Performance of a Wind-Profiling Lidar in the Region of Wind Turbine Rotor Disks

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ABSTRACT

As the wind energy sector continues to grow, so does the need for reliable vertical wind profiles in the assessment of wind resources and turbine performance. In situ instrumentation mounted on meteorological towers can rarely probe the atmosphere across the full span of modern turbine rotor disks, which typically extend from 40 to 120 m above the surface. However, by measuring the Doppler shift of laser light back-scattered by particles in the atmosphere, remote sensing lidar is capable of estimating wind speeds and turbulence at several altitudes in this range and above. Consequently, lidar has proven a promising technology for both wind resource assessment and turbine response characterization. The aim of this study is to quantify data availability for a coherent detection wind-profiling lidar—namely, the Leosphere Windcube.

To determine situations of suitable data return rates, a Windcube, collocated with a Vaisala CL31 ceilometer, was deployed as part of the Skywatch Observatory at the University of Colorado at Boulder. Aerosol backscatter, as measured by the ceilometer, and lidar carrier-to-noise ratio (CNR) are strongly correlated. Additionally, lidar CNR was found to depend on atmospheric turbulence characteristics and relative humidity in another deployment at a location in the United States Great Plains. These relationships suggest an ability to predict lidar performance based on widely available air quality assessments (such as PM2.5 concentration) and other climatic conditions, thus providing guidance for determining the utility of lidar deployments at wind farms to characterize turbine performance.

1. Introduction

The importance of reliable vertical wind profiles for both resource assessment and evaluation of turbine performance continues to rise with the rapidly escalating use of wind power in both domestic and worldwide energy production. Meteorological towers used to collect wind data, however, are usually constructed no higher than 60 m in the United States for reasons concerning structural stability, cost, and zoning regulations. With hub heights of 80–100 m and rotor diameters of 80 m or more, modern wind turbines are so tall that in situ instrumentation mounted on meteorological towers can rarely probe the atmosphere across even the lower half of the rotor disk. And while turbine nacelles may be equipped with cup and sonic anemometry, hub-height point measurements are not representative of the wind speeds over the entire swept area of the rotor (Wagner et al. 2009). As a result, remote sensing techniques, such as lidar and sodar, will play an increasingly prominent role in the measurement of atmospheric conditions at wind farms. In particular, the Leosphere Windcube, a pulsed coherent Doppler wind lidar, is capable of measuring wind speeds within a claimed uncertainty of 0.1 m s\(^{-1}\) at 10 different altitudes greater than 40 m above ground level (AGL). Yet the availability of wind speed measurements, quantified by the carrier-to-noise ratio (CNR) of the laser signal, is dependent upon weather conditions such as aerosol backscatter, turbulence, humidity, and precipitation. By examining the impact of these four parameters on CNR, this study aims to determine the most appropriate circumstances for implementing wind lidar in the assessment of turbine performance. Despite particular reference to the Windcube, our results and experience may serve to guide characterization of other lidar systems, such as Natural Power’s ZephIR and SgurrEnergy’s Galion as well.

2. Background and previous work

In optical remote sensing, it is possible to image features on the order of the signal wavelength or larger. Typically operating in the visible or near-infrared range,
The measured speed of light, $c$, is the speed of light, and $b$ is Planck’s constant. The frequency, $B$, is the oscillation frequency, and $r$ is the round-trip coherence length, defined as

$$r = 0.627(k^2 C_n^2)^{-3/5}$$

for uniform turbulence conditions. Here, $k$ is the wave number of the signal, $C_n^2$ is the refractive index structure parameter, and $z$ is propagation distance. High values of $C_n^2$ on the order of $10^{-13}$ to $10^{-12}$ m$^{-2/3}$ are indicative of a strongly turbulent atmosphere; for lower values on the order of $10^{-16}$ to $10^{-15}$ m$^{-2/3}$, atmospheric optical turbulence is considered negligible over optical paths of less than 2 km (Tunick 2003). Figure 1 shows the theoretical reduction factor versus $C_n^2$ for the Windcube at 40 m AGL. Although nearly unaffected for weak and moderate turbulence levels, CNR can be reduced by 20%–80% in the strong turbulence regime.

Aerosol scattering is a complex function of refractive index and particle size, both of which depend on relative humidity (RH). Although the refractive index tends to
decrease with increasing humidity, this effect is small and is dominated by the swelling of hygroscopic particles near the saturation point. Wulfmeyer and Feingold (2000) found that scattering remains nearly constant for low-to-moderate levels of humidity and increases rapidly for RH > 0.8. It is also possible for the lidar signal to scatter from water droplets, enhancing CNR during precipitation events but also causing a false indication of vertical wind speed.

In summary, the primary atmospheric conditions expected to influence CNR, and thus lidar performance, are aerosol backscatter, atmospheric refractive turbulence, relative humidity, and precipitation. The effects of each are examined using the two datasets described in the following section; observations are presented in section 4.

3. Data and methods

A Windcube lidar was deployed in late summer 2010 as part of the Skywatch Observatory—a set of meteorological instruments on the roof (approximately 15 m AGL) of the Duane Physics building at the University of Colorado at Boulder, elevation 1663 m. Backscatter was measured at a vertical resolution of 10 m from ground level to 7690 m AGL using a Vaisala CL31 ceilometer, which has an operational wavelength of 910 nm and was also located on the roof, approximately 5 m east of the Windcube. Similar to the Windcube, the ceilometer consists of a vertically pointing laser and a collocated receiver. Short laser pulses are sent through the atmosphere, and a small component of the light is scattered by aerosols, water droplets, and low-level clouds and then returned to the receiver. The strength of the returned signal is recorded and its timing is transformed into a spatial range using the speed of light, thus producing a vertical profile of backscatter within the atmosphere. Measurements of lidar CNR and ceilometer backscatter were collected at heights of 40, 50, 60, 80, 100, 120, 140, 160, 180, and 200 m throughout August 2010; see Fig. 2. (Please note that all further references to backscatter measurements should be understood to come from the ceilometer.) Lidar and ceilometer data were taken at rates of 1 and 0.0625 Hz, respectively, and then averaged over 2-min intervals for comparison.

In addition, a second dataset was collected with the Windcube at the same altitudes during a deployment at a wind farm in central Iowa in late June and early July 2010. A flux station 142 m due west of the Windcube collected measurements of wind speed, temperature, and absolute humidity at 20 Hz. Wind speed and temperature were measured at 6.45 m AGL with a Campbell Scientific sonic anemometer (CSAT3), while absolute humidity measurements were collected by a Li-Cor LI-7500 gas analyzer at this same height. Precipitation and relative humidity were also measured at this same flux station with a Campbell Scientific tipping-bucket rain gauge (TE525) at 3 m AGL and a Vaisala probe (HMP45) at 9 m AGL, respectively. A sketch of the flux station measurements is provided in Fig. 3. These data were used to determine momentum flux, heat flux, and latent heat flux over 30-min averaging periods; in turn, the refractive index structure parameter was then calculated and compared to the lowest available CNR measurement at 40 m AGL. Following Andreas (1988), $C_n^2$ is given by

$$C_n^2 = z^{-2/3}(A t_o + B q_o) g(\zeta),$$

where $z$ is altitude and $\zeta = z/L$ is the stability parameter. Here, the length scale is the Obukhov length

$$L = \frac{\nu^2}{\kappa g} \left[ t_o + \frac{0.61 T}{\rho + 0.61 Q q_o} \right]^{-1},$$

where $\gamma$ is the acceleration of gravity, $\kappa = 0.4$ is von Kármán’s constant, $T$ and $Q$ are representative values of temperature and absolute humidity in the surface layer, and $\rho$ is the density of moist air. The temperature and humidity scales are defined as
respectively, where $u_0$ is the friction velocity, $w$ is vertical wind velocity, and primes indicate turbulent fluctuations from the mean, while the similarity function is

$$g(\xi) = \begin{cases} 4.9(1 - 6.1\xi)^{-2/3} & \text{for } \xi \leq 0 \\ 4.9(1 + 2.2\xi^{2/3}) & \text{for } \xi \geq 0 \end{cases}$$

For visible and near-infrared wavelengths (0.36–3 μm), the coefficients $A$ and $B$ are

$$A = -10^{-6} m_1(\lambda) (P/T^2)$$
$$B = 4.62 \times 10^{-6} [m_2(\lambda) - m_1(\lambda)],$$

where $P$ is atmospheric pressure measured in hectopascals, $T$ is temperature measured in kelvins, and

$$m_1(\lambda) = 23.7 + \frac{6840}{130 - \lambda^2} + \frac{45.5}{38.9 - \lambda^2}$$
$$m_2(\lambda) = 64.9 + 0.581\lambda^{-2} - 0.00712\lambda^{-4} + 0.000885\lambda^{-6}$$

are functions of wavelength $\lambda$ in micrometers. For the Windcube ($\lambda = 1.54 \mu m$), then, the two coefficients are $A = -7.77 \times 10^{-5} (P/T^2)$ and $B = -5.80 \times 10^{-5}$.

### 4. Results

Lidar performance is expected to be influenced by aerosol backscatter, atmospheric refractive turbulence, humidity, and precipitation. The effects of these parameters are examined in the following subsections.

#### a. Aerosol backscatter

From section 2, CNR is expected to be linearly proportional to the backscatter coefficient at fixed altitude in the absence of turbulence. In Fig. 4, CNR and $\beta$ at 100 m AGL are compared for the week 22–29 August 2010 in Boulder; note the logarithmic scale on the horizontal axis, as CNR is measured in decibels. The correlation coefficient is 0.7, indicating a fairly high degree of linear dependence between the variables. Outliers are likely due to variations in atmospheric conditions, such as turbulence and humidity.

Accordingly, the maximum available altitude (MAA) of the Windcube—defined as the highest altitude for which CNR $>-22$ dB at a given measurement time—should be influenced by the amount of aerosol backscatter. For each Windcube measurement during the month of August 2010, the MAA was determined along with the corresponding backscatter coefficient at that height. The points in Fig. 5 represent the average level of backscatter corresponding to each MAA, and the error bars indicate the standard deviation of each set; the rightmost point actually represents all altitudes greater than or equal to 200 m, thus the larger standard deviation for this point than the rest. To verify the trend in Fig. 5, one must consider both the average CNR at each MAA and the range-dependent collection efficiency of the Windcube (see Fig. 6)—which Lindelöw (2007) modeled using the results of Sonnenschein and Horrigan (1971)—since...
from Eq. (1) backscatter varies as $\beta \sim (\text{CNR}/\eta)R^2$. Indeed, Fig. 7 shows that the left- and right-hand sides of this proportionality are linearly related for the 10 distinct MAAs, with a correlation coefficient of 0.932.

To relate lidar performance to air quality assessments, we note that optical backscatter and PM$_{2.5}$—a measurement of the concentration of atmospheric particles less than 2.5 $\mu$m in diameter—have been found to be highly correlated in the lowest 200 m of the boundary layer (Charles et al. 2007). A similar relationship is thus expected between CNR and PM$_{2.5}$. Hourly measurements of PM$_{2.5}$ at a resolution of 1 $\mu$g m$^{-3}$ were available for the first two weeks of August in Boulder from an air monitoring station located approximately 500 m due north of the Windcube and operated by the Colorado Department of Public Health and Environment. Indeed, as indicated in Fig. 8, greater concentrations of particulate matter correspond to higher levels of CNR in general. Notably, Fig. 9 shows that, on average, a concentration of just 2–3 $\mu$g m$^{-3}$ is required for a maximum range of 120 m—a height corresponding to the top of the rotor disk of a typical modern wind turbine. By comparison, the average annual PM$_{2.5}$ concentration for 766 monitoring stations across the United States has hovered between 11 and 13 $\mu$g m$^{-3}$ over the last decade, and just 10% of sites measured average annual concentrations of less than 8 $\mu$g m$^{-3}$ in that time span (U.S. Environmental Protection Agency 2010). While particulate matter concentrations obviously vary with location and time, these results suggest that the Windcube is generally well suited for wind energy applications throughout much of the United States.
Also noteworthy is that the Boulder dataset exhibits a regular diurnal cycle in CNR, inducing a diurnal pattern in the MAA of the Windcube. The diurnal variation of CNR at 40 m AGL was averaged over the days of August 2010 in Boulder and can be seen in Fig. 10. Typically reaching a local minimum in early morning around 0600 local time (LT), CNR increases as aerosols are lifted with the development of convective conditions after sunrise. Countering this effect is the increase of the boundary layer height, which tends to lower aerosol concentration with the entrainment of cleaner air from above, and thus CNR reaches a peak in mid- to late morning. The local maximum around 1500 LT is due to rain, which is a common occurrence in midafternoon for the local climate. The last local maximum near 1730 LT is likely the result of increased vehicular aerosol emissions during rush hour. Although the height of the boundary layer diminishes after sunset, anthropogenic aerosol production also decreases and aerosols close to the surface are lost by sedimentation, leading to lower CNR. This diurnal cycle—due to variations in local anthropogenic activity, meteorological conditions, boundary layer height, and removal mechanisms—is typical of urban areas (Gomes et al. 2008). A similar pattern is apparent for the average diurnal variation of MAA in Fig. 11, which indicates how high the Windcube can be expected to operate throughout the course of the day. On average, the MAA in summertime Boulder ranges from about 140 m AGL in early morning to about 180 m AGL just before noon—well above the reach of modern turbine blades.

b. Atmospheric refractive turbulence

While aerosol backscatter exerts the primary influence on CNR, strong levels of atmospheric refractive turbulence can cause signal degradation. Unfortunately, independent flux measurements for quantifying the effect of atmospheric refractive turbulence on lidar performance were only available during the field campaign in Iowa. From Fig. 1, CNR should only noticeably decrease in strongly turbulent conditions—say $C_n^2 > 5 \times 10^{-14} \text{m}^{-2/3}$—a situation that occurred less than 1% of the time in Iowa. Because refractive turbulence levels were most often weak or moderate, there is no discernible relationship between the two variables, as indicated in Fig. 12. Despite the fact that the lowest available CNR measurement at 40 m AGL is compared to $C_n^2$ at 9 m, refractive turbulence is expected to be even weaker at 40 m based on several boundary layer models (Lawson and Carrano 2006).
c. Humidity and precipitation

Figure 13 shows the effect of RH on CNR during the Iowa field deployment. The bold black line is a non-linear regression of the form $\text{CNR} = a(1 - \text{RH})^b$, following the regression for backscatter versus RH used in Im et al. (2001). Here, $a = -16.3$ and $b = 0.0734$. There is almost no correlation for RH $< 0.8$, but CNR does increase above this level of humidity, thus confirming the results in Wulfmeyer and Feingold (2000); the increase is especially sharp near saturation. During August 2010 in Boulder, which has a high desert climate, RH was never greater than 0.9 even during precipitation events: CNR and RH were almost completely uncorrelated for this time period.

One possible advantage of lidar over sodar technologies is that sodar is known to collect erroneous measurements during precipitation events. Although the manufacturer suggests that the Windcube is capable of taking measurements during periods of rain, Fig. 14 indicates that measurements of vertical velocity are likely invalid; horizontal velocity measurements may be uncontaminated (Albers and Janssen 2008). During precipitation events, $w$ ranges between 1 and 5 m s$^{-1}$, which is of the same order as the terminal velocity of a raindrop (Foote and du Toit 1969) and almost certainly too large to be actual vertical wind speed, as no microbursts or similar type of meteorological phenomena were reported to be in the area at the time according to forecast discussions released by the National Weather Service. Similarly, previous studies, such as Gottschall and Courtney (2010), have found it necessary to filter out Windcube data in the presence of rain. Thus, rain may interfere with operation of the Windcube, and measurements of vertical velocity during precipitation events must be evaluated with caution.

d. Summary of data availability

A comparison of data availability at different heights for the Boulder and Iowa field deployments can be seen in Fig. 15; note that the data availability in Iowa is higher at all altitudes. Additionally, the fractional occurrence of a particular MAA was calculated by dividing the number of measurements for which that height was the maximum available by the total number of Windcube measurements in the given dataset. Figure 16 compares the occurrence of each MAA in Boulder and Iowa. The Windcube could “see” at or above 200 m only about 20% of the time in Boulder, whereas measurements were available at or above this height over half the time in Iowa.

The mean PM$_{2.5}$ concentrations during the month of August 2010 in Boulder and during the Iowa field deployment were 5.7 and 8.2 $\mu$g m$^{-3}$, respectively, suggesting that the improved Windcube performance in Iowa can probably be explained by higher concentrations of particulate matter. While humidity was higher in Iowa than in Boulder, PM$_{2.5}$ is expected to be the dominant influence on optical backscatter and, hence, on CNR. We hesitate to attribute the greater amount of
data availability in Iowa to the effects of humidity with such a limited dataset, especially since PM$_{2.5}$ and humidity tend to be negatively correlated (Sharma et al. 2005).

5. Conclusions

To determine situations of acceptable data availability, the theoretical parameter dependence of lidar CNR has been investigated in the field using a Windcube. The four most significant factors found to influence lidar performance are aerosol backscatter, atmospheric refractive turbulence, humidity, and precipitation. In summary, Windcube CNR tends to be higher during the day than at night and is linearly proportional to aerosol backscatter, which is highly correlated to PM$_{2.5}$ in the lowest part of the boundary layer. Because CNR is proportional to the inverse of the square of propagation distance, more backscatter is needed at higher altitudes for suitable data return. Accordingly, it should be possible to monitor Windcube performance during future field deployments by using a ceilometer to measure vertical aerosol concentrations and the height of the boundary layer. Although the loss due to atmospheric refractive turbulence can be quite severe in theory, such strongly turbulent conditions did not occur in the present datasets even though data were taken in midsummer daytime, and therefore this effect could not be discerned. While practically uninfluenced by low levels of humidity, CNR increases sharply near the saturation point. Windcube performance is adversely affected by precipitation, as rainfall is measured instead of vertical wind speed.

Overall, our results show that lidar can be expected to reliably provide profiles of wind speed, direction, and turbulence intensity at altitudes within a typical wind turbine rotor disk. The average hub height and rotor diameter of wind turbines installed in 2009 in the United States was 78.8 and 81.6 m, respectively (Wiser and Bolinger 2010), meaning that measurements between about 40 and 120 m above the surface will be required for accurate resource assessment and evaluation of turbine performance at modern wind farms. In particular, for the Windcube considered in this study, data were available up to 120 m AGL more than 90% of the time both in Boulder and at a wind farm in the Great Plains. Given that the mean PM$_{2.5}$ concentrations during both experiments were below the national annual average, this type of lidar seems a promising candidate for widespread use in the wind energy industry, especially at humid sites characterized by relatively high concentrations of particulate matter.

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