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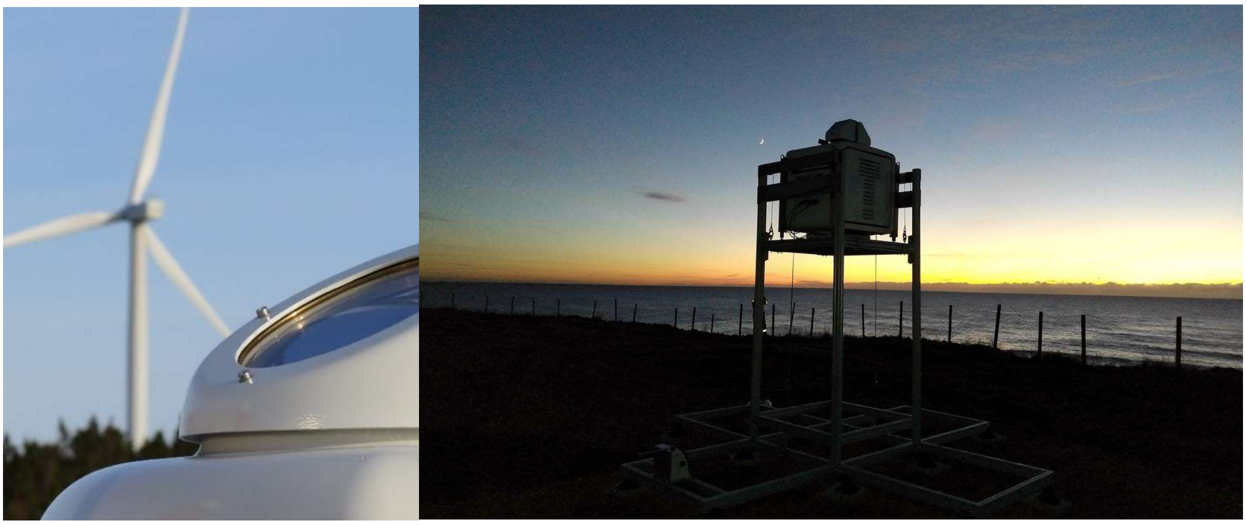
D4.1 Recommendation on use of wind lidars



Authors: Joachim Reuder (UiB), Etienne Cheynet (UiB), Andrew Clifton (USTUTT), Marijn Floris van Dooren (UOL), Julia Gottschall (IWES), Jasna B. Jakobsen (UiS), Jakob Mann (DTU), Jose Palma (UPORTO), David Schlipf (FUAS), Mikael Sjöholm (DTU), Juan-Jose Trujillo (UL), Ludovic Thobois (Leosphere), Ines Würth (USTUTT), Alberto Zasso (POLIMI)
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Photo credit: Front page left: DTU short-range WindScanner, photo by Mikael Sjöholm; Front page right: Scanning lidar deployed during the COTUR campaign on the Norwegian west Coast at Obrestad, photo by Pablo Saavedraa

Publisher: Geophysical Institute and Bergen Offshore Wind Centre (BOW) University of Bergen, 5007 Bergen, Norway

Preface

The 15 Early Stage Researchers (ESRs) in the LIKE project investigate topics in which wind lidar play a significant role. This report provides the ESRs an introductory reading and gives a short introduction into the basic principles, as well as an overview on the practical application of lidar wind measurement technology for a wide range of research fields, including a corresponding literature review. Wherever possible, it will also give the ESRs recommendations on the use of lidars and related best practices and provide corresponding state-of-the-art documents in the attachment.

Contents

1. Introduction

1.1 Focus area

Lidar (light detection and ranging) remote sensing has a wide range of applications in atmospheric research, including the characterization of atmospheric aerosol particles (Ansmann and Müller, 2005), clouds and visibility (Werner et al., 2005), concentration of various trace gases (as ozone (Gimmestad, 2005), mercury (Sjöholm et al., 2004) or water vapor (Bösenberg, 2005)), and atmospheric temperatures (Behrendt, 2005; Bösenberg, 2005). This report will, however, purely focus on the remote sensing of wind.

We will also limit ourselves, at least to a large extent, to ground and wind-turbine-nacelle-based systems and not cover satellite-based wind measurements (e.g., from the Aeolus satellite (Witschas et al., 2020)) or lidar wind measurements from manned aircraft (e.g., Witschas et al., 2017). The exception is a short description of a recent development of a drone-mounted miniaturized lidar for application in wind energy related research (Vasiljević et al., 2020).

Most of the presented lidar applications are confined to the altitude range in the atmospheric boundary layer (ABL) relevant for state-of-the-art wind turbines (up to ca. 300 m). We will, however, also shortly introduce systems and measurement approaches for higher levels (up to ca. 3 km above ground) that are important for airborne wind energy (AWE) applications (Ahrens et al., 2013; Cherubini et al., 2015) or for air safety considerations with respect to terrain induced turbulence at exposed airports (Chan, 2010).

1.2 Short history on lidar wind measurements

The history of lidar wind measurements has been written to various levels of details in various publications. For instance in Gryning et al. (2017) the following history is provided: "Lidars for meteorological applications emerged in the early 1960s shortly after the invention of the red ruby laser. Wind lidars based on the so-called coherent detection principle of Doppler-shifted frequency in backscattered radiation were one of the first applications of the emerging laser technology. The technology used in lidars has since expanded vastly in capability". Furthermore, Gryning et al. (2017) outlines the technology development by writing "Originally lidars were large heavy instruments, but owing to the use of components developed for use in optical fiber communication, lidars have improved in compactness, reliability, and ease of use. The development of eye-safe fiber-based lidars started in the mid-1990s and the first commercially available products became available about 15 years later."

In summary, lidar technology has been there since the early days of development of lasers, however, as related in Mikkelsen et al. (2014) the real turning point for its application in wind energy came with a technological change around the end of the last millennium. Namely, more compact and robust systems were possible with the all-fibre Doppler wind lidar (Karlsson et al., 2000). An overview of the application of lidar technology is given in e.g., Liu et al. (2019) and Clifton et al. (2018).

2. Short introduction in lidar technology

During the last decades, remote sensing has become popular in the wind energy sector. Especially Doppler wind lidar (Werner, 2005) has proven itself as a reliable measurement technique for the wind speeds at wind turbine installation sites. Lidar has several commercial applications, such as site assessment and power curve measurement, but is also widely used in research, for which the ITN LIKE project is a prime example.

The principle of wind lidar is based on the Doppler effect applied on an emitted infrared laser beam. A lidar emits a laser beam with a fixed frequency, which will be reflected by small aerosols in the air. Those particles are assumed to be moving with the local wind speed, which causes a frequency shift in the laser beam signal, used to determine the wind speed.

The Doppler effect can be expressed in Eq. (1);

$$f_r = f_e\left(1 + 2\frac{v_{LOS}}{c}\right), \tag{1}$$

where f_e is the emitted frequency, f_r is the reflected frequency, v_{LOS} is the line-of-sight wind speed measurement of the lidar and c is the speed of light ($3.0\cdot 10^8$ m/s). One can rewrite this formula to calculate the line-of-sight wind speed v_{LOS} from Eq. (2);

$$v_{LOS} = \frac{1}{2}c\frac{f_r - f_e}{f_e} = \frac{1}{2}c\frac{\Delta f}{f_e}, \tag{2}$$

based on the known and measured parameters, and where the frequency shift (or Doppler shift) is defined as $\Delta f = f_r - f_e$. If the wind speed is pointed towards the observer, the frequency shift and the wind speed will be positive, and if the wind is moving away, the shift will have a negative sign.

A common shortcoming of lidar is that every single measurement is a one-dimensional projection of the 3D wind speed vector on the line-of-sight of the laser beam, Eq. (3);

$$v_{LOS} = \begin{bmatrix} \cos(\chi)\cos(\delta) \\ \sin(\chi)\cos(\delta) \\ \sin(\delta) \end{bmatrix} \cdot \begin{bmatrix} u \\ v \\ w \end{bmatrix}, \tag{3}$$

where χ and δ are the geometrical azimuth and elevation angles of the laser beam in the mathematical reference frame. From a single v_{LOS} measurement it is not possible to reconstruct the wind speed vector $[u\ v\ w]^T$, however with three linearly independent measurements (e.g., from three different lidars) it is possible to measure a full 3D vector.

The following sections will explain the different types of wind lidar systems.

2.1 Continuous wave lidar and pulsed lidar

The two main lidar technology classes are continuous wave (CW) and pulsed lidar. They both have their own advantages and disadvantages, and thus differing applications.

A continuous wave lidar (Slinger and Harris, 2012) will have an uninterrupted emission of laser light, which is focused on a specific point in space. The line-of-sight wind speed cannot be determined at an infinitesimal point in space but is rather an average within the so-called probe volume, described by a Lorentzian weighting function around the desired focus point. The probe volume should be interpreted as a thin cylindrical volume in space, with a length defined as the full width at half maximum of the Lorentzian weighting function (see Fig. 1).

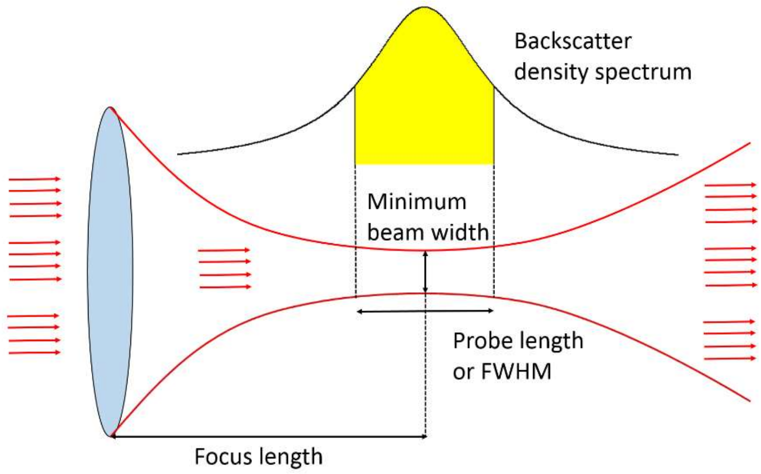

***Fig. 1**: Focus principle of continuous wave lidar.*

The Lorentzian Function F is defined by Eq. (4);

$$F = \frac{1}{\pi}\left(\frac{\Gamma}{(s-f)^2+\Gamma^2}\right), \quad (4)$$

where Γ is the half width at half maximum, s is the coordinate along the line-of-sight, and f is the focus distance. The half width at half maximum can be calculated as a quadratic function of the focus distance according to Eq. (5):

$$\Gamma = \frac{\lambda f^2}{\pi a^2}, \quad (5)$$

where λ is the laser light wavelength and a is the minimum beam width. The theory indicates that continuous wave lidar will have a reduced resolution at further away focus distances. Therefore, continuous wave lidars will most commonly also be short range lidars (see Sect. 2.3).

Pulsed lidar (Cariou, 2013) is fundamentally different from continuous wave lidar since the laser light is emitted as pulses. The pulse pattern and accumulation time in between pulses are both important values that must be selected carefully. The pulses pattern gives us a trigger signal, which lets us calculate the focus distance according to the time of flight of the laser beam, by Eq. (6);

$$r = \frac{1}{2}ct, \quad (6)$$

where r is the range and t is the time of flight. This omits the need to focus the laser beam at a specific point in space (like CW) and opens the possibility of measuring the wind speed at multiple ranges along the line-of-sight simultaneously. Practically, this is managed by 'cutting up' the reflected pulse signal into several so-called range gates. These range gates usually have a width of about 30 m until the furthest range. Pulsed lidar can usually reach further distances than CW lidar can, because the beam is not focused on a specific distance and therefore penetrates the atmosphere as far as the weather conditions allow. Therefore, whereas the accuracy of CW lidar is mainly determined by the focus distance, the furthest range a pulsed lidar can measure is mostly determined by how much backscatter will still be obtained by the lidar. This, however, can be slightly influenced by setting the parameters like pulse width and accumulation time correctly. Pulsed lidars can be both short-range and long-range.

Because of the physics of the measurement process, continuous wave lidars usually allow for a more precise wind measurement, with a larger spatial resolution, but at shorter distances. Pulsed lidar can define the wind speed at many different measurement points at the same time, which allows for the coverage of very large areas by scanning (see Sect. 2.2); however, with a lower spatial resolution than continuous wave. Both types of lidar have clear advantages, which will be underlined by the applications discussed in the following.

2.2 Profiling and scanning using wind lidar

To provide the vertical profile of the wind vector, the Doppler Beam Swinging scenario (DBS) can be used, which combines the radial wind speeds measured for at least 3 LOS to retrieve the three components of the wind vector. In the Windcube Scan software, the DBS mode consists of 5 lines of sight (LOS) including 4 LOS spaced 90° apart with a fixed elevation angle θ, and one vertical LOS. Expressed in the Lidar spherical coordinate system, the 5 LOS are (0°, θ), (90°, θ), (180°, θ), (270°, θ), and (0,90°)

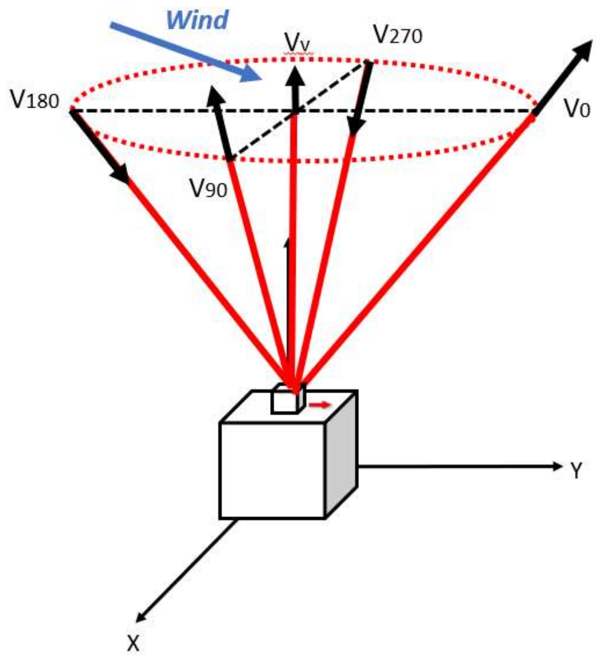

Fig. 2*: Scheme of the DBS mode.*

All along each LOS, multiple range gates are defined to perform individual measurements of the Doppler velocity or radial wind speed. The radial wind speeds measured for the LOS at 0°, 90°, 180°, 270° and towards zenith are noted V_0, V_{90}, V_{180}, V_{270}, V_v.

Profiling continuous wave lidars like the ZX lidars perform VAD (velocity-azimuth display) scanning where the beam emerging from one point is deviated by an optical prism, which is rotated around the axis of the incoming laser beam, which forms scanning on a conical surface. Similar to the DBS technique, the wind can be retrieved but here using all the directions on a circle instead of only the four directions mentioned above.

2.3 Multi-lidar strategies

Various lidar scanning strategies are defined within the IEA Task 32's proto lidar taxonomy (Clifton et al., 2015). Multi-lidar scanning strategies with convergent beams (the topic of this section) are subsets of the general scanning lidar category but with more freedom in the control of azimuth and elevation angles of the laser beams. Generally, three lidar units are needed for simultaneous measurements of the three components of the wind vector, but sometimes only two lidars are used which can be justified when the laser beams are close to horizontal and the measurement geometry reduces to two dimensions. These measurement scenarios can be called triple and dual Doppler Lidar, respectively (Newman et al., 2015; Newman et al., 2016; Debnath et al., 2017).

DTU started the development of convergent beam strategies based on modern Doppler lidars in 2007 by performing the first Musketeer (Dumas, 1844) experiment, see Figure 3, using three fixed crossing lidar beams from three Leosphere wind cubes (Mann et al., 2009). This measurement campaign was the onset of the development of synchronized multi-lidar instruments that become called WindScanners (Mikkelsen et al., 2008). A general overview can be found in Gryning et al. (2017).

Fig. 3*: The first DTU Wind Energy Musketeer experiment using three staring wind cubes. Jean-Pierre Cariou and Remy Parmentier from Leosphere aligning an alignment laser at a cold December evening at Høvsøre, western Jutland, Denmark.*

Subsequently, two complementary development paths were followed at DTU Wind Energy for WindScanners making the best use of the advantages of pulsed and continuous-wave Doppler lidars in collaboration with French Leosphere and British Qinetiq (later Natural Power, ZephIR Lidar, and now ZX Lidar). A double-mirror-based scan head was developed for the pulsed long-range WindScanners based on a Leosphere Lidar in collaboration with IPU and Heason. Later, this scanning technology was adopted by Leopsphere and is now commercially available. The technical details have been outlined e.g., in Vasiljevic et al. (2016).

A double-prism-based scan head was invented for the continuous-wave short-range WindScanners based on an idea by Torben Mikkelsen when he was shopping with his family at the Swedish furniture company IKEA and found a night lamp that could be rotated, see Figure 4.

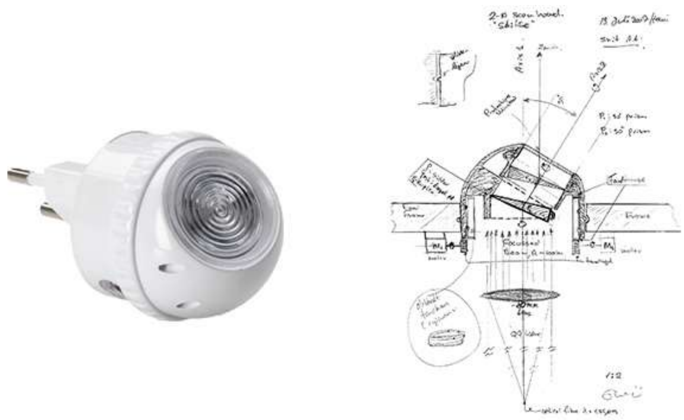

Fig. 4*: The original double-prism scanner idea for the short-range Windscanner (Ryde, 2016).*

The short-range WindScanner has been used in several measurement campaigns described in other sections of this document (e.g., 3.2 and 3.4) as well as for the measurement of downdraft under helicopters, which can be read about in Sjöholm et al., 2014 where the short-range WindScanner is described for the first time. A more recent description of the system with further references can be found in Sjöholm et al. (2018). During the development period of more than a decade, various versions have been designed and the latest incarnation is all integrated at DTU Wind Energy.

The latest developments include increased size of the optics using telescopes of 6-inch diameter, see Figure 5, instead of 3 inch allowing for even more spatially detailed measurements. Other major developments have been pursued in the signal detection and processing steps utilizing optical hybrids for detection of the sign of the Doppler shift instead of the original acousto-optic frequency offset methodology (Abari, 2015) as well as in-house programmed signal processing utilizing National Instruments FPGA-based FlexRIO modules.

The latest WindScanner measurement applications include Lidar scanning of wind turbine induction zone wind fields over sloping terrain (Mikkelsen et al., 2020) as well as rapid measurements of wind turbine wake dynamics (Larsen et al., 2019) and spatially detailed wind turbine wake measurements (van der Laan et al., 2019).

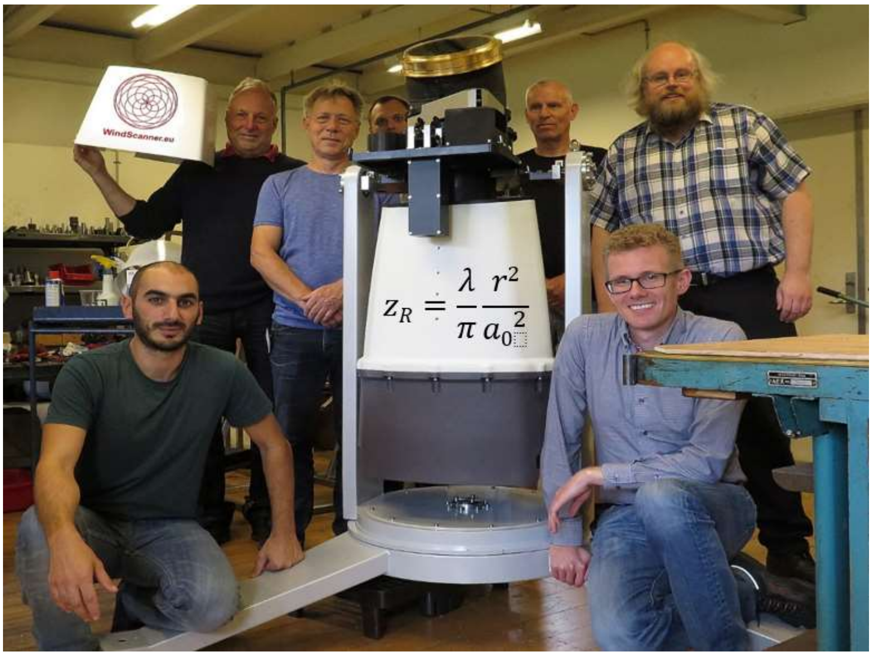

Fig. 5: *The first-generation, 6-inch short-range WindScanner with part of the DTU Development team.*

2.4 Floating lidar

Floating lidars, defined as wind lidars positioned on or integrated in a floating platform, appeared in a wind energy context for the first time around 2010. Buoy-based systems have been developed to provide the measurement basis for offshore wind resource assessments as required for the development of the upcoming offshore wind projects. It could be quickly demonstrated that the obtained measurement data are considerably more cost-efficient than measurements by offshore met masts and more accepted for project financing than numerical model data, as e.g., from reanalysis or Numerical Weather Prediction (NWP) models, only. A comprehensive overview of the emergence of buoy-based floating lidar systems (FLS) and their primary application in the wind industry is given in Gottschall et al, 2017. Due to their relevance for the offshore wind industry, guidelines for the use of FLS have soon been pushed forward by different stakeholder groups: the so-called OWA roadmap was published in 2013[1] and updated in 2018[2], introducing three maturity stages for floating lidar technology and corresponding requirements for key performance indicators of FLS data availability and accuracy; an IEA Wind report on recommended practices (RP18[3]) was published in 2017; and an IEC technical specification (to be published as IEC TS 61400-50-4) is in preparation at the time of writing.

A scientific challenge to the realization of floating lidar measurements and their interpretation is the compensation of motion effects in the recorded wind data. While the influence on mean wind speeds is

[1] Carbon Trust Offshore Wind Accelerator Roadmap for the Commercial Acceptance of Floating LiDAR Technology, Version 1.0, 2013

[2] ... Version 2.0, 2018 (https://prod-drupal-files.storage.googleapis.com/documents/resource/public/owa-w-uflr-updated-fl-roadmap_18102018.pdf)

[3] IEA Wind Expert Group Report on Recommended Practices 18. Floating Lidar Systems, 2017 (Recommended Practices - IEA Wind TCP)

almost negligible – see Gottschall et al. (2017) – a high-resolution motion correction is essential for the reproduction of smaller scales or turbulence quantities such as turbulence intensity. Solution to this challenge were e.g., presented in Gottschall et al. (2014), Gutiérrez-Antuñano et al. (2018) and Kelberlau et al. (2020b).

A second type of floating lidars is represented by lidars that are installed on moving vessels or ships. As detailed e.g., in Hill et al. (2008) a motion compensation can be implemented in similar way as for buoy based FLS even if other degrees of freedom of movement dominate. Basically, it can be said that most buoy-based FLS are more strongly determined by tilt and heave movements, while for lidars on moving ships the consideration of the ship velocity and heading is of highest relevance, cf. (Wolken-Möhlmann et a., 2014; Duscha et al., 2020). Ship-based floating lidars are even more flexible in their applications than their buoy-based counterparts but at the time of writing less relevant for the wind industry since they miss a well-defined use case. Buoy-based FLS, on the other side, were specifically developed for offshore wind resource assessments and serve this application as the primary instrument today. Applications of ship-based floating lidars are reported in e.g., Achtert et al. (2015), Zentek et al. (2018), Gottschall et al. (2018), and Renfrew et al. (2019). The suitability of lightships in the German Bight, to carry mid to long-term quasi stationary measurements in North Sea has been demonstrated by Cañadillas et al. (2018). This type of measurement is being run and replicated on other lightships at the time of writing.

2.5 Nacelle based lidar

Lidar systems have been installed on nacelles of wind turbines already in 2003, quite early in its development, see Kajiyama and Kameyama (2015) and Harris at al. (2006). The main applications of nacelle-based lidar systems are turbine performance assessment, load verification and lidar-assisted control. Additionally, due to convenience in data analysis, nacelle lidars are also applied for characterization of wind turbine wakes.

For power performance, nacelle-based lidars are a very attractive alternative to traditional measurements with meteorological masts, especially offshore. These lidar systems measure the inflow usually several rotor diameters in front of the rotor. Here, mainly the mean of the horizontal wind speed and the wind direction is collected over 10 minutes together with the power of the wind turbine. Very good agreement with power curves with cup anemometers has been reported (Wagner et al., 2014). Since the lidar system is always pointing upwind, the correlation with the power is usually higher compared to cup anemometers and the lidar measurements are never in the wake of the tested turbine and thus the wind sectors usable for power curve measurement are larger. Further, in complex terrain or for large rotor, an induction model can be included in the wind field reconstruction and measurement can be done closer to the rotor, see Borraccino et al. (2017).

For load verification, lidar systems are used to verify that wind turbines withstand the loads for which they have been designed. Here, reference conditions are used to establish the design load basis for the purpose of certification of turbines. Further, certified turbines need to be further verified to operate safely with site-specific loads during the entire lifetime, when site conditions exceed the reference conditions. Traditionally, environmental conditions are obtained from anemometers installed on meteorological masts close of the wind turbine location and then used in aeroelastic simulations. Nacelle-based lidar systems have the advantage, that an installation of a mast can be avoided, and that more information can be collected, e.g., wakes of other wind turbines, see Conti at al. (2020).

For lidar-assisted control, lidar systems help to optimize the energy production and reduce structural loads. This is because wind turbines are highly dynamic systems that are excited by stochastic loads from the wind and most of the wind turbine control is designed to deal with variations in this disturbance. However, traditional feedback controllers are only able to react to impacts of wind changes on the turbine dynamics after these impacts have already occurred. Control algorithms with preview information of the wind are promising to provide an improved operational performance over conventional control algorithms with the aim of increasing the energy yield while keeping the structural loads low, see Schlipf (2016) and Bossanyi et al. (2014). Lately, active wake steering has become of high interest to improve wind farm efficiency. Experimental work measuring the path of the wake, and other characteristics, under yaw error has been documented. For instance, in the near wake by Trujillo (2016), and in the far wake by Bromm et al. (2018) and Brugger et al. (2019).

2.6 Lidar in combination with drone

With the decreasing size and weight of lidar systems as result of general progress in miniaturization of electronic components, and the increasing availability of ready-to-fly multicopter drone systems with appropriate payload capacities during the last years, it is now possible to develop lidar systems deployable on drones with a take-off weight in the order of 15 kg. The first successful application of a corresponding system is described in Vasiljević et al. (2020).

3. Application areas for ground-based lidar remote sensing

With the accelerating growth of wind energy deployment, this research area has become the primary field of application of ground-based lidar remote sensing. This is also documented by the fact that most of the LIKE ESR projects are closely related to wind energy research. The corresponding lidar technology and available instrumentation is, however, also beneficial to and thus successfully applied in other research areas, spanning from basic atmospheric boundary layer research to applied research, e.g., in bridge and building design and air traffic safety. Some main application areas are described in more detail in this chapter.

3.1 Wind energy

In the wind energy sector, lidar systems are primarily used in the field of resource assessment, for the study of turbine and wind farm wakes, and recently also increasingly for the characterization of turbulence characteristics, as e.g., coherence.

3.1.1. Resource assessment

Resource assessment is the process of quantifying the wind conditions at a potential wind farm site. The parameters that need to be measured are, for instance, wind speed and direction, turbulence intensity or gusts at several heights above ground. This information is crucial to estimate the annual energy production of the wind farm or also to plan the layout or turbine type of the wind farm (e.g., Brower, 2012; Murthy et al., 2017)

Onshore, ground-based vertically-profiling wind lidars are used to measure wind speed and wind direction over several heights up to 300 m above ground. These measurements can be used to validate hub height wind speeds that were vertically extrapolated from a lower met mast measurement (Poveda and Wouters, 2015) or to directly measure the wind speed and wind direction over the potential rotor area (Wagner et al., 2014. An alternative to profiling lidar is scanning lidars, which can measure the wind speed and direction over a large area of several kilometers.

Offshore floating lidars can be mounted on fixed platform close to a potential wind farm site (Hasager et al., 2013) or mounted on buoys (Gottschall et al., 2017). The latter, called floating lidar systems (FLS; see also section 2.4), can be a viable alternative to conventional met masts. There are several FLS manufactures on the market and the common approach is to use a conventional vertically-profiling lidar on a buoy equipped with e.g., additional energy supply, data storage, GPS tracking, and data transfer option. The FLS then measure the wind speed and direction over several heights.

The advantages of using a lidar, instead or in addition to a small met mast for resource assessment, are that more flexible campaigns, with lower cost and measurements over a larger height or area are possible.

There are some barriers to the use of lidar for resource assessment that include the usage of lidar in complex terrain, the measurement of turbulence intensity, the compensation of the motion of the FLS or the lack of guidelines or standards (Clifton et al., 2018). Organizations and platforms such as the IEC commitees or the IEA Wind Task 32 [https:// iea-wind.org/task32/] are working on gathering knowlegde, experience and methods to overcome those barriers. The results are documents approved by the community such as the Recommended Practices 15 on Ground-Based Vertically-Profiling Lidars (Clifton et al., 2013) or Recommended Practices 18 on Floating Lidar Systems (Bischoff et al., 2017).

3.1.2. Wake measurements

The early application of lidars in wake characterization, was motivated by the need of understanding wake dynamics. Bingöl et al. (2010) and Trujillo et al. (2011) developed successfully scanning and analysis techniques to quantify the so-called wake meandering. Trabucchi et al. (2015) showed later how to quantify wake dynamics by means of staring lidar along the wake. The first experimental work showed the great potential of lidars in quantifying the wind field in the wake and motivated Käsler et al. (2010) to measure the wake of a multi-MW wind turbine by means of a long range lidar. They showed different behavior of wakes under stable and unstable conditions. This and more detailed characterization of the wake was further performed by Iungo et al. (2013), Smalikho et al. (2013), Iungo and Porté-Agel (2014), Aitken and Lundquist (2014), Aitken et al. (2014), and Kumer et al. (2015), among others. Most of the mentioned studies relate to characteristics of wake deficit and wake recovery distance, mainly from measurements applying all-sky scanners. Wildmann et al. (2018) showed the advantage to use synchronously three lidar scanners to measure wakes in complex terrain. With respect to the uncertainties in using standard vertical profilers to measure the wake speed, Lundquist et al. (2015) quantified errors by means of numerical simulations. Lately active wake steering has become of high interest to improve wind farm efficiency. Experimental work in this area has been done, for instance, by Bromm et al. (2018) and Brugger et al. (2019).

3.1.3. Turbulence and coherence studies

Lidar are generally excellent for measuring the mean wind velocity. The measurements align extremely well with the best calibrated ordinary anemometers as has been shown already by Smith et al. (2006). While this is certainly true over flat terrain, lack of homogeneity over the scanning cone in complex terrain may introduce errors of a few percent in the mean wind speed (Bingöl et al., 2009).

The situation is quite different for turbulence quantities. Here two effects complicate the turbulence measurements: 1) Averaging of the turbulence within the effective measurement volume of the lidar along the laser beam, and 2) The combination of components of the velocity vector measures at different positions in space. The first effect leads to a suppression of turbulence because the wind fluctuations within the measurement volume are averaged out. To counter this effect, it is preferred to have as small and compact a volume as possible. The second effect can lead either of under- or overestimation of the turbulence depending on how much the velocity vector at the different positions are correlated and which components enters in the line-of-sight projection. In order to avoid this so-called cross-contamination. Sjöholm et al. (2009) and Mann et al. (2009) proposed to use three Doppler lidars focused on the same point. While this method works well it is probably not going to be used widely because of the difficulties and expenses in deploying three instruments comparted with one. An alternative solution to the problem of measuring different components in different points was proposed by Kelberlau and Mann (2019) and Kelberlau and Mann (2020a) where measurement in one side of the cone was delayed before combination with measurements from the other side of the cone. In this way the lidar was essentially interrogating the same blob of air (assuming Taylor's hypothesis) from different angles and the cross-contamination effect was minimized.

Sathe et al. (2011) investigated how profiling lidars used in the wind energy industry estimated the standard deviations of the three velocity components as a function of height. They compared lidar measurement with sonic anemometer measurements from a tall mast at DTU's test station at Høvsøre, Denmark. They also calculated the expected difference between the standard deviations for lidars and sonic anemometers based on the three-dimensional velocity spectrum of Mann (1994).

Sathe and Mann (2013) reviewed the many works that have been performed on estimating turbulence quantities by Doppler lidars, not only of the standard deviations, but also spectra, the dissipation rate of turbulent kinetic energy (see also newer work of Bodini et al., 2018), coherences, higher order moments, etc. Turbulence measurements around wind turbines have also been performed recently, for example in the wake (Kumer et al., 2016) or in the approach flow (Mann et al., 2018).

The ability of Doppler wind lidars (DWL) to scan the flow with a high spatial and temporal resolution offers new opportunities to study the coherence of turbulence. This potential was already mentioned by Kristensen et al. (1989), but the first pilot studies started during the 2000s only. The coherence of turbulence can be explored with a single pulsed DWL in a direction parallel to the scanning beam with a fixed azimuth and elevation angle. This was achieved by e.g., Lothon et al. (2006), Davoust & von Terzi (2016), Cheynet et al. (2017a), or Debnath et al. (2020).

For wind energy and wind engineering purposes, information on the coherence is most valuable when the flow is scanned in the crosswind direction. During the OBLEX-F1 campaign in the North Sea (Cheynet et al, 2016a), a single pulsed lidar using a Plan-Position-Indicator scan was conducted within a narrow sector to study the lateral and vertical coherence of the along-wind component. To ensure a sampling frequency high enough to provide reliable statistics, multiple-lidar configurations can be used. Nevertheless, they need dedicated configuration, which were explored in e.g., Cheynet et al. (2017a) or Letson et al. (2019). Beside pulsed long-range instruments, synchronized short-range DWLs have also been utilized to assess the coherence of turbulence at crosswind separation with encouraging results (Cheynet et al., 2016b) but their potential remains relatively unexplored.

3.2 Bridge and building design

Wind loads are among the governing factors in the design of long-span bridges. Bridge planning and design can therefore benefit from remote sensing of wind conditions, above the water surface at considered bridge sites.

Long-range scanning lidars are suitable for measurements over large distances from shore, relevant to several kilometers' long crossings. Two synchronized lidars are required to resolve the wind velocities in a horizontal plane and are typically deployed on the either side of a strait. The prime information of interest is the mean wind speed in the middle of the bridge span, in relation to the data from anemometers on land and the related computational models. Dedicated scans can be adopted to access the flow uniformity along the bridge span and reveal various local terrain effects (Cheynet et al. 2017b). Turbulence components, with periods of 2 seconds and longer, can be monitored by adopting the line of sight (LOS) measurements, typically directed towards the middle of the bridge span (Jakobsen et al. 2015). Simultaneous LOS recordings by several lidars are required to investigate spatial characteristics of turbulence, e.g., in terms of cross-spectra (Cheynet et al., 2017a; Ágústsson et al., 2018).

Floating wind lidars equipped with a short-range wind profiler can supplement the above measurements by providing the information on the wind profile in the middle of crossing. In case of multi-span bridges, wind profile mapping at the position of bridge towers may also be relevant.

A system of two or more synchronized short-range scanning lidars is well suited for studies of wind characteristics upstream of an existing bridge, as part of a short-term wind-structure monitoring system (Cheynet et al., 2016b). Such a lidar system can also be used to explore the bridge deck and tower aerodynamics in full-scale, e.g., by monitoring the bridge girder and tower wakes (Cheynet et al. 2017c). Similar studies can focus on wind conditions around buildings, a wind break fence (Mikkelsen et el., 2017) etc. The ongoing development of short-range lidars towards smaller measurement volumes (Mikkelsen et al., 2020) opens for their applications in a broader range of civil engineering applications and in wind tunnel investigations. For the latter, the so-called lidics are highly relevant for flow studies around the small-scale models (Pedersen et al., 2012; Sjöholm et al., 2017).

3.3 Turbulence for air safety in the vicinity of airports

Enhanced turbulence and coherent turbulent structures, as, e.g., roll vortices (Lunnon, 2016), are an important risk factor for air safety which could represent up to 71 % of the accidents according to a study over ten years conducted by the National Transport Safety Board NTSB in the USA (e.g., Sharman and Lane, 2016; Gulteppe, 2019). Passengers may be familiar to clear air turbulence occurring at the altitude of the tropopause (about 10km) and inducing strong vertical accelerations of the aircraft linked to updraughts and downdraughts. Clear air turbulence occurs only at high altitudes, many processes can, however, induce significant turbulence at all altitudes (e.g.,WMO, Education and Training Programme, 2007):

- Convective turbulence
- Mechanical, associated mostly with low level turbulence, and induced by surface friction
- Orographically induced turbulence, induced by obstructions disrupt airflow
- Clear air turbulence (CAT)
- Low level jets
- Wake turbulence / wake vortices

Aircraft are vulnerable to atmospheric turbulence and wind shear, in particular during final approach and landing, as they are operating in low air speed and with low engine thrust. Low-level turbulence refers to rapid, irregular fluctuations in wind speed and direction as encountered by an aircraft, bringing sudden jumps or jolts which might cause passenger discomfort or even injuries. According to the ICAO definition (International Civil Aviation Organization), low-level turbulence follows the same spatial criteria (1600 ft, three nautical miles) while its intensity is quantified in terms of an aircraft-independent physical parameter, the cube root of the eddy dissipation rate (EDR1/3). Features of low-level wind shear and turbulence are known to follow spatial and time scales on the order of few hundred meters and tens of second, making ground-based remote sensing measurements of high spatio-temporal resolution the primary choice for their observation and detection.

Turbulence directly at or very close to the runway can be triggered by local terrain, buildings and roll vortices created by starting or landing aircraft. In addition, can the surrounding topography, in particular along the gliding path towards landing, create terrain induced turbulence that impose an air traffic risk. Prominent examples are Hong-Kong airport (Chan, 2011), Innsbruck in the Austrian Alps, and a series of smaller and larger airports in Norway, as Alta (Rasheed and Mushtag, 2014) or Trondheim Værnes.

Hong Kong observatory (HKO) (Chan, 2009, 2010, 2016, Hon and Chan, 2020) was the first meteorology office in the world to develop and implement a low-level turbulence alert system. Due to the complex orography in its vicinity, Hong Kong airport is frequently affected by both low-level wind shear and turbulence. To improve the mitigation of those wind hazards to the air traffic, Doppler Lidars were used to generate automatic wind shear and turbulence alerts. The turbulence alerts are based on the eddy dissipation rate (EDR), calculated by the structure function of the flow corresponding to the difference of Doppler velocities measured at two points spaced of a certain distance with high resolution azimuthal scans. The algorithm was based on the work of Frehlich, 2001. It is important to mention that EDR was chosen by ICAO to characterize atmospheric turbulence for aviation. Compared to flight data, retrieved EDR data with a Doppler Lidar had a mean error of 20%. These values were used successfully to issue turbulence alerts with a probability of detection of 80%. Maps of EDR were also provided to support the forecasters at the airport. They revealed that a significant part of the turbulence affected one of the runways was induced by the Congress tall building located just a few hundred meters upstream the runway.

At Keflavik airport in Iceland, Yang et al., 2020 performed a research study to provide vertical profiles of EDR based on the algorithm developed by Frehlich, 2001. The EDR profiles allow to determine at which altitude the turbulence occurs as well as its horizontal position relative to the Lidar.

Wake vortices consist in two contra-rotative vortices generated behind each wing by each flying aircraft. They correspond to one of the main limiting factors of airport capacities. Indeed, ICAO regulations on distance separations between aircrafts were established forty years ago in order to prevent the danger for a follower aircraft to encounter wake vortices generated by a leader in still atmosphere. Designed thanks to basic measurement techniques, the old and conservative ICAO regulations were outdated. Many research projects (CREDOS[4], AWIATOR[5], FARWAKE[6]) have been launched to characterize in details wake vortices thanks to scanning Doppler Lidars (Thobois, 2016). They are the only one sensor capable of measuring wake vortices in using vertical scans with high resolution (better than 10m) and high refresh rate (better than 10s per scan). Spectra data (Frehlich, 2004) or radial wind speed data (Smalikho, 2015) can be post-processed to detect and

[4] CREDOS: Crosswind-Reduced Separations for Departure Operations, EU Project Program: FP6-AEROSPACE, Ref.: 30837,Start date: 2006-06-01, End date: 2009-11-30, Record Number: 8146

[5] AWIATOR Project reference: G4RD-CT-2002-00836, Funded under: FP5-GROWTH

FAR WAKE Fundamental Research on Aircraft Wake Phenomena, EU project Funded under: FP6-AEROSPACE Ref.: 12238, Start date: 2005-02-01, End date: 2008-05-31 localize wake vortices. Their strength, called circulation, which is the main parameter of interest as linked to the risk of wake vortex encounter can also be estimated by the integration of the tangential velocity of the wake vortices by the distance to their cores. Over a long period, large dataset of wake vortices can be collected by scanning Dopper Lidars with a specific vortex configuration and wake vortex processing algorithm. These data can be then analyzed to determine the statistical decay in terms of circulation with regards to aircraft and weather conditions. Such data collection and analysis of large wake vortex data have been conducted at several major airports in the world (Paris-Thobois, 2017, London, Dubai, Hong Kong). As for the turbulence measurements, the biggest data collection of wake vortex have been collected at Hong Kong airport with more than 200000 aircrafts for which their wake vortices were tracked both for departure and arrival aircraft. The statistical analysis conclude the possibility to implement operationnally reduced separations as proposed by the RECAT US-EU concept. Next generation of wake turbulence concepts are currently under development based on the dynamic adjustment of separations with weather conditions like crosswinds and EDR, which have respectivelly a direct impact on the advection of wake vortices and on their decay. Such concept have been investigated by the UFO EU project (Oude Nijhuis et al., 2018).

3.4 Lidar measurements in wind tunnels

A growing attention came in the recent years to wind tunnel applications of the Lidar technology. We are mentioning here the typical fields of application, focusing on emulation of full-scale complex environment in boundary layer wind tunnels for wind engineering and/or wind energy studies, but covering also the aerodynamic airfoils classical wind tunnel testing.

For what concerns environmental applications emulating the atmospheric flows, the recent large test section boundary layer facilities (e.g., 22.5 x 4.5m at the Southwest Jiaotong University in China / 14 x 4 m at the Politecnico di Milano Italy / 25m diameter WindEEE Dome at Western Ontario University Canada) are allowing to emulate complex scenarios of wind-structure interaction / wind turbine - wind farm interaction in repeatable and fully known boundary conditions. The traditional synoptic winds (typically neutral boundary layer) as in the first two examples, but also tornadoes and thunderstorm complex structures as in the WinEEE Dome, are considered as a known input for the interaction experiments.

The great advantage of Lidars and specifically Lidar WindScanner technology is clearly to offer a remote reading, potentially 3D, of the flow conditions over the full section, so that removing the highly time consuming and invasive traditional Hot Wire anemometers traversing sessions. In January 2016, two short-range WindScanners R2D2 and R2D3, continuous-wave, coherent Doppler Lidars were installed in Politecnico di Milano boundary layer wind tunnel together with three G1 TUM scaled wind turbine models (rotor diameter 1.1m), allowing simultaneously wind farm control experimental testing and two focused laser beams synchronous scanning over a common trajectory. The POLIMI wind tunnel experiment is fully described in van Dooren et al., 2016 and 2017. A master thesis by Wasi, 2018 is based on the data coming from the experiment, with great details on the flow mapping of the very large test section made available through fast short-range WindScanner lidars. Lidar WindScanner technology offered the chance not only to map the flow of the free chamber but as well to accurately measure the wakes of scaled wind turbine models. The next natural application field in large boundary layer wind tunnels is for wind-structure interaction topics and specifically long-span cable supported bridges, where the full-bridge aeroelastic scaled models are spanning the full test section and the boundary layer flow distribution over the slender structure is the key boundary condition of the experiment emulating the full-scale environmental conditions.

Similar experiments mapping the wake of a scaled model wind turbine were also performed at NTNU Wind Tunnel within the L4WT EERA IRPWind Joint Experiment described in Sjöholm et al. (2017). Two continuous wave lidar in the configuration of short-range WindScanner have been adopted, but at the same time also the compact telescopes Lidar technology (Lidics) developed at DTU has been tested as described in Sjöholm et al. (2017). Lidics can offer, in addition to the compactness of the 3 inches diameter telescopes, also the ability to focus the laser beam at very short sub meter distances, as shown in another wind tunnel demonstration described in Pedersen et al. (2012).

The scaled wind turbine wake deflection was also studied with Short Range Lidar Technology as a wind tunnel application at the turbulence researcher of the University of Oldenburg's ForWind Center for Wind Energy Research, as described in Hulsman et al. (2020).

Finally, the high performance Poul la Cour DTU wind tunnel application must be mentioned, where is adopted the technology of Lidics 3 inches compact telescopes, handled by a robotized pan and tilt head. The wind Tunnel studies are belonging to the AeroLoop project to make available a fast improvement of the wind turbine blade sections performances developing and implementing new measurement methods and benchmarks.

3.5 Basic boundary layer research

Wind lidars have a large potential for basic boundary layer research, already by simple profiling in DBS or VAD mode and thus providing wind profiles in rather high temporal resolution in the order of seconds and a vertical resolution of several tenths of meters (e.g., Pichugina et al., 2012; Barthelmie et al., 2014.; Kumer et al., 2014; Mariani et al., 2020).

Extended scanning capabilities using RHI and PPI scanning patterns, enable the characterization of the wind field by taking quasi-2D snapshots that, when combined, can also be used to create quasi-instantaneous 3D pictures of LOS velocities that then can be reprocessed to a 3D wind field over volumes of several km with a spatial resolution in the order of 20 to 100 m. This allows for the investigation of micro to sub-meso scale phenomena, as e.g., the investigation of modifications of the wind field along and across the coastline (Pichugina et al.; 2012) or the detection of sea-land-breeze circulations (Kumer et al., 2014), as well as the topographic modulation of the wind field in a fjord (Cheynet et al., 2017a).

Another interesting application is the operation of lidars in zenith-pointing staring mode, in particular in the vertical, as this provides direct estimates of the vertical velocity variance, an important parameter to characterize turbulence in the boundary layer. Based on variances and higher-order statistical moments derived from profiles of the vertical velocity and its fluctuations can be used for the advanced characterization of the turbulence structure in the CBL, e.g., with respect to integral length scales of turbulence and anisotropy (e.g., Lothon et al., 2006; Lenshow et al., 2012).

Lidar measurements allow also for a physically based mixed layer height (MLH) determination (Martucci et al., 2007; Schween et al., 2014; Barthelmie et al., 2014) that typically outperforms the often-used MLH determination by ceilometers, as it gives a direct measure of atmospheric turbulence in form of vertical velocity variances, instead of relying on the aerosol distribution that might react with delay on changes in the turbulent patterns in the BL. The lidar derived parameters backscatter coefficient, vertical velocity skewness, dissipation rate of turbulent kinetic energy, and vector wind shear have also been used for the development of a physically based boundary layer classification (Manninen et al., 2018).

Multi-lidar approaches during the Perdigao experiment in Portugal (Fernando et al., 2019) have shown promising results with respect to the estimation of the turbulence dissipation rate and its spatio-temporal variation between two parallel ridges (Wildmann et al., 2019)

While earlier investigations mainly focused on the land based investigation of the convective boundary layer (CBL), recent research also highlights the applicability and value of lidar measurements for the stable atmospheric boundary layer (SBL) (Pichugina et al., 2008; Mariani et al., 2020; Kral et al., 2018; Banakh and Smalikho, 2018; Kral et al., 2020) as well as for the ship-based characterization of the marine atmospheric boundary layer over the ocean (Pichugina et al., 2012; Gottschall et al., 2018; Renfrew et al., 2019).

4. Data

Lidars are generating data which is the basis for decision making in different applications. The data that is produced is influenced by several factors such as the setup of the measurement campaign, the local meteorological conditions or the data processing algorithms, which are needed to generate valuable information from the raw lidar data.

Ideally, there would exist a set of processes and tools which can be used to handle lidar data from different lidars and for different applications. These tools would contain knowledge from lidar users and would allow the collaboration between users and facilitate the use of lidars, especially also for new users.

A few openly available tools already exist, such as a lidar campaign planning methodology (Vasiljević et al., 2017a), a campaign planning tool (Vasiljević et al., 2020) , and a tool called YADDUM to calculate the uncertainty of the lidar measurement (Vasiljević, 2019).

The basis for a common tool set is a common lidar data format. At the moment, the raw data files of different lidar types and manufacturers all have a different format and set of measured parameters. Therefore, the e-WindLidar initiative (Vaslijevic et al. (2017)] started in 2017 with a focus on development of community-based tools for the facilitation of lidar data analysis, planning of lidar-based experiments, and lidar configuration. The first result of this initiative is a proposal for the universal lidar data format (Vasiljević et al., 2017b) [Vasiljevic] which is in accordance with the FAIR principles (Wilkinson et al., 2016). This common data format should be used by all lidar users when writing code and developing tools and methods, to be able to add to the suite of tools that already exists.

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https://www.zxlidars.com/lidar-publications/

http://data.windenergy.dtu.dk/ontologies/view/IEATask32Glossary/en/a.windenergy.dtu.dk/ontologies/view/IEATask32Glossary/en/

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6. Appendix

The following documents had been included as appendix in the internal version of this report available for all project members. To avoid potential copyright issues, the appendix has for this published version been replaced by the corresponding web links.

4.1: IEA Wind Task 32 Expert group study on recommended practices "15. GROUND-BASED VERTICALLY PROFILING REMOTE SENSING FOR WIND RESOURCE ASSESSMENT"https://community.ieawind.org/HigherLogic/System/DownloadDocumentFile.ashx?DocumentFileKey=7492ade3-03e1-419f-466f-4b6aacc271df&forceDialog=0

4.2: IEA Wind Task 32 Expert group study on recommended practices "18. FLOATING LIDAR SYSTEMS" https://community.ieawind.org/HigherLogic/System/DownloadDocumentFile.ashx?DocumentFileKey=99ec44ff-4493-4bad-6510-d42d152ae963&forceDialog=0

4.3: IEA Wind Task 32 publication "Review of Guidance for Using Ground-Based Vertically-Profiling Wind Lidar For Wind Resource Assessment"
https://zenodo.org/record/3862384#.YG9REc_itaQ

4.4. MEASNET Procedure: Evaluation of site-specific wind conditions, Version 2
https://www.measnet.com/wp-content/uploads/2016/05/Measnet_SiteAssessment_V2.0.pdf

The LIKE project in brief

The project LIKE Lidar Knowledge Europe H2020-MSCA-ITN-2019, Grant no. 858358 is funded by the European Union and project partners.

The project partners are DTU Wind Energy (DK, co-ordinator), University of Oldenburg (DE), University in Bergen (NO), University Stuttgart (DE), PoliTechnico Milano (IT), University Porto (PT), University in Stavanger (NO), Flensburg University of Applied Sciences (DE), Fraunhofer IWES (DE) and UL (DE).

The project period is from 1st October 2019 to 30th September 2023 (4 years).

LIKE fosters training and education of young researchers on emerging laser-based wind measurement technologies and their translation into industrial applications.

Doppler Lidars (light detection and ranging) that measure the wind in the atmosphere remotely have reduced in price and increased in reliability over the last decade mainly done by European universities and companies serving the growing wind energy industry. This opens the possibility for new applications in many areas.

LIKE improves, tests and refines the technology thus expanding these areas of application. LIKE promotes wind energy applications such as wind resource mapping using scanning lidars and control of single wind turbines or entire wind farms in order to increase energy production and reduce mechanical loads.

LIKE maps unusual atmospheric flow patterns over airports in real-time and thus improves the safety of landing aircrafts. LIKE explores wind and turbulence under extreme conditions at the sites of future European bridges paving the road for optimal bridge design. LIKE trains 15 ESRs to an outstanding level at European academic institutions and industrial companies, thus forming strong interdisciplinary relations between industry and technical sciences.

These relations are implemented through employment of the ESRs at academia as well as industry, and through inter-sectoral secondments.

The project web-site is http://www.msca-like.dk/