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A comparison of ground-based LiDAR and met mast wind measurements for wind resource assessment over various terrain conditions

Daeyoung Kim[a], Taewan Kim[b], Gwanjun Oh[c], Jongchul Huh[d], Kyungnam Ko[e,*]

[a] Applied Meteorology Research Division, National Institute of Meteorological Research, Korea Meteorological Administration, Jeju, South Korea
[b] Namjeju Thermal Power Plant Wind Farm Management Team, Korea Southern Power Cp., Ltd, South Korea
[c] DoArm Engineering Co., Ltd, 86-9, Cheomdanro 8 Gil, Jeju, South Korea
[d] Dept. of Mechanical Engineering, Jeju National University, 102 Jejudaehakro, Jeju, South Korea
[e] Faculty of Wind Energy Engineering, Graduate School, Jeju National University, 102 Jejudaehakro, Jeju, South Korea

A R T I C L E I N F O

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A B S T R A C T

In order to assess reliability of measurements from LiDAR (Light Detection and Ranging), a measurement campaign was led using ground-based LiDAR of WINDCUBE V2 and meteorological masts at three measurement sites: Sumang, Gangjeong, and Susan, on Jeju Island, Korea. Each site had a different topographical complexity, which was evaluated by using a Ruggedness Index (RIX). Wind data was collected for 11–14 days from four heights on each site's met mast. Data filtering was done to ensure data comparability between LiDAR and wind sensors. Analyses of LiDAR error, standard deviation, turbulence intensity and LiDAR error rate were conducted on data coming from each site. Also, the CFD analysis was performed at Sumang with the highest RIX. As a result, the concurrent wind measurement slopes were all close to one based on linear regression analysis. The coefficient of determination was almost all more than 0.9 for all heights at each site. LiDAR error rates for the measurement sites ranged approximately between 2% and 6%. The result of the CFD analysis showed that the depression was formed between two parasitic cones, between which the measurement point of Sumang was located, which led to greater positive LiDAR error.

1. Introduction

Accurate wind resource estimation is important for developing efficient wind farms. The conventional method of measuring wind conditions is using a cup anemometer and wind vane (IEC, 2005), because the related technologies and the measurement uncertainty are well- established (e.g., Kristensen, 1998; Paradopoulos et al., 2001; Pedersen, 2003). The cup anemometer should not be affected by flow distortion due to surrounding terrain and obstacles, and should be installed near the hub height of a wind turbine.

In the past few years, wind turbine sizes have increased continuously, which has led to increasing hub heights. However, it is very expensive and time-consuming to measure wind data over 100 m above ground level (a.g.l.) using cup anemometers on traditional met masts. In general, the measurement height is lower than the hub height, which may result in inaccurate wind resource assessment due to extrapolating from recorded wind speeds at the lower measurement height and interpolating from those recorded at the hub height. For these reasons, it is necessary to find an alternative method to substitute the conventional method for wind measurement using cup anemometers and wind vanes on met masts.

For the last few years, instead of met masts, the application of remote sensing techniques via instruments such as SoDAR (Sonic Detection And Ranging) and LiDAR (Light Detection And Ranging) has grown in popularity for wind resource measurement. Higher vertical resolution measurement through the swept area of a wind turbine can be carried out using ground-based LiDAR (e.g., Banta et al., 2015; Emeis et al., 2007). However, it is essential to understand the advantages and disadvantages of LiDAR technique before accepting it as a standard wind measurement technique. In Europe, many verification campaigns have been conducted to approve LiDAR as the standard measuring device for wind resource assessment and power performance measurements in the IEC (International Electro-technical Commission) standards (e.g., Gottschall et al., 2010; Peña et al., 2009).

A comparison of measurements for 3 months from the QinetiQ ZephIR LiDAR and a 100 m-height met mast was done in the North Sea off the German coast in 2007. In this campaign, the correlation coefficient was close to 1, although the values of regression line slopes of LiDAR versus met mast wind speeds decreased with height a.g.l. (Kindler et al., 2007). The comparison was done using wind data measured by cup anemometer up to 100 m and continuous wave (CW)

* Corresponding author.
E-mail address: gnkor2@jejunu.ac.kr (K. Ko).

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LiDAR (ZephIR). It showed a linear regression line slope of 0.96~0.99 for flat and homogeneous terrain (Smith et al., 2006). It was reported by Shu et al. (2016) that the correlation coefficient between CW LiDAR and met mast wind speed measurements were more than 0.99 with a regression slope of 1.0–1.03.

On the other hand, wind speed data from the LiDAR system yielded differences of 4~6% from those of cup anemometers for complex terrain (Brower, 2012). A wind velocity deficit of about 6% was found between measurements of the LiDAR and anemometers for complex terrain by Foussekis et al. (2009). There was 4~7% error reported in wind speeds from LiDAR and anemometers, depending on the values of the Ruggedness Index (RIX) for two types of complex terrain (Bingöl et al., 2009).

Overall, LiDAR system wind measurements have been similar to those taken from anemometers and wind vanes for flat terrain. However, over complex terrain, the LiDAR system can lead to larger errors in wind speeds than over flat terrain.

As the CFD models are developed (e.g., Ayotte, 2008; Jackson et al., 2011; Prospathopoulos et al, 2012), these techniques has been applied to correct the measurements bias over complex terrain (e.g., Behrens et al., 2012; Harris et al., 2010; Indasi et al., 2012). Also the LiDAR and CFD analysis has been done together in complex and rough terrains for estimating wind profile in detail (e.g., Jeannotte et al., 2014). However, these sophisticated CFD models may present over-compensation (Bradley et al., 2015).

As mentioned above, the studies on LiDAR measurements validation have been carried out continuously. However, it is still necessary to verify wind measurements from LiDAR and reduce the uncertainty of LiDAR measurements over various complexities of terrain. In this study, we verified measurements from ground-based LiDAR over the three measurement sites on Jeju Island, South Korea, each with different terrain conditions. In addition, the CFD analysis was carried out on the most complex terrain of the three sites in order to estimate the terrain effect on wind speed when measured using anemometers on a met mast.

2. Description of the test site and measurement conditions

Fig. 1 shows the three measurement sites of Jeju Island, off the southern coast of Korea. Halla mountain (1950 m) is located in the centre of the Island, and hundreds of parasitic cones are spread throughout the Island. The parasitic cone (also called a satellite cone) is a small volcano located on the main ridge of a large volcanic crater. It is similar to a hill in shape.

The measurement sites were Gangjeong, Sumang and Susan. Gangjeong is situated on the coast without any obstacles. Sumang and Susan are surrounded by multiple parasitic cones which are covered with bush and forest. More detailed description for the measurement sites is shown in Table 1.

Table 1
Description of measurement sites.

Parameter		Sumang	Gangjeong	Susan
Location	Latitude	33°21′9.94′′N	33°13′37.67′′N	33°27′25.97′′N
	Longitude	126°40′20.45′′E	126°28′24.03′′E	126°51′3.88′′E
Altitude [m]		362.2	2.63	113.58
Terrain condition		Middle mountain area	Coastal area	Middle mountain area

Fig. 2 shows three-dimensional images of each measurement site, taken from 10 km×10 km terrain maps. The black points in the images indicate the measurement spots. Note that there are several parasitic cones around Sumang and Susan, while Gangjeong has just one. The measurement point of Sumang is close to a parasitic cone, while that of Susan is further away from some parasitic cones.

Information on met masts and measurement periods is listed in Table 2. The measurement campaign was carried out during the winter, when strong winds blow in Korea. The measurement periods were 14 days for Sumang and Susan, and 11 days for Gangjeong, respectively.

The wind sensors of NRG and Thies products were used, and the ground-based pulsed LiDAR system, WINDCUBE V2 uninstalled FCR (Flow Complexity Recognition) software, by Leosphere was employed for this campaign. The ten-minute averaged wind data was measured at heights ranging from 40 m to 80 m a.g.l. at the sites. Models of wind sensors organised by height are presented in Table 3. The LiDAR equipment was situated about 15 m away from each site's met mast (Fig. 3).

3. Data filtering

Before the analysis, wind data filtering criteria were set to ensure data comparability between wind sensors and the LiDAR system. The following data was used for the analysis:

- wind speed data ranging 4~16 m/s (e.g., Cañadillas and Westerhellweg, 2011; Gottschall and Courtney, 2010).
- Data with a Carrier-to-Noise Ratio (CNR) of more than −22 dB (Cañadillas and Westerhellweg, 2011).
- Data with LiDAR availability over 80% (WINDCUBE V2 LIDAR REMOTE SENSOR User Manual version 06).
- Data collected in precipitation less than 10 mm.
- Data unaffected by the tower's shadow.

Table 4 shows the data recovery rate and the amount of data after

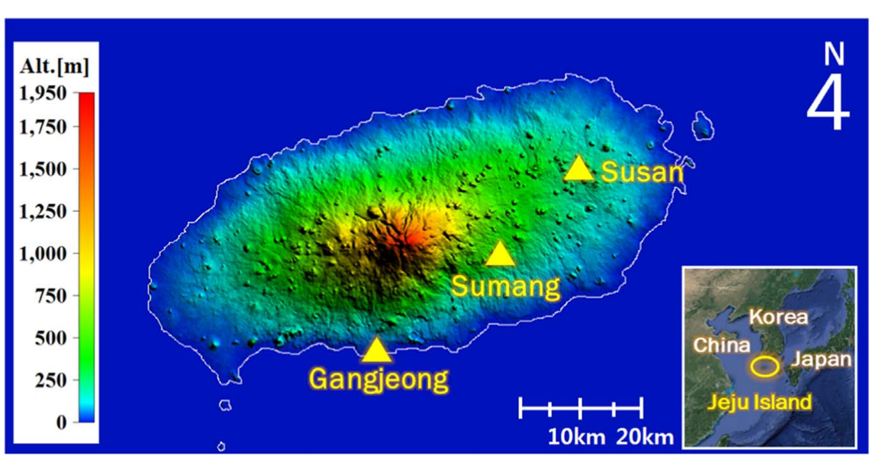

Fig. 1. Location of Jeju Island and measurement sites.

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