Answers to comments of referee 1:

Review of "Calibration of 3D wind measurements on a single engine research aircraft"
Authors: Ch. Mallaun, A. Giez and R. Baumann

General Comments: *New methods for calibrating 3-D wind measurements on a small research aircraft are tested. Unfortunately, the new algorithms use unrealistic simplifying assumptions, inconsistent and/or poorly explained methodology, and do not provide a useful comparison with established approaches to calibrating similar aircraft data. The calibrated winds appear to exhibit minimal aircraft motion errors and high fidelity, but it is unclear what accuracy is achieved and what corrections are most needed to produce these results. The error analysis which propagates white noise through the data reduction presents a novel approach, but incorrect application leads to underestimation of errors. Major revision is needed before publication.*

We thank the referee for his/her comments. We are happy that the referee agrees with us about the high quality of the calibrated winds. We do not agree with the finding of "*unrealistic simplifying assumptions and inconsistent methodology".* It is our impression that we were not clear enough when describing the new methods which led to misunderstanding and doubt. The procedures we present are combining well established calibration methods with new features where required. We prove the validity of the described methods by straight forward argumentation based on well-known properties of flight dynamics and atmospheric physics. The error propagation method presented to estimate the overall measurement uncertainties of the derived quantities is based on fundamental mathematical principles. We hope that we are capable of making the points clearer with our answers to the specific comments below and will for sure improve the respective chapters when we are allowed to submit a revised version of the paper. The comments of the referee will be in *italic* type followed by our answers.

Specific Comments (by line number):
121: *Earth fixed coordinates are oriented with the x-axis East, y-axis North, and z-axis upward.*

We define the coordinate systems (CS) according to international aeronautic standards as for example defined by the German DIN9300. This is defining the CS as usually used in aviation and for which the rotational matrix (line 126) is valid. The above defined CS is usually used in meteorological discussions and we also mention this in line 152. We will shift the definition for the meteorological CS to the explanation of Eq. (4) in order to avoid unclear definitions.

131*: These equations aren't new; see Lenschow, D.H.: Aircraft measurements in the boundary layer. Probing the Atmospheric Boundary Layer, D.H. Lenschow, ed., American Meteor. Soc., 29-38, 1986. Suggest, "The simplified wind equations (Lenschow, 1986) give an estimation of the first order terms during straight horizontal flight." Delete similar sentence at lines 137-138.*

This is exactly what we intended to say. The simplified equations can also be found in the above cited document Lenschow and Spyers-Duran 1989 which we were relying to. We will cite the Lenschow (1986) as it is the earlier document.

186: *Not necessarily true. Equations (4) show that if there is a wind shift, but heading angle, ground speed and true airspeed are maintained, there must also be a shift in β. If you observe that there is no correlation in your data, simply state as much without drawing broad conclusions.*

This conclusion is a very important feature of the airborne wind measurement and we think that it is not yet stated that clear in the existing literature. Depending on its inertia the aircraft will always turn its nose directly into a mean wind and the sideslip angle (β) becomes small. On the other hand, the drift angle (δ) becomes non zero and determines the strength of a mean cross wind component while the sideslip angle (β) is reflecting the turbulent fluctuations. For wind fluctuations in the frequency range between 0.1 Hz and 1 Hz the aircraft is still reacting to the changes of the wind direction but it is no more capable to compensate it completely. In this frequency range both δ and β are contributing to the wind, above 1 Hz β usually becomes the dominating factor of the cross wind component.
The statement: "On the other hand, a mean β angle (e.g. over several seconds) has nothing to do with the wind speed which is determined by δ." is generally true for any aircraft; just the transition region is individual. A mean β angle has different sources such as a misalignment of the IRS, dynamical effects (e.g. sidewash), small deviations of the symmetry of the aircraft or bad trimming of the aircraft. For single propeller aircraft the mean sideslip angle might also depend on the engine thrust.

226: *Equation (6) won't give you the right answer. For one thing, mean attack angle is typically nonzero and varies over the course of a flight, and even if sideslip angle is close to zero, there is usually a small bias. Sensitivity coefficients are needed to scale the raw measurements from the nose boom (see eqns. 6 & 8 of Khelif, Burns, and Friehe, 1999) before it is possible to determine angular offsets using the resulting winds. Also, while changing an attack angle offset will move <w> to the desired zero average, so will other adjustments such as the sensitivity coefficient, or the pitch angle from the IRS. Which one is correct?*

For the first part of the comment see the answer to issue 3 of our answers to referee 2.
We agree with the referee that exact sensitivity coefficients are essential for the correct calculation of the flow angles and therefore, we give a detailed description on how we obtain the needed sensitivity coefficients in chapter 4.2 "Static flow angle calibration". The method described in chapter 2.2 to calculate the flow angle offsets is useful, because due to mechanical reasons the angular offset between the gust probe and the reference IRS can change and thus, is not necessarily constant between the different flights. In contrast to the sensitivity coefficients these angular offsets are calculated for each individual flight following the presented inflight calibration method. The method is described at the beginning of the paper because it is a consequence following from the basic considerations about the wind measurement discussed in chapter 2 and adds important information when calculating the wind. Furthermore, the calculation is independent of the test flights and calibration procedure, but it is an essential requirement in order to obtain optimum results.
The flow angle correction coefficients (ε_b, η_b) are handling both: changes in the orientation of the gust probe as well as in the IRS, because they describe the tilt between the two coordinate systems (CS). We cannot directly answer which one of the two has changed from one flight to the other, but this is not necessary anyway. As explained in the beginning of chapter 2.2 the orientation of the IRS is taken as the reference CS on the aircraft and all the relevant properties are corrected in order to accord with it. A change of the sensitivity coefficient of alpha or beta is not capable of correcting a geometric angular offset, but is changing the magnitude of the turbulent fluctuations.

238: Why should only the vertical wind component be independent of aircraft attitude? How does limiting your approach in this way impact your methodology?

It is clear that also the horizontal wind components must be independent of aircraft attitude in the same way as it is true for the vertical wind. We just do not have a method to exploit this feature in a fruitful manner. The basic conditions in Eq. 6 lead to a simple and very robust method to find the angular offsets for the flow angles. Both conditions are focusing only on the vertical wind component. Therefore, we did not see the necessity to discuss the analogy to the horizontal wind components (or any other independent meteorological parameter).

The aim of the presented procedure is – after having determined and applied proper sensitivity factors to the flow angle and airspeed measurements – to determine on a flight-by-flight basis, and without the necessity of specific flight maneuvering, static offsets of the flow angle measurement which may be caused by mechanical misalignment occurring from time to time e.g. after mounting-dismounting etc. .
The two ideas behind equation (6) are: a) if there is a constant offset of the angle of attack (alpha) it will show up in a shift of the vertical wind, and our first order assumption is, that the mean vertical wind along a reasonably extended flight track should be very close to zero, as the total mean vertical wind in the atmosphere is zero due to mass conservation; and b) if there is a constant offset in the sideslip angle beta, i.e. boom is tilted either to the left or right, then any rotation around the x-axis, e.g. during turns, would effectively tilt up or down the boom, too; this vertical tilt would produce an artificial signal in the vertical wind, which is the product of the sine of the roll angle times the beta-offset (η_B) times the true airspeed. Because the sign of the "wrong" vertical wind changes according to whether it is a left turn or a right turn, it can be discerned from possible errors due to changes of upwash, which would not depend on the direction of the turn.

258-271: This procedure corrects for angular differences between the nose boom and the IRS inside the cabin, but have you considered the possibility of non-orthogonal axes on the nose boom itself? In other words, could you have a little bit of yawing incorporated into attack angle fluctuations, and vice-versa? How would you correct for that?

It is true that we do not correct for a possible rotation around the aircraft x-axis of the gust probe CS relative to the IRS CS. Realistic magnitudes of this error are about φ ~ 1°-2° after careful integration of the system on the aircraft with minor effects on the flow angles (e.g. $\alpha_{new} \approx \alpha \cdot \cos\varphi - \beta \cdot \sin\varphi$). If there would be a significant contribution of this effect on the wind measurements the dynamic tests described in chapter 5 would reveal this clearly.

297: Is there evidence of compression and flow distortion impacting these results? If yes, then you must describe the problem and find a method to reduce it. If no, why do mention it here?

Yes, every aircraft is modifying the pressure field and the airflow in its vicinity. We describe in chapter 4 an extensive test and calibration program in order to quantify and correct these effects on the pressure and flow angle measurements. Furthermore, we suggest the method described in chapter 2.2 to correct for the angular offsets between the gust probe and the IRS which might change for example after new system integration.
However, in line 297 we are referring to alternative ground based methods (e.g. theodolite measurements). In order to make the statement clearer we will change it to: "Additionally to the technical difficulties, no ground based procedure is available to account for the aero-dynamical effects (e.g. compression, flow distortion) significantly influencing the result as well."

575: If equation 13 provides local indicated flow angles, what transformation equation accounts for the "dynamical effects" mentioned here, yielding αNB and βNB of equation 5?

In subsection 4.2.1 (starting in line 579) we describe the method applied for the correction of the attack angle (*α) which results in linear correction coefficients of* "0.78 and 0.77 for clean and flaps10 configuration respectively" (see line 620). Thus, $\alpha_{NB} = 0.78 \cdot \alpha_i$ for clean configuration with the index i for indicated and nb for the true values. In subsection 4.2.3 we introduce the method used for the correction of the sideslip angle and give as a result in line 770: "The calibration shows an underestimation of β of just 4%.". Thus, $\beta_{NB} = 1.04 \cdot \beta_i$
To make the text easier to understand we will add these equations in the appropriate chapters.

602: How can the Cessna be "perfectly stabilized" so as to eliminate vertical aircraft velocity? Show a time series plot of the vertical velocity and provide statistics of the typical variability

during tower flybys and racetrack flight segments. Assuming vertical wind is zero, a relatively small 0.3 ms-1 vertical drift in an airplane traveling at 80 ms-1 will produce an offset between pitch and attack angle of 0.2°. That's not particularly good for a small aircraft such as this.

Even when the pilots try to keep the aircraft as stable as possible during the test points there will always be a residual in the vertical velocity or other aircraft attitude and height parameters. The following plot (Fig. R1) shows on the left hand the variability of the vertical aircraft velocity of the 13 test legs during the racetrack flight #3 and on the right hand the corresponding deviation from the mean altitude of each individual leg.

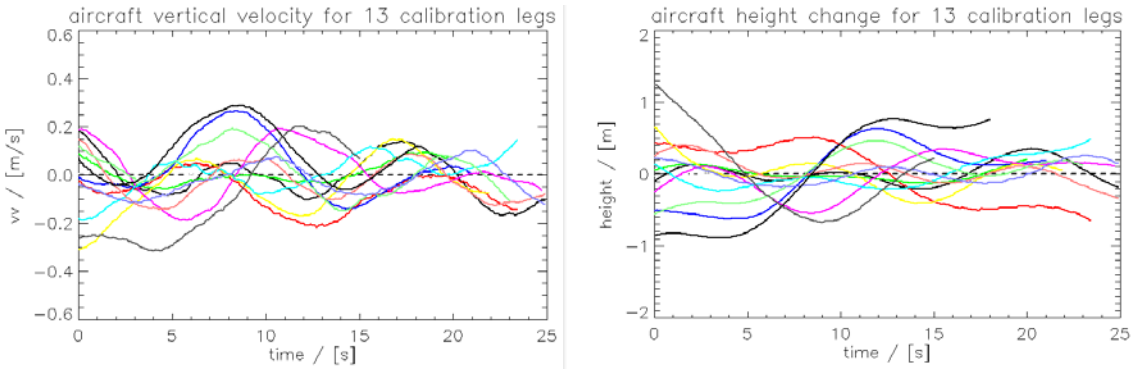

Fig. R1: left: Timeseries of aircraft vertical velocity (vv) during 13 test points for the alpha calibration. Each test point with duration of 15 s to 25 s is represented by one solid line. Right: Same for the deviation from the mean geometrical altitude.

For the test points in this flight the mean vertical velocity is about 1 cm/sec while the variance is 0.01 m^2/s^2. The same statistic are valid for the other racetrack flights while the variance is slightly enhanced (~0.1 m^2/s^2) for the tower flyby flights, because it is more difficult to keep the aircraft that stable during the low level flights. On the right hand side of Fig. R1 it can be seen that the height deviation during the test points is usually below 1 m which can only be achieved during good weather conditions for the test flight as described in chapter 4.2.1 (starting with line 589). In the height range where the Caravan is operating also vertical wind velocities with a similar magnitude as the described aircraft vertical velocity must be expected. The averaging over the period of each test point (the duration is between 15 s to 25 s) cannot eliminate these effects completely and their residuals are remaining as the scatter in the results shown in Fig. 6 of the paper.

620: If you prefer to use quasi-level flight rather than pitching maneuvers, I would suggest removing the assumption that pitch and attack angles are equal. Instead, calculate the vertical winds as in section 5 of Khelif, Burns, and Friehe (1999) and use these to calibrate attack angle. To do so, tune the linear coefficient to minimize vertical wind oscillations induced by the non-zero vertical aircraft velocities. Can you improve on the scatter in figure 6b with this approach?

It is the one of the main goals of our calibration procedure to use direct calibration methods for the different measurement parameters. This is true also for the alpha calibration where we are able to use the very simple nature of flight dynamics that pitch and attack angles are equal during stable horizontal flight segments (Haering Jr., 1995). We know and understand the method of Khelif, Burns, and Friehe (1999) and are convinced that in our case the method described in our paper is advantageous for the calibration of the Caravan for the above mentioned reason. The residual error of the calibration is integrated in the overall error of alpha which has a high accuracy.

624: I don't think you are correcting both effects. What range of Mach number is represented in the racetrack and flyby data? If it only makes <0.1% difference in K value across the

range, other analysis errors are likely much larger and you could simply average Mach across all maneuvers and apply a constant K in Equation (13). Otherwise, you can only correct both effects with one step using linear regression analysis, thus fitting αref – αind = f (Mach, αind).

The Mach number dependency of alpha indicated in Eq. 14 is very low and a result of the calibration of the manufacturer which we use unaltered to calculate alpha indicated. The statement in line 624 is referring to the calibration step described in this chapter. The main purpose of it is to correct for the flow induced effects around the aircraft and this correction is exclusively depending on alpha indicated. If there would exist any uncertainties of the 5HP calibration such as a biased K value the calibration procedure would account for this as well. We did not find a dependency of alpha on other parameters (e.g. height) and therefore, apply this very simple linear correction.

665: Add the height-corrected static pressure trace to the top panel of figure 7a. Reference the data to the right axis and zoom in, i.e., reduce the pressure range relative to the bottom panel so that the pressure variation fills the frame and allows easy comparison to the sideslip angle trace.

Figure 7a should show that after height correction of the pressure signal a significant residual error is visible represented by the red line in the lower panel of Fig. 7a in the order of 1 hPa. The comparison of the pressure deviation and beta indicated can easily be done with Fig. 7b where all the individual test points are presented.

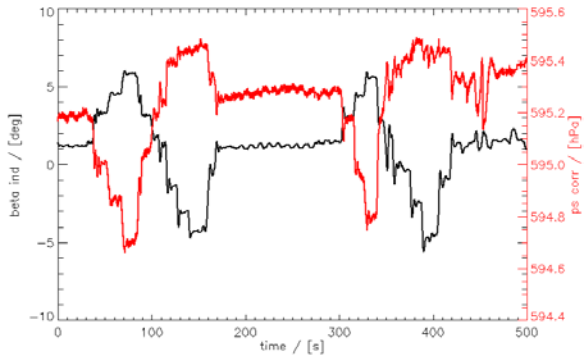

Fig. R2: same as Fig. 7a upper panel with the corrected pressure signal of Fig. 7a lower panel included.

Figure R2 shows the plot as asked for. It shows the same correlation that can also be seen in Fig. 7b in the paper. We suggest highlighting the test points of Fig. 7a in Fig. 7b by choosing a different color for the involved points.

775: Unless you have a valid reason to omit data with high wind variability, you have to accept the scatter as is. Delete the sentence beginning with "Therefore the scatter is too pessimistic…"

We want to follow the suggestion nr. 17 of the second referee: Perhaps "…too pessimistic…" should be "…too large…". We definitely accept the scatter as it is and state the main reason for this is the unavoidable variability of the horizontal wind component involved in the calculation. Thus, the scatter is a measure for the wind variability and not the calibration error of beta. A better estimation of the relative error of beta is presented beginning with line 776

782: I believe there is another source of error in addition to the bias ηb and the relative error due to small sample statistics. Suppose the data set comprised of an infinite sample that fit ideally with slope = 1 and no offset (ηb= 0°), but the scatter standard deviation was the same as yours (σ = 0.3°) despite negligible uncertainty in the slope due to huge sample size. The

scatter statistic describing (βref – βind) would in fact have to contribute to the error in β; in fact, it is the uncertainty in determining ηb. The same reasoning would apply to attack angle data.

The question one has to answer in this hypothetical case is where the observed scatter comes from and if it is connected to the accuracy of beta. We find the variability of the wind as a basic source for the scatter which would lead to an overestimation of the error of beta. In parts the scatter is also coming from beta uncertainties which we can define and quantify with different means as described in the text. We estimate the overall measurement uncertainty of beta as a composition of three sources: the uncertainty of the involved sensors itself (e.g. differential pressure and dynamic pressure), the relative error derived from the variability of the linear coefficients during the different measurement flights and the variability of the correction factor η_B. We think, this is a clear and restrictive way to estimate the overall measurement uncertainty of beta.

809: If this is the uncertainty in the correction angles due to their variability, the uncertainty of εb should be 0.2° as stated on line 632, and for ηb it should be 0.3° (see comment, line 782). It should be clearly explained that relative flow angle error which scales with flow angle results from measurement uncertainty rather than the offset calibration.

The variability of ε_B and η_B are the measures for their uncertainties as we would expect constant values in a perfect system. The values presented in line 632 and 782 are not related to this. The meaning and consequence of these parameters are discussed in the respective subsections and also in the comments above. In lines 812-817 we clearly state, that the total error is the sum of three major contributions, where the numbers presented in 809 is just one of these.

847: To Figure 10 please add the horizontal wind components with uncalibrated attack and yaw angle and uncalibrated static/dynamic pressure data. Label the right axis if needed to place data on the same scale. Estimate the error in the uncalibrated cross-wind component, and describe which calibration procedure is most responsible for removing the yawing motion from the winds.

The effects of different calibration states on the horizontal or vertical wind components are already discussed in different publications (e.g. Boegel, W. and Baumann, R.,1991, Khelif, Burns, and Friehe 1999,Tjernstroem, M. and Friehe 1991). Switching on and off different calibration coefficients can produce a variety of wrong wind signals. We think that this does not add substantial insight in this discussion here and therefore, we suggest to stick to the comparison of the corrected horizontal wind signals with $TAS \cdot \sin \beta_{max}$ and the vertical wind component with the aircraft vertical velocity as suggested by Lenschow and Spyers-Duran (1989). All corrections we are applying to the different measurement sources have a significant impact on the wind calibration and therefore, all these corrections must be applied.

876: To Figure 11 please add the vertical wind with uncalibrated attack and yaw angles and uncalibrated static/dynamic pressure data. Label the right axis if needed to place data on the same scale. Estimate the error in the uncalibrated vertical winds, and describe which calibration procedure is most responsible for removing the pitching motion from the vertical winds.

See our answer to the previous comment. As an example we want to show the effect of switching off the alpha calibration on the vertical wind.

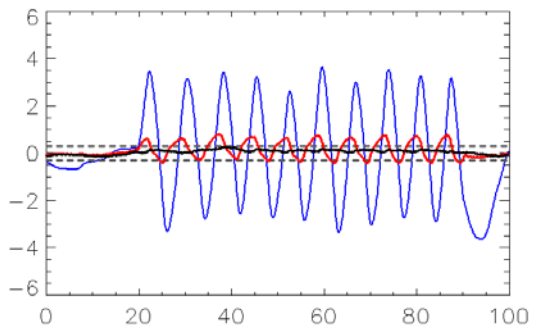

Fig. R3: same as Fig. 11, the added red line represents the vertical wind velocity calculated with alpha indicated instead of the corrected value of alpha.

980: In this alternative method of error analysis, white noise should be added to ALL the parameters that are used in the calculation of the target data product (e.g., static temperature). Accordingly, I would modify the sentence to read, "the error of a single measurement parameter can be represented by a white noise contribution which is applied to each of the original data time series which impact that measurement."

This is exactly what we do – the respective measurement uncertainty is added to all the parameters in the calculation which allows for the explained error analysis. We will modify the sentence in the text as suggested. Furthermore, regarding also the other comments and questions of both of the referees about the error analysis we see the necessity to describe the method clearer. This will be completed for the revised version of the paper if we are allowed to submit it.

1036: To what data are you adding the white noise signal to? Total air temperature? What about adding white noise to static (and dynamic) pressure also, which are used to convert total to static temperature in the processing algorithm? Isn't that the whole point of using this method?

Yes, as mentioned in the previous comment we add the white noise to all the involved time series. These are position and attitude, other avionic data (e.g. ADC pressure or ADC temperature) and all pressure, flow angles, temperature or humidity signals of the METPOD.

1094: What other parameters were involved in the calculation? These are never mentioned!

The artificial white noise is added to all measurement parameters of the installed sensor system as described in the previous comment.

1120: Shouldn't overall uncertainties for α and β increase a bit? If the uncertainty of α is equally divided between the offset and relative terms, shouldn't the total sum (in quadrature) to ~0.3°? Likewise if the relative error for β is negligible, shouldn't the offset error be ≥0.3°?

In fact, the overall uncertainties for α and β do increase a bit. The offset error for alpha ~0,1° and beta ~0.2° as stated in line 808 are increased to ~0.25°. In the section following line 1120 we discuss the influence of different turbulence intensities on the overall measurement uncertainties of the flow angle which has significant impact on alpha and thus, also on the vertical wind component.

1135-1139: I believe this is faulty reasoning. Why should horizontal wind measurement uncertainty of the along-wind component only come from true airspeed, or the cross-wind component only come from sideslip angle? Why should vertical wind measurement

uncertainty be limited to attack angle calibration errors? Just with respect to vertical wind, what about true air speed errors (with all the attendant uncertainties associated with static and dynamic pressures, and total temperature), pitch angle errors (IRS units don't measure perfectly), and vertical aircraft velocity errors? All these sources of uncertainty should be included in an error analysis, not just the cherry picked ones mentioned here. You can't just isolate noise to a particular channel and conveniently turn all the others off.

We do not state that the described error sources are the only sources, but the most important ones. Different to earlier measurement systems (e.g Boegel, W. and Baumann, R.,1991, Khelif, Burns, and Friehe 1999) the measurement uncertainty of aircraft position and attitude is very small in our case. Thus, the biggest error sources for the wind calculation are true airspeed (TAS), alpha and beta. In Eq. 3 it becomes obvious why an error in the TAS is most important for the along-wind component in aircraft fixed CS and as well where our statements about the influence of alpha and beta on the vertical and cross wind components, respectively, come from. The intention of this discussion is to deepen the insight in the 3D wind measurement on research aircraft. We are not cherry picking because we in fact do not just include the most influencing factor in a "first order" error analysis, but instead included all known error sources as white-noise terms to the input signals. We tried to explain in this section, that the analysis revealed the major contributions of along wind and cross wind component to be linked with true airspeed and sideslip angle respectively. Therefore we are convinced to describe a useful and new method on how the overall measurement uncertainty can be calculated for complex systems and deliver additional information about the main error sources in the connected discussion.

We change the following technical comments as suggested.
Technical Comments (by line number):

48: Begin new paragraph.
171: Begin new paragraph.
182: Suggest, "The bigger and heavier the aircraft, the slower it usually reacts to changes in the wind signal. The magnitude of β fluctuations correspond to the strength of turbulence and inertia of the aircraft."
199: Suggest, "As usually an aircraft navigation system does not measure the flow angles…"
265: Suggest "Eq. 5."
351: Suggest "hand side".
749-755: Delete sentences beginning with "To understand…" and "An important step…"
764: Suggest: "will perturb and increase the scatter of the results."
864: This is backwards. It should read, "While the former would indicate any deficiencies in the TAS calibration, the latter would be sensitive to error in the β calibration."
1029: Suggest "processed" rather than "unprocessed". Use of the word "original" already indicates that this data has not been recomputed with added white noise.
1033: End parentheses after "Fig. 13b".
1150: Should be "dependent" rather than "depending".
1219: Begin new paragraph with "We calculated…"

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