

Reply to the Comment by Mauder on “How Well Can We Measure the Vertical Wind Speed? Implications for Fluxes of Energy and Mass”

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Abstract In Kochendorfer et al. (Boundary-Layer Meteorol 145:383–398, 2012, hereafter K2012) the vertical wind speed (w) measured by a non-orthogonal three-dimensional sonic anemometer was shown to be underestimated by $\approx 12\%$. Turbulent statistics and eddy-covariance fluxes estimated using w were also affected by this underestimate in w . Methodologies used in K2012 are clarified here in response to Mauder’s comment. In addition, further analysis of the K2012 study is presented to help address questions raised in the comment. Specific responses are accompanied with examples of time series, calculated correlation coefficients, and additional explanation of the K2012 methods and assumptions. The discussion and analysis included in the comment and in this response do not affect the validity of the methods or conclusions presented in K2012.

Keywords Angle-of-attack error · Cosine error · Eddy covariance · Energy balance closure · Sonic anemometer · Transducer shadowing

1 Introduction

We thank Mauder for his analysis and for providing a forum for further discussion of the experiment described in Kochendorfer et al. (2012, hereafter K2012). We agree that the significant sonic anemometer errors and the correspondingly significant flux errors presented in K2012 justify close scrutiny. Before addressing the specific points from Mauder (2013, hereafter M2013) it should be emphasized that none of the comments in M2013 includes a

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mechanism capable of causing the significant sonic anemometer bias demonstrated by K2012. In this respect, M2013 does not present any issues that undermine the main conclusions reached in K2012, which are:

- (1) The non-orthogonal sonic anemometers examined significantly underestimate the vertical wind speed.
- (2) The orthogonal sonic anemometer examined measures the vertical wind speed accurately.

The most serious criticism from M2013 describes a perceived turbulence sampling issue capable of inducing random errors on the wind-velocity corrections presented in K2012. It is suggested in M2013 that this sampling issue undermines the validity of the conclusions reached in K2012. M2013 states, “the correction factors presented by K2012 should be handled with care since the experimental design is fundamentally flawed,” but no explanation is offered for how the perceived flaws could produce the results presented in K2012. We demonstrate below that the errors related to small eddies and poor correlation between the spatially separated 0.1-s sonic anemometer measurements were actually quite small; but it should be stated here that even if they were significant they could not cause a prevailing measured underestimation of the vertical wind speed (w). An experimental flaw capable of causing such a prevailing underestimation of w would indeed be serious and “fundamental,” but the perceived flaw described in M2013 is not.

In K2012, the w measured by a tilted sonic anemometer was compared to the wind speed measured simultaneously using two adjacent and vertically oriented sonic anemometers. Over 1000 measurements were recorded at over 100 orientations, with a total of over 340,000 sub-selected 10-Hz conditional samples included in the final analysis. The K2012 w measurement errors were based on the average of these conditional samples. All of the sub-selected vertical velocities measured at a given orientation were averaged together before estimating the orientation-specific C_w . The prevailing underestimate of w found in K2012 was not based on the comparison of individual 0.1-s samples or the assumption that all three sonic anemometers always measured the same wind vector. Due to some prevailing bias, the tilted central sonic anemometer underestimated the mean w (W_t) in comparison to the mean wind-speed measurements made by the adjacent vertically oriented anemometers. Turbulent variability, random error, or insufficient sampling would increase the variance of the results, but it could not cause the prevailing bias observed in K2012.

The bias was present either in the sonic anemometers under examination or in the flow across the three sonic anemometers. Because the horizontal velocities measured across the sonic anemometer array were quite comparable, with an average correction to the horizontal velocity of 1.01, the indication is that the flow did not diverge in the cross-wind direction around the array. In addition, the vertical wind speed was significantly underestimated at both positive and negative angles-of-attack, so the vertical wind-speed underestimation was probably not caused by a vertical bias in the flow across the anemometers. With no evidence for a lateral bias in the horizontal or vertical flow across the sonic anemometer array, this indicates that the K2012 study produced estimates of a measurement bias in the sonic anemometer itself, as it was designed to do.

2 Specific Responses

Responses to the six questions raised in M2013 are provided below.

(a) *Can a similar underestimation of w with non-orthogonal sonic anemometers be seen from other intercomparison experiments?*

In the four sonic anemometer intercomparisons known to the authors that included an orthogonal ATI (Applied Technologies, Inc., Longmont, Colorado), (T. Horst, personal communication, 2012; Loescher et al. 2005; Mauder et al. 2007; Frank et al. 2012) the ATI consistently produced larger vertical wind-speed variances and covariances in all except the Loescher et al. (2005) study. The Mauder et al. (2007) sonic anemometer intercomparison also included an orthogonal Kaijo Denki (TR90-AH). Similar to the orthogonal ATI sonics in the same Mauder et al. (2007) study, the Kaijo Denki (TR90-AH) sonic measured significantly larger sensible heat fluxes and vertical wind-speed variances than the non-orthogonal anemometer used as the standard. With that exception, little has been published recently regarding the orthogonal Kaijo Denki anemometers, particularly with the TR-62X head, and the cross-comparison included in M2013 is clearly welcome and needed in this regard. The discrepancy between the M2013 Kaijo Denki intercomparison and most of the ATI intercomparisons may be due in part to the fact that the orthogonal ATI anemometers included the Kaimal et al. (1990) wind-shadowing correction, which was developed in conjunction with the ATI. However this does not explain why the Kaijo Denki sonic tested in Mauder et al. (2007) agreed with the ATI sonics included in that study in their measurement of larger vertical wind-speed statistics with respect to the standard.

As demonstrated in M2013, the results of such sonic anemometer intercomparisons are affected by the specific sensors used. In addition, the (co)sine corrections applied, the coordinate rotation (Leuning et al. 2012), the sonic anemometer firmware version (Burns et al. 2012), the orientation of the sonic anemometers with respect to the wind direction, and the flux-angle distribution (e.g. Gash and Dolman 2003) can all affect the results of such sonic anemometer intercomparisons.

(b) *Why should 1.2-m separated sonic anemometers “see” the same turbulent wind vector and hence show the same angle-of-attack?*

This question is based on a misinterpretation of the K2012 methods and assumptions. This is demonstrated by the fact that in M2013 two sonic anemometers separated by 7 m were compared. For both experiments, the physical separation of the sonic anemometers was addressed using the same assumption, which is that sufficient averaging allows for the comparison of wind velocity measurements separated by some distance. If sufficient averaging is performed and the mean flow is the same at the measurement locations, systematic differences in the mean measurements cannot be attributed to separation distance.

The primary experiment presented in K2012 did not require that the individual 0.1-s measurements be without random measurement error or recorded simultaneously within the same parcel of air. A high correlation coefficient between the 0.1-s wind vectors measured by the three sonic anemometers was not assumed, despite speculation to the contrary presented in M2013. Turbulence is defined as quasi-random variations around some mean, and the effects of turbulent variation on the mean wind speed can therefore by definition be removed by averaging. The K2012 experiment could actually have been performed with the sonic anemometers separated by a significantly larger distance. Further separation of the sonic anemometers would admittedly affect the application of the corrections; such corrections would be less specific to a given orientation due to increased differences in the angle-of-attack and wind direction between the measurement locations. An increased separation distance would therefore require an increased sample size and altered data selection requirements to create an accurate and representative C_w , but the K2012 experiment did not rely upon simultaneous measurement of the same wind vector by all the sonic anemometers. As demonstrated below in response to question (d) from M2013, averaging of the sub-selected measurements minimized the errors caused by spatial separation and sensor noise. The only strict requirements of the experiment in this regard were that the mean flow across all three sonic anemometers

Table 1 Mean correlation coefficients calculated from 0.1-s wind-speed measurements from the outer two sonic anemometers (a and b) and the center sonic anemometer (t) when all of the sonic anemometers were oriented vertically (a & b , a & t , b & t , and $(a + b)/2$ & t). Mean correlation coefficients calculated from the sub-selected actual wind-speed measurements estimated using the outer two sonic anemometers (act) and the sub-selected wind-speed measurement measured by the tilted center sonic anemometer (t) for all of the 0.1-s data used to create the K2012 Table 2 (act & t)

Anemometer	a & b	a & t	b & t	$(a + b)/2$ & t	act & t
w_{corr}	0.27	0.46	0.53	0.62	0.76
u_{corr}	0.78	0.86	0.88	0.92	0.97

was the same, and that the flow was sampled sufficiently to calculate a representative mean.

Although variability in the wind vectors measured by the three sonic anemometers in K2012 does not violate the experimental premises, the question of how well correlated the 0.1-s measurements are in the K2012 experiment still merits discussion. The M2013 correlation analysis was based on lagged data recorded from a single sonic anemometer, and is not directly applicable to the K2012 experiment. Data were sub-selected for inclusion in the K2012 analysis only when the angle-of-attack measured by both of the outer sonic anemometers was within $\pm 0.5^\circ$ of zero and the measured wind direction for both of these vertically oriented sonic anemometers was within $\pm 10^\circ$ of the perpendicular to the lateral axis of the anemometer array. The 0.1-s vertical wind speed measured by the tilted central sonic anemometer (w_t , where lower case is used here to indicate 0.1-s values) and the 0.1-s vertical wind speed estimated from the mean of the two horizontal wind-speed measurements from the two outer sonic anemometers (w_{act}) were used to create the mean W_t , W_{act} , and C_w (K2012, Eqs. 1–3). It is difficult to estimate the correlation of such quantities using a single vertically oriented sonic anemometer. Many of the conditions present in the K2012 experiment tended to increase the correlation between the 0.1-s wind speeds measured at the central sonic anemometer and the 0.1-s wind speeds derived from the outer sonic anemometers. This is demonstrated below using correlation coefficients calculated separately for every orientation, for all of the sub-selected 0.1-s data used to calculate C_w and C_u . For comparison with M2013, correlation coefficients were also calculated from 0.1-s data recorded during two periods when all three sonic anemometers were oriented vertically.

When all three sonic anemometers were oriented vertically, 26 half-hour periods of data were available with the mean wind speed $> 1 \text{ m s}^{-1}$ and the mean wind direction within $\pm 30^\circ$ of perpendicular to the lateral axis of the anemometer array. Correlation coefficients between 0.1-s wind speeds measured at the central sonic anemometer and 0.1-s wind speeds measured from the outer two sonic anemometers were calculated from all of the 10-Hz data from these 30-min periods. Agreeing remarkably well with the M2013 analysis, which was performed using lagged vertical wind-speed data recorded from a single sonic anemometer, the average vertical wind-speed correlation between the two outer sonic anemometers was 0.27 (Table 1). The correlation between the 0.1-s vertical wind speed measured using the central sonic anemometer with the vertical wind speeds measured from each of the outer sonic anemometers (w_a and w_b) were 0.46 and 0.53, respectively. The correlation coefficient between the 0.1-s vertical wind speed measured by the central sonic anemometer and the mean of the two 0.1-s vertical wind speeds simultaneously measured by the two outer sonic anemometers ($(w_a + w_b)/2$) was 0.62. As employed in K2012, averaging of the wind velocity measured by the two outer sonic anemometers significantly increased the correlation with

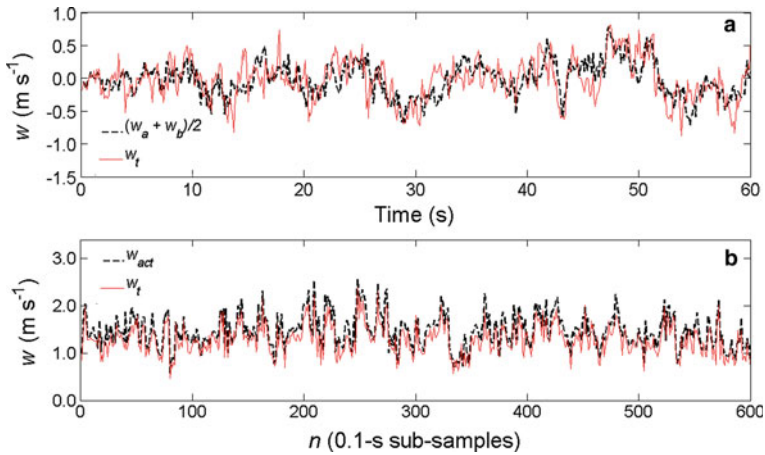


Fig. 1 Continuous 10-Hz vertical wind-speed (w) measurements from the central sonic anemometer (w_t , thin red line), and the average w measured by the two outer sonic anemometers ($(w_a + w_b)/2$, dashed black line) recorded during a period when all three sonic anemometers were oriented vertically (a). Conditionally sub-sampled 0.1-s vertical wind speeds used in the calculation of C_w ($C_w = W_{act}/W_t$, K2012) when the central sonic anemometer was oriented with $\alpha = 30^\circ$, wind direction = 90° (b)

Table 2 Mean vertical wind-speed corrections (C_w) and measured angles-of-attack (α_m) for all R.M. Young angles-of-attack (α) tested

α	-30°	-15°	-10°	-5°	5°	10°	15°	30°	45°
α_m	-23.8°	-14.0°	-8.8°	-4.3°	4.4°	9.7°	15.0°	26.5°	35.8°
C_w	1.24	1.07	1.13	1.16	1.13	1.03	1.00	1.12	1.21

the vertical wind speed measured by the central sonic anemometer (Table 1). An example of these data is shown in Fig. 1a. Using the same vertically oriented sonic anemometer data, correlation coefficients calculated for the 0.1-s horizontal wind-speed measurements were much higher, with a correlation coefficient between the two outer anemometers of 0.78, correlation coefficients between the individual outer sonic anemometers and the central sonic anemometer of 0.86 and 0.88, and a correlation coefficient between the mean of the two outer sonic anemometers and the central sonic anemometer of 0.92 (Table 1).

The sub-selection criteria used in the calculation of C_w and C_u further improved the correlation between the spatially-separated sonic anemometer measurements. This was particularly true for the orientations with larger angles-of-attack, where the measurements were more dependent on the more coherent horizontal wind speed. For every orientation included in Table 2 of K2012, correlation coefficients were calculated for the conditionally sub-selected data used in the estimation of C_w and C_u (Table 1). The mean correlation coefficient between the 0.1-s w_{act} and w_t measurements was 0.76, including the orientations with small angles-of-attack, where the small signal-to-noise ratio resulted in lower correlation coefficients. An example of the sub-selected w_{act} and w_t data is presented in Fig. 1b. The mean correlation coefficient between the 0.1-s w_{act} and w_t was 0.97, and it showed little variability with the angle-of-attack. In summary, the sub-selection criteria used in K2012, the coordinate transformation employed in K2012, and the averaging of the wind speeds measured by the two

outer sonic anemometers performed in K2012 produced a significantly higher correlation coefficient than that estimated in M2013.

(c) *Why does C_w not tend toward 1.0 as the angle-of-attack approaches zero, which is a prerequisite for this approach?*

After communicating personally with Dr. Mauder, we restate here our understanding of this comment:

K2012 relies upon the assumption that the error in w at near-zero angles-of-attack is zero because vertically oriented sonic anemometers were used to measure the wind vector when the measured angle-of-attack was near-zero. Because K2012 does not indicate that C_w approaches 1.0 at near-zero angles-of-attack, either the K2012 assumptions or the K2012 results are invalid.

The K2012 study did not actually rely upon the assumption that C_w approached 1.0 as the angle-of-attack approached zero. The vertical velocity measured by the vertically-oriented sonic anemometers was only relied upon to conditionally sub-sample the data; data were included in the C_w estimation when the angle-of-attack measured by the two vertically oriented sonic anemometers was within $\pm 0.5^\circ$ of zero. Although C_w is actually undefined at an angle-of-attack of zero, our results indicate that $C_w \approx 1.1$ as the angle-of-attack approaches zero. This w correction would result in an actual acceptable range of angle-of-attack of $\pm 0.55^\circ$. Such an increase in the size of the angle-of-attack range would not significantly affect the K2012 results.

Although we did not assume that the vertically-oriented sonic anemometers measured w accurately, we did assume that they measured the horizontal wind speed accurately. This assumption was based on the manufacturer's calibration, which was performed with the anemometers oriented vertically. The anemometers were calibrated in laminar flow however, allowing for the possibility that the calibration was not valid in turbulent flow. This basic measurement issue may merit further study, but it was beyond the scope of the K2012 experiments.

This question (c) from M2013 is also related to the presentation of the data and the assumptions implicit in different modes of presentation. Methodologies optimized to reduce the sine error (e.g. van der Molen et al. 2004; Nakai et al. 2006; Meyers et al. 2010) obscure the true impact of w errors. For example, we detected a 0.6° error in the sine response for the 5° angle-of-attack orientations, but in reality the corresponding 13 % w error was certainly not trivial (Table 2). Presentation of the sonic anemometer sine error erroneously implies that the sonic anemometer angle-of-attack error approaches zero as the angle-of-attack approaches zero. Vertical velocity corrections were presented in K2012 because they are more easily interpreted and they are directly applicable to eddy-covariance fluxes.

(d) *Are the C_w values presented in Fig. 4 of K2012 significantly different from one?*

For many of the orientations in Fig. 4 from K2012 the 0.1-s C_w values are not significantly different from 1.0. As Fig. 4 demonstrates, this is particularly true at small angles-of-attack. Figure 4 was based on individual 0.1-s C_w , and was included in K2012 to demonstrate the variability of the 0.1-s values at small angles-of-attack. It should not be used to estimate the significance of the mean C_w , however, which were calculated from more than 1000 individual measurements. In retrospect, more careful notation should have been used to differentiate the mean C_w from the 0.1-s C_w presented in Fig. 4. A more significant and separate question is if the mean C_w values presented in K2012 Table 2 are significantly different from one.

Wind velocity measurements recorded in turbulent flow must be averaged to produce representative values. The C_w published in the K2012 Table 2 were estimated as the ratio of two mean vertical velocities, not as the mean of many ratios. This method was chosen as it

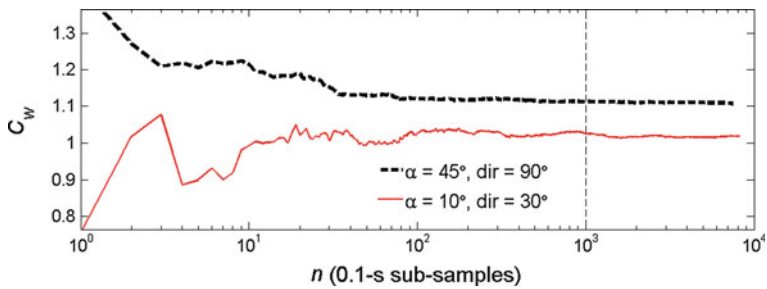


Fig. 2 C_w variability as a function of sample size for two of the sonic anemometer orientations selected for their large (>5000) sample size. The minimum number of samples was 1000

effectively weighted the samples based on the volume of air passing by the sensor, and it was also well constrained at small angles-of-attack. Samples with greater wind speeds carried more weight, and this was considered appropriate because these samples contained more information and were less sensitive to small errors. The specific averaging method employed was especially important at small angles-of-attack, where the 0.1-s w_t were occasionally zero or of opposite sign as the 0.1-s w_{act} (K2012, Fig. 4).

One estimate of the error in the C_w presented in K2012 Table 2 can be obtained by observing the variability in C_w with sample size. During the experiment, based on the first orientations tested, we empirically determined that a sample size of 1000 was needed to measure a representative C_w . In response to the M2013 question about C_w errors, further testing was performed on all of the orientations with more than 5000 sub-selected values ($n = 21$). Data from two such orientations are shown in Fig. 2. Including the smaller angles-of-attack, which demonstrated more sensitivity to sample size, the difference between the C_w estimated from the first 1000 values and the C_w estimated from all the values was always <0.02 . Similarly, using the same dataset of all the orientations with more than 5000 samples, C_w was estimated from the first, second, third, fourth, and fifth set of 1000 samples and compared with the C_w calculated from all of the available samples. The average error estimated using this method was 0.01. The largest difference between C_w calculated from 1000 samples and the ‘true’ C_w calculated from all of the available samples error was 0.03, and was measured at one of the 5° angle-of-attack orientations. These C_w error estimates can be used for all orientations, and in response to the M2013 question about the significance of the K2012 results, they indicate that most of the C_w values presented in K2012, Table 2 were indeed significantly greater than one.

(e) *What is the energy balance closure before applying the proposed correction for the data shown in Fig. 8 of K2012?*

The energy balance closure was $y = 0.88x - 5$ prior to applying the vertical wind-speed correction.

(f) *How large is the flow distortion of the ATI Vx measurements when the wind is not coming from ahead?*

We cannot answer this question because the ATI Vx probe was only tested from ideal wind directions, where minimal transducer wakes were expected to affect the vertical wind-speed measurement. It is true that from some wind directions the orthogonal sonic anemometer transducers used to measure the horizontal components of the wind velocity may induce transducer-shadowing effects on the w measurement axis. This problem is, however, dependent upon the specific orthogonal sonic anemometer design, and it does not indicate that the only important sonic anemometer design criterion is the ratio between the sonic path length

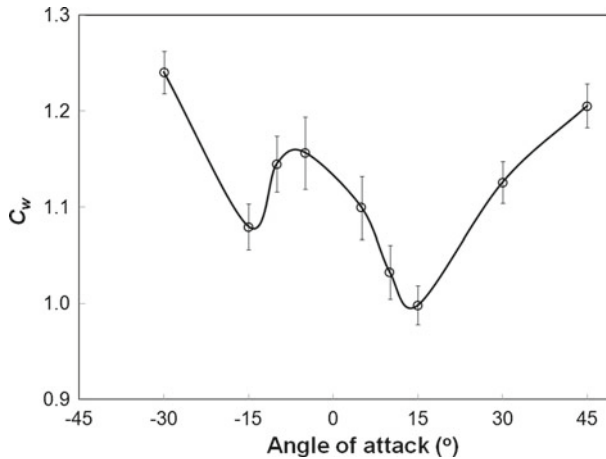


Fig. 3 Corrections to the vertical velocity (C_w) averaged by angle-of-attack. Error bars standard error of the C_w estimates available for every angle-of-attack

and the transducer diameter. Maximizing this ratio, maintaining a small measurement volume, and allowing for omni-directional wind vector measurements are all important design goals. Researchers must balance these requirements based on their specific needs and resources, and we are not suggesting that the ATI Vx style probe is ideal for all applications. It was, however, a useful tool in diagnosing an important problem, and K2012 indicates that orthogonal sonic anemometers can be used as a standard for eddy-covariance and vertical wind-speed measurements. More importantly, K2012 demonstrates that non-orthogonal sonic anemometers significantly underestimate the vertical wind speed at all wind directions.

3 Correction to Original Paper

Figure 3 from K2012 was not based on the final C_w results presented in K2012. The other figures, tables, statistical analyses, and discussions included in K2012 were all based on the correct and final results, and the corrected K2012 Fig. 3 is included here (Fig. 3).

Acknowledgments We thank Matthias Mauder for raising these questions, which prompted further analysis, discussion, and consideration among the authors. The exchange has expanded our own understanding of the experiment we performed, and others interested in this work will certainly benefit from this discussion as well. We also thank Tom Horst and Maggie Robinson for examining this response and providing valuable guidance.

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