A comparison of LiDAR and meteorological mast wind measurements in the Karoo

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Abstract: Accurate wind resource assessments are key to developing efficient wind farms. Due to the steady rise in the dimensions of wind turbines in recent years, meteorological masts with heights of 100m and beyond are typically now required for wind resource estimation. There is a need to explore alternative methods in the interest of saving time and costs. In this study, an analysis is done to determine the feasibility of using new technologies based on remote sensing, such as LiDAR (Light Detection and Ranging), for measuring wind speed and wind direction. A measurement campaign was conducted over a 16-day period using ground based LiDAR and one of the meteorological masts erected near the town of Sutherland as part of the Wind Atlas of South Africa project. Sutherland is situated in the South African Karoo, an area known for relatively high altitude, generally non-complex terrain and low aerosol levels. A WindCube V2 LiDAR unit was deployed at the meteorological mast site. Measurements taken with the LiDAR and cup anemometers on the mast were compared at heights of 40m and 60m. A regression statistical analysis was performed on the datasets to calculate metrics such as the coefficient of determination. Data filtering, which includes wind speed range selection and application of LiDAR data availability thresholds, is done to ensure compatibility between the two datasets. In addition, an adjustment was required to account for time stamp differences between the data sets. The wind speed and wind direction results between the LiDAR and cup anemometers compared well. The coefficient of determination was 0.98 or higher for the two datasets evaluated.

Additional keywords: Wind energy systems, Renewable energy resource assessment, LiDAR, meteorological mast, CNR

Nomenclature

Roman

a	Power law exponent
CNR	Carrier-to-noise ratio [dB]
R^2	Coefficient of determination
RIX	Ruggedness Index [%]
V_h	Wind speed at height h [m/s]
V_z	Wind speed at height z [m/s]

Subscripts

h	Height [m]
z	Height [m]

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1 Introduction

The amount of power that can be harvested from a wind farm is proportional to the cube of the wind speed. Such a strong dependence makes accurate wind resource assessments crucial for the development of efficient wind farms. Traditionally wind measurements with cup anemometers and wind vanes are regarded as the only means of reliably measuring the wind resource [1]. In addition remote sensing techniques have developed sufficiently to allow the use of SoDAR (Sonic Detection And Ranging) and LiDAR (Light Detection And Ranging) units. LiDAR's'Their popularity stems from advantages such as the units' mobility and its ability to measure higher than 100m above ground level at a relatively low cost. Complex terrain, as well as low ambient aerosol levels, still presents a challenge to LiDAR [2].

Recently, one of Europe's largest producers and retailers of electricity and heat announced that they will exclusively rely on a fleet of LiDARs for their wind resource assessments needs [3]. It is not clear if LiDAR will gain such popularity in South Africa anytime soon. Meteorological masts equipped with cup anemometers and wind vanes remain the default option and were also used to develop the Wind Atlas of South Africa (WASA). Available data shows that wind energy projects awarded under the initial Renewable Energy Independent Power Producer Procurement Programme (REIPPPP) bid windows initially all relied to some extent on the WASA wind climate observations [4].

In this study, 16 days of measurements from a ground-based LiDAR unit were compared with data from one of the WASA project's meteorological masts. The mast is located near the town of Sutherland, a remote location in the semi-arid Karoo region of South Africa. It is located more than 250 km away active aerosol sources and the vegetation typical of the area, infrequent fires, and limited dust from wind ablation contribute to low aerosol generation [5]. LiDAR depends on the presence of particulate matter suspended in air, also known as aerosol, to function properly [6]. The aim of the study was to assess the performance of LiDAR when deployed in an area with non-complex terrain and known for low aerosol levels.

2 Description of WM06 test site

The Wind Atlas of South Africa (WASA) project [4] aims to build capacity and develop skills that will empower authorities, investors, the power sector, and industry to explore and plan for large-scale wind power generation. The project operates under a twinning arrangement between South African partners and the Danish Technical University (DTU). The WASA project is particularly useful in two key areas: facilitating the development of large grid-connected wind farms and providing more accurate wind resource data to

identify potential off-grid electrification opportunities.
The WASA project is managed by a consortium comprising South African National Energy Development Institute (SANEDI), the South African Weather Services (SAWS), the Council for Scientific and Industrial Research (CSIR), the University of Cape Town (UCT), and DTU. It is financially supported by the Royal Danish Embassy (RDE) and the Global Environment Facility (GEF) through the South African Wind Energy Project (SAWEP), with support from the United Nations Development Programme (UNDP) Country Office.
WASA 1 (2009-2014) focused on the Western Cape and parts of the Northern and Eastern Cape provinces. WASA 2 (2014-2018) extended to KwaZulu-Natal, the Free State, and the remaining areas of the Eastern Cape. WASA 3 (2017-2020) covered the remaining regions of the Northern Cape province. The forthcoming WASA 4 will focus on the northern provinces, including North West, Mpumalanga, and Gauteng. During WASA 1, a wind mast was erected near the town of Sutherland and designated as WM06. Figure 1 shows its location.

Figure 1 A map of the Southwestern region of South Africa highlighting the location of WM06 relative to major towns and cities in the area.

A WindCube V2 ground-based pulsed LiDAR unit from the manufacturer Vaisala was deployed on site for the measurement campaign. The exact placement of the LiDAR unit is determined by practical considerations to ensure optimal operation. The chosen location is typically a relatively flat area with a surface of approximately 4 square meters, free from rocks and other obstructions. The site is selected to maintain sufficient distance from the mast structure, preventing interference of the laser beam with the mast, while being close enough to ensure that both instruments measure wind speeds at comparable conditions. In this study, the LiDAR and ancillary equipment was situated approximately 43m away from the mast. Figure 2 shows a typical LiDAR deployment site featuring the unit used in this study.

Ruggedness Index (RIX) is a measure of the complexity of terrain. It is calculated for a given terrain by extending a number of radii originating at the site to a set distance and dividing each radius into line segments when they cross height contour lines. A critical slope is defined and those segments representing lines with a slope greater than the

Figure 2 A typical LiDAR deployment site showing the WindCube V2 unit in the foreground with ancillary equipment and the transport vehicle in the background.

critical slope is separated from those that do not. The RIX value for the site is the ratio of the separated line segments to the total, expressed as a percentage [7]. In this investigation, the RIX was obtained using a radius of 3500m and a critical slope of 0.3, which are the default values used in the commercially available software WAsP (Wind Atlas Analysis and Application Program). WAsP is designed to predict wind climates, assess wind resources, and estimate energy production from wind turbines and wind farms. Figure 3 shows the RIX for the area surrounding the site as well as the loction on the LiDAR. Since the critical slope of 0.3 was not exceeded anywhere in the area under consideration, a RIX value of 0.0% was returned, and all the colours in the colour scale indicates a RIX value of 0.0%.

Figure 3 RIX-values in the area surrounding the meteorological mast and LiDAR, confirming that the critical slope is not exceeded.

3 Data capture and filtering

Ten-minute averaged wind speed data was measured with the LiDAR unit at heights of 40m and 60m above ground level and wind direction data was measured at 60m. Mast WM06 has anemometers at heights of 20m, 40m and 60m. The mast was inspected on 22 June 2022 and all instruments were found to be in good working order. Data were collected continuously for a period of 16 days, from 5 to 20 November 2022.

Wind data filtering criteria were specified to ensure the maximum level of comparability between the mast sensors and the LiDAR. These criteria were determined by consulting available literature [8] [9] and summarized in Table 1.

Table 1 The filtering criteria used indicating the percentage of data excluded when applied individually and in combination

Measure	Criterion	60m	40m
		% of data excluded	
Speed	4 - 16 m/s	21.6%	22.6%
Carrier-to-noise ratio	> -22dB	0.3%	1.9%
Availability	> 80%	10.7%	30.2%
Wind direction Δ	< 40°	2.9%	-
Combining all criteria	-	31.4%	48.1 %

The filtering of wind speed data that fall outside the 4 - 16m/s range is in accordance with methods used by the the Danish Technical University's (DTU) Risø National Laboratory for Sustainable Energy [8]. DTU do not reveal the carrier-to-noise ratio (CNR) limitation used but a value of -22dB has been used by others [9]. A data availability threshold of 80% is recommended by the manufacturer. The "Wind direction Δ" measure addresses the occurrence of superficial spikes near 0° (true North). A change of 2° beyond 359° will reset the directional value to zero and continue to 1°, indicating a numerical difference of 358° while there is actually only a 2° difference. The blue circles in Figure 4 shows an example of such superficial spikes. The calculation of the coefficient of determination in the regression analysis (R^2) is sensitive to such large numerical differences necessitating such a filter.

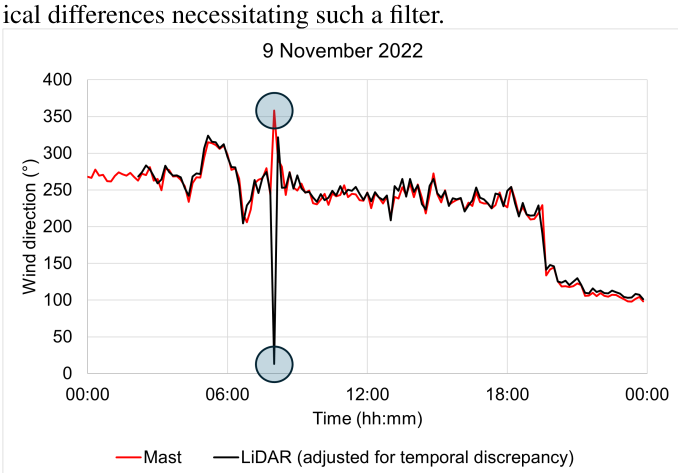

Figure 4 Superficial spikes observed in the data near true North, for example 359° and 0° significantly differ numerically, but not in reality.

The average CNR-values at 40m and 60m are listed in Table 2. The percentage of data points that fell below the threshold of -22dB was relatively low at 1.9% and 0.3% at 40m and 60m, respectively (see Table 1). The average CNR-value was also relatively low, and close to the threshold of -22dB below which it would be filtered. For comparison, a study comparing LiDAR measurements from three sites at heights ranging from 40m to 200m, reported an average of -10dB [1].

Table 2 Average CNR-values for the full datasets

Height	CNR (dB)	Standard deviation
40m	-17.89	3.08
60m	-16.58	3.62

4 Results and discussion

An initial visual comparison of the data revealed the temporal offset shown in Figure 5. The blue and red lines represent data recorded on 12 November 2022. Shifting the LiDAR data by 2 hours and 10 minutes results in the green line that aligns very well with the mast data. It was not possible to determine if the incorrect time stamp originated from the LiDAR or mast data. The wind direction data were treated in a similar way and revealed that an additional downward shift was required to achieve the best fit, as shown by the black line in Figure 6. It was concluded that this additional adjustment was required due to misalignment with true North when the unit was deployed.

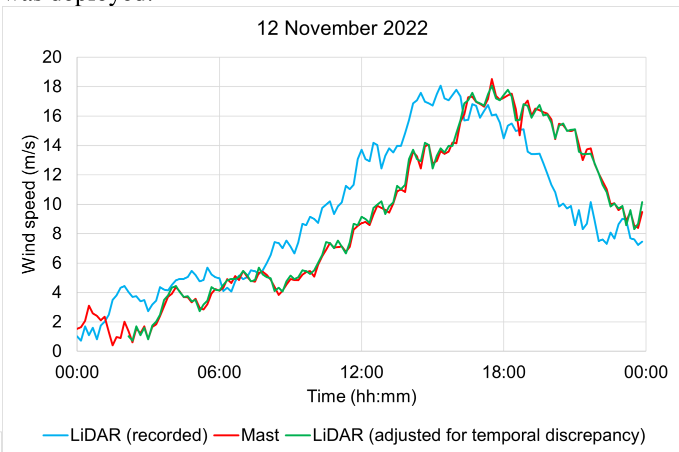

Figure 5 A temporal shift was required to obtain a best fit

The need for a temporal adjustment of the datasets revealed by the initial visual assessment was further confirmed by comparing the R^2 values of the data collected on three randomly selected days: 9, 12 and 18 November 2022. R^2, also known as the coefficient of determination, serves as a statistical measure in a regression model, indicating the proportion of variance in the dependent variable that can be explained by the independent variable. In simpler terms, it indicates how much change in the dependent variable can be directly attributed to a change in the independent variable. The results of the comparison is shown in Figure 7 and reveal a sustained increase in R^2 values as the temporal shift is incrementally increased from an initial amount of 1 hour and 40 minutes. A maximum is reached with a shift of 2 hours 10 minutes after which the R^2 values decline.

The trend is similar for the wind direction data. The coefficient of determination is a measure of change, used

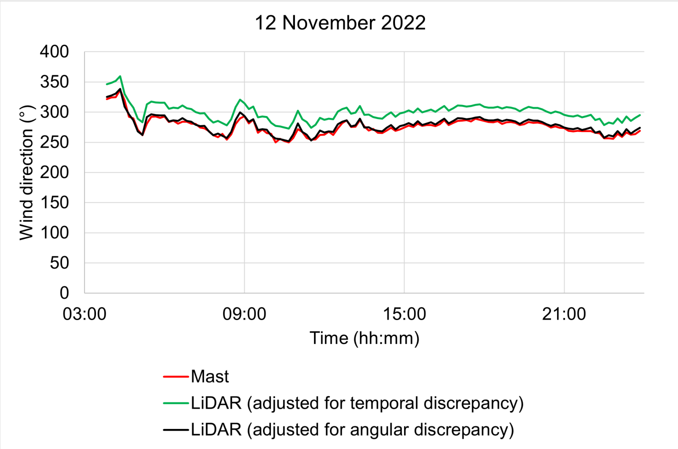

Figure 6 An angular shift was required to obtain a best fit

to indicate to what extent a change in one variable (in this case data recorded with the LiDAR) is the result of a change in another variable (in this case data recorded with the mast). If the coefficient of determination is used in a case where the second data set is identical to the first except for a y-offset, the change when moving from one data point to the next along the x-axis will be the same for both sets leaving the coefficient of determination unaffected. This result was confirmed by comparing the R^2 values obtained when using the dataset before the adjustment for the misalignment with true North, labelled 'LiDAR (adjusted for temporal discrepancy)' with those obtained after the shift, labelled LiDAR (adjusted for angular discrepancy) in Figure 6. The R^2 values remained identical. The R^2 values calculated using the data collected on 12 November 2022 with different temporal offsets are also shown in Table 3.

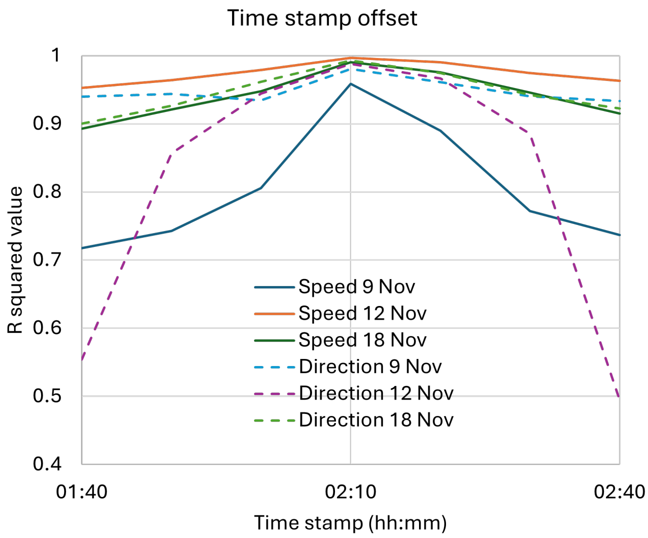

Figure 7 A temporal shift of 2 hours and 10 minutes resulted in maximum R^2 values.

The three datasets available for comparison were the wind speed measurements at 40m, 60m and the wind direction measurements at 60m. All three datasets were adjusted based on the considerations described above. Figures 8 to 10 show scatter plots of the full 16-day datasets. The result of a linear regression analysis is also included on the graphs.

Table 3 R^2 values calculated using data collected on 12 November 2022.

Time stamp	Wind speed	Wind direction
01:40	0.9527	0.5539
01:50	0.9640	0.8569
02:00	0.9791	0.9442
02:10	0.9971	0.9882
02:20	0.9904	0.9668
02:30	0.9744	0.8856
02:40	0.9634	0.4945

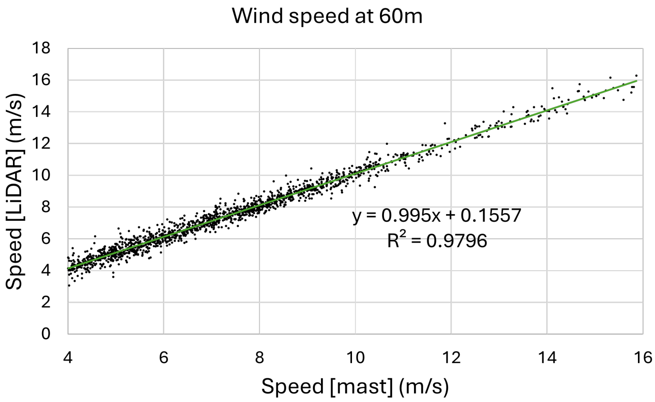

Figure 8 Scatter plot of full wind speed dataset at 60m

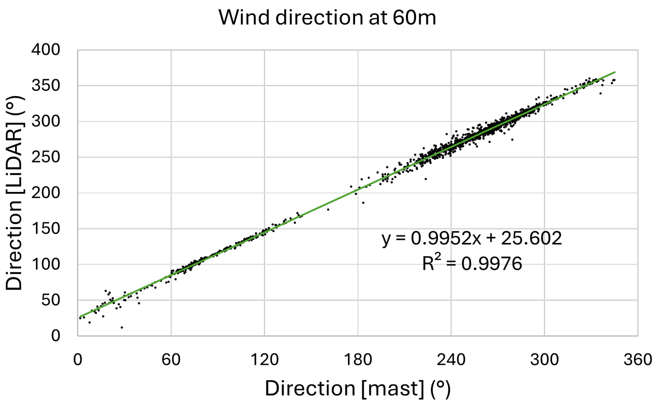

Figure 9 Scatter plot of full wind direction dataset at 60m

The slopes of the concurrent wind speed and direction data were all close to 1.0. The R^2 values are shown on the graphs and in Table 4.

Table 4 also contains columns that indicate the effect on the R^2 values if some filters are removed. Removing the speed filter allows wind speeds of less than 4m/s and higher than 16m/s to be included and has a minimal effect on the R^2 values. The relatively low value of 0.7128 obtained for the wind direction data when all filters are removed is due to the inclusion of the superficial spikes (as shown in Figure 4).

To determine wind shear, the power law was applied. The formulation below relates the wind speed at one height with that at another using the following equation:

$$V_z = V_h \left(\frac{z}{h}\right)^a \qquad (1)$$

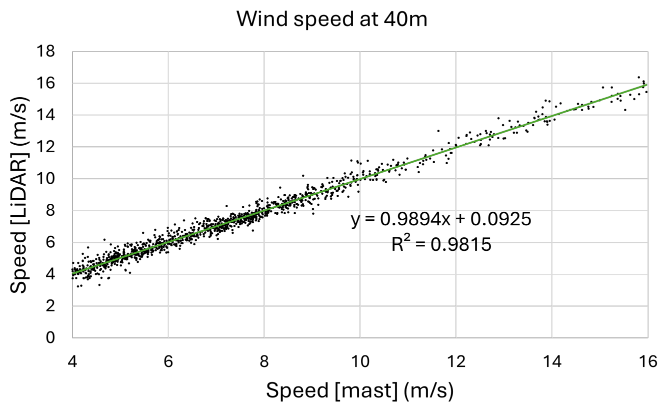

Figure 10 Scatter plot of full wind speed dataset at 40m

Table 4 The effect on the R^2 values if some filters are removed.

Dataset	Criterion removed None	Speed	all
Speed 60m	0.9796	0.9873	0.9849
Direction 60m	0.9976	0.9953	0.7128
Speed 40m	0.9815	0.9889	0.9683

with V_z and V_h the wind speeds at heights z and h, respectively. The exponent a depends on the surface roughness of the site. If equation 1 is used to define lines that include the average wind speed at 40m and 60m, exponent values of 0.0283 and 0.0621 are required for the mast and LiDAR datasets, respectively. A power law exponent of 0.01 is associated with sand and a exponent of 0.13 is typically associated with low grass [10]. The ground cover at the measurement site is a combination of sand interspersed with low vegetation. The wind shear profiles and the wind speed averages are shown (as filled circles) in Figure 11.

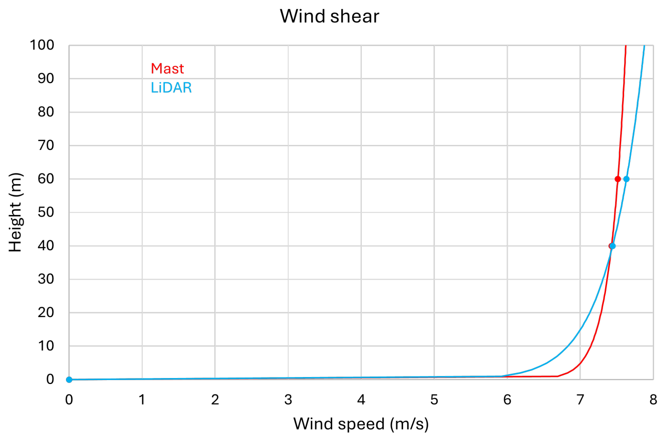

Figure 11 The wind shear profiles shown as lines and wind speed averages as filled circles.

5 Conclusions

From the findings in the study it is concluded that

1. It is possible to obtain good quality LiDAR measurements in remote areas in South Africa such as Sutherland in the Karoo which is remote from major sources of aerosol.
2. Significant offsets in data can occur if data logger time stamps are not regularly calibrated and if the LiDAR unit is not properly aligned during deployment.
3. The correlation was obtained in terrain with a low RIX and additional comparisons are required before the results of this study can be generalised.

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