Anonymous Referee #2

1 General comments

In the manuscript by Vasiljevic et al. a proof of concept is presented for a drone-mounted lidar for wind measurements. This concept is an important development in wind measurement technology and opens a lot of possibilities for scientific applications. The results that are presented are very promising and are definitely worth publishing in the journal "Atmospheric Measurement Techniques". I have some concerns about the presentation of the results and requests for changes which the authors should consider before submitting a revised manuscript.

Dear referee,

We would like to thank you for the positive review of our paper.
We have incorporated your suggestions and made changes to our manuscript.

We provide point-by-point responses (in blue) together with the attached revised manuscript which contains highlighted differences between the original and revised manuscript (latexdiff was used for this task). However, we must notice that the older version of our manuscript has been reviewed and not the latest one. The difference between the first and second version are not major, however, there are some differences (e.g., the second version has improved Discussion, figures representing measurement setup, grammar issues fixed, EURO replaced by €, etc.).

Besides the revised manuscript which contains the highlighted differences we are also submitting separately the revised manuscript without the highlighted differences.

Drone-mounted lidar measurements are introduced in this manuscript as a possible replacement for ground-based lidar measurements or meteorological masts. I am very skeptical if this is a realistic scenario, given the logistical constraints that drone measurements have. With this I mean flight time, regulations, operation in all weather conditions (what are maximum wind speeds for example? What about rain?). The authors mention in the conclusion that a lot more development needs to happen before drones can be a serious alternative for power and load verification. However, I think that even with the present research version of this system, a lot of important measurements towards validation of ground-based lidars, studying of wake dynamics and especially turbulence research can be done. I think these applications should be emphasized much more. For this purpose, I wish to see a comparison of turbulence spectra between sonic anemometers and drone lidars for the presented measurements.

Currently, the drone-based wind lidars cannot replace met masts. However, considering the ongoing developments in drone technology (which is not driven by wind energy or science but due to the need of for example cheaper way of delivering goods) there is potential that this becomes realistic scenario.
The turbulence analysis, indeed of high importance, is not the scope of this paper primarily since the described measurement setup is not suitable to acquired necessary data (e.g., missing accurate information of the gimbal orientation). Nevertheless, it will be investigated in future.

The description of the state of the art is very weak on external references to both, drone-based measurements and short-range lidars. Most of the references are DTU-internal, although a lot of work is done world-wide on Doppler wind lidars. What are other CW-lidar systems and how is the used system different. Drone measurements are the topic of many research groups within the ISARRA community. It would be good to evaluate the presented system to other concepts which exist internationally (for example sonic anemometers or flow probes on drones). I want to urge the authors to improve their literature research and give credit to other researchers working in the field.

In the revised manuscript, we provide an overview of sUAS measurements of wind speed also the list of references related to the wind lidar measurements in wind energy domain has been extended.

A major concern for many drone-users are regulations and flight permissions. It would be great if the conditions for flights at the Riso campus could be explained in the experiment section.

In the revised manuscript we have stated that we operated the drone in accordance to the Danish drone rules. Also we added weather conditions during the flights.

2 Specific comments
2.1 Abstract
p.1,l.1: The authors mention substantially lower costs at the very beginning of the abstract and thus the manuscript, but do not mention the costs of the presented system at all. Can they make any comment on the costs? If not, please remove the statement.
Since at this stage we cannot provide the exact reduction in costs of such a system the statement was removed.

p.1,l.8: I suggest to make the statement "Generally, very good agreement was found" a little more specific.
The stated sentence was replaced with the following one:
"On average, an agreement to about 0.1 m/s between mast- and drone- based measurements of the horizontal wind speed was found"

2.2 Introduction
p.2,l.20: Maybe any kind of precipitation should be added to problematic conditions for lidar measurements.
The following sentence was added to the revised manuscript:
"Furthermore, any precipitation will affect the wind speed measurements by lidars. Specifically the vertical component of the wind will be biased since the lidar will dominantly measure the fall velocity of the precipitation (e.g., rain droplets)."

p.2,l.9: Give references for CW-lidars for wind energy research or atmospheric research in general. Same for pulsed lidars.
A number of references targeting specific wind energy applications has been cited in Introduction of the revised manuscript.

p.3,l.11: The explanation that the AOM can be eliminated should go into the system description in Sect. 2. A literature review of other methods to sense wind with drones would be very adequate in the introduction. There are a lot more references than Brosy et al. 2017.
We have revised the manuscript accordingly. The AOM explanation is moved to Section 2, while the Introduction contains a review of different methods of sensing wind with drones and fixed-wing sUAS.

p.3,l.20: Are measurements above thick forests with a drone lidar with fibre connection to the ground really realistic?
Due to the indicating location in the manuscript for this comment it seems that the reviewer did not review the second version of our manuscript since the indicated statement appears in the second version of manuscript at p.3, l27. Nevertheless, it is realistic to do such measurements with non-tethered drone which is now stated in the indicated sentence.

2.3 Section 2

p.4-7, Fig. 1-3: Instead of pictures of the single components, it would be good to have a picture with the lidars mounted on the drone gimbal.
FIgure 2 and Figure 3 show two telescopes mounted on the drone gimbal.

p.3, l.8: What does 100% duty cycle mean here?
It means that the laser beams are simultaneously lased through the two telescopes, thus that measurements are performed on two channels continuously and simultaneously (which is stated in the manuscript). As it is not bringinging any additional information '100% duty cycle' has been removed from the manuscript. We are confirming that the reviewer reviewed the first version of the manuscript due to the indicated page and line number of the comment.

p.5, Tab. 1: Please add lidar wavelength and weight of the telescopes, as well as the focal range that can be adjusted.
We have added requested information to the revised manuscript.

p.5, l.9: "... with payload." How big is the payload?
The stated flight time is with a payload of 5 kg. This information is now enclosed in the text of the manuscript.

p.5, ll.10ff: If I understand correctly the system has three GNSS-systems, plus another DGNSS system. This seems quite excessive. Isn't the RTK-DGNSS-system more than enough? Real-time DGNSS is not a synonym for RTK. RTK needs a feed of correction data from a nearby base station (not on the rover) to achieve the cm-accuracy. Is this really given in the setup? I think the most important feature are the two antennas for improved pitch and yaw estimation. With the short baseline of only 25 cm it is however quite questionable if this information really improves the IMU-information. Has this been evaluated? Please be more specific in this explanation and distinguish between a dual-antenna setup with a baseline between the two antennas on the rover and an RTK setup with a baseline between base and rover that can be up to a few kilometers and I am not sure if this is really given here. If not (as suggested in the discussion), it is not relevant in this study and should not be "advertised" here.
The system by default comes with three GNSS-system antennas. The additional two are antennas are part of so-called D-RTK system (differential GPS measurements + RTK) which beside the two additional antennas contains local mobile ground based RTK station (i.e., rover). In our tests we only used differential measurements and not RTK due to some issues in setting up the local rover. Also, the stated accuracy and other drone or gimbal specifications are provided in DJI product sheets which are now refered to.

p.7, Fig.3: Please indicate the lidar telescopes. Since they look much different than in Fig.1, this is quite confusing. I suggest to remove Fig. 1 and label Fig. 3 accordingly.
Figure 1 was removed, the telescopes are highlighted on Fig3 (now Fig 2).

Section 2: How big is the actual take-off weight of the system in this configuration?
About 3 kg (gimbal + gimbal payload(telescopes, GoPRo camera) + fiber cables)

2.4 Section 3
p.8, ll.1-14: I think it does not really add much to the study to present the preliminary tests with yet another system that has not been fully described, so I suggest to just skip this test and only present the results of the POC system introduced in Sect.2. Figure 4 could be removed in my opinion as well because there is no reference instrument or further evaluation.
We agree with the reviewer and accordingly we have removed the part of the manuscript related to the preliminary tests.

p.8, l.22: Does 'VT' and 'TW' have any specific meaning?
VT stands for V52 Tower (VT), while TW stands for True Wind (TW).

p.9, l.1: Please mention what kind of sonics are mounted.
Metek USA-1 3D sonic anemometers

p.9, l.2f: I am not sure if I understand the positioning procedure. What does it mean that adjustments were done using the GoPro camera?

DJI Drone has built in camera. However the telescopes were attached to the gimbal which can 'freely' move with respect to the drone. Therefore, we used the drone camera to roughly know that we are close to the reference instrument, while the GoPro camera (which was attached at the tray which carried the telescopes) was used to make sure that we are at the same height as the reference instrument and that we are pointing the laser beams in a right direction (avoiding the beams hitting the mast). We enclosed this clarification in the revised manuscript.

p.10: I would suggest to make a list of flights that are analyze in this study, with flight time, flight height, telescope orientation and wind and weather conditions.

New table has been added to the manuscript.

p.11, l.12: Giving a probed area of 7.07 m x 0.15 m seems a bit awkward and confusing. Maybe it would be easier to understand if you say that homogeneity at the two measured lidar focus points needs to be assumed.

We agree with the reviewer.

p.13, ll.11ff: I think this conclusion can not be drawn. The higher R^2-value is probably due to the higher number of samples at 70 m. The standard deviation is mostly a measure for turbulence in this case, and in fact the slope of the linear regression is furthest from one. I doubt if a statistical analysis of these very short measurement periods makes any sense at all. I would suggest to show the time series and a comparison of the vertical profiles of tower and drone lidar, including the standard deviation as error bars and quantifying the mean difference instead of the linear regression and point clouds.

We reformulate the statement regarding why the best comparison is at 70 m according to the reviewer comment. Regarding the presentation of the results in plots we prefer to keep our approach. Besides the linear regression plots we do indeed show the mean difference between the sonic- and drone- based measurements (see Table 4 in the reviewed manuscript).

p.15, Figs. 11-15: I would suggest to combine these plots in some way. It is probably not necessary to show the single telescope radial wind speeds. I do also not think that the point clouds and linear regressions are necessary and even statistically significant. So, maybe just show the comparison of time series of drone lidar horizontal wind compared to sonic anemometers on all heights in one plot with subplots.

The indicated figures are combined as a single plot and radial velocities from individual telescopes are removed from plots. We prefer keeping the linear regression plots since they are more indicative on the quantitative aspect of the measurement accuracy, while the time series plots are more useful for qualitative analysis.

2.5 Section 4

p.20, l.11f: I actually disagree and think this is a very good way to show the influence of the out-of-line wind component on the reconstruction from a single beam. I do not think this could be done any better with drone-internal data which is subject to many other uncertainties. However, a comparison of these drone-internal methods with the lidar would be very interesting in future, of course.

We improved that part of manuscript stating that various methods should be tested to find a suitable one for single beam applications.

p.20, ll.16ff: Has any indication been found that the downwash distance depends on wind direction and wind speed? If not, this could be a field of further research and areas on to be more conservative in future tests as well.

We did not investigate the downwash behaviour under different wind conditions. We agree that the future studies should include a dedicated research on the behaviour of the downwash under different conditions (wind speed, wind direction, payload, etc.). We have highlighted this in the revised manuscript.

p.21, ll.23ff: I would recommend to not describe technical details of possible future developments in a scientific paper. Depending on how developments go, concepts might have to be adapted and it is not really relevant for the scientific ideas and visions

The reviewer refers to the first version of the manuscript which undergone a brief assessment whether it is suitable for the AMT or not. After that first version of the manuscript we have submitted the second version, which actually does not contain the technical details on the future development.

3 Technical corrections

p.2,l.15: Use the proper text euro sign instead of EURO.

Similar like the previous comment. i.e. this was already changed in the second version of our manuscript. Therefore, the revised manuscript (version three) also has the correct sign.

p.3,l.23: The abbreviation POC is only introduced in the abstract, but should be introduced in the main text as well.

We followed the reviewer recommendation.

p.4,l.5: There is something wrong here: what is a "demonstrator for an nairborne windspeed requirement"?

We have removed the indicated part of the sentence.

p.20,l.9: Some grammar issue here.

The manuscript was revised accordingly.

Anonymous Referee #3

Dear referee,

We would like to thank you for the positive review of our paper.
We have incorporated your suggestions and made changes to our manuscript.

We provide point-by-point responses (in blue) together with the attached revised manuscript which contains highlighted differences between the original and revised manuscript (latexdiff was used for this task).

p 2-3: the list of criteria, should, at least for EPAs, also include a long duration (months) of the measurements, as a requirement

We agree with the reviewer and we do indeed discuss the current probl. The manuscript has been updated accordingly.

Table 1: weight of telescopes?

The table has been updated with the requested information.

Fig 7b: I don't understand why they have been put directly in front of each other? Potential flow distortion?

This is correct, the used setup indeed can induce flow distortion. However, we did not have other options since we used the on-board camera to be sure that the reference sensor is in our viewfield. In future comparison studies we will avoid such setup and use positioning system of the drone itself.

How to measure profiles?

With a single telescope: perform sort of a spiral flights with the drone (rotate drone or gimbal 360˚ while moving drone up - down between the desired range of heights). With a dual-telescope: flight the drone up-down between the desired range of heights.

Other ways of using a drone to measure the wind speed (eg differential motor power).

This has been now discussed in the introduction.

Wind sensing with drone mounted wind lidars: proof of concept

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Abstract. The fusion of drone and wind lidar technology introduces the exciting possibility of performing high-quality wind measurements virtually anywhere~~for substantially lower costs than established in-situ and remote sensing techniques. In this paper we will~~. We present a proof of concept (POC) drone-lidar system and report results from several test campaigns that demonstrate its ability to measure accurate wind speeds. The POC system is based on a dual-telescope Continuous Wave (CW) lidar, with drone-borne telescopes and ground-based opto-electronics. Commercially available drone and gimbal units are employed. The demonstration campaigns started with a series of comparisons of the wind speed measurements acquired by the POC system to simultaneous measurements performed by nearby mast based sensors. ~~Generally very good agreement was~~ On average, an agreement to about 0.1 m/s between mast- and drone- based measurements of the horizontal wind speed is found. Subsequently the extent of the flow disturbance caused by the drone downwash was investigated. These tests vindicated the somewhat conservative choice of lidar measurement range made for the initial wind speed comparisons. Overall, the excellent results obtained without any drone motion correction and with fairly primitive drone position control indicate the potential of drone-lidar systems in terms of accuracy and applications. The next steps in the development are outlined ~~in the paper~~ and several potential applications are discussed.

1 Introduction

For many years, wind energy has been one of the fastest growing power production technologies in Europe. Based on the average predictions the wind will deliver a quarter of power demands in Europe by 2030 (EWEA, 2015). The annual installed capacity of wind energy has seen a consistent growth of about 5%. Wind power accounted for 55.2 % of total installed power in Europe in 2017 (WindEurope, 2018), and overall represents 18% of total installed power generation capacity. Wind energy satisfies about 11.6% of EU total electricity demands (WindEurope, 2018).

The growth of wind energy is heavily dependent on accurate wind speed measurements, which are essential for various applications such as the prediction of annual energy production (AEP) for wind farms and power curve verifications. Given

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the size of modern wind turbines, which today operate between 60 to 220 m above ground level (agl), and the need to capture wind across the entire rotor plane, there is a demand for measurements at heights well above 100 m.

However, already beyond 60 m agl conventional in-situ wind speed measurements require costly towers. Offshore especially, any tower-based measurement is usually prohibitively expensive. These economic realities have fostered the development of ground-based (Courtney et al., 2008), nacelle-mounted (Borraccino et al., 2016), floating (Gottschall et al., 2017) and multi-lidar (Vasiljevic et al., 2016) systems all of which are now competitive in various wind energy use cases.

Wind lidars, unlike conventional anemometry, retrieve information about the wind without being in direct contact with the moving air. This is done by remotely probing the atmosphere using laser light. Two types of Doppler wind lidars are available distinguished by how they probe the atmosphere ~~Courtney et al. (2008)~~(Courtney et al., 2008). CW lidars stream a continuous laser beam, focused at the location of interest. Pulsed lidars stream a burst of short laser pulses and can retrieve wind speeds at various distances along this line. CW lidars have a typical range from 10 to 250 m with a high measurement frequency (several hundred scans per second are possible in good conditions) at a single range. Pulsed lidars have a range from 50 m up to 10 km with a low measurement frequency (around 1 Hz) but the ability to measure at many ranges simultaneously.

Since the introduction of wind lidars in wind energy domain in 2003 (Harris et al., 2007) they have been extensively used in industry and research for resource assessment Krishnamurthy et al. (2013), wind turbine power curve measurements Wagner et al. (2014), feed-forward control Simley et al. (2018), wake measurements Herges et al. (2017), wake steering Fleming et al. (2017) and short-term forecast Würth et al. (2019). Over the last decade wind lidars have became an established measurement technique within the wind energy community. Beyond the wind energy domain, wind lidars have been used in wind engineering especially to provide wind measurements to properly estimate wind loading on bridges (Cheynet et al., 2017). Historically, (since the 1980s) wind lidars have been used extensively in variety of atmospheric science studies (e.g., McCarthy et al., 1982; Newsom et al., 2008; C ..

Even though wind lidars are cost-attractive instruments for measurements beyond 100-m they are still relatively expensive. A minimum cost of an accurate wind lidar is about 60 k€ and 1-2 M€ for on-shore and offshore applications respectively.

Also, there are circumstances where wind lidars can experience difficulties, in which traditional in-situ measurements can measure successfully. Lidar range is influenced by the atmospheric conditions (i.e., aerosols concentration), which impacts the data availability (in certain locations lidar data availability can fall below mast-based sensor data availability). For example, clouds~~and fog~~, fog and snow are highly attenuating for the laser beam which limits the lidar range, and thus data availability. Furthermore, any precipitation will affect the wind speed measurements by lidars. Specifically the vertical component of the wind will be biased since the lidar will dominantly measure the fall velocity of the precipitation (Lindelöw, 2009).

Beyond the range of 50 m, independent of the lidar type, the effects of measurement volume become significant, and this limits the lidar applicability for the assessment of small-scale turbulence. Single lidars only measure the projection of the wind velocity on the laser propagation path (i.e., radial velocity), which in fact requires assumption of the horizontal homogeneity of the flow to reconstruct the wind speed (Browning and Wexler, 1968; Strauch et al., 1987). This bounds the usability of single lidars to offshore (Peña et al., 2008) and sites with simple topography on-shore (Courtney et al., 2008). Therefore, when the flow is complex, as it is the case in more than 50% of the onshore sites (e.g., hilly terrain) with good wind resources (Bingöl,

2010), multi-lidar instruments such as long-range (Vasiljevic et al., 2016) or short-range (Sjöholm et al., 2014) WindScanner systems are needed to accurately retrieve the full wind flow. This of course drastically increases costs (several lidars) as well the complexity of measurements (installation, configuration, synchronisation and monitoring) and corresponding data analysis (processing and integrating several datasets). This is one of the main reasons why multi-lidar measurements are mainly used in research projects for short-term measurement campaigns (e.g., Lundquist et al., 2017; Mann et al., 2017; Fernando et al., 2019).

To formulate the research problem, currently there are no measurement solutions that would provide:

– low cost yet accurate measurements in all sites (offshore, flat and complex terrain) and at altitudes where modern wind turbines operate (60 to 220 m agl),

– simple approach to perform measurements in different locations in the atmosphere (mobile measurements)

– high frequency measurements with a small probe volume (i.e., simultaneous mean flow and turbulence measurements), and

– high availability of data (i.e., not to be hindered by fog, low clouds, etc.).

– long measurement duration (e.g., months)

A potential solution for the above formulated problem is to use a ~~drone as~~ Small Unmanned Aircraft System (SUAS), such as multi-copter drones, as a platform for a wind lidar ~~. This idea~~ even though currently SUAS cannot offer a long uninterrupted operation. Typically SUAS acquire wind speed information either by utilizing flow sensors such multi-hole pitot tube probes (e.g., Wildmann et al., 2014) or sonic anemometers (e.g., Nolan et al., 2018) or without flow sensors by measurements and conversion of aircraft dynamics (e.g. Neumann and Bartholmai, 2015). For example, studies Neumann and Bartholmai (2015) , Palomaki et al. (2017) and Brosy et al. (2017) utilized real-time measurements of multi-copter dynamics to estimate wind speed. These studies reported a good agreement of the estimated wind speed with the speed measured by mast-mounted sonic anemometers, where the sonic and estimated wind speed agreed to about 0.5 to 0.7 m/s for 10 s averaged data (Palomaki et al., 2017; Brosy et and 0.3 m/s for 20 s averaged data (Neumann and Bartholmai, 2015). Brosy et al. (2017) stated that the wind speed estimated using only drone dynamics should not be used as information about atmospheric turbulence since due to the volume drones don't react to the small eddies, and thus this approach cannot capture a full range of wind speeds. In LAPSE-RATE experiment (Barbieri et al., 2019) several multi-copter drones were equipped with sonic anemometers. The calibration flights of such drones (which entail hovering the equipped drones close to masts equipped with sonic anemometers) showed agreement of the mast and drone-based 15-s averaged wind speed measurements to about 0.75 m/s (Nolan et al., 2018). Like in case of multi-copter drones, the aircraft dynamics of fixed-wing SUAS can be used to determine wind speed (Rautenberg et al., 2018) with the wind speed accuracy generally worse than multi-copter drones (Barbieri et al., 2019). As stated in Rautenberg et al. (2018) utilizing a flow sensor such as pitot tube on-board of fixed-wing SUAS generally provides better results. Nevertheless, as reported in Barbieri et al. (2019) an average accuracy of SUAS of both fixed-wing and multi-copter concepts with or without flow sensors is about 0.5 m/s, which for the majority of wind energy applications is not sufficient.

However, if we use a wind lidar as a flow sensor, potentially the accuracy could be improved and also given the ability to acquire turbulence measurements. Equiping SUAS with wind lidars has been suggested in an early study of using ~~unmanned flying platforms with on-board wind sensors~~ SUAS for wind energy applications (Giebel et al., 2012). At the time of the study, it was technically unfeasible to pursue this idea. Roughly a decade later, both the lidar and drone technology have advanced significantly unlocking the potential to explore the proposed idea.

In the concept we propose in this paper the drone would be used to position the lidar in the vicinity of the measurement points and to steer the outgoing laser beam. This would have several radical implications on the wind lidar development.

First, the required maximum range would be in the order of a few meters (i.e., just enough to avoid the impact of the drone downwash on intended measurements of the free flow). Second, since the drone can be used to steer the outgoing laser beam the lidar would not need to have a variable focus or a scanning mechanism. Third, since the drone alone can be used to sense the wind (see Brosy et al. (2017)) we can eliminate an acousto-optic modulator (AOM) from the lidar design because the Doppler shift sign can be calculated from the drone ~~tilt. For systems that use AOMs, the outgoing laser light frequency is shifted in order to be able to detect the sign of the Doppler shift of the backscattered light. One approach to eliminate an AOM from the lidar design is to have an external source of information about the wind direction, which in case of for example Zephir profiling lidars is accomplished by having an additional wind sensor attached to the lidar (Courtney et al., 2008).~~ dynamics.

The combination of the above-described implications leads to a significant reduction in the lidar complexity (fewer and cheaper components), size, weight and power consumption, and thus potentially in the overall costs.

The requirements for the drone-mounted lidar can be met by a low-power small-optics CW lidar with a manual focus adjustment. The use of CW technology will allow for a high measurement frequency ($\sim$50 Hz). Due to the expected short focus range the resulting probe length would be rather small ($\sim$10 cm), allowing accurate measurements of both the mean wind and turbulence. Additionally, short-range measurements would not be hindered by fog or clouds. In fact these atmospheric conditions would be favorable due to the substantially increased backscatter, and thus an improvement in signal-to-noise (SNR) ratio and data availability. Additionally, ~~measurement~~ if we have a fully non-tethered drone measurements can be made in difficult locations such as above thick forests that do not have suitable clearings for ground-based lidars.

In this paper we present the preliminary results of realizing the aforementioned drone-lidar system in practice. Specifically we will present the results of the ~~POC~~ proof of concept (POC) stage of a drone-based wind lidar system development. As such the POC system is developed only to demonstrate the feasibility of the proposed concept, ~~in other words~~ thus to show that the concept has practical potentials.

The paper is organized as follows. Section 2 presents the POC drone-based wind lidar system. Section 3 presents results of several demonstration experiments conducted with the described measurement system. Section 4 discusses the results of the POC stage as well as outlines our future work, while Section 5 provides our concluding remarks.

2 Measurement system description

2.1 Overview

For the POC, we used a non-production dual-telescope CW lidar system built by ZX Lidars (ZXT2 lidar), and off-the-shelf drone and gimbal system (DJI Matrice 600 Pro and Ronin-MX). The selected drone and gimbal system are typically used in the motion picture industry, while the lidar was optimized for wind tunnel measurements or for turbine blade mounting, thus the transceiver units (telescopes) are separated from the rest of the lidar.

Instead of mounting the entire lidar to the drone, for the POC we mounted only the telescopes to the gimbal (attached to the drone). The telescopes were connected to the lidar located on the ground using 100-m long optical fibres. The drone was battery powered.

The main reason why the POC system was built as described above was that it did not required any costly development since many of the parts were already built, or readily available off the shelf. Moreover, since we intended to investigate the overall feasibility of the proposed concept, this type of study (i.e., proof-of-concept) is often undertaken on a much lower budget and before investing in the build of a full prototype or product development.

In the text that follows, we will describe each part of the POC measurement system in more details.

2.2 Lidar system

The ZXT2 lidar is an experimental system built in 2014 ~~as a concept demonstrator for an airborne wind speed requirement~~ (Neininger, 2017). It has since been used in a variety of trials including several wind tunnel tests and lidar calibration exercises. ZXT2 is a two-channel CW wind lidar system consisting of a 3U 19" rack unit with two separate staring transceiver units (telescopes), allowing simultaneous, continuous and independent line-of-sight (LOS) wind measurements ~~with 100% duty cycle (Figure ??)~~. It achieves this by sharing the laser power 50/50 between the two channels. As a result, the unit exhibits reduced sensitivity compared to a unit that uses 100% of the power in a single channel. The main specifications are listed in Table 1.

~~Assembled ZXT2 system ready for use~~

The rack unit contains an internal Windows PC; normal operation involves accessing the internal PC via remote desktop. ~~Figure ?? shows the system fully set up on the bench. Here the telescopes are connected to the rack via 10-m armoured fibre cables (detachable at both ends).~~ In the drone experiment, ~~these were replaced~~ the telescopes with 1" aperture ~~telescopes~~ were connected to the rack unit with lightweight 100m fibre cables. Four fibres were required to provide the transmit and receive paths on the two channels.

The beam from each telescope is brought to a near-diffraction-limited focus, at a distance that can be manually adjusted on the ground then locked in position. The total laser output can range from 0.3 W to 1.3 W, but here it was set to 0.8 W, giving an output of order 0.3 W on each channel (after accounting for losses). This output level provided excellent signal strength under the conditions experienced during the tests. Care was taken to avoid fibre bend losses during flight operations.

The detector output is sampled at 100 MHz, and Doppler signals are obtained as an average of 4000 independent 512-point FFT spectra. Each averaged spectrum consists of 256 bins, spanning a speed range 0-39 m/s, and allowing calculation of LOS

Table 1. Basic specifications of ZXT2 lidar

Base unit dimensions	3U 19" rack unit
Length of fibres connecting telescopes to base unit	100 m
Type of fibres	single-mode
Telescope dimensions	Length 25 cm by diameter 3 cm
Telescope weight	100 grams
Focal range	0.5m to 50 m
Transmitted laser power	300mW CW per channel
Laser wavelength	1.56 μm
Probe length (~~HWHM~~FWHM)	Approx 5cm at 3m range
Line-of-sight speed range	± 0.3 – 39.0 m/s (sign not distinguishable)
ADC sample rate	100 MHz on both channels simultaneously
Data rate	48.83 Hz independent line-of-sight speed values on both channels
Number of averages per measurement	4000
Bin width	0.1523 m/s

wind speed via different estimation algorithms. For this experiment, a simple median method was used (e.g., Held and Mann, 2018), so that the basic output consists of two simultaneous channels of speed values at nearly 50Hz data rate. ZXT2 is a homodyne system (no AOM), and therefore the sign of the Doppler shift was not detected. For systems that use AOMs, the outgoing laser light frequency is shifted in order to be able to detect the sign of the Doppler shift of the backscattered light.

5   One approach to eliminate an AOM from the lidar design is to have an external source of information about the wind direction, which in case of for example Zephir profiling lidars is accomplished by having an additional wind sensor attached to the lidar (Courtney et al., 2008). All raw spectral data are stored to allow more detailed analysis to be carried out if required.

2.3 Drone and gimbal

DJI Matrice 600 Pro is an aerial platform build for various industrial and scientific applications (DJI, 2018). This hexacopter

10   has a solid loading capability and hovering time of about 20 min with a payload of about 5 kg (see Table 2 for the basic drone specifications). The flight time can be significantly improved by converting the drone to be tethered (e.g., power line auto-track tension system). The drone ~~is~~ originally comes equipped with three Global Navigation Satellites Systems (GNSS) receivers for position measurements (accuracy of a few meters). The drone has a modular design which allows the integration of both the DJI branded sensors as well as third-party sensors. For boosting the accuracy of position measurements and providing improved

15   measurements of the drone orientation we have additionally equipped the drone with two receivers for real-time differential GNSS measurements (DGNSS) ~~. The~~ which communicate with a mobile ground based real-time ~~DGNSS measurements, also known as real-time~~ kinematics (RTK) ~~, bring the position measurement accuracy to a cm level~~station (i.e., rover). The baseline
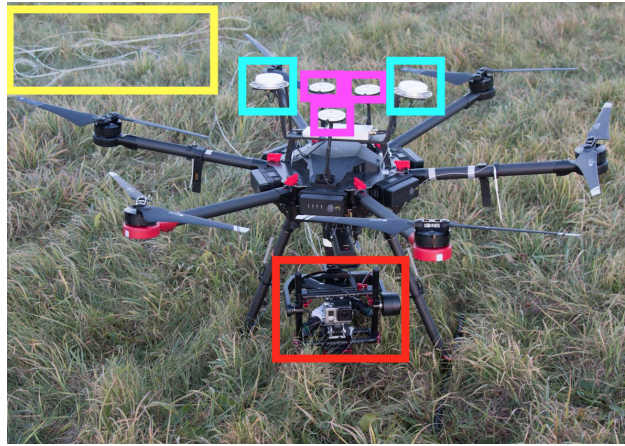
Figure 1. Complete system on ground: ~~purple squares -~~ three central ~~antennas – GNSS~~ ~~receivers~~ antennas for positioning, ~~two side antennas~~ ~~turquoise squares -~~ ~~GNNS RTK~~ two DGNNS receivers with RTK for real time position correction, ~~white cable~~ yellow square - four joined optical fibres and red square - gimbal with telescopes and GoPRO camera. Picture taken from the photo gallery https://work.courtney.dk/#collection/7.

distance between the two DGNSS antennas of 25 cm allows the orientation measurements accuracy of about $0.8°$ as stated by DJI in the product sheet (DJI, 2017). Beside the GNSS receivers, the drone is equipped with three inertia measurement units (IMU). The combination of RTK and IMU should in principle provide a solid foundation for accurate measurements of the drone 6 degrees of freedom (6DOF) in real-time (i.e., position, orientation, leveling, velocity and acceleration). The drone has
5   been equipped with an on-board camera to provide visual information. DJI provides a well-document software development kit (SDK) and an application programming interface (API) for the drone which allows the development of automated drone applications.

To improve the stability (e.g., damp vibrations), orientation and tilt of the drone-mounted telescopes we have equipped the drone with a three-axis programmable gimbal system (Ronin-MX, see basic specifications in Table 3 extracted from the
10   product sheet DJI (2016)). This avoids developing a custom beam steering unit. The gimbal system can be used standalone and as an integrated part of the drone. It comes with its own IMU and a 32-bit Digital Signal Processor (DSP), which acts as a control unit for three servo motors equipped with encoders on their shafts. There are wired and wireless options when comes to the communication with the gimbal system. Like in the case of the drone, DJI provides a well-documented SDK and AP for the gimble system, allowing for example the implementation of custom motion profiles for all three axes either
15   as feed rate (constant velocity) or time moves. Therefore, the gimbal system alone can act as a very good beam steering unit (i.e., scanner). Overall, the entire drone ecosystem (hardware, software, documentation, etc.), provides means for developers to adapt the drone and gimbal for various applications. It should be pointed out that the specifications provided in Table 2 and 2 are acquired from DJI product sheets, and thus need to be validated.

Table 2. Basic specifications of ~~DJI~~ drone from DJI product sheet (DJI, 2018, 2017)

Dimensions	1668 mm (width) × 1518 mm (length)× 727 mm (height)
Dimensions (folded)	437 mm (width)× 402 mm (length)× 553 mm (height)
Weight	$\sim$ 10 kg
Maximum takeoff weight	$\sim$ 15 kg
Hovering time no payload	$\sim$ 35 min
Hovering time with $\sim$ 5kg payload	$\sim$ 20 min
Operating temperature	-10°C to 40°C
Maximum angular velocity	Tilt: 300°/s, Yaw: 150°/s
Maximum ascent velocity	5 m/s
Maximum descent velocity	3 m/s
Maximum flying velocity in zero wind	18 m/s
Maximum wind resistance (recommended)	8 m/s
Hovering uncertainty	Horizontal: ±1.5 m, Vertical: ±0.5 m
Position read-out uncertainty (with RTK)	Horizontal: ±1 cm, Vertical: ±2 cm
Orientation read-out uncertainty (with RTK)	±0.8°

Table 3. Basic specifications of ~~DJI~~ gimbal from DJI product sheet (DJI, 2016)

Dimensions	280 mm (width) x 370 mm (length)x 340 mm (height)
Maximum dimensions of attached peripherals (recommended)	160 mm (width) x 120 mm (depth) x 130 mm (height)
Weight (with vibration absorber)	2.15 kg
Maximum payload weight	4.5 kg
Runtime	3 hours
Operating temperature	-15°C to 50°C
Maximum controlled angular velocity	Yaw axis: 200°/s, Pitch axis: 100°/s, Roll axis: 30°/s
Angular range	Yaw axis: endless, Pitch axis: +270° to -150°, Roll axis: ± 110°
Angular accuracy	± 0.02°

To attach the two telescopes to the gimbal, we have 3D printed a mounting bracket for the telescopes. The bracket was made such that it allows manual setup of the 'opening' angle between telescopes. The bracket was attached to a custom-made aluminium 'tray' which slides into the gimbal camera mounting system. The tray also had a mount for a GoPro camera. The entire custom-built sensor setup is shown in Figure 2.

Figure 2. Gimbal payload: GoPro camera and two telescopes highlighted with T1 and T2 (here mounted with 90° opening angle between them) with protective lens caps. Picture taken from the photo gallery https://work.courtney.dk/#collection/7.

3 Measurement campaigns description

As a part of the POC stage of the drone-based wind lidar system development we performed several measurement campaigns. In comparison to more typical wind measurement campaigns (e.g. Vasiljević et al., 2017) the POC stage campaigns were shorter in duration (10 to 30 min). With the POC campaigns our prime focus was to demonstrate the feasibility of the drone-based wind lidar concept.

Prior to the acquisition of Matrice 600 Pro and Ronin-MX, we made a preliminary test flight with a relatively inexpensive drone (DJI Phantom 3) to which we attached a single telescope. This was connected to the same ZXT2 lidar via two 100 m fibres and similar settings were used as in the main experiments; the second channel was left unconnected. The measurements were carried out close to Malvern U.K. in July 2018, and provided important experience that was carried forward to the trials in Denmark. The biggest challenge involved handling of the 100-m fibres to avoid snagging, which could lead to bend loss and disturbance of the drone 's flight. Careful stacking of the uncoiled fibres on the ground was essential, with separation of the T (transmitting) and R (receiving) fibres to minimise risk of tangling.

Wind measurements were made by manually rotating the drone to point the telescope into the wind. The weather was hot and sunny with light winds (5 m/s and lower) from the south-southwest (SSW) direction. High quality 50 Hz LOS wind data were obtained over the full flight duration at heights of up to 70 m above ground level. Figure ?? shows a time series covering the middle seven minutes of the flight, when the beam was clear of any obstructions such as trees and buildings. The experiment provided encouragement for the viability of drone-mounted wind lidar, and notably there were no observed problems caused by vibrations of the lidar telescope on the drone . No obvious showstoppers were identified from this preliminary demonstration, and this provided the impetus to plan the next set of more rigorous tests in Denmark.

Time series showing measured LOS wind speed from preliminary drone-mounted lidar experiment

Figure 3. Aerial photo of test center at Risø campus: blue point - position of 10 m mast denoted 'TW', red point - position of 70 m mast denoted 'VT'. Aerial data: ©Google Maps, DigitalGlobe.

~~As earlier mentioned, the main campaigns, which will be described in the following subsections of this paper, were performed with Matrice 600 Pro, thus with the system described in Section 2 of the paper.~~ To operate the drone we followed the Danish drone rules set by Danish transport, construction and housing authority. Our drone pilots were required to have drone licences. The campaigns took place at the DTU Risø campus. The campus is located 5 km north of Roskilde, on the island of Zealand,

5 Denmark . Within the campus there is a test center for wind turbines (Figure 3). The test center is surrounded by the Roskilde fjord (towards west), campus buildings (towards north), and agricultural land (towards east and south). It is located in flat terrain, though the terrain mildly slopes in the direction from the fjord towards the row of turbines. The prevailing wind direction is from the fjord, thus from the west. The test center includes test pads for small wind turbines (currently three in use) and several well-instrumented met masts. For the purpose of the drone campaigns we used measurements from two masts denoted

10 as 'VT' mast and 'TW' mast in Figure 3. These two masts are 70 m and 10 m tall respectively. The masts are IEC compliant and include calibrated in-situ wind sensors (cup or sonic anemometers and wind vanes). In this study we used measurements from a number of Metek USA-1 3D sonic anemometers. The flight conditions during the campaigns were good with relatively low wind speed and no precipitation (Table 4). The biggest challenge involved during the measurements was handling of the 100-m fibres to avoid snagging, which could lead to bend loss and disturbance of the drone's flight. Careful stacking of the

15 uncoiled fibres on the ground was essential, with separation of the T (transmitting) and R (receiving) fibres to minimise risk of tangling.

Instead of developing the drone/gimbal customization via SDK for the POC stage we decided initially to assess to what level the drone and gimbal straight "out of the box" are already a turn-key solution for wind lidar applications. Hence, we simply
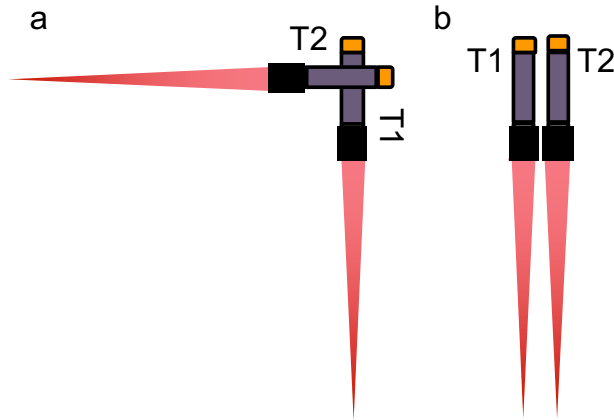
Figure 4. Telescope setup: a) opening angle of $90°$, b) opening angle of $0°$

attached the telescopes to the gimbal system and manually positioned the drone and oriented the gimbal system using the on-board drone camera and GoPro camera mounted on the gimbal tray. The drone was manually steered to hover within a couple of meters from the mast mounted sonic anemometers. These sensors were used as the reference for the comparisons in the text that will follow. The on-board drone camera was used to coarsely position the drone at the right height. ~~The fine adjustment~~
5 ~~of the drone position and gimbal orientation were done using the GoPro camera mounted on the tray~~ Since the telescopes were attached to the gimbal, the GoPro camera was used to make sure that the telescopes are at the same height of the reference instrument and that they are pointing the laser beams in the desired directions. Once this was performed, simply the drone and gimbal were locked in the position. Afterwards, the drone A3 Pro flight controller automatically maintained the drone position, and orientation and leveling of the telescopes carried by the gimbal. The focus of the telescopes and the opening angle between
10 them were adjusted on the ground prior flights.

We used two configurations of the opening angles (see Figure 4). In the first configuration the opening angle between telescopes was set to $90°$, thus the outgoing beams were perpendicular to each other (Figure 4a). In the second configuration the opening angle was set to $0°$, thus the outgoing laser beam were parallel to each other (Figure 4b).

We performed four ~~approximately 20-minute long experiments~~ experiments (See Table 4 with details). We started first with
15 an experiment in which we hovered the drone in the vicinity of a sonic anemometer mounted 8-m agl on the 10-m mast (TW mast in Figure 3). With this experiment we secured the first batch of data for the inter-comparison between the mast and drone based wind sensors to prove the concept feasibility. In the second experiment we hovered the drone at several heights next to the 70-m mast (VT mast in Figure 3) attempting to test the feasibility of doing multi-height measurements (i.e, vertical profiling of the wind) as well as acquiring the wind speed measurements beyond 60 m agl. In the third experiment,
20 we explored the possibility of using measurements from a single telescope to reconstruct the horizontal wind speed since the single telescope concept is a lower cost option for drone-based wind lidar development. In these three campaigns we used the telescope configuration shown in Figure 4a, in which the focus distance of the two telescopes was fixed to 5 m to be sure that we

Table 4. Overview of experiments

Experiment no	Flight time [min]	Flight height [m]	Telescope orientation [deg]	Telescope setup [deg]	Wind speed [m/s]	Wind direction [deg]	Weather condition
1	22	8	240	90	3 - 7	190 - 260	Clear sky
2	15	18, 31, 44, 57 and 70	20	90	2 - 6	206 - 259	Clear sky
3	16	70	20	90	3 - 6	206 - 251	Clear sky
4	6 x 5	5	30-70	0	1-4	30-70	Cloudy

are measuring the flow undisturbed by the drone presence. In the last experiment the goal was to detect the drone disturbance zone, i.e. the area of the air disturbed by the drone downwash (telescope configuration shown in Figure 4b). Although it would be logical to start with the downwash experiment, we first needed to get an assurance that the proposed drone-based lidar concept really works. Therefore we started directly by acquiring wind speed measurements close to a mast-mounted sensor with what later proved to be a rather conservative configuration of the focus distance.

3.1 Experiment 1: Hovering next to 10-m mast

To gain the experience in operating the newly-built drone-lidar system we started with measurements close to the TW mast. The 10-m mast was chosen for the first measurements as it does not have guy wires that could impose a risk while flying the drone close to it. We performed three flights next to this mast. During these flights the drone was positioned 6 m upstream of the sonic (8 m from the mast). We used the telescope configuration with the opening angle of 90° (see Figure 4a). This telescope configuration allowed us a straightforward measurements of the horizontal wind speed amplitude:

$$V_h = \sqrt{V^2_{LOS\_T1} + V^2_{LOS\_T2}}, \tag{1}$$

where V_h is the horizontal wind speed, while V_{LOS_T1} and V_{LOS_T2} are LOS speeds measured by the telescope 1 and 2 respectively.

Undoubtedly the previous relation is true assuming that:

– the gimbal is capable of retaining the leveling of the telescope mount,

– the flow is homogeneous ~~within the probed 'area' of the air (7.07m x 0.15 m)~~ at the two measured lidar focus points

The focus distance as previously mentioned was set to 5 m, which considering the size of the optics results in the effective probe lengths of about 15 cm for each telescope. During the flights, using the gimbal system we were able to point the bisector of the LOS to face the sonic by pointing the beams downwind (see Figure 5). The wind direction during the flight was about 240°. As earlier mentioned with this configuration we measured the horizontal wind speed next to the sonic anemometer mounted 8 m agl at the 10-m mast denoted TW in Figure 3.
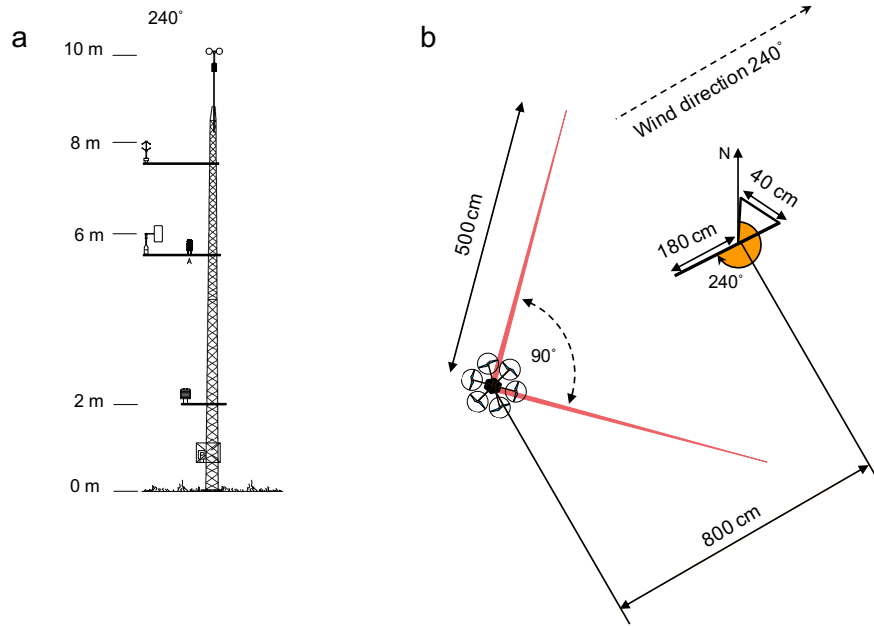
Figure 5. First experiment configuration: (a) 10-m mast sketch with position of instruments (2 m - humidity and temperature probe, 6 m - wind vane and humidity and temperature probe, 8 m - sonic anemometer, 10 m - cup anemometer); (b) 10-m mast cross section at 8 m height with the orientation of the drone with respect to the boom at which the sonic anemometer is installed.
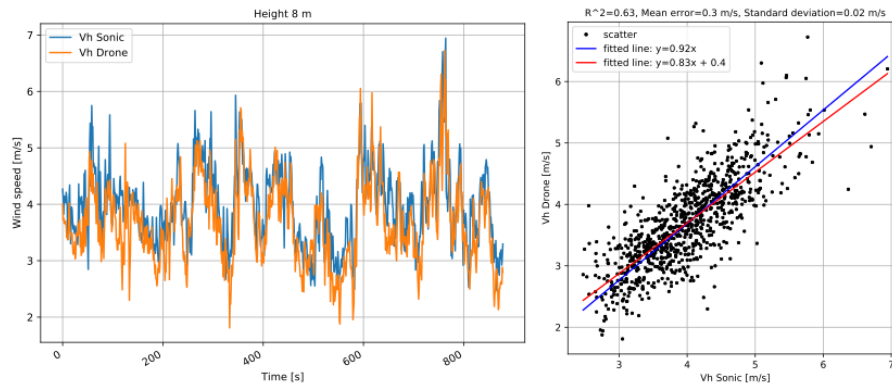

Figure 6. Measurements acquired next to the TW mast: left - 1 Hz time series of the horizontal wind speed acquired with the drone-lidar system and the sonic anemometer, right - linear regression plot.

The LOS velocity from the two telescopes and the horizontal wind speed measured with the sonic were collected with a 50 Hz data rate, though on two separate data acquisition system. To simplify the data sync and a follow up inter-comparison, both the sonic and drone data were averaged to give a 1 Hz datasampling rate.
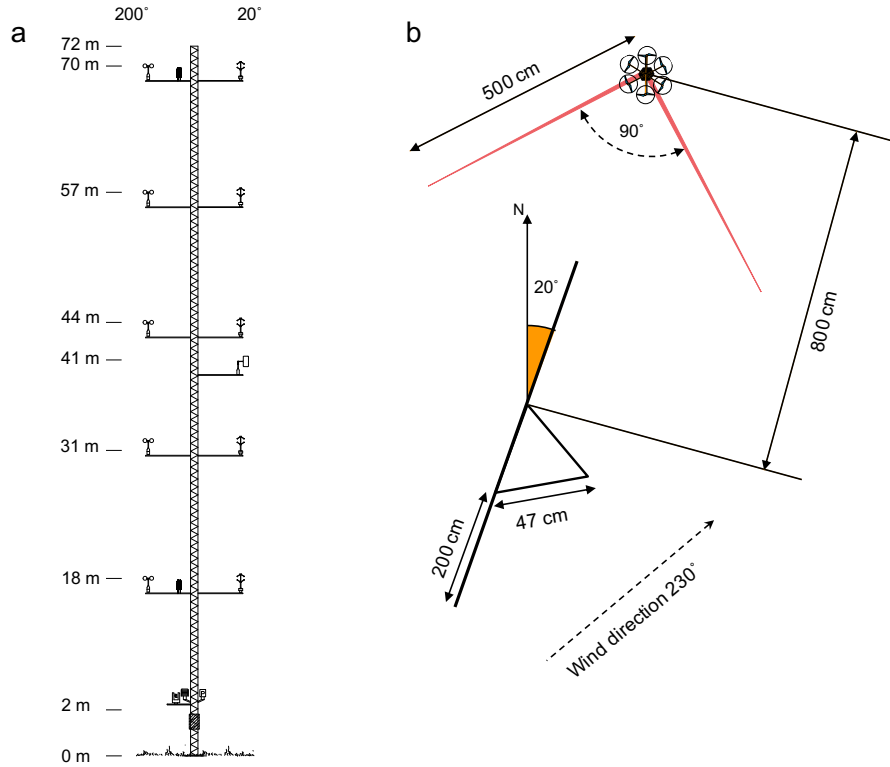
Figure 7. Second experiment configuration: (a) 70-m mast sketch with positions of instruments (2 m - humidity/temperature probe, 18 m - cup and sonic anemometers and humidity and temperature probe, 31 m - cup and sonic anemometers, 41 m - wind vane, 44 m - cup and sonic anemometers, 57 m - cup and sonic anemometers, 70 m - cup and sonic anemometers and humidity and temperature probe); (b) 70-m mast cross section at 70 m height with the orientation of the drone with respect to the boom at which the sonic anemometer is installed.

Figure 6 shows a time series and the correlation plot from ~~one the three flights~~ the flight done next to the sonic anemometer mounted 8 m agl at the TW mast. Considering that we do ~~no~~ not account for the movement of the drone, which will influence the measured wind speed, the comparison is reasonably good.

3.2 Experiment 2: Hovering above several different heights next to V52 mast

Once we got confident in operating the drone-lidar system we started measurements next to the VT mast which has sonic anemometers installed at five heights (18 m, 31 m, 44 m, 57 m and 70 m agl see Figure 7a). With a total of 21 anchor points distributed at seven heights the mast is fixed to the ground using corresponding number of guy wires, which required an extra caution during the drone flight. We have retained the opening angle of 90° between the two telescopes (see Figure 4a and Figure 7b). Using the gimbal system we were able to point the bisector of the LOS to face the sonic anemometers, however this time the beams were pointed into the wind (see Figure 7b). The wind direction during the flight was around 230°.

Figure 8. Drone parked next to sonic at 70 m agl

The aim of ~~the first campaign~~ this experiment peformed next to the VT mast was to hover and measure wind speed next to each of the sonic anemometers (Figure 8), to vertically profile the wind. The total measurement time was approximately 15 minutes.

We started with the lowest sonic anemometer (18 m agl), measured for a period of time and then re-positioned the drone to the next height. This process continued until we reached the top mounted sonic anemometer. Once the measurements next to the top mounted sonic anemometer were completed we initiated the landing of the drone. During the measurement campaign the wind was coming from the southwest (mean wind direction of $230°$). Accordingly, we positioned the drone the northeast of the mast, and oriented the gimbal system such that the laser beams were steered towards the southeast. In this way, the bisector of the two beams pointed approximately into the wind, thus the drone itself did not interfere with the flow where the beams were focused.

During the measurement campaign, we have manually started and stopped the measurements at each height. More accurately, we waited for the drone and gimbal operators to position the drone, and once this was completed we initiated measurements.

Table 5. Summary of comparison of multi-height measurements

Parameters	18 m	31 m	44 m	57 m	70 m
Number of samples	157	104	89	108	323
R^2	0.68	0.52	0.48	0.45	0.77
Mean difference [m/s]	~~-0.08~~ 0.08	0.05	0.06	0.02	0.11
Standard deviation [m/s]	0.04	0.06	0.08	0.06	0.03
Slope	1.01	0.98	0.98	0.99	0.97

Similarly, after a certain period of time we have stopped the measurements and indicated to the operators to move the drone to the consecutive height. At each height we produced two datasets which corresponded to the two telescopes.

Since we did not record the orientation of the gimbal system for each height we were able to determine only the amplitude of the horizontal wind speed. Like in case of the experiment next to the TW mast we averaged the 50 Hz data from the lidar and sonic anemometers to 1 Hz. Figure ~~?? - ??~~ 9 shows 1 Hz data recorded by both sonic anemometers and drone-lidar system. Table 5 summarizes the results of all the comparisons.

From the aforementioned ~~figures~~ figure and table we can see that the best comparison between the measurements from the drone and mast is at the top height ~~. A potential explanation for this is~~ mainly due to the fact that ~~as we go higher above the ground level there is less of the mast supporting structure (e.g., guy wires) which can cause shadowing effects at positions where the laser beams are focused. Also, we~~ we did spend most of the time hovering next to the ~~top mounted sonic, which is reflected in the improved R^2 value~~ corresponding sonic. Nevertheless, the comparisons are quite good for all heights considering that they are using high frequency (1Hz) data.

~~Comparison of measurements acquired at 31 m agl~~
~~Comparison of measurements acquired at 44 m agl~~
~~Comparison of measurements acquired at 57 m agl~~
~~Comparison of measurements acquired at 70 m agl~~

3.3 Experiment 3: Single-beam trial

The simplest, cheapest configuration for drone-mounted lidar is a single horizontally-aligned staring telescope~~, as used in the preliminary UK experiment~~. This is capable of measuring accurate wind speed if the beam is aligned closely to point along the wind direction. The resulting speed error is an underestimate given by the cosine of the misalignment angle. As such, the error is relatively small even for quite a significant misalignment (e.g., 1.5% for 10 degrees). This concept was tested in an experiment where the drone was hovered in close proximity to the sonic at 70 m, and only one of the telescope outputs (T1) was used for speed comparisons (Figure 10). It is likely that simple methods can be devised to align the beam with the wind based on drone flight characteristics, but in this experiment it was achieved by minimizing the Doppler offset observed by the
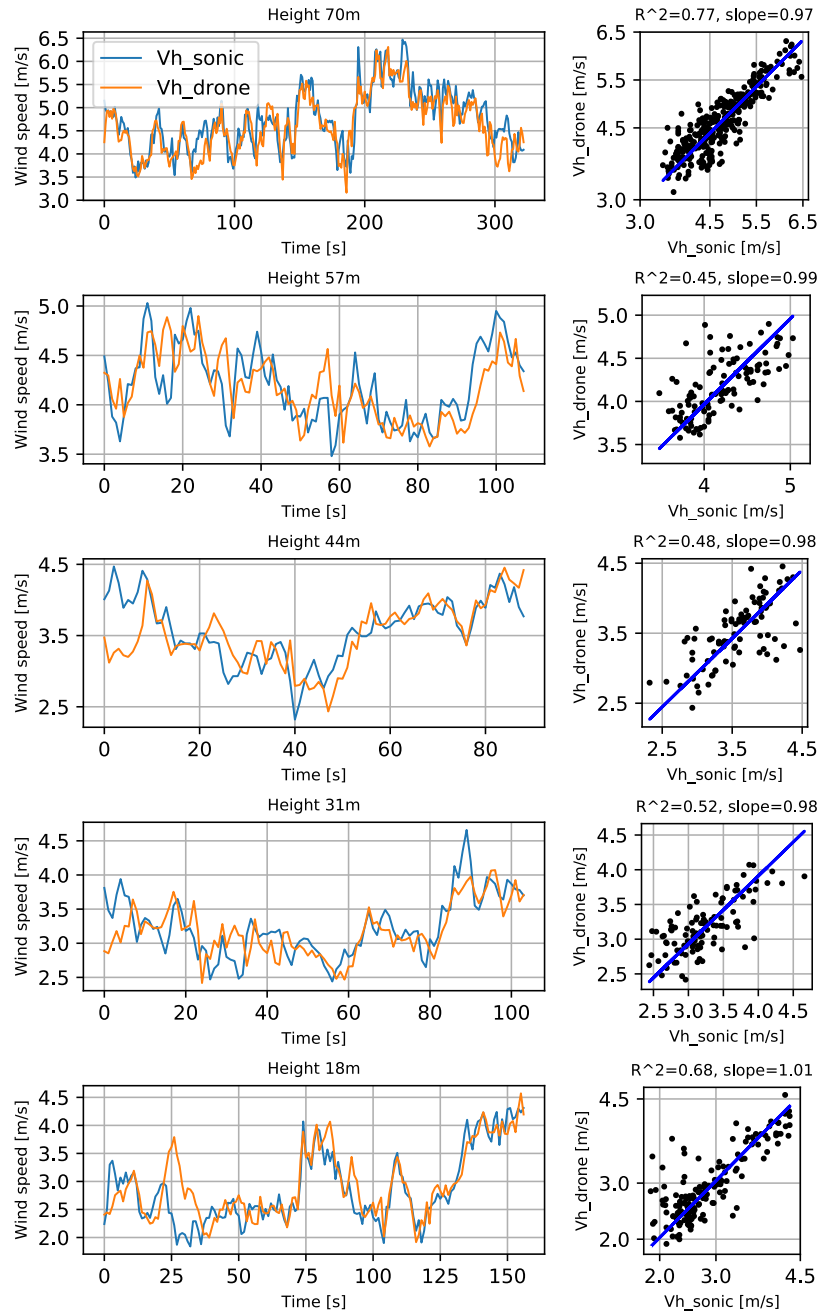
Figure 9. Comparison of ~~multi-height~~ measurements ~~acquired at 18 m agl~~ from the second experiment: left figures - time series, right figures - linear regression plot forced through zero
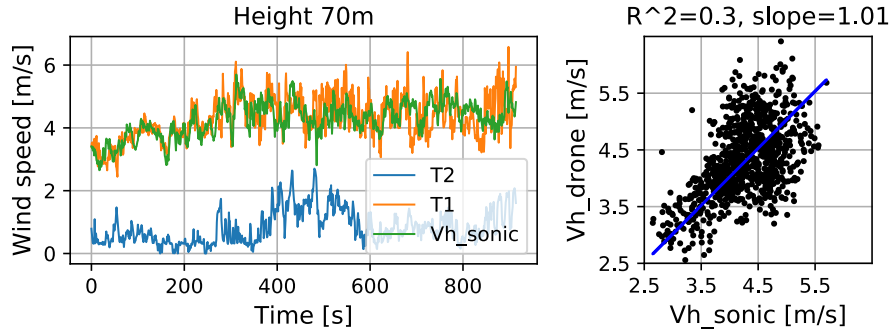
Figure 10. Single beam comparison at 70 m: left figure - time series, right figure - linear regression forced through ($R^2 = 0.3$, slope = 1.01, $\mu_{(Vh_{sonic}-T1)} = 0.05$ m/s, $\sigma_{(Vh_{sonic}-T1)} = 0.03$ m/s)

other, orthogonal, telescope (T2). If this speed from T2 can be maintained close to zero, then this ensures the beam from T1 is closely aligned with the wind. Figure 10 shows the time series from analysis of approximately 15 minutes of data. When the speed measured by T2 is low, as in the first 250 seconds, then agreement between sonic and T1 is very good. Although the corresponding correlation plot from the full data period (Figure 10) exhibits significant scatter (a consequence of high data rate combined with drone-sonic separation of several metres), however, the mean wind speeds are in close agreement. The mean difference between the wind speed measured by sonic and T1 is 0.05 m/s with the standard deviation of difference of 0.03 m/s.

From this brief experiment we conclude that this approach could be a viable option as long as a reliable simple method of beam alignment along the wind direction can be devised.

3.4   Experiment 4: Drone disturbance zone

It is obvious that the downwash from the drone itself can severely influence the lidar measurements and it is therefore important to establish how far out from the drone centre this disturbance zone stretches. This was done by mounting the telescopes on top of each other in the gimbal with the laser beams pointing parallel and horizontally out from the drone (see Figure 4a). We first started by conservatively guessing that given the size of the drone at the distance of 5 m from its center the drone downwash should not have any impact on the free stream. Accordingly, in the first measurement series both telescopes were focused at 5 m and data acquired for about five minutes. The drone was then landed and the focus distance of telescope 2 decreased by approximately 1 m while that of telescope 1 was kept constant and a new measurement series acquired. We repeated this process six times until a focus distance 0.7 m for telescope 2 was reached.

Figure ?? The top image in Figure 11 shows an example of a 1 Hz time series obtained with telescope 2 focused at 2 m. With the measurement volumes being separated by only 3 m the measurements from telescope 1 and 2 are expected to resemble each other to a high degree and that is indeed seen to be case. Any differences between the two are mostly due to the measurement volumes not being exactly co-located. In contrast, Figure ?? the bottom image in Figure 11 shows a time series where telescope
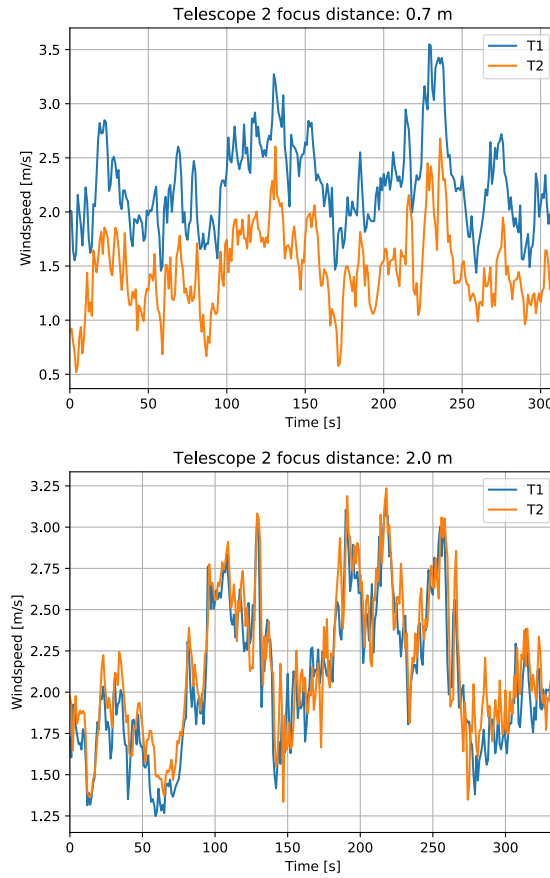
18

Figure 11. Example of 1-s averaged wind speed measurements acquired by the two telescopes~~with~~ : top image - telescope 1 focused at 5 m and telescope 2 at 2 m, bottom image - telescope 1 focused at 5 m and telescope 2 at 0.7 m.

2 is focused at 0.7 m with the measurement volume clearly within the drone disturbance zone. All though some general features are seen to be the same in the two plots telescope 2 measures a significantly lower average wind speed which is due to the blockage effect of the drone, while the downwash is perpendicular to the beam and hence has no Doppler contribution. ~~Example of 1-s averaged wind speed measurements acquired by the two telescopes with telescope 1 focused at 5 m and telescope 2 at 0.7 m. Clear differences are seen due to telescope 2 measuring inside the drone disturbance zone.~~

5   Figure 12 shows the relative difference in average wind speed measured by the two telescopes as function of telescope 2 focus distance. With the measurement volumes co-located at 5 m focus distance there is as expected virtually no difference between the measured average wind speeds and the difference stays low (less than 1%) down to 3 m. At 2 m focus distance there is a positive difference of about 3.9% and at 1 m the difference becomes negative with a value of -2.3% indicating that
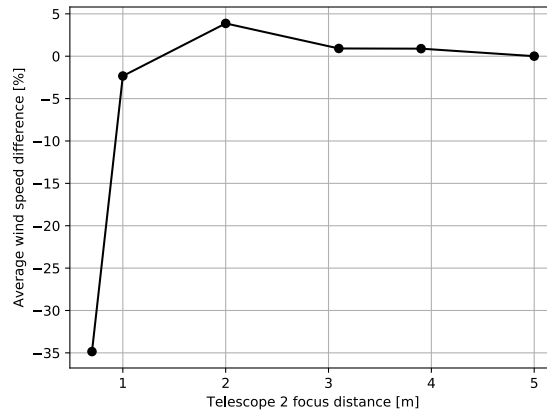
Figure 12. Relative difference in average wind speed measured by the two telescopes as function of telescope 2 focus distance.

the downwash starts to disturb the measurement. Finally, there is a very large difference of -35% when telescope 2 is focused at 0.7 m and thus measuring directly inside the disturbance zone.

From these measurements we conclude that the disturbance zone stretches between one and two metres from the drone centre, and when focusing the laser beams at three metres or more the influence of the drone itself on the measurements is negligible.

4 Discussion

In our first two experiments (Section 3.1 and 3.2) we have endeavoured to demonstrate that the wind speed measured by the drone system is consistent with that measured by the nearby sonic anemometers. This has been successfully accomplished as can be seen from both the time series and scatter plots in Figures 6 and **??-??**9. A summary of the results from the VT mast is shown in Table 5. Here we can see that the slope of the constrained linear regression is close to unity in all cases.

Whilst these tests serve to demonstrate the plausibility of the measured drone system wind speed, a more detailed and convincing testing methodology needs to be developed which can be used to assign a traceable uncertainty to the drone system. Two inherent problems are firstly the short flight time available and secondly the necessary separation between the drone system and the reference mast instrumentation. The latter gives rise to an inherent degradation in correlation at the time scales available as dictated by the former (only a few minutes of flight time).

There are some obvious improvements to be made here before the method becomes applicable to practical real-world measurements - primarily maximising the flight time at any given height. Battery-powered drones cannot provide continuous measurements over long periods of many hours. Therefore, ultimately we envisage using a tethered system receiving flight power on its umbilical. Using such a system it should be possible to measure for hours as opposed to minutes. Alternatively, a charging deck with several drones could be employed allowing near-uninterrupted measurements (a short interruption would

20

probably occur during the drone substitute). However, even if we provide a continuous power to the drones, still the life expectancy of their motors is currently in the realm of couple of days of continuous operation after which the motors may need to be serviced or replaced. Nevertheless, the recent pace of development of drone technology suggests that we can expect significant improvements in their capabilities; this work aims to anticipate these developments that could make drone-mounted lidar a practical and cheaper option in the future.

A second approach to assessing the uncertainty could be using what has become known as the 'white box' approach in the field of nacelle-mounted lidar calibration (Borraccino et al., 2016). For these systems it has been found that it is essentially impossible to compare the reconstructed wind speed directly with a reference measurement in a calibration environment. Instead the component uncertainties comprising the line-of-sight speed uncertainty and the uncertainty in the lidar geometry are propagated through the reconstruction algorithm to give an estimate of the uncertainty on the reconstructed speed. Drone-based lidar speed measurements lends itself to this technique for two reasons: Firstly the very short range lidars can be calibrated directly using a flywheel approach (Pedersen and Courtney, 2018) which has a much lower reference uncertainty than the alternative of using calibrated cup anemometers. Secondly the geometry and reconstruction is simple and easy to solve analytically.

Despite this being a first attempt we have already accomplished a close agreement to the nearby mast instrumentation. This has been achieved using only the basic drone position stabilisation and without correcting in any way for the drone motion. A clear next step (outlined below) is to implement the differential GPS positioning (already installed but inoperable in the initial tests) and to log this data. Not only will the drone be even more stable but we will be able to correct for the induced speed from the perturbations.

Our first experiments had the primary aim of demonstrating the recording of plausible wind speed from the drone system. Should the system later fail, our proof-of-concept would have been already been achieved. Actually the system proved to be quite robust (we had no catastrophic failures) and we were able to proceed with secondary but important tests. In the second experiment we have hovered the drone at multiple heights (mimicking mast measurements) which corresponded to the locations of sonic anemometers. In principle to measure wind profiles with the described system, a drone could vary position only in height (fixed Northing and Easting position of the drone), thus repetitively flying up and down between the range of heights. In the third experiment (Section 3.3) our aim was to investigate to what extent a single beam system would suffice to measure wind speed. Critical readers might with some justification claim that using two beams to show that only one is necessary is unconvincing. ~~We must~~ Potentially, we could substitute the second beam (here we used it to ensure that the cross-wind component was close to zero) with data from the drone (e.g., tilt or differential motor power) to substantiate that we are pointing into the wind. ~~This will be possible once a data connection to the drone control system is developed and operational~~Alternatively, using the gimbal or drone itself a single beam could be steered in multiple directions performing a full or partial plan position indicator (PPI) scans and wind speed reconstructed from the acquired LOS measurements using know techniques such as Chen et al. (2017). Nevertheless, various methods for the substitution of the second beam should be tested to find the most suitable one.

In the last experiment (section 3.4) we tested our assumption that our initial focus distance of 5 m was outside the drone downwash influence zone. This was confirmed and it appears over-conservative for the set-up and conditions experienced here.

We can conclude that at 3 m no downwash influence is discernible. In future testing we will use this as the focus distance, ~~although caution will be required if the drone payload is increased since the downwash will also become stronger~~. However, a dedicated study and modeling of the downwash under different conditions is necessary since we expect it to have different behaviour with respect to the payload and wind conditions.

5   Reducing the focus distance will reduce the separation between the probing beams. This is an advantage as the drone system will be able to measure in inhomogeneous flow with reduced error. In homogeneous flow, with a smaller probe separation, the drone system will be able to acquire meaningful time series of wind speed to a higher frequency since the flow will remain correlated at the two probe positions over shorter averaging times. It will thus be possible to perform scalar averaging without significant error (this is a known problem with nacelle lidar systems).

10   Probe separation could be further reduced by using a smaller opening angle than the 90° used in this initial trial, or by separating the telescopes as much as possible and converging their beams. Conceivably the opening angle could be reduced to as little as 30° (common for nacelle-mounted lidars) especially if the drone tilt or differential rotor power can be used to keep the beams more or less aligned with the wind direction and away from the (for homodyne CW lidars) troublesome trans-zero zone where radial speed polarity issues (inability to distinguish between positive and negative) could also arise. Further work

15 is clearly needed to find the optimal probe geometry for measuring horizontal as well as vertical wind speeds.

     ~~Due to~~ Conventionally, it has been troublesome for lidar to carry out point measurements of turbulence analogous to what a cup or sonic would measure: probe volumes extend typically over many metres, and the beams that interrogate the flow at different angles in a scanning system are often separated in space by many 10's of metres. By contrast, due to their short measurement range and very small measuring volume, drone lidar systems will be able to make turbulence measurements in

20 and above the frequency range relevant in wind energy aplications. The lidars we have used have a probe length (FWHM) of 5 cm when focused at 3 m. This would be sufficient for useful wind speed spectral content up to at least 10 Hz at 10 m/s wind speeds. The lidar data acquisition is able to acquire signals at ~~50Hz.~~ 50 Hz. The generation of accurate turbulence data from drone-mounted lidar requires knowledge of the telescope's orientation and speed to allow motion compensation, and this will form the topic for future study.

25   An obvious application is in-situ wake turbulence measurements where the drone can be positioned at a desired position relative to the turbine or perform a pre-described trajectory. Multiple drones (swarms) could also be envisioned to provide simultaneous measurements at a number of positions.

     Similarly a drone swarm upstream of a wind turbine could provide inflow data of unprecedented detail and quality for power performance or load validations, including horizontal and vertical shear, wind veer, turbulence intensities and also the spatial

30 structure (coherence) of (at least) the longitudinal turbulence component.

     Many other drone-lidar applications can be envisioned once some degree of drone autonomy can be developed (ability to fly pre-programmed sequences, land and re-charge automatically, fly again,...). Indeed, the power and load verification duties described above only become realistic outside a research environment once these abilities are developed. Truly operational applications could include flow monitoring inside and upstream of wind farms. This could both enhance wind farm control and

35 provide a degree of forecasting. Outside wind energy there are obvious applications in wind engineering (e.g. flow, turbulence

and coherence measurements at remote sites) as well as exciting possibilities in a variety of recreational areas (sailing, golfing, ski-sport).

5 Conclusion

A novel wind measurement technique based on the fusion of a standard drone with a prototype wind lidar has been reported. We have described the proof of concept (POC) drone-lidar system which was developed to demonstrate the feasibility of this new measurement technique. Besides the POC system description, we have reported on the first experiments performed with this system. In these experiments the drone-disturbance zone (caused largely by the influence of drone downwash) was characterized, and inter-comparison was performed of wind measurements acquired by the drone-based wind lidar with those acquired by adjacent mast-mounted sonic anemometers. A good agreement between the sonic anemometers and the drone-based wind lidar measurements has been found even without any motion compensation.

It is expected that motion compensation will result in further improvement of wind speed accuracy, and will also allow detailed investigation of turbulence. The rapid data rates and very small measurement volume suggests the exciting prospect of tracking fast atmospheric fluctuations, and deriving turbulence spectra for comparison with cup and sonic anemometers.

Overall, excellent results have been obtained in these first attempts with a fairly simple measurement system which provide a necessary vindication for the proposed measurement technique and secure the foundation for the technique's future developments.

Competing interests. Michael Harris and Mark Pitter are employed at ZX Lidars which is a company focused on the commercialization of the wind lidar technology. Other authors declare that they have no conflict of interest.

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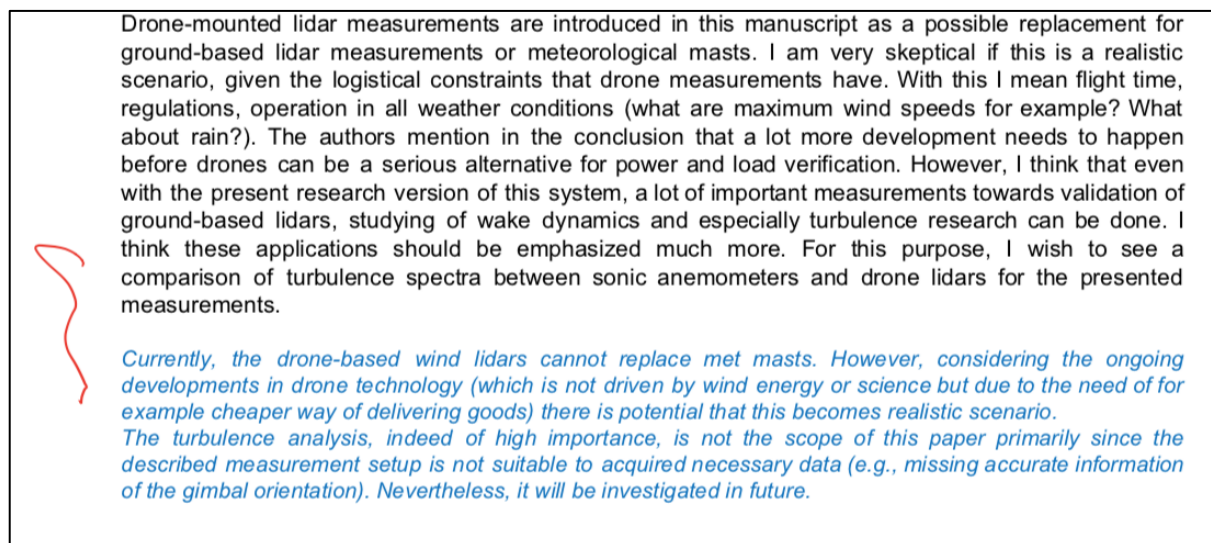
Review of Robert Sica feedbacks

This document contains feedbacks from the editor, which are taken as 'screenshots' from the document:

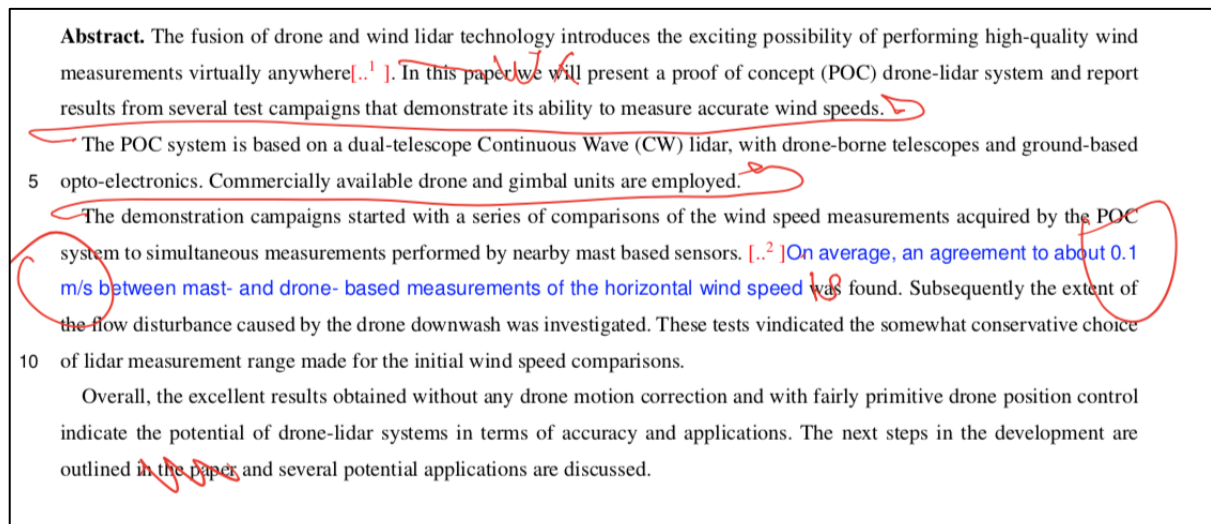`amt-2019-102-comments-to-author-4.pdf`

The above document contains total of 34 pages, and we will use a page number to emphasize the location of the editor's feedback. For each feedback we provide details how they were addressed in the manuscript revision.

Pg 1. There is a red curved line connecting anonymous referee 2 feedback together with our response in blue, as the screenshot of that part of the document indicates:

> Drone-mounted lidar measurements are introduced in this manuscript as a possible replacement for ground-based lidar measurements or meteorological masts. I am very skeptical if this is a realistic scenario, given the logistical constraints that drone measurements have. With this I mean flight time, regulations, operation in all weather conditions (what are maximum wind speeds for example? What about rain?). The authors mention in the conclusion that a lot more development needs to happen before drones can be a serious alternative for power and load verification. However, I think that even with the present research version of this system, a lot of important measurements towards validation of ground-based lidars, studying of wake dynamics and especially turbulence research can be done. I think these applications should be emphasized much more. For this purpose, I wish to see a comparison of turbulence spectra between sonic anemometers and drone lidars for the presented measurements.
>
> *Currently, the drone-based wind lidars cannot replace met masts. However, considering the ongoing developments in drone technology (which is not driven by wind energy or science but due to the need of for example cheaper way of delivering goods) there is potential that this becomes realistic scenario.*
> *The turbulence analysis, indeed of high importance, is not the scope of this paper primarily since the described measurement setup is not suitable to acquired necessary data (e.g., missing accurate information of the gimbal orientation). Nevertheless, it will be investigated in future.*

We are not sure what the curve line means, thus we did not perform any corresponding changes to our manuscript. A further explanation from the editor would be appreciated in order to improve the manuscript.

Pg 7. The editor requests several changes of the abstract (style + language), as the following screenshot indicates:

> **Abstract.** The fusion of drone and wind lidar technology introduces the exciting possibility of performing high-quality wind measurements virtually anywhere[..[1]]. In this paper we will present a proof of concept (POC) drone-lidar system and report results from several test campaigns that demonstrate its ability to measure accurate wind speeds.
> The POC system is based on a dual-telescope Continuous Wave (CW) lidar, with drone-borne telescopes and ground-based
> 5 opto-electronics. Commercially available drone and gimbal units are employed.
> The demonstration campaigns started with a series of comparisons of the wind speed measurements acquired by the POC system to simultaneous measurements performed by nearby mast based sensors. [..[2]]On average, an agreement to about 0.1 m/s between mast- and drone- based measurements of the horizontal wind speed was found. Subsequently the extent of the flow disturbance caused by the drone downwash was investigated. These tests vindicated the somewhat conservative choice
> 10 of lidar measurement range made for the initial wind speed comparisons.
> Overall, the excellent results obtained without any drone motion correction and with fairly primitive drone position control indicate the potential of drone-lidar systems in terms of accuracy and applications. The next steps in the development are outlined in the paper and several potential applications are discussed.

We have interpreted the editor annotations as the following:
- The abstract should be composed of a single paragraph (i.e., connect paragraphs)
- Sentence 'On average, an agreement to about 0.1 m/s between mast- and drone-based measurements of the horizontal wind speed **was** found' , should be rewritten to 'On average, an agreement to about 0.1 m/s between mast- and drone- based measurements of the horizontal wind speed **is** found'
- Remove 'in the paper' from the last sentence of the abstract

However, we were not sure why '0.1 m/s' was highlighted. A further explanation from the editor would be appreciated in order to improve the manuscript.

This is the screenshot of the improved abstract:

Abstract. The fusion of drone and wind lidar technology introduces the exciting possibility of performing high-quality wind measurements virtually anywhere. We present a proof of concept (POC) drone-lidar system and report results from several test campaigns that demonstrate its ability to measure accurate wind speeds. The POC system is based on a dual-telescope Continuous Wave (CW) lidar, with drone-borne telescopes and ground-based opto-electronics. Commercially available drone and gimbal units are employed. The demonstration campaigns started with a series of comparisons of the wind speed measurements acquired by the POC system to simultaneous measurements performed by nearby mast based sensors. On average, an agreement to about 0.1 m/s between mast- and drone- based measurements of the horizontal wind speed is found. Subsequently the extent of the flow disturbance caused by the drone downwash was investigated. These tests vindicated the somewhat conservative choice of lidar measurement range made for the initial wind speed comparisons. Overall, the excellent results obtained without any drone motion correction and with fairly primitive drone position control indicate the potential of drone-lidar systems in terms of accuracy and applications. The next steps in the development are outlined and several potential applications are discussed.

Pg 8. The editor has requested more appropriated references for atmospheric experiments which were using scanning lidars, as well a reference regarding the impact of the precipitation on the vertical wind speed measured by wind lidars:

The following references were added:
- Regarding the atmospheric experiment which were using lidars:
  McCarthy et al., 1982; Newsom et al., 2008; Collier et al., 2005; Grubišic et al., 2008; Fernando et al., 2015

- Regarding the impact of the precipitation on the vertical wind speed measurements: Lindelöw, 2009

Accordingly, we provided the screenshot of the improved part of the manuscript:

especially to provide wind measurements to properly estimate wind loading on bridges (Cheynet et al., 2017). Historically,

20 (since the 1980s) wind lidars have been used extensively in variety of atmospheric science studies (e.g., McCarthy et al., 1982; Newsom et al., 2008; Collier et al., 2005; Grubišić et al., 2008; Fernando et al., 2015).

Even though wind lidars are cost-attractive instruments for measurements beyond 100-m they are still relatively expensive. A minimum cost of an accurate wind lidar is about 60 k€ and 1-2 M€ for on-shore and offshore applications respectively.

Also, there are circumstances where wind lidars can experience difficulties, in which traditional in-situ measurements can

25 measure successfully. Lidar range is influenced by the atmospheric conditions (i.e., aerosols concentration), which impacts the data availability (in certain locations lidar data availability can fall below mast-based sensor data availability). For example, clouds, fog and snow are highly attenuating for the laser beam which limits the lidar range, and thus data availability. Furthermore, any precipitation will affect the wind speed measurements by lidars. Specifically the vertical component of the wind will be biased since the lidar will dominantly measure the fall velocity of the precipitation (Lindelöw, 2009).

Pg 9 There is a request for several changes of the introduction text, as indicated by the screenshot below:

– high availability of data (i.e., not to be hindered by fog, low clouds, etc.).

– long measurement duration (e.g., months)

Upper Case S

A potential solution for the above formulated problem is to use a [..⁵]Small Unmanned Aircraft System (sUAS) (such as

20 multi-copter drones) as a platform for a wind lidar [..⁶]even though currently sUAS cannot offer a long uninterrupted operation. Typically sUAS acquire wind speed information either by utilizing flow sensors such multi-hole pitot tube probes (e.g., Wildmann et al., 2014) or sonic anemometers (e.g., Nolan et al., 2018) or without flow sensors by measurements and conversion of aircraft dynamics (e.g. Neumann and Bartholmai, 2015). For example, studies Neumann and Bartholmai (2015) , Palomaki et al. (2017) and Brosy et al. (2017) utilized real-time measurements of multi-copter dynamics to estimate

25 wind speed. These studies reported a good agreement of the estimated wind speed with the speed measured by mast-mounted sonic anemometers, where the sonic and estimated wind speed agreed to about 0.5 to 0.7 m/s for 10 s averaged data (Palomaki et al., 2017; Brosy et al., 2017) and 0.3 m/s for 20 s averaged data (Neumann and Bartholmai, 2015). Brosy et al. (2017) stated that the wind speed estimated using only drone dynamics should not be used as information about atmospheric turbulence since due to the volume drones don't react to the small eddies, and thus this approach

30 cannot capture a full range of wind speeds. In LAPSE-RATE experiment (Barbieri et al., 2019) several multi-copter drones were equipped with sonic anemometers. The calibration flights of such drones (which entail hovering the equipped

⁵removed: drone as
⁶removed: . This idea

We have performed the following changes in our manuscript:
- Changed sUAS to SUAS
- Removed brackets around text 'such as multi-copter drones'
- Did not removed 'even though'
- We were not sure what 'c' means
- It was not clear how to interpret 'by', should it be placed after 'studies' ?

The screenshot of the changed manuscript is provided below:

> 15   A potential solution for the above formulated problem is to use a Small Unmanned Aircraft System (SUAS), such as multi-copter drones, as a platform for a wind lidar even though currently SUAS cannot offer a long uninterrupted operation. Typically SUAS acquire wind speed information either by utilizing flow sensors such multi-hole pitot tube probes (e.g., Wildmann et al., 2014) or sonic anemometers (e.g., Nolan et al., 2018) or without flow sensors by measurements and conversion of aircraft dynamics (e.g. Neumann and Bartholmai, 2015). For example, studies Neumann and Bartholmai (2015), Palomaki
> 20 et al. (2017) and Brosy et al. (2017) utilized real-time measurements of multi-copter dynamics to estimate wind speed. These studies reported a good agreement of the estimated wind speed with the speed measured by mast-mounted sonic anemometers, where the sonic and estimated wind speed agreed to about 0.5 to 0.7 m/s for 10 s averaged data (Palomaki et al., 2017; Brosy et al., 2017) and 0.3 m/s for 20 s averaged data (Neumann and Bartholmai, 2015). Brosy et al. (2017) stated that the wind speed

Pg 10. The sentence 'However, if we use a wind lidar as a flow sensor, potentially the accuracy could be improved and also ability to acquire turbulence measurements' was requested to be changed, by inserting 'given the' in front of 'ability to acquire turbulence measurements':

> drones close to masts equipped with sonic anemometers) showed agreement of the mast and drone-based 15-s averaged wind speed measurements to about 0.75 m/s (Nolan et al., 2018). Like in case of multi-copter drones, the aircraft dynamics of fixed-wing sUAS can be used to determine wind speed (Rautenberg et al., 2018) with the wind speed accuracy generally worse than multi-copter drones (Barbieri et al., 2019). As stated in Rautenberg et al. (2018) utilizing a
> 5 flow sensor such as pitot tube on-board of fixed-wing sUAS generally provides better results. Nevertheless, as reported in Barbieri et al. (2019) an average accuracy of sUAS of both fixed-wing and multi-copter concepts with or without flow sensors is about 0.5 m/s, which for the majority of wind energy applications is not sufficient. *given the*
>   However, if we use a wind lidar as a flow sensor, potentially the accuracy could be improved and also ability to acquire turbulence measurements. Equiping sUAS with wind lidars has been suggested in an early study of using [..[7]]sUAS for wind
> 10 energy applications (Giebel et al., 2012). At the time of the study, it was technically unfeasible to pursue this idea. Roughly a decade later, both the lidar and drone technology have advanced significantly unlocking the potential to explore the proposed idea.

We did introduce this change, however, potentially we've misinterpreted the editor feedback. In our opinion by introducing this modification the revised sentence does not read well. A further explanation from the editor would be appreciated in order to improve the manuscript.

Pg 16. The editor indicates problems with formatting, as the screenshot below indicates:

> experiments; the second channel was left unconnected. The measurements were carried out close to Malvern U.K. in July 2018, and provided important experience that was carried forward to the trials in Denmark. The biggest challenge involved handling of the 100-m fibres to avoid snagging, which could lead to bend loss and disturbance of the drone 's flight. Careful stacking of the uncoiled fibres on the ground was essential, with separation of the T (transmitting) and R (receiving) fibres to minimise risk of tangling.
>   [31]removed: Wind measurements were made by manually rotating the drone to point the telescope into the wind. The weather was hot and sunny with light winds (5 m/s and lower) from the south-southwest (SSW) direction. High quality 50 Hz LOS wind data were obtained over the full flight duration at heights of up to 70 m above ground level. Figure **??** shows a time series covering the middle seven minutes of the flight, when the beam was clear of any obstructions such as trees and buildings. The experiment provided encouragement for the viability of drone-mounted wind lidar, and notably there were no observed problems caused by vibrations of the lidar telescope on the drone . No obvious showstoppers were identified from this preliminary demonstration, and this provided the impetus to plan the next set of more rigorous tests in Denmark.
>   [32]removed: Time series showing measured LOS wind speed from preliminary drone-mounted lidar experiment
>   [33]removed: As earlier mentioned, the main campaigns, which will be described in the following subsections of this paper, were performed with Matrice 600 Pro, thus with the system described in Section 2 of the paper.
>   [34]removed: The fine adjustment of the drone position and gimbal orientation were done using the GoPro camera mounted on the tray
>
> *FORMATING ?*
>
>   **10**

As mentioned in our email correspondence this is mainly the product of latexdiff command which was positioning a part of the manuscript that was removed from the original text in the footer of the compiled pdf. The latest latexdiff command does not do that, but instead it

keeps the removed text while using ~~strikethrough~~ to indicate that it has been removed in the revised manuscript.

Pg 29 The editor requests changes of the sentence 'The generation of accurate turbulence data from drone-mounted lidar requires knowledge of the telescope's orientation and speed to allow motion compensation, and this will form the topic for a future paper', which can be seen in the screenshot below:
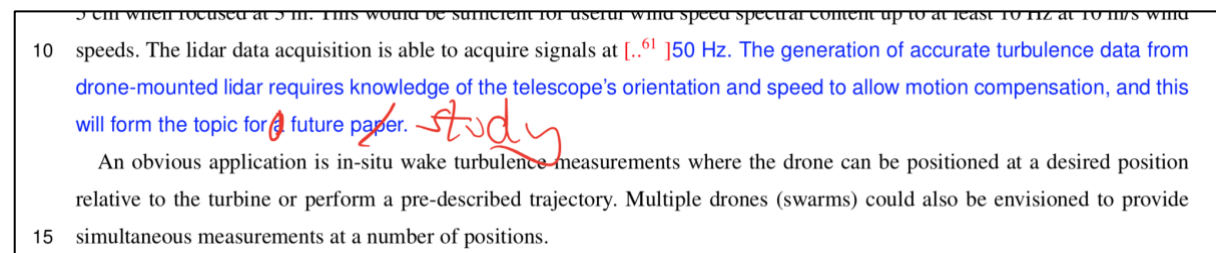
The editor request was understood as following:
- remove 'a' in front of 'future paper'.
- replace 'paper' by 'study'

Based on this interpretation, the manuscript was improved as it can be seen from the screenshot below: