the 0.49° beamwidth, the azimuthal beam spread at the location of the turbine was 23 m. The sector revisit time was 3 s, allowing for a high temporal depiction of wake evolution. TTUKa2 performed 30° sector scans at the 1.2° elevation angle with a sector revisit time of 4 s. Azimuthal beam spread at the location of the turbine from TTUKa2 was 22 m and the beam height was 53.7 m. A sample PPI sector scan of radial velocity and spectrum width from both radars is provided in Fig. 2. The turbine is denoted by the black dot. Assuming a conservative upwind radial velocity of 9 m s^{-1} from TTUKa1, radial velocity deficits

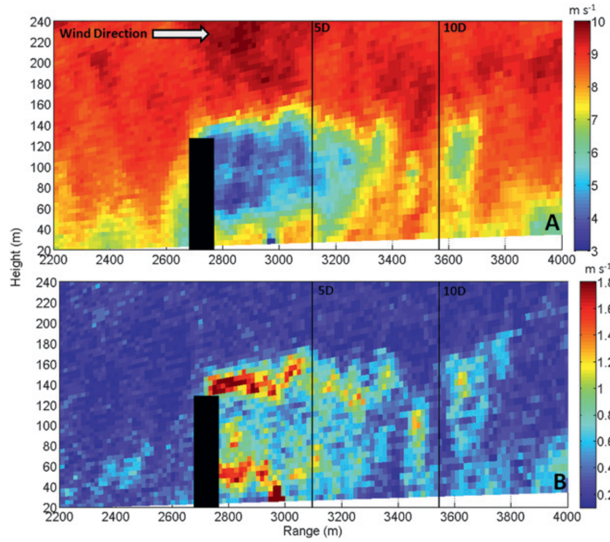

FIG. 3. TTUKa1 RHI scan of (a) radial velocity (m s^{-1}) and (b) spectrum width (m s^{-1}) aligned through a single turbine. The turbine is denoted by the black rectangle. The prevailing wind direction is also shown. The thin vertical black lines indicate a distance of 5D and 10D downstream of the turbine (D = 86 m).

in excess of 50% can be seen immediately downwind of the turbine (Fig. 2a). Similar lidar analyses from Käsler et al. (2010) from the wake of a megawatt turbine in comparable wind speed conditions show radial velocity deficits at hub height of 66% 1D downstream. The influence of the turbine wake in the TTUKa1 snapshot can be seen in excess of 15D downstream. Though the beam of TTUKa2 was not aligned with the mean wind direction, a radial velocity snapshot (Fig. 2c) shows the wake influence extending in excess of 30D downwind of the turbine, extending across the entire sector sampled. The spectrum width fields from both radars also show enhanced turbulence associated with the wake. Enhanced spectrum width can be seen at the interface between the turbine wake and the adjacent flow, where turbulence between these two regions is maximized, and where blade tip vortices are expected to reside (Vermeer et al. 2003). Spectrum width provides an additional tool for tracking downwind wake length.

TTUKa1 also collected long-duration, consecutive RHI data between 0° and 30° elevation at a constant azimuth oriented through the turbine. The scan revisit interval was 7 s, emphasizing a high temporal resolution to capture wake evolution in the vertical dimension. A snapshot RHI scan is shown in Fig. 3. The influence of the turbine is denoted by the black vertical box. Using a conservative upwind radial velocity of 8 m s^{-1} near hub height, wake deficits in excess of 50% are evident within 2D downwind of the turbine while farther downwind (beyond 6D) the effects of wake meandering become

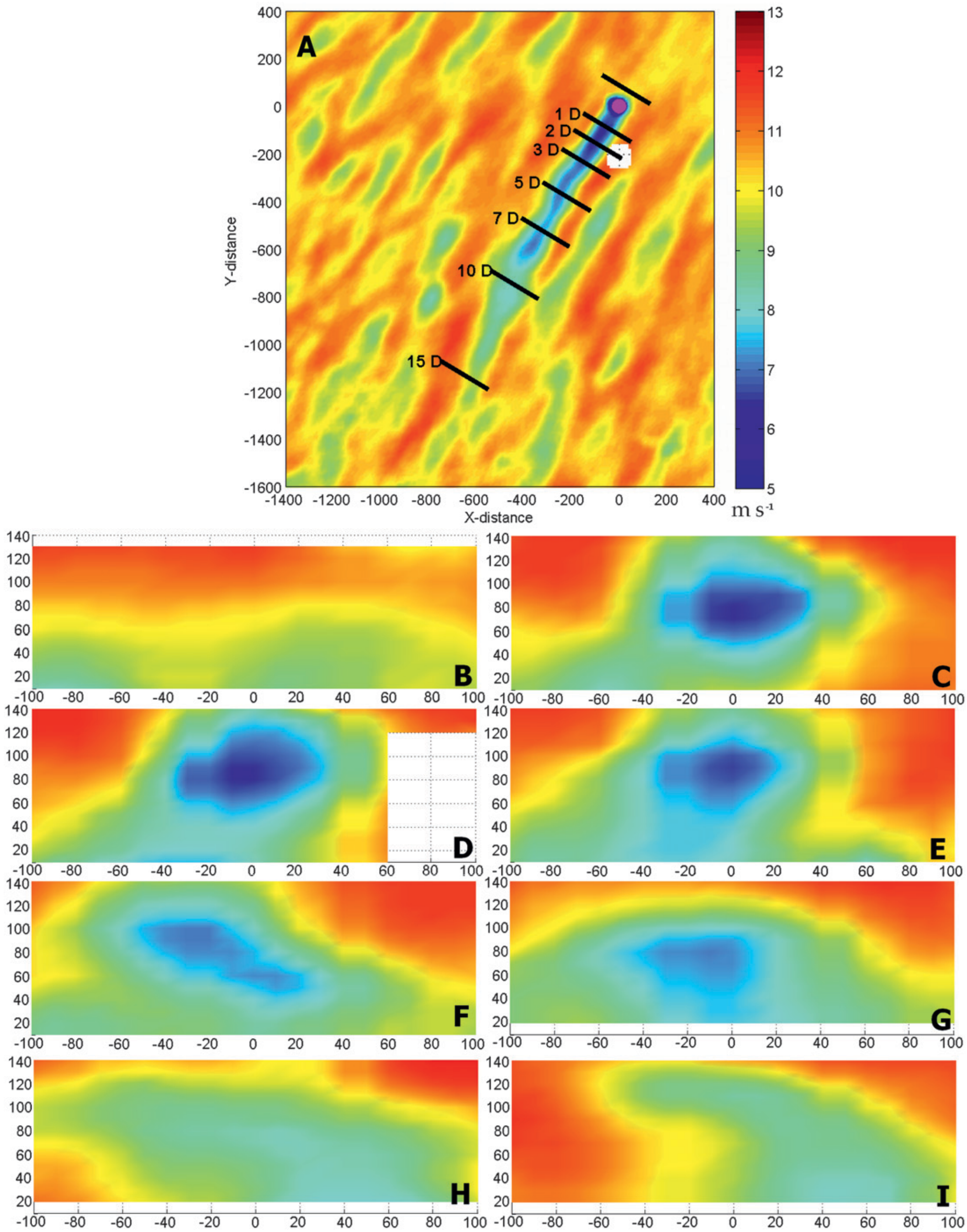

FIG. 4. (a) TTUKa1 radial velocity gridded volume at 80 m AGL. The location of the turbine is located at the origin, denoted by the magenta dot. Vertical cross sections oriented normal to the wake are also shown at (b) 1*D* upstream, (c) 1*D* downstream, (d) 2*D* downstream, (e) 3*D* downstream, (f) 5*D* downstream, (g) 7*D* downstream, (h) 10*D* downstream, and (i) 15*D* downstream. Cross-section *x* axis is horizontal distance (m) and *y* axis is height (m). The color bar is shared for all panels.

more evident. Though this cross section is not perfectly aligned with the downwind wake, wake effects in this RHI snapshot are evident in excess of 11*D* downstream of the turbine. Similar to the signature in the PPI scan presented, spectrum width (and therefore turbulence) in the RHI scan is maximized on the wake periphery. These analyses suggest a ring of maximized turbulence separates the wake from the ambient free streamflow

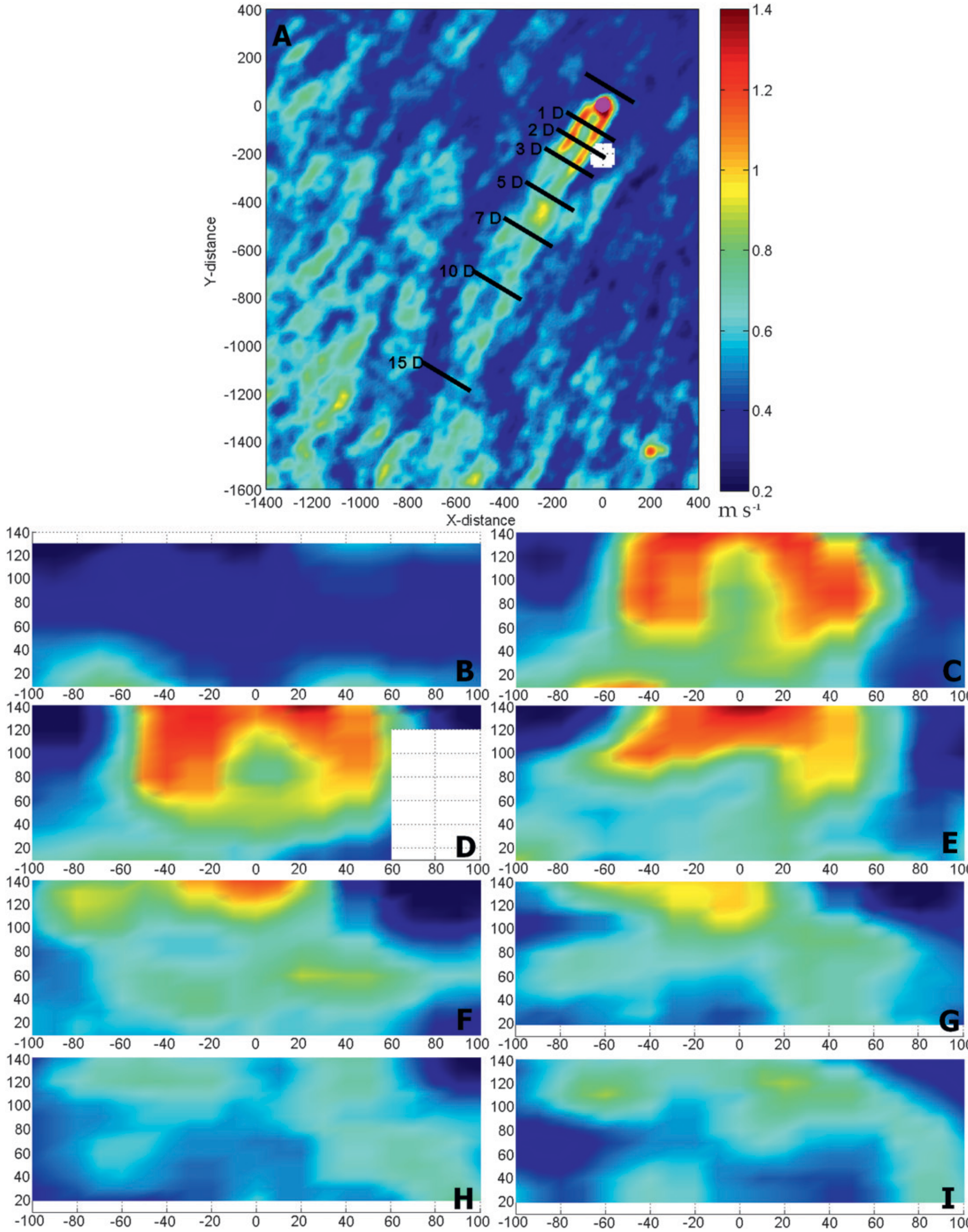

FIG. 5. As in Fig. 4, but for spectrum width (m s^{-1}).

immediately downstream of the turbine. The shape of this ring becomes highly variable and collapses with increased range as turbulent mixing and wake meandering complicate the wake structure.

A single volume of data collected by TTUKa1 was interpolated to a three-dimensional grid to analyze the mean wake structure. The volume comprised 30° sector scans for 10 elevation angles taken every 0.2° between 0.6° and 2.4°. Data collection for the volume took approximately 45 s to complete. Fig. 4 shows a plan view of the gridded analysis at 80 m (hub height) along with gridded vertical cross sections upwind of and through the wake at various downwind D distances. The cross sections are viewed from downwind looking back toward the turbine. At 1D (Fig. 4c), the radial velocity deficit centered on the hub ($x = 0$, $y = 80$ m) is in excess of 40% of what is observed upstream (Fig. 4a). The 5D cross section shows a less defined wake structure; however, the influence of the wake is still evident at 10D. Beyond 10D, the wake scales with the surrounding wind streaks in the ambient flow, and it is difficult to discern the wake from the variability in the surrounding flow field. How these features interact is currently unknown. Similar analyses of spectrum width (Fig. 5) show a ring of higher turbulence surrounding the hub, associated with the interface between the faster adjacent flow and the slower wake flow. The ring of spectrum width is consistent with the PPI and RHI analyses previously presented. This ring structure is traceable through about 5D, after which the wake turbulence is no longer as significant as mixing promotes the ring structure to collapse (Sanderse et al. 2011).

4. Discussion of future work

Various scales must be considered when investigating turbine wake structure, ranging from small blade tip vortices to broad wake widening and meandering as a function of surrounding atmospheric conditions and wind turbine and farm design. As observational capabilities improve, the ability to observe the full spectrum of wake scales will help validate numerical simulations, ultimately providing better power output forecasts. The TTUKa mobile radar systems are well equipped to explore the full length of turbine wakes, including wake width expansion, wake meandering, lateral wake merging (Barthelmie et al. 2010), and wind farm to wind farm interaction with range resolution and coverage that exceeds current lidar technologies. Though this introduction focused on a single utility-scale turbine, future data collection from turbine arrays is planned.

Various techniques will be used moving forward to analyze this and other TTUKa wake datasets. Composites of several long-duration PPI and RHI scan periods will be constructed to assess mean wake structure using mean radial velocity deficit and mean spectrum width signatures. At greater D, the magnitude and frequency of wake meandering will be explored. The analysis techniques presented thus far utilize single-Doppler data. Coordinated volumetric scanning from two radars with a sufficient look angle can be used to construct a dual-Doppler (DD) synthesis of the full wind field throughout a three-dimensional gridded volume. Multiple consecutive DD volumes are available for analyses to provide another method of assessing mean wake structure and evolution. Preliminary DD analyses look promising for assessment of mean structure of large utility-scale turbine wakes. Supporting meteorological tower data will be analyzed to corroborate the radar wind measurements and assess atmospheric stability (Barthelmie et al. 2009).

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