We again want to thank Anonymous Referees #1 and #2 for their feedback.

Printed in blue, the author has added some final comments to the already published responses.

Author's response to Anonymous Referee #1

1. **The title is not concrete and very broad and does not cover what is discussed in the paper precisely.**

The authors agree with Anonymous Referee #1. The title might have led to wrong expectations and will therefore be changed in "Method for airborne measurement of the spatial wind speed distribution above complex terrain"

The title has been updated accordingly.

2. **Research questions: the paper lacks a clear and well-posed research question, or questions and sub questions. As such also the conclusion is rather generally formulated.**

Within the paper, research questions have been presented in form of two specific challenges (lines 54-62) towards an airborne measurement system to investigate the distribution of mean wind speeds above complex terrain. The conclusion concerning the second presented challenge (separation of temporal and spatial effects) will be further refined for the final paper.

Introduction and conclusion have been rewritten to further point out, which knowledge gaps are addressed within the paper. This is also taken into account within "Measurement strategy and evaluation methodology" section, lines 236-250.

3. **Methodology: The title suggests this paper is about wind speed deviations/variability. So I do not understand why the paper does not show spectra or wavelet analysis**

Due to the former, misleading title, the authors understand the expectations of Anonymous Referee #1. Within this paper, we are focusing on the distribution of mean wind speeds at specific positions above complex terrain. 'Deviations' were therefore meant in the spatial and not in the temporal manner. With our application in mind (site evaluation for wind farms) and taking into account the current status of the method, spectral and wavelet analyses are considered to be outside the scope of this paper.

Spectra and wavelet analyses are still considered to be outside the scope of this paper.

4. **Discussion: the paper also lacks a discussion section that reflects on the strengths and weaknesses of the study, and overall also put the work in context with other studies. Only then the paper can show how it extends the existing knowledge.**

Strengths and weaknesses of the airborne measurement system have not been discussed within a specific section, but qualitatively throughout the complete paper, for example in context to CFD simulations as well as state-of-the-art measurement equipment. The authors agree, that the paper will benefit from a more detailed assessment of the method at the results chapter, pointing out strengths and weaknesses in a context of other studies. However, the current status of the project does not yet allow a quantitative in-depth validation of the method, which will be part of future publications.

Strength and weaknesses of the method are further described within the introduction and are discussed within the results chapter in a greater extent.

Also the paper misses a discussion about the representativeness of the atmospheric conditions that were studied.

The wind speed distribution within this paper is a result of a single, short term (approx. 2hrs) measurement campaign and serves as a proof of concept for the presented method. It is assumed to be representative for the prevailing atmospheric conditions during the campaign, but not for any different weather situations. Therefore, representativeness of the atmospheric conditions was not discussed in detail.

The results of the method presented within the paper only serve as a proof of concept. Therefore, representativeness was not discussed.

5. Figures: the paper contains far too many figures. 24 figures is a bizar number, and many of these figures are not essential. Figures 5 and 10 can be removed. I also find that the left panels of figs 6-9 and 11-18 of very limited value, since they are also not much discussed. Figure captions are also not mature and panels have not been labelled a) and b).

Figure 5 was considered to be necessary to enable the reader to evaluate the test conditions. Figure 10 will be removed. The authors agree that figures 6-9, 11-14 and 15-18 could be further reduced to an exemplary plot for each of the following comparisons:

- UAV wind speed measurement to low level anemometer measurement
- UAV wind speed measurement to met mast measurement,
- UAV wind direction measurement to met mast measurement

The left panels (time plots) are considered to be helpful for plausibility, also allowing to point out special events like pilot interaction within the measurement data.
Panels will be labelled a) and b) within the final paper.

The number of figures has been reduced accordingly throughout the paper.

Author’s response to Anonymous Referee #2

__General comments:__

“While results of the field studies are reasonably well presented, further work is required to interpret the results in the context of the state of the art, including comparisons to other research efforts. More emphasis should be placed on describing how this work contributes to overcoming existing knowledge gaps. Recommendation is for reconsideration after significant revision - Spelling and grammar should be reviewed - some suggestions are provided below but manuscript would benefit from thorough proof-reading. “

A comparison to other research efforts, especially CFD and LIDAR with their advantages and disadvantages, has been performed in a qualitative manner throughout the paper. A quantitative in-depth analysis is not yet possible due to the status of our project, but it is planned for future publications.

For the final paper, a more detailed insight on research of measuring wind speed distributions above complex terrain will be given. Additionally, we will explain, that the current project is still ongoing and the paper contains results of the proof-of-concept phase. We will discuss in more detail, which further steps are necessary to raise the UAV’s full potential to overcome the presented disadvantages of LIDAR and CFD based wind analysis.

The focus of the paper has been shifted towards the measurement method to better address existing knowledge gaps. A more extensive comparison to existing technologies and research efforts has been added to the introduction (from line 36 to the end of the chapter).

__Specific comments__

“You indicate that limitations of the current measurement strategy are too significant to be considered valid (Line 258). It would be useful to describe what criteria are being used to evaluate the validity of the measurement strategy, and to provide additional details on what advancements are believed to be necessary to overcome this issue. “

The limitations of the current measurement strategy are too significant to be considered valid *in general*. During an ongoing simulation campaign, several measurement strategies, in particular the presented approach, have been evaluated concerning their performance. This is done by virtual test flights within a simulated wind field and shall be part of a future publication. One result is, that the used prototype strategy (single flying measurement system plus single stationary sensor) depends on a reference, which is representative for the area-wide wind situation. We assume this to be the case in the described situation because of the good correlation between normalised wind speeds of the mobile and the stationary system (Fig. 22). In other experimental cases, with differently positioned stationary references and at other wind conditions, we have seen higher variations. The particular strategy therefore is not capable to deliver a plausible wind field without a careful choice of the location of the stationary reference.

For the final paper, this context will be described. Because simulations are still ongoing, more detailed results are not available yet.

A subchapter concerning the used methodology has been added. Additionally, the measurement described above has been added to the results chapter for a more comprehensible and transparent evaluation of the measurement strategy.

“Further to the above comment, you mention in Line 32 the notion of bankable site assessments for regions of complex terrain - can you comment on the extent to which UAV-based

measurements need to be further developed to meet this benchmark? Is this a desired research outcome? Where do IEC standards fit in with respect to UAV measurements? "

At the moment, a single airborne measurement can only deliver a "snapshot" of a specific weather situation in terms of wind speed and direction. The results are planned to be used for site assessment in the same way as a single CFD calculation (but without the corresponding modelling uncertainties). However, necessary long-term statistics for a complete UAV-based site assessment can only be realised by a fully autonomous operation, which is not only a technical issue, but also a legal issue in Europe and therefore a mid-term objective.

A short comment has been added to the paper (lines 329 ff).

"Line 201: If possible, it would be useful to indicate the elevation gain from the base of the hill to the peak, as this would give additional context in relation to the measurement plane height of 100m above ground level. It would also be valuable to supply the geographic co-ordinates of the test sites, and the source for the 3D terrain model if applicable. "

The elevation gain is roughly 200 m, the 3D model is based on open data from the county of North-Rhine Westphalia. Within the final paper, geographic coordinates and more of the surrounding landscape will be added for additional context.

More detailed information has been added, see Figure 9, Table 6 and line 212.

"Title of the manuscript could be improved to be more reflective of content, e.g. "Detecting wind speed deviations in complex terrain through airborne measurement" or similar. "

The authors agree. For the final paper, it shall be changed to "Method for airborne measurement of the spatial wind speed distribution above complex terrain".

The title has been updated accordingly.

"It would be useful to compare the UAV measurements against CFD and LIDAR studies of the same site; this could possibly be suggested as an area of further work"

Depending on the LIDAR system, such study usually does not allow to gain insight into the spatial distribution of wind speeds. This specific problem shall be addressed by the UAV based measurement approach. A CFD study nevertheless would be a suitable method for a more in-depth validation of the airborne measurement method, but is not yet in scope due to the status of the project. This shall be addressed in future publications.

This has been mentioned in line 323.

<u>Figures and tables</u>

Figure titles will be combined, and the location of the ultrasonic anemometer will be added to Fig. 19.

The position was added in Figure 9.

<u>Typos and spelling/grammar</u>

We want to thank Anonymous Referee #2 for his/her suggestions and take them into account for the final paper.

The suggestions have been taken into account.

Method for airborne measurement of the spatial wind speed distribution above~~Wind speed deviations in~~ complex terrain

Christian Ingenhorst[1/3], Georg Jacobs[1], Laura Stößel[2], Ralf Schelenz[2], Björn Juretzki[3]

[1] Institute for Machine~~Maschine~~ Elements and Systems Engineering, Aachen, 52062, Germany
[2] Center for Wind Power Drives, RWTH Aachen, Aachen, 52074, Germany
[3] IME Aachen GmbH Institut für Maschinenelemente und Maschinengestaltung, Aachen, 52074, Germany

Correspondence to: Christian Ingenhorst (christian.ingenhorst@imse.rwth-aachen.de)

Abstract. Wind farm sites within complex terrain are subject to local wind phenomena, which have a relevant~~huge~~ impact on a wind turbine's annual energy production. To reduce investment risk, an extensive site evaluation is therefore mandatory. Stationary long-term measurements are supplemented by CFD simulations, which are a commonly used tool to analyse and understand the three-dimensional wind flow~~flows~~ above complex terrain. Though being under intensive~~heavy~~ research, such simulations still show a high~~huge~~ sensitivity for various input parameters like terrain, atmosphere and numerical setup. In~~Within~~ this paper, a different approach aims to *measure* instead of simulate wind speed deviations above complex terrain by using a flexible, airborne measurement system. An unmanned aerial vehicle is equipped with a standard ultrasonic anemometer. The uncertainty of the system is evaluated against stationary anemometer data at different heights and shows very good agreement, especially in mean wind speed (<0.12 ms^{-1}) and mean direction (< 2.4 °) estimation. A test measurement was conducted above a forested and hilly site to analyse the spatial and temporal variability of the wind situation. A position dependent difference in wind speed increase up to 30 % compared to a stationary anemometer is detected.

1 Introduction

Complex and mountainous terrain gains importance for wind farm development due to land use conflicts and a high wind potential by speed-up effects at escarpments and steep ridges. Nevertheless, such orographic features as well as obstacles, roughness differences and jet/tunnel effects result in a complex wind field. On these sites,~~, increase~~ the risk of annual energy production (AEP) overestimation is increased ~~as it was pointed out by~~ (Lange et al., 2017). Within a wind farm in complex terrain, that was analysed by (Ayala et al., 2017), the AEP of single wind turbines varied up to 25 %, although wake effects seem ~~to be~~ neglectable when taking into account the park layout and prevailing wind directions.

An increasing demand of renewable energy and high investment risks in case of a false AEP prognosis make wind flows in complex terrain an intensively investigated research topic, concerning both measurement and simulation. Computational Fluid Dynamics (CFD) simulations are a common tool to investigate the spatially distributed wind speeds above complex terrain and is widely used in site assessment and research.~~.~~ Although huge advances in computational power allow even more detailed flow simulations in recent years, CFD simulations still show great sensitivity for assumptions and simplifications such as terrain details and surface roughness (Jancewicz and Szymanowski, 2017; Lange et al., 2017), atmospheric stability (Koblitz et al., 2014), turbulence models (Tabas et al., 2019) in addition to ~~aside of~~ various numerical parameters. Remaining uncertainties and long computation times make extensive measurements for sites in complex terrain mandatory for a bankable site assessment ~~. This is also taken into account by various guidelines~~ (International Electrotechnical Commision, 2009; Measnet, 2016; Fördergesellschaft Windenergie und andere Dezentrale Energien, 2017).

Nevertheless, guideline-compliant measurement equipment such as met masts and light detection and ranging (LIDAR) systems~~LIDARs~~ are operated stationary with a focus on a maximum statistical coverage. Such systems are not applicable to investigate the spatial deviation of wind speeds within a certain area. State ~~A state~~ of-the-art ~~measurement approach is the combination of several scanning LIDARs~~ to measure three-dimensional~~a 3D~~ wind fields above complex~~field. Such systems were successfully used to detect and analyse wind phenomena in several experiments, from wind tunnel~~ (van Dooren et al., 2017)~~ to full scale experiments~~ (Pauscher et al., 2016; Vasiljević et al., 2017)~~. However, scanning LIDARs are rather costly and have a reasonable installation effort, especially in steep and forested~~ terrain are multiple doppler LIDAR configurations. Depending on the number of LIDARs, wind speeds in one, two or three directions can be measured remotely, even at a distance~~when line~~ of kilometres.~~sight matters.~~ This successfully has been performed in various field studies in complex terrain. For example in Kassel, Germany , triple doppler LIDAR measurements showed good agreement concerning wind speeds in comparison to a sonic anemometer. At Perdigão, scanning LIDARs successfully measured wind speed distributions between a double ridge . Nevertheless, these measurement ~~topic gets even more important, when the planned measurement campaign requires careful positioning of the single LIDAR~~ systems do have some limitations: as Stawiarski points out, the measurement error of a LIDAR depends, amongst other things, on the angle of the intersecting beams. This can lead to ~~to avoid increasing measurement~~ errors "[…] on the order of 0.3 to 0.4 ms^{-1}" . Additionally, multi LIDAR systems do have a significant acquisition cost and take a considerable effort to get erected and operated in steep terrain. Additionally, turbulence intensities measured by multi LIDAR systems still are a topic of ongoing research(Stawiarski et al., 2013).

A ~~Within this paper, a~~ different approach to measure meteorological variables at specific positions~~towards a *measured* 3D wind field~~ is the usage of an ~~presented, based on a measurement strategy with a multi-rotor~~ unmanned aerial vehicles~~vehicle~~ (UAV~~) equipped with an ultrasonic anemometer (USA~~). Autonomous UAVs, especially fixed-wing systems with pitot-typed~~based~~ wind sensors, have been used for atmospheric research for~~since the last~~ 20 years (Holland et al., 2001; Spiess et al., 2007; Reuder et al., 2009). In recent years, a ~~opposite to~~ fixed-wings system with a 5-hole-probe has been developed to analyse wind speed, inclination angle and turbulence intensity at an escarpment within the swabian alps . In , a measurement of a fixed wing system was compared to CFD simulations at the WINSENT test site. Both systems showed plausible results, although the ~~-wing UAVs, which have a minimum~~ necessary minimum flight speed of fixed wing systems in general only allows short time measurements for a specific position. Additionally, measurement values also were averaged for a certain flight distance, resulting in an increased probe volume size of several meters. Although both studies aimed to investigate the spatial distribution of wind speeds, temporal changes of the overall wind situation during a single measurement campaign have not been taken into account.

Contrary to fixed wing systems, rotary-~~-~~wing aircrafts can hold their position mid-air for several minutes. This has three major benefits: first of all, it allows an easier system validation by just performing hovering flights close to a stationary sensor. This was for example done by and , ~~of measurement. Such systems~~ already showing~~showed~~ promising results. A further overview is given by , comparing the root mean square error (RMSE) of wind speed and direction measurements of several UAV sensor combinations in literature. So far, turbulence intensity measurements have not been compared ~~for single wind measurements in~~ (Bergmann et al., 2017; Palomaki et al., 2017; Vasiljević et al., 2019)~~, but have not~~ yet. The second benefit is, that a stationary, airborne measurement also allows a reduction of stochastic measurement errors by calculating averaged values for wind speed and direction. Furthermore, rotary-wing UAVs offer greater flexibility concerning their measurement strategy. An exact number, position and duration of measurement points can be chosen. A safe operation at low flight levels is also possible. ~~been used to investigate spatial deviations of wind speeds and directions above complex terrain.~~

Within our project called *WindLocator*, we have equipped~~The investigation described within this paper was performed with a commercial full-scale 3D USA mounted on~~ a multi-~~-~~rotor UAV with a 3D ultrasonic anemometer. In combination with a suitable~~. The~~ measurement strategy, we are aiming towards a cost-efficient~~system is highly portable~~ and accurately measured spatial distribution~~offers great flexibility, allowing USA measurements over any kind~~ of wind speed, direction, turbulence intensity and inclination angles. This, finally, would overcome several main limitations of CFD (remaining uncertainties), scanning LIDARs (costs) and fixed wing systems (probe volume size).~~terrain.~~ However, two main challenges have to be overcome within the project before establishing~~met to establish~~ airborne measurement systems~~measurements~~ as an alternative to common CFD simulations or LIDAR measurements for investigating complex flow fields:

1. The surrounding air (and its fluctuation) is ~~the~~ measured variable, ~~but at the same time~~ working medium and disturbance for the flying carrier system at the same time. Movements and rotations of the UAV as well as rotor induced flows have a significant impact on the measured wind speed, direction and turbulence intensity. Accuracy of a single measurement point has to be evaluated. In section 2 of this paper, we are going to present the achieved measurement accuracy of the WindLocator UAV, not only for wind speed and direction, but also for turbulence intensity. ~~Measurement accuracy therefore has to be validated and is discussed in Section 2 of this paper.~~
2. CFD Simulations offer the possibility to investigate the 3D wind field at each ~~calculation~~ point for every single time step. UAVs~~The UAV~~ instead measure~~measures~~ one point after another and, contrary to scanning LIDARs, take ~~takes~~ considerable time in doing so. The question arises what kind of measurement strategy~~The challenge~~ is suitable when it comes to merging individual measurement points into one single distribution of meteorological variables. In Section 3,~~to separate~~ the influence of diurnal~~measured~~ wind speed variation is investigated during two test campaigns above ~~deviations into spatial deviations (due to~~ complex terrain, utilizing a simple measurement strategy. Results of~~topography) on~~ the WindLocator are compared~~one hand and temporal deviations (due~~ to a ground-level anemometer to decide to what extent such system is suitable as a~~changes of the general wind situation) on the other hand. In Section 3 of this paper, a first approach including a stationary~~ reference. In the future, those findings combined with a simulation campaign will be used to find a robust measurement strategy ~~is evaluated and discussed~~.

2 Measurement System “WindLocator”

2.1 Design

The measurement system, which has been used for the measurement campaigns within this paper, has two main, independent components: a powerful carrier system and a sensor unit, which consists of a commercially available ultrasonic anemometer and a self-developed compensation and data acquisition unit.

The foldable, commercial carrier system is a battery powered octocopter with a flight time of 25 min~~mins~~ and a maximum take-off-weight of 12.5 kg. Including the sensor unit, the complete system only weighs 8.5 kg and therefore has a considerable performance reserve. Flights at turbulent air as well as during gust speeds of 25 ms^{-1} have successfully been tested. A real-time-kinematics (RTK) GPS is included to perform high accuracy positional navigation and speed estimation. The open source flight controller has been adapted for an easy setup of specific measurement strategies, which then are autonomously being followed. Although a completely unobserved operation is technically possible, European laws at this moment require an operator to be within sight.

Figure 1: Measurement system WindLocator (unfolded) without battery packs

Table 1 Specifications of carrier system

Dimensions	1060mm (diameter motor-motor), 1250mm (height)
Weight (incl. sensor unit)	8,5 kg

Maximum take-off weight	12 kg
Rotors	8 x 385mm carbon fibre reinforced polymer rotors
Battery	2 x 10.000 mAh
Flight Controller	Pixhawk Cube
Flight Times (incl. sensor unit)	~25 mins
Air speed	10 ms^{-1}

The Gill WindMaster 3D ultrasonic anemometer is placed on top of the compensation unit centred above the rotor plane. Mounting the sensor on top of the UAV has several advantages. First of all, the rotational symmetry of the system allows wind measurement independent from yaw angle and wind direction. Additionally, this setup results in a horizontally centred mass during hovering and therefore leads to relatively small moments to be compensated by the UAV. This improves flight performance and flight time. Aside of that, the downwash above the rotors is less turbulent than~~then~~ below.
The distance of the sensor's measurement volume to the rotor plane is 750 mm and is considered as a trade-off between manoeuvrability and reasonable interaction between wind sensor and propeller induced flows.

Table 2 Specifications of the ultrasonic anemometer

Type		Gill WindMaster 1590-PK-020
Wind Speed	Range	0-50 ms^{-1}
	Resolution	0.01 ms^{-1}
	Accuracy	< 0.18 ms^{-1}
Direction	Range	0-359°
	Resolution	0.1°
	Accuracy	2° @ 12 ms^{-1}
Measurement	Internal sample rate	20 Hz

Except for the power supply, the self-developed compensation and data acquisition unit is completely independent from the UAV. If requirements concerning the carrier system change, the compensation unit as a whole can be reapplied easily on a new aircraft. It weighs 420 gr and contains all necessary sensors as well as an additional RTK-GPS for an accurate position and speed estimation by means of sensor fusion. Based on analytical calculations and various synthetic experiments, a compensation algorithm was developed, that efficiently reduces measurement errors due to movements of the airborne system as well as its~~it's~~ rotors. Additional telemetry transmits measurement data such as wind speeds and directions live to a ground station for in situ analysis. The anemometer data is additionally saved to an internal storage at~~with~~ a rate of 10 Hz.

2.2 Validation of the system

All following calculations and measurements have been evaluated based on data~~,~~ that has been processed by the compensation unit. The system validation in general was conducted on several levels of detail, beginning with the Guide to the Expression of Uncertainty in Measurement (GUM) to evaluate the standard uncertainty of a single point of measurement ~~datum~~. The GUM allows the calculation of the standard uncertainty without the necessity of a true reference value. Error estimation is done by creating a mathematical model of the WindLocator, including relevant influences and their uncertainties and combining them into the system's standard uncertainty, which is +/- 0.37 ms^{-1} in our case.

After several synthetic tests with a fixated UAV to evaluate rotor influences (Figure 2), the WindLocator's compensation unit was tested during an indoor flight under~~at~~ zero-wind conditions (Figure 3).

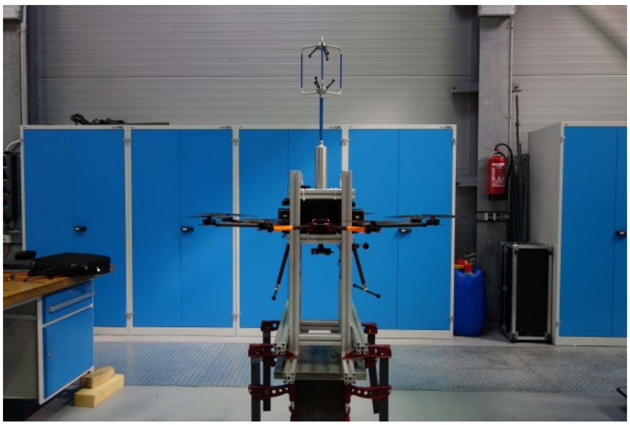


Figure 2 fixed UAV

Figure 3 Indoor flight at zero-wind conditions

Utilizing~~Because no stable GPS signal could be received during the indoor flight, the WindLocator was set to "Altitude Hold", which utilizes~~ the internal barometer ~~to maintain~~ an altitude of around 4 m was maintained during our test and ~~automatically stabilizes~~ pitch and roll axis for minimum horizontal movements were automatically stabilized. Nevertheless, small sensor inaccuracies made pilot interventions necessary to remain at sufficient distance to walls. After compensation, the wind data is given out in a global north-east-down coordinate system and is ~~therefore~~ independent from the specific orientation of the UAV.

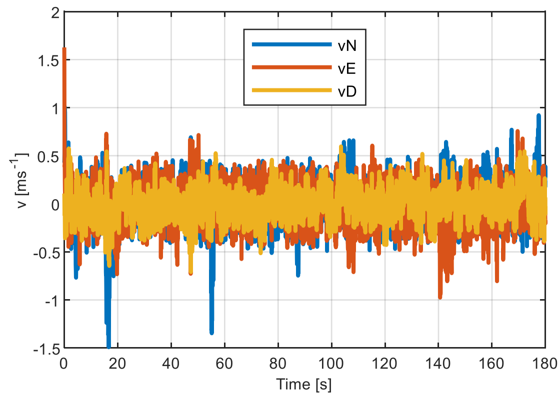


Figure 4 North-East-Down wind speed components of indoor flight at zero wind conditions

Figure 4 shows the data in all three measured directions at a resolution of 10 Hz. Peaks, e.g. in vN-direction at second 17 (- 1.5 ms^{-1}) and 55 (- 1.31 ms^{-1}) are a result of the UAV's horizontal translation due to operator intervention.

Table 3: Measured~~Results of measured~~ wind speed components during indoor flight

	Wind speed north (vN)	Wind speed east (vE)	Wind speed down (vD)
Mean value [ms^{-1}]	0.01	-0.02	0.00
Standard deviation [ms^{-1}]	0.23	0.21	0.16

As expected, mean wind speeds during the indoor flight are ~~very~~ close to zero. Standard deviations up to 0.23 ms^{-1} meet our expectations according to GUM, but clearly show the influence of manual operator control and of the sensor being rather close to the turbulent downwash induced by the rotors.

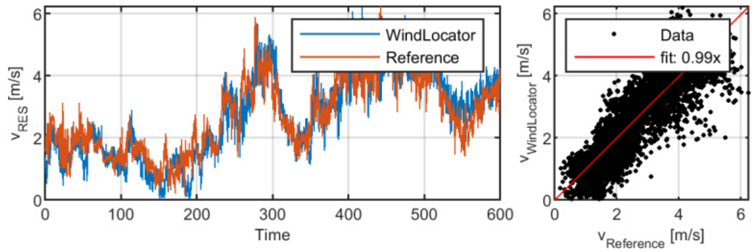
After proving~~showing~~ that under zero-wind conditions, mean values are in good agreement with our expectations, a measurement setup was created to compare the performance of the WindLocator with a stationary anemometer. In flat~~, agricultural~~ terrain 2 km west of Aachen (North Rhine-Westphalia~~Northrhine-Westfalia~~, Germany), a stationary anemometer of the same type as the UAV's anemometer was mounted at a height of 3 m above ground level (AGL).~~.~~ Data acquisition and storage for the stationary anemometer were realised at 10 Hz by a self-developed data acquisition system, which uses time stamps synced with an online~~internet~~ time server. The UAV time stamps are derived from GPS time signals. The UAV was set to hold position at a height of 3 m. A distance of 4 m to the stationary anemometer orthogonal~~rectangular~~ to the main wind direction was chosen to avoid interactions of the two measurement systems (Figure 5).

Figure 5 WindLocator hovering close to stationary anemometer

Four ten-minute measurements with ~6000 data points each have been conducted, with a short break to switch batteries after the second measurement point. Unlike~~In opposite to~~ the indoor tests, all three wind components are combined into a resulting~~single~~ wind speed v for every point of measurement~~ datum~~ to improve comparability to the stationary anemometer. However, the vertical component v_D in general has a minor impact on the resulting wind speeds.

$$v = \sqrt{v_N^2 + v_E^2 + v_D^2}$$

The following ~~diagrams (~~Figure 6~~-~~9diagram () shows exemplary~~) show~~ the compensated wind speeds of the WindLocator in comparison to the stationary reference as well as the corresponding regression plot.



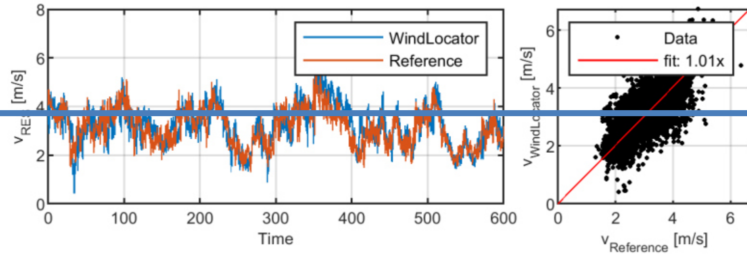
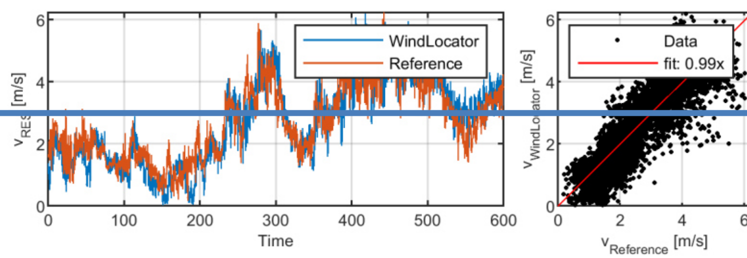
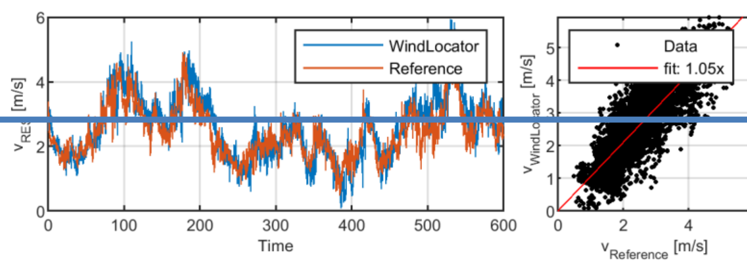


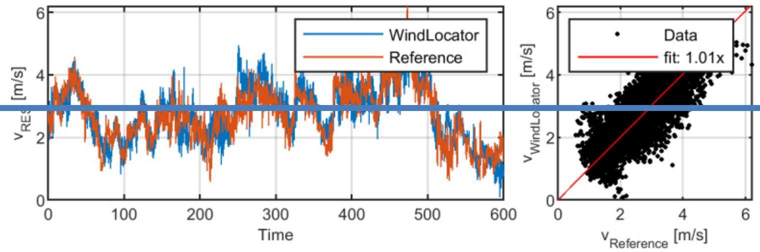
Figure 6: ~~resulting ground level wind speed and regression plot of measurement 1~~



~~Figure ~~7Resulting~~: resulting~~ ground level wind speed and regression plot of measurement 2



~~Figure ~~8~~: resulting ground level wind speed and regression plot of measurement 3~~



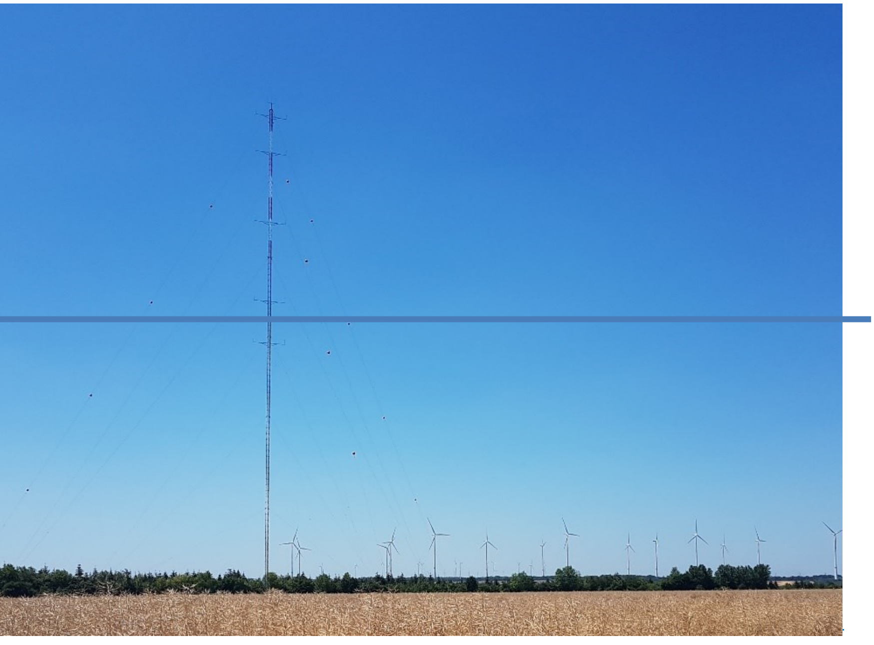
~~Figure~~ 9~~: resulting ground level wind speed and regression plot of measurement 4~~

For all measurement points (see Table 4), a very good agreement of the ten-minute-mean wind speed between WindLocator and reference has been achieved, especially when taking into account the turbulent wind situation during such a low-altitude flight. Turbulence intensities (TI) up to 44 % have been calculated for the stationary reference. Although there are absolute differences of +1 % (measurement 1) to +6 % (measurement 2 & ~~/~~4), the WindLocator already provides~~gives~~ a good estimation of the prevailing turbulence intensity.

Table 4 Comparison of measurement points on ground level

	Measurement 1	**Measurement 2**	**Measurement 3**	**Measurement 4**
Mean speed difference [ms^{-1}]	-0.07	-0.12	-0.06	0.02
TI Reference [%]	24,5%	32,2%	32,2%	44,3%
TI UAV [%]	25,1%	37,7%	32,8%	50,2%
R^2	0.53	0.69	0.63	0.78
Standard deviation [ms^{-1}]	0.58	0.55	0.58	0.64

An analysis of wind directions during this experiment was not yet possible, because an accurate orientation of the stationary measurement system could not be guaranteed. This is taken into account for the next experiment at a 134 m met mast under more realistic conditions ~~(~~10~~).~~



~~Figure~~ 10. ~~: 134 m met mast at Windtest Grevenbroich GmbH test site in Germany~~

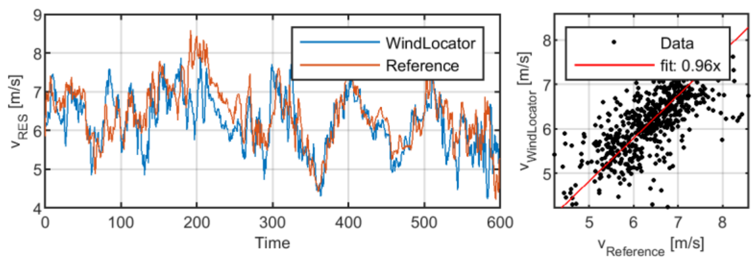
The measurement system was tested ~~on a sunny day~~ close to a met mast on a small plateau. Four measurements of 8-10 minutes have been conducted and are compared to the velocity data of a cup anemometer at 134 m and the directional data of a wind vane at 130 m above ground level. The WindLocator was held on~~flown to~~ a height of 134 m based on barometer and GPS data and was then moved closer towards the met mast using the onboard camera system. Because the flight was performed without autopilot, distances to the met mast and exact height vary throughout the measurements (see Table 5). Additionally, that table contains wind speed data analogue to Table 4 as well as information concerning the accuracy of wind direction estimations. For all following calculations, the WindLocator data was averaged to 1 Hz for better comparability to the met mast.

Table 5: Comparison of measurements on 134m

parameter	Measurement 1	Measurement 2	Measurement 3	Measurement 4
Distance to met mast [m]	26	24	17	16
measurement height [m_{agl}]	134	133	135	135
Mean speed difference [ms^{-1}]	-0.21	0.01	0.20	-0.06
TI Reference [%]	15.1	18.5	11.8	15.1
TI UAV [%]	13.4	17.2	12.3	15.2
R^2	0.28	0.49	0.44	0.80
Standard deviation [ms^{-1}]	0.88	0.88	0.63	0.47
mean angular difference [°]	1.2	-0.7	2.0	2.4

R^2	0.56	0.49	0.82	0.71
Standard deviation [°]	8.5	10.8	5.1	4.6

The results during the met mast experiment show a slightly different picture compared to the ground level measurements. The ~~Still comparable to the former test is the reasonable performance of the~~ turbulence intensity is still reasonably well estimated.~~estimation of the UAV.~~ Additionally, measurements 2 ~~(~~12~~)~~ and 4 ~~(~~14~~)~~ show a good correlation of the WindLocator with~~and~~ the corresponding~~corresponding~~ reference speed. However, mean wind speed deviations for the first and third measurement are not only higher than before, but also vary a lot more compared to the other measurements of that day. Significant~~Serious~~ deviations mainly occur during the first half of the measurements (Figure 11~~;~~-13)~~,) in a temporary manner,~~ e.g. seconds 180 to 270 for measurement 3.



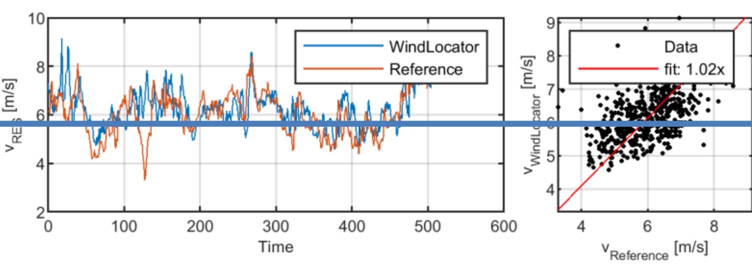
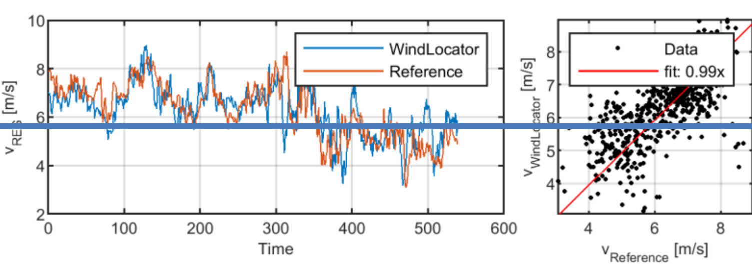
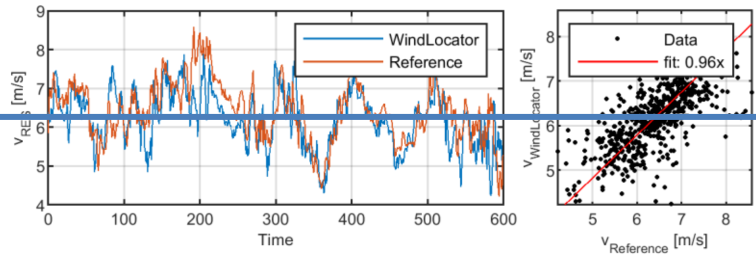


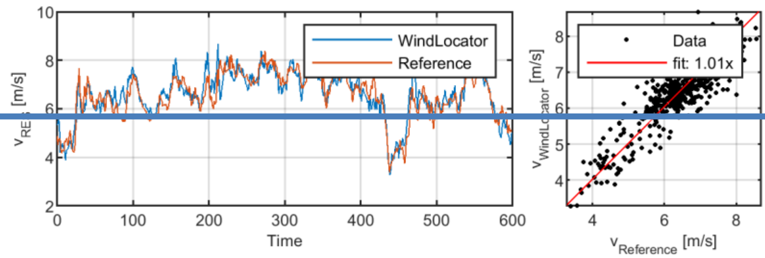
Figure 11~~: resulting wind speed at 134m and regression plot of measurement 1~~



~~Figure~~ 12~~: resulting wind speed at 134m and regression plot of measurement 2~~

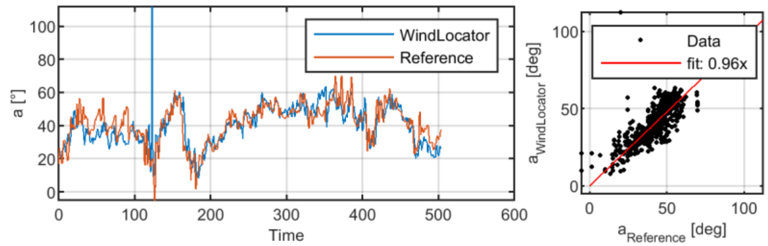


~~Figure~~ 13: Resulting~~: resulting~~ wind speed at 134m and regression plot of measurement 3



~~Figure~~ 14~~: resulting wind speed at 134m and regression plot of measurement 4~~

Those deviations are a result of the pilot still doing positional adjustments during the measurement point. Nevertheless, those adjustments seem not to have a critical impact on the UAV's wind direction estimation, which shows very good correlation through all measurement points with a maximum mean deviation between met mast and WindLocator of 2.4 °. As an example, absolute~~Absolute~~ wind direction~~directions~~ and its~~their~~ regression plot for measurement 3 is~~plots are~~ shown in Figure 15-18.



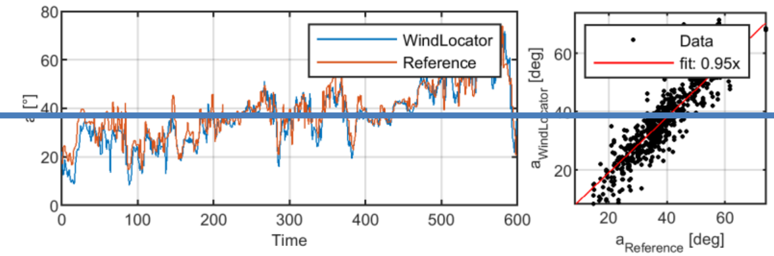
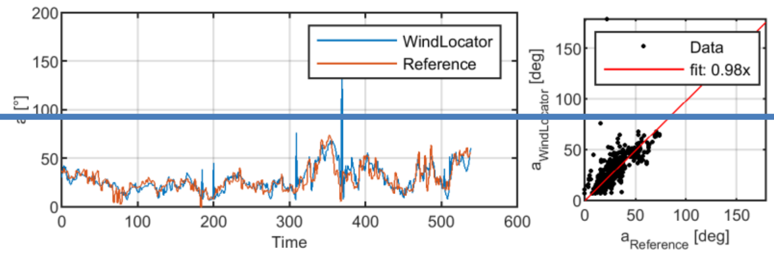
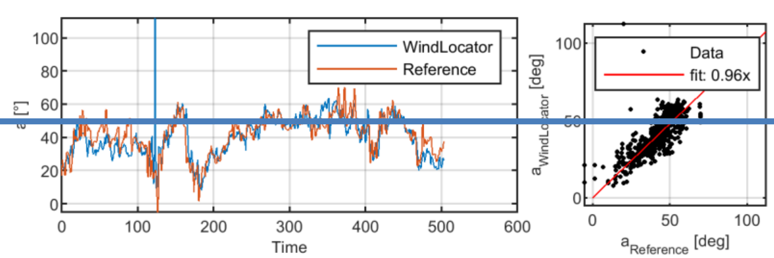


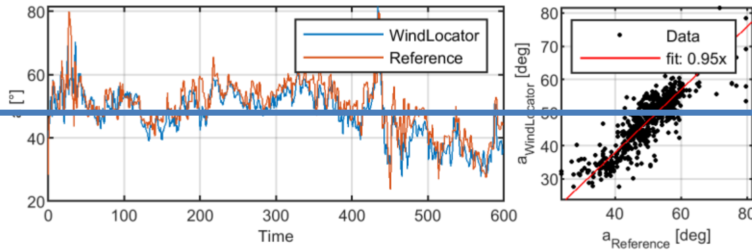
Figure 15~~: wind direction at 134m and regression plot of measurement 1~~



~~Figure~~ 16~~: wind direction at 134m and regression plot of measurement 2~~



~~Figure~~ 17: Wind~~: wind~~ direction at 134m and regression plot of measurement 3



~~Figure~~ **18**The~~: wind direction at 134m and regression plot of measurement 4~~

~~Despite its challenging but beneficial design with the anemometer mounted above the rotor plane, the~~ WindLocator performed very well throughout the tests, especially concerning the calculation of averaged measurement quantities like speed and direction. When the system uses its GPS based hover mode without interference~~"disturbance"~~ by a pilot, mean wind speed differences compared to a reference were below 0.12 ms^{-1} and wind direction differences smaller than 2.4 °. The maximum absolute difference in turbulence intensity was 5.9 % for a high turbulence intensity measurement. Although more measurement points are necessary to finally evaluate the system's performance, initial results in comparison to scanning LIDAR errors seem promising. It also has to be taken into account that~~Because~~ the airborne measurement system and a reference cannot measure at the exact same place at the exact same time. Remaining~~, remaining~~ uncertainties always~~ also~~ might be a result of spatial deviations in the wind situation, which will be discussed in more detail in the following section.

3 campaign**Test site description**~~and measurement setup~~

The test site~~aim of the campaign is to investigate mean wind speed deviations above complex terrain by using the WindLocator. The area~~ for this measurement strategy~~campaign~~ is a small hill in the south of North-Rhine~~Northrhine~~-Westphalia in the German~~german~~ Eifel and was chosen for the following reasons:

- With a yearly mean wind speed of 6.5-7 ms^{-1} at 100 m above ground level, the area has rather high wind speeds compared to the rest of the county. Main wind direction is southwest.
- The terrain is considered to be complex~~ (~~Figure 19.~~).~~ The slope around the hill at most parts is greater than 40 degrees. Forests extend to the south and west of the hill. A small village is located to the northeast, see .~~.~~
- The region in general is easily accessible and was considered ~~to be~~ suitable for wind turbines~~ and has a good accessibility~~.

All diagram coordinates within this chapter are referenced to the UTM coordinate 32U 308450 5604720.

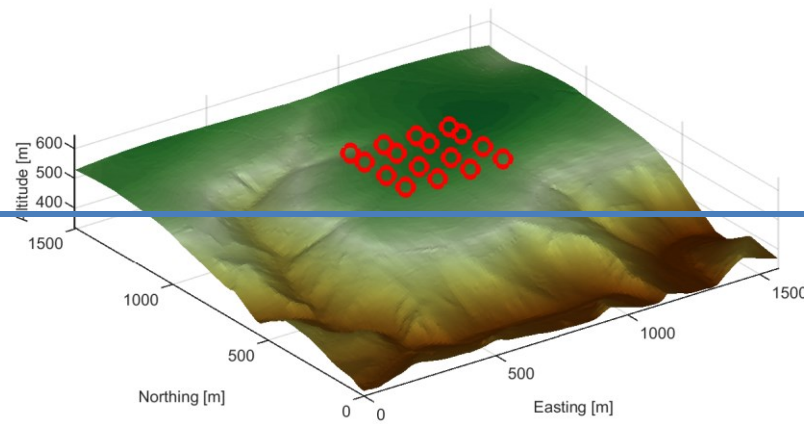


Figure 19: Test ~~terrain model of the test~~ **area** (▭) **and** stationary **measurement** location (X) (Source: Geobasis NRW~~points (red~~)

~~To reduce experimental complexity, wind speed deviations within a two-dimensional plane above the described complex landscape are going to be investigated. The plane to be surveyed is roughly 500 m x 500 m and placed on the middle of the hill with equal distance to the edges in the south and west. All planned measurement points, which are displayed as red circles in~~ Figure 19~~, are at the same height above sea level and around 100 m above the lift-off point. Additional information is summarized in~~ 6~~.~~

~~**Table**~~ **6**~~**: Summary of the measured plane**~~

Number of points	16 (4 x 4)

Distance between points	~ 120 m
Measurement time per point	5 mins
Measurement rate	10 Hz
Measurement points per battery charge	4

Within this paper, two different measurement campaigns are presented. While the mean wind speeds are within a similar range, wind directions differ resulting in different inflow conditions into the measuring area.

3.2 Measurement strategy and evaluation methodology

The presented campaign aims to investigate the feasibility of using a simple measurement strategy for the identification of the spatial distributions of meteorological variables (wind speed, turbulence intensity, inclination) above complex terrain. This information will be used in the further course of the project for the development of the final measurement strategy.

The measurement strategy can be described as follows:

- ~~workflow begins with the activation of the WindLocator's autopilot.~~ The WindLocator~~system then~~ automatically flies to one measuring~~the first, predefined measurement~~ point after another and measures at each~~holds~~ position for a specified duration.

This duration is chosen as five minutes in~~before heading for~~ the framework of~~next point. For~~ this feasibility study, which is~~five minutes were~~ considered to be a reasonable trade-off between limited battery time and statistical coverage for each point. ~~After four measurement points, the UAV automatically returns to its lift-off position for a battery change. Afterwards, the measurement process continues with the next point. During post-processing, measurement points are automatically detected within the data for further analysis.~~

- To reduce experimental complexity, measurement points are located within a two-dimensional plane. The surveyed plane is roughly 400 m x 400 m and placed on the middle of the test area. All planned measurement points are at the same height above sea level and around 100 m above the lift-off point, see .
- At each measurement point, relevant variables like averaged wind speed and direction, turbulence intensity and inclination angle are measured and saved together with the position and a timestamp derived from the GPS.

Additionally, a ground-level (3 m) anemometer measures wind speed and direction throughout the whole campaign. This ~~Aside of the WindLocator, an additional stationary~~ ultrasonic anemometer is placed~~was in use during the campaign. It was placed at a height of 3 m~~ on free grassland surrounded by sparse hedges and captures three-dimensional wind~~, nearly centred under the measurement plane and also acquires~~ data at 10~~-~~Hz.

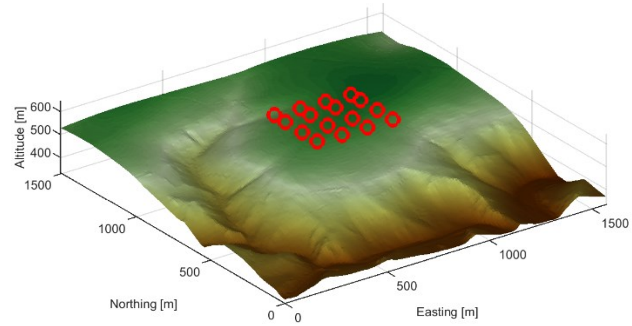


Figure : terrain and measurement points (data source: Geobasis NRW)

The feasibility study within this paper addresses two basic questions on the postprocessing of the gathered measurement data. In the first step it will be discussed whether the temporal change of the wind speed during the measurement campaign has to be taken into account for the further investigation of the spatial distribution of the meteorological variables. A necessary condition for a constant spatial distribution is a constant wind direction, which will be verified in the beginning. Variations of averaged wind speeds at the stationary reference are used to estimate the impact of temporal variations within the airborne measurements in comparison to expected spatial variations. The result of this analysis is also valid for turbulence intensity, as it depends on the wind speed. Additionally, the spatial distribution of turbulence intensities is checked for plausibility. The influence of temporal changes on inclination angles is checked in a qualitative manner by comparing them to the terrain.
Assuming that the temporal change of the wind speed has a significant effect on the measurement, in a second step it will be investigated whether the ground-level (3 m) anemometer can be used as a reference to compensate temporal changes of the respective variables. Therefore, the ground-level anemometer needs to represent the overall wind situation. This is evaluated using the correlation between ground and airborne measurement data, assuming a linear dependency between those measurements. If correlation is confirmed, wind speed measurements of the WindLocator shall be used to calculate a local speed-up factor in comparison to ground-level wind speed. This distribution then is checked for plausibility.

~~3.2~~3.3 Results and discussion

Figure 20 gives an overview of the measured resulting wind speeds v from the moving WindLocator and the stationary reference on ground, exemplarily shown for M1.~~.~~ After the data acquisition was started, the UAV heads to~~for~~ the first measurement point, where it is holding position for five minutes 100 m above the start level~~ground~~, before moving on to~~heading for~~ the next waypoint at the same height. A measured wind speed deviation between WindLocator and reference is expected because of the differences in height and horizontal position of both systems. During the battery swap after four measurement positions, ~~obviously~~ no WindLocator data is available. The stationary reference instead measures non-stop.

Measuring 16 points of five minutes, yielding~~making it~~ 80 minutes of usable measurement data, has taken around two hours in total.

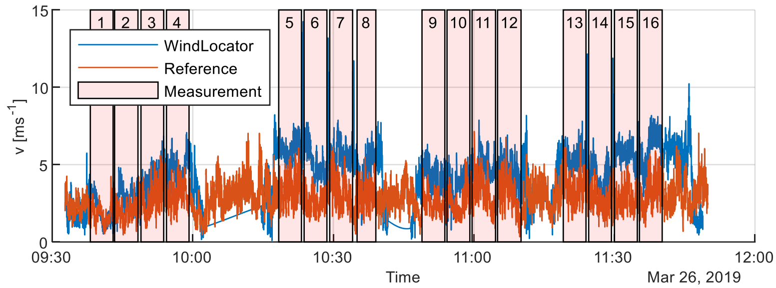


Figure 20: Comparison of resulting wind speeds from WindLocator (compensated) and Reference at 10Hz for M1

represents all measurement points for both campaigns, showing the results of the single points measured one after another. During both measurements, wind directions are in good agreement with the mean wind direction. With mean absolute deviations of 9.9 ° (M1) and 11 ° (M2), no significant changes in wind direction during the measurement time of 2 hrs each are found. This validates our assumption, that the distributed wind field will not be influenced by a change in wind direction.

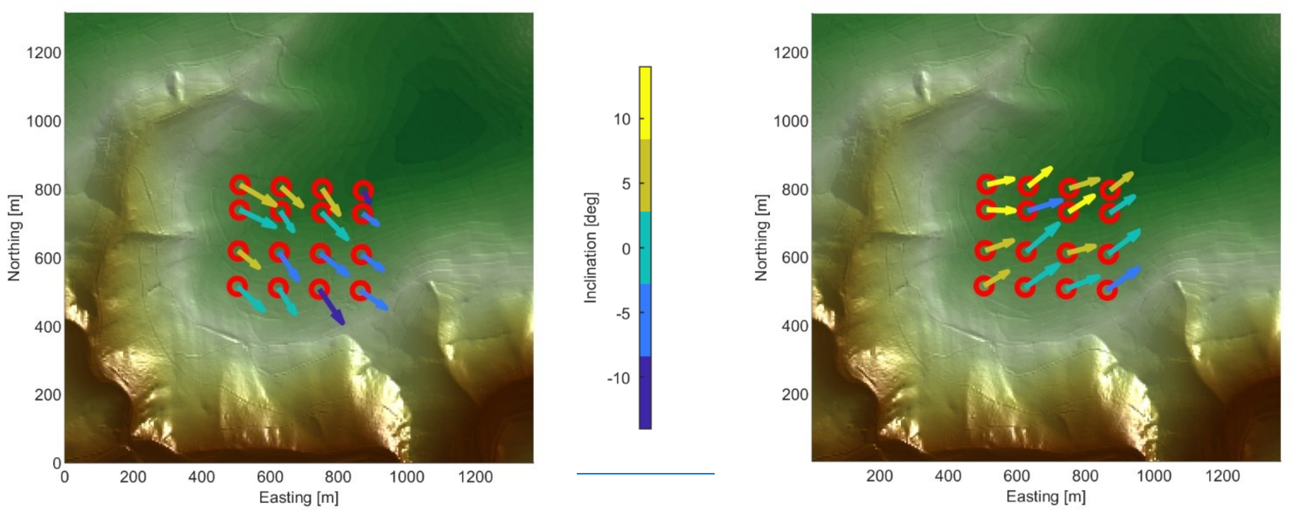


Figure 21 measurement points, wind vector and inclination angle of M1 (left) and M2 (right)

shows the averaged wind speeds for one after another measurement point for WindLocator and ground station. Over all UAV measurement points, an absolute variation of mean wind speeds between 2 and 6 ms^{-1} has been detected (22). As ~~it was already~~ implied earlier, these variations are considered to be too high for~~in the introduction, this obviously is not only a result of~~ spatial deviations due to complex terrain only, especially when taking into account the measurement height of around 100 m. These fluctuations~~, but~~ also are a consequence of wind variation over time.

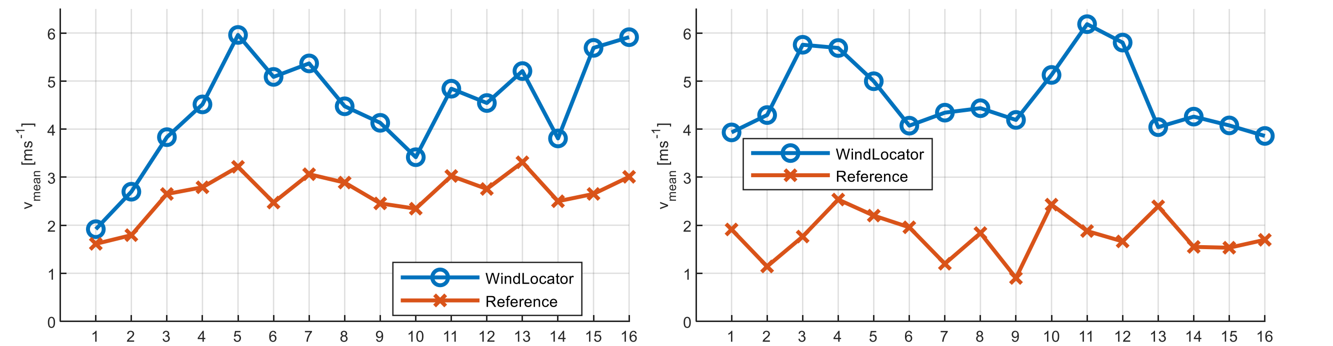
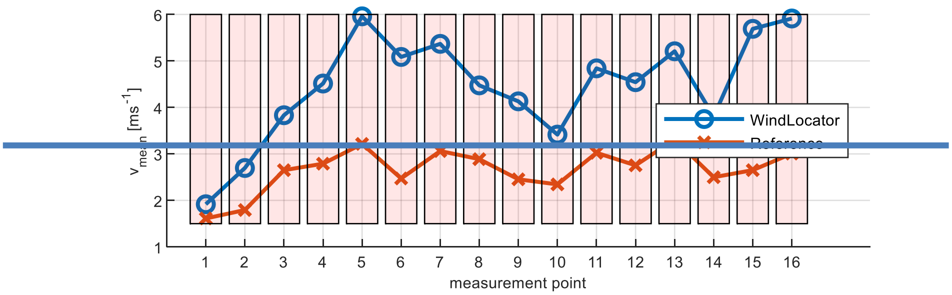


Figure Mean wind speeds of WindLocator and ground station for M1 (left) and M2 (right)

Otherwise, the stationary reference (assuming it to be an indicator for the overall wind situation) would not have shown any significant differences in wind speed over time.



~~Figure~~ 22~~: absolute mean wind speeds of WindLocator and reference~~

This is clearly not the case, especially when looking at the normalised reference wind speed, calculated by dividing the mean wind speed value of each point by the maximum mean value of all points of that measurement ~~points~~ (). Normalised variations of the stationary reference and the WindLocator data are in a comparable order of magnitude (-70 % compared to the maximum wind speed). Because those are comparable and even higher than expected spatial variations Figure 24 up to 30%, temporal variations clearly have to be compensated for a successful measurement.

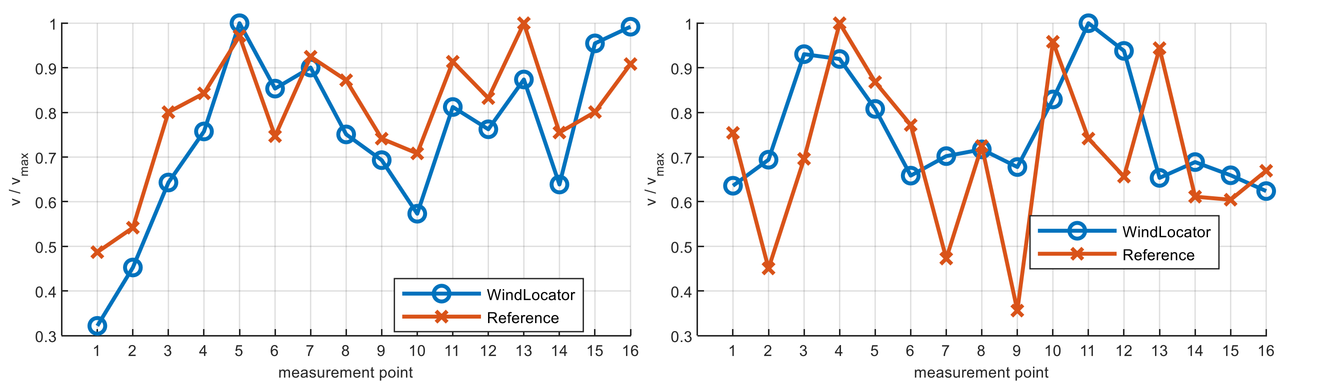


Figure : normalised wind speeds for M1 (left) and M2 (right)

shows turbulence intensities measured at each single point. The mean turbulence intensity over all measurement points of M2 is 18% and therefore slightly higher than during M1 with 15%. This seems plausible due to the forested and steep escarpment in upwind direction for M2. However, single turbulence intensities within the measured field seem to vary rather strongly (between 10% and 30%) and without obvious influences by terrain and surface. As the normal turbulence model of IEC61400 predicts, turbulence intensity depends significantly on mean wind speed. Very low average speeds of only 2-3 ms^{-1} (see left, Measurement points one and two) might be an explanation for unexpected high turbulence intensity in the north east of M1, for example. Consequently, temporal changes in wind speed have to be taken into account when measuring turbulence intensity distributions.

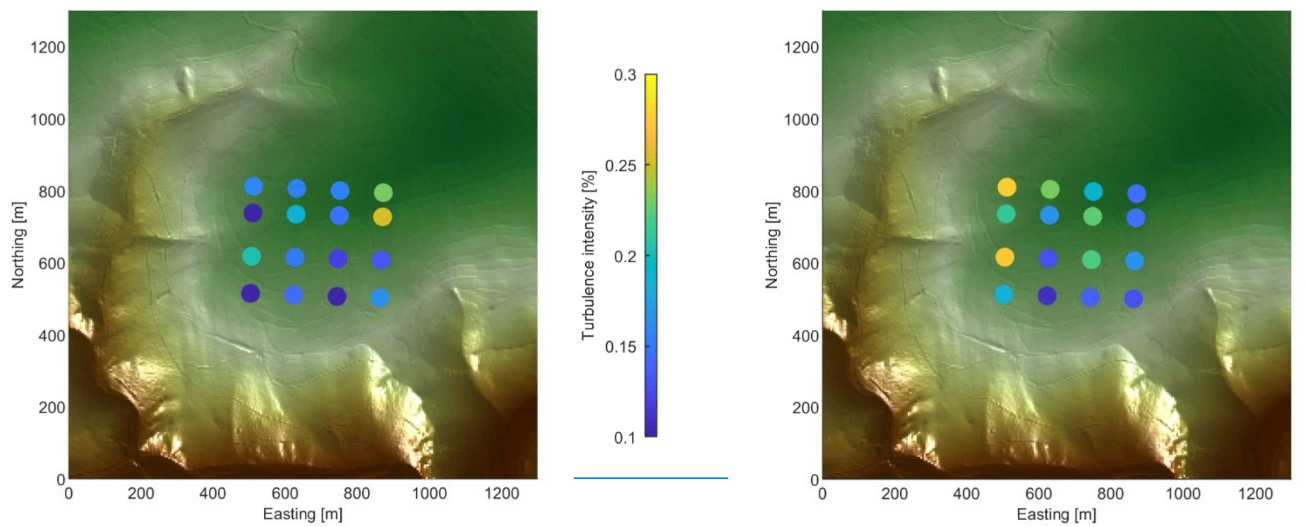
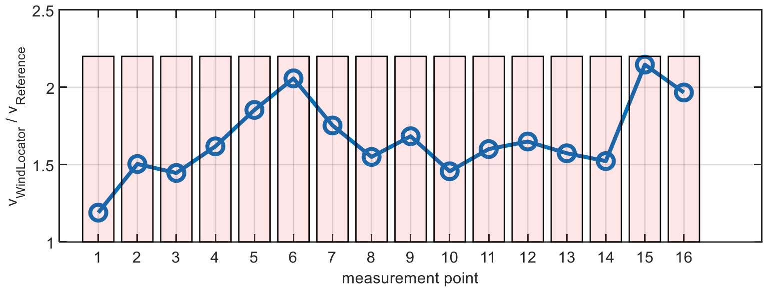


Figure 23 Turbulence intensities of M1 (left) and M2(right)

Although wind speeds vary significantly over time, inclination angles do show plausible results (). The flow, and therefore the inclination angles, follow the terrain pretty well for M1, varying mostly between +5 ° at the luv side of the hill, switching their sign at the ridge and having -5 ° at the lee side, with a peak of -9 ° at the south close to the escarpment. For M2 on the other side, nearly all angles are above 0, especially in the north with several measured inclination angles higher than 8 °, even up to 12.7 °. Positive inclination angles are considered to be a plausible result from winds passing the steep escarpment in the south west. Temporal variations of wind speed seem to have a minor impact on inclination angle measurements.

All in all, temporal wind speed variations do have a significant impact while measuring a wind speed distribution and therefore have to be compensated. A simple approach would be calculating a wind speed-up value compared to a representative stationary reference. Although the stationary reference in this experiment is only 3 m high, a~~). The~~ strong correlation (R=0.86) between relative mean speeds of WindLocator and reference data for M1 is observable, in opposite to M2 (R=0.32). We assume this to be~~is~~ an indicator, that the ground level stationary anemometer for the~~this~~ particular campaign M1 is a suitable reference to also track temporal changes of the overall wind situation. The remaining differences between WindLocator and reference tend to be local wind speed deviations, e.g. due to terrain. shows the speed-up value over time.



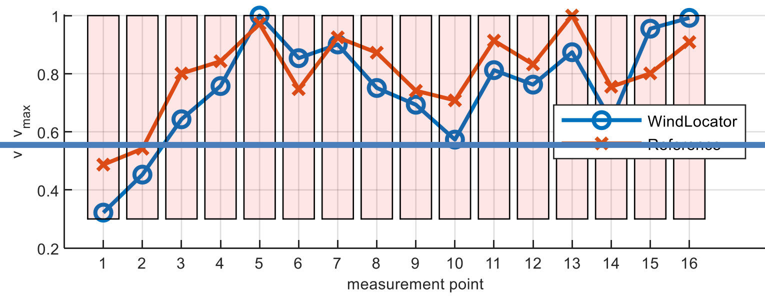
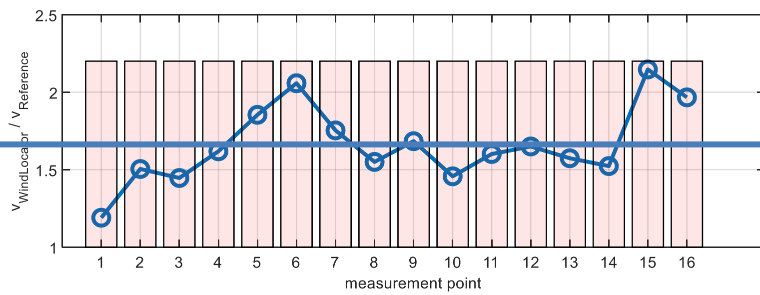


Figure 24~~: normalized mean wind speeds of WindLocator and reference~~

~~Taking this into account, a very simple measurement strategy seems suitable as a first approach: the time offset between single UAV measurement points can be compensated by referencing them to the stationary anemometer data. The result is a measured wind speed increase compared to the reference and is summarized in~~ 7~~.~~



~~Figure~~ 25: wind speed increase from reference to WindLocator for M1

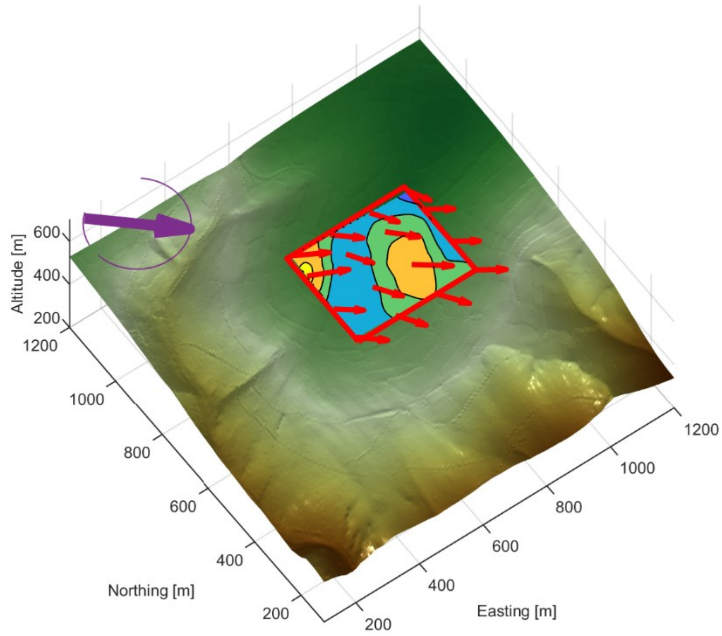
~~Table~~ 7 ~~wind speed increase compared to reference~~

Mean	1.66
Maximum	2.15 (+30% compared to mean value)

Minimum	1.19 (-28% compared to mean value)
Standard deviation	0.25 (15% of mean value)

~~This measurement strategy, nevertheless, depends on various parameters concerning the stationary reference, its positioning and expected spatial variations and therefore cannot be considered to be valid in general. Advanced measurement strategies and criteria are currently under development.~~

370 Figure 26 combines the measured results on the one hand and the UAV's GPS data on the other hand to a spatial distribution. The purple arrow indicates the mean wind direction. Each red arrow represents a measurement point, showing the measured horizontal wind direction and indicating with its length the wind speed increase compared to the stationary reference. The~~For a better insight, the~~ wind speed increase then is interpolated linearly between measurement points to create a contour plot. The background shows the digital terrain model data.


Altitude [m]
600
400
200
1200
1000
800
600
400
200
Northing [m]
200
400
600
800
1000
1200
Easting [m]

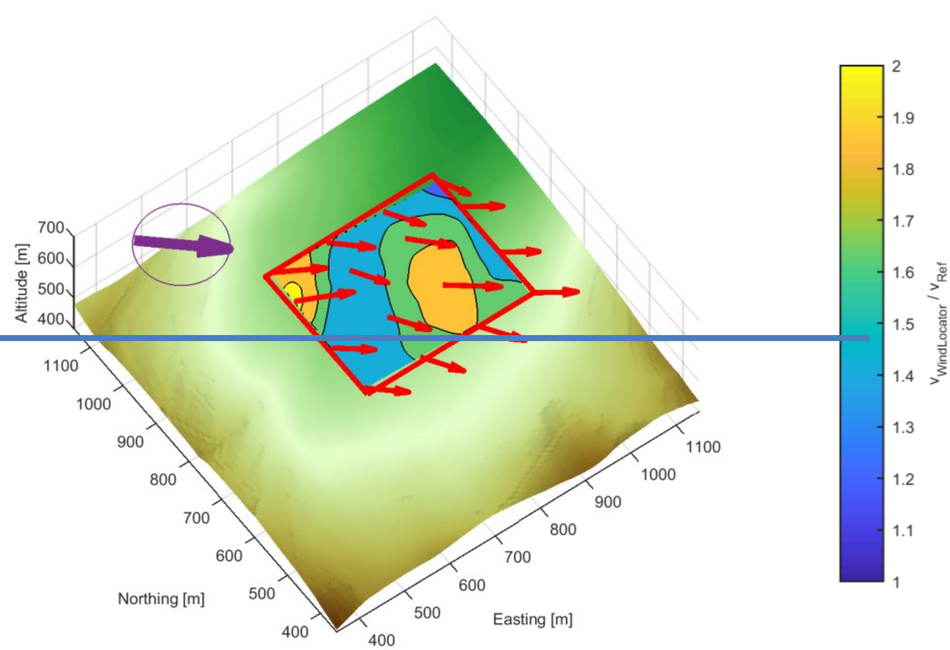

Altitude [m]
700
600
500
400
1100
1000
900
800
700
600
500
400
Northing [m]
400
500
600
700
800
900
1000
1100
Easting [m]
2
1.9
1.8
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1
v_WindLocator / v_Ref

Figure 26 measured mean wind speed distribution above complex terrain

The calculated speed-up factor of around two seems plausible, when assuming a logarithmic wind profile with a roughness length of 0.2 m. A variation of the speed-up factor of +30 %/-28 % compared to the mean value is calculated. The highest increase in wind speed compared to the stationary anemometer is located towards the ridge at the upwind side, which meets our expectations concerning ~~of~~ a speed-up effect at a steep hill. Nevertheless, directly over the highest point, where inclination angles are close to zero~~The following area of lower wind speeds might then be a result of flow separation. Downwind of the hill, towards the southeast ridge~~, an unexpected decrease of wind speed-up is detected, followed by an~~additional~~ area of higher wind speeds at negative inclination angles.~~is located.~~ Towards the plateau in northeast direction, we do see an expected decrease of wind speeds. The results clearly show, that temporal effects must be considered when dealing with turbulence intensities or averaged wind speeds in general. The simple measurement strategy with a representative ground-level anemometer can be regarded as a proof-of-concept, leading to an improved estimation of spatial wind deviations for M1 when comparing it to unreferenced data. The wind speed variations are rather high, but comparable to other campaigns in complex terrain . A plausible explanation for a decrease in wind speed directly on top of the ridge~~lowest wind speed increase~~ has not yet been found. For the future, a CFD validation shall give insight, whether these effects are a result of measurement errors.~~measured.~~

As seen for M2, the presented measurement strategy obviously depends strongly on the stationary reference, its positioning and expected spatial variations and therefore cannot be considered to be valid in general. A change in wind direction from 310 °(M1) to 240 ° (M2) leads to even lower, less correlated changes in ground level wind speeds with increased turbulence intensity, presumably as a consequence of surrounding obstacles like hedges. A more robust measurement strategy would probably make use of a more representative stationary reference in greater height.

These findings are currently being evaluated with a simulative approach to find more robust measurement strategies, independent from terrain, location, surface and prevailing wind situation. Once this has been obtained, UAV based measurements can be used in a similar way to CFD simulations for bankable site assessment.

4 Conclusion

Within this paper, a UAV-based measurement system called WindLocator, its validation and its experimental application above complex terrain were presented. The measurement system consists of an~~a powerful~~ octocopter, a commercial ultrasonic anemometer centred above the rotor plane and a self-developed compensation and data acquisition unit. The latter was the enabler to efficiently reduce wind measurement errors due to movements of the UAV and rotor influences. This has been shown in two test scenarios at different wind and turbulence conditions.

At both tests, very good agreement with reference data could be achieved. Mean wind speeds have been estimated with a maximum difference of 0.12 ms^{-1}, wind directions with a maximum difference of 2.4 ° during position-controlled hovering.

Though rotor influences are a challenge, turbulence intensity estimation was reasonably good. Nevertheless, the compensation unit is under continuous development to improve accuracy at all relevant flight situations.

The biggest advantage of an airborne measurement system is its flexibility, allowing accurate measurements at any arbitrary point in a wind field above any kind of landscape. This could make the WindLocator ~~to~~ a potential alternative for CFD simulations in complex terrain, delivering an analogue result for a specific weather situation without long computation times or modelling uncertainties. ~~To do so, temporal and spatial variations of wind speed have to separated.~~

During two measurements at a~~A~~ hilly and forested region in the German~~germen~~ Eifel, diurnal wind variations were found to be relevant for measuring ~~is investigated concerning its local~~ wind speed distributions and turbulence intensity. Plausible wind direction and inclination were measured even without taking into account temporal variations.~~deviations by using the WindLocator.~~ Although more advanced measurement strategies are currently under development, for one~~this~~ specific campaign~~case~~, a ~~very~~ simple strategy was sufficient to reduce the influence of diurnal wind speed variations~~due to a good time correlation between reference and UAV~~: while the WindLocator automatically was flying from point to point, a stationary reference at ground level was used to compensate the temporal wind speed variations~~time offset~~ between single measurement points. The result was a plane of four times four measurement points, including information of wind speed increase compared to the reference and three-dimensional wind directions. Spatial differences of approximately +/- 30% compared to a mean value have been found at plausible locations, underlining the necessity of intensive site evaluation in complex terrain. However, this approach significantly depends on how representative the stationary reference is and therefore cannot be considered valid in general.

Acknowledgements

We thank Windtest Grevenbroich Gmbh for providing validation data from a meteorological mast at their test site.

Competing interests

Christian Ingenhorst is PhD student at the Institute for Machine Elements and Machine Design (IMSE) and employee at the IME Aachen GmbH. This company is offering airborne wind measurements as a service.

Author contributions

Christian Ingenhorst: validation, measurements and analysis

Laura Stößel: measurement site and strategy

Georg Jacobs: supervision of Christian Ingenhorst and paper correction

Ralf Schelenz: supervision of Laura Stößel

Björn Juretzki: supervision of Christian Ingenhorst and paper correction

References

Ayala, M., Maldonado, J., Paccha, E., and Riba, C.: Wind Power Resource Assessment in Complex Terrain: Villonaco Case-study Using Computational Fluid Dynamics Analysis, Energy Procedia, 107, 41–48, https://doi.org/10.1016/j.egypro.2016.12.127, 2017.

Bergmann, D., Bischoff, O., Denzel, J., Cheng, P. W., Hofsäß, M., Lutz, T., Peters, B., and Schulz, C.: Entwicklung von Lidar-Technologien zur Erfassung von Windfeldstrukturen hinsichtlich der Optimierung der Windenergienutzung im bergigen, komplexen Gelände, Abschlussbericht des Forschungsprojektes ein Vorhaben des WINDFORS, Windenergie Forschungscluster Forschungsnetzwerks Projektpartner: Universität Stuttgart, Universität Tübingen, Karlsruher Institut für Technologie, Fördergesellschaft Windenergie, 2017.

Fördergesellschaft Windenergie und andere Dezentrale Energien: Technische Richtlinien für Windenergieanlagen, 10th ed., 2017.

Holland, G. J., Webster, P. J., Curry, J. A., Tyrell, G., Gauntlett, D., Brett, G., Becker, J., Hoag, R., and Vaglienti, W.: The Aerosonde Robotic Aircraft: A New Paradigm for Environmental Observations, Bull. Amer. Meteor. Soc., 82, 889–901, https://doi.org/10.1175/1520-0477(2001)082<0889:TARAAN>2.3.CO;2, 2001.

International Electrotechnical Commision: Windenergieanlagen: Teil 12: Messung des Leistungsverhaltens von Elektrizität erzeugenden Windturbinen basierend auf Gondelanemometrie, 2009.

Jancewicz, K. and Szymanowski, M.: The Relevance of Surface Roughness Data Qualities in Diagnostic Modeling of Wind Velocity in Complex Terrain: A Case Study from the Śnieżnik Massif (SW Poland), Pure Appl. Geophys., 174, 569–594, https://doi.org/10.1007/s00024-016-1297-9, 2017.

Koblitz, T., Bechmann, A., Berg, J., Sogachev, A., Sørensen, N., and Réthoré, P.-E.: Atmospheric stability and complex terrain: comparing measurements and CFD, Boundary-Layer Meteorol, 555, 12060, https://doi.org/10.1088/1742-6596/555/1/012060, 2014.

Lange, J., Mann, J., Berg, J., Parvu, D., Kilpatrick, R., Costache, A., Chowdhury, J., Siddiqui, K., and Hangan, H.: For wind turbines in complex terrain, the devil is in the detail, Environ. Res. Lett., 12, 94020, https://doi.org/10.1088/1748-9326/aa81db, 2017.

Measnet: Evaluation of site-specific wind conditions, 2016.

Palomaki, R. T., Rose, N. T., van den Bossche, M., Sherman, T. J., and Wekker, S. F. J. de: Wind Estimation in the Lower Atmosphere Using Multirotor Aircraft, J. Atmos. Oceanic Technol., 34, 1183–1191, https://doi.org/10.1175/JTECH-D-16-0177.1, 2017.

Pauscher, L., Vasiljevic, N., Callies, D., Lea, G., Mann, J., Klaas, T., Hieronimus, J., Gottschall, J., Schwesig, A., Kühn, M., and Courtney, M.: An Inter-Comparison Study of Multi- and DBS Lidar Measurements in Complex Terrain, Remote Sensing, 8, 782, https://doi.org/10.3390/rs8090782, 2016.

Reuder, J., Brisset, P., Jonassen, M. M., and Mayer, S.: The Small Unmanned Meteorological Observer SUMO: A new tool for atmospheric boundary layer research, metz, 18, 141–147, https://doi.org/10.1127/0941-2948/2009/0363, 2009.

Spiess, T., Bange, J., Buschmann, M., and Vörsmann, P.: First application of the meteorological Mini-UAV 'M2AV', metz, 16, 159–169, https://doi.org/10.1127/0941-2948/2007/0195, 2007.

Stawiarski, C., Träumner, K., Knigge, C., and Calhoun, R.: Scopes and Challenges of Dual-Doppler Lidar Wind Measurements—An Error Analysis, J. Atmos. Oceanic Technol., 30, 2044–2062, https://doi.org/10.1175/JTECH-D-12-00244.1, 2013.

Tabas, D., Fang, J., and Porté-Agel, F.: Wind Energy Prediction in Highly Complex Terrain by Computational Fluid Dynamics, Energies, 12, 1311, https://doi.org/10.3390/en12071311, 2019.

van Dooren, M. F., Campagnolo, F., Sjöholm, M., Angelou, N., Mikkelsen, T., and Kühn, M.: Demonstration and uncertainty analysis of synchronised scanning lidar measurements of 2-D velocity fields in a boundary-layer wind tunnel, Wind Energy Science, 2, 329–341, https://doi.org/10.5194/wes-2-329-2017, available at: https://www.wind-energ-sci.net/2/329/2017/wes-2-329-2017.pdf, 2017.

Vasiljević, N., Harris, M., Tegtmeier Pedersen, A., Rolighed Thorsen, G., Pitter, M., Harris, J., Bajpai, K., and Courtney, M.: Wind sensing with drone mounted wind lidars: proof of concept, 2019.

Vasiljević, N., L. M. Palma, J. M., Angelou, N., Carlos Matos, J., Menke, R., Lea, G., Mann, J., Courtney, M., Frölen Ribeiro, L., and M. G. C. Gomes, V. M.: Perdigão 2015: methodology for atmospheric multi-Doppler lidar experiments, Atmos. Meas. Tech., 10, 3463–3483, https://doi.org/10.5194/amt-10-3463-2017, 2017.