Analysis and Verification of Wind Data from Ground-based LiDAR

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Abstract- A study on the verification of reliability of measurements by the LiDAR (Light Detection and Ranging) system was conducted in Kimnyeong, on Jeju Island, South Korea. Also, the accuracy of the LiDAR measurements taken from the relatively flat-terrained Kimnyeong site was determined after factoring in the wind disturbance caused by the wake behind wind turbines. The 2.5-month wind data collected by the LiDAR were compared with concurrent wind data collected by the conventional anemometry on a nearby 120 m-high met mast for the verification. The measurement sectors (the area around the wind turbine where undisturbed wind speeds were measured) and the disturbed sectors (the areas around the wind turbine prone to wind disturbance) were estimated in accordance with the International Electrotechnical Commission, IEC 61400-12-1. Data filtering was performed based on the criteria suggested by previous researches. As a result, at 116 m above ground level, comparatively high LiDAR error rates of - 0.50~12.69 % were found in the disturbed sector, while relatively low LiDAR error rates of - 0.93~4.26 % were shown in the measurement sector. In the measurement sector, the absolute values of LiDAR error rates were about 5 % with the standard deviations of about 5 % at the heights of 100 and 116 m above ground level. The power law exponents calculated by using the met mast and the LiDAR data collected from the measurement sector were very similar to each other, whereas met mast and LiDAR data collected from the disturbed sector showed major discrepancies.

Keywords Wind energy, Wind data, Light detection and ranging (LiDAR) system, Wind shear, Power law.

1. Introduction

As wind turbine sizes have increased, so have their hub heights. At present, it is becoming more common to see wind turbines over one-hundred meters high [1, 2]. The conventional method to measure wind conditions is to use a tall met mast with wind sensors, to correspond with modern wind turbine hub heights. However, installing a tall met mast is time consuming and expensive [2, 3]. As an alternative to this, ground-based remote sensing systems such as SoDAR (Sonic Detection and Ranging) and LiDAR have been growing in popularity due to comparatively easy deployment and mobility as well as recently falling cost [4, 5, 6].

There have been many studies done comparing LiDAR and conventional anemometry wind data in order to improve the reliability of LiDAR measurements. Smith et al. [7] found that there was a high level of agreement between the LiDAR and the calibrated cup anemometer wind data; that is, the coefficient used to determine wind speed, R^2, was found to be more than 0.99 at different heights. Kindler et al. [8] examined the LiDAR on the west coast of Denmark based on pre-defined acceptance levels for performance. They showed that LiDAR met most requirements for establishing the reliability of a wind measuring device. The LiDAR data measured on an offshore platform were compared with the met mast measurements by Shu et al [9]. The linear regression slope plotted using 10-min averaged wind speed data ranged from 1.0 to 1.03 with correlation coefficients above 0.99. Kim et al. [10] pointed out that the LiDAR measurement error became higher as the complexity of terrain conditions increased. However, it is still necessary to continue investigation of reliability of LiDAR measurements under various circumstances.

The purpose of this study is to examine the reliability of LiDAR wind data measured within a non-disturbed sector and a sector disturbed by neighbouring wind turbines in operation. In addition, in order to clarify the effect that the wake behind wind turbines has on the accuracy of LiDAR measurements, two types of wind shear estimated based on met mast and LiDAR measurements are revealed within the non-disturbed sector and the disturbed sector.

2. Sites and Wind Data

Fig. 1 shows the location of Jeju Island and Kimnyeong, the wind measurement site. Jeju Island is located off the southern coast of the Korean peninsula and has an area of 1,849.2 km^2, with a length of approximately 73 km running east to west and 41 km north to south [11]. Kimnyeong is situated on the northeast coast of Jeju Island. A 120 m-high met mast was installed close to the sea and a LiDAR system, WindCube V2, was situated about 15 m away from the met mast. The two 100 m-high wind turbines, the HQ 5500 and HS 139, operate about 312 m south and 478 m southeast of the met mast.

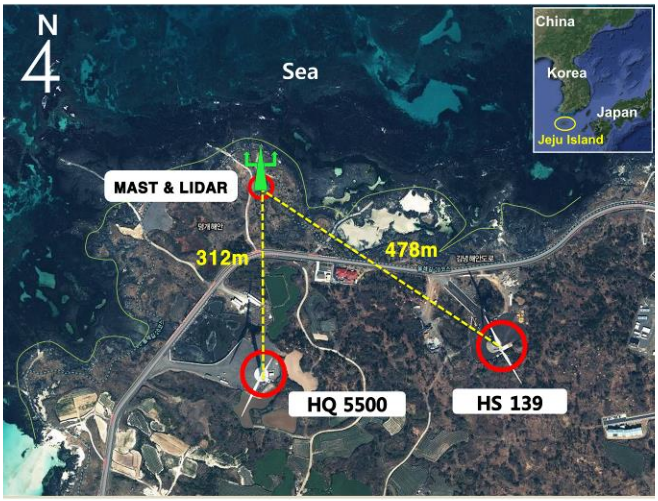


Fig. 1. The location of Jeju Island and wind measurement site.

Table 1 shows site and measurement conditions. The 10-minute average wind data from the LiDAR and wind sensors on the met mast were recorded for 76 days from September 1st to November 15th, 2014. The common measurement heights of the two wind measurement devices are 120, 116 and 100 m high for wind speed measurement, and 116 m and 96 m high for wind direction measurement. The average wind speed at the met mast was 7.07 m/s and the prevailing wind directions were from the northwest (NW) and east (E) at 100 m above ground level. The RIX (Ruggedness Index) value [3] representing terrain complexity was calculated for the Kimnyeong site, which was 0.22 % meaning that the site is flat terrain. Specifications of measurement sensors are indicated in Table 2 [12, 13].

Table 1. Site and measurement conditions.

Parameter		Description
Location	Latitude	33°33′54.50″N
	Longitude	126°45′55.89″E
Altitude [m]		2
Measurement period		1 Sep 2014 - 15 Nov 2014 (76 days)
Measurement height of met-mast [m]		Wind speed: 120, 116, 100, 70, 30
		Wind direction: 116, 96, 30
Measurement height of LiDAR		Wind speed & direction: 200, 180, 160, 140, 120, 116, 100, 96, 80, 60, 40
Avg. wind speed [m/s] (Mast)		7.07 @ 100 m
Prevailing wind direction (Mast)		NW, E
RIX [%]		0.22
Topographical condition		Coastal area

Table 2. Specifications of measurement sensors.

Items	Met mast		LiDAR
	Wind speed	Wind direction	
Model	Thies First class advanced	Thies wind vane	WindCube v2
Measuring range	0.3~50m/s	0~360°	0~60m/s (Speed)
			0~360° (Direction)
Accuracy	1% of meas.	±0.75 °	0.1m/s (Speed)
			2° (Direction)
Operation temperature	-50~+80℃	-50~+80℃	-30~+45℃
Type	3-cup	Wind vane	Pulsed Doppler laser

Table 3 shows information on the neighbouring two wind turbines [14, 15]. The HQ 5500 is a 5.5 MW wind turbine with a rotor diameter of 140 m, while the HS 139 is a 5.0 MW wind turbine with a 139 m-long rotor diameter.

3. Data Filtering

Before the wind data analysis, wind data filtering was performed to obtain more reliable results. The criteria for wind data filtering are given below, and the data which did not meet this criteria were eliminated [12, 16, 17, 18].

Table 3. The information of wind turbines.

Model	HQ 5500	HS 139
Rated Power [kW]	5,500	5,000
Cut-in / Rated / Cut-out wind speed [m/s]	3.5 / 13.0 / 25.0	3.4 / 11.0 / 25.0
Hub Height [m]	100	100
IEC Class	Ⅰ B	Ⅱ B
Rotor diameter [m]	140	139
Swept area [m2]	15,393	15,175
Tower type	Tubular steel	Tubular steel
Power control	Pitch	Pitch
Generator type	SYNC PM	SYNC PM

- Wind speed data ranging from 4 m/s to 16 m/s
- Data with Carrier-to-Noise Ratio (CNR) more than - 22 dB
- LiDAR system delivers over 80 % of available data
- Data collected in conditions where precipitation is less than 10 mm
- Data unaffected by the tower's shadow

In addition, the measurement sector suggested by the International Electrotechnical Commission, IEC 61400-12-1 [19] (hereinafter called the IEC standard) was estimated for undisturbed wind data selection. In this work, the disturbed sector could be determined according to the IEC standard Annex A using the following equation [19]:

$$\alpha = 1.3\arctan(2.5D_n / L_n + 0.15) + 10 \qquad (1)$$

where α represents the direction of the disturbed sector, D_n is the rotor diameter and L_n is the actual distance from the neighbouring wind turbines in operation. By using this equation, the disturbed sector of the studied site was determined and it ranged from 92° to 219°.

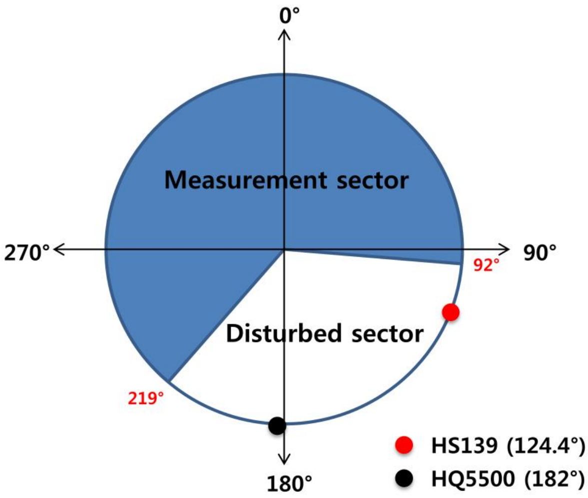


Fig. 2. Measurement and disturbed sectors.

Table 4. The number of data before and after filtering.

Measurement height [m]			Number of data: Met mast	Number of data: LiDAR	Data reducing rate [%]
Before filtering	Speed	116	10,944		-
		100			
	Direction	116			
		96			
After filtering	Speed	116	6,006		45.1
		100	5,721		47.7
	Direction	116	6,006		45.1
		96	6,439		41.2

Fig. 2 shows the measurement sector and disturbed sector at the studied site. LiDAR measurement error was assessed using the wind data collected within both the measurement sector and the disturbed sector. Table 4 shows the difference in the amount of data before and after filtering. Data reducing rates were no more than 45.1 % for wind direction and 47.7 % for wind speed.

4. Results and Discussion

4.1. Comparison of met mast and LiDAR concurrent wind data

In order to assess the reliability of the LiDAR measurements, the LiDAR wind data were compared with the met mast wind data that is the latter being regarded as the reference wind data. Comparisons were made between concurrent wind data at the same height. The wind speed data at 116 m and 100 m a.g.l. were selected for the error analysis of LiDAR wind speed, while 116 m and 96 m a.g.l. were chosen for the error analysis of LiDAR wind direction.

Fig. 3 shows scatter plots for wind speed and direction of LiDAR versus met mast including the result of linear regression analysis. Note that the wind data collected within the measurement sector alone were analysed to avoid the wake effect by the two wind turbines. Slope values of linear regression were all close to one in both wind speed and direction. In addition, the values of coefficient of determination, R^2, were also close to one. To be precise, the values of R^2 for the wind speed were 0.97 at 116 m and 0.96 at 100 m, while those for wind direction were both 1.00 at 116 m and 96 m. Accordingly, it was confirmed that the wind data measured from LiDAR were highly correlated with data from the met mast.

4.2. LiDAR error rate

In order to find differences between the LiDAR and the reference met mast wind speeds, the LiDAR error rate was defined in the following equation [10]:

$$\frac{LiDAR\ wind\ speed - Met\ mast\ wind\ speed}{Met\ mast\ wind\ speed} \times 100\ [\%] \quad (2)$$

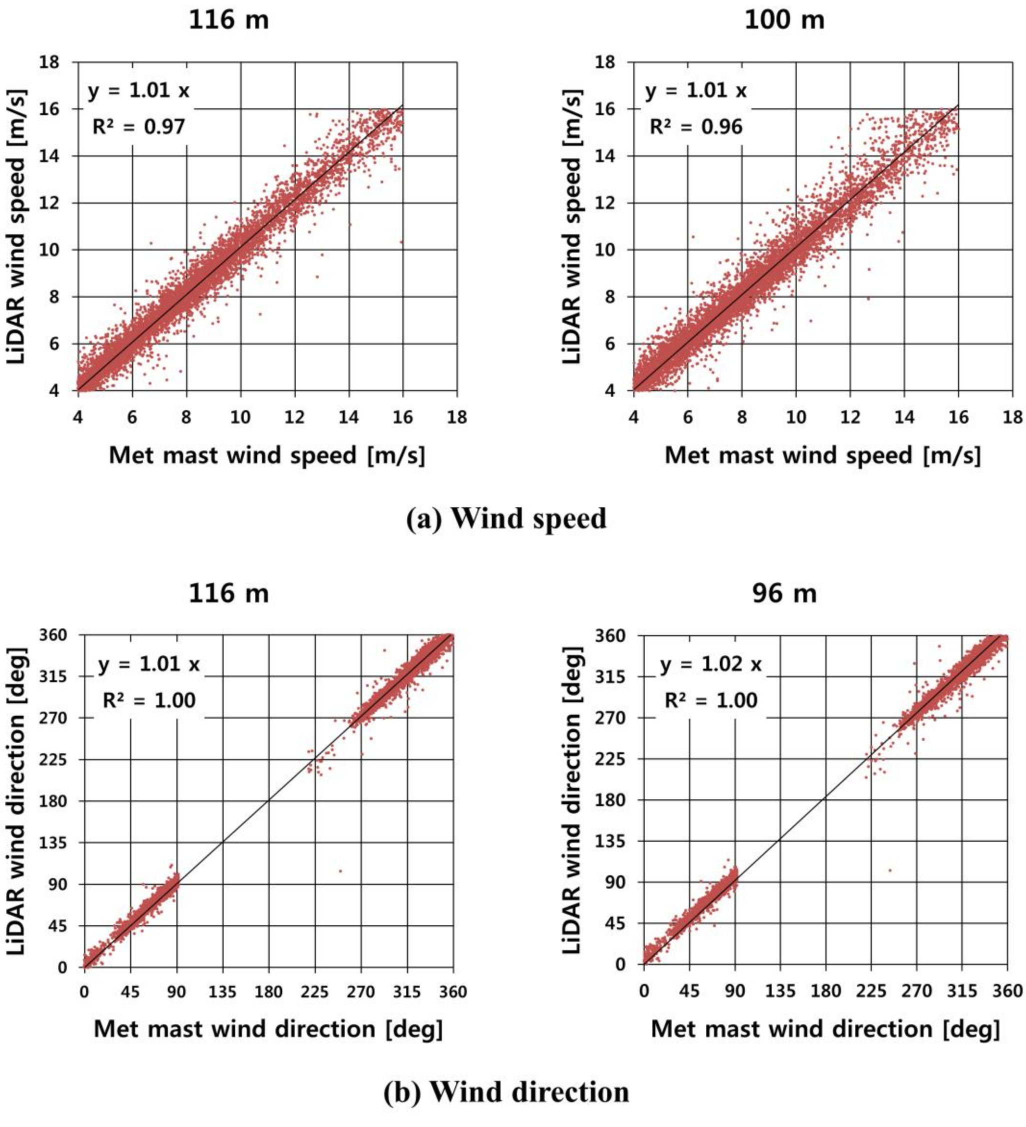


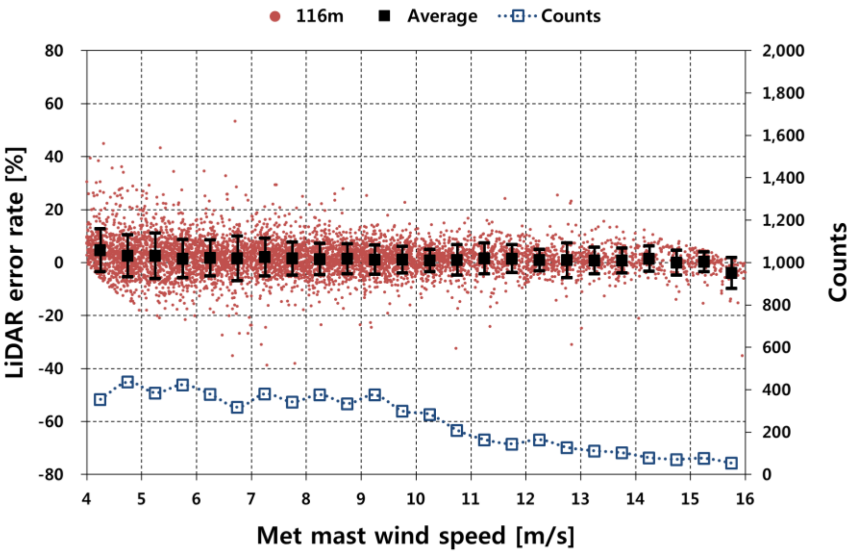
Fig. 3. Scatter plots for wind speed and direction of LiDAR versus met mast.

Fig. 4 presents LiDAR error rates versus met mast wind speed with the number of data in the measurement sector. 0.5 m/s was selected as the bin size of wind speed to calculate the average and standard deviation of error. The error bar represents the average and one standard deviation in each bin. There were not big differences in LiDAR error rates for all the wind speeds. The LiDAR error rate did not vary with wind speeds. The range of error rates at the height of 116 m were - 3.79~4.76 % for the average and 3.67~8.55 % for the standard deviation, respectively. At the height of 100 m, the averages of the error rates were from - 3.29 % to 4.44 % with the standard deviation of 4.08~8.27 %.

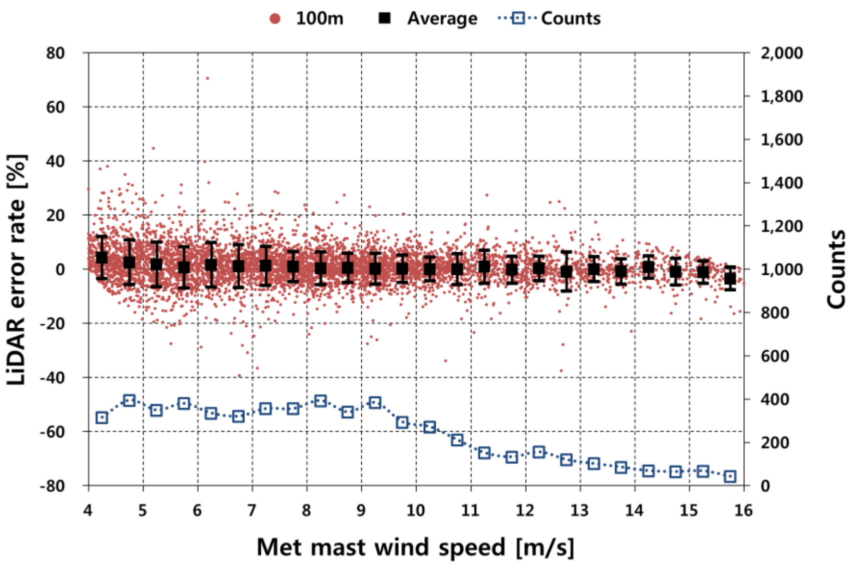
Fig. 5 shows LiDAR error rates versus met mast wind direction with the number of data in all the sectors. The wind data in all sectors were used for the analysis to compare the

LiDAR error rates in the measurement sector and the disturbed sector. The average and one standard deviation of LiDAR error rates were represented with the bin size of 10 degrees. The error bar was not given to the bins with less than ten data points. As shown in Fig. 5, the disturbed sector had comparatively larger LiDAR error rates than did the measurement sector. At the height of 116 m, error rates averaged - 0.50~12.69 % with a standard deviation of 3.97~16.90 % in the disturbed sector. The measurement sector had the error rate of - 0.93~4.26 % for the average and 3.49~6.89 % for the standard deviation. At the height of 100 m, the average LiDAR error rates were - 0.62~8.48 % having a standard deviation of 6.42~24.62 % in the disturbed sector, while the averages were - 0.98~4.19 % with the standard deviation of 4.67~10.15 % in the measurement sector.

The reason why comparatively larger standard deviation appeared in the disturbed sector may have come from the wake generated by the two wind turbines. In other words, unstable wind flow caused by the wake could break the assumption for accurate measurement that horizontal flow is uniform through the scanned volume of laser emitted by LiDAR system [20], which might lead to larger standard deviation of LiDAR error rate in the disturbed sector.



(a) A height of 116m



(b) A height of 100m

Fig. 4. LiDAR error rates versus met mast wind speed with the number of data in measurement sector.

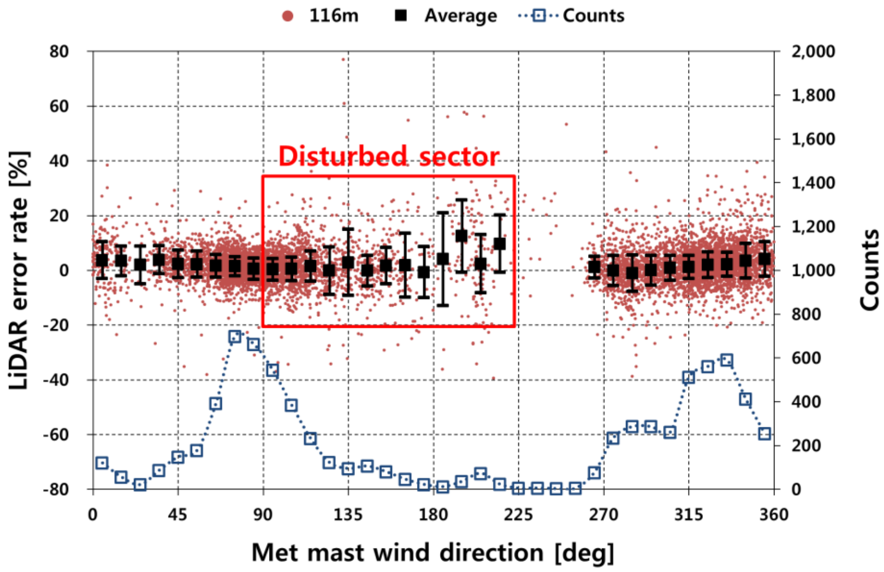
Fig. 6 shows absolute values of LiDAR error rates in the measurement sector for the two measurement heights. The average values were 4.94 % at the height of 116 m and 4.85 % at 100 m, with standard deviations at 4.79 % and 4.75 % respectively

4.3. Wind shear analysis

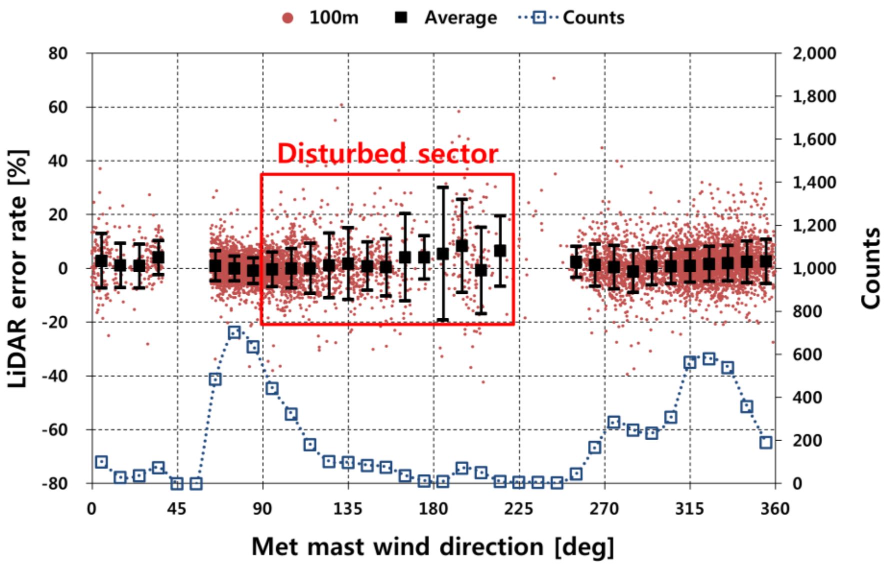
Wind shear describes how wind speed changes with height, measured above ground level (a.g.l). The power law is commonly used to estimate wind shear, which can be defined in the following equation [21, 22, 23]:

$$\frac{V_2}{V_1} = \left(\frac{Z_2}{Z_1}\right)^{\alpha} \tag{3}$$

Here, V_1 and V_2 are the average wind speeds at heights a.g.l. of Z_1 and Z_2, respectively. Also α is the power law exponent depending on terrain condition.



(a) A height of 116m



(b) A height of 100m

Fig. 5. LiDAR error rates versus met mast wind direction with the number of data in all sectors.

The wind shear based on the met mast and the LiDAR measurements in the measurement sector is shown in Fig. 7. The wind shear of LiDAR measurements matched very well with that of the met mast measurements; the power law exponents were 0.051 for met mast measurements and 0.048 for LiDAR measurements, respectively.

Fig. 8 shows wind shear based on both the met mast and LiDAR measurements in the disturbed sector. There were some differences between them, which may have been caused by the wake from the two neighbouring wind turbines. That is, since the LiDAR measurement accuracy may be subject to the wake behind wind turbines, the LiDAR measurements should be used with caution. The estimated power law exponents were 0.165 for the met mast measurements and 0.179 for LiDAR measurements.

Fig. 9 shows directional power law exponents derived from the met mast and LiDAR measurements. Six sectors describe wind directions of E, ESE, SE, SSE, S and SSW and together make up the disturbed sector, while the remaining sectors (the remaining wind directions) belong to the measurement sector. The power law exponent of the LiDAR measurements was in good agreement with that of the met mast measurements in the measurement sector. On the other hand, significant disagreement was found between the two power law exponents in the disturbed sector, especially in the sectors of S and SSW. That is, the power law exponent was 0.101 for met mast measurements and 0.254 for LiDAR measurements in the sector of S, while it was 0.212 for met mast measurements and 0.360 for LiDAR measurements in the sector of SSW.

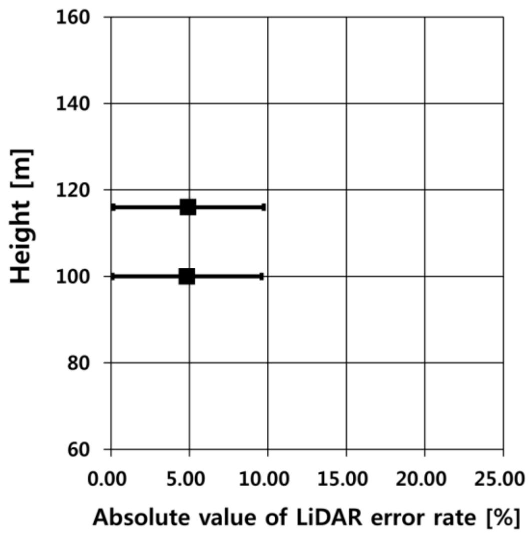


Fig. 6. Absolute values of LiDAR error rates in the measurement sector for the two measurement heights.

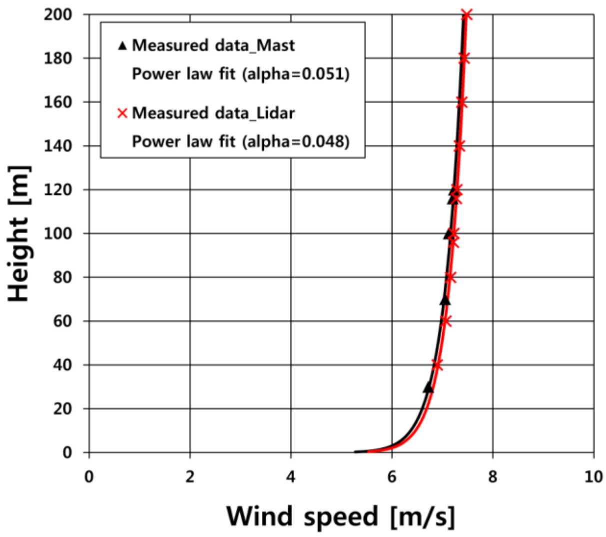


Fig. 7. Wind shear based on the met mast and the LiDAR me asurements in the measurement sector.

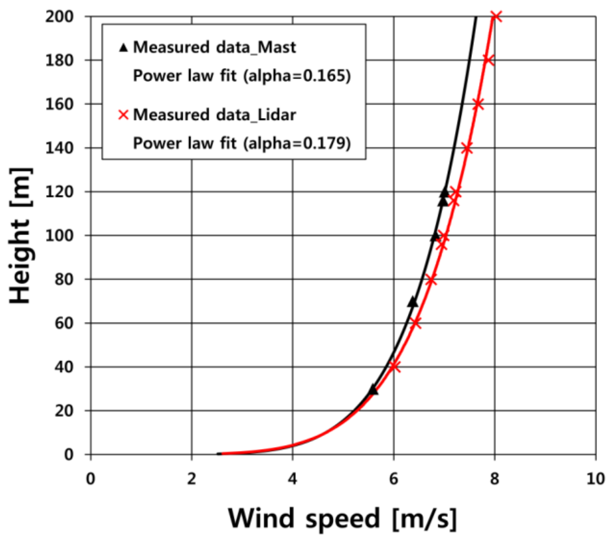


Fig. 8. The wind shear based on the met mast and the LiDAR measurements in the disturbed sector.

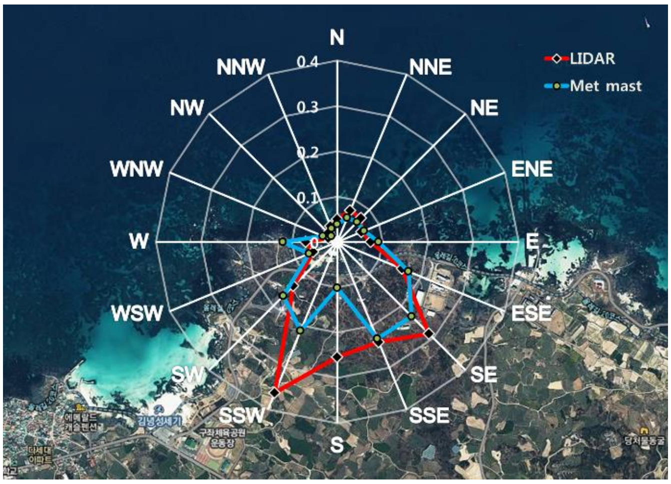


Fig. 9. Directional power law exponents derived from the met mast and the LiDAR measurements.

5. Conclusion

In this study, wind data collected by the LiDAR system were compared with data collected by the conventional wind sensors on a nearby met mast to verify the reliability of LiDAR measurements. Also, the accuracy of the LiDAR measurements was assessed in the disturbed sector where the wake behind wind turbines exists. The results are summarized as follows:

1) In the correlation analysis between the met mast and the LiDAR measurements, the coefficient of determination was 0.96~0.97 for wind speed and 1.00 for wind direction using a linear regression method.
2) The area (the disturbed sector) affected by the wake generated from the nearby two wind turbines had comparatively high LiDAR error rates of - 0.50~12.69 %, while the measurement sector without the wake indicated the error rate of - 0.93~4.26 % at 116 m a.g.l.
3) At the Kimnyeong site, in the measurement sector, the absolute values of LiDAR error rates ranged 4.85 ~ 4.94 % with standard deviations of 4.75 ~ 4.79 % at the heights of 100 and 116 m a.g.l.
4) It was confirmed that the wind shear estimated by the met mast measurements was in agreement with that predicted by the LiDAR measurements in the measurement sector, while there was not close agreement between the two kinds of wind shear in disturbed sector.

Acknowledgements

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