Diurnal evolution of wind structure and data availability measured by the DOE prototype radar system

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Abstract. A new Doppler radar prototype has been developed and deployed at Texas Tech University with a focus on enhancing the technologies' capability to contribute to wind plant relevant complex flow measurements. In particular, improvements in data availability, total data coverage, and autonomous operation were targeted to enable contributions to a wider range of wind energy applications. Doppler radar offers rapid scan speeds, extended maximum range and excellent along-beam range resolution allowing for the simultaneous measurement of various wind phenomena ranging from regional and wind plant scales to inflow and wake flow assessment for an individual turbine. Data examples and performance improvements relative to a previous edition of the technology are presented, including insights into the influence of diurnal atmospheric stability evolution of wind structure and system performance.

1. Introduction

Scanning Doppler radar has emerged as a proficient remote sensing technology for measuring wind plant complex flows. Doppler radar offers rapid scan speeds, extended maximum range and excellent along-beam range resolution allowing for the simultaneous measurement of various wind phenomena ranging from regional and wind plant scales to inflow and wake flow assessment for an individual turbine [1]. It is particularly well suited to document the spatial and temporal evolution of wind structure (e.g. gusts, lulls, wind streaks, etc.) over measurement domains comprising hundreds to thousands of square kilometers, which provides an opportunity to effectively investigate the influence of atmospheric stability on the wind flows within and surrounding wind plants [2] [3].

Historically, Texas Tech University (TTU) employed two mobile Ka-band research radars to measure wind plant complex flows on a case study basis [4] [5]. These TTUKa radar systems were originally designed for atmospheric science research applications generally focused on documenting storm scale structure. However, the radar technology and analysis techniques were successfully adapted and applied to document smaller scales of motion across wind turbine arrays.

Building on the success of the original Ka-band radar case studies, TTU designed and built a next-generation radar prototype specifically dedicated to the measurement of wind plant complex flows. In particular, this United States Department of Energy (DOE) funded radar prototype was designed to improve data availability, enhance maximum range, and provide more autonomous system operation relative to the Ka-band radars. The DOE radar prototype was successfully deployed at the Reese Technology Center (RTC) in Lubbock, TX in May 2016.
This paper will present initial analysis of wind flow measurements collected by the DOE radar prototype during the summer months of 2017. Data availability is quantitatively assessed as a function of radar range and compared to a Ka-band radar to assess data availability improvements. Documentation of the diurnal variability of the measured wind flow structure is also qualitatively assessed in the context of the potential impacts of stability on data availability and ultimately wind plant performance.

2. Technical Specifications and Data Collection Methods
The DOE radar system has been designed to run autonomously and is constructed in a modular fashion to support portability to different deployment locations (Figure 1). All core components of the radar system (transmitter, receiver chain, signal processor, operations server, data storage server, UPS, etc.) are housed within a 20-ft (6.1 m) sea container that is affixed to concrete pilings using tandem lock anchors at the four corners of the container. A secondary wall has been constructed inside the sea container which contains a door, a commercial air conditioning unit, and appropriate electrical service connections and distribution points. When the radar is deployed and operational, this wall becomes the exterior wall while the doors of the sea container are fixed in the open position. The doors are then closed for system transport. A steel exoskeleton support structure straddles the sea container and provides a platform for the radar pedestal and antenna systems to be mounted. The pedestal and antenna systems are housed within a protective radome which provides shelter to wind loading and other atmospheric hazards such as hail. Total system height from the ground to the top of the radome is approximately 8.5 m.

![Figure 1. Co-located DOE-X prototype (left) and TTU Ka-band (right) radars positioned for comparative performance testing. The DOE-X radar sea container and interior wall can be seen as well as the exoskeleton support structure straddling the sea container and radome housing the pedestal and antenna systems.](image)

The DOE radar operates in the X-band at a frequency of 9.3 GHz. The radar maintains a half-power beam width of 0.5° and an along beam resolution of 9-15 m, depending on the pulse configuration used. Variable scan speeds in excess of 30° s⁻¹ can also be used. The transmitter allows a maximum pulse repetition frequency (PRF) of up to 4000 Hz for a 20 µsec compressed pulse, which yields a maximum range of 35 km. Pulse types, scan speeds and PRFs can all be configured to accommodate the data collection objective of interest.

Data were collected between 30 June and 28 September 2017 at the RTC to assess system data availability spanning several months. The radar system was configured to run a single 360° horizontal
Plan Position Indicator (PPI) scan at the 1.0° elevation tilt every five minutes. Two scans speeds were used, 2.5° s⁻¹ and 30° s⁻¹ to assess the impact of varying scan speed (thus varying the number of available samples to construct the Doppler velocity spectra) on data availability. Scan durations were 144 s and 12 s, respectively. A 20 µs frequency modulated compressed pulse was used, resulting in an along-beam range resolution of 15 m between the first available range bin at 3 km and the maximum range bin of 32 km. Specifications for the DOE radar operation during this data availability study are provided in Table 1. In total 23,955 individual PPI scans for each scan speed were acquired during the approximately three month period. Minimal “forced” radar downtime occurred during several short time periods to accommodate other nearby experiments at RTC requiring radar silence.

| Table 1. Technical specifications of the DOE prototype radar used for the summer 2017 RTC data availability study. |
| Parameter | Specification |
| Peak Transmit Power | 11 kW |
| Transmit Frequency | 9.3 GHz |
| Wavelength | 3 cm |
| Antenna Diameter | 4.6 m |
| Half-Power Beam Width | 0.5° |
| Pulse Length | 20 µs |
| Range Gate Spacing | 15 m |
| PRF | 4000 Hz |
| Range | 3-32 km |
| Azimuthal (PPI) Resolution | 0.352° |
| Pointing Accuracy | 0.05° |
| Velocity Accuracy | 0.03 m s⁻¹ |
| Horizontal Scan Speed | 2.5, 30° s⁻¹ |

Radar data were collected through a wide range of atmospheric conditions including both precipitating and non-precipitating (e.g. clear-air) environments. A simple quality control procedure was implemented on the raw radial velocity data to remove the influence of ground clutter and point targets, second-trip echos (range aliasing) and noise. Significant diurnally driven variability in the structure of the radial velocity field was common, particularly in clear-air environments where minimal sensible weather was occurring.

3. Diurnal Variability

Diurnal trends through the day of 06 September are presented in Figure 2. PPI scans using the 30° s⁻¹ scan speed are shown at 0301 UTC, 0901 UTC, 1801 UTC and 2101 UTC (Figure 2a-d). A 5-min average potential temperature (Figure 2e) and turbulence intensity (Figure 2f) profile is constructed using measurements from nine instrumentation levels (between 1-158 m) of the TTU meteorological tower located roughly 345 m southwest of the DOE radar (Figure 2e). The tower samples continuously at 50 Hz. Significant diurnal evolution of the boundary layer wind structure is evident on the presented PPI scans which can be related to background stability changes. During the evening and overnight hours (e.g. 0301 UTC and 0901 UTC), the boundary layer wind structure is qualitatively smooth coincident with a temperature inversion noted on the meteorological tower, indicative of stable atmospheric conditions. Turbulence intensity values constructed from the meteorological tower sonic anemometer wind measurements are quite low during this same time period, generally less than 10% above 10 m. As atmospheric mixing begins to increase with surface heating, a more streaky structure is seen in the
boundary layer flow (e.g. 1801 UTC) as the temperature inversion has mixed out and the stability regime has started to transition back towards unstable. Further surface heating and mixing into the afternoon hours (e.g. 2101 UTC) results in an unstable boundary layer with much larger turbulent structures evident in the boundary layer flow. During the afternoon hours, turbulence intensity values increase to 25-40% above 10 m. This diurnal evolution is prevalent most days during the test period lending insights into the evolution of stability and turbulence in the background boundary layer flow on a day to day basis. Obtaining a better understanding of these diurnal variations is of great importance for the wind energy industry to improve turbine wake and wind plant layout modelling, as well as develop the next generation of (proactive) turbine control strategies to further optimize collective wind plant performance.

Figure 2. DOE radar measured radial velocity (m s$^{-1}$) PPI sweeps at the 1.0° elevation tilt using a scan speed of 30° s$^{-1}$ from 06 September at (A) 0301 UTC, (B) 0901 UTC, (C) 1800 UTC and (D) 2100 UTC. TTU instrumented tower 5-minute (E) averaged potential temperature (K) profile and (F) turbulence intensity for the day of 06 September.

4. Data Availability Assessment
Data availability was assessed for each PPI scan as a function of radar range. Since a 360° PPI scan was used with an azimuthal sampling resolution of 0.352°, approximately 1022 data bins exist at a given range ring from the radar. Data availability for each range ring was constructed as the percentage of azimuthal bins containing valid data compared to the total available bins (Figure 3). Nominally, data availability decreased with range, though the variety of atmospheric conditions measured contributed to the construction of diverse data availability curves. For example, during a period of widespread precipitation, data availability never dropped below 94% (Figure 3a) while during a period of marginal clear-air return, data availability decreased from an average of 87% between 3-5 km to 48% between 20-22 km. Figure 4 presents the composite mean data availability analysis with range using the full set of 23,995 PPI scans. Using the 30° s$^{-1}$ scan speed, availability at 3, 5, 10, 20 and 30 km is 72%, 70%, 58%, 35% and 18%, respectively. When the scan speed is slowed to 2.5° s$^{-1}$, availability increases to 84%, 81%, 70%, 47% and 27%, respectively for the same
ranges. Therefore, slowing the scan speed yielded an availability increase of 12% at near ranges and 9% at far ranges for the period.

Figure 3. DOE radar measured radial velocity (m s⁻¹) PPI sweeps at the 1.0° elevation tilt using a scan speed of 30° s⁻¹ from (A) 02 July at 0801 UTC, (B) 02 July at 1801 UTC and (C) 26 September at 2201 UTC. The red, blue and green circles represent the 5, 20 and 30 km range rings, respectively. (D) Data availability (%) assessment with range (km) for the individual PPI scans A-C. Red, blue and green vertical bars represent the 5, 20 and 30 km range distances, respectively.

Figure 4. Composite DOE prototype radar data availability (%) assessment with radar range (km) using the 30° s⁻¹ (black curve) and 2.5° s⁻¹ (red curve) scan speeds.

Data availability was also assessed by time of day to note diurnal trends (Figure 5). During the data collection period, daytime hours ranged from roughly 11 UTC – 01 UTC while night time hours ranged from roughly 01 UTC – 11 UTC. When segregating and compositing the full collection of PPI scans
into hourly bins, two distinct availability maximums are evident, the first between 02-04 UTC and the second between 16-19 UTC. As discussed in Section 2, this bimodal distribution of availability appears directly linked to diurnal stability evolution and the associated scattering mechanisms associated with each. For example, during the daytime hours, it is believed that convective boundary layer mixing generated by surface heating aided in lofting and distributing effective radar scatterers (pollen, dust, etc.) supportive of higher availability. As the afternoon transitioned to evening, this mixing process weakened allowing the distributed scatterers to settle yielding a relative decrease in availability. During the evening and overnight hours, insect activity increased and surface cooling aided in the development of a boundary layer temperature inversion contributing to a pronounced vertical density gradient. It is believed the resulting vertical density gradient yields favorable conditions for the DOE prototype radar to benefit of Bragg scattering. Near and just after the time of sun rise, a general weakening in the overnight density gradient created a decrease in availability. As the sun angle continued to increase during the morning hours, surface heating once again contributed to the start of surface mixing, and the cycle repeated. Based on measurements using the 30° s⁻¹ scan speed, the net result of this diurnal cycle was a peak in composite availability at 3 km range of 72% during the day time hours and 81% during the night time hours with an associated minimum in availability just after sunrise of 58%.

![Composite DOE prototype radar data availability (%) assessment with radar range (km) and time of day (UTC) using the 30° s⁻¹ scan speed.](image)

An important distinction between the DOE prototype radar and other currently available scanning remote sensing technologies is the significant maximum range available, and therefore extensive domain of possible data coverage. If data were 100% available between 3-32 km, the total spatial coverage of radar measurements would be nearly 3200 km². To assess the impact of data availability on total data coverage, the summed area of all valid data on each individual PPI sweep using the 30° s⁻¹ scan speed
(e.g. scan duration of 12 s) is calculated and compared to the data availability assessed at the 3 km range (Figure 6). When data availability at 3 km is in excess of 90%, mean total data coverage across the entire PPI sweep is 1993 km². Availability at 3 km of 70-80% yields a mean areal coverage of 1037 km² across the entire PPI sweep and between 50-60% yielded a mean areal coverage of 592 km² across the entire PPI sweep.

![Figure 6](image_url)

**Figure 6.** DOE prototype radar data coverage (km²) versus availability (%) at 3 km range for each individual PPI sweep using the 30° s⁻¹ scan speed.

5. **Performance Comparison to TTUKa**

To better understand the magnitude of data availability enhancement achieved between the existing TTUKa radars and the DOE prototype radar, a single TTUKa radar was deployed beside the DOE system during a period of relatively low data availability on 3-4 August 2016 (Figure 1). Each radar scanned an identical 90° sector at the 0.5° elevation tilt once every 15 minutes for a total of 97 scans. Data availability was again assessed as a function of range using the methods described above, where the maximum range of the TTUKa radar was 10 km (using the configuration settings for a nominal wind plant data collection campaign). In general, the DOE prototype radar demonstrated a significant increase in data availability at all times and at all ranges, with mean increases in availability of 38%, 38%, 35% and 32% at 4, 6, 8 and 10 km range, respectively (Figure 7), and a peak availability increase of 75%. A significant finding from this comparison was the substantial increase in availability found during the night time hours, with increases between 60-70% common at all four ranges assessed. In fact, beyond 4-6 km, little to no data availability can even be found in the TTUKa radar measurements, which may be due to the smaller wavelength of the TTUKa radar being unable to benefit from Bragg scattering.
These initial comparisons show that the DOE prototype system represents a monumental advancement in data availability capability from the existing TTUKa radar technology. The area of potential data coverage is also substantially increased in the DOE prototype system compared to the existing TTUKa radar when both system are configured to run for a nominal wind plant measurement campaign. As previously discussed, the available data range for the DOE system is 3-32 km while for the TTUKa system is 3-10 km, both with an along beam resolution of 15 m. The resulting total areal coverage of the DOE radar is 3200 km² as compared to only 285 km² for the TTUKa system, a factor increase of greater than 11.

6. Concluding Thoughts

The DOE prototype radar was constructed to provide increased data availability, enhanced maximum range and autonomous operation when compared to the existing TTUKa radars. Deployed at the RTC in Lubbock, TX a data availability study was conducted during the summer months (30 June – 29 September) of 2017. Data were collected using a 360° PPI scan on a 1.0° elevation tilts using the scan speeds of 2.5° s⁻¹ and 30° s⁻¹. Statistics generated from measurements obtained using the faster scan speed and collected in a variety of atmospheric conditions reveal a composite data availability of 72% at 3 km range, decreasing to 58% and 35% at 10 and 20 km range, respectively. Using the slower scan speed, data availability at 3 km range is 84%, an increase of 12%. When compared to the existing TTUKa radar, data availability is markedly increased on the order of 40-70%, especially during the nocturnal hours where the DOE prototype radar produced considerably higher quality data when compared to the TTUKa availability. The total area of potential data coverage provided by the DOE prototype radar is also greater than 11 times that which was historically provided by the TTUKa systems.
Hourly segregated and composited data availability highlighted a clear diurnal trend, with relative maxima in the afternoon and nocturnal hours, and relative minimums in the morning and early evening hours. This evolution of availability appears tied to diurnal cycles of boundary layer stability and the subsequent influence of stability on the existence of relevant scatterers supportive of quality measurements by the DOE prototype radar. Background turbulence was qualitatively assessed by viewing individual PPI scans and qualitatively supported by data collected from a nearby meteorological tower instrumented at multiple levels during a single diurnal cycle. Smooth boundary layer flow was observed during periods characterized by a temperature inversion and low turbulence intensity (less than 10% above 10 m) while larger turbulent structures were observed during periods where the temperature profile was more uniform as a result of boundary layer mixing and turbulence intensity was generally much higher (25-40% above 10 m).

The DOE prototype radar developed at TTU represents a substantial advancement in the effort to employ Doppler radar to measure wind plant complex flows. Data availability and maximum range enhancements allow for wind measurements to reliably be made in a much wider spectrum of atmospheric conditions and over larger spatial domains compared to the original TTUKa radars. In particular, the DOE prototype allows for the investigation of wind plant complex flows throughout the diurnal cycle. These results show that the DOE prototype radar is well positioned to assist the wind energy community in enhancing its understanding of wind plant complex flows. The first commercial application [1] [6] of this technology is currently being evaluated for offshore wind plant monitoring at the Westermost Rough wind plant in the UK.

7. References
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