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In this manuscript seven sonic anemometers from six non-orthogonal designs and four manufactures are compared during a two and a half-week study at the TERENO/ICOS site in southern Germany. Half-hourly mean wind velocity, mean and standard deviation of temperature, standard deviation of vertical wind velocity, friction velocity, and buoyancy flux were compared between the seven anemometers. In general, all anemometers were reasonably similar, with the largest discrepancy being temperature measurements with the Gill anemometers.

The topic of this study is timely, with a growing interest in the accuracy in sonic anemometer measurements. The work presented here is clear, convincing, and thorough. I believe there is one main comment and a few minor issues that need to be addressed before it is acceptable for publication in Atmospheric Measurement Techniques.

I have one main comment that should be addressed. The discussion states "it is also possible that the flow distortion errors were very small for our experimental set-up because the angles of attack are close to being surface-parallel" with support from Figure 9 showing that most angles were within ±6° with a majority falling within an even narrower window. I am concerned that there is a high likelihood that each of these non-orthogonal anemometers have erroneous and unpredictable measurements of σ_w for winds with very small angles-of-attack. This is described in Appendix 2 of Frank et al. (2016a) where it is demonstrated for the CSAT3 that as the angle-of-attack approaches 0° (i.e., near surface-parallel) that systematic *w* measurement uncertainties approach ±∞. This finding could be extended to any of the non-orthogonal anemometers included in this study, and I have included an Appendix at the end in this review to expand upon this topic. The discussion also states "The other interpretation that all anemometers are afflicted with the same bias appears less likely, since it is difficult to imagine that several instruments measure the same quantity equally wrong, despite the obvious differences in sensor geometry and internal data processing."

I suggest that "the other interpretation" might actually be true, that these systematic *w* measurement uncertainties that approach ±∞ could explain why these "instruments measure the same quantity equally wrong". A key component of this experiment is the inclusion of the CSAT3, which does not apply any transducer shadowing correction, which has been modeled (Huq et al. 2017) and observed (Horst et al. 2015) to have transducer shadowing errors that when transformed into orthogonal coordinates lead to unpredictable measurements for near surface-parallel winds (Frank et al. 2016a). It is nearly impossible to know exactly what happens for near surface-parallel winds, but a simple evaluation of the Kaimal correction (Kaimal et al. 1990) applied to the CSAT3 yields a range of ± ~4° where systematic measurement errors approach ±∞ as shown in Figure 3f of Frank et al. (2016a). Because most angles were within ±6° in this study, I consider it extremely likely that the CSAT3 data has such errors. At the same time, all other anemometers in this study are probably more susceptible to this problem because their transducers are all tilted closer to the horizontal plane (45° for the Gill, R. M. Young and Metek versus 60° for the CSAT3).

I have two suggestions that can help address this issue. First, the authors could do a sensitivity analysis to quantify the potential impact of transducer shadowing on the CSAT3 σ_w and buoyancy flux measurements. I would suggest using both the piecewise (Kaimal et al. 1990) and sinusoidal (Wyngaard and Zhang 1985) corrections presented in the following appendix. While it is important to note that there is no consensus that these corrections are accurate (two studies have shown that they might account for about half of the shadowing (Frank et al. 2016b, Huq et al. 2017)), this will help to evaluate the statement that "the flow distortion errors were very small". Second, in conjunction with the histogram in Figure 9, an analysis of the relative contribution of winds from each angle of attack bin to the total σ_w and buoyancy flux measurements would be useful. Figure 9 currently shows that most data is in the bins -1° to 0° and 0° to 1°. How important are the measurements in these bins to the total σ_w and buoyancy flux measurements reported in figures 5 and 8? What is the contribution of winds that exist within -4° to 4° (i.e., a range over which the Kaimal correction as applied to the CSAT3 could conceivably result in unpredictable measurements)?

I very much look forward to the authors' critical evaluation of this topic as I believe it will be an immense benefit to the research community to thoroughly discuss non-orthogonal wind measurements.

I have a minor comment about interpreting results based on offset/bias versus slope differences. My impression is that the authors focus more on offset/bias differences and less about slope. One example is on page 12, lines 4-5 "the fluctuations of sonic temperature agree much better". When I compared Tables 3 to 5, my attention immediately focused on the slopes, which are not much different. The average absolute difference from 1.00 (i.e., an extremely simple metric to summarize the group differences) was 4.0% for Table 3 (i.e., 1.05, 0.97, 1.01, 1.05, 1.06, 1.04 -> +5%, -3%, +1%, +5%, +6%, +4% -> (5+3+1+5+6+4)/6 = 4%) and 3.5% for Table 5. Similarly, on page 12, lines 12-14 it is commented the high slope of 1.06 "might be a direct consequence of the almost equally high regression slope of 1.05". This is not surprising, because ideally, slope errors in measuring T_s should commute to slope errors in σ_{Ts}.

Specific comments:
The introduction is excellent, and one of the better that I've read for sonic anemometer studies.
What is the sampling rate of the sonic anemometers?
Figure 2: It would be good to mention either on the figure or in the caption that the model of anemometer corresponds to the same names listed in Table 1.
Page 7, line 15: Are the obstructed wind directions based on 30-minute mean direction or some other metric?
2.2 Data processing: The software R should be cited, with details provided by the R function "citation()".
Table 2 and Figure 3: There is a slight difference in nomenclature between "mean wind velocity" and "total wind velocity". Based on the 2-D rotation, these should be the same, but consistent labels would be good.
Table 2 and 4. The slope difference between the CSAT3 anemometers is actually quite large (1.02 versus 0.97 for U and 0.98 versus 1.03 for σ_w). Do the authors believe that this is due more to the repeatability of measurements using the same anemometer design or to the 54 m separation distance?

Tables 2-7 and Figures 3-8: I could imagine all information from these tables could be moved to the blank space of the corresponding figures, thus saving space in the manuscript. I would also mention that something like R-squared values might be very useful to include as well.
Tables 3, 5, and 6: What was the metric used to identify "unusually large deviations from the etalon"? This should be mentioned in the methodology.
Page 12, Line 14-15: What does "agreement between the two CSAT3 is except for a few outliers" mean?
Page 13, line 4: "Yount" should be "Young".
Page 13, line 11-12: It could be noted that CSAT3_2 is the second lowest, so both CSAT3 are fairly low.
Figure 7: One of the ylabels are missing.
Page 16, line 6: "error of due" should be "error due".
Figure 9: Are the magnitudes of the numbers of y-axis correct? The number of occurrences seems extremely low for instantaneous 10 Hz or 20 Hz data. Or is this half-hour average angle-of-attack? The number of occurrences seems similar to the number of half-hours. If this is the case, then all text that refers to "small … angles of attack" (beginning with page 16, lines 25-26) must be revised to reflect the instantaneous angles experienced by the anemometers.
Page 18, line 11-14: The discussion of "type A" and "type B" should occur earlier in the paper than the conclusion.

Appendix. The measurement error of *w* using non-orthogonal sonic anemometers is unpredictable for near surface-parallel winds

A1. Defining the limit of the measurement error of w as the angle-of-attack approaches surface parallel

This examination of the measurement error of *w* expands upon Appendix 2 in Frank et al. (2016a). There, it was demonstrated that with a non-orthogonal sonic anemometer the measurement error of *w*, or conversely the correction for *w*, was unpredictable for near surface-parallel winds as long as any systematic errors occur with the individual transducers. That derivation was specific to the CSAT3 sonic anemometer, but the main conclusion can be generalized for other non-orthogonal anemometer designs.

For a CSAT3 sonic anemometer the original measurements in non-orthogonal transducer coordinates (u_A, u_B, and u_C) can be transformed into orthogonal sonic coordinates (u, v, and w) via matrix multiplication.

$$\begin{bmatrix} u \\ v \\ w \end{bmatrix} = \begin{bmatrix} -\frac{4}{3} & \frac{2}{3} & \frac{2}{3} \\ 0 & \frac{2}{\sqrt{3}} & -\frac{2}{\sqrt{3}} \\ \frac{2}{3\sqrt{3}} & \frac{2}{3\sqrt{3}} & \frac{2}{3\sqrt{3}} \end{bmatrix} \begin{bmatrix} u_A \\ u_B \\ u_C \end{bmatrix} \qquad \text{(A1)}$$

Conversely, original measurements in sonic coordinates can be transformed back into transducer coordinates via multiplication with the inverse matrix.

$$\begin{bmatrix} u_A \\ u_B \\ u_C \end{bmatrix} = \begin{bmatrix} -\frac{1}{2} & 0 & \frac{\sqrt{3}}{2} \\ \frac{1}{4} & \frac{\sqrt{3}}{4} & \frac{\sqrt{3}}{2} \\ \frac{1}{4} & -\frac{\sqrt{3}}{4} & \frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} u \\ v \\ w \end{bmatrix} \tag{A2}$$

If it is assumed that each transducer has systematic measurement errors that can be expressed as corrections (α_A, α_B, and α_C) that are functions of wind latitude (λ, i.e., wind direction) and longitude (φ, i.e., angle of attack), then the corrected $\widehat{w}$ is simply the sum of the corrected transducer measurements.

$$\widehat{w} = \frac{2}{3\sqrt{3}}\left[u_A\alpha_A(\lambda,\varphi) + u_B\alpha_B(\lambda,\varphi) + u_C\alpha_C(\lambda,\varphi)\right] \tag{A3}$$

The relative correction is expressed as the corrected $\widehat{w}$ divided by the original w.

$$\frac{\widehat{w}}{w} = \frac{2}{3\sqrt{3}}\left[\frac{u_A}{w}\alpha_A(\lambda,\varphi) + \frac{u_B}{w}\alpha_B(\lambda,\varphi) + \frac{u_C}{w}\alpha_C(\lambda,\varphi)\right] \tag{A4}$$

With substitution from Eq. A2 this can be expressed using only sonic coordinates.

$$\frac{\widehat{w}}{w} = \frac{2}{3\sqrt{3}}\left[\frac{-\frac{1}{2}u+\frac{\sqrt{3}}{2}w}{w}\alpha_A(\lambda,\varphi) + \frac{\frac{1}{4}u+\frac{\sqrt{3}}{4}v+\frac{\sqrt{3}}{2}w}{W}\alpha_B(\lambda,\varphi) + \frac{\frac{1}{4}u-\frac{\sqrt{3}}{4}v+\frac{\sqrt{3}}{2}w}{W}\alpha_C(\lambda,\varphi)\right] \tag{A5}$$

This can be further simplified to the following:

$$\frac{\widehat{w}}{w} = \frac{2}{3\sqrt{3}}\left[\left(-\frac{1}{2}\frac{u}{w}+\frac{\sqrt{3}}{2}\right)\alpha_A(\lambda,\varphi) + \left(\frac{1}{4}\frac{u}{w}+\frac{\sqrt{3}}{4}\frac{v}{w}+\frac{\sqrt{3}}{2}\right)\alpha_B(\lambda,\varphi) + \left(\frac{1}{4}\frac{u}{w}-\frac{\sqrt{3}}{4}\frac{v}{w}+\frac{\sqrt{3}}{2}\right)\alpha_C(\lambda,\varphi)\right] \tag{A6}$$

With $\tan(\lambda) = v/u$ and $\tan(\varphi) = w/\sqrt{u^2+v^2}$, the ratios u/w and v/w can be expressed as:

$$\frac{u}{w} = \frac{\cos\lambda}{\tan\varphi} \tag{A7}$$

$$\frac{v}{w} = \frac{\sin\lambda}{\tan\varphi} \tag{A8}$$

Eqs. A7 and A8 can be substituted into Eq. A6, which results in Eq. A17 of Frank et al. (2016a):

$$\frac{\widehat{w}}{w} = \frac{2}{3\sqrt{3}}\left[\left(-\frac{\cos\lambda}{2\tan\varphi}+\frac{\sqrt{3}}{2}\right)\alpha_A(\lambda,\varphi) + \left(\frac{\cos\lambda+\sqrt{3}\sin\lambda}{4\tan\varphi}+\frac{\sqrt{3}}{2}\right)\alpha_B(\lambda,\varphi) + \left(\frac{\cos\lambda-\sqrt{3}\sin\lambda}{4\tan\varphi}+\frac{\sqrt{3}}{2}\right)\alpha_C(\lambda,\varphi)\right] \tag{A9}$$

It is important to note that λ and φ are the original, or erroneous, wind direction and angle of attack measurements. An equation similar to Eq. A9 can be expressed with respect to the corrected angles $\hat{\lambda}$ and $\hat{\varphi}$:

$$\frac{w}{\widehat{w}} = \frac{2}{3\sqrt{3}}\left[\left(-\frac{\cos\widehat{\lambda}}{2\tan\widehat{\varphi}} + \frac{\sqrt{3}}{2}\right)\frac{1}{\alpha_A(\widehat{\lambda},\widehat{\varphi})} + \left(\frac{\cos\widehat{\lambda}+\sqrt{3}\sin\widehat{\lambda}}{4\tan\widehat{\varphi}} + \frac{\sqrt{3}}{2}\right)\frac{1}{\alpha_B(\widehat{\lambda},\widehat{\varphi})} + \left(\frac{\cos\widehat{\lambda}-\sqrt{3}\sin\widehat{\lambda}}{4\tan\widehat{\varphi}} + \frac{\sqrt{3}}{2}\right)\frac{1}{\alpha_C(\widehat{\lambda},\widehat{\varphi})}\right] \quad \text{(A10)}$$

In Eq. A9, the left-hand side is the relative correction while in Eq. A10 it is the relative error. Finally, as shown in Eq. A18 of Frank et al. (2016a), the limit of $\widehat{w}/w$ as the winds become near surface-parallel is:

$$\lim_{\varphi\to 0}\frac{\widehat{w}}{w} = \frac{1}{3}\left(\alpha_A(\lambda,\varphi) + \alpha_B(\lambda,\varphi) + \alpha_C(\lambda,\varphi)\right) + \frac{2}{3\sqrt{3}}\left[\left(-\frac{\cos\lambda}{2}\right)\alpha_A(\lambda,\varphi) + \left(\frac{\cos\lambda+\sqrt{3}\sin\lambda}{4}\right)\alpha_B(\lambda,\varphi) + \left(\frac{\cos\lambda-\sqrt{3}\sin\lambda}{4}\right)\alpha_C(\lambda,\varphi)\right]\lim_{\varphi\to 0}\frac{1}{\tan\varphi} \quad \text{(A10)}$$

As described in Appendix 2 in Frank et al. (2016a), this will approach $\pm\infty$ for most functions of α, unless $\alpha_A = \alpha_B = \alpha_C$ near the horizontal plane. The most notable solution for this is $\alpha_A = \alpha_B = \alpha_C$ = constant (i.e., there are no differences in transducer biases from different wind directions).

A2. Potential systematic measurement errors

At this point, the systematic measurements errors are described ambiguously. This was done to demonstrate that any systematic transducer error will cause uncertain *w* measurements when the angle of attack approaches 0°.

The most commonly described systematic measurement error is transducer shadowing (Kaimal et al. 1990, Horst et al. 2015, Frank et al. 2016b, Huq et al. 2017). This phenomena was demonstrated in wind tunnel experiments by Kaimal (1979) where measured wind velocities were underestimated when the angle between the wind and the transducer pair was within ~75°. For a CSAT3, each transducer pair is tilted 60° from horizontal which would suggest that for most surface parallel winds at least one transducer pair would experience transducer shadowing. Transducer shadowing has been shown to occur in the CSAT3 with large eddy simulations (Huq et al. 2017) and is supported by field observations (Horst et al. 2015). As shown by Kaimal (1979), the shadowing bias is stronger as the angle between the transducer pair and the wind becomes smaller. This should be concerning for other non-orthogonal designs with transducers tilted 45° from horizontal (e.g. anemometers from Gill, Metek, or R. M. Young) because for surface-parallel winds at least one transducer pair will experience an even smaller shadowing angle than occurs with the CSAT3.

Finally, it is important to note that *w* measurements will be uncertain for near surface-parallel winds, regardless of the magnitude of the systematic bias. Even the smallest of biases will cause $\widehat{w}/w$ to approach $\pm\infty$ as long as $\alpha_A(\lambda, \sim 0°) \neq \alpha_B(\lambda, \sim 0°) \neq \alpha_C(\lambda, \sim 0°)$. Yet, magnitude is important in determining the region of small angles-of-attack that can be considered uncertain. In Frank et al. (2016a), the Kaimal correction for a CSAT3 resulted in *w* being uncertain for $|\varphi| < \sim 4°$; their Bayesian posterior correction had a wider region of uncertainty with $|\varphi| < \sim 7°$. For anemometers that apply a calibration correction (i.e., Gill, R. M. Young, etc.) it is entirely possible that much

of this systematic bias has been removed. Yet, unless these calibrations perfectly mitigate the biases in near surface-parallel winds, there will exist some range of φ where measurements are uncertain. Whether that is $|\varphi| < 4°$, $|\varphi| < 3°$,$|\varphi| < 2°$, etc., is extremely difficult to determine without exact knowledge of the measurement error.

A3. A numerical illustration

Two examples are presented to numerically illustrate the measurement uncertainty in w. The anemometer is a CSAT3. In both cases, the wind is near-equatorial ($\varphi = \pm 1°$) and blowing toward $\lambda = -120°$ (i.e., above the lower transducer of pair B). Systematic errors related to transducer shadowing are evaluated as (1) a piecewise linear function of the angle between the wind and the transducer pair (θ) such that $u_{transducer}/\hat{u}_{transducer}$ = 1-0.16+0.16θ/75 for $\theta \leq 75°$ and 1 for $\theta > 75°$ (Kaimal et al. 1990) and (2) a continuous function $u_{transducer}/\hat{u}_{transducer}$ = 1-0.16+0.16sin(θ) (Wyngaard and Zhang 1985).

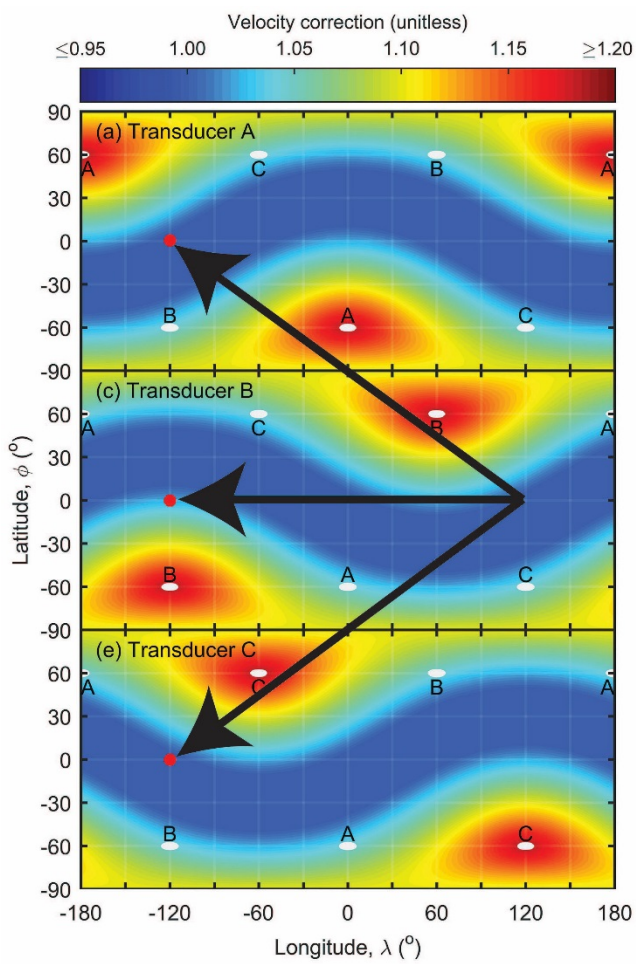

Figure A1. The location of winds in both examples. In this example of the Kaimal correction, transducers A and C will experience minimal shadowing error while transducer B (middle panel) will experience a small error, regardless of whether the wind is blowing slightly up or down. Figure borrowed from Frank et al. (2016a).

Example 1: λ = -120°, φ = -1°
In case 1, the wind is blowing slightly downward. The unit vector for this wind in sonic coordinates is:

$$\begin{bmatrix} u \\ v \\ w \end{bmatrix} = \begin{bmatrix} -0.4999 \\ -0.8659 \\ -0.0175 \end{bmatrix}$$

The corresponding transducer measurements are calculated using Eq. A2:

$$\begin{bmatrix} u_A \\ u_B \\ u_C \end{bmatrix} = \begin{bmatrix} 0.2348 \\ -0.5151 \\ 0.2348 \end{bmatrix}$$

For this example θ = 76.4°, 59°, and 76.4° relative to the A, B, and C transducer pairs, such that for (1) $u_{transducer}/\hat{u}_{transducer}$ is 1.0000, 0.9659, and 1.0000 for transducer pairs A, B, and C and for (2) $u_{transducer}/\hat{u}_{transducer}$ is 0.9955, 0.9771, and 0.9955, respectively. The transducer measurements are corrected by multiplying by the inverse of these errors, such that the corrected transducer measurements are:

$$\begin{bmatrix} \hat{u}_A \\ \hat{u}_B \\ \hat{u}_C \end{bmatrix} = \begin{matrix} \begin{bmatrix} 0.2348 \\ -0.5333 \\ 0.2348 \end{bmatrix} for\ (1)\ piecewise \\ \begin{bmatrix} 0.2359 \\ -0.5270 \\ 0.2359 \end{bmatrix} for\ (2)\ sinusoidal \end{matrix}$$

Finally, the corrected measurements in sonic coordinates are calculated using Eq. A1:

$$\begin{bmatrix} \hat{u} \\ \hat{v} \\ \hat{w} \end{bmatrix} = \begin{matrix} \begin{bmatrix} -0.5120 \\ -0.8869 \\ -0.0245 \end{bmatrix} for\ (1)\ piecewise \\ \begin{bmatrix} -0.5086 \\ -0.8809 \\ -0.0213 \end{bmatrix} for\ (2)\ sinusoidal \end{matrix}$$

The relative changes in *u*, *v*, and *w* after correction are: (1) +2.4%, +2.4%, and +40.0% for the piecewise linear function, and (2) are +1.7%, +1.7%, and +21.7% for the sinusoidal function.

Example 2: λ = -120°, φ = +1°
This case is similar except the wind is blowing slightly upward.

$$\begin{bmatrix} u \\ v \\ w \end{bmatrix} = \begin{bmatrix} -0.4999 \\ -0.8659 \\ 0.0175 \end{bmatrix}$$

$$\begin{bmatrix} u_A \\ u_B \\ u_C \end{bmatrix} = \begin{bmatrix} 0.2651 \\ -0.4848 \\ 0.2651 \end{bmatrix}$$

In this situation, θ = 74.6°, 61°, and 74.6° relative to the A, B, and C transducer pairs. The systematic biases for transducer shadowing are (1) 0.9991, 0.9701, and 0.9991 for transducers A, B, and C and (2) 0.9943, 0.9799, and 0.9943, respectively. The corrected measurements are:

$$\begin{bmatrix} \hat{u}_A \\ \hat{u}_B \\ \hat{u}_C \end{bmatrix} = \begin{matrix} \begin{bmatrix} 0.2653 \\ -0.4997 \\ 0.2654 \end{bmatrix} for\ (1)\ piecewise \\ \begin{bmatrix} 0.2666 \\ -0.4947 \\ 0.2667 \end{bmatrix} for\ (2)\ sinusoidal \end{matrix}$$

$$\begin{bmatrix} \hat{u} \\ \hat{v} \\ \hat{w} \end{bmatrix} = \begin{matrix} \begin{bmatrix} -0.5100 \\ -0.8834 \\ 0.0119 \end{bmatrix} for\ (1)\ piecewise \\ \begin{bmatrix} -0.5075 \\ -0.8791 \\ 0.0149 \end{bmatrix} for\ (2)\ sinusoidal \end{matrix}$$

The relative changes in *u*, *v*, and *w* after correction for (1) are +2.0%, +2.0%, and -31.8%, and for (2) are +1.5%, +1.5%, and -15.1%.

In both examples there are minimal changes to any of transducer measurements (between 0% and +3.5%). Also, there are minimal changes *u* and *v* (between +1.5% and +2.4%). But, there is a large disparity in the *w* correction between example 1 (+21.7% and +40.0%) and example 2 (-15.1% and -31.8%). The reason for this is because $w \sim u_a + u_b + u_c$ (Eq. 1). In example 1 the sum of $u_a + u_b + u_c$ is negative (-0.0455) and becomes slightly more negative with the stronger correction to transducer B (between -0.0552 and -0.0637). In case 2 this sum is positive (0.0454) and becomes slightly less positive with the stronger correction to transducer B (between 0.0310 and 0.0385). These examples also demonstrate that slight differences in characterizing the shadowing error result in very different corrections for *w*. In both examples, the largest difference between the piecewise versus sinusoidal equations for any transducer correction was < 1.2%. Yet, the correction for *w* differed by 18.3% in example 1 and 16.7% in example 2.

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