ORTHOGONAL AND NON-ORTHOGONAL SONIC ANEMOMETERS COMPARED

H.A. Zimmerman, W.R. Dagle, and B.A. Dagle,
Applied Technologies, Inc., Longmont, CO 80501
and
J.C. Kaimal
Hamilton, NY 13304

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 intercomparison 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 recent Applied Technologies Application Note (Kaimal and Zimmerman, 2014), 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 $\overline{W'T'}$.

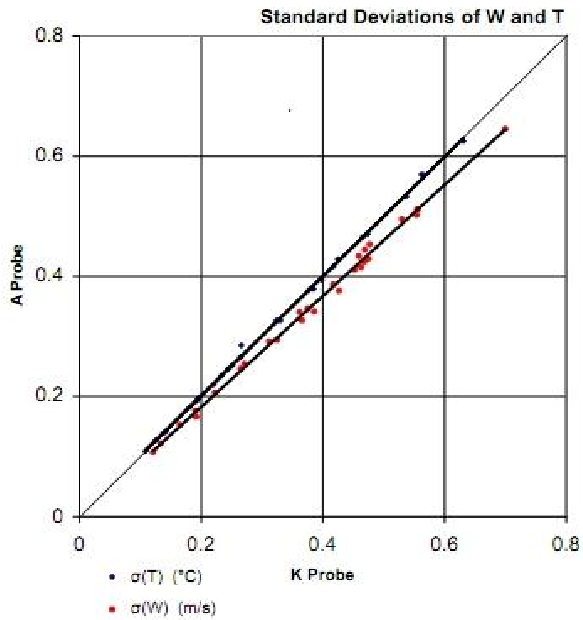

Figure 2(a): Scatter diagram of W and T standard deviations.

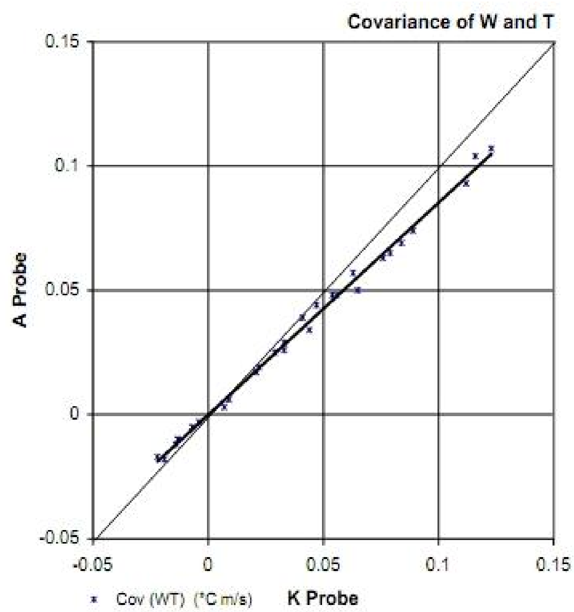

Figure 2(b): Scatter diagram of $\overline{W'T'}$.

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.

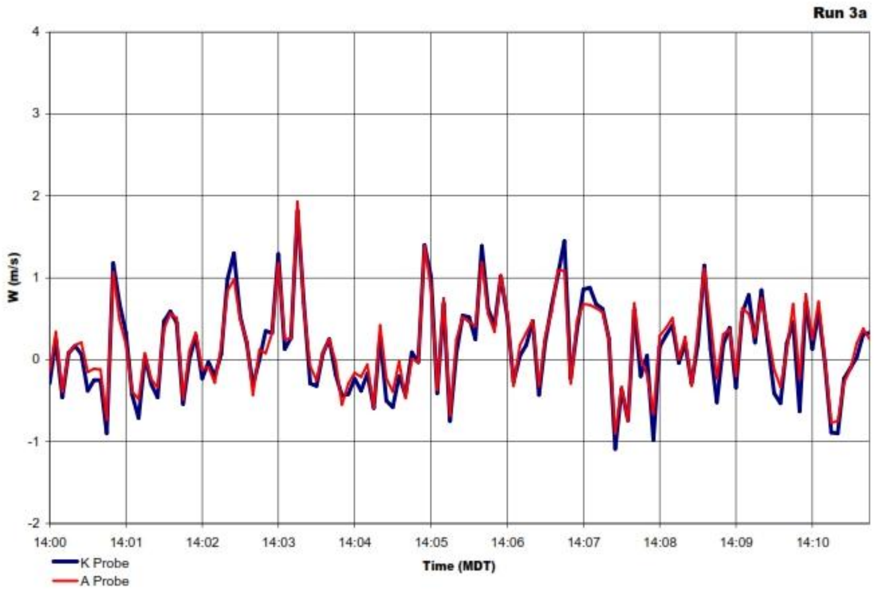

Figure 3(a): Plot of W fluctuations during Run 3(a).

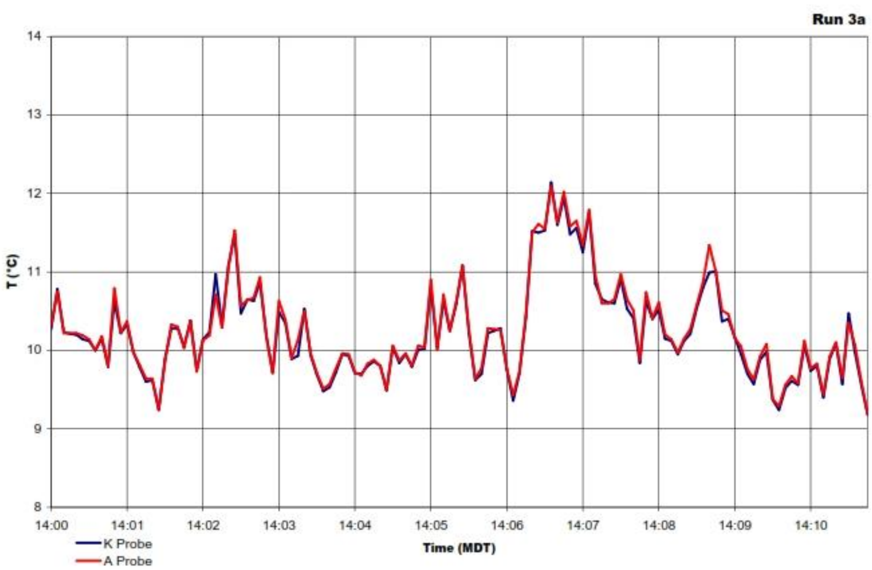

Figure 3(b): Plot of T fluctuations during Run 3(a).

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%.

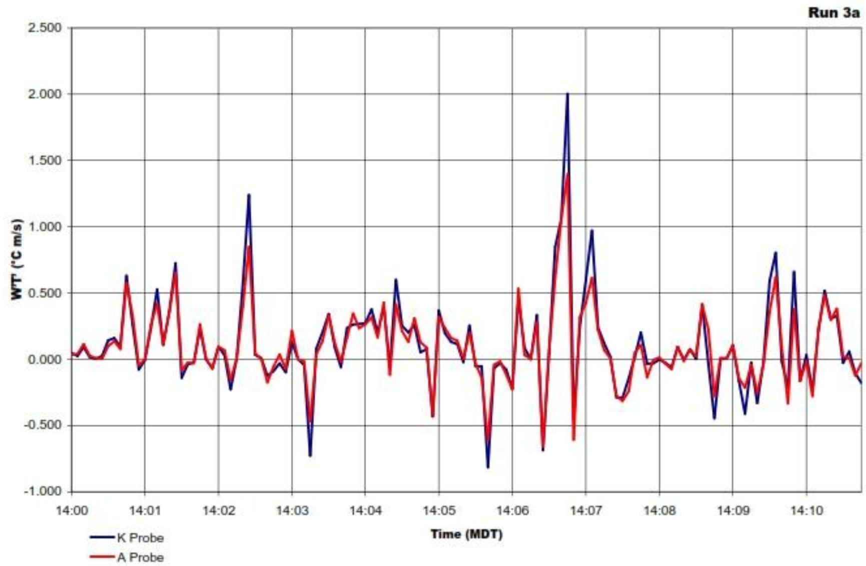

Figure 4(a): Plot of W'T' fluctuations during Run 3(a).

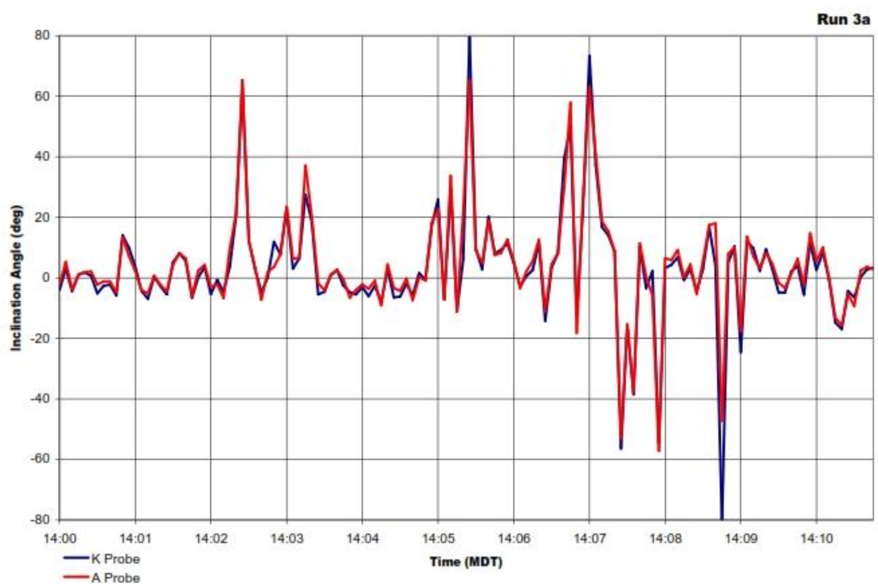

Figure 4(b): Plot of wind inclination angles during Run 3(a).

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.

REFERENCES

Frank, J.M., W.J. Massman, and B.E. Ewers, 2013: Underestimation of heat flux due to vertical velocity errors in non-orthogonal sonic anemometers, Agricultural and Forest Meteorology, 171:72-81.

Kochendorfer, J.P., J.P. Meyers, J.M. Frank, W.J. Massman and M.W. Heuer, 2012: How well can we measure the vertical wind speed: Implications for fluxes of energy and mass, Boundary-Layer Meteorology, 145(2):383-398.

Kaimal, J.C. and H.A. Zimmerman, 2014: Understanding non-orthogonal sonic anemometers (Understanding non-orthogonal sonic anemometers.pdf).

Dagle, W.R., and H.A. Zimmerman, 2014: Sonic thermometry today (Sonic Thermometry Today.pdf).