FLOMEKO2019
18th International Flow Measurement Conference
Portugal | Lisbon | LNEC | 26-28 june 2019

Bistatic wind lidar system for traceable wind vector measurements with high spatial and temporal resolution

S. Oertel, M. Eggert, C. Gutsmuths, P. Wilhelm, H. Müller, and H. Többen

Physikalisch-Technische Bundesanstalt, Dept 1.4: Gas Flow, 38116 Braunschweig, Germany
E-mail (corresponding author): stefan.oertel@ptb.de

Abstract

Wind lidar systems have become a cost-efficient alternative to wind met masts in the recent years to measure and monitor the wind velocity in many applications in the fields of wind energy and meteorology. Conventional wind lidar systems work according to the monostatic measurement principle that is inherently accompanied by a spatial and temporal averaging procedure. This averaging procedure complicates the traceability of such systems as the uncertainty of the measured wind velocity depends on the homogeneity of the investigated wind fields. In contrast, the wind lidar system presented here works according to a bistatic measurement principle that measures the velocity vector of single aerosols in a spatially highly resolved measurement volume in heights from 5 m to 250 m with a resolution of about 0.1 m/s. The novel system has the potential for traceable wind speed measurements in homogeneous as well as in inhomogeneous wind fields as was proven by comparison measurements with a wind met mast. At PTB, the aim is to use the bistatic wind lidar as a traceable reference standard to calibrate other remote sensing devices, necessitating an in-depth validation of the bistatic lidar system and its measurement uncertainty. To this end, a new, specially designed wind tunnel with a laser Doppler anemometer (LDA) as flow velocity reference has been built up to validate the bistatic lidar in detail. First validation measurements in the velocity range from 4 m/s to 16 m/s are presented, showing an average deviation between the bistatic lidar and the LDA of 0.37 %.

1. Introduction

Wind met masts with cup anemometers are currently the most precise wind speed measuring devices for traceable wind speed measurements as they are necessary, for example, for the site assessment of prospective wind farms in the field of wind energy [1]. However, tall masts covering hub heights of modern wind turbines of more than 100 m are very expensive and will exceed mechanical and financial limits at future hub heights [2]. In the recent years, ground-based wind speed remote sensing by means of conventional monostatic wind lidar (light detection and ranging) systems has become an efficient measurement technique to supplement and extend wind met mast measurements [3]. The monostatic measurement principle (see Figure 1) utilized by conventional wind lidars is based on a common transmitting and receiving beam that is tilted in different directions to measure the complete wind vector. Due to the large measurement volume determined by the tilt angle this technique is inherently accompanied by a spatial and temporal averaging procedure. Provided that the wind field is almost homogeneous within the measurement volume, these systems deliver reliable measurement results [4]. However, leaving flat terrain and having to consider the inhomogeneous wind conditions that predominate on complex terrain, significant errors for the wind speed measured arise and can be on the order of 10 % [5].

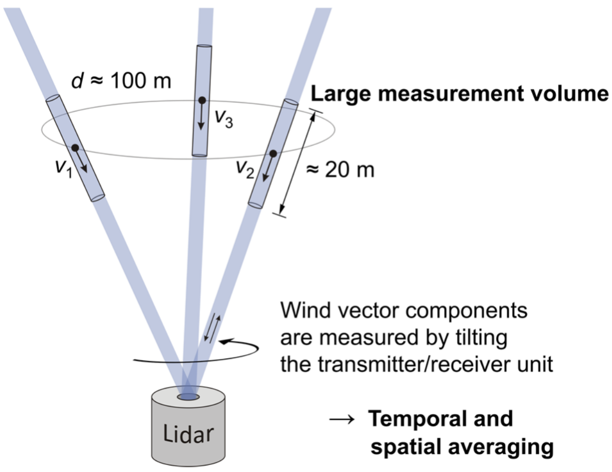

Figure 1: Conventional monostatic measurement principle

The new three-component fiber laser-based wind lidar sensor developed by the Physikalisch-Technische Bundesanstalt (PTB) uses one transmitting unit and three receiving units to measure the velocity vector of single aerosols in a spatially highly resolved measurement volume (with diameter *d* and length *l*) in heights from 5 m (d = 300 µm, l = 2 mm) to 250 m (d = 14 mm, l = 4 m) with a resolution of about 0.1 m/s (see Figure 2). Detailed comparison measurements with a 135 m high wind met mast and a conventional lidar system have proven that the high spatial and temporal resolution of the new, so-called bistatic lidar leads to a reduced measurement uncertainty compared to conventional lidar systems [6, 7]. Furthermore, the comparison demonstrated that the deviation between the bistatic lidar and the wind met mast lies well within the measurement uncertainty of the cup anemometers of the wind met mast for both homogeneous and inhomogeneous wind fields. Thus, the novel system has the potential for traceable wind speed measurements in flat as well as in complex terrain. At PTB, the aim is to use the bistatic wind lidar as a traceable reference standard to calibrate other remote sensing devices, necessitating an in-depth validation of the bistatic lidar system and its measurement uncertainty. To this end, a new, specially designed wind tunnel with a laser Doppler anemometer (LDA) as flow velocity reference has been erected on a platform at a height of 8 m; this allows the new wind lidar to be positioned below the wind tunnel test section to be validated in detail for wind vector measurements that are traceable to the SI units. First validation measurements within the wind tunnel test section at seven different velocities in the velocity regime from 4 m/s to 16 m/s are presented, showing an average deviation between the bistatic lidar system and the LDA of 0.37 %.

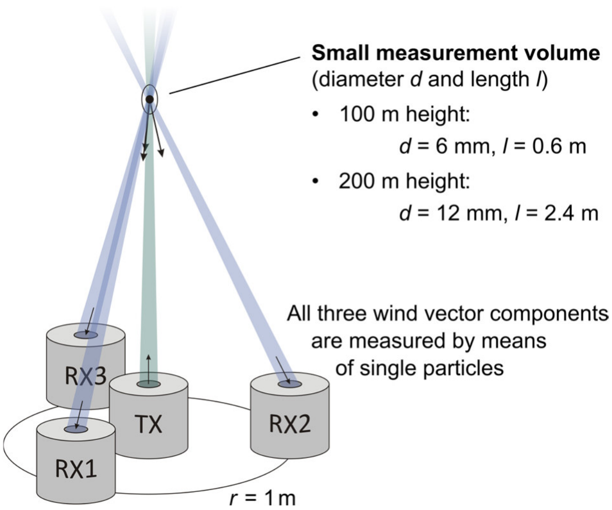

Figure 2: Bistatic measurement principle consisting of one transmitting unit TX (green beam) and three receiving units RX (blue beams)

2. Setup

Similar to monostatic lidar systems, the bistatic system designed by the Physikalisch-Technische Bundesanstalt (PTB) comprises a narrow bandwidth (< 1 kHz) master laser with a wavelength of 1550 nm, an acousto-optic modulator (AOM) for signal conditioning and a high-power (up to 30 W), erbium-doped fiber amplifier (EDFA) to generate the laser light transmission (Figure 3a). However, in contrast to monostatic systems, which typically use a common transmitting and receiving unit and an optical circulator to separate the received scattering light, the bistatic system is based on one transmitter and three discrete, spatially separated receivers. The receivers are positioned at a radius of 1 m around the transmitter to ensure both sufficient particle-scattering light intensity (quasi-backward direction) and sufficient resolution for the determination of the horizontal velocity component. Three heterodyne receivers convert the particle scattering light (three receiving beams) after the generation of optical beat signals into three electrical signals by differential photodetectors (PD). The transmitter beam as well as the beams of the three receivers are focused into a small measuring volume by the use of motor-controlled lenses and mirrors (see Figure 3b), forming Gaussian beams with a diameter of about 35 mm at the lenses and thereby centering the beam waists in the measuring volume.

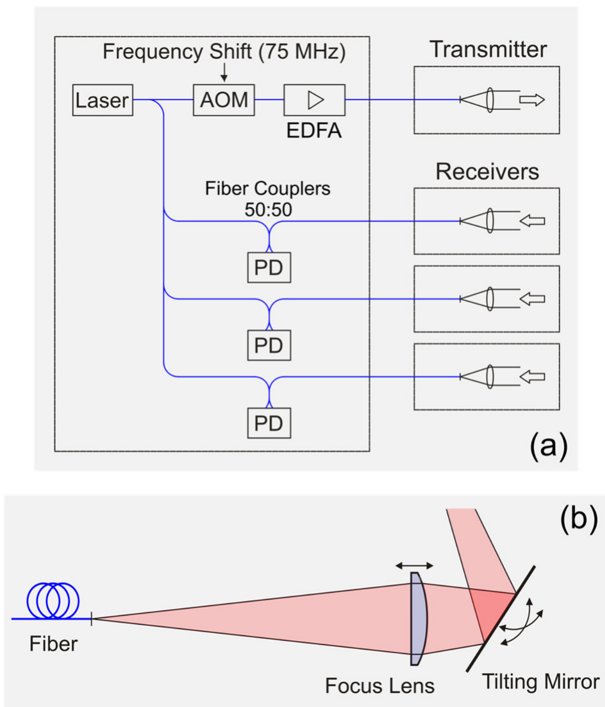

Figure 3: (a) Block diagram of the bistatic lidar system. **(b)** Sketch of the transmitter and receiver optics.

The resulting measuring volume is locally highly resolved and depends on the measuring distance. Typical measurement volume dimensions calculated according to Gaussian beam optics are shown in Figure 2. An optical phase delay measurement and correlation techniques between the three detection channels are applied to ensure that wind vector measurements are based on the scattering light from the same particles in the selected measuring distance between 5 m and 250 m. To ensure a mobile operation with stable working conditions in the field, especially with respect to requirements on the mechanical setup and the optoelectronics, the bistatic lidar system has been enclosed in an air-conditioned housing unit mounted on a trailer (Figure 4 and 5).

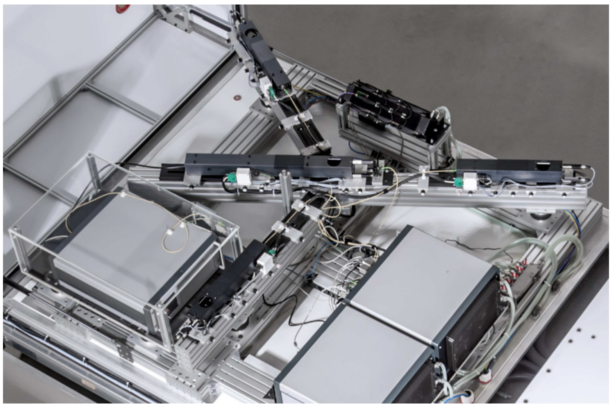

Figure 4: Optical installation inside the PTB lidar (opened trailer housing).

3. Wind tunnel test facility

A wind tunnel test facility (WTTF) was built up in the metrological Competence Center for Wind Energy (CCW) at PTB to analyze and investigate the bistatic wind lidar, its reliability and its measurement uncertainty in controllable and well-defined flow fields with a precise flow velocity reference traceable to the SI units. The specially designed wind tunnel from Deutsche WindGuard Wind Tunnel Services GmbH is erected on a platform at a height of 8 m enabling the bistatic lidar system to be positioned below the test section of the wind tunnel (Figure 5). The wind tunnel has an open test section 0.75 m in length with a cross-sectional area of 0.5 m x 0.5 m and a flow velocity range of 1 to 30 m/s. In the relevant part of the test section that is used for validation measurements of the bistatic lidar system, i.e., in the core of the flow field, the turbulence level is for all flow velocities below 0.35 % and the homogeneity of the flow field is 0.01 % per cm. An LDA 1-D fp50-unshift from Intelligent Laser Applications (ILA) R&D GmbH with a measurement uncertainty of 0.18 %, with the type being identical to an LDA used as transfer standard in the CIPM key comparison of air speed CCM.FF-K3.2011 [8], serves as a reference standard for the flow velocity within the wind tunnel test section. A more detailed description and characterization of the wind tunnel can be found in [7].

Figure 5: Bistatic PTB lidar (opened trailer housing) positioned below the test section of the wind tunnel test facility.

4. Validation measurements

For all comparison measurements between the bistatic PTB lidar and the LDA reference standard in the wind tunnel both the lidar measurement volume (d = 400 µm, l = 4 mm) and the LDA measurement volume (d = 300 µm, l = 2.5 mm) resided – perpendicular to each other – within the same volume of about 1 cm^3 in the core of the wind tunnel flow field, i.e., the sector of the test section with high homogeneity and low turbulence level. Figure 6 depicts the results of a long-term comparison lasting 3 h with the z component of the lidar system pointing along the flow field direction. For data analysis the raw data were averaged over time intervals (averaging time Δt) from 0.1 to 600 s. The resulting mean values were further used to calculate the standard deviations σ for each averaging time. The red ($\sigma_{\mathrm{Lidar},z}$) and the black ($\sigma_{\mathrm{LDA}}$) line in Figure 6 show the result of this data evaluation for the lidar system (relevant z component) and the LDA, respectively. A lower signal-to-noise ratio in addition to a lower data rate of the lidar system leads to higher standard deviations of the lidar system compared to the LDA which are, however, well within the same order of magnitude. For long averaging times both standard deviations reach the same asymptotic value caused by a long-term drift of the wind tunnel of about 0.003 m/s per 1 h. Figure 6 also shows the standard deviations of the two other vector components ($\sigma_{\text{Lidar,x}}$ and $\sigma_{\text{Lidar,y}}$) measured by the lidar system and, additionally, the mean values v_{mean} of the measured flow velocities averaged over the complete long-term measurement (3 h). The deviation between the lidar system ($v_{\text{z,mean}}$) and the LDA ($v_{\text{LDA,mean}}$) for this single measurement is about 0.005 %.

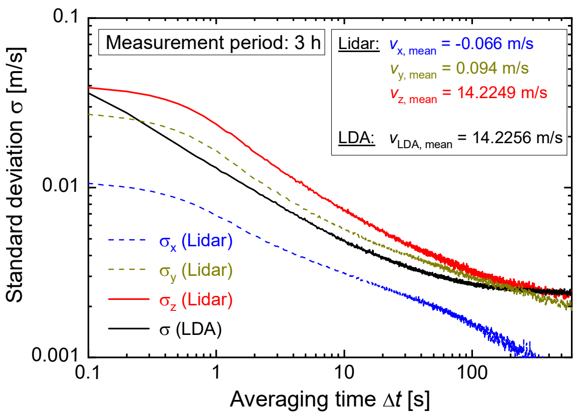

Figure 6: Long-term comparison measurement of the PTB lidar and the LDA.

A comparison of the lidar system with the LDA in the WTTF in the velocity range from 4 to 16 m/s is shown in Figure 7. For all measurements the measurement time was 1 h with an averaging time Δt of 1 s. The blue circles are the mean velocities measured by the lidar system referred to the LDA whereby the red line is the identity. More interesting, the squares show the mean deviations of the PTB lidar that are in the complete velocity range well below 0.5 %. The magenta-colored square at 10 m/s is a measurement at which the lidar system was rotated about 90° with respect to the other measurements. Both values at 10 m/s (black and magenta) are within both measured standard deviations demonstrating a consistent result regarding the measurement geometry of the lidar system. The average mean deviation (dashed line) of all measurements is 0.37 % ± 0.06 % indicating a small systematic error that is supposed to arise from an inaccuracy in the determination of the measurement height of the lidar system within the wind tunnel test section. Further extensive measurements with the WTTF will be performed in the future especially with an improved and more accurate measurement height determination to investigate and validate the PTB lidar and its accuracy.

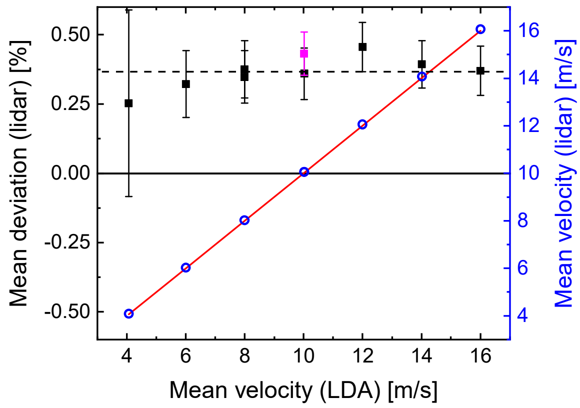

Figure 7: Comparison of the PTB lidar with WTTF reference (LDA).

5. Conclusion

A new three-component fiber laser-based bistatic wind lidar system constructed at the Physikalisch-Technische Bundesanstalt (PTB) enables traceable wind velocity measurements in heights from 5 m to 250 m. Due to the bistatic setup of the system the PTB wind lidar offers a high spatial and temporal resolution resulting in a reduced measurement uncertainty compared to conventional monostatic wind lidar systems and a potential application for traceable wind velocity measurements in flat as well as in complex terrain. For a detailed analysis and validation of the PTB wind lidar as a new reference standard for other wind speed remote sensing devices a new wind tunnel test facility (WTTF) was built up at the PTB that enables the measurement uncertainty of the bistatic wind lidar system to be determined quantitively in controllable and well-defined flow fields. First comparison measurements show a measurement behavior of the lidar system comparable with the LDA of the WTTF concerning the evolution of the standard deviation during long-term measurements. Furthermore, the average deviation of the lidar system in the flow velocity range from 4 m/s to 16 m/s was determined to be 0.37 % ± 0.06 % and is for all measured flow velocities below 0.5 %.

References

[1] IEC 61400-12-1, Edition 2.0: *Wind energy generation systems – Part 12-1: Power performance measurements of electricity producing wind turbines*, 2017.
[2] Emeis, S., Harris, M., and Banta, R. M., "Boundary-layer anemometry by optical remote sensing for wind energy applications", *Meteorol. Z.*, **16**, 337–347, 2007.
[3] Albers, A., Janssen, A. W., and Mander, J., "How to gain acceptance for lidar measurements", available at: *https://www.windguard.de/veroeffentlichungen.html* (last access: 4 January 2019), 2010.

[4] Gottschall, J., Courtney, M. S., Wagner, R., Jørgensen, H. E., and Antoniou, I., “LiDAR profilers in the context of wind energy – A verification procedure for traceable measurements”, *Wind Energy*, **15**, 147–159, 2012.

[5] Bingöl, F., Mann, J., and Foussekis, D., “Conically scanning lidar error in complex terrain”, *Meteorol. Z.*, **18**, 189–195, 2009.

[6] Eggert, M., Gutsmuths, C., Müller, H., and Többen, H., „Time resolved wind vector comparison measurements between the PTB Lidar transfer standard and a 135 m wind met mast”, in *Proc. Experimentelle Strömungsmechanik* (German Association for Laser Anemometry, Karlsruhe), 3.1 – 3.7, 2016.

[7] Oertel, S., Eggert, M., Gutsmuths, C., Wilhelm, P., Müller, H., and Többen, H., "Validation of three-component wind lidar sensor for traceable highly resolved wind vector measurements", *J. Sens. Sens. Syst.*, **8**, 9–17, 2019.

[8] Müller, H., Caré, I., Lucas, P., Pachinger, D., Kurihara, N., Lishui, C., Su, C.-M., Shinder, I., and Spazzini, P. G., “CCM.FF-K3.2011: Final report for the CIPM key comparison of air speed, 0.5 m/s to 40 m/s”, *Metrologia*, **54**, 07013, 2017