Flow-Distortion Errors in a Non-Orthogonal Sonic Anemometer

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Part 1 - UNDERSTANDING NON-ORTHOGONAL SONIC ANEMOMETERS

Non-orthogonal sonic anemometers have been around for about twenty years. We define them as having three measurement axes inclined at an angle of 60 deg to the horizontal and intersecting at their midpoints to form a small sampling volume. The open aspect of the array was immediately appealing to users. There are several makes on the market and each solved the problem of holding the transducers in place in different ways. Zhang at al. (1986) have analyzed the response characteristics of an earlier array and Oncley et al. (1996) have described how the data from that instrument were treated and analyzed after a field experiment in Wyoming. A large majority of the users today have this type of anemometer. Still available are ATI's orthogonal sonic anemometers for those who prefer to get their vertical wind component directly from a vertical probe and take the consequences: spatial separation between the sampling volumes in two models and possible interference from support structures in the others. The orthogonal arrangement makes transducer-shadow corrections easier on measurements in real time (Kaimal et al., 1990). Many agricultural and forestry stations continue to use the orthogonal probes.

Investigators who have data collected from all their sites (Kochendorfer et al., 2012 and Frank et al., 2013) are finding that data from stations using the non-orthogonal probes were underestimating both the vertical wind component and the heat flux by about 15% compared to those using ATI's orthogonal K-probes. This seems to match the discrepancy in the energy budget calculations from those sites, implying a possible connection. Could the non-orthogonal configuration be responsible for underestimating the vertical wind? Earlier comparison tests revealed differences of this magnitude, but it was assumed the orthogonal probes were the ones reading too high. Perhaps the transducer-shadow corrections are superfluous! The exhaustive tests and analyses reported by these two groups of investigators make it clear that the non-orthogonal probes, for reasons unknown, were indeed underestimating the vertical wind. The orthogonal probes in the tests seemed to have no trouble sensing the wind to within 1% accuracy. Kochendorfer et al. recommend application of an angle of attack correction to fix old data but adding a vertical axis to future sonic probes for a better vertical wind. Frank et al. conclude that the underestimation is intrinsic to the non-orthogonal configuration.

We think the problem lies buried in the way the coordinate transformation works and it may be making the vertical wind component particularly prone to underestimation. That is the variable we most need to be accurate for its effect on the vertical flux estimates that go into the energy balance calculation. The transformation has a surprisingly simple form.

Figure 1 - Lineup of Campbell Scientific non-orthogonal probes beside an ATI orthogonal probe (center) in a comparison test described by Frank et al. (2013)

Assume u_A, u_B, and u_C are the wind components along the axes (A, B, C) of the non-orthogonal probe, all pointing upward, and U, V, and W are the orthogonal wind components referenced to the probe as in Fig. 1 (U is pointing in the same direction as u_A, and W is along the assigned vertical for the probe). It is clear from the probe geometry that the wind components u_A, u_B, and u_C can be expressed as:

$$u_A = U \cos 60 + W \sin 60 \qquad (1)$$
$$u_B = -U \cos 60.\cos 60 + V \sin60.\cos60 + W \sin 60 \qquad (2)$$
$$u_C = -U \cos 60.\cos 60 - V \sin60.\cos60 + W \sin 60 \qquad (3)$$

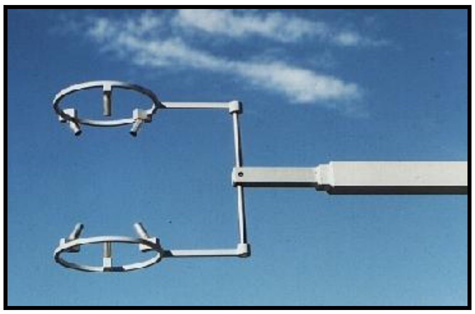
Solving for U, V, and W leads directly to the coordinate transformation equations:

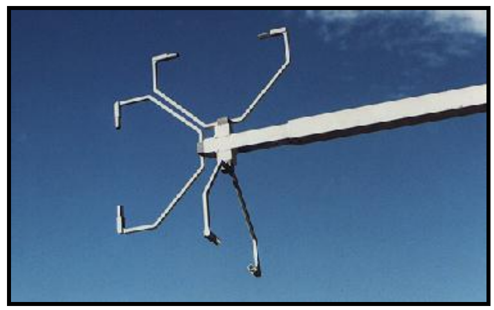
$$U = 1.33\, u_A - 0.67\, (u_B + u_C) \qquad (4)$$
$$V = 1.15\, (u_B - u_C) \qquad (5)$$
$$W = 0.385\, (u_A + u_B + u_C) \qquad (6)$$

The coefficients in the equations above are what is left of the sines and cosines of 60 deg in (1), (2), and (3). This expression renders the inner operation of the instrument much more transparent than the more complex formulation by Zhang et al. for the mean wind vector.

We can test this transformation by assuming that only the W component exists. The three sonic axes will each read this as (W sin 60) and 1/ (3 sin 60) is the 0.385 we see in (6). This works because the contributions from U and V in (1), (2), and (3) cancel out precisely to give us W. In practice, however, they may not cancel out. We have probe axes pointing in three different directions, occupying three different spaces and subject to shadowing and flow distortions from probe supports and transducers in adjacent channels. The un-cancelled remnants of the U and V contributions will show up as "noise" in the calculated W. To determine how serious the problem can be, and under what conditions, we need to compare W traces from a non-orthogonal probe with those from a single vertical probe mounted next to it.

We believe the non-orthogonal configuration also creates an extra sensitivity to blockage of the vertical wind flow. This is because the W deficits from the three probe axes simply add up, whether the flow is up or down. Imagine being in the middle of a large convective updraft (or downdraft) and it is easy to visualize how W can be degraded by the support structures in many commercial anemometers. The stronger the updraft (or downdraft) the greater could be the deficit. This too can be spotted through comparison with a vertical probe.





Figures 2a and 2b - ATI's new non-orthogonal A-Probe and their K-Probe for inter-comparison tests

To address the blockage problem Applied Technologies has been working on a new probe design that will permit vertical air flow through the space between adjacent transducers. In their ATI A-Probe (Fig. 2a), the transducers are mounted on two rings (separated vertically) to form a non-orthogonal array. Some prototypes have been tested, but our goal now is to compare the U, V, and W signals from an A-Probe with those directly measured by an ATI K-Probe (Fig.2b) mounted close to it. We plan to check the signals as well as the statistics from the digital readings to learn in detail how the non-orthogonal probe works and whether the A-Probe design represents a significant improvement. We will be presenting our findings as they unfold.

Part 2 - ORTHOGONAL AND NON-ORTHOGONAL SONIC ANEMOMETERS COMPARED

1. Introduction

The performance of non-orthogonal sonic anemometers has been the subject of much discussion in recent years. It followed findings that they underestimated vertical winds and vertical heat fluxes by 10-15%. For agricultural and forestry scientists who depended on them for their large-scale energy balance studies this was a bad surprise. They had collected turbulence data from hundreds of monitoring stations and found imbalances of that order in stations using non-orthogonal probes. The probes were supplied by three different vendors: R. M. Young, Gill Instruments, and Campbell Scientific. The stations (fewer in number) that used orthogonal sonic anemometers (ATI's K-Probes, Sx-Probes and Vx-Probes) seemed to do well.

Studies of past field data and the results of their own inter-comparison experiments led the scientists to conclude that the underestimations were a consequence of the non-orthogonal design and that the best vertical winds were those measured along a vertical acoustic path. The exact cause of the underestimation was never determined.

In a Part 1, we started to look for clues to this underestimation in the coordinate transformation equations. We wondered if there is something in the equation for the vertical component that made it vulnerable to interference from the probe's support structure. The equations we examined converted wind measurements along the three tilted paths to components along fixed orthogonal coordinates as defined in the ATI - K-Probe: U along the probe's support boom, V pointing sideways and W vertical. W turned out to be simply the sum of the winds along the three tilted axes (times 0.385). Any slowing down of winds along the non-orthogonal paths would directly affect W. Support structures needed to hold the transducers in place could cause that if the updrafts and downdrafts encountered are steep enough. If such events are frequent, how badly would they distort the W signals? To answer that we needed to look at actual signals from orthogonal and non-orthogonal sonic anemometers over a range of atmospheric conditions.

2. Test Set-up

We were able to conduct our own comparison tests in the spring of 2014 in ATI's backyard. By then we had developed our own non-orthogonal sonic anemometer-thermometer, the A-Probe seen in Fig. 1, mounted next to our K-Probe on a 10 ft tower facing west.

Figure 1 - The A Probe and the K Probe on a 10 ft tower facing west.

In the A-Probe the transducers are mounted on two rings to allow for easier vertical air flow in the space between the transducers. Path lengths are set at 15 cm, same as in the K-probe, but the sonic temperature is calculated along the forward-tilted path. In the K-Probe, the vertical path served both W and T. This K-Probe had been the subject of Dagle's sonic thermometry studies (Dagle and Zimmerman, 2014) and we knew we could trust it. Having temperature signals enabled us to compare kinematic heat flux (W'T') signals alongside W to see if their underestimations match. (The primes indicate departures from the mean.)

We limited our time series to 5-sec averages of U, V, W and T to minimize the effect of spatial separation between the probes. The signals were processed in the ATI building about 30 ft from the tower. We recorded data in 25-min segments which were long enough to catch significant fluctuations encountered under daytime conditions. At night we had to limit it to 10 min to keep trends in temperature to a minimum. In all cases we were careful not to let the wind directions stray much beyond 45 deg in either direction to prevent the probes from getting in each other's way.

3. Observations

The data collected so far show a very consistent pattern. Under moderately unstable to slightly stable conditions the two probes track U, V, and T very closely but W is clearly being underestimated by the A-Probe. The scatter diagrams in Fig. 2 show a steady 10% drop in the standard deviation of W and a 15% drop in $\overline{W'T'}$.

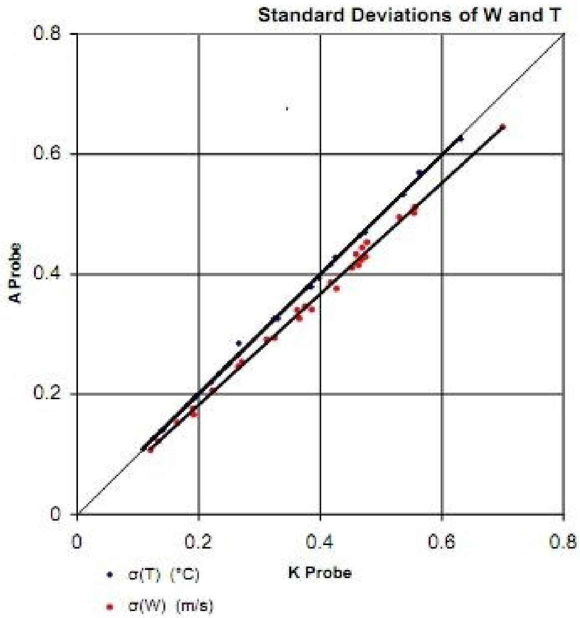


Figure 2(a): Non-orthogonal A-Probe.

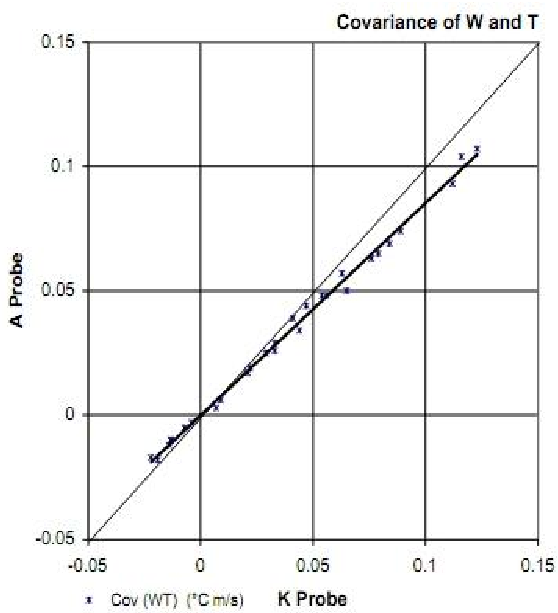


Figure 2(b): Orthogonal K-Probe.

These numbers are close to what Frank et al. (2013) had reported. We seem to be confirming their observation that the underestimation in a non-orthogonal probe is intrinsic to the tilted probe geometry, not a function of the vendor's design preference. What surprised us was the larger drop in $\overline{W'T'}$. We had assumed the two shared the same underestimation.

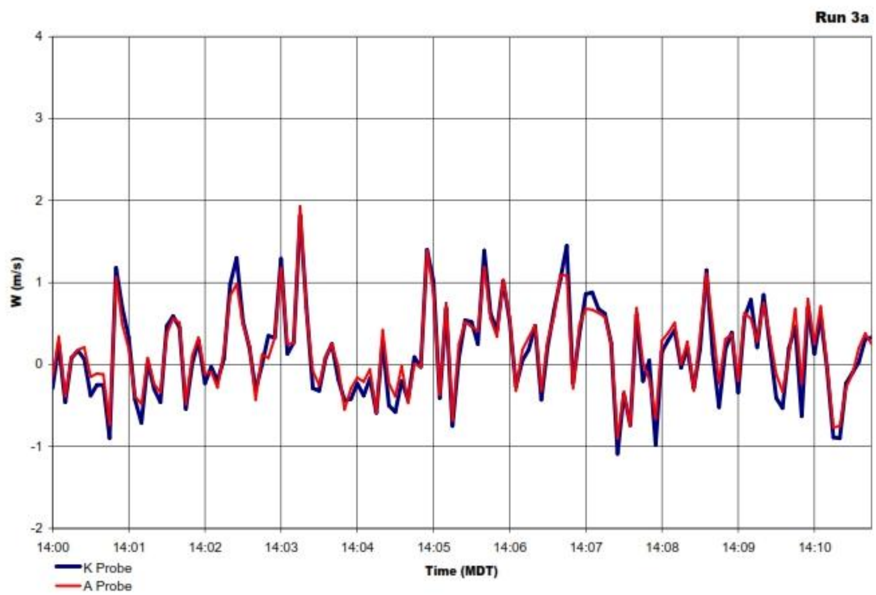


Figure 3(a): Plot of W fluctuations during Run 3(a).

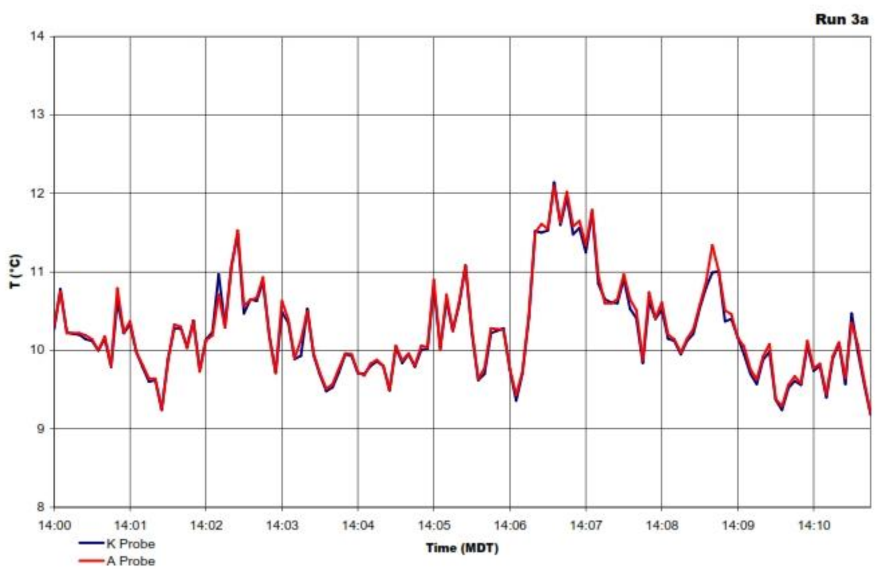


Figure 3(b): Plot of T fluctuations during Run 3(a).

We expanded a 10-min segment of one of our earlier runs (Run 3) looking for patterns in the distribution of the underestimation. The plots presented in Figs. 3 and 4 are typical for a brisk afternoon in March with 4-6 m/s winds and its mix of eddies and thermals. The A-Probe follows the K-Probe temperature closely but selectively misses the peaks in W by more than 10%.

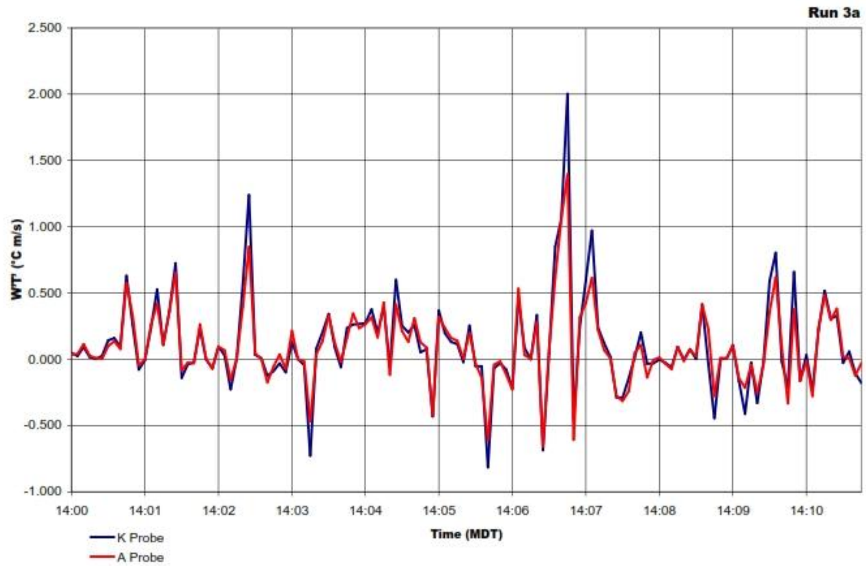


Figure 4(a): Plot of W'T' fluctuations during Run 3(a).

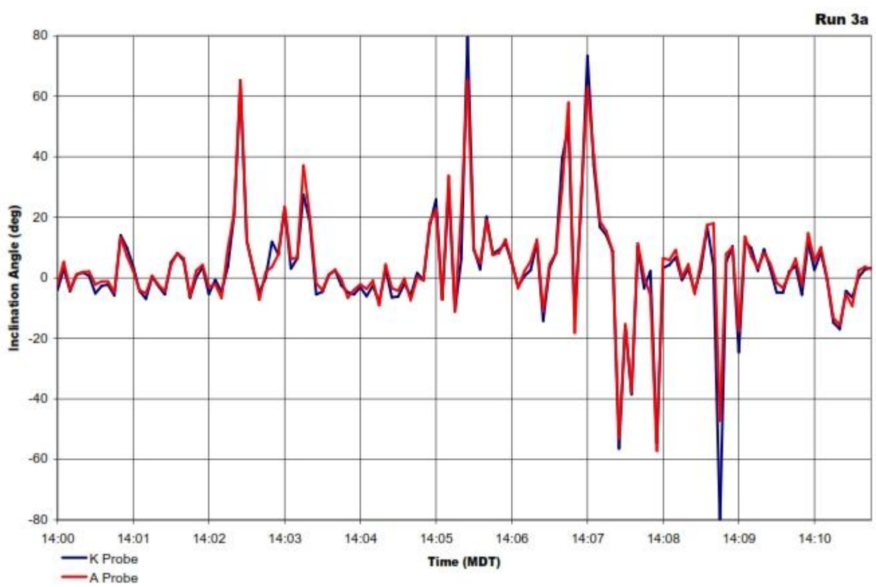


Figure 4(b): Plot of wind inclination angles during Run 3(a).

The deficits in W'T' are even more pronounced, 25-30%, and well coordinated with peaks in W. The wind inclination plot in Fig. 4(b) makes it clear that the episodes of large underestimation coincide with wind inclinations greater than 30 deg. Although intermittent, they are frequent, with slopes often exceeding 50 deg. Gill Instruments, for one, had recommended keeping the angle to within 10 deg of the horizontal and warned against going over 30 deg. We know what happens when we exceed 30 deg with our A-Probe. We can see how it degrades W and $\overline{W'T'}$ and how it shapes the statistics in Fig. 2.

4. Conclusions

The consistency in our data leads us to believe that with proper corrections the A-Probe can be relied on to provide dependable turbulence statistics. That would be adequate for many applications. The ring design of the A-Probe may not have helped the underestimation, but seems to have removed the directional dependence found in earlier non-orthogonal probes that called for elaborate angle-of-attack corrections (Kochendorfer et al., 2012).

For users who prefer their vertical data uncontaminated, the K-Probe offers the best hope at 10-ft heights and above. With its very close agreement in horizontal wind components to the A-Probe, the benefits of the latter’s small common volume seem more illusory than real. For the wary, ATI has an Sx-Probe that brings the horizontal axes closer together, at the price of some mutual interference in U and V.

We plan to continue our observations through the summer of 2014, looking at events in more detail.

Part 3 - ORTHOGONAL PROBE PERFORMANCE FROM A NON-ORTHOGONAL SONIC ANEMOMETER

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.

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

Where, $|\alpha|$ is the magnitude of the inclination angle α (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.

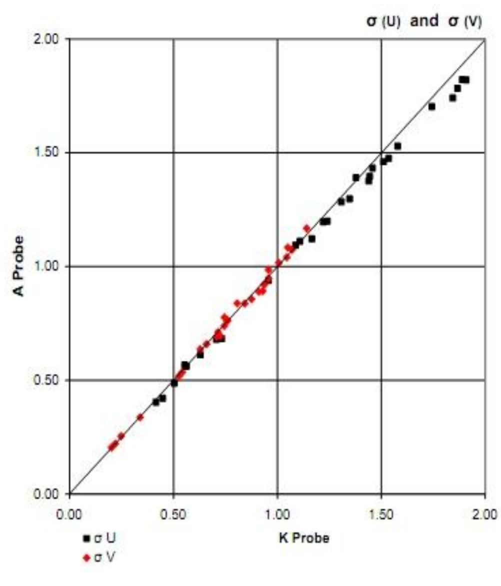


Figure 1. Scatter diagram of measured U and V standard deviations.

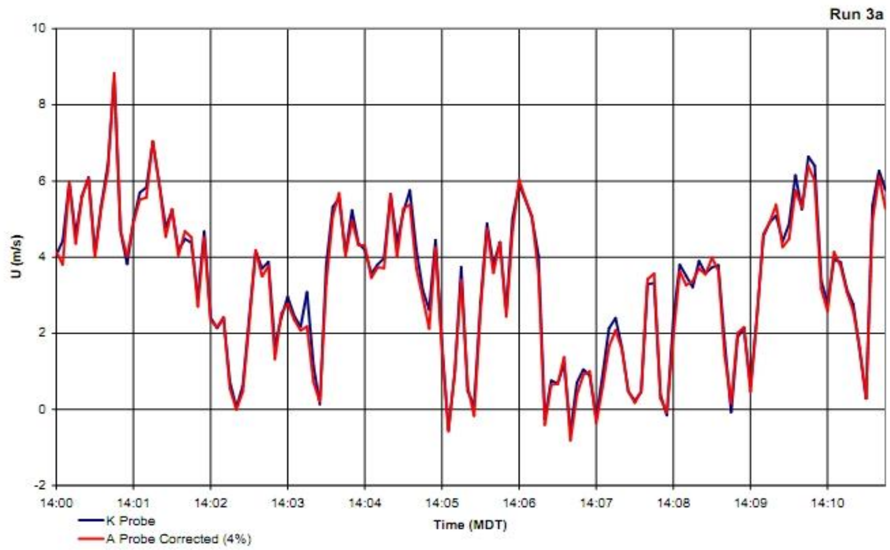


Figure 2(a). Plots of U with A-Probe raised 4%.

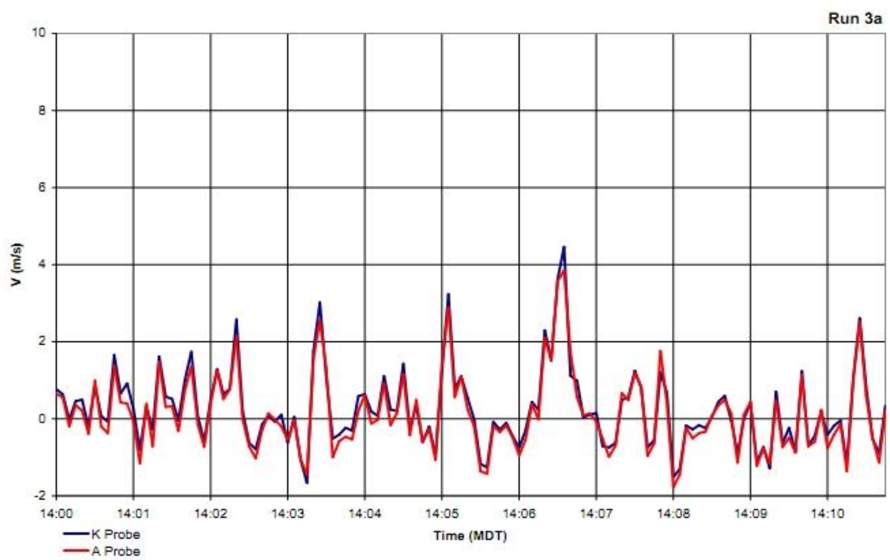


Figure 2(b). Plots of V with no corrections.

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.

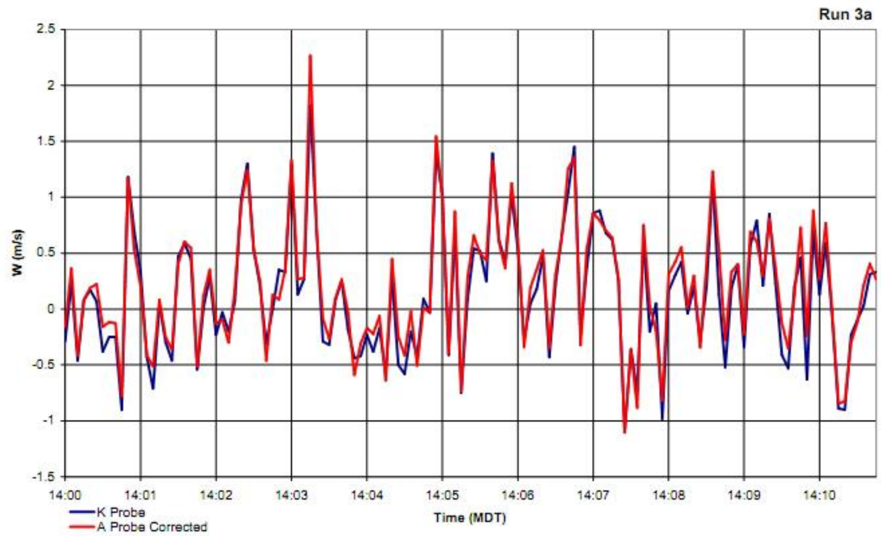


Figure 3(a). Plots of W with Eq. (1) correction on the A-Probe.

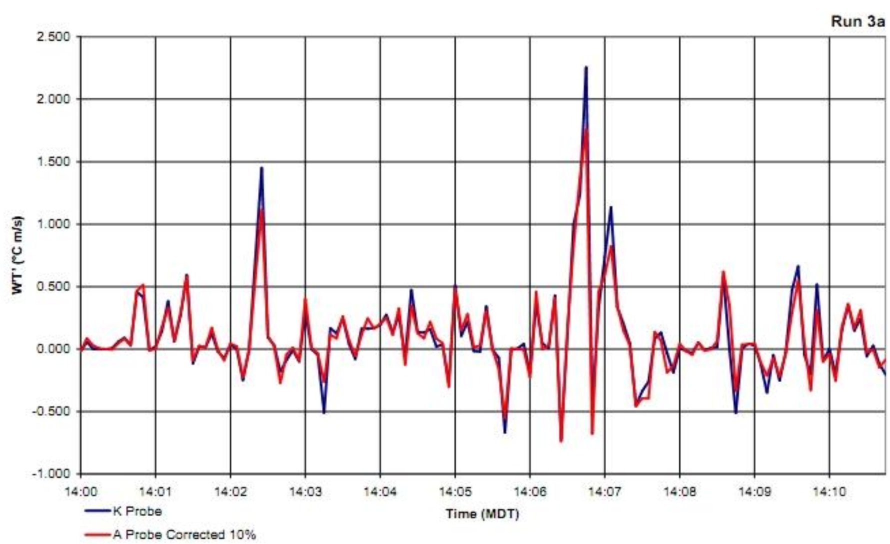


Figure 3(b). Plots of W'T' with corrected A-Probe W.

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.

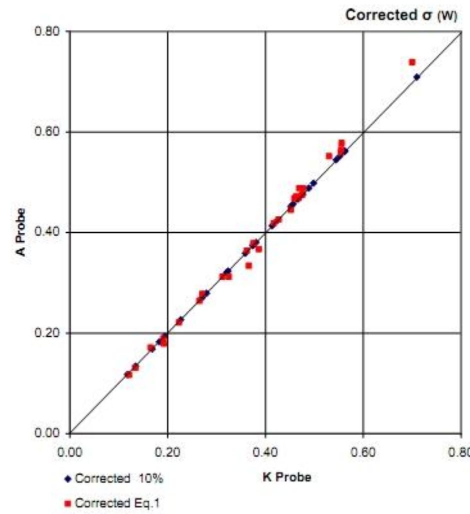


Figure 4(a). Scatter diagram of corrected W standard deviations.

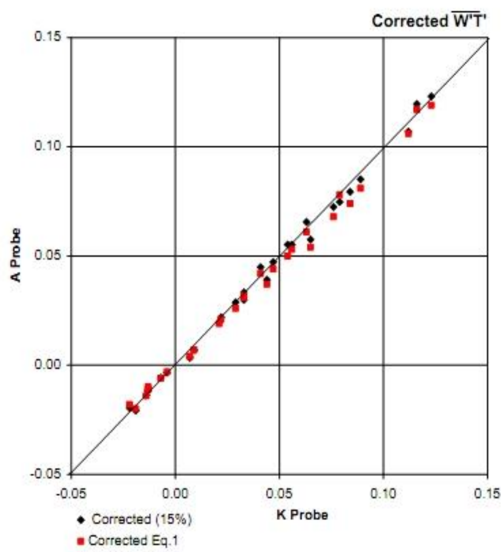


Figure 4(b). Scatter diagram of corrected WT covariances.

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 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.

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