Interactive comment on “Towards accurate and practical drone-based wind measurements with an ultrasonic anemometer” by William Thielicke et al.
Anonymous Referee #1, Received and published: 21 November 2020

Dear Referee, thank you very much for taking the time to review our manuscript! We think that by incorporating your input into our manuscript (see details below), we have improved the quality and scientific significance of the paper. Here are our replies and the changes that we implemented:

1. **Little attention is paid to undisturbed flow in PBL. Include a comparison between wind lidar at higher altitudes.**
   a. Measurements in turbulent environment with a UAV appears to be most challenging to the authors, that is why we put a focus on this aspect. Data at higher altitudes (80 m and 100 m) is however included in Table 2. Flying at more than 100 m height would have required a special permit at the lidar measurement site. Additionally, the lidar data rate decreases and the measurement volume increases at altitudes > 100 m. We think that if our drone system is able to capture highly turbulent flow with small bias and RMSE, then this would only improve with altitude as the accuracy of our sonic anemometer does not depend on altitude.

2. **Discuss errors of vertical and horizontal wind component separately.**
   a. We agree that vertical and horizontal wind should be discussed separately. We implemented these changes:
      - Added Figure 10 (right) to section 3.2 showing the vertical wind component during wind tunnel testing of the full drone
      - Added the following text in section 3.2: The story is different for the wind elevation and the vertical speed. Here, the propeller induced flow has a large effect for wind speeds <= 10 m/s (see Figures 11 and 12). The wind elevation bias at very low wind speeds reaches 11°, and the vertical speed bias is around 0.4 m/s.
      - Added the column “vertical speed” in table 2, showing vertical speed bias and vertical speed RMSE in comparison the lidar measurement.
      - The conclusions do not change as the existing sentence “Propeller-induced flow mainly adds a vertical component to the flow without adding a horizontal component - even at large pitch angles. The vertical component can effectively be compensated by subtracting a value that is proportional to the mean motor throttle.” does already include a suitable statement about the vertical flow component.

3. **Test the Trisonica also on the UAV, not only in wind tunnel**
   a. The initial plan was to use the Trisonica for UAV based wind measurements, so we acquired this device. When mounted on a drone, the sensor will be tilted because of the drone’s pitch angle. Additionally, the propellers induce a vertical flow component which increases the resulting angle of attack at the sensor. During initial wind tunnel testing, we discovered that this sensor has problems to measure flows at high tilt angles. The error is not negligible and very difficult to compensate, because it also depends a lot on the yaw angle. This is why it was decided early in the design process that the accuracy will not be sufficient for the application. However, there are
already applications that use the Trisonica on a gimbal which ensures that the tilt angle is kept low. These applications will not be able to measure the vertical flow component, so measurements of the up- and downwash of a wind turbine (as presented in this paper) would not be possible. Therefore, this sensor is not suitable for our application, and consequently, we didn’t test it in flight. We implemented the following change:

- Added the following sentence at the end of section 3.1: This study therefore focuses on in-flight measurements with the GILL Windmaster full-size sonic anemometer.

4. **Authors claim that the Optokopter is better than COTS platforms due to a longer flight time. Why is a long flight time advantageous? Describe advantage also in relation to statistical measures.**

   a. We do not explicitly claim that the drone is better than COTS platforms, but we are happy that the referee perceived it in this way! There are several advantages of long endurance which we admittedly did not clearly state in the manuscript: A: Figure 15 shows the advantage of long flight time. Bias and RMSE decrease with averaging interval length. The longer the averaging interval, the less data points can be measured during a single flight. B: When measuring at high altitudes, a significant portion of the flight is spent to reach the measuring location. Having a shorter flight time would at some point make measurements at high altitudes unreasonable, because the drone would spend most of the endurance for climbing and descending after an exchange of the battery. C: Discharging a lipo battery at close to 1C (which would result in 1 hr flight time) is beneficial, as high-capacity lipos should not be charged at more than 2C. Charging at 2C results in a theoretical recharge time of 30 minutes, however due to the gradual reduction of charge current at the end of the charging process, a full charge typically takes 45 minutes. With the OPTOkopter, we can therefore fly almost uninterruptedly with only two lipo batteries. Flying with a lipo as large as possible ensures that the time between these interruptions is long (45 minutes in our case). The manuscript doesn’t state these advantages; therefore, we implemented these changes:

   - Updated Figure 4 with range
   - Added the following in section 2.2: When measuring at remote locations and / or at high altitude, a significant portion of the flight time is spent for reaching the measurement location. Therefore, a long flight time is beneficial, as a larger fraction of the total endurance can be spent for acquiring wind speed at the desired location. This allows for longer averaging intervals and / or more measurement locations in a single flight. Significantly less time for swapping batteries is spent during long measurement campaigns. Additionally, the drone is equipped with a dual power supply. Batteries can be swapped without cutting power of the drone, so no reboot or GNSS reacquisition is required.

5. **Describe in more detail the lessons learned: How can an existing design be optimized for most accurate wind measurements?**

   a. We have put more focus on the “lessons learned” in the update:

   - Renamed Conclusions section to Conclusions and recommendations
   - Added in conclusions: The performance of an anemometer that is to be installed on a drone should be verified at suitable tilt angles in a precision wind tunnel. The maximum tilt angle needs to be determined with drone test flights at the maximum desired wind speed.
• Added in conclusions: Placing the wind sensor far away from the rotors is a key requirement for this simple correction to work: As has been shown in Figure 6, flow distortion at the sonic anemometer is very small. This ensures that changing the pitch angle of the drone will not change the amount of flow distortion that is present at the anemometer location. In this case, a simple correction for the vertical flow component, that depends only on the average motor throttle, can be used. The gain of this correction should ideally be determined and verified in a large wind tunnel.

• Mounting an anemometer on such a long lever arm significantly increases the moment of inertia of the drone. It is therefore necessary to adjust the control loop parameters (e.g. proportional gain (P) of roll and pitch was increased by a factor of 4 and derivative gain (D) by a factor of 3). Care has to be taken to mount the anemometer exactly on top of the centre of gravity, otherwise roll and pitch motion of the drone results in an additional yaw moment. Yaw control is typically the weakest axis in quadrotors, so this could lead to serious control problems during flight. Furthermore, the anemometer mount needs to be very stiff in roll, pitch and yaw axes, otherwise oscillations (due to the increased P and D) are very likely to happen.

6. Add information about which anemometer was used in Section 3.2 and 3.3,
   • Added sentence in first paragraph of section 3.2: The GILL Windmaster was used as wind measuring device on the drone (see Figure 9).
   • Added sentence in first paragraph of section 3.3: After testing the performance of individual components in the measurement system, the accuracy of the full flying setup (OPTOkopter with GILL Windmaster and all compensations running) was assessed.

7. Combine Figures 14-16
   a. Done

8. Combine figures 18-20
   a. Done
Interactive comment on “Towards accurate and practical drone-based wind measurements with an ultrasonic anemometer” by William Thielicke et al.

Anonymous Referee #2, Received and published: 21 November 2020

Dear Referee, thank you very much for taking the time to review our manuscript! We think that by incorporating your input into our manuscript (see details below), we have improved the quality and scientific significance of the paper. Here are our replies and the changes that we implemented:

1. **How was data in Fig. 4 obtained? Explain.**
   a. Added the following
      - Added text in section 2.2: The relation between air speed, pitch angle and power consumption has been determined for the drone (including GILL Windmaster as shown in Figure 4 by automatically flying circles (D = 300 m) at ground speeds between 2 and 18 m/s, while logging IMU data with 10 Hz.

2. **How do accuracy and pitch angle of the sensors relate at wind speeds < 15 m/s?**
   a. The accuracy of the wind sensors have been determined for 4 pitch angles. For each pitch angle, we measured the accuracy for 36 different yaw angles (0-360 degrees). As these measurements have taken a full day per anemometer and are very expensive to do in the calibration wind tunnel, we did not perform complete pitch & yaw measurements at different wind speeds. However, we sampled different wind speeds (1, 2, 3, 5, 8, 10, 12, 15 m/s) at two different yaw angles (0° and 60°) and at zero pitch. The results show that the accuracy does not change significantly at different speed and / or yaw. We agree that measuring different pitch angles at lower speed too would be a valuable addition. However, these measurements of the isolated anemometers were mainly intended to select a suitable anemometer. We have shown in the comparison with the PTB lidar that the anemometer we selected does measure accurately at lower wind speeds / tilt angles too (as we have low bias and RMSE with long averaging intervals (see Figure 15): Wind speed bias is 3% ± 1%.

3. **Comparison with wind lidar: Compare PSD of velocities measured by drone and lidar. Are there any peaks related to stabilization of the drone?**
a. We cannot detect a clear peak, respectively a distinctive peak difference in the spectrum of wind speed measurements:

We think that most of the drone motion is effectively compensated through our compensation algorithms. This is also shown in the (updated) figure 12 (now figure 11): Erroneous wind measurements (that would result from drone motion or rotation) are suppressed with a factor of about 13. We think that the figure sufficiently shows the suppression of drone stabilization related wind measurement uncertainty.

4. Combine figures 10 and 11
   a. Done

5. Combine figures 14-16
   a. Done

6. Combine figures 18-20
   a. Done
Additional changes to the manuscript due to an update in the contributing authors

As the list of authors for this manuscript was updated, there are additional minor changes to the manuscript that we describe below:

1. Updated the wording so it is compatible with different parties being involved in the presented research. E.g. replaced (“We developed something” by “Something was developed”).
2. The PTB lidar is validated at 8 meters height, but not at higher altitude. Therefore, using the word “validated” when presenting data at altitudes higher than 20 m is misleading. We replaced it with “analysed”.
3. Updated all figures with correct axis labels (e.g. “Power [W]” replaced by “Power in W”).
4. Updated Abstract: Removed “average absolute bias”, as this is not comprehensible. Replaced this with a range of bias and RMSE for all the flights we performed.
5. Updated the Abstract with details on how an improved accuracy was reached:
   • “Key requirements for the accuracy are the use of a full-size sonic anemometer, a large distance between anemometer and propellers, and using a suitable algorithm for reducing the effect of propeller-induced flow.”
6. Section 3.1: Instead of constantly jumping between Windmaster and Trisonica, each instrument now has its own paragraph, Trisonica is discussed first, therefore Table 1 shows the Trisonica on the left now.
7. Section 3.2: Mentioned more clearly that we used data recorded during free flight tests for setting parameters of pitch, and front / rear motor throttles in the wind tunnel:
   • “The drone was fixed to a rigid mount during most of the measurements, but using the data from normal free flight allowed to set realistic motor throttles and pitch angles for each wind tunnel speed.”
8. Section 3.2: Results of the free flight inside the wind tunnel stated more clearly:
   • “This test confirmed that motor throttles and pitch angle during free wind tunnel flight and during free outside flight were in close agreement.”
9. Re-worked the power spectral density plot (Figure 12 in the initial submission). Initially, we took wind speed magnitude (scalar quantity, calculated from all velocity components) for the analysis. A better approach is to directly use a velocity component. As we were oscillating in East-West direction, we took the corresponding velocity component. The resulting plot is more suitable and correct, and still shows that the motion of the drone is suppressed by a factor of about 13. The wording in all places that reference this result was adjusted accordingly.
10. Section 3.4: Removed “(within 1 m range)”, as the exact (sub-second) synchronization between the timing unit in the lidar and in the drone has not been tested.
11. Section 3.4: Changes sentence about correlation of TI and RMSE to “A significant linear correlation was found also for turbulence intensity and wind speed RMSE (r = 0.76), azimuth RMSE (r = 0.90) and elevation RMSE (r = 0.87).”
12. Section 3.4: Replaced the “Conditions for high / low RMSE” equation with the sentence “A large distance between the measurement volumes, together with a high TI, will therefore result in high RMSE.”
13. Section 3.4: Added sentence “The relative position of the OPTOkopter to the measurement volume of the lidar changed significantly while we were flying circles around the lidar. If there would be a significant influence from the OPTOkopter, then this should be visible as periodic bias error, but this is not the case.”
14. Figure 16 (original Figure nr. 21), left: Did show slightly incorrect scaling, fixed
15. Conclusions: Replaced “Based on our tests of the individual components and the full system, we think that the total measurement accuracy is equal to the accuracy of the anemometer alone, as tested in the wind tunnel.” with “Based on our tests of the individual components and the full system, we think that mounting the anemometer on our drone does not significantly increase the measurement uncertainty of the anemometer.”
16. The PTB lidar data has been removed from the open data repository after a request by the PTB.
Wind data collection in the atmospheric boundary layer benefits from short term measurements using unmanned aerial vehicles (UAVs) fixed-wing drone technology. Different fixed-wing drones designed with diverse anemometer technology have been used in the past to provide such data, but the accuracy still has the potential to be increased. We developed a light weight drone (weight including sensor $\leq 5 \text{ [unit: kg]}$) with long flight endurance (>45 [unit: min]) for carrying an industry standard sonic anemometer at high tilt angles in a calibration wind tunnel, with the drone flying in a large wind tunnel, and with the full system flying at different heights next to a bistatic lidar reference.

The propeller-induced flow deflects the air to some extent, but this effect is compensated for in the data by using a data fusion scheme that relies on an analysis between ground speed and wind speed. When compared with the bistatic lidar in very turbulent conditions, with 16-seconds averaging time and looking into interactions between ground speed and wind speed, reference wind speed measurements have an average absolute bias of 1.3\% (95\% confidence interval: 0.7\% to 1.9\%) and mean absolute error 1.6\% (95\% confidence interval: 0.7\% to 2.7\%). The vertical wind speed bias is between -0.07\text{[unit: m/s]}$ to 0.7\text{[unit: m/s]}$, elevation bias is between -6.3\text{[unit: $^\circ$]}$ to 7.2\text{[unit: $^\circ$]}$, and azimuth bias is between -2.6\text{[unit: $^\circ$]}$ and 7.2\text{[unit: $^\circ$]}$. Several studies, including the ones mentioned above, use COTS drones (e.g. by companies such as 3DR, Yuneec) to carry the sensor payload. However, the flight time of a drone can only be optimized for a specific payload weight. Most COTS drones with sufficient endurance (>30 min) are designed for larger payloads (>1 kg) and have take-off weights easily exceeding 10 kg. Therefore, a custom quadrotor drone around a well-proven, highly customizable, open source flight controller (ardupilot.org), enabling us to combine a custom frame with appropriate COTS components and a lightweight, reliable wind sensor. Keeping the total weight below 5 kg reduces the amount of required administrative decisions for take-off, and a long flight time is achievable with only a small difference in payload mass.

The identification of suitable sensors is most suitable for the application in rotary-wing UAVs. The S-pole (H OPTech, S0-[unit: m/s$^{-1}$]) is a commercially available 3-axis anemometer. The vertical acceptance angle is up to 30\text{[unit: $^\circ$]}$ (95\% confidence interval: 0.5\% to 2.6\%) for some models. The vertical wind speed bias is between -0.07\text{[unit: m/s]}$ to 0.7\text{[unit: m/s]}$, elevation bias is between -6.3\text{[unit: $^\circ$]}$ to 7.2\text{[unit: $^\circ$]}$, and azimuth bias is between -2.6\text{[unit: $^\circ$]}$ and 7.2\text{[unit: $^\circ$]}$.

The system was finally flown in the wake of a wind turbine, successfully measuring the spatial vertical velocity deficit and downwash distribution during forward flight. Yielding results that are in very close agreement to lidar measurements and the theoretical distribution. We believe that the results presented in this paper can provide important information for designing flying systems for precise air speed measurements either for short duration or continuous operation at a single or multiple locations (battery powered) or for long duration at a single location (power supplied via cable). UAVs that are able to accurately measure three-dimensional wind might be used as cost effective and flexible addition to measurement masts and lidar scans.
The relation between air speed, pitch angle and power consumption has been determined for the drone and is shown in Fig. 7. A theoretical maximum flight time of 54 minutes can be achieved. In practice, only 85% of the stored energy should be used for safety and battery lifetime reasons, which results in 46 minutes flight time. When measuring at remote locations and at high altitude, a significant portion of the flight time is spent for reaching the measurement location. Therefore, a long flight time is beneficial, as a larger fraction of the total endurance can be spent for acquiring wind speed data at the desired location. This allows for longer averaging intervals and more measurement locations in a single flight. Significantly less time is spent during long measurement campaigns. Additionally, the drone is equipped with a dual power supply. Batteries can be swapped without cutting power of the drone, so no reboot of OS is necessary.

Wind speed is transformed from a body-fixed reference system (BFRS) to the terrestrial reference system (TRS) using standard rotation matrices. We also compensate for the airflow induced by velocity, position, and orientation in the flight path of the UAV. The input and output data for this transformation is given in Fig. 2. All these calculations are performed on an onboard computer (Raspberry Pi 3B+) that is getting wind speed data from the sonic anemometer at 16 Hz and attitude, position, and ground speed information from the flight controller of the UAV at 16 Hz.

Measurements were compared with a calibrated propeller anemometer (measurement uncertainty ±1%) at 20°C, 950 hPa, and 47% humidity. In a wind tunnel, similar to the setup of the Trisonica tests, measurements were performed with a miniature sonic anemometer (TriSonica Mini Wind and Weather, Anemoment 2020) and a full-size sonic anemometer (type TESMET 614, accredited according to ISO/IEC 17025, Eidgenössisches Institut für Metrologie METAS, Switzerland) at wind speeds between 0 < wind speed < 15 m/s and 0 - 360° yaw angle at four different wind tunnel circles (D = 300 m) at ground speeds between 2 and 18 m/s. The pitch angle is kept constant at a minimum of 17.3° with a RMSE of 16.2%. A pitch angle of 30° (49°) is not exceeded in normal forward flight. The measurement uncertainty is ±1% at a minimum wind speed of 10 m/s. With a miniature sonic anemometer, a theoretical maximum flight time of 54 minutes can be achieved. In practice, only 85% of the stored energy should be used for safety and battery lifetime reasons, which results in 46 minutes flight time. When measuring at remote locations and at high altitude, a significant portion of the flight time is spent for reaching the measurement location. Therefore, a long flight time is beneficial, as a larger fraction of the total endurance can be spent for acquiring wind speed data at the desired location. This allows for longer averaging intervals and more measurement locations in a single flight. Significantly less time is spent during long measurement campaigns. Additionally, the drone is equipped with a dual power supply. Batteries can be swapped without cutting power of the drone, so no reboot of OS is necessary.

...
flying at constant altitude to ensure that the vertical wind component is low. The accuracy of the full-size anemometer is within the specs given by the manufacturer. Therefore, we chose to use the anemometer as the reference. We believe that the full-size anemometer is a more suitable instrument for the highly 3D flow on a rotating wing and manoeuvring non-stationary UAV.

An anemometer that is mounted on a rotary-wing UAV is potentially measuring a velocity component that is different from the wind speed. We have found that the wind vector can deviate from the wind direction by a certain pitch angle and propeller speed. We therefore determined suitable pitch angles and throttle values (voltage supply) for a geometrically well-defined flight circle so that the wind direction is kept as close as possible to the normal direction of the wind. The wind speed was measured at different speeds while sampling pitch angle and motor throttle at 10\text{-Hz} (see Fig. 1). Only a small influence (about 1\% deviation) was found on the wind speed for wind speeds above 0.3\text{-m\,s^{-1}}. The effect of the compensation method is also shown in Fig. 6. The method keeps the bias of wind elevation below 1\text{-unit}\, (\text{Fig. 1c)}, and the bias of the wind below 0.3\text{-unit}\, (\text{Fig. 1b}). The effect of the compensation method is also shown in Fig. 6. For measurements with stopped motors, there is only a small influence (about 1\% change of the bias of wind speed, even at high wind speeds).

We used this data for measurements in the wind tunnel of the Technische Universität Dresden (open test section, diameter = 3\text{-m\,s^{-1}}). Wind speeds between 1 and 19\text{-m\,s^{-1}} were tested with the OPTOkopter being tethered to a variable pitch mount. The drone was also flown freely inside the wind tunnel to validate that the mount did not influence the measurements.

![figure1](figures/speed_vs_throttle_pitch.pdf)

The method keeps the bias of wind elevation below 1\text{-unit}\, (\text{Fig. 1c}). The effect of our compensation method is also shown in Figure 1. To conclude, the compensation method is effective. The drone was also tested in a large wind tunnel (open test section, diameter = 3\text{-m\,s^{-1}}). The bias at very low wind speeds reaches 11\text{-unit}\, (\text{Fig. 1c}). This is remarkable, because in comparison to previous studies (see Introduction), the OPTOkopter has a large distance between the anemometer and the propeller disks (1.15\, = \, 2.5\, rotor diameters). The effect diminishes with increasing air speed, however. We compensate for this propeller induced flow using a simple correction algorithm. The wind speed bias is smaller than 1.5\% for wind speeds above 0.3\text{-m\,s^{-1}} (see Fig. 1c).

The FFT analysis (see Fig. 6) reveals, that the power spectral density of the wind speed at the relevant frequency (0.208\text{-Hz}) is at 5 to 7 orders of magnitude larger than those of the yaw angle and pitch angle variables. These analyses indicate that our fusion algorithm results in a ground speed that is independent of wind speed and wind motion rotation in general. This is very important for airborne measurement systems that do not only perform point measurements in hovering flight, but are also capable of measuring while flying a mission. Such a measurement is presented in Section 6.5 (example).

In a situation with zero wind, air speed and ground speed as measured by the UAV must be identical. We checked for such problems by rapidly flying the UAV between two points that were 10\, apart with a sinusoidal ground speed peaking at about 4\text{-unit\,s^{-1}}. Ground speed was calculated using the recorded air speed (as reported by the anemometer) and wind speed (as reported by the data fusion) was recorded and converted to the frequency domain using fast Fourier transform (FFT). The FFT analysis revealed that the spectral density of wind speed is at 5 to 7 orders of magnitude larger than those of the yaw angle and pitch angle variables. The correlation coefficient for ground speed and air speed yields a Pearson’s correlation coefficient of 0.78.

The FFT analysis (see Fig. 6) reveals, that the amplitude spectrum of the wind speed at the relevant frequency (0.104\text{-Hz}) is about an order of magnitude smaller than air speed and pitch angle variables. For higher wind speed and wind motion, the effect of the compensation method is still visible. This effect is caused by the fact that our measurement system that is mostly independent of ground speed and motion rotation in general. This is very important for airborne measurement systems that do not only perform point measurements in hovering flight, but are also capable of measuring while flying a mission. Such a measurement is presented in Section 6.5 (example).
We compared our wind measurements with the bistatic Doppler lidar, developed at the Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig, Germany. A data output rate of 10 units/s was used in the PTB lidar, and different heights between 20 and 100-unit(m) were tested.

A linear deming regression of the data in 1-unit(s) averaging intervals has a slope of 1.03 and a correlation coefficient of 0.96, indicating a good linear relation between both methods (see Figure ref{fig:ptb_deming}).

We also analysed the effect of increasing averaging intervals (between 0.1 and 100-unit(s)) on bias and RMSE. A high correlation coefficient (r = 0.98) is observed for the wind speed measurement, bias is between 2.9 and 3.7-%, which is very similar to what we observed in our previous experiments. For the wind speed measurement, RMSE is strongly dependent on averaging interval: It decreases from 3.7-unit(^{\circ}) at 0.1-unit(s) to 1.9-unit(^{\circ}) at 100-unit(s) (see Figure ref{fig:bias_rmse_vs_averaging_ptb_azimuth}).

A significant linear correlation was found also for turbulence intensity and wind speed RMSE (r = 0.90) and elevation RMSE (r = 0.87). As a matter of course, the correlation coefficient is 0.99, indicating a good linear relation between both methods (see Figure ref{fig:ptb_deming}).

Steady flow over a flat terrain and wind speed above 10-unit(m/s) is a prerequisite for effective wind measurement. Turbulence intensity and wind speed RMSE are strongly dependent on averaging interval: It decreases from 3.7-unit(^{\circ}) at 0.1-unit(s) to 1.9-unit(^{\circ}) at 100-unit(s) (see Figure ref{fig:bias_rmse_vs_averaging_ptb_azimuth}).

The bistatic PTB lidar and the OPTOkopter hence give closely matched results, even at 1-unit(s) sampling interval. Naturally, this consistency increases with longer averaging intervals. When measuring at slightly different locations, the influence of spatial and temporal wind speed variations reduces over time, while increasing averaging intervals also reduce measurement noise of both methods, again decreasing RMSE.

We compared the drone wind measurements with the bistatic Doppler lidar, developed at the Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig, Germany. A data output rate of 10 units/s was used in the PTB lidar, and different heights between 20 and 100-unit(m) were tested.

A significant linear correlation was found also for turbulence intensity and wind speed RMSE (r = 0.76), azimuth RMSE (r = 0.90) and elevation RMSE (r = 0.87). As a matter of course, when averaging interval is increased, lowering RMSE decreases turbulence and wind speed RMSE.

Steady flow over a flat terrain and wind speed above 10-unit(m/s) is a prerequisite for effective wind measurement. Turbulence intensity and wind speed RMSE are strongly dependent on averaging interval: It decreases from 3.7-unit(^{\circ}) at 0.1-unit(s) to 1.9-unit(^{\circ}) at 100-unit(s) (see Figure ref{fig:bias_rmse_vs_averaging_ptb_azimuth}).

The bistatic PTB lidar and the OPTOkopter hence give closely matched results, even at 1-unit(s) sampling interval. Naturally, this consistency increases with longer averaging intervals. When measuring at slightly different locations, the influence of spatial and temporal wind speed variations reduces over time, while increasing averaging intervals also reduce measurement noise of both methods, again decreasing RMSE.
Despite sometimes we were flying very close to the lidar, we believe that the presence of the UAV did not significantly change the flow in the measurement volume of the lidar. The measurements of the OPTOkopter have been successfully compensated for propeller induced flow (see Figure 3). If the UAV had interfered, e.g., by changing the vertical flow component in the measurement volume of the lidar, then there would be a large discrepancy between the measurements of the different UAV versions (uncompensated) lidar measurements. Furthermore, measurements at more remote locations that cannot be observed by the Lidar. In fact, the OPTOkopter hovering on spot at a constant altitude will not have changed the vertical flow component in the measurement volume of the lidar, then there would be a large discrepancy between the measurements of the different UAV versions. The position of the lidar changed significantly while we could not measure the data. If the OPTOkopter hovering on spot at a constant altitude would not have changed the vertical flow component in the measurement volume of the lidar, then there would be a large discrepancy between the measurements of the different UAV versions. The position of the lidar changed significantly while we could not measure the data. If the OPTOkopter hovering on spot at a constant altitude would not have changed the vertical flow component in the measurement volume of the lidar, then there would be a large discrepancy between the measurements of the different UAV versions. Therefore, the OPTOkopter hovering on spot at a constant altitude should not be observed by the lidar measurements. In our design, the battery is responsible for 49% of the total weight. It can be replaced and recharged before the next flight. The battery’s power supply will be enough for the flights at a single location at different altitudes up to 100 m.

The wind turbine (Enercon E 70 - E 4) is located in the Black Forest in southern Germany (47°45'53.43"N; 007°51'11.68"E) at about 1012 m above sea level. The nacelle height is 50 m, and the rotor diameter (D) is 70 m.

Wind velocity was determined at 20 m behind the rotor disk. Measurements were taken at 16 Hz. The OPTOkopter was oscillating at constant altitude near nacelle height with a velocity of 5- \( \overline{u}/u_{ref} \) on a path parallel to the rotor disk (see Figure 5). We used a reference anemometer (see Figure 5). The measurements were not influenced by the slope behind the wind turbine (see Figure 5). We used a reference anemometer (see Figure 5). The measurements were not influenced by the slope behind the wind turbine (see Figure 5).

A relatively constant velocity deficit (5- \( \overline{u}/u_{ref} \)) of 25% is found behind the full diameter of the rotor disk. Further away from the rotor tips, the velocity becomes even larger than \( u_{ref} \). This is due to the turbulence below the rotor disk. We did not capture data at \( \overline{u}/u_{ref} \) of 25% is found behind the full diameter of the rotor disk. Further away from the rotor tips, the velocity becomes even larger than \( u_{ref} \). This is due to the turbulence below the rotor disk. We did not capture data at \( \overline{u}/u_{ref} \) of 25% is found behind the full diameter of the rotor disk. Further away from the rotor tips, the velocity becomes even larger than \( u_{ref} \). This is due to the turbulence below the rotor disk. We did not capture data at \( \overline{u}/u_{ref} \) of 25% is found behind the full diameter of the rotor disk. Further away from the rotor tips, the velocity becomes even larger than \( u_{ref} \). This is due to the turbulence below the rotor disk. We did not capture data at \( \overline{u}/u_{ref} \) of 25% is found behind the full diameter of the rotor disk. Further away from the rotor tips, the velocity becomes even larger than \( u_{ref} \). This is due to the turbulence below the rotor disk. We did not capture data at \( \overline{u}/u_{ref} \) of 25% is found behind the full diameter of the rotor disk. Further away from the rotor tips, the velocity becomes even larger than \( u_{ref} \). This is due to the turbulence below the rotor disk. We did not capture data at \( \overline{u}/u_{ref} \) of 25% is found behind the full diameter of the rotor disk. Further away from the rotor tips, the velocity becomes even larger than \( u_{ref} \). This is due to the turbulence below the rotor disk. We did not capture data at \( \overline{u}/u_{ref} \) of 25% is found behind the full diameter of the rotor disk. Further away from the rotor tips, the velocity becomes even larger than \( u_{ref} \). This is due to the turbulence below the rotor disk. We did not capture data at \( \overline{u}/u_{ref} \) of 25% is found behind the full diameter of the rotor disk. Further away from the rotor tips, the velocity becomes even larger than \( u_{ref} \). This is due to the turbulence below the rotor disk. We did not capture data at \( \overline{u}/u_{ref} \) of 25% is found behind the full diameter of the rotor disk. Further away from the rotor tips, the velocity becomes even larger than \( u_{ref} \). This is due to the turbulence below the rotor disk. We did not capture data at \( \overline{u}/u_{ref} \) of 25% is found behind the full diameter of the rotor disk. Further away from the rotor tips, the velocity becomes even larger than \( u_{ref} \). This is due to the turbulence below the rotor disk. We did not capture data at \( \overline{u}/u_{ref} \) of 25% is found behind the full diameter of the rotor disk. Further away from the rotor tips, the velocity becomes even larger than \( u_{ref} \). This is due to the turbulence below the rotor disk. We did not capture data at \( \overline{u}/u_{ref} \) of 25% is found behind the full diameter of the rotor disk. Further away from the rotor tips, the velocity becomes even larger than \( u_{ref} \). This is due to the turbulence below the rotor disk. We did not capture data at \( \overline{u}/u_{ref} \) of 25% is found behind the full diameter of the rotor disk. Further away from the rotor tips, the velocity becomes even larger than \( u_{ref} \). This is due to the turbulence below the rotor disk.

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Propeller-induced flow mainly adds a vertical component to the flow without adding a horizontal component. This is due to the fact that the vertical component of the flow created by the propellers is directed upwards, whereas the horizontal component is directed sideways. The vertical component of the flow is typically much smaller than the horizontal component, which is why it can be ignored in most cases. However, in some cases, such as when the drone is flying near obstacles or when the wind is blowing from a direction that is close to the direction of the drone’s flight, the vertical component of the flow can become significant.

Based on our tests of the individual components and the full system, we think that total measurement accuracy is equal to the accuracy of the anemometer alone, as tested in the wind tunnel. Wind speed and elevation are sensed accurately, when data fusion is performed as described, and separation between wind sensor and propellers is large enough (here: 2.5 rotor diameters). Additionally, the maximum tilt of the drone must not exceed the maximum acceptance angle of the anemometer (2\degree) in any case.

We thank the Technische Universität Dresden, Fakultät Maschinenwesen, Institut für Luft- und Raumfahrttechnik, Experimentelle Aerodynamik and especially Veit Hildebrand for the opportunity to compare our wind measurements with the bistatic lidar.

Based on our tests of the individual components and the full system, we think that the measurement of wind direction is also as accurate as the anemometer alone, as tested in the wind tunnel. However, the measurement of wind direction is sensitive to the orientation of the anemometer in hovering flight. Wind speed and elevation are sensed accurately, when data fusion is performed as described, and separation between wind sensor and propellers is large enough (here: 2.5 rotor diameters). Additionally, the maximum tilt of the drone must not exceed the maximum acceptance angle of the anemometer (2\degree) in any case.

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