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Development of a LIDAR array to study and classify wakes at the U.S. Department of Energy (DOE)/Sandia National Laboratories Scaled Wind Farm Technology (SWiFT) facility

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Abstract

Wind turbine wake has the wind speed deficit and the increased turbulent flow to the downstream turbines as signatures. Various experiments and simulations have been performed over the years to investigate the wake parameters; however, a statistical characterization of wake states is still to be uncovered. An innovative wake measurement approach that uses five ground-based Spidar Light Detection and Ranging (LIDAR) has been developed in partnership with Texas Tech University (TTU), Sandia National Laboratories, and Pentalum Technologies to develop, test, and validate a system and methodology that enables the capture of statistically significant wake dynamics in real atmospheric conditions. This article will discuss the potential of this new direct detection remote sensing equipment for studying the wake states as well as report the validation process of the LIDAR and the feasibility of continuing to pursue the primary purpose of the initiative.

Keywords

Wake characterization, LIDAR, field measurements

Introduction

One of the biggest challenges in maintaining the efficiency of wind farms is due to the power production losses (Hansen et al., 2012), and increased turbine loading (Crespo et al., 1999) from wind turbine wakes. Several investigations have been deploying wind measurement sensors in the past years seeking a better understanding of wind turbine wakes, ranging from the conventional approach of meteorological towers to remote sensing methods (e.g. Elliott and Barnard, 1989; Hirth and Schroeder, 2013; Högström et al., 1988; Kumer et al., 2017). While these experiments provide a solid base for the general understanding of the wake structure, a statistical characterization of instantaneous wake dynamics has the potential to improve wake modeling accuracy and support the development of new wind turbine control strategies.

Since 14 November 2016, five ground-based LIDAR manufactured by Pentalum Technologies have been continuously measuring wind parameters at the U.S. Department of Energy (DOE)/Sandia National Laboratories Scaled Wind Farm Technology (SWiFT) site, located in Lubbock, TX. The initiative aims to investigate and classify wakes according to their development, which can result from wind turbine control settings and variation of inflow conditions.

The Pentalum LIDAR, called Spidar, is the first commercial LIDAR for wind measurements based on a direct detection mechanism (Afek et al., 2013). Although coherent Doppler LIDAR are the most common method for wind investigations, wind vector retrieval can be a source of error due to the cross-contamination related to the probe volume averaging using a ground-based LIDAR in a velocity-azimuth display (VAD) configuration (Sathe et al., 2015). Also, Doppler LIDAR uses a transceiver that usually requires the use of controlled wavelength and phase laser sources, detectors with thermal stabilization and mechanical shock sensitivity, which make the LIDAR more expensive and more power consuming (Sela, 2012).

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In comparison, the Pentalum LIDAR data deliver straightforward horizontal wind velocity, and the main property of the direct detection is that it is based only on the intensity of the back-reflected signal, regardless of the wavelength or phase of the light source. It uses commercially available components. The Spidar system includes a 1.55 µm fiber-laser source (Pentalum, 2015; Sela, 2012). Intrinsically simpler as do not need a coherent detection transceiver and reception design, the outcome is a robust and lower cost system allowing multiple units to be deployed spatially flexible in the field.

The Spidar operates by cross-correlating the backscatter signal intensity measured at several points to determine the wind speed and direction derived by tracking aerosol particles, correlated in various locations and at different times. The strength of the signal is dependent on the aerosols density in the flow. The accuracy of the cross-correlation method relies on the assumption that aerosol structure do not change significantly in the time that it takes for the wind to pass from one beam to the other. The Spidar system produces a set of eight conically scanning beams with a full cone angle of 10° (±5°) to generate signal. The cone angle determines the measurement volume leading to design trade-off between LIDAR velocity resolution and the atmosphere homogeneity assumption (Afek et al., 2013), but it is worth noting that for a Spidar, small cone angles increase correlation. According to Sela (2012), because of the small cone angles and the correlation technique used, the Spidar LIDAR has been found to perform better in high turbulence, such as in complex terrain, as compared to typical coherent Doppler LIDAR systems with wide cone angles.

In the present study, the Spidar wind measurements are used to investigate wind speed deficits and increased turbulence intensity conditionally sampled by the incoming wind direction. The goal of this initiative is to develop an analysis method that enables statistically significant characterization of instantaneous wake states using ground-based LIDAR data including the atmospheric stability conditions and wind turbine parameters. The Spidar array was tested during a 5-month campaign, known as Phase 1 (Westergaard et al., 2016), to determine the feasibility of the initiative.

The field experiments were conducted at the Sandia SWiFT facility. In addition, wake center measurements from a downwind-facing, nacelle-mounted Technical University of Denmark (DTU) SpinnerLidar (Herges et al., 2017) were included in this investigation as a comparison to the Spidar array instantaneous wake measurements. A side-by-side comparison of Spidar mean and instantaneous wind speed data against the site meteorological tower was also conducted, but the main focus here was the comparison with the DTU SpinnerLidar data. Section "Methodology" describes the measurement campaigns and a brief presentation of the data processing. The results of the assessment are presented in section "Results and discussion" in the form of a case study. Concluding discussion and description of future work are given in section "Conclusion."

Methodology

Data collection is divided into three major phases, each having a different focus. In the first phase, the LIDAR array was deployed in proximity to the meteorological tower located 2.5 rotor diameters (D) upstream the turbine. The objective of this phase, other than to test the Spidar for the wake detection capability, is to understand the extent of lateral inflow variability and its effect during the turbine operation for the wake states. In the second and third phases, the LIDAR array will be deployed downstream (prevailing southerly wind) in two different geometrical configurations. The objective of these phases is to capture wake signatures in the Spidar data and map them to the inflow conditions and the turbine operation state. Instantaneous wake characteristics will be obtained for particular inflow and turbine state conditions that will be binned or classified appropriately. The detailed, reviewed, and approved configurations can be found in Westergaard et al. (2016).

Test facility and instrumentation

The SWiFT facility located at Reese Technology Center in Lubbock, Texas near Texas Tech University (TTU) Campus, presents low surface roughness of flat terrain surrounded by grassland with no major obstacles from the main wind directions. Three turbines are arranged in a triangular arrangement of three turbines in a 3-5-6 diameter spacing array (Figure 1). All three turbines are Vestas V27, originally with a rating of 225 kW at 43 r/min. The turbines have the original collective pitch system but have been modified to full variable speed operation with a maximum rating of 300 kW. The controls system and all its parameters can be accessed and synchronously logged with all data from the site. Hub height is 32.1 m. The 60 m meteorological tower at the south end of the wind turbines has a low-mounted three-dimensional sonic anemometer at 10 m and a top-mounted sonic anemometer at 58.5 m; other sonic anemometers are located at 18m, 32m, and 45 m above the ground. The met tower also has cup anemometers at 18m, 32m, and 45 m, and a wind vane at 29.5 m. At 2 m and 27.5 m, temperature, relative humidity, and barometric pressure are measured.

In Figure 2, it should be noted that the LIDAR array only take into consideration the wake of the turbine located at the southeastern end of the multi-turbine SWiFT site (named WTGa1). The Spidar measurements range from 20m to 65 m at 10

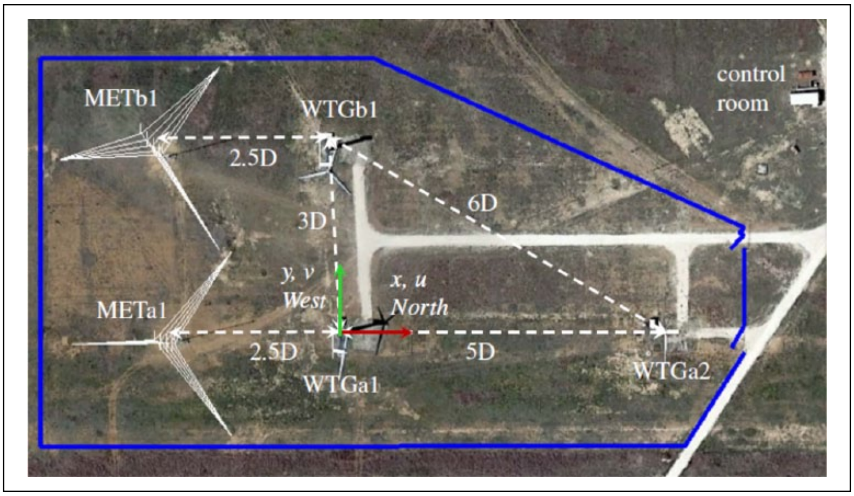

Figure 1. Top view of the SWiFT facility layout and coordinate system.
Source: Herges et al. (2017).

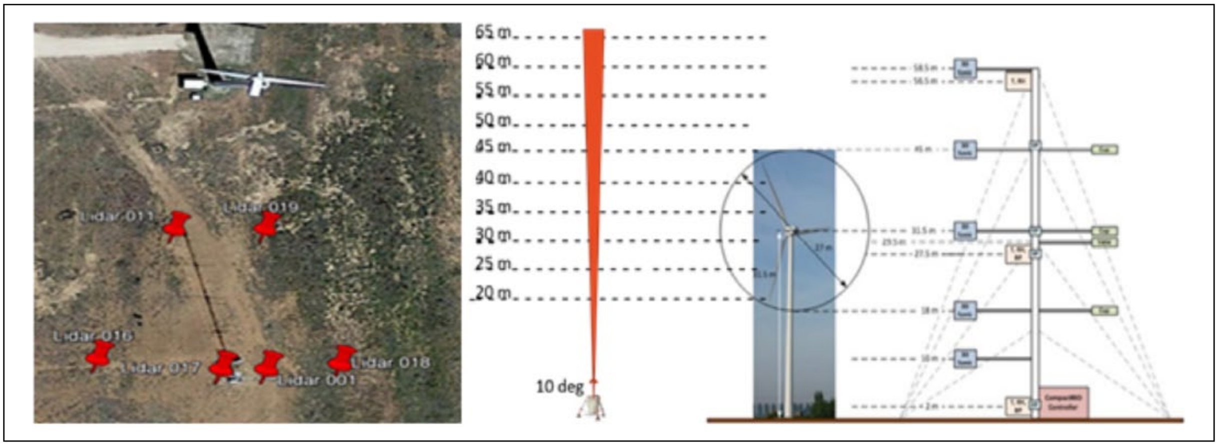

Figure 2. Top view of the SWiFT facility layout with the Spidar array positioning at the south of the turbine WTGa1 and the comparison between the met tower and the Spidar measurement ranges regarding the turbine. The width of the Spidar cone is 3.3m and 8.0 m at rotor bottom and rotor top, respectively.

points, vertically, encompassing the entire rotor swept area. The Spidar spatial resolution is 5 m. The LIDAR delivers data every 5s. Figure 2 presents the array pattern for Phase 1. Each LIDAR is named by its three final serial numbers (LIDAR AG 011, 016, 017, 018, and 019). Note that LIDAR 001 is not part of this initiative. For this setup, the two Spidar nearest the WTGa1 are located 1.5 D (~41 m) upstream the turbine, and the others are at a distance of 2.5 D (~69 m) from the turbine. In this configuration, the five Pentalum LIDAR were in the wake of WTGa1 when northerly winds occurred, and it was during those occasions that the comparison between Spidar and the DTU SpinnerLidar was done. The approximate locations of the instrumentation are noted in Table 1.

Data processing

The Spidar measures horizontal wind velocity at the full range of heights simultaneously. Each wind speed measurement is accompanied by a quality score (Q value) from 0 to 100 (lowest to highest confidence). The quality score is determined based on a combination of several parameters such as correlation level of the current measurement to other 10-min measurements in close measurement ranges and close time stamps. Signal or equipment problems such as low atmospheric reflectivity and heavy fog for the Spidar result in a quality score of 0 (Pentalum, 2016).

Before any analysis, Spidar's manufacturer guidelines (Pentalum, 2016) recommend a filtering process that should consider the measurement quality that results in reasonable data availability. Standard deviation data calculated by the

Table 1. Locations of the instrumentation at the SWiFT facility (GPS coordinates of WTGa1: 33°36’28.6”N 102°02’55.0”W, base elevation 1018.0 m).

Instrument	X (m), North	Y (m), West	Z (m), base height
Turbine (WTGa1)	0.00	0.00	0.00
Met tower—base (METa1)	−69.50	−3.29	0.22
Lidar 011	−41.99	9.39	0.88
Lidar 019	−42.06	−7.26	1.08
Lidar 016	−69.36	20.42	0.93
Lidar 017	−69.70	2.24	1.13
Lidar 018	−69.87	−18.88	1.22

Figure 3. One of the five Pentalum Spidar LIDAR and the DTU SpinnerLidar installed in the WTGa1 nacelle.

Spidar is more sensitive to noise in the signal. (Pentalum, 2016). This project considers the 5 s data for wake effects with the filtering process based on the quality score and the atmospheric conditions data (cloud cover, precipitation, temperature, humidity, etc.) of other instrumentations which will be described below.

The timestamp is a critical feature of this work since the goal is to investigate the development of the wake. Each Pentalum LIDAR measures as soon as it is powered on and works independently of the other LIDAR. Therefore, to be able to check all the Spidar at the same time, the data processing involves a timestamp check to effectively obtain synchronous, instantaneous data across all LIDAR.

Validation

The first campaign data consider the raw and average samples (5 s and 10 min) from Phase 1. A validation process was applied to ensure the system is deemed fit for the project purpose, that is, the accuracy of the cross-correlation method would hold on the wake field motion, besides to observe whether the whole Spidar array was performing to a universal standard.

For specific atmospheric stability, the LIDAR data were binned by the particular inflow and a set of turbine state parameters. The DTU SpinnerLidar data were used to corroborate the Spidar measurements. When the DTU LIDAR captured a wake center near a Spidar, data from the Pentalum LIDAR during that time were analyzed for evidence of a wake. Figure 3 presents one of the Spidar and the DTU SpinnerLidar mounted in the WTGa1 nacelle. In the first step, northerly winds in stable atmospheric conditions were chosen when the turbine was producing power. The SWiFT turbine operating conditions are continuously recorded including the power output, yaw position, blade pitch angle, rotor rotational velocity, and wind speed and direction from the anemometer installed on the nacelle.

Table 2. TTU West Texas Mesonet observations from 6:30 a.m. to 6:55 a.m. (local time) on 24 February 2017.

Time CDT	Temperature (°F)				Dew point temperature	Wind (mph)			Wind speed at 6.5 ft	Altimeter setting	Relative humidity	Rain
	6 ft	6.5 ft	30 ft	ΔT 6.5–30 ft		Direction	Speed	Gust				
6:55 a.m.	29.7	30.5	31.3	−0.8	26.6	004	8	12	4	29.87	89	0
6:50 a.m.	30	30.6	31.4	−0.8	26.8	002	7	9	4	29.87	89	0
6:45 a.m.	30.3	31.1	31.7	−0.6	27.2	001	8	10	4	29.87	89	0
6:40 a.m.	30.3	31.2	31.8	−0.6	27.4	356	9	12	5	29.87	90	0
6:35 a.m.	30.3	31.2	31.8	−0.6	27.6	350	10	12	6	29.87	91	0
6:30 a.m.	30.1	30.8	31.8	−1	27.4	346	9	10	5	29.87	91	0

Source: WTM Weather (n.d.).

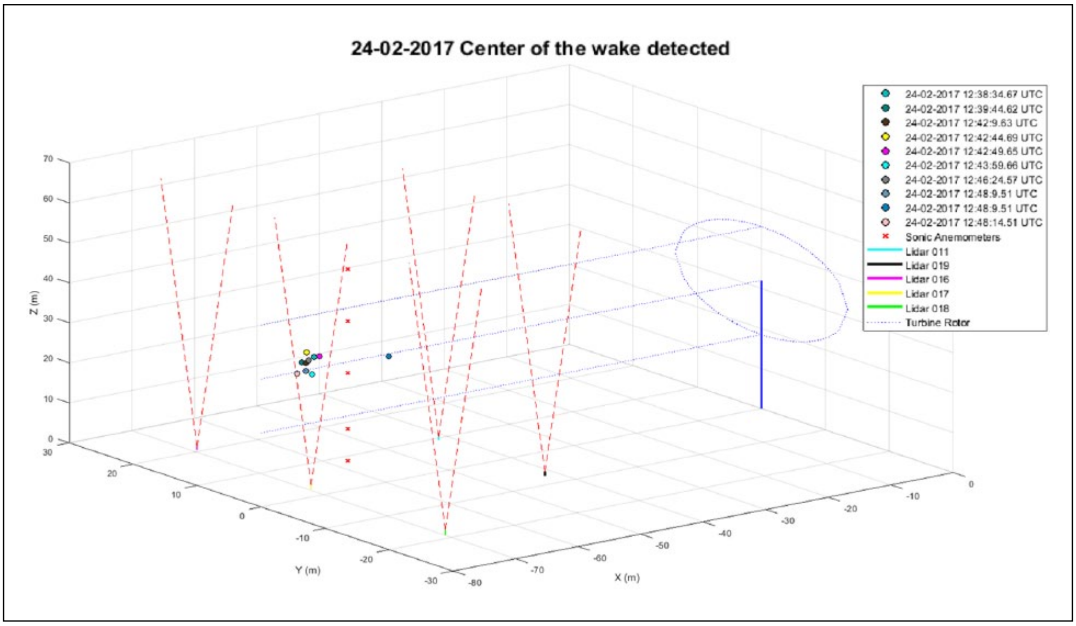

Figure 4. Experimental setup during a period of Northern winds near turbine WTGa1. Dots indicate wake center detected by the DTU SpinnerLidar. Dashed lines indicate location of each Spidar measurement cone.

Results and discussion

The results shown here are to illustrate the data processing and validation through a case study during the first phase. Primary, data were filtered to only include a quality higher than 10%. The chosen data set comes from the measurement sector between 350° and 10° (wind from North) on 24 February 2017, from 12:38 UTC to 12:48 UTC - Universal Time Coordinated (06:35 a.m. to 06:55 a.m., local time, sunrise was at 07:21 a.m.). This sector has been chosen to select stable cases where the turbine wake center is mostly likely to be on the Spidar array and SWiFT site met tower. Most data filtered presented a quality score better than 50%. Thus, the cross-correlation accuracy was found to be valid for this period. For the test, the Spidar wake measurements were also compared with the SWiFT sonic anemometer measurements. Table 2 presents the environmental conditions of that day. The data from the Reese Center station collected by the Texas Tech University (TTU) West Texas Mesonet (33° 36′ 27.32″ N, 102° 02′ 45.50″ W) indicate clear sky, relative humidity of approximately 90%, and no precipitation (WTM Weather, n.d.). The TTU Mesonet is being observed here maintaining the impartiality of the instrumentation since the SWiFT site met station was also in the waked area.

Figure 4 shows the wake locations measured by the DTU SpinnerLidar relative to each Spidar LIDAR and turbine WTGa1 for Northern wind direction. The dashed lines in Figure 4 are a representation of each Spidar measurement cone. It can be observed that most of the data points were in the LIDAR 017 cone. Figure 5 represents the instantaneous velocities measured by each LIDAR as color intensity (white spots are missing/invalid data). The colder the color, the higher

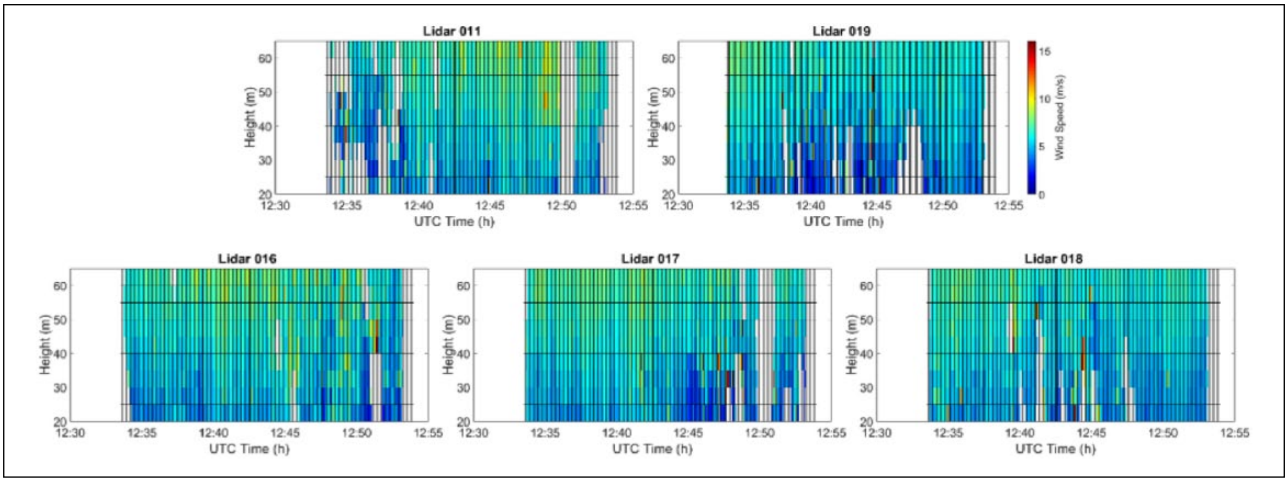

Figure 5. Wind velocity graphs through the selected time interval of each Spidar. Color indicates velocity in 5 s step at all heights. The position of the graphs is an illustration of the field configuration (not to scale). The time range is from 12:33 UTC to 12:53 UTC encompassing the studied interval of 12:38 UTC to 12:48 UTC (06:35 a.m. to 06:55 a.m., local time).

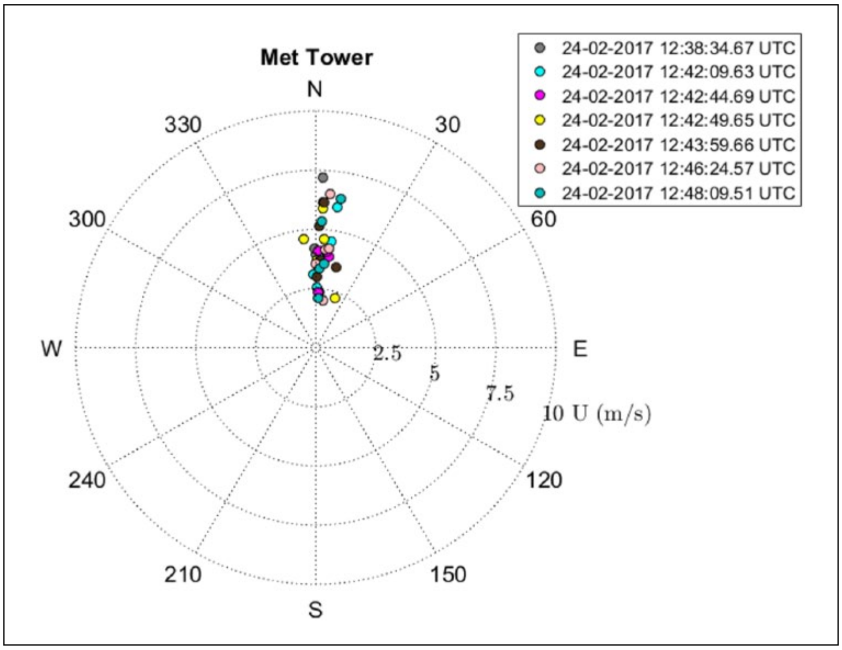

Figure 6. Wind direction for each instant of the studied interval as detected by the SWiFT site sonic anemometer.

the velocity deficit in the wake. The time range shown in Figure 5 is from 12:33 UTC to 12:53 UTC encompassing the studied interval of 12:38 UTC to 12:48 UTC (06:35 a.m. to 06:55 a.m., local time) for inflow consideration. Reminding the rotor is 27 m; within the observation of Figure 5, it is detected a wind heterogeneity in the profiles through the turbine swept area through the time.

Figures 6 and 7 present wind directions in comparison with the SWiFT met tower. Spidar and the met tower have a good agreement regarding the north inflow in general. However, an interesting difference is observed in Figure 7. LIDAR 011 and LIDAR 016 show the data points spread slightly toward the West, while LIDAR 019 and LIDAR 018 data points are primarily centered in the North. Presumably, since the wake is shifted to the West, the Eastern LIDAR cannot detect the wind direction variation.

The instantaneous wind velocity recorded for each Spidar during the selected interval is reported in Figure 8 as a function of their ranges. The wind velocity is normalized by their respective wind velocity recorded at the highest

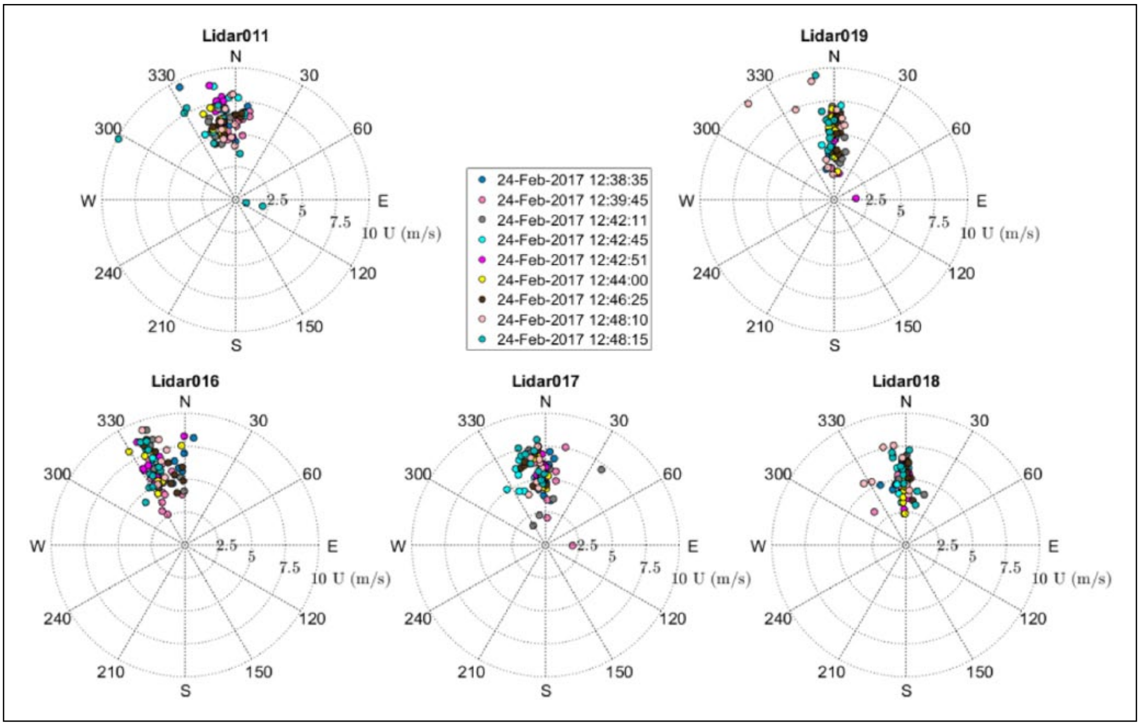

Figure 7. Wind direction for each point of the studied interval as detected by each Spidar. The position of the graphs is an illustration of the field configuration (not to scale).

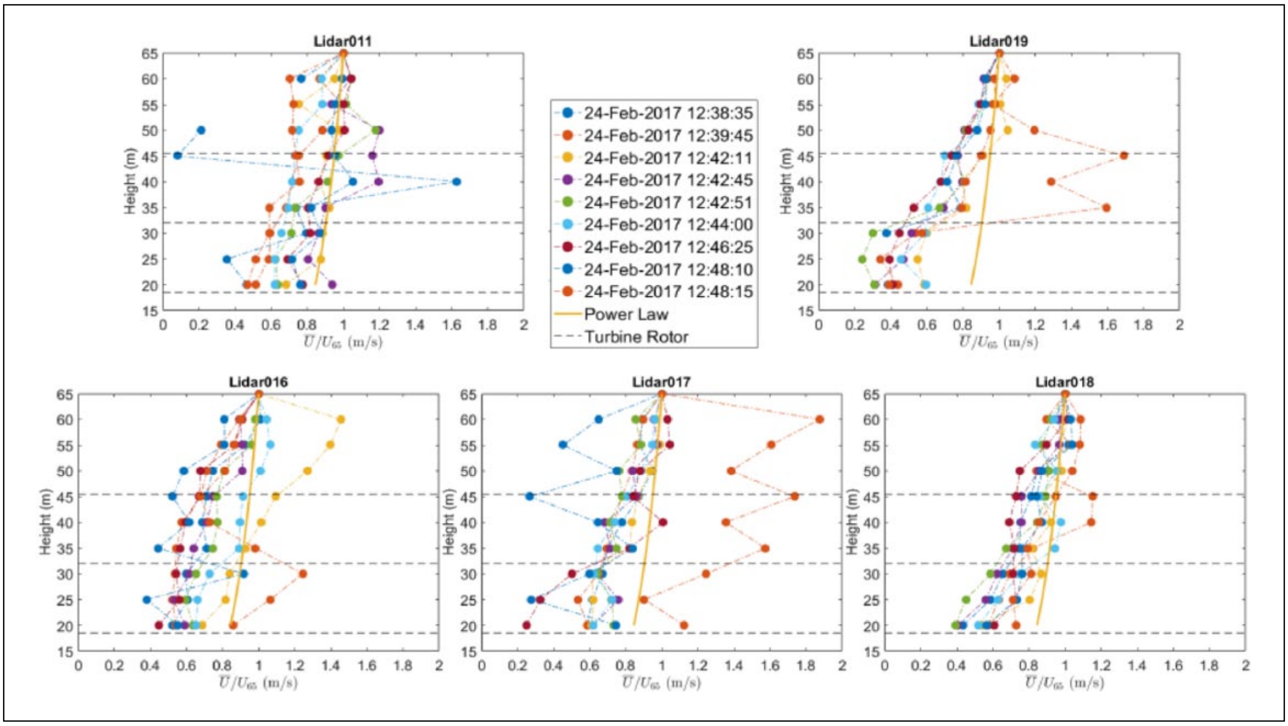

Figure 8. Normalized wind velocity profile for each instant of the studied interval measured each Spidar. The position of the graphs is an illustration of the field configuration (not to scale).

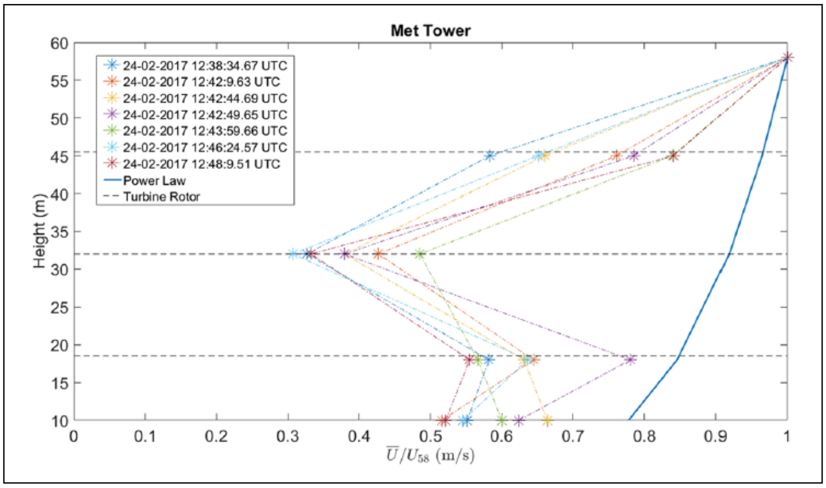

Figure 9. Wind velocity at each instant of the studied interval as detected by the SWiFT site sonic anemometers.

height. Hub height and turbine rotor are also shown in the figures, as the estimated power law is reported with a yellow line, for the Spidar, and purple line, for the met tower. It is noteworthy that all the Spidar at some point indicate an acceleration in the area of the rotor (Figure 8) which does not happen for the met tower in any case (Figure 9). It seems intuitive at first glance to neglect these cases; however, further investigation must be done since the data was manually checked and those values still passed the data filtering criteria employed. Such discrepancy can be an indicative of the large velocity variability inside the wake, as suggested by Figure 5, which cannot be detected by 5 anemometers, but can be detected by the LIDAR array, nevertheless, further investigation is required for definite conclusion.

The preliminary results presented here show that the Spidar is capable of capturing instantaneous wake characteristics under dynamics field conditions. The comparative analysis performed between the Pentalum LIDAR and the DTU SpinnerLidar indicates the LIDAR array is deemed fit for the project purpose. In addition, this setup enables understanding of the extent of lateral inflow variability and its effect during the turbine operation. The wake center detected by DTU SpinnerLidar, for the time period analyzed here, crossed the LIDAR 017 measurement cone. LIDAR 011 and 016 also detected wake perturbation.

Conclusion

The feasibility of observing turbine wake using Pentalum, an array of 5 Spidar LIDAR, has been presented. The wake location was compared with a downwind-facing, nacelle-mounted DTU Spinner and a met tower. The procedure presented in this paper can be perceived as an initial approach of a novel method for detection and validation of wake effects by the LIDAR array, but it is evident further work in needed. The data processing needs to be refined and more wake measurements are needed to achieve a statistical characterization. Future work will also include dual-binning of different atmospheric stability regimes and operating conditions of the turbine.

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