HOW FAR DO WE SEE? ANALYSIS OF THE MEASUREMENT RANGE OF LONG-RANGE LIDAR DATA FOR WIND POWER FORECASTING

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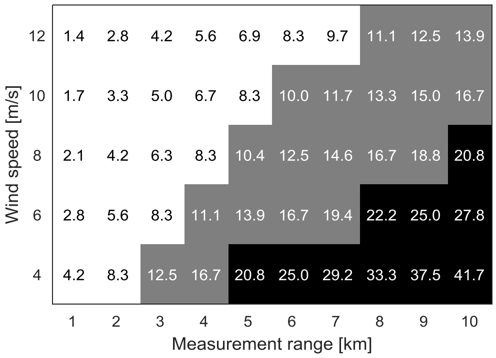
Summary

This paper investigates the measurement range of a long-range lidar for the application of very short-term forecasting of wind power. To this end a measurement campaign with a Stream Line XR lidar is carried out for several months and the environmental conditions are recorded simultaneously on a meteorological mast. It is found that mainly three factors impact the range of the lidar measurement: the filter algorithm used in post processing, the number of pulses set in the scan configuration of the device and the atmospheric humidity which is an indicator for cloud and fog formation. The lidar measures 4 km or more in 70% of the time when configured to use 40,000 pulses. However, in foggy and cloudy weather conditions, the lidar is blind.

1. Introduction

One of the main challenges for the electrical grid operator is to match an electric load profile to the power fluctuations of the renewable, weather dependent power sources. Therefore, power predictions of the different sources are necessary [1]. Within the national funded WindForS research project VORKAST, the University of Stuttgart investigates the usage of a long-range lidar for the application of wind power forecasting in a time range of up to 60 min. One of the key questions is how far the lidar actually measures the wind speed, as the measurement range directly impacts the forecasting horizon but varies greatly due to external conditions and device parameters [2]. In Figure 1, different forecasting horizons in minutes depending on wind speed and measurement range are given. The simple calculations are based on Taylor's hypothesis [3] and show for example that forecasting horizons over 20 minutes are only possible for a measurement range of 7 km and more. This paper analyzes the maximum measurement range of a long-range lidar system and evaluates the results in terms of the application of wind power forecasting.



	1	2	3	4	5	6	7	8	9	10
12	1.4	2.8	4.2	5.6	6.9	8.3	9.7	11.1	12.5	13.9
10	1.7	3.3	5.0	6.7	8.3	10.0	11.7	13.3	15.0	16.7
8	2.1	4.2	6.3	8.3	10.4	12.5	14.6	16.7	18.8	20.8
6	2.8	5.6	8.3	11.1	13.9	16.7	19.4	22.2	25.0	27.8
4	4.2	8.3	12.5	16.7	20.8	25.0	29.2	33.3	37.5	41.7

Figure 1: Forecasting horizon based on Taylor for different wind speeds and measurement ranges; horizon given in minutes; white: <10 min, grey: 10-20 min, black: >20 min.

2. Measurement Setup

The long-range lidar used for the VORKAST project is a Stream Line XR lidar from the company Halo Photonics. Details of the lidar device are given in [4].
The lidar was chosen as it is a pulsed scanning lidar with a maximum measurement range of 10 km, has a compact design and weights 60 kg. The long range and light weight allow flexibility in placing the lidar for measurement campaigns.
In the first campaign in this project the lidar is deployed on the top level platform of a radio tower in the Swabian Alps with unobstructed view in the main wind direction. The scanning trajectory is set to a horizontal scan with 1° increment and an opening angle of 40° in prevailing wind direction. The wind speed measurements used for the analysis in this paper are carried out between April and November 2016.
1.3 km away from the lidar the SWE meteorological (met) mast records the environmental conditions at the site up to a height of 100 m above ground. Wind speed and wind direction, humidity and rain are measured using sonic anemometers, humidity and rain sensors respectively. In Figure 2 the measurement setup is depicted in a terrain profile in mean wind direction.

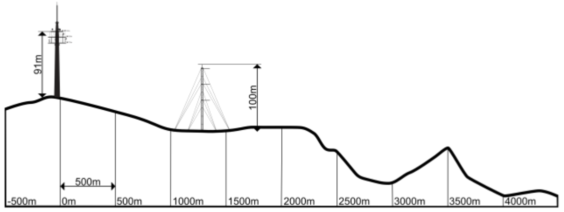
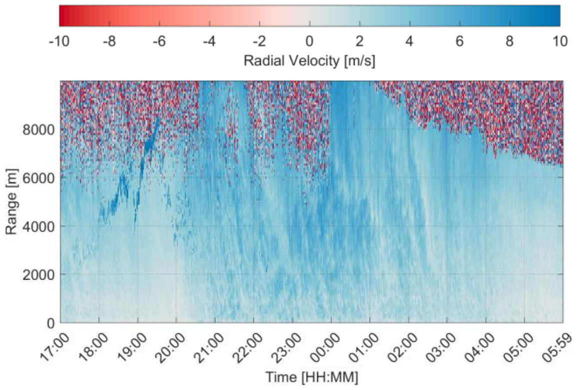


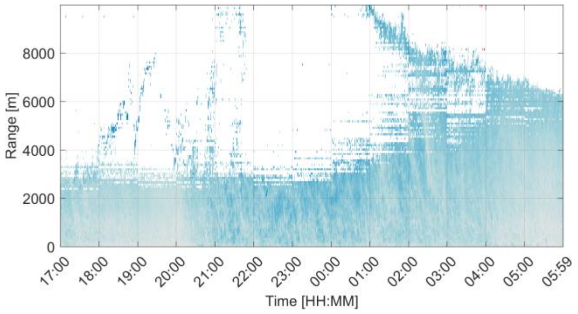
Figure 2: Terrain profile of the measurement site in prevailing wind direction.

3. Influences on the lidar measurement

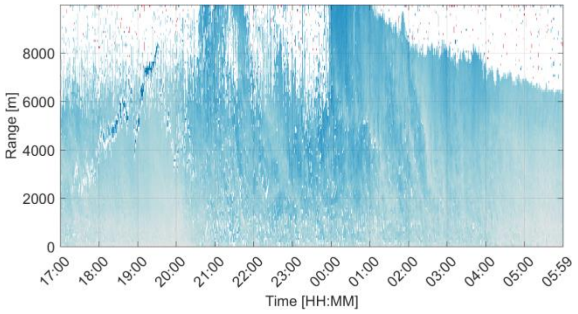
The lidar measurement principle is based on the backscatter of laser pulses on particles in the air which backscatter the light with a frequency shift due



(a) Radial velocity data set, unfiltered



(b) Radial velocity data set, CNR filtered



(c) Radial velocity data set, range filtered

Figure 3: Radial velocity data set of the long-range lidar Stream Line XR filtered with different filter algorithms.

to the airspeed of the particles [5]. The measurement depends on the existence of these aerosols and if the concentration in the air is too high or too low, or the laser energy of the scan is set too low, the device records a noisy signal. As a consequence lidar data needs to be filtered and the measurement range may deviate from the maximum range given in the product data sheet. The lidar data recorded with the Stream Line XR are analyzed in terms of range in the following sections and the influencing factors are discussed.

3.1 Filter algorithm

The standard approach to detecting outliers and noise in the lidar raw data is to take the carrier to noise ratio (CNR) into account which is an indicator for the signal quality and an output signal of the lidar device. For this CNR value a threshold is defined above which the measured radial wind speed is considered valid. In Figure 3 (a) an example timeline of unfiltered radial wind speed data of the Stream Line XR is given in relation to the measurement distance. In the data set, the data becomes noisy in a measurement distance of 6 km and more. The maximum measurement range of the device can be determined visually. When applying the CNR filter to the data set, noisy data is removed as depicted in Figure 3 (b). However, the filter is conservative and also removes valid data. Consequently the measurement range decreases significantly due to the post processing of the data. As a result new filter algorithms have to be developed in order to achieve a measurement range that is not determined by the post processing algorithm but the physical limits of the measurement process. In Figure 3 (c) an example of such a filter algorithm is applied to the data set which is here called a *range filter*.

3.2 Determining the measurement range

After filtering the data it becomes clear that oftentimes no clear distinction between an area of valid and invalid data is possible. With increasing measurement distance, valid data is perforated with invalid data. In Figure 3 (c) for example, valid data is sparse between a measurement range of 6 km and 8 km in the first 4 hours. However, in order to statistically analyze the measurement range of the lidar device, the maximum range needs to be clearly defined. Two methods are therefore developed and compared. The first is called *sum range* and sums up the range gates with valid data of each scan ray and corresponds the result to a measurement range.

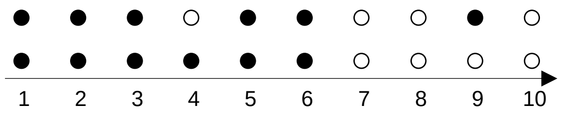
$$\begin{aligned}&\text{sum range}\\&= \sum \text{number of range gates with valid data}\end{aligned}$$

The second method *weighted range* takes into account the perforation of the data in a ray and weights sections with adjacent areas of valid measurement data, so called blocks, higher compared to perforated ones. This means the number of valid data as well as the length of a block with valid data is taken into account.

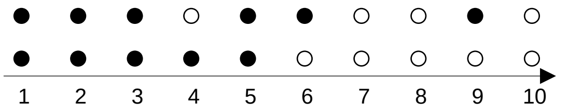
$$\text{weighted range} = \frac{\sum \text{block end} \cdot \text{block length}}{\sum \text{block length}}$$

The results of both methods are schematically visualized in Figure 4. In the first row an exemplary data ray with 10 range gates is given where black dots mark valid data after filtering. The second row then shows the range according to the method. The comparison shows that the perforation in the data leads to a lower range using the weighted range method.

To decide which method to use for the statistical analysis, both methods are applied to different data sets. As can be seen in Figure 5, for periods with a higher range, both methods work well and result in a plausible range. However, for periods with a measurement range close to zero, the weighted range method gives too high ranges as scattered data in farther ranges is weighted too high. Therefore the determination of the range is carried out with the Sum Range method in the further analysis.



(a) sum range method



(b) weighted range method

Figure 4: Schematic visualization of the results of sum range (a) and weighted range (b) method to calculate the maximum range of a lidar measurement.

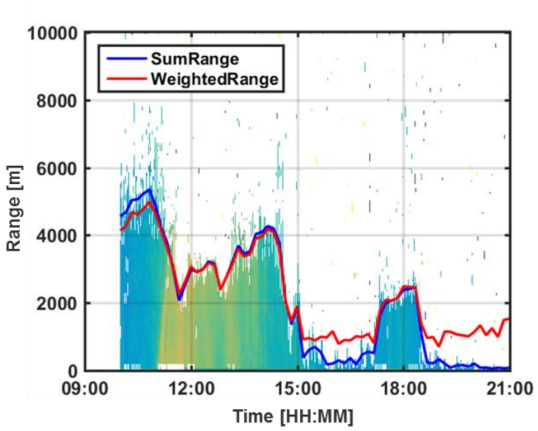


Figure 5: Comparison of the Sum Range and Weighted Range method applied to a filtered data set.

3.3 Device parameters

One device parameter that has to be defined when setting up a lidar measurement with the Stream Line XR is the number of pulses that are being sent out per ray. In other lidar devices the parameter that can be set is the accumulation time, which is calculated from the number of pulses and the pulse frequency. The more number of pulses are chosen, the more laser energy is emitted and the higher the probability of a good return signal becomes. However, at the same time the accumulation time per ray increases as well.

During the 8 months measurement period, four different measurement configurations with number of pulses ranging from 10,000 to 60,000 pulses are chosen and the scans are carried out for several weeks respectively. After filtering the data and classifying the measurement points as valid or invalid, the frequency of valid measurement point can be calculated for each range gate (Figure 6). The ratio of valid measurement points decreases for all number of pulses with increasing range. For high ranges the ratio is close to zero. Figure 6 shows as well that for a scan with 10,000 pulses the range is the lowest and for 40,000 pulses the maximum range is achieved. Increasing the number of pulses to 60,000 does not increase the maximum range.

It should also be kept in mind that increasing the number of pulses increases the time to carry out one scan. Thus it becomes more difficult to measure a coherent image of the wind field. Therefore the number of pulses should be chosen according to the application.

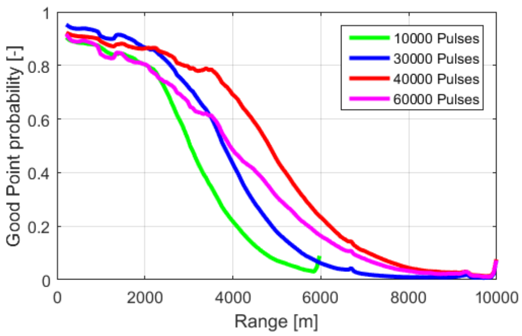


Figure 6: Averaged frequency of valid measurement points per range gate for different number of pulses.

3.4 Environmental conditions

The aerosol concentration, size and shape have an impact on the range of lidar measurements. The aerosols in turn are influenced by environmental conditions [6]. In this section the range of the lidar data is correlated to environmental parameters that are measured on the met mast. As a first parameter, the impact of the atmospheric humidity is investigated. In Figure 7 ten-minute averages of the relative humidity are set in relation to the ten-minute averaged range of the lidar system. For this analysis one month of data is used where the lidar scan is set to 10,000 pulses. The plot shows that the relationship between humidity and range can be divided into three areas:

1. A cluster of data points with ranges close to zero and humidity around 90 %.
2. A transition area with ranges up to 2,000 m and humidity ranging from 55 % to 93 %.
3. An area where no correlation can be detected and ranges are from 2,000 m – 5,000 m.

The conclusion therefore is that the range of the lidar measurement is only close to zero in case of high humidity. As the relative humidity is an important indicator for cloud and fog formation, it is assumed that rain and fog are the cause for the range drop. To prove this assumption, the measurement range and the humidity of one day are analyzed and webcam pictures of the site are used for a direct indication of the weather conditions. In Figure 8 a twelve hour timeline of the measured lidar range and relative humidity of a day in June 2016 is shown. On this day significant changes in range and humidity are observed. Two points in time are chosen here for analysis. Around 2 pm the humidity decreases and the range peaks to 4,200 m. The corresponding webcam picture in Figure 9 (a) shows good visibility and clear weather conditions without rain which is the cause for the humidity drop. Clouds and fog are forming afterwards and 1.5 h later the wind turbine in 500 m distance is barely visible (cf. Figure 9 (b)). The humidity has risen accordingly and the range has dropped to around 500 m. The analysis therefore shows clearly that indeed fog and cloud formation are responsible for low measurement ranges and that the lidar range corresponds well with the visibility range. In times of very foggy and/or rainy weather conditions, the lidar is almost blind.

Other environmental parameters that are analyzed are wind speed, turbulence intensity and wind direction. Due to limited space and as there are no correlations to the measured lidar range detected, the plots are not shown in this paper.

4. Conclusion and outlook

The analysis in this paper shows that the measurement range of a long range lidar varies mainly due to three factors: the filtering algorithm that is applied in the post processing of the data, the number of pulses that are set for the scan in the device configuration and the atmospheric humidity which is an indicator for fog and cloud formation. The respective impact on the range of these factors differs. For the Stream Line XR it is found that with a robust filter algorithm and 40,000 pulses, the measurement range is 4 km or more in 70 % of the time at the site in the Swabian Alps. However, in foggy and rainy conditions the lidar is blind. For the application of very short term forecasting of the power output of a wind turbine, this means that the expected maximum forecasting horizon is around 15 minutes on a regular basis. In further investigations, the lidar measurement range will be analyzed in offshore conditions and a comparison between the range of the Stream Line XR and other commercial long-range lidars should be carried out.

Acknowledgements

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References

[1] Marquis M et al, “Forecasting the wind to reach significant penetration levels of wind energy” 2011, Bulletin of the American Meteorological Society.

[2] Davoust S. et al.: Assessment and Optimization of Lidar Measurement Availability for Wind Turbine Control, EWEA, Barcelona, 2014.

[3] Taylor, G. I., “The spectrum of turbulence“, Proceedings of the Royal Society of London, 1938

[4] Pearson G et al.: An Analysis of the Performance of the UFAM Pulsed Doppler Lidar for Observing the Boundary Layer, Journal of Atmospheric and Oceanic Technology 2009.

[5] Newsom R. K.,: Doppler Lidar (DL) Handbook / ARM, Climate Research Facility, Handbook, 2012

[6] Kokhanovsky A. A., “Aerosol optics: light absorption and scattering by particles in the atmosphere.” Berlin, Springer, 2008.

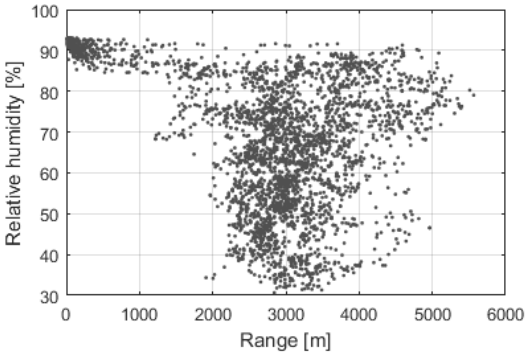

Figure 7: Correlation of 10 minute mean values of relative humidity and range for one month of measurement data (10,000 pulses).

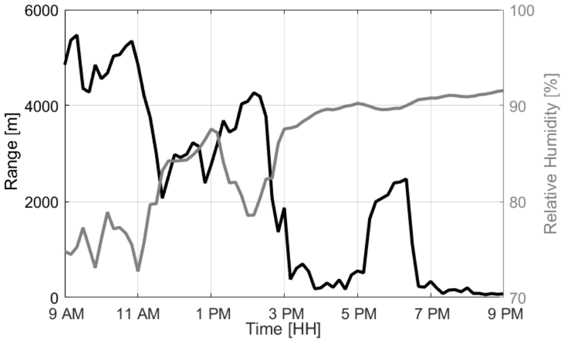

Figure 8: Timeline of ten minutes mean values of range and relative humidity on 8 June 2016.

(a) 01:59 pm

(b) 03:38 pm

Figure 9: Webcam pictures of the measurement site with time stamp on 8 June 2016.