Towards vertical wind and turbulent flux estimation with multicopter UAS

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1 Review response

We want to thank the reviewer for their careful and valuable review. We hope that we can clarify our analyses and clear out some of the concerns with our response.

1.1 Review Comment 1

1. *The model presented in Eqs. (4) – (6) should be described as a point mass model instead of a rigid body model as it only accounts for translational forces and accelerations. A rigid body model account for sUAS rotational dynamics as well.*
   We do not completely agree to this comment. A point mass only has three degrees of freedom, whereas a rigid body model has six degrees of freedom, including rotational terms. Strictly speaking, we are presenting the equations for the translational part of the rigid body model, which includes the rotational angles and gyroscopic terms, but we do not take the momentum equations into account. In a revised manuscript, we will be more clear about this.

2. *The authors assume gyroscopic terms to be small. To verify this assumption, the authors need to include a time history plot for each gyroscopic term.*
   The variance of the gyroscopic terms are two orders of magnitude smaller than the variances of the linear accelerations. This particularly applies as we are only considering the hovering parts of the flights. We give that information in Wetz and Wildmann (2022) and will also include it in this manuscript. We show a time history plot of the terms in Fig. 1. It shows the large difference between the terms, but we think that it is sufficiently well described in the text of the manuscript without the plot, which is not adding much information.

3. *In addition to reasons mentioned in line 89, absolute thrust can be influenced by the performance of GPS and barometer measurements, which are both used for hovering at a fixed height.*
   We agree that the performance of GPS and barometer measurements influence the thrust indirectly. Errors in the height measurement can lead to a control input of the autopilot to the motors, causing an ascend or descend of the quadrotor. This is definitely a potential source of error. Any measured vertical velocity of the UAS is subtracted from the wind measurement as described by Eq. 13. In general, the wind measurement depends largely on the accuracy of the Kalman

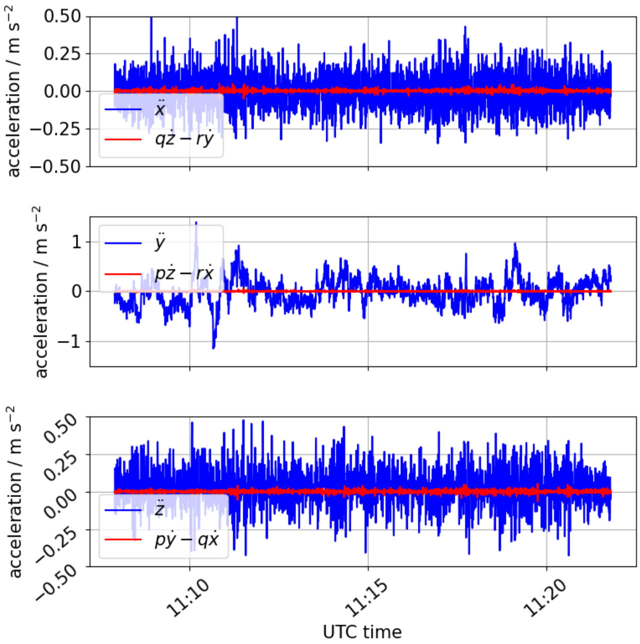

Figure 1. Example of time series of body-frame accelerations in x-,y- and z-direction for a flight on 02 July 2021 by UAS#13. Translational acceleration terms (blue) are compared to gyroscopic terms (red) for a hover period of the flight.

Filter solution for orientation angles and translational velocities. Our approach is to treat these uncertainties as unknown and validate the overall uncertainty of the system in the field. Determining the true accuracy of the state estimator in flight is extremely challenging, because no independent measurements are available. Sophisticated measurement setups with cameras or other external sensors could be set up in future, but are beyond the scope of this work.

4. *In Section 2.4, the authors mention employing the methods proposed by Weltz and Wildmann (2022) to calibrate curves for estimating wind velocity components in the body reference frame. However, curve fitting results are provided only for w_b in Section 4.2.3. The u_b and v_b calibration results need to be presented as well for completeness.*

   In this study, we focus on the vertical wind component. As written, we have shown in Wetz and Wildmann (2022) and Wetz et al. (2021) that horizontal components can be well measured and presented the calibration curves. We believe that another presentation of that calibration could be conceived as a repetition of old results. In Figure 8 of this manuscript we also give the validation of the horizontal wind component.

5. *With regards to assertion made in line 199 about optimality, an optimal fit is not always a good fit. The data scatter shown in Figure 6 is quite high, which minimizes the value of using a nonlinear model for relating forces to airspeed. The authors should compare the residual error from linear and nonlinear fits to justify the curve fitting formulation described in Eq (11).*

We agree that optimization is not always good, particularly with a noisy dataset. We agree that a linear fit could be applied locally in the small range of observed vertical wind speeds. Actually, the exponential curve is very close to a linear function in that range. Nevertheless, we think it is reasonable and justified to fit a curve with an increasing slope at higher wind speeds, because this is what we would physically expect for drag. An exponential function is a natural choice in our opinion, considering drag models such as the Rayleigh drag equation with an exponent of 0.5. As we state in the conclusions, we believe that dedicated laboratory (wind tunnel) experiments should be performed in future to improve the accuracy of the physical model. This is however not possible with the current dataset.

6. *In Section 4.3, the authors state that variance of the lateral and vertical wind components is a better parameter for evaluating the performance of the wind estimation retrieval. This approach is not sensible as two signals with different mean values can have a similar variance.*

   From our point of view, the approach is sensible, because we do not look at two random variables without a causality. We describe the physical process that causes the fluctuations. The control algorithm of the weather-vane mode of the UAS will minimize the lateral wind component by yawing the UAS into the wind, which means that the lateral wind component will always be very close to zero and thus the mean value can hardly be used to evaluate its accuracy. In flat terrain, we will also mostly find average vertical wind speeds that are close to zero, so that an evaluation of the performance of the algorithm is also quite unreasonable with mean values of w. Since we are interested in turbulence, we think that looking at variances is not only sensible, but also important for the evaluation of the measurement system.

7. *In Section 4.3, It is not clear why the authors argue that it is more meaningful to rotate UAS and sonic anemometer wind observation into a wind reference frame. As shown in Figure 8, doing so makes it difficult to validate estimates of u, v, and w, as well as respective time fluctuations, u',v', and w'. Additionally, validation of resolved turbulence scales need to be performed in a N-E reference frame.*

   We will try to make the selection of the frame of reference more clear. For two reasons, looking at streamwise and lateral wind direction is more meaningful than a N-E frame. First, from a measurement perspective of the UAS wind algorithm, the streamwise velocity component reflects the rotation of the quadrotor in the pitch-axis and the lateral component in the roll-axis. This is particularly interesting because the weather vane mode is a controller that minimizes the roll angle. It is true that the mean value of v becomes less meaningful, but the variance of v' is important to check, as it reflects the disturbance of the weather vane controller. Second, if we want to study turbulent structures, e.g. the coherence or the length scales of large eddies, it is more meaningful to look at streamwise and lateral components than a N-E frame, which is not related to the flow field. We thus do not agree that turbulence scales need to be validated in the N-E reference frame.

8. *The conclusions made in this manuscript are largely unsupported unless a meaningful validation of wind velocity components u, v, and w, as well as respective time fluctuations, u',v', and w' are demonstrated with respect to an inertial reference frame.*

   As stated above, we disagree that an analysis in a N-E frame would be more meaningful. We believe that our conclusions are based on a solid database, which is far beyond what has been presented from UAS measurements so far, given the large number of flights and atmospheric conditions in comparison to sonic anemometers on two height levels. We present calibration and validation for all the parameters of interest. As the reviewer suggests, we present here the results of the validation in the meteorological frame of reference and will include it in a revised manuscript:

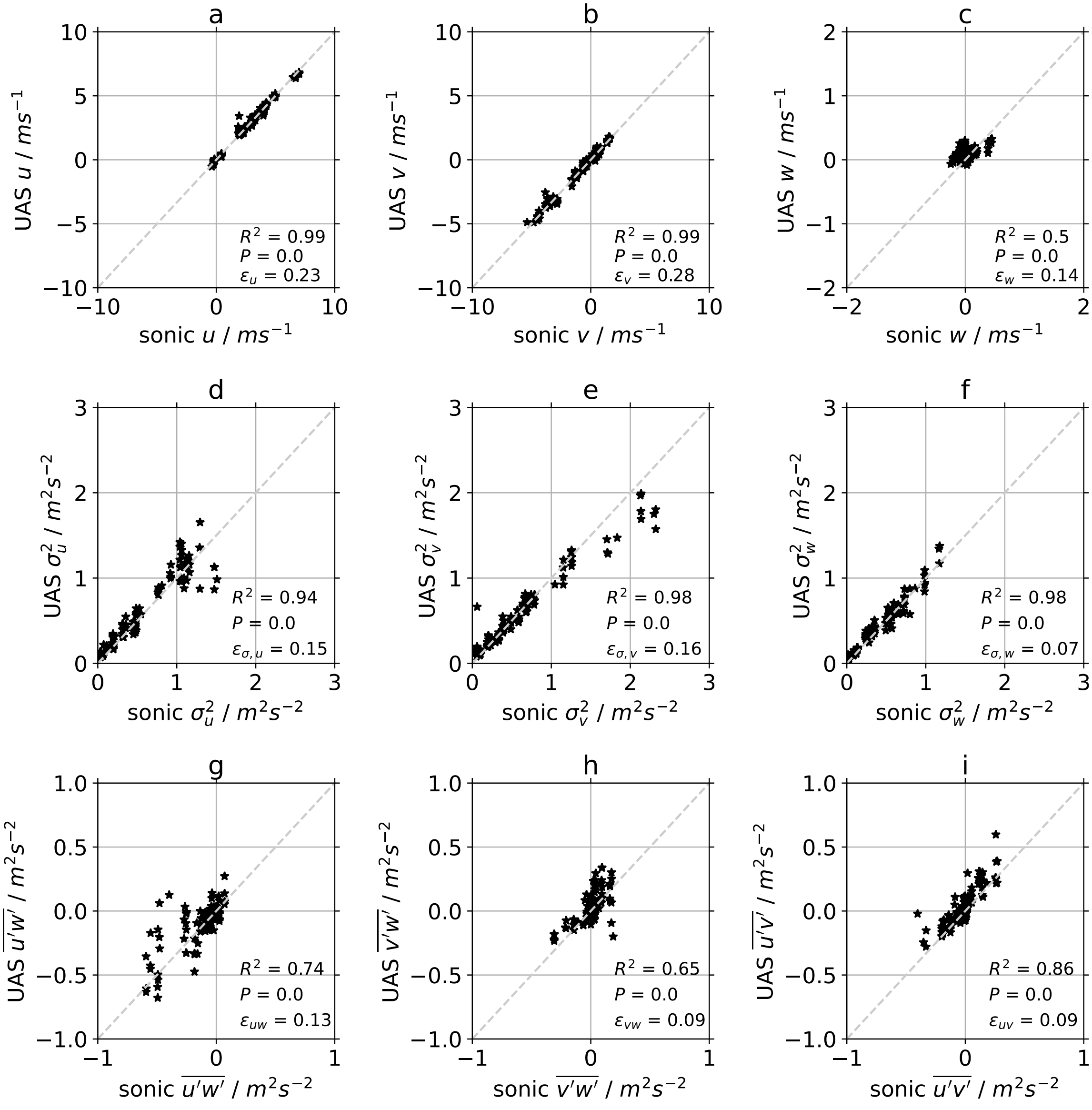

Figure 2. Scatter plots of flight-averaged UAS measurements versus sonic anemometer for u, v and w (a-c), as well as the corresponding variances (d-f) and covariances (g-i) in the meteorological frame of reference.

The N-E components are a rotation of the results in the streamwise and lateral direction by the wind direction. It can be seen that RMSE and R-values are of the same magnitude as presented for the wind reference frame.

References

Wetz, T., Wildmann, N., and Beyrich, F.: Distributed wind measurements with multiple quadrotor unmanned aerial vehicles in the atmospheric boundary layer, Atmospheric Measurement Techniques, 14, 3795–3814, https://doi.org/10.5194/amt-14-3795-2021, 2021.

Wetz, T. and Wildmann, N.: Spatially distributed and simultaneous wind measurements with a fleet of small quadrotor UAS, Journal of Physics: Conference Series, 2265, 022 086, https://doi.org/10.1088/1742-6596/2265/2/022086, 2022.