UNDERSTANDING NON-ORTHOGONAL SONIC ANEMOMETERS

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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:

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

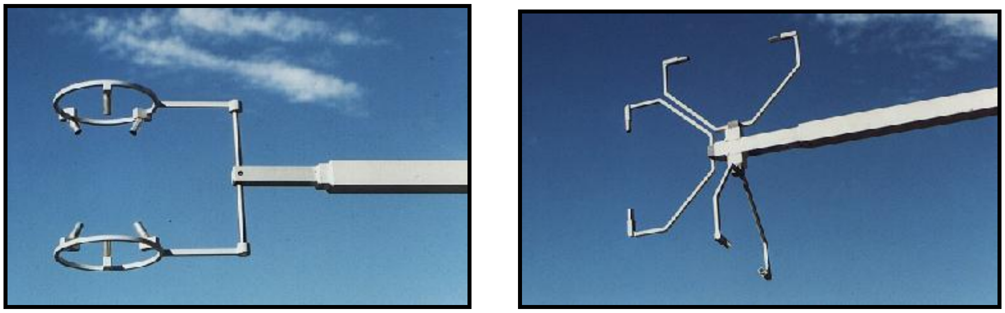
Solving for U, V, and W leads directly to the coordinate transformation equations:

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

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.

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