Development of a multispectral scanning LiDAR system for measuring wind velocity, air temperature and moisture

Björn Klaas[a,b], Claudia Baulig[a], Katharina Predehl[a], and Stefan Schwarzer[a]

[a]Fraunhofer Institute for Physical Measurement Techniques IPM, Freiburg, Germany
[b]University of Freiburg, Department of Sustainable Systems Engineering, Freiburg, Germany

ABSTRACT

Measurements of atmospheric parameters, such as wind velocity, air temperature and moisture, provide important information for a diverse set of fields, ranging from estimating energy output of wind farms to predicting extreme weather events to understanding urban climatology. Performing these measurements quickly, reliably and with high accuracy presents a yet unsolved challenge. Especially when working in or close to complex terrain, such as forests, hillsides or urban landscapes, no available system can properly perform such measurements.

The Fraunhofer Institute for Physical Measurement Techniques IPM is developing a novel multispectral scanning LiDAR system. The goal is to simultaneously and accurately measure wind speed, air temperature and moisture over complex terrain for the first time.

We present the current state of a scanner system for synchronized steering of multiple laser beams from different LiDAR units towards positions in the commonly visible intersection volume, subtending up to 7/8th of the full solid angle. We also present the state of an in-house developed Doppler Wind LiDAR and our current proposal for a combined wind, air temperature and water vapor LiDAR.

Keywords: Doppler-LiDAR, DIAL, HSRL, coherent LiDAR, wind velocity, air temperature, moisture

1. INTRODUCTION

Fraunhofer Institute for Physical Measurement Techniques IPM (Fraunhofer IPM) develops a novel, scanning LiDAR system for atmospheric profiling. Highly spatially and temporally resolved measurements of atmospheric properties such as wind velocity, air temperature and moisture content are required for the advancement of a diverse set of fields from wind energy to weather forecasting to urban climatology. In wind energy larger turbines and more complex sites require wind velocity measurements with improved range and spatial resolution. Forecasting a growing number of extreme weather events such as spontaneous heavy rain and subsequent flooding requires improved understanding of cloud physics and turbulent convective flows below the clouds, facilitated by highly resolved measurements spanning large areas. Increasing pollution and heat transfer problems in growing cities require highly spatially resolved wind velocity, temperature and aerosol measurements to improve city planning and thus human health.

Current LiDAR units measure only a subset of the required values and are mostly one or two orders of magnitude less precise than what is required for the aforementioned purposes. Many systems also measure along only one vertical line and therefore do not offer the necessary flexibility and spatial spread of measurement locations. To enhance e.g. the forecasting of spontaneous, heavy rainfalls the meteorological models require measurements with $2\,\mathrm{km}$ range, $10\,\mathrm{m}^3$ spatial resolution, a sampling rate of at most $1\,\mathrm{s}$ and accuracies of $0.1\,\mathrm{m\,s}^{-1}$ three-dimensional wind velocity, $1\,\mathrm{K}$ air temperature and $2\,\%$ moisture. Although commercial scanning wind LiDAR, available from Leosphere and HALO Photonics, achieve the range, they do not offer sufficiently fine range resolution (both $\geq 24\,\mathrm{m}$). Commercial temperature and moisture LiDAR such as the Purple Pulse LiDAR also achieve the necessary range but again are not sufficient regarding spatial and temporal resolution ($50\,\mathrm{m}$ to $300\,\mathrm{m}$ at $10\,\mathrm{s}$ to $600\,\mathrm{s}$). To our knowledge the LiDAR currently promising the highest resolution measurements is the *Cloud-Observing Radar and Lidar* (CORAL) developed at Max-Planck-Institute for Meteorology,[1] but

Send correspondence to: bjoern.klaas@ipm.fraunhofer.de

actual results are not yet published. Currently no system is available that combines all three measurements and no system, neither commercial nor experimental, achieves the desired resolution.

Currently we are developing a multi-head, scanning Doppler Wind LiDAR (DWL) for accurate wind measurements in complex terrain. We present a two-mirror beam steering unit developed for that purpose in Section 2. Section 3 describes a custom DWL currently in development and Section 4 the air temperature and moisture measurement methods investigated to extend the scanning DWL towards a scanning, multi-purpose LiDAR. In Section 5 we present our current working proposals for such an integrated wind velocity, air temperature and moisture measurements LiDAR. Throughout this publication we refer to the beam steering unit as *scanner*, a stand-alone LiDAR as *LiDAR* or *LiDAR unit*, a LiDAR with a scanner as *scanning LiDAR* and several, synchronized scanning LiDAR as a *(scanning) LiDAR system*.

2. SCANNING MULTI-HEAD LIDAR

We require a flexible, fast and accurate scanner to provide a high number of measurements spread over a large area. Since DWL measure only line-of-sight wind velocity multiple synchronized scanners are necessary for measuring all wind velocity components. Such a scanner system capable of working with many compact LiDAR units is being developed at Fraunhofer IPM. The system is currently designed to provide beam steering capabilities for atmospheric LiDAR with a beam diameter of $\leq 5\,\mathrm{cm}$, without changing the optical properties of the laser beam and thus interfering with measurements. These scanners are of special interest for measurements in complex terrain, such as hillsides and urban settings. Figure 1 shows two exemplary sites and scan patterns.

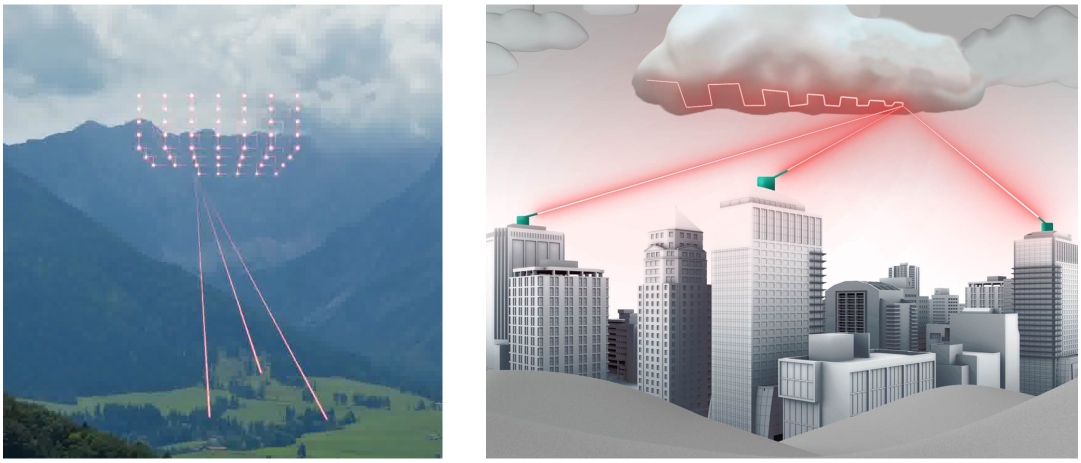

Figure 1. To be able to measure arbitrary scan patterns throughout the atmosphere, from city streets below the scanner up to the cloud edge, the scanner has to provide a wide range of motion in both polar angle θ and azimuth angle ϕ.

The scanner pointing mechanism is capable of covering 7/8th of a sphere around the LiDAR unit to match the requirements poised by the highly variable scan patterns. Some restrictions regarding the optical transceiver placement of the underlying LiDAR apply to render the full range available, otherwise the unit obstructs the downwards angles. Fraunhofer IPM designs the multi-purpose LiDAR, presented in Sections 3 to 5, to meet these constraints.

Each scanner uses two rotary motors and two mirrors for beam steering. Figure 2 shows a schematic of the scanner. The horizontal motor is a PI M-062.DG covering an azimuth range of $0^\circ \leq \phi \leq 180^\circ$ at $7.5\,^\circ\,\mathrm{s}^{-1}$. The vertical motor is a PI M-062.PD providing unrestricted rotation at $90\,^\circ\,\mathrm{s}^{-1}$. Both motors allow for a maximum beam diameter of 5 cm. The scanner can be outfitted with different mirrors and lenses to suit most types of LiDAR, from the ultraviolet to the infrared. The standard configuration uses two mirrors specially coated for high reflectivity in both s- and p-polarization at $1.5\,\mu\mathrm{m}$. The scanner is dust- and waterproof with a default output window selected for high transmittance at $1.5\,\mu\mathrm{m}$ and mounted slightly tilted to minimize reflections.

To accurately direct the laser beam at a chosen point in a global reference frame the position and orientation of the scanner need to be precisely determined. A Differential GPS measures the latitude, longitude, height and

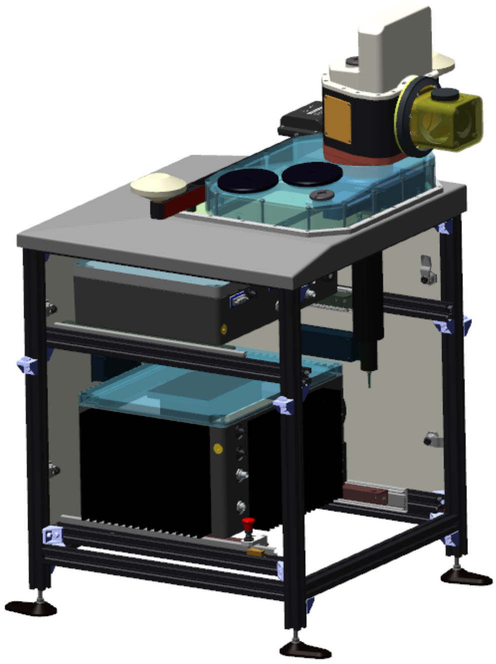

Figure 2. The scanner provides beam steering in 7/8th of a sphere around the unit. This is achieved by placing the scanner in a corner of the supporting frame and rotating 180° horizontally and 360° vertically. The frame can hold most small to medium sized LiDAR units.

yaw angle (angle from north), a Kelag KAS1002-52A two-axis tilt sensor the two remaining orientation angles (pitch and roll). Our operating software calculates the motor positions and measurement range to reach a chosen measurement position based on this information. Without manual intervention we monitor and continuously update the roll and pitch angles to achieve high steering precision throughout a measurement campaign. For the production version we plan continuous position and yaw angle monitoring as well.

Measurements were performed to determine the overall beam steering precision and automated steering correction accuracy. For these measurements a scanner was mounted on a tilt table and equipped with a precision laser pointer which pointed at a target 13 m from the scanner. The scanner was rotated up and down around multiple axes while the movement of the laser beam on the target was recorded. The experiment showed an angular error of less than 0.01°, we thus expect a positioning error of less than ±0.5 m at a target distance of 500 m. Further verification using actual LiDAR units and *Carrier to Noise*-mapping at larger distances is ongoing. First results obtained using real GPS positions and 300 m target distance are very promising.

Aside from high spatial precision a multi-head system requires very good synchronization and alignment for performing true point measurements. Synchronization is based on GPS clocks connected to the scanners and a network protocol requiring all messages to carry timestamps signaling either the intended execution time of a command or the completion time of a command. This procedure allows precise monitoring of the position and status of all scanners and on-the-fly adjustment of the measurement schedule according to system response and real-time measurement results. A schematic of the system topology including some parts of the software stack is shown in Figure 3.

In order to avoid deterioration of the measurement capabilities of the attached LiDAR unit the scanner must not significantly affect beam properties such as intensity, shape and state of polarization. Intensity is slightly reduced according to the reflectivity of the mirrors, while the beam shape is mostly unaffected. The state of polarization however can be altered significantly by a two-mirror scanner.[2] To determine the magnitude of the effect for our mirrors at 1550 nm we moved the scanner through its full range of motion while observing the backscatter intensity of a polarization sensitive DWL connected to the scanner. To correct for changes in intensity due to space- and time-dependent inhomogeneous aerosol distribution in the atmosphere we rotated

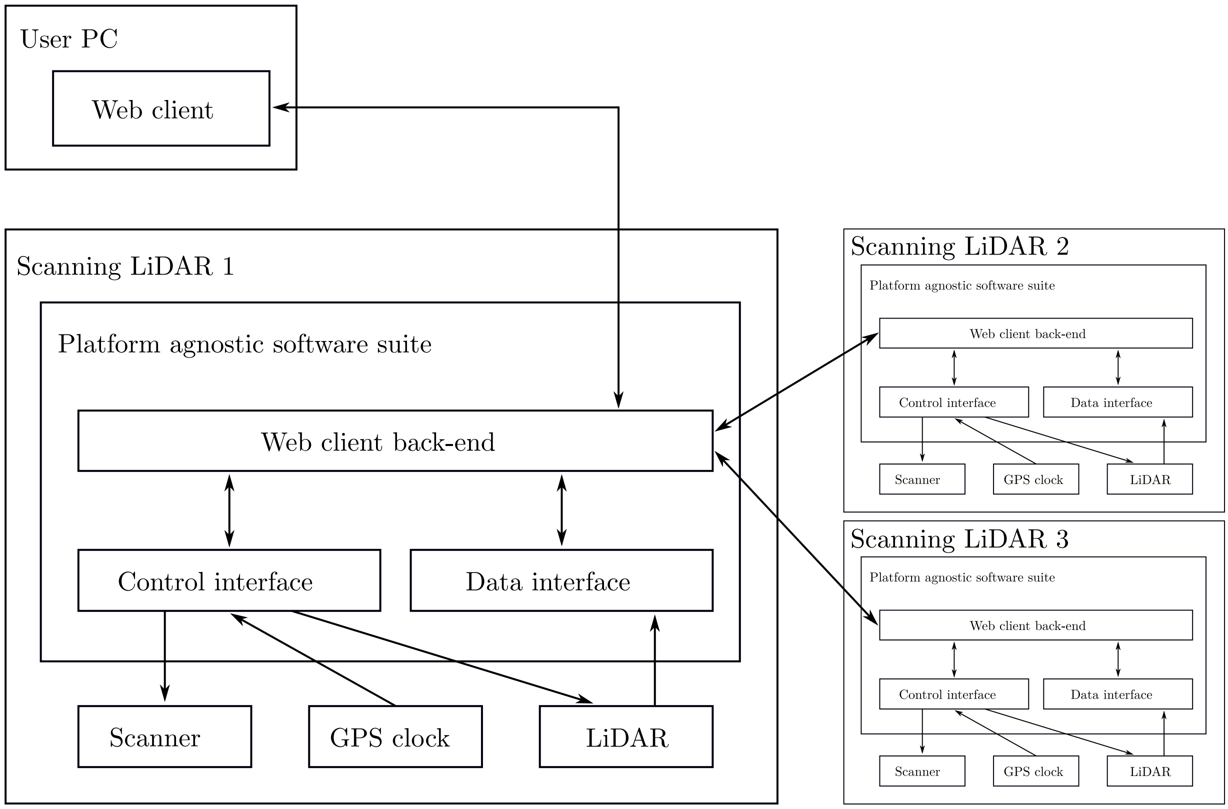

Figure 3. The scanner system hardware and software were designed to function independently of the underlying LiDAR unit. Depending on the LiDAR unit the platform agnostic software stack can be installed on the LiDAR unit or an additional computer. Therefore the scanner system provides spatially and temporally synchronized measurements for any LiDAR system matching the hardware requirements.

the scanner around its vertical axis by 90° after each 90° azimuthal scan segment. Thus each segment produced measurements in the same atmospheric volume. Additionally, reference measurements without the scanner were taken before and after each measurement. The obtained backscatter intensities presented in Figure 4 show no dependence on the azimuth angle ϕ but significant dependence on polar angle θ with much higher intensities for vertical measurements ($60° < \theta < 120°$) than horizontal ones. Fortunately, there are no angles with zero intensity, so measurements can be performed at all angles, albeit with lower range for horizontal measurements. Further investigation in a proper polarization test set-up is planned for the coming weeks. Depending on the results we plan to further optimize the mirrors and, if feasible, add active polarization correction to the scanner.

3. WIND VELOCITY LIDAR

A DWL measures wind speed along its line-of-sight by observing the Doppler-shifted backscatter from aerosols. At least three independent measurements from different angles are required to yield all components of the three-dimensional wind vector. Common DWL obtain these measurements from a single unit by pointing their laser beam in different directions and combining the retrieved values to a single measurement above the unit (c.f. *Doppler Beam Swinging* (DBS) and *Velocity-Azimuth Display* (VAD)[3]). These types of measurement produce good results in homogeneous flow but introduce significant errors of up to 10 % in inhomogeneous flow or under turbulent conditions as commonly encountered above complex terrain.[4–6] Some recent systems employ multiple LiDAR units to achieve true point measurements and greatly reduce the complex terrain error.[7] We aim to improve on such systems and their end-user experience by improving portability, simplifying the set-up process,

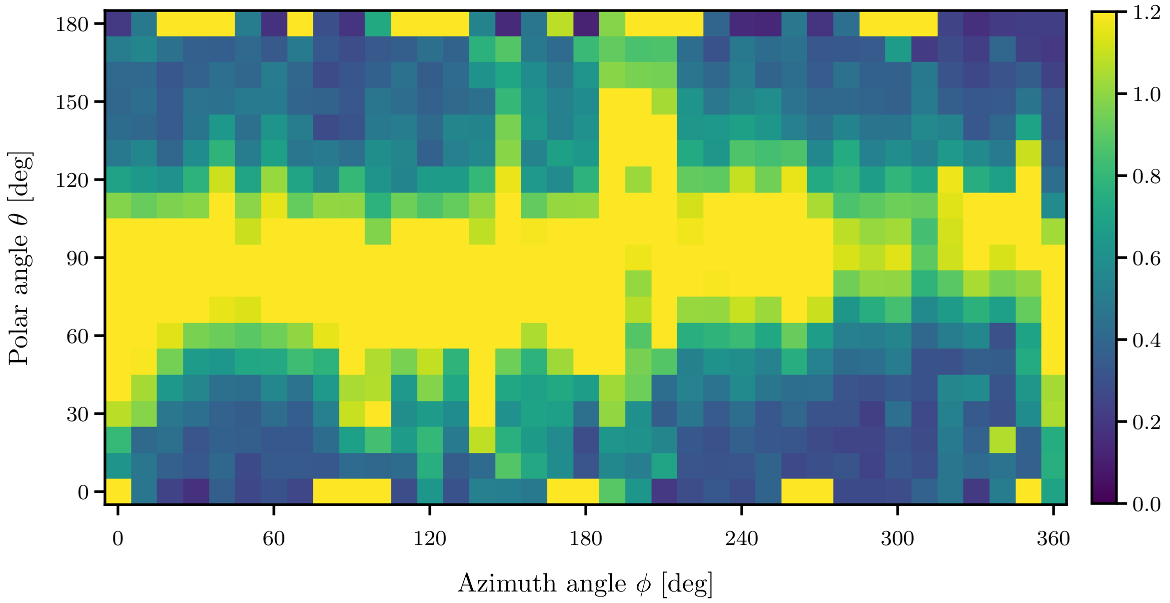

Figure 4. The polarization of the outgoing and incoming laser beams is essential for many coherent and several other LiDAR. The plot shows the backscatter intensity measured by a coherent wind LiDAR attached to the scanner as a function of azimuth angle ϕ and polar angle θ, where $\theta = 0°$ and $\theta = 180°$ represent horizontal measurements and $\theta = 90°$ vertical measurements. Intensity is shown in arbitrary units. Reference measurements without the two-mirror scanner showed homogeneous intensity throughout all angles. The high intensity values at some horizontal positions are caused by hard targets like buildings and trees. The data show a strong dependence of intensity on the polar angle, which is controlled by the second mirror,

minimizing system maintenance during measurement campaigns, reducing system cost, providing evaluated and raw data to users and eventually improving spatial resolution.

In order to quickly outfit three scanners with LiDAR units we acquired two commercially available units while developing one unit ourselves. The different units provide reference measurements already during development of our own unit and help proving the flexibility of the scanner early on. As commercially available units we chose a *Leosphere Windcube v1* and an *OpticSense Whirlwind*. From the Windcube we removed the prism to produce a vertical beam and installed the scanner control software, data converter and synchronization client. The Whirlwind was acquired as on open unit without the standard housing and placed in a custom enclosure with altered telescope placement better fitting the scanner. We also added the scanner control software, a data converter and the synchronization client to the Whirlwind. Figure 5 shows both the scanning Windcube and Whirlwind side-by-side. The self-developed unit is based on an *Abacus Laser* 1.5 µm laser module.

Once all units meet the aimed for accuracy, spatial resolution and measurement frequency we plan to equip the entire system with self-developed LiDAR units to provide end-users with complete, high resolution data streams from all measurement directions. So far the self-developed unit follows the well established DWL design shown in Figure 6. The seed laser, acousto-optic modulator (AOM), amplifiers and circulator are part of the Abacus Laser module, while the optic mixer, detector, digitizer and control and monitoring parts were added by us. We currently use a standard 50:50 polarization-maintaining single-mode fiber-optic coupler for mixing the local oscillator (LO) and backscatter signal, a Thorlabs PDB480C-AC for detection and a PicoScope 3206D as digitizer. Laser, AOM and amplifier control and pulse monitoring is done on a Red Pitaya STEMLab 125-14 with self-developed FPGA firmware. A first validation of the entire scanning LiDAR system is planned to take place at the 200 m metmast at the *Rödeser Berg* complex terrain site in central Germany in 2019 and 2020.

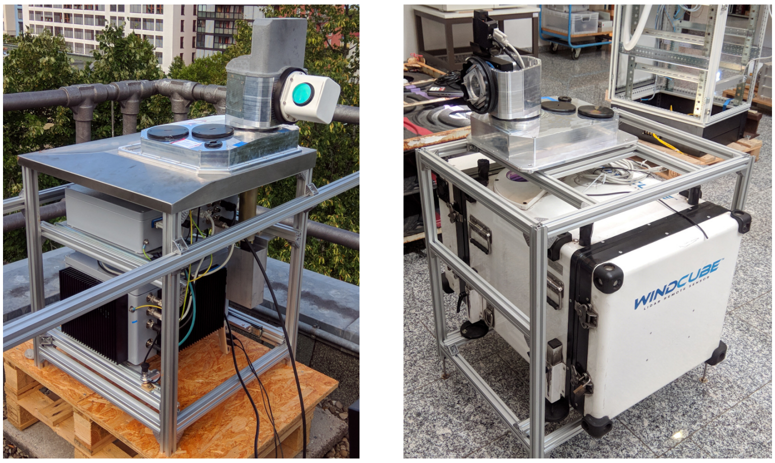

Figure 5. Images of the first two scanning LiDAR units. The left unit contains an OpticSense Whirlwind, the right contains a Leosphere Windcube v1.

4. AIR TEMPERATURE AND MOISTURE LIDAR

Current LiDAR employ various techniques for measuring air temperature and moisture content. We briefly review state-of-the-art approaches which appear suitable for precise measurements and integration with a wind velocity LiDAR in a single LiDAR unit.

Air temperature in the lower atmosphere is measured by either *High Spectral Resolution LiDAR* (HSRL), *Raman LiDAR* or *Differential Absorption LiDAR* (DIAL).

HSRLs measure temperature by determining the spectral width of the Rayleigh peak from the molecular backscatter signal. The peak width is temperature dependent due to increasing Doppler broadening with increasing temperature caused by growing thermal movement of the air molecules. HSRLs employ various types of optical filters to only detect backscattered photons at specific wavelengths. The Rayleigh peak height and

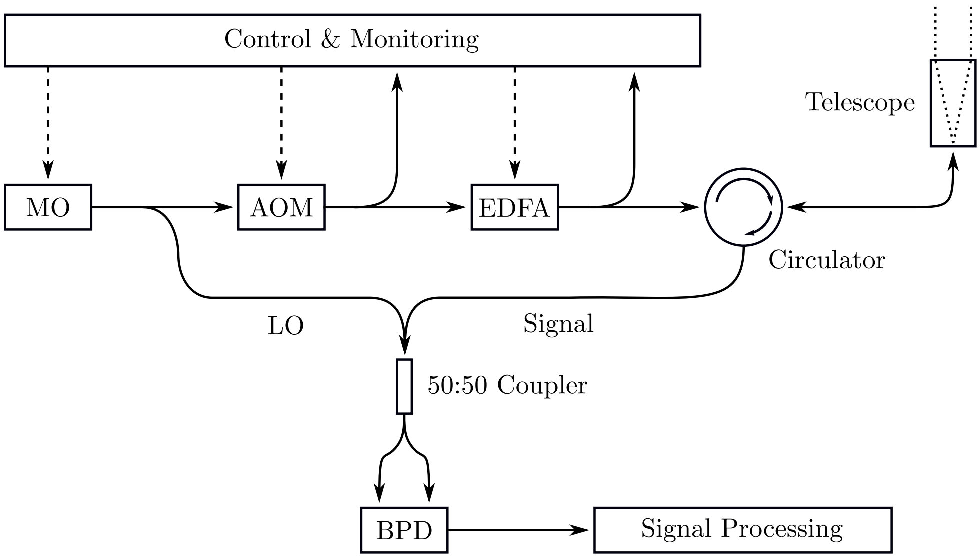

Figure 6. Schematic of the Doppler Wind LiDAR developed at Fraunhofer IPM. MO: Master oscillator, AOM: acousto-optic modulator, EDFA: Erbium-doped fiber amplifier, BPD: balanced photo-detector.

width is then calculated from the difference in amplitude at the measured wavelengths. Current HSRLs typically achieve a precision of 2 K and range resolution of ≈ 200 m at integration times on the order of minutes to an hour and measurement ranges up to 10 km.[8–11] Most HSRLs use UV lasers to generate sufficient signal-to-noise ratios, because the molecular backscatter cross-section β decreases with increasing wavelength λ ($\beta \propto \lambda^{-4}$). HSRLs require large telescopes with apertures ≥ 20 cm and very stable and narrow linewidth lasers and filters.[10] Additionally the achievable precision is limited, since the Rayleigh peak is flat and broad and only estimated from two measured wavelengths.

Raman LiDARs use the temperature dependent population of rotational levels of molecules such as diatomic Nitrogen (N_2).[12] Such LiDARs achieve a precision of 1 K and range resolution of ≈ 100 m at integration times on the order of minutes down to 10 s and measurement ranges of several kilometers.[13–15] Raman LiDARs suffer from even smaller, also wavelength-dependent backscatter cross-sections and thus require high power UV lasers, large aperture telescopes and high precision and high-efficiency optical spectroscopes with narrow filters to detect the few backscattered photons. Therefore Raman LiDARs tend to be bulky and expensive.[10,16,17] Nevertheless, Raman LiDAR is to date the most reliable remote sensing technique for air temperature and the only technique for which a range resolution and integration time suited for turbulence measurements has been demonstrated.[14,15]

Temperature DIALs utilize the temperature dependent absorption spectrum of e.g. diatomic Oxygen (O_2). Air temperature is determined by comparing the backscatter intensity of at least two laser beams at different absorption lines, one of which is only present in excited molecules. Such LiDARs achieve a precision of 2 K and range resolution of ≈ 150 m at integration times on the order of minutes and measurement ranges of several kilometers.[18] The DIAL method as well requires very stable and narrow linewidth lasers at two or more different wavelengths, usually in the near infrared, large aperture telescopes and narrow filters. Despite comparable specs and suitable lasers and filters more readily available due to recent advances in laser technology Bunn 2019[19] seems to be the only recent publication concerning temperature DIAL development.

Moisture content in form of water vapor and water droplets is measured using *Differential Absorption LiDAR* (DIAL). These DIALs measure the difference in backscatter intensity of a wavelength strongly absorbed by water and a wavelength with only little absorption. Current narrowband lasers are capable of generating wavelengths spaced only fractions of nanometers apart, which allows exploiting very narrow absorption lines within the water spectrum. Using similar wavelengths reduces measurement artifacts introduced by e.g. wavelength-dependent scattering cross-sections to a minimum. Such LiDARs achieve relative errors ≤ 10 % and range resolution of ≈ 150 m at integration times on the order of minutes and measurement ranges of tens of kilometers.[19,20] Just as temperature DIALs, moisture DIALs require very stable and narrow linewidth lasers, usually also in the near infrared, narrow optical filters and large aperture telescopes. Again, recent advances in laser and amplifier technology made such components available at lower cost and in smaller packaging, allowing for rapid advances in DIAL design.[21]

5. MULTI-PURPOSE LIDAR SYSTEM

To date several LiDAR units combining temperature and moisture measurements have been documented.[14,22,23] These units either use only DIAL, only Raman, or a combination of DIAL and Raman LiDAR. A project combining wind and temperature measurements in a standard DWL at $\lambda = 1.5$ µm has not yet been realized.[24] To our knowledge no LiDAR for simultaneous measurement of wind velocity, air temperature and moisture content exists. We are currently investigating two approaches for creating such a system. The first is based on combining the proven measurement techniques achieving the best resolutions in a single, scanning device. The second approach is based on the development of a novel, coherent detection molecular backscatter LiDAR.

For the first approach we consider combining a DWL, a rotational Raman temperature LiDAR and a water vapor DIAL. Based on our review of the state-of-the-art, these seem to be the techniques best suited for our target specifications. Since DWL typically operate at 1550 nm, moisture DIAL at 822 nm and Raman LiDAR at 355 nm such a LiDAR unit requires at least three light sources and three separate scanners with different lenses, mirrors and likely mechanics, due to the large difference in apertures. Therefore, this approach likely produces a bulky, expensive and complex system with little to no benefit over three separate LiDAR units. We are currently investigating whether it is feasible to perform DWL and water vapor DIAL measurements at the same wavelength to reduce the number of required light sources and scanners to offer advantages over three separate LiDAR units. For this approach, we expect measurement resolutions similar to the state-of-the-art of the individual techniques.

The second approach is based on the development of a novel, coherent detection molecular backscatter LiDAR for temperature measurements. Coherent detection has the benefits of low laser energy requirements, no sensitivity to background light and high measurement resolution. The technique has been proposed for molecular backscatter signals before[25] and recently been demonstrated on a 2 µm, airborne DWL.[26] Due to the small Rayleigh backscatter cross-section at large wavelengths separation of the Rayleigh signal is very difficult, so we propose building a coherent detection molecular backscatter LiDAR at a much smaller wavelength. The wavelength range is mostly limited by the electronics available for sampling the spectral width of the Rayleigh peak, which increases with smaller wavelengths. We expect 532 nm to produce a spectral width of about 1.1 GHz half width at half maximum (HWHM), which is at the limit of current electronics and therefore currently our target wavelength. By also resolving the much narrower aerosol backscatter signal we expect to obtain an accurate wind velocity measurement from the same LiDAR. We are investigating whether a different wavelength offers a better compromise regarding laser requirements and electronics requirements and allows simultaneous moisture measurements, Integrating moisture measurements as well would result in a completely integrated, compact, low-power, low-cost LiDAR unit. For this approach, we expect a wind velocity and temperature range resolution of 10 m at up to 2 km range with accuracies of $0.1\,\mathrm{m\,s^{-1}}$ and 1 K respectively, while providing moisture measurements comparable to the state-of-the-art.

We propose the LiDAR design shown in Figure 7, which is similar to the current DWL design shown in Figure 6. A narrowband, continuous wave 1064 nm seed laser is split into an LO and signal path. The signal path beam is chopped into pulses by an AOM and then amplified and frequency doubled. The LO is also frequency doubled and interferes with the backscatter signal to produce an amplified beat note. The beat note is detected and digitized, using a large bandwidth photo detector and high speed electronics.

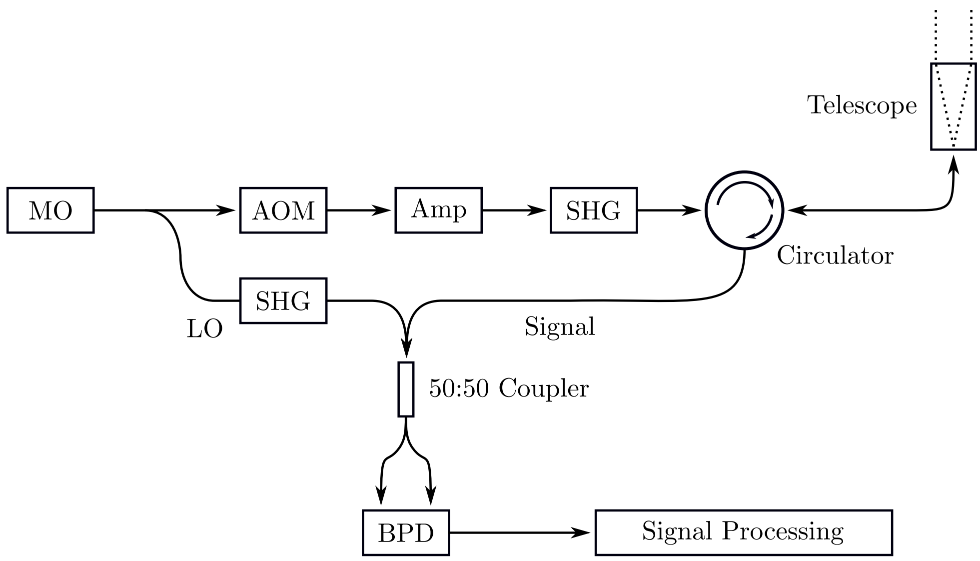

Figure 7. Schematic of a proposed coherent molecular backscatter LiDAR at 532 nm. MO: Master oscillator, AOM: acousto-optic modulator, Amp: Amplifier, SHG: Second-harmonic generation, BPD: balanced photodetector.

6. CONCLUSION

At Fraunhofer IPM a multi-head, scanning LiDAR system providing high resolution measurements of wind velocity, air temperature and moisture for wind energy, extreme weather forecasting and urban climatology is being developed. So far we created a flexible, self-monitoring, small aperture scanner and a network protocol for linking and synchronizing multiple scanners and data streams. Preliminary tests predict an angular positioning accuracy of better than 1 m in both azimuth and polar angle at a range of 500 m. Experiments to determine the absolute accuracy in a global coordinate system are ongoing. So far we combined the scanner with two commercially available DWL, while a self-developed DWL is nearing completion. Verification measurements of the complete, multi-head scanning DWL system will be carried out at a 200 m metmast in complex terrain and are planned for late 2019 and early 2020.

Investigations regarding available techniques and achievable accuracies for air temperature and moisture measurements are ongoing. Based on the current state of the investigation we developed two proposals for integrated, multi-head, scanning wind velocity, air temperature and moisture LiDAR systems. One of the approaches includes the development of a novel, coherent detection molecular backscatter temperature LiDAR, which promises higher spatial resolution and lower (optical) power requirements compared to current systems. It also has the potential of integrated wind velocity and possibly moisture measurements. We expect starting hardware development in 2020 and obtaining first results proving the feasibility of the proposed system in 2021.

ACKNOWLEDGMENTS

We thank the German Federal Ministry of Education and Research (BMBF) and the Fraunhofer Society for funding this project. We also thank Fraunhofer IEE and Mr. Christoph Bollig of Abacus Laser for their contributions.

REFERENCES

[1] Stevens, B., Farrell, D., Hirsch, L., Jansen, F., Nuijens, L., Serikov, I., Brügmann, B., Forde, M., Linne, H., Lonitz, K., and Prospero, J. M., "The Barbados cloud observatory: Anchoring investigations of clouds and circulation on the edge of the ITCZ," *Bulletin of the American Meteorological Society* **97**(5), 735–754 (2016).

[2] Gimbal, S., Li, Q., and Petrova-Mayor, A., "Polarization effects induced by a two-mirror laser beam scanner," in [*Remote Sensing System Engineering IV*], **8516**(October 2012), 85160F (2013).

[3] Cliff, W. C. and Huffaker, R. M., "Application of a single laser Doppler system to the measurement of atmospheric winds," *NASA Technical Memorandum* **NASA TM X-** (oct 1974).

[4] Cheong, B. L., Yu, T. Y., Palmer, R. D., Yang, K. F., Hoffman, M. W., Frasier, S. J., and Lopez-Dekker, F. J., "Effects of wind field inhomogeneities on Doppler beam swinging revealed by an imaging radar," in [*Journal of Atmospheric and Oceanic Technology*], **25**, 1414–1422 (aug 2008).

[5] Bingöl, F., Mann, J., and Foussekis, D., "Lidar performance in complex terrain modelled by WAsP Engineering," *Ewec 2009* , 9 (2009).

[6] Bradley, S., Perrott, Y., Behrens, P., and Oldroyd, A., "Corrections for Wind-Speed Errors from Sodar and Lidar in Complex Terrain," *Boundary-Layer Meteorology* **143**, 37–48 (apr 2012).

[7] Mikkelsen, T., Mann, J., Courtney, M., and Sjöholm, M., "Windscanner: 3-D wind and turbulence measurements from three steerable doppler lidars," *IOP Conference Series: Earth and Environmental Science* **1**, 012018 (may 2008).

[8] Liu, Z.-S., Bi, D.-C., Song, X.-q., Xia, J.-B., Li, R.-z., Wang, Z.-j., and She, C.-Y., "Iodine-filter-based high spectral resolution lidar for atmospheric temperature measurements," *Optics Letters* **34**, 2712 (sep 2009).

[9] Witschas, B., Lemmerz, C., and Reitebuch, O., "Daytime measurements of atmospheric temperature profiles (2–15 km) by lidar utilizing Rayleigh–Brillouin scattering," *Optics Letters* **39**, 1972 (apr 2014).

[10] Abo, M., Le Hoai, P. P., Aruga, K., Nagasawa, C., and Shibata, Y., "High Spectral Resolution Lidar Based on a Potassium Faraday Dispersive Filter for Daytime Temperature Measurement," *EPJ Web of Conferences* **119**, 17007 (jun 2016).

[11] Razenkov, I. I. and Eloranta, E. W., "Advances in atmospheric temperature profile measurements using high spectral resolution lidar," *EPJ Web of Conferences* **176**, 01023 (apr 2018).

[12] Cooney, J., "Measurement of Atmospheric Temperature Profiles by Raman Backscatter," *Journal of Applied Meteorology* **11**(1), 108–112 (1972).

[13] Radlach, M., Behrendt, A., and Wulfmeyer, V., "Scanning rotational Raman lidar at 355 nm for the measurement of tropospheric temperature fields," *Atmospheric Chemistry and Physics* **8**(2), 159–169 (2008).

[14] Froidevaux, M., Serikov, I., Burgos, S., Ristori, P., and Simeonov, V., "A new lidar for water vapor and temperature measurements in the Atmospheric Boundary Layer," *AsiaFlux Newsletter* (28), 13–17 (2009).

[15] Behrendt, A., Wulfmeyer, V., Hammann, E., Muppa, S. K., and Pal, S., "Profiles of second- to fourth-order moments of turbulent temperature fluctuations in the convective boundary layer: First measurements with rotational Raman lidar," *Atmospheric Chemistry and Physics* **15**(10), 5485–5500 (2015).

[16] Hammann, E., Behrendt, A., Le Mounier, F., and Wulfmeyer, V., "Temperature profiling of the atmospheric boundary layer with rotational Raman lidar during the HD(CP)2 Observational Prototype Experiment," *Atmospheric Chemistry and Physics* **15**(5), 2867–2881 (2015).

[17] Shen, F., Zhuang, P., Shi, W., Qiu, C., Wang, B., and Xie, C., "Fabry–Perot etalon-based ultraviolet high-spectral-resolution lidar for tropospheric temperature and aerosol measurement," *Applied Physics B: Lasers and Optics* **124**, 138 (jul 2018).

[18] Wulfmeyer, V., "Ground-based differential absorption lidar for water-vapor and temperature profiling: development and specifications of a high-performance laser transmitter," *Applied Optics* **37**, 3804 (jun 1998).

[19] Bunn, C. E., "Diode-Laser-Based Micro-Pulse Differential Absorption Lidar (DIAL) for Thermodynamic Profiling of the Lower Troposphere," in [*Optical Sensors and Sensing Congress*], (2019).

[20] Spuler, S. M., Repasky, K. S., Morley, B., Moen, D., Hayman, M., and Nehrir, A. R., "Field-deployable diode-laser-based differential absorption lidar (DIAL) for profiling water vapor," *Atmospheric Measurement Techniques* **8**(3), 1073–1087 (2015).

[21] Spuler, S., Repasky, K., Hayman, M., and Nehrir, A., "Micro-pulse, differential absorption lidar (dial) network for measuring the spatial and temporal distribution of water vapor in the lower atmosphere," *EPJ Web of Conferences* **176**, 05012 (apr 2018).

[22] Wulfmeyer, V. and Bösenberg, J., "Ground-based differential absorption lidar for water-vapor profiling: assessment of accuracy, resolution, and meteorological applications," *Applied Optics* **37**, 3825–3844 (jun 1998).

[23] Behrendt, A. and Wulfmeyer, V., "Combining water vapor DIAL and rotational Raman lidar for humidity, temperature, and particle measurements with high resolution and accuracy," in [*Lidar Remote Sensing for Environmental Monitoring IV*], Singh, U. N., ed., **5154**, 61, International Society for Optics and Photonics (dec 2004).

[24] Abari, C. F., Chu, X., Mann, J., and Spuler, S., "A Micropulse eye-safe all-fiber molecular backscatter coherent temperature lidar," *EPJ Web of Conferences* **119**, 25005 (jun 2016).

[25] Rye, B. J., "Molecular backscatter heterodyne lidar: a computational evaluation," *Applied Optics* **37**(27), 6321 (1998).

[26] Chouza, F., Witschas, B., and Reitebuch, O., "Heterodyne high-spectral-resolution lidar," *Applied Optics* **56**, 8121 (oct 2017).