ORTHOGONAL PROBE PERFORMANCE FROM A NON-ORTHOGONAL SONIC ANEMOMETER

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1. Introduction

In the spring of 2014 we conducted an experiment in the backyard of Applied Technologies, Inc. comparing the performance of two of our sonic anemometers, the orthogonal K-Probe and the non-orthogonal A-Probe (Zimmerman et al., 2014). We were responding to concerns in the sonic anemometer user community about the reliability of vertical velocity measurements in the non-orthogonal versions. Agricultural and forestry scientists who had used them in very large numbers in their energy balance studies were finding underestimations on the order of 10-15% in the vertical winds and the heat fluxes computed from them. Observing stations that used orthogonal sonic anemometers did not have that problem. They came to the conclusion that the tilted geometry of the non-orthogonal probe was responsible for the underestimation (Frank et al., 2013).

2. Comparison Test

The two sonic anemometers were mounted side-by-side on top of a 10-ft tower, facing west, the prevailing wind direction, and their signals were monitored and processed in the ATI building 30 ft away. We had the luxury of waiting for the right wind conditions and experimenting with sampling rates and run durations to get the best visual representation of the turbulence we were dealing with. We were hoping to find in the analog traces of the wind and temperature fluctuations clues to the underestimations in the vertical winds and heat flux. In the K-Probe the vertical wind came directly from its vertical axis. In the A-Probe it was resolved from measurements along its three tilted axes (Kaimal and Zimmerman, 2014). Transducer shadow corrections are standard in the K-Probe. None were applied to the A-Probe axes. We settled on run durations of 25 min for unstable periods, which was long enough to catch major eddies and thermals, and 10 min for stable periods to avoid serious trends in temperature. Five-second averaged time series gave us the best definition of peaks and valleys in the velocity traces. Our observations covered a range of stabilities—from moderately unstable to lightly stable and winds from calm to over 8 m/s.

The data we have collected so far show surprising consistency (Zimmerman et al., 2014). Our initial look at the vertical wind W and the sonic temperature T statistics showed a steady 10% drop in the A-Probe W standard deviation and a 15% drop in $\overline{W'T'}$. Absent was any wind direction dependence common in non-orthogonal probes with three-prong transducer supports. We attributed this to our ring design. What we did find in the time series plots was an inclination angle dependence that suggested blockage of the sampling volume by the transducers and their ring supports. Comparing fluctuations of W and the wind inclination angle from the A-Probe, we could trace the diminished W peaks to when the inclination angles were larger than 30 deg. The effect on the $W'T'$ trace was more severe. Clearly, the underestimations that gave us the 10% and 15% drops in the statistical plots are not evenly distributed over the fluctuations, but biased toward high inclination angles.

3. Role for Corrections

To many users the most compelling feature of the non-orthogonal sonic anemometer was the small common sampling volume with its promise of finer spatial resolution and greater accuracy in its wind measurements. Those promises have long since been overshadowed by findings of underestimations in W and wind tunnel evidence of flow distortion within the sampling volume. Kochendorfer et al. (2012) describe a complicated correction scheme that depended both on wind direction and angle of attack. They did field tests to create a look-up table for each combination of wind direction and wind inclination angle to correct each vertical wind measurement.

With the data we have acquired so far we have come up with a far simpler approach to correcting all underestimations in the A-Probe. We start with the horizontal U and V which past observers had found acceptable. The U standard deviations from the A-Probe show a consistent 4% drop as seen in Fig. 1, possibly from flow distortions in the forward-pointing acoustic path. This is easily fixed with a 1.04 multiplier. The V component seen in Fig. 1 needs no such correction. For W, with its inclination angle dependence, the following equation seems to work well.

$$\text{W (corrected)} = \text{W (measured)} \times [1.05 + |\acute{a}| / 300] , \qquad (1)$$

where $|\acute{a}|$ is the magnitude of the inclination angle $\acute{a}$ (in degrees), calculated from each UVW reading. For an inclination angle of 30 degrees the correction factor would be 1.15, for 60 degrees 1.25 and so on. This corrected W can now be used to calculate a new $W'T'$ time series.

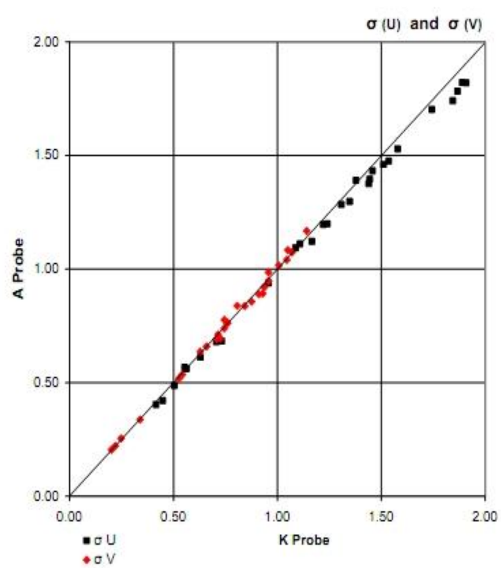

Figure 1. Scatter diagram of measured U and V standard deviations.

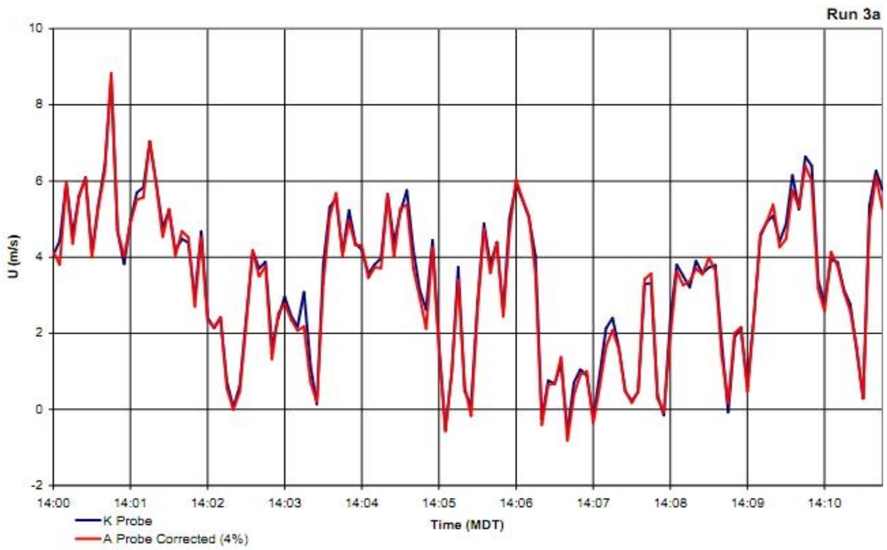

Figure 2(a). Plots of U with A-Probe raised 4%.

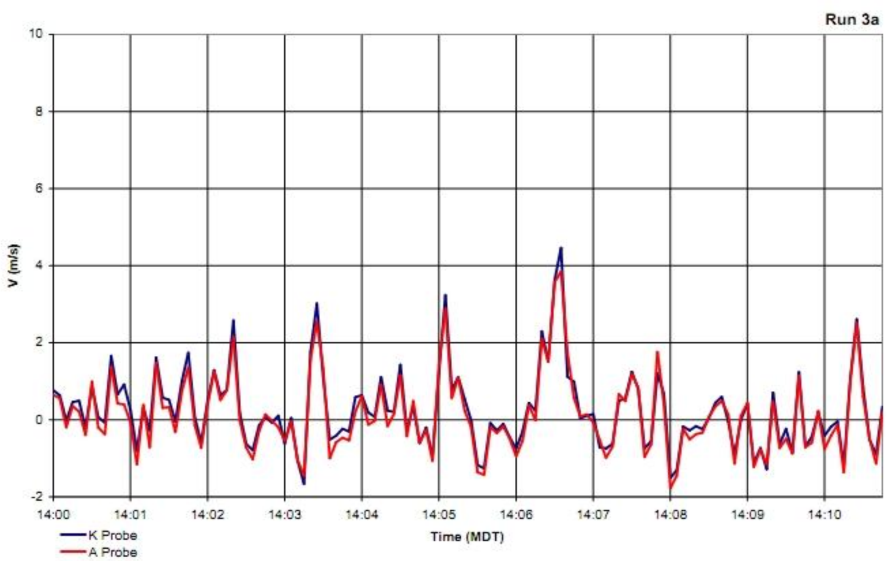

Figure 2(b). Plots of V with no corrections.

The effects of the above corrections are apparent in the time series plots of Fig. 2 and 3. The corrected U from A-Probe looks surprisingly like the K-Probe U. The corrected W has recovered most of its peaks, the $W'T'$ a little less so. The A-Probe's V needed no adjustment.

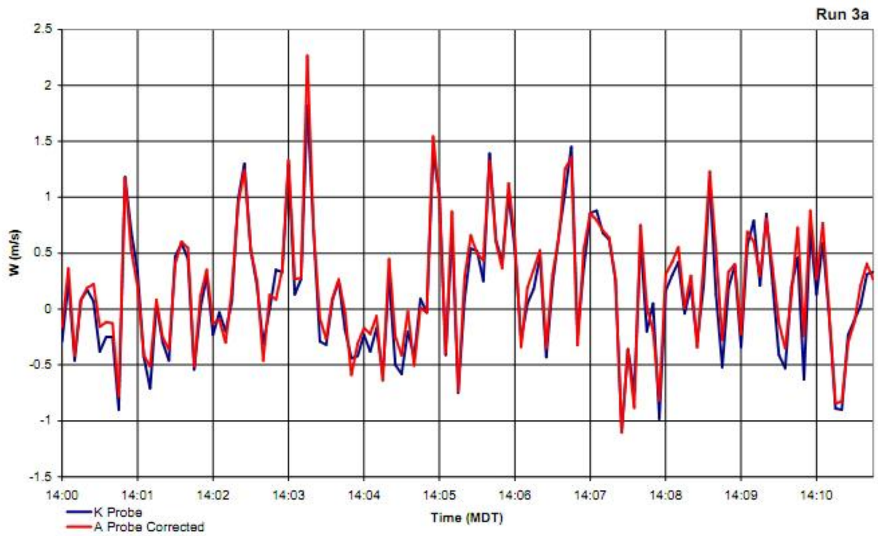

Figure 3(a). Plots of W with Eq. (1) correction on the A-Probe.

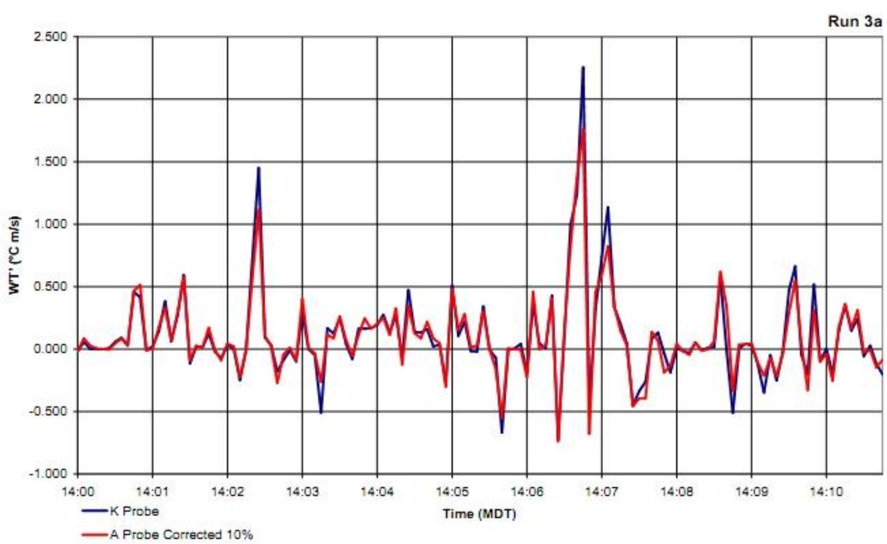

Figure 3(b). Plots of $W'T'$ with corrected A-Probe W.

The test of any correction scheme is how it applies to runs taken under different wind and stability conditions. We applied our corrections to data from all 26 runs represented in Fig. 1. The new standard deviations of U (not shown) fall in line as expected.

The standard deviations of W (in red) in Fig. 4(a) look very good except for a couple of points that essentially define the limits of Eq. (1). The over-corrected last point is a case of windless free convection and the under-corrected mid-point, the other extreme, strong steady horizontal winds.

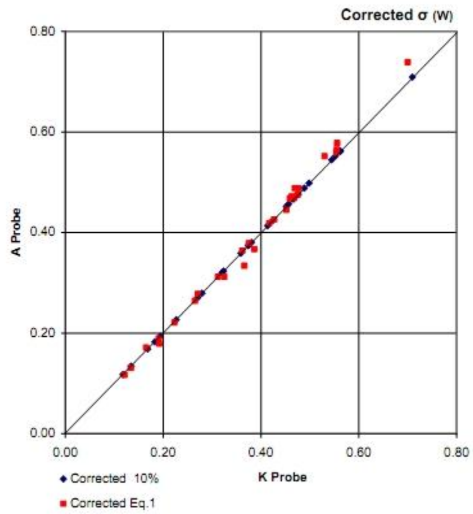

Figure 4(a). Scatter diagram of corrected W standard deviations.

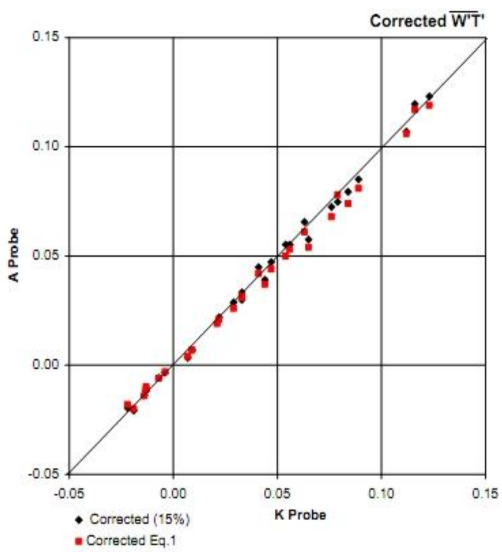

Figure 4(b). Scatter diagram of corrected WT covariances.

Against them, in black, are the straight 10% adjusted W which, not surprisingly, fall on the 1:1 line. The $\overline{W'T'}$ plots in Fig. 4(b) follow the same pattern. The 15% corrected data (black) show very good agreement. The Eq. (1) corrected points (red) have four points falling short by 5-10%, all cases of steady winds above 7 m/s with little convection. Thus, we have two correction schemes for W: one that offers excellent statistical data with just a percentage correction, but does not restore the peaks to their full value, and another that restores the peaks but falls short in their statistics under some conditions.

The constants 1.05 and 300 we picked for Eq. (1) were designed to provide a balanced enhancement of the W fluctuations, both at the peaks and in-between the peaks as in Fig. 3(a). The numbers can, of course, be changed to accommodate a much different mix of convective and shear turbulence.

4. Concluding Remarks

By looking closely at time series plots of the wind fluctuation from the two probes we have been able to trace the much-discussed underestimation of W in non-orthogonal probes to blockage of flow by the transducers and their supports. This showed up as diminished peaks in the W signal. The drops in these peaks allowed us to devise a correction scheme that restored the signals to K-Probe levels. The restored W also improved the $\overline{W'T'}$ peaks which were even more seriously impaired.

We also found that the measured standard deviations of W and U and the covariance $\overline{W'T'}$ from all the runs can be brought close to their K-Probe values with a straight percentage upgrade: 10% for W, 4% for U and 15% for $\overline{W'T'}$. To our surprise these corrections have turned out more consistent and dependable than the inclination angle correction when it comes to just statistical summaries. It gives the user the option of using the percentage corrections for statistical data and saving the inclination angle correction for eddy correlation calculations of fluxes of parameters like momentum and moisture. The lateral wind V and the sonic temperature T needed no corrections. For users who prefer their data with the percentage corrections included, we provide a parallel corrected set. Those users need to remember, however, that heat fluxes they calculate will need a 4.54% boost to bring them to the 15% corrected levels in Fig. 4(b). Any other flux calculations they do may need similar boosts.

Our findings clarified two assumptions that have been around for over 20 years. One was that the small common sampling volume of the non-orthogonal probe brought with it increased resolution and accuracy. Evidence was mounting that it instead brought flow distortion errors in W, the most critical of our wind components. Now we know what is happening. Happily for the A-Probe, the corrections are fairly simple, an unexpected consequence of our ring design. The second arose from concerns about the vertical spacing between the U and V axes in the K-Probe. We had not been recommending its use below 15 ft. Horizontal winds were not the main focus of this study, but the agreement we found between the K-Probe and the A-Probe U and V traces at 10 ft has been most reassuring. For the most demanding applications we recommend the K-Probe. The rugged A-Probe is more appropriate for higher elevations and stronger winds. Both probes offer research grade data that the user can trust.

REFERENCES

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