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Interactive Comment

Interactive comment on "Towards higher accuracy and better frequency response with standard multi-hole probes in turbulence measurement with Remotely Piloted Aircraft (RPA)" *by* N. Wildmann et al.

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Many thanks for the detailed review. In the following I will comment on each point. The referee comments will be repeated in italic before the answer.

General remarks

- *In Figs 4 and 5, it must be clearly indicated what is really measured (how many transducers and where). In Fig. 5, what is Ps? What is the length of the "long tube"?*
  Each bubble in the figure represents a pressure transducer, Ps is declared in the caption as the measurement of a barometric pressure transducer. The length of the long tube cannot be given in general. In an ideal system, a tube would not be necessary at all. If all low pressure ports are measuring the same signal, the signal will cancel out in further calculation. The long tube is recommended to prevent possible disturbances like resonance or small time shifts between the single transducers, which cause errors for high frequency signals. The longer the tube, the better, to cancel as much high frequencies as possible. However, also the tube diameter and tubing material effects the low-pass cut-off frequency. In our experiments, we used a silicone tube of 5 mm diameter and one meter length.

- *In Fig. 10, the tubing system connected to the acoustic box must be represented in detail (with its various branches, lengths, etc.).*
  The tubing systems are explained in detail in figures 4 and 5 and chapter 3. The test was carried out with exactly the two setups described there. Figure 10 was meant to give a general, schematic idea of the setup. A full drawing of the setup would be much more confusing. It should be explicitly stated in chapter 3 that what is depicted as the "tubing under investigation" in figure 11 is first replaced with the branched M^2AV setup, including connections to four additional pressure transducers at the HP port, and in the second experiment is replaced with the MASC setup (a direct connection to one transducer).

- *In p. 9788-9789, the equations must be developed in a logical way. The starting point is (2) and (4), and it must be clearly explained how the various terms*

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in these equations are obtained from the measurements. In (3), k_p and k_q are presented as dependent on k_α and k_β, whereas in Table 1, they depend on p and q (which are "final" atmospheric parameters). This is really confusing and needs clarifications. If the authors think this requires too long developments for the section, they could put them in an appendix at the end of the paper, but these developments are indispensable. I consumed a lot of time in trying to understand the physical connexions of the sensors and the computations, but I failed.

For a better understanding, a detailed step by step description of the measurement with a five hole probe will be given here and added to the appendix of a revised manuscript. The description needs to be divided into the windtunnel calibration procedure and the actual instantaneous measurement of the airspeed vector.

Wind-tunnel calibration

A windtunnel calibration is essential for the measurement with a multi-hole probe. The goal of the wind-tunnel calibration is to find a best-fit relationship between the measured pressures dP_i and the airflow vector v_{tas}. In order to make this fit robust against changes in airspeed, a polynomial fit is not directly done between angles and pressure readings (respectively airspeed, barometric pressure and pressure readings), but dimensionless coefficients are defined (see table 1).

The presetting of the wind tunnel is a certain dynamic pressure q and static pressure p, that should be continuously measured with an independent measuring system. k_p and k_q can be understood as correction values for dynamic pressure and static pressure with regards to the airflow angle at the probe. k_α and k_β serve as the variables of the polynomial functions for α, β, k_p and k_q.

$$\alpha = f_\alpha(k_\alpha, k_\beta)$$
$$\beta = f_\beta(k_\alpha, k_\beta)$$

	Bohn et al, 1975 (M^2AV)	Treaster and Yocum, 1979 (MASC)
ΔP	$\left[\frac{1}{5}\sum_{i=0}^{4}\left(P_i-\frac{1}{5}\sum_{j=0}^{4}P_j\right)^2\right]^{\frac{1}{2}}+\left[P_0-\frac{1}{4}\sum_{i=1}^{4}P_i\right]$	$\frac{(dP_1+dP_2+dP_3+dP_4)}{4}$
k_α	$\frac{dP_{01}-dP_{03}}{\Delta P}$	$\frac{dP_1-dP_3}{dP_0-\Delta P}$
k_β	$\frac{dP_{02}-dP_{04}}{\Delta P}$	$\frac{dP_2-dP_4}{dP_0-\Delta P}$
k_q	$\frac{q-dP_{0s}}{\Delta P}$	$\frac{dP_0-q}{dP_0-\Delta P}$
k_p	$\frac{P_s+dP_{0s}-p}{\Delta P}$	$\frac{P_s+\Delta P-p}{dP_0-\Delta P}$

Table 1. *Comparison of two methods to define dimensionless coefficients for five hole probe measurements.*

$k_\mathrm{p} = f_s(k_\alpha, k_\beta)$
$k_\mathrm{q} = f_q(k_\alpha, k_\beta)$

The functions $f_x(k_\alpha, k_\beta)$ are arranged as a polynomial of order m and the two variables k_α and k_β in the following manner:

$$f_x(k_\alpha, k_\beta) = \sum_{i=0}^{m}(k_\alpha)^i\left[\sum_{j=0}^{m}X_{ij}(k_\beta)^j\right] \tag{1}$$

with X_{ij} the coefficients $c_{\alpha,\mathrm{ij}}$, $c_{\beta,\mathrm{ij}}$, $c_{\mathrm{s,ij}}$ and $c_{\mathrm{q,ij}}$, for the estimation of α, β, k_p and k_q respectively. To achieve a good accuracy with the polynomial fit, calibration with angle steps of two degree is recommended. The calibration range for the MHP under investigation is suggested to be not larger than 20 degrees in all directions. A sufficiently large number n of calibration settings yields four overestimated systems of linear equations, which can be presented in matrix notation:

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$$\begin{bmatrix} \alpha_0 \\ \alpha_1 \\ \vdots \\ \alpha_n \end{bmatrix} = \begin{bmatrix} 1 & k_{\beta 0} & k_{\beta 0}^2 & \dots & k_{\alpha 0} & k_{\alpha 0}k_{\beta 0} & k_{\alpha 0}k_{\beta 0}^2 & \dots & k_{\alpha 0}^n k_{\beta 0}^n \\ 1 & k_{\beta 1} & k_{\beta 1}^2 & \dots & k_{\alpha 1} & k_{\alpha 1}k_{\beta 1} & k_{\alpha 1}k_{\beta 1}^2 & \dots & k_{\alpha 1}^n k_{\beta 1}^n \\ & & & & \vdots & & & & \\ 1 & k_{\beta n} & k_{\beta n}^2 & \dots & k_{\alpha n} & k_{\alpha n}k_{\beta n} & k_{\alpha n}k_{\beta n}^2 & \dots & k_{\alpha n}^n k_{\beta n}^n \end{bmatrix} \cdot \begin{bmatrix} c_{\alpha,0} \\ c_{\alpha,1} \\ \vdots \\ c_{\alpha,\mathrm{n}} \end{bmatrix}$$

$$\begin{bmatrix} \beta_0 \\ \beta_1 \\ \vdots \\ \beta_n \end{bmatrix} = \begin{bmatrix} 1 & k_{\beta 0} & k_{\beta 0}^2 & \dots & k_{\alpha 0} & k_{\alpha 0}k_{\beta 0} & k_{\alpha 0}k_{\beta 0}^2 & \dots & k_{\alpha 0}^n k_{\beta 0}^n \\ 1 & k_{\beta 1} & k_{\beta 1}^2 & \dots & k_{\alpha 1} & k_{\alpha 1}k_{\beta 1} & k_{\alpha 1}k_{\beta 1}^2 & \dots & k_{\alpha 1}^n k_{\beta 1}^n \\ & & & & \vdots & & & & \\ 1 & k_{\beta n} & k_{\beta n}^2 & \dots & k_{\alpha n} & k_{\alpha n}k_{\beta n} & k_{\alpha n}k_{\beta n}^2 & \dots & k_{\alpha n}^n k_{\beta n}^n \end{bmatrix} \cdot \begin{bmatrix} c_{\beta,0} \\ c_{\beta,1} \\ \vdots \\ c_{\beta,\mathrm{n}} \end{bmatrix}$$

$$\begin{bmatrix} k_{\mathrm{p}0} \\ k_{\mathrm{p}1} \\ \vdots \\ k_{\mathrm{p}n} \end{bmatrix} = \begin{bmatrix} 1 & k_{\beta 0} & k_{\beta 0}^2 & \dots & k_{\alpha 0} & k_{\alpha 0}k_{\beta 0} & k_{\alpha 0}k_{\beta 0}^2 & \dots & k_{\alpha 0}^n k_{\beta 0}^n \\ 1 & k_{\beta 1} & k_{\beta 1}^2 & \dots & k_{\alpha 1} & k_{\alpha 1}k_{\beta 1} & k_{\alpha 1}k_{\beta 1}^2 & \dots & k_{\alpha 1}^n k_{\beta 1}^n \\ & & & & \vdots & & & & \\ 1 & k_{\beta n} & k_{\beta n}^2 & \dots & k_{\alpha n} & k_{\alpha n}k_{\beta n} & k_{\alpha n}k_{\beta n}^2 & \dots & k_{\alpha n}^n k_{\beta n}^n \end{bmatrix} \cdot \begin{bmatrix} c_{\mathrm{s},0} \\ c_{\mathrm{s},1} \\ \vdots \\ c_{\mathrm{s,n}} \end{bmatrix}$$

$$\begin{bmatrix} k_{\mathrm{q}0} \\ k_{\mathrm{q}1} \\ \vdots \\ k_{\mathrm{q}n} \end{bmatrix} = \begin{bmatrix} 1 & k_{\beta 0} & k_{\beta 0}^2 & \dots & k_{\alpha 0} & k_{\alpha 0}k_{\beta 0} & k_{\alpha 0}k_{\beta 0}^2 & \dots & k_{\alpha 0}^n k_{\beta 0}^n \\ 1 & k_{\beta 1} & k_{\beta 1}^2 & \dots & k_{\alpha 1} & k_{\alpha 1}k_{\beta 1} & k_{\alpha 1}k_{\beta 1}^2 & \dots & k_{\alpha 1}^n k_{\beta 1}^n \\ & & & & \vdots & & & & \\ 1 & k_{\beta n} & k_{\beta n}^2 & \dots & k_{\alpha n} & k_{\alpha n}k_{\beta n} & k_{\alpha n}k_{\beta n}^2 & \dots & k_{\alpha n}^n k_{\beta n}^n \end{bmatrix} \cdot \begin{bmatrix} c_{\mathrm{q},0} \\ c_{\mathrm{q},1} \\ \vdots \\ c_{\mathrm{q,n}} \end{bmatrix}$$

A solution for the coefficients c can be found with a least squares method. For the coefficients $c_{\alpha,\mathrm{i}}$ this would e.g. yield:

$\boldsymbol{\alpha} = \mathbf{K} \cdot c_\alpha$
$S(c_\alpha) = \sum_{i=1}^{m} |\alpha_i - \sum_{j=1}^{n} K_{ij} c_{\alpha,\mathrm{j}}|^2 = \|\boldsymbol{\alpha} - \mathbf{K} \cdot c_\alpha\|^2$
$\hat{c}_\alpha = c_\alpha arg\,min\,S(c_\alpha)$

where S is the minimization criterium and $\hat{c}_\alpha$ is the best fit for the given calibration. For linear independent columns, a unique solution can be found by solving the normal equation:

$\mathbf{K}^T K \cdot \hat{c}_\alpha = K^T \boldsymbol{\alpha}$
$\hat{c}_\alpha = (K^T K)^{-1} \cdot K^T \boldsymbol{\alpha}$

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Thus, the output of the wind-tunnel calibration is the coefficients c_α, c_β, c_s and c_q.

Measurement with the multi-hole probe

Once the probe has been calibrated, velocity and flow angles in arbitrary flows may be estimated as follows:

- The instantaneous pressures across each hole of the probe are converted to instantaneous $\Delta P, k_\alpha, k_\beta$ according to table 1.
- Subsequently, k_p, k_q, $\boldsymbol{\alpha}$ and $\boldsymbol{\beta}$ are estimated as follows:

  $\boldsymbol{\alpha} = \mathbf{K} \cdot c_\alpha$
  $\boldsymbol{\beta} = K \cdot c_\beta$
  $\boldsymbol{k}_\mathrm{p} = K \cdot c_\mathrm{s}$
  $\boldsymbol{k}_\mathrm{q} = K \cdot c_\mathrm{q}$

- Finally, the static pressure and the dynamic pressure are calculated with the solutions of the the equations in table 1 for p and q respectively:

	Bohn et al, 1975 ($\mathrm{M^2AV}$)	Treaster and Yocum, 1979 (MASC)
p	$P_s + dP_{0\mathrm{s}} - k_\mathrm{p} \cdot \Delta P$	$P_s + \Delta P - k_\mathrm{p} \cdot (dP_0 - \Delta P)$
q	$dP_{0\mathrm{s}} + k_\mathrm{q} \cdot \Delta P$	$dP_0 - k_\mathrm{q} \cdot (dP_0 - \Delta P)$

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Specific comments

1. *p. 9785, line 13: Why is the fuselage disturbance reduced on RPA with respect to manned aircraft?*
First, the wing span, wing load and therefore upwash of the aircraft is much smaller than for any manned aircraft. How this affects the measurements can be read in Crawford et al. (1996). Second, the fuselage is considerably smaller. Wyngaard et al. (1985) describes how turbulence is affected by disturbance of the airflow by an axisymmetric body like a fuselage of an aircraft. Naturally, the disturbance effects scale with the size of the obstacle.

2. *p. 9787, lines 6-7: Is there a reference to support this sentence?*
The wind tunnel measurements that support this sentence have not been published, yet. It was the intention to focus on the airflow measurements of the probe itself in this publication. Future publications should focus on the actual wind measurement on the aircraft and all the investigations that go along with it. An additional hint that the observations done for MASC are plausible can be found in Crawford et al. (1996), where it is shown that a small aircraft ('Long-EZ') with pusher engine has considerably less flow distortion than other research aircraft ('Twin-Otter').

3. *p. 9788, line 14: Give the order of the polynomial fit.*
A 9th order polynomial fit was chosen. Higher orders only marginally increase accuracy. The information will be given in a revised manuscript.

4. *p. 9789, (4): Define p and q.*
Static pressure p and dynamic pressure q as defined in p.9788, l. 23.

5. *p. 9789, line 4: Why use of dry air constants? Which is the resulting error?*
In the post-processing of scientific data collected by MASC with the complete thermodynamic sensor package, specific heat and gas constant are calculated

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for moist air. The specific heat of air at constant pressure C_p and constant volume C_V are corrected for moisture

$$C_p = (1 + 0.87 \cdot Q) \cdot C_{p_d} \quad , \tag{2}$$

$$C_V = (1 + 0.97 \cdot Q) \cdot C_{V_d} \quad , \tag{3}$$

with the specific heat at constant pressure for dry air $C_{p_d} = 1005$ Jkg^{-1}K^{-1}, the specific heat at constant volume for dry air $C_{V_d} = 717$ Jkg^{-1}K^{-1} and the specific humidity Q, which is calculated using the mixing ratio m:

$$Q = \frac{m}{1 + m} \tag{4}$$

Now the gas constant $\Re$ corrected for moisture is determined

$$\Re = C_p - C_V \quad , \tag{5}$$

and ultimately the ratio κ_{hum} of the gas constant and the specific heat is found for moist air

$$\kappa_{\text{hum}} = \Re / C_p \quad . \tag{6}$$

For the sake of simplicity, this step was left out in the description in this manuscript. The resulting true airspeed error for the U.S. standard atmosphere at sea level ($\text{T}_{\text{tot}} = 288.15$ K, p $= 101325$ Pa) a dynamic pressure of 300 Pa and a neglected mixing ratio of 12 g/kg would be approximately 0.006 m/s.

6. *p. 9789, line 21: Number the figure.*
   Should be figure 8. A few references to figures got mixed up in the discussion paper publication. This will be corrected in a revised manuscript.

7. *p. 9790, line 17: “not only on” instead of “on not only”.*
   This will be corrected in a revised manuscript.

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8. *p. 9795, line 1: Expand MEMS.*
   MicroElectroMechanical System. This will be added in a revised manuscript.

9. *Fig. 13 and related comments p. 9795: Why is there no correlation between the acceleration along the y direction and the membrane-based sensor signal?*
   The MEMS membrane surface inside the sensor is oriented in the xz-plane. Only accelerations perpendicular to that plane can deform the membrane and result in a voltage output of the piezoelectric elements. In figure 13 it can be seen that accelerations along the y-direction and the membrane based sensor signal do correlate.

10. *p. 9796, line 18: Why 10%?*
    This is admittedly a rather arbitrary value. The sentence should be rephrased to state that a minimum error is strived for.

11. *p. 9797, line 7: Is the the digital or the combined filter considered here?*
    The combined filter is considered, since the digital filter is dominant in this frequency range.

12. *p. 9797, lines 14-15: Wrong! On a signal sampled at a frequency f_s, an aliased frequency f_a would appear at the frequency $f_a - f_s$.*
    This is true. We apologize for this mistake and the passage needs to be changed in the following way:
    'Logging at 100 Hz is another oversampling step to achieve anti-aliased data up to 20 Hz at least. Sampling at 100 Hz, signals between 100 Hz and 150 Hz can fold into the frequency range up to 50 Hz. The previous steps explained how these signals are already damped to less than 25 %. Frequencies above 150 Hz are damped to less than 6 %. This means that in the frequency range from 0 Hz to 50 Hz, a maximum error caused by aliasing of 25 % is theoretically possible [...]'
    We would like to emphasize that for a physical turbulent signal, this theoretical

error is highly overestimated, since the natural decay of the turbulent signal has the effect that signals above 100 Hz have a power which is only a fraction of the power at only a few Hertz (power law in the inertial subrange of turbulence).

13. *p. 9797, line 22: Remove extra dot.*
    This will be corrected in revised manuscript.

14. *Section 6: No sounded conclusion can be drawn from the comparison between two single runs performed at different times, different heights, etc.. So, this section should be restricted to the analysis of the "MASC" signal.*
    In fact, the selected runs are not chosen randomly, and are not the only runs that were analysed to compare the two systems. They were chosen because they represent the systems in their most recent application in field experiments. M^2AV flights from the following experiments were analysed:

    - Halley Station, 2007, van den Kroonenberg et al. (2008).
    - Mallorca, 2009, (not published).
    - LITFASS09, Beyrich et al. (2012).
    - LITFASS10, Martin and Bange (2013).
    - Lindenberg 2011, Martin et al. (2013)

    The spectral analysis of the individual flights can differ slightly. Especially in the early experiments, undefined noise can be found in the data. For the experiment Lindenberg 2011, only 30 Hz data is available. Therefore one example of the LITFASS campaigns was chosen for the comparison in the discussion paper. A similar amount of MASC flights from the years 2012 and 2013 were analysed and showed consistent data quality. We believe that it is important to the majority of the readers to get an impression of how much data quality can, or cannot be improved, following the advice that is given in this paper.

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15. *p. 9798, lines 18-19: The structure function is computed according to time lags, not to frequencies.*
However, a certain time lag in the structure function is associated to a signal with a certain frequency in the power spectra. The sentence will be rephrased in a revised manuscript.

16. *Table 1: What is dP?*
The definition of the pressures dPi is given in figures 4 and 5. The definition of the dimensionless coefficient k_p contains an error. It should be:

$$\frac{P_s + \Delta P - p}{dP_0 - \Delta P} \tag{7}$$

17. *Fig. 1: Indicate where the MHP is located.*
The MHP is located on the nose boom, approximately 15 cm in front of the tip of the fuselage. An indication in the picture will be given in a revised manuscript (see figure 1).

18. *Fig. 5, caption: Indicate what are LP and HP.*
The definition of LP and HP is given in the caption of figure 4 and will also be added to the caption of figure 5 in a revised manuscript.

19. *Fig. 6 and foll.: The units on the axes must be given between parentheses (instead of after a forward slash).*
Because of the lack of a clear style guide by AMT for the notation in graphs, we refer to the E.A. Guggenheim notation, which suggests the use of a forward slash to seperate the variable from the unit. However, we agree that parentheses are the more common practice and the figure labels will be changed in a revised manuscript.

20. *Fig. 6, caption: Which pressure ports?*
The pressure ports in front of the ring P_{static}. The variable name will be added to the manuscript.

21. *Fig. 7: I did not find any comments of this figure in the text. The black lines are impossible to distinguish on the plots.*
The graph will be changed to be easier to read and supply more information in a revised manuscript (see answers to referee #2 comments).

22. *Fig. 9: The spectra computed through the two methods exhibit differences at high frequencies, as stated by the authors, but also at medium and low frequencies. Why?*
The signal that is introduced by the ring port holes has contributions in all frequencies. A consistent noise spectra of this turbulent signal at the ring ports could not be found. See answers to referee #2 for a second example with less influence in the whole frequency range.

23. *Fig. 11: The caption should describe all the elements of the figure.*
A description of the phase response and all single lines in the plots will be added in the caption in the revised manuscript.

24. *Fig. 12, caption: Which "tubing system" and which "transducers" signals are illustrated here?*
The complete experiment is described in p.9794, l.5ff. The figure shows a comparison of the two tubing systems under investigation. The caption will be rephrased to make this more clear.

25. *Fig. 14, caption: Describe all the elements of the figure.*
A description of the different lines in the figure will be given in the caption in a revised manuscript.

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26. *Fig. 15: True airspeed is not a "meteorological" velocity (the signal involves the movements of the RPA with respect to the ground), so why should it follow the -5/3 power law in the inertial subrange?*
    The main difficulty of sensor response for turbulence measurement is in the high frequency range of the spectra. The inertia of the dynamics of the aircraft and the airspeed controller of the autopilot will not allow ground speed variations with frequencies of 1 Hz or higher. Therefore, dynamic pressure and true airspeed measurements can legitimately be used for turbulence measurement at high frequencies. True airspeed was consciously chosen over wind speed, in order to focus on the flow probe measurements in the analysis, and not have influences by the inertial measurement unit or GPS system.

27. *Fig. 15: Use conventional scientific notation on the axes (instead of "1e-05", etc.).*
    The notation will be changed in a revised manuscript to 10^{-5} etc. (see also the answers to referee #2).

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Fig. 1. Research RPA MASC. The position of the MHP approximately 15∼cm in front of the fuselage nose tip is depicted with the red ellipse.

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