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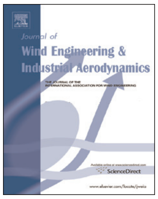

Measuring turbine inflow with vertically-profiling lidar in complex terrain

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ABSTRACT

Two Laser and Detection Ranging (lidar) units were deployed in the Altamont Pass region of California to study complex flow dynamics at a moderately complex terrain wind farm. The lidars provided wind measurements at the base and along the slope of a 140 m tall ridge and captured air flow as it moved up and along the ridge towards an unwaked turbine under varying stability conditions. Elevation enhanced wind speed during well-mixed or near-neutral conditions at the top of the ridge; however, the hill “speed-up” was smaller than expected during stable conditions. At these times the upwind terrain played a significant role in local flow variability as did terrain features within the wind farm. The observations were next analyzed to assess the ability of using vertically-profiling lidar in complex terrain to measure free-stream inflow for evaluating power generation response. Better agreement between the lidar wind speed and expected power was found once the lidar measurements had been adjusted for stability-dependent hill speed-up effects. This suggests that vertically-profiling lidar can be used in complex terrain to measure inflow if the terrain-induced flow features are also considered.

1. Introduction

Wind farm estimations of the local wind resource and evaluations of turbine power performance are largely based on methodologies prescribed by the International Electrotechnical Commission (IEC) 61400-12-1 Standard (IEC, 2007). These standards require that free-stream wind measurements, used for turbine siting and generating measured power curves, be made using calibrated cup anemometers on an upwind meteorological tower. To date, there is no formal recommendation by the IEC regarding the alternative use of remote sensing devices such as laser detection and ranging (lidar) or sound detection and ranging (sodar) instruments for measuring the free-stream wind. Yet, these systems have some advantages over traditional meteorological towers, including their ease of mobility and ability to measure multiple flow characteristics (e.g., shear, veer, velocity, turbulence) across the full turbine rotor-disk profile. In attempts to fill this void the International Energy Agency (IEA) Wind Task Group Expert Group recently published a guide of recommended practices for ground-based, vertically-profiling remote sensing systems for wind resource assessment (IEA, 2013). The guide provides recommendations on installing, operating, and processing lidar data to produce accurate measurements of wind speed and direction with remote sensing instruments. It also stresses the need for additional field studies, particularly in complex terrain, to better quantify the limitations of using lidar to measure free-stream wind flow at wind farms.

Wind turbines are frequently sited along the crest of hills or ridgelines to take advantage of terrain-enhanced flows. While complex terrain can favor increased wind speeds, it also can cause uncertainty in the expected wind field as the wind profile no longer follows the classical logarithmic wind speed profile (e.g., Panofsky and Ming, 1983; Kaimal and Finnigan, 1994). The effect of terrain also makes it difficult to predict turbine power generation based on observed wind conditions; it becomes increasingly hard to accurately measure the free-stream flow or “inflow” into the turbine as the topography becomes more complex. The IEC 61400-12-1 Standard recommends that wind measurements be taken 2–4 rotor disk lengths in front of a turbine to capture un-obstructed, free-stream inflow (IEC, 2007). In flat homogenous terrain, these measurements are likely a close representation of the actual wind conditions experienced by the turbine; however, in complex terrain this is no longer true as changes in terrain and surface roughness alter the flow's mean wind speed, direction and scales of turbulence.

Here, we present high-resolution, multiple lidar observations from a wind farm in the Altamont Pass Wind Region of California,

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USA for the purposes of measuring the free-stream wind flow, including any changes in wind speed, direction and turbulence as air moved up and along an elongated ridge towards an unwaked turbine. In addition, we quantitatively assess the use of lidar wind speed measurements in complex terrain for providing inflow data into measured power curves. This paper is motivated by an earlier study done at the identical wind farm by Bulaevskaya et al. (2015). In that study the authors used lidar measurements as input into statistical power curve models to estimate power generation uncertainty. Measurements made during the single lidar campaign suggested the presence of significantly large velocity accelerations or hill "speed-ups" encountered by the evaluated turbine, e.g., the nacelle wind speed was often higher than the lidar measurements. With this finding in mind, we designed here a multi-lidar campaign to further study the speed-up behavior of wind flow as it approached the ridgeline turbine. The specific goals of the present study are to (1) characterize the local flow features at the Altamont Pass wind farm, (2) quantify the magnitude of hill "speed-ups" under different atmospheric stability conditions, (3) evaluate the use of vertically-profiling lidar for measuring free-stream inflow in complex terrain, and (4) evaluate the accuracy of measured power curves using the lidar inflow data.

2. Hill flow theory

As air travels over a complex landscape changes occur to the mean and turbulent components of the flow. These changes may include a decrease or increase in wind shear, wind veer and/or turbulence, and occurrences of negative wind shear (e.g. katabatic flow), lee-side flow separation, and hilltop flow acceleration (e.g., anabatic flow). Here, we concentrate on the latter, as hilltop flow acceleration is the primary reason for the siting of turbines on ridgelines. The acceleration of flow over a hill or ridge crest (i.e., hill "speed-up") is due to a pressure minimum that develops at the top of the hill and is accompanied by streamline convergence on the windward side (e.g., Taylor et al., 1987; Kaimal and Finnigan, 1994). A hill speed-up (Δs) expression can be used to describe the fraction of change in the wind speed above a hill or ridge to the approaching undisturbed wind speed. Following Eq. (1), Δs is a function of the difference between the mean velocity on the top of the hill and the upwind mean velocity (Coppin et al., 1994):

$$\Delta s(x,z) = \frac{\bar{U}(x,z) - \bar{U}_0(z)}{\bar{U}_0(z)} \tag{1}$$

where $\bar{U}(x,z)$ is the mean wind speed at the top of the hill and $\bar{U}_0(z)$ is the upwind mean wind speed.

The hill speed-up phenomenon has been studied extensively, in part, using linearized theory based on Jackson and Hunt (1975). This early theory for a simple two-dimensional hill has been expanded and tested to include three-dimensional hills (Hunt et al., 1988a), rougher surfaces (e.g., Finnigan et al., 1990; Cao and Tamura 2006), steeper slopes (e.g., Arya et al., 1987; Weng et al., 2000), escarpments (e.g., Lemelin et al., 1988; Imamura et al., 2003), elongated ridges (e.g., Sacré 1979; Coppin et al., 1994) and effects of thermal stability (e.g., Hunt et al., 1988b; Coppin et al., 1994; Takahashi et al., 2005; Bleeg et al., 2015). Following Hunt et al. (1988b), flow over a simple hill is characterized into three flow regions: an inner layer, middle layer, and outer layer. The inner layer is defined as the region where the flow field is in equilibrium with the surface and flow acceleration, pressure gradient, and divergence of the turbulent momentum flux are all important. In the middle layer the flow is inviscid and rotational and outer layer flow is described as inviscid and irrotational. The outer layer describes the height at which shear in the upwind profile is no longer significant. Δs should be highest in the inner region, although during stable or strongly stable conditions Δs in the middle and outer layers can also be significantly large (Coppin et al., 1994).

Table 1
Characteristics of the studied ridge and experimental details. D is rotor diameter distance. $z_o \sim 0.10{*}$canopy height.

Ridge characteristics		Experimental details	
Length of elongated ridge	~ 3 km	Base lidar elevation	120 m a.s.l.
Ridge height (h)	140 m	Hill lidar elevation	220 m a.s.l.
Ridge length (L)	740 m	T08 elevation	260 m a.s.l.
Ridge half length (L_h)	362 m	Base lidar distance to T08	630 m or 10.3 D
Mean ridge slope	10°	Hill lidar distance to T08	220 m or 3.6 D
Surface roughness (z_o)	~0.02 m	Bearing of lidars from T08	238°

Modern wind turbines generally sit in the fluctuating middle layer although this can change when the atmosphere becomes more stable or more convective. In this study we did not have the necessary measurements to calculate specific layer depths under different stability regimes; instead the calculations for near-neutral conditions are presented here. In near-neutral flow, the inner-layer depth (l) (m), following Hunt et al. (1988a), is calculated from Eq. (2):

$$\frac{l(\ln(l/z_o))}{L_h} = 2k^2 \tag{2}$$

where z_o is the roughness length (m), L_h is the hill-half length (m), and k is the von Karman constant (0.4). The values for z_o and L_h are listed in Table 1. The middle layer height (h_m) (m) for near-neutral flow is calculated from Eq. (3):

$$h_m = L_h\left[\ln\left(\frac{L_h}{z_o}\right)\right]^{-1/2} \tag{3}$$

These expressions are based on a simple, isolated hill in near-neutral conditions. In contrast, wind farms in non-flat terrain are almost always placed in locations with far more complex topography (e.g., non-isolated ridgelines, forested hills, etc.) and full range of stability conditions. Even so, it is beneficial to evaluate how the linearized theory of Jackson and Hunt (1975) and Hunt et al. (1988a) compares to real field cases as linearized flow models commonly used in the wind industry, e.g., WAsP (Mann et al., 2002), rely on these assumptions (Bleeg et al., 2015).

3. Site description and wind climatology

The wind farm studied here is located in the Altamont Pass Wind Region in Northern California, approximately 70 km east of San Francisco. The exact location and name of the wind farm are proprietary information; for our purposes here, the farm is referred to as the Altamont Pass Wind Farm. The farm consists of 38, EC Class IIA horizontal-axis turbines which are located along the top of roughly parallel ridgelines. The wind turbines are blade-pitch controlled, 1 MW Mitsubishi (MWT62-1000 A). Cut-in speed is 3.0 m/s, rated speed is 12.5 m/s, and cut-out speed is 25.0 m/s. Hub-height is 55 m, rotor diameter is 61.4 m and blade length is 29.5 m. This puts the minimum blade distance above ground at 24 m and maximum blade distance above ground at 86 m.

The terrain upwind of the Altamont Pass Wind Farm is moderately complex and includes the Cañada de los Vaqueros hills in the Diablo Range (Fig. 1). Locally, the hills and ridgelines have