MINIMIZING FLOW DISTORTION ERRORS IN A SONIC ANEMOMETER

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Abstract. This paper describes a simple approach to minimizing probe-induced flow distortion errors in a three-axis sonic anemometer. By separating the three axes, mutual interference between the transducers and supports in the three arrays is reduced. Only a transducer shadow correction determined from wind tunnel tests is needed to obtain measurements that are virtually insensitive to probe orientation relative to the mean flow. Preliminary results from a series of three atmospheric tests verify the effectiveness of this correction.

1. Introduction

Sonic anemometers have been used in field experiments for more than two decades. Their rapid response to wind fluctuations and their selective sensitivity to wind components along clearly defined axes make them ideally suited for studies of turbulence in the lower atmosphere. With the availability of increasingly smaller and operationally more stable versions of the instrument from several vendors, we have seen a sudden increase in their use, for applications that range from micrometeorology to optical propagation. Some of the newer probe designs have raised concerns about possible errors in measurements from transducer shadowing and from flow distortions introduced by the probe and its supports (Wyngaard, 1981; Wyngaard and Zhang, 1985; Baker, 1988). Not surprisingly, the errors are different for the different transducer configurations. Correction procedures can be simple (Kaimal and Gaynor, 1983) or more complicated (Kraan and Oost, 1989), depending on probe design. In many probes, the errors can be quite large (Grant and Watkins, 1989) for wind directions that exceed the relatively narrow (±45º) acceptance range for which the array was originally intended. Booms, masts, and supports used in field installations can produce additional upwind deflections of 2º-3º (Dyer, 1981; Coppin and Taylor, 1983) which appear as offsets in the vertical velocity measurements, further complicating the corrections.

In response to these concerns, we developed a new probe with minimum support structure and an equal distribution of mass above and below the probe's central axis, which is oriented along the boom. The three orthogonal axes are separated from each other to reduce wake effects and to simplify the correction procedure. The probe is held together by a small hub assembly at the end of a horizontal boom and configured to accept winds from all directions, except perhaps a narrow section to the rear where the flow might be disturbed by a supporting mast or tower. Two important criteria are violated in this design. The wind components are not measured within the same sampling volume, as one might prefer, and perfect

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vertical symmetry is not achieved. Neither condition, it seems, can be achieved without adding to the density of support members in the vicinity of the sampling volumes. We make the assumption that the only correction needed is a straightforward compensation for transducer shadowing in the horizontal winds, based on a first-order approximation of the wind direction (Kaimal, 1979; Kaimal and Gaynor, 1983; Wyngaard and Zhang, 1985). (This correction is performed in real time by a microprocessor which controls both the sonic anemometer operations and the data processing. The outputs generated are the corrected wind components.) In this paper we describe a series of atmospheric measurements designed to test three implications of that assumption:

(1) That the real-time transducer shadow corrections applied to the wind components are the appropriate ones.

(2) That the effects of the vertical separation in the horizontal axes are negligible at heights sufficiently removed from the ground.

(3) That the wind speed dependence in the transducer shadow effect observed in some probes (Hanafusa et al., 1982; Baker, 1988) does not apply here.

The focus of this paper is narrow, defined largely by wind sensing needs in the Wave Propagation Laboratory. Our tests should be viewed as preliminary, but we demonstrate that the wind statistics obtained from the new probe are independent of probe orientation with respect to the mean flow, at least within the resolution of the instrument.

2. The New Probe

The new probe (Applied Technologies, Inc., Model No. SWS 211/3K) has three orthogonal axes, arranged as shown in Figure 1. The length of each path is 15 cm, and a single transducer at each end alternates as transmitter and receiver to provide the transit time measurements needed to compute wind components along the paths (Appendix A). In concept, the probe is similar to many other orthogonal probes in use today, but the vertical separation of the horizontal axes by a distance of 37 cm is new, as is the structure and construction of the transducer supports, which are made from individual sheets of uniform-grained aluminum alloy. This material can be milled to very small dimensions (0.6 cm for the support arm) without compromising the structural integrity of the probe. The overall dimensions of the probe are 0.314 m(l) X 0.244 m(w) X 0.377 m(h). Transducers used in this array are of the same type used in earlier ATI and EG&G probes (Kaimal, 1979). The associated electronics incorporate a microprocessor which controls the transmitting and receiving functions, computes the reciprocals of the transit times to extract information, applies the shadow correction (Appendix B) in real time, and provides several digital outputs in meteorological units that can be accessed by a personal computer. The zero-wind calibration is performed in a small anechoic box. The procedure is simple: the microprocessor, using the box temperature information provided by the operator, computes the exact path lengths, taking into account typical time delays in the transducers, and subtracts residual offsets in the transit times to provide a stable zero-reading in the outputs. The outputs are wind readings presented every 0.1 s, but each reading is an average of 10 equally spaced 0.01 s samples (to reduce aliasing). The velocity resolution in each sample, determined by the clock frequency, is 0. 03 in s- 1, which translates to an effective resolution of about 0.01 m s-' for the averaged output in a fluctuating wind field.

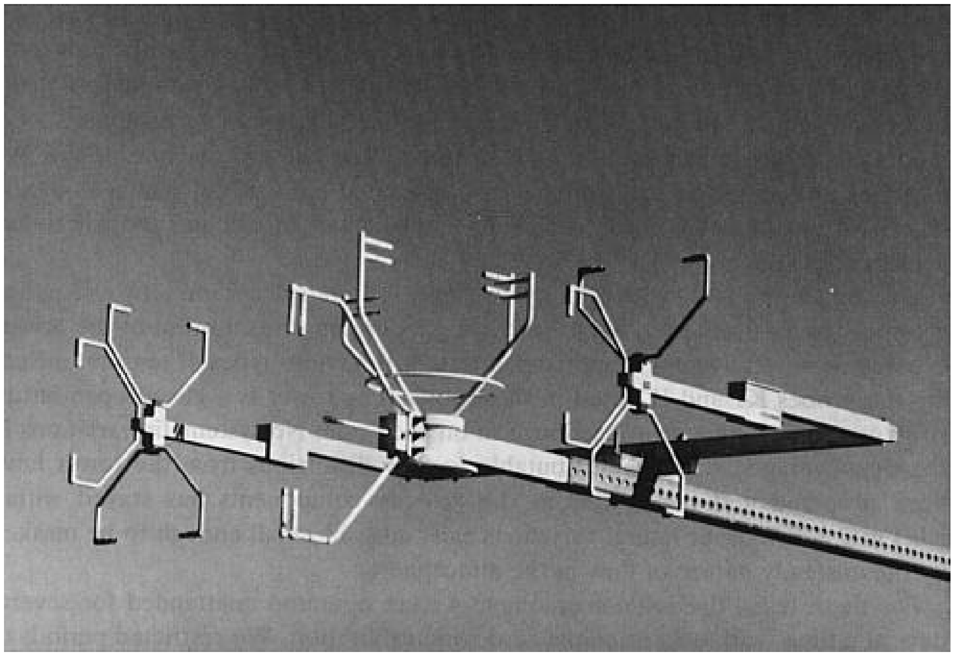

Fig. 1. Line-up of sonic anemometers used in the tests. Left to right: New K1 probe, BAO probe, and new K2 probe (inverted).

3. Field Tests

Three sets of tests were conducted at the Boulder Atmospheric Observatory (BAO). The tests were made over a period of several months (Appendix C) to answer specific questions as they arose regarding the operation of the new instrument. Our goal was to cover as broad a range of stability conditions as possible. However, the choice of boom orientation and height was dictated by the prevailing winds and the operational status of the standard BAO sonic anemometers at the two lowest levels: 10 and 22 m. For all these tests, the sensors compared were mounted 1 m apart at the end of a 4-m boom (Kaimal and Gaynor, 1983). We used two of the new sonic anemometers (designated K1 and K2) shown alongside the BAO anemometer probe in Figure 1, and an R.M. Young propeller-vane anemometer (not shown).

Our assumption of near-equality in the wind statistics within two sampling volumes spaced 1 m apart, 4.5 m (including mounting arm) upwind of the tower, is based on several years of comparison tests with various types of sensors, including the probes K1 and K2 used in these tests. The tower is a guyed open-lattice structure of triangular cross-section, 3 m on each side. No systematic variations in the time-averaged statistics attributable to flow distortions from the tower have been observed and the scatter in the velocity components has stayed within ±0.1 m s^{-1}. Whatever lateral variations exist must be small enough to be masked by the unsteady nature of flow in the atmosphere.

For these tests, the sonic anemometers were operated unattended for several days at a time, with only an initial zero-wind calibration. We restricted periods of analysis to 20-min segments when the mean wind stayed within ±45º of the boom direction. With this restriction, we hoped to avoid mutual shadowing of the sonic probes being compared. Only in the third test with the propeller-vane did we relax the wind direction range to ±90º because the propeller-vane was mounted slightly above and behind the single sonic probe.

Test No. 1. This test compared the BAO probe with probe K1. Its purpose was (1) to check the reasonableness of the correction algorithm used for transducer shadowing, taken from Kaimal's (1979) original plots for BAO-type four-transducer array (the new array used only two transducers per axis) and (2) to check if separating the two horizontal axes eliminated the 0. 1 to 0. 2 m s^{-1} negative biases observed in the vertical velocities routinely measured on the BAO tower. The biases had been attributed initially to asymmetry in the BAO probe and later to a combination of probe asymmetry and terrain slope (Skibin *et al*., 1985). This test was conducted in July and August of 1988.

Test No. 2. In this test we compared two identical new probes in a highly adverse configuration: K1 and K2 each turned 22.5º toward the other, with K2 inverted (Figure 2). By examining how the calculated 1-min horizontal wind vectors and vertical winds compared as a function of wind direction, we were looking for subtle flow distortion effects and biases that may not have shown up in Test No. 1. This test was conducted in October of 1988.

Test No. 3. This test addressed our remaining concern as to whether the transducer shadow effect varied as a function of wind velocity. For this we compared probe K1 with the propeller-vane anemometer over long periods and examined the measurements in 20-min and 1-min segments. Baker's (1988) wind tunnel tests of a 15-cm. path sonic anemometer showed wind speed dependence similar to what Hanafusa *et al*. (1982) had reported. They found the shadow error decreasing with wind speed. This test was conducted in April 1989.

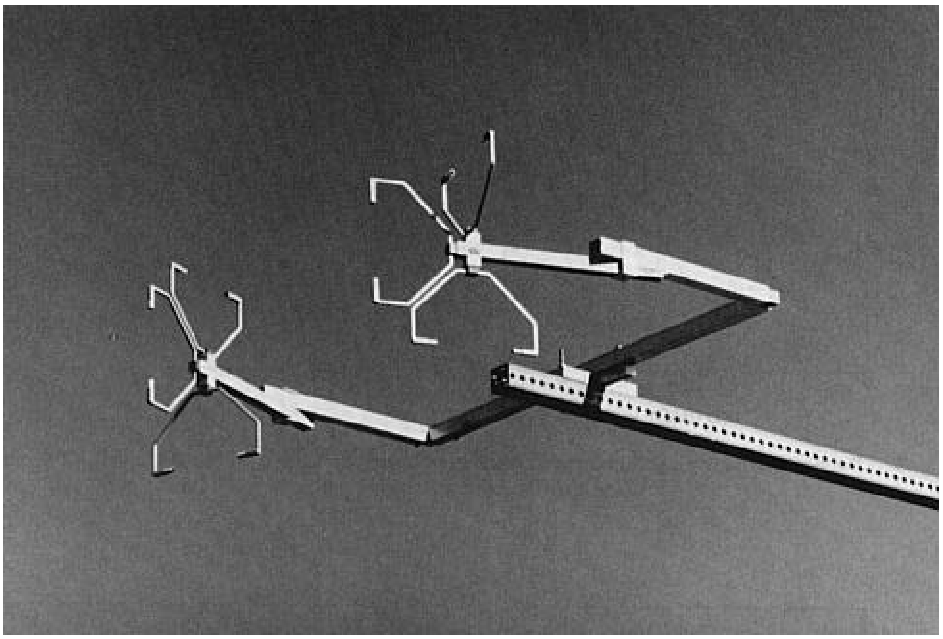

Fig. 2. New probes K1 (left) and K2 (right) turned 22.5º toward each other. K2 is inverted with respect to K1.

4. Results

With Test No. 1 data, we compared wind components measured along the acoustic paths [U along the direction of the boom (X), V lateral to it (Y), and W along the vertical (Z)] of the BAO and K1 probes. The 20-min averaged horizontal components $\overline{U}$ and $\overline{V}$ plotted in Figures 3a and b showed very good agreement (within ±0.1 m s $^{-1}$). The agreement in $\overline{W}$ (Figure 4a) is also very good (±0.02 m s $^{-1}$) for the stable and neutral runs, but the unstable runs show an 0.08 m s $^{-1}$ offset that could be attributed to either instrument. On the basis of earlier tests on the BAO probe (unpublished) and the results from Test No. 2, we conclude that the bias is in the BAO probe, possibly due to the concentration of support structures above the boom, but apparent only in light wind convective conditions when the wind inclination angles tend to be large. The agreement in the stable and neutral runs was a surprise. The consistent updraft and downdraft associated with those two stabilities confirmed some earlier concerns, notably that the chainlink fence upwind of BAO's 10-m SSE boom creates an updraft that would be sensed by anemometers at that level although not at 22m or above where the effect of terrain slope reported by Skibin *et al*. (1985) dominates.

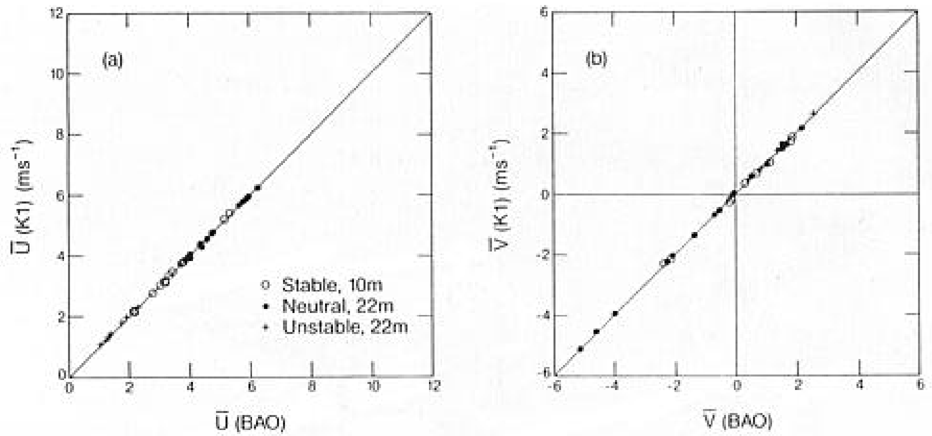

Fig. 3. Twenty-minute averaged horizontal wind components measured by the BAO and KI probes along their horizontal acoustic paths.

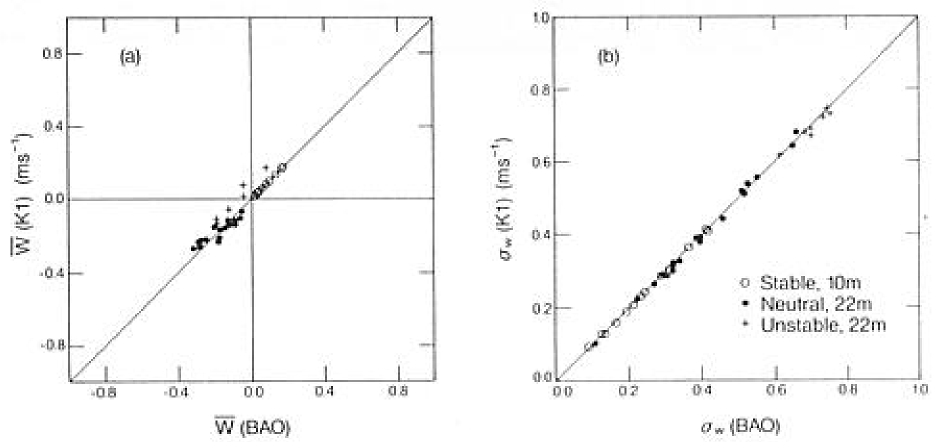

Fig. 4. Twenty-minute means and standard deviations of the vertical wind components measured by the BAO and KI probes.

The 20-min standard deviation of W (Figure 4b) showed excellent agreement and so did those for U and V (not shown), establishing confidence in the scaling factors and corrections used with the new probe. We also examined the 1-h spectra of those three wind components and found no significant differences or patterns of behavior. Thus, Test No. 1 provided a basis for proceeding to more detailed tests with the new probe; it also confirmed the presence of site-induced flow distortion effects at the BAO.

With data from Test No. 2, we compared 1-min horizontal wind vectors V_H, mean wind directions $\overline{q}$, and mean vertical winds $\overline{W}$ from probes KI and K2 (Figure 5) as a function of wind direction. We plotted $\overline{q}$'s and $\overline{W}$'s as differences to enhance their sensitivity to wind direction changes. Any flow distortion error inherent in the probe design should appear magnified in these plots. The two 1-h runs presented here were characterized by steady winds with stabilities ranging from slightly stable to slightly unstable. The probes were mounted on the 22-m boom pointing NNW, following our usual practice of operating on that side of the tower during the fall and winter months.

Our data show no systematic trends or dips in any of the plots. The ratios of V_H, deviate no more than ±3% from unity; the $\overline{q}$'s agree to within ±2° of one another and $\overline{W}$'s to within ±0.03 m s^{-1}, the basic resolution of each 0.01-s wind sample. Test No. 2 results confirmed that no significant residual flow distortion errors remain and that the measured mean flow is independent of the probes' exposure to the flow, excluding winds from the rear, of course.

The results of Test No. 3 (Figure 6a) show no evidence of wind speed dependence in the corrected V_H values even across the extended ±90º azimuth range. The data points represent 20-min V_H ratios separated into three wind speed categories. The averaging period, admittedly, is too long to reveal effects close to 0º where the correction would be the largest, so we expanded the three periods closest to 0º into 1-min segments (Figure 6b) and still found no particular trend with wind speed. Recent wind tunnel tests on probe K2 at the NOAA Fluid Modeling Facility at Research Triangle Park, NC (Bruce Baker, private communication, 1989) confirm this finding. We now believe that the wind speed sensitivity is caused by probe configurations which channel the flow toward the sampling volume, particularly in arrays where all four horizontal transducers lie in the same plane. (Such a configuration also produces additional dips in the response Curves at 90º and 270º because of blockage by the cross-channel transducers.)

Taking the analysis one step further, we examined stresses and cospectra for evidence of flow-distortion-related errors. We computed u', v', and w', fluctuating components along the longitudinal, lateral, and vertical directions. The 20-min $\overline{u'v'}$ values (Figure 7a) show some scatter in unstable air but less than for $\overline{u'v'}$ (Figure 7b). The neutral runs, which behave more predictably, show BAO stresses biased +0.02 $m^2 s^{-2}$ in about half the cases. The 10-min stresses from KI and K2 (Figures 8a and b), even with their unaligned axes, show less scatter. However, the stresses encountered during Test No. 2 did not reach the high values reached in Test No. 1.

The cospectra of *u* and *w* did not offer any additional clues. For the record we present in Figure 9 the 1-h cospectra from Test No. 2. The agreement is very good, but we hasten to point out that the agreement was even closer for some of the periods in Test No. 1.

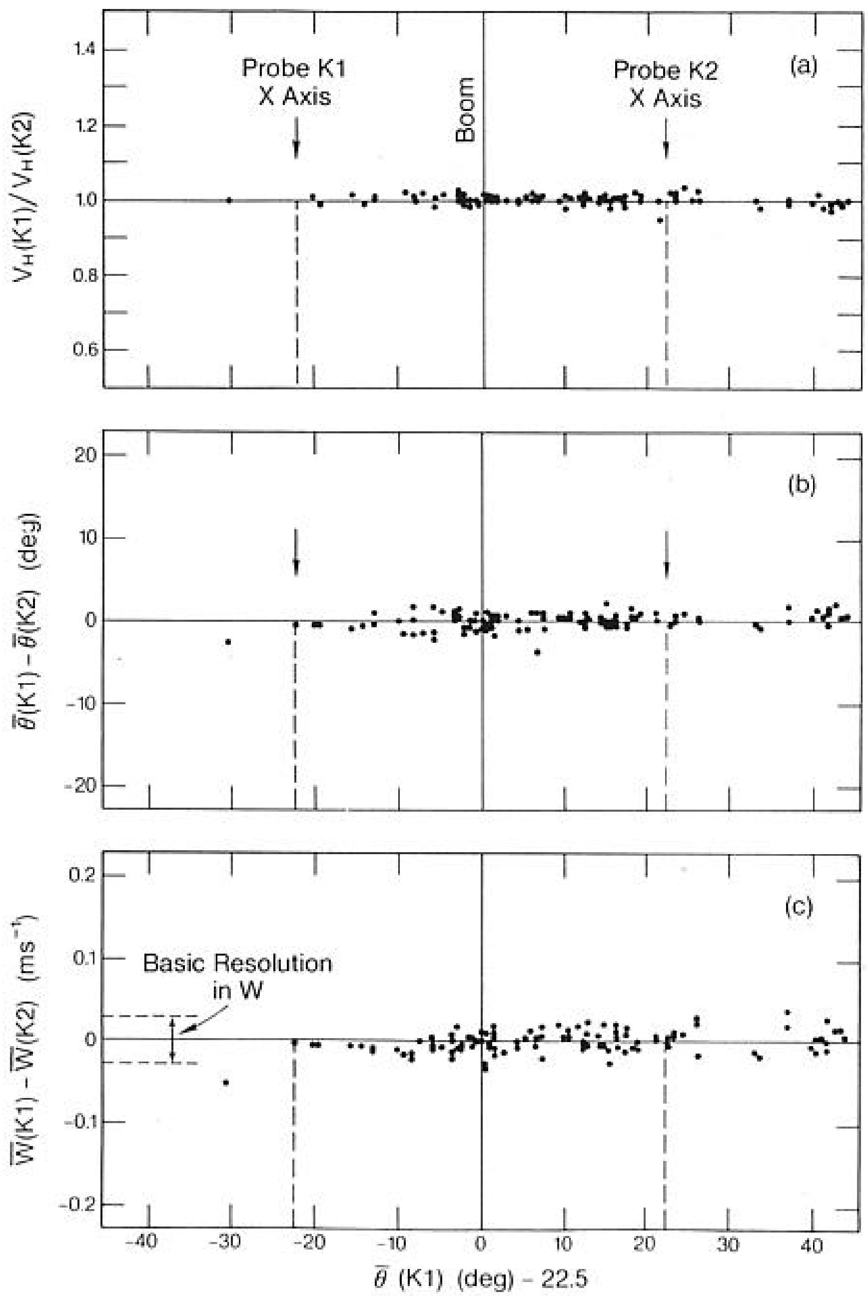

Fig. 5. One-minute horizontal wind vectors, vector directions and virtical winds measured by probes K1 and K2 in the configuration shown in Fig. 2.

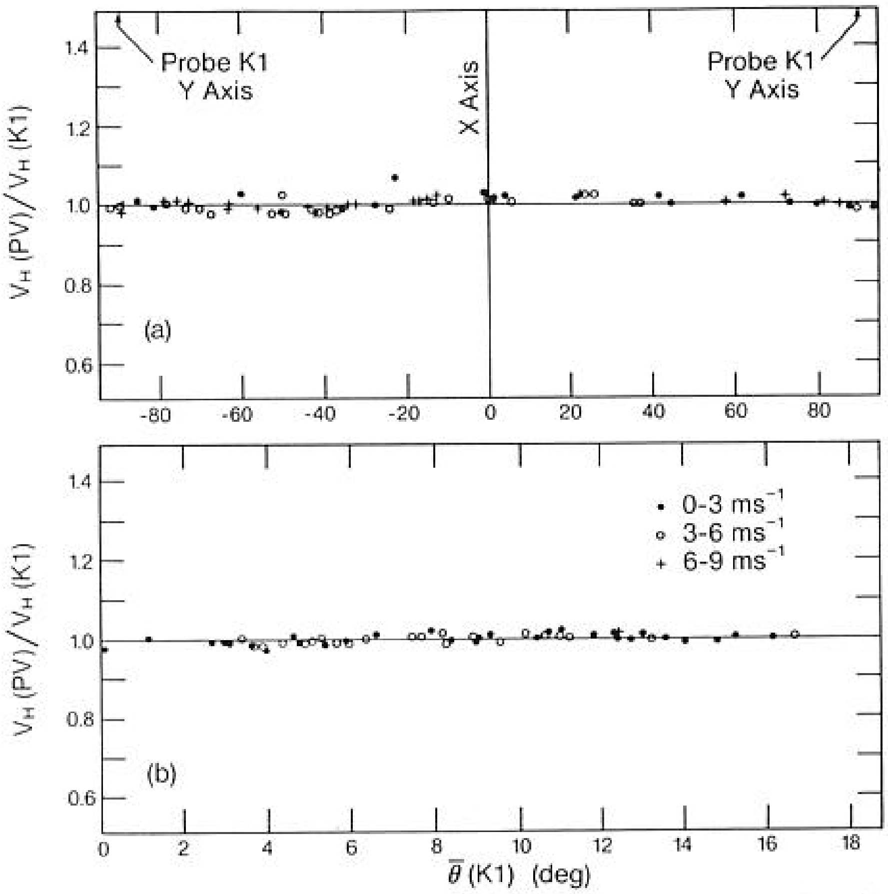

Fig. 6. Horizontal wind vectors measured by the propeller-vane anemometer and Kl probe:
(a) Twenty-minute averages for all the periods listed in Table 1.
(b) One-minute averages for the three periods in (a) close to the X axis.

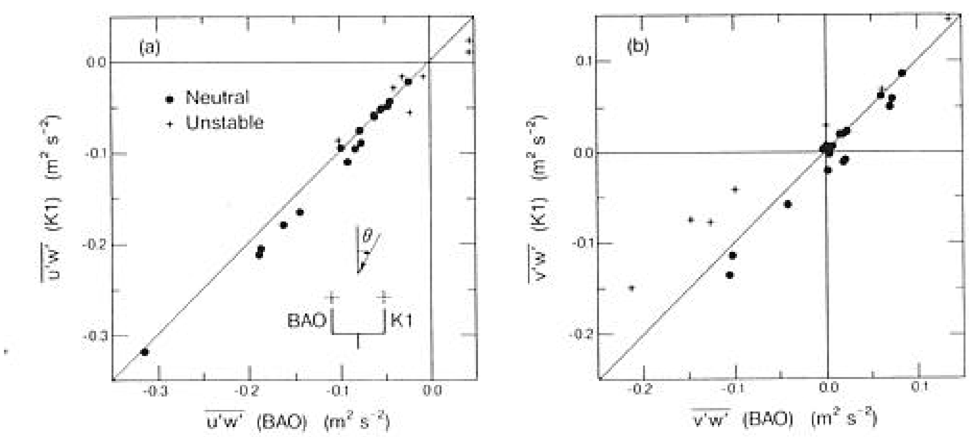

Fig. 7. Twenty-minute averaged $\overline{u'v'}$ and $\overline{v'w'}$ for runs in Test No. 1. (No raw data for the stable runs.)

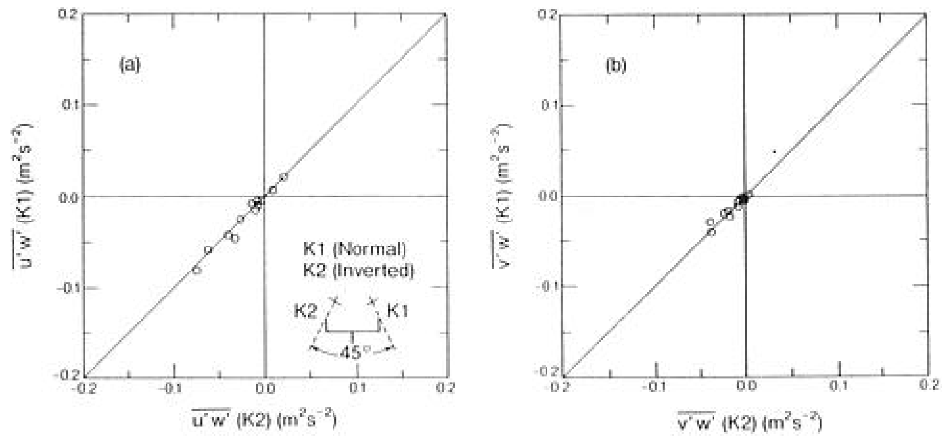

Fig. 8. Ten-minute averaged $\overline{u'v'}$ and $\overline{v'w'}$ for runs in Test No. 2.

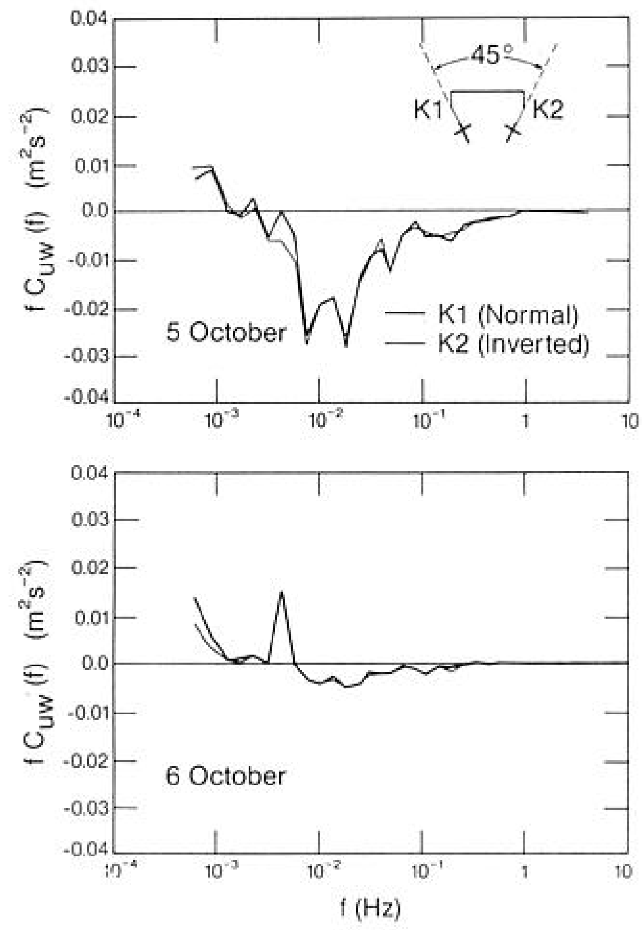

Fig. 9. One-hour cospectra from the slightly unstable (5 October) and slightly stable (6 October) periods in Test No. 2.

5. Summary

Our tests at the BAO show that with a simple rearrangement of the acoustic paths and judicious design of the support structure, it is possible to reduce probe-induced flow-distortion errors to negligible levels. The new sonic anemometer probe requires only a straightforward transducer shadow correction on each of its axes. There are no biases, wind speed dependencies, or wakes from adjacent axes to account for. The 37-cm vertical separation in the horizontal axes imposes a minimum limit on the height at which it can be operated with confidence. Our observations above 10 rn show no detectable effects. The degradation with proximity to the ground can be expected to be gradual, but we recommend that the probe not be used below 4 m, where wind speed gradients are typically the strongest.

Acknowledgements

We are grateful to J. C. Wyngaard and C. B. Baker for many helpful discussions on flow distortion errors in sonic anemometers. Our thanks to Norbert Szczepczynski and David Gregg for expertly carrying out the tests described in this paper. Their role was central to the success of the endeavor. We also thank David Welsh for the computer analysis and plotting of the data.

Appendix A: Sonic Anemometer Wind Sensing

Two methods are used for extracting wind information from the transit times t_1 and t_2 of sound pulses traveling in opposite directions along the same path. In the new sonic anemometers, t_1 and t_2 are observed sequentially and their reciprocals computed using the relationship (Hanafusa *et al*., 1982)

$$1/t_1 - 1/t_2 = \frac{2}{d} \; V_d \quad , \tag{1}$$

where d is the path-length and V_d is the velocity component along the path. In older anemometers of the type used at the BAO, the sound pulses are transmitted simultaneously in opposite directions and the transit time difference ($t_2 - t_1$) is measured directly without the benefit of microprocessors. Here

$$t_2 - t_1 = \frac{2d}{C^2} \; V_d \quad , \tag{2}$$

where C is the velocity of sound, which makes the calibration slightly sensitive to temperature ($C^2 \cong 403T$, where T is the temperature in degrees K).

Appendix B: Transducer Shadow Corrections

The transducer shadow corrections for the BAO and the new probes were derived from Kaimal's (1979) response curves which showed attenuation as a function of angle è between the wind direction and the acoustic path. The measured wind component $(V_d)_m$ for the 25-cm path BAO probe is approximated by

$$(V_d)_m = \begin{cases} V_d \left(0.87 + 0.13\theta/75\right) \; ; & 0^\circ \le \theta \le 75^\circ \\ V_d \; ; & 75^\circ \le \theta \le 90^\circ \end{cases} \quad , \tag{3}$$

For the 15-cm path in the new probe, the measured wind component is approximated by

$$(V_d)_m = \begin{cases} V_d\left(0.824 + 0.176\theta/75\right) & ; \quad 0^\circ \le \theta \le 75^\circ \\ V_d & ; \quad 75^\circ \le \theta \le 90^\circ \end{cases} , \tag{4}$$

The curves presented in Kaimal (1979) are given for various ratios of pathlength to transducer diameter. Both probes use the same type of 1-cm diameter transducers.

Appendix C: Observing Periods

TABLE I

Background information on the tests conducted

Test No.	Date (mm/dd/yy)	Time (MST)	Ht (m)	Boom	V_H ($m\,s^{-1}$)	Stability
1	07/25/88–07/26/88	2140–0200	10	SSE	2.2–5.3	Stable
	08/09/88	1540–2200	22	SSE	3.6–8.1	Near neutral
	08/18/88	1120–1440	22	SSE	1.3–2.8	Unstable
2	10/05/88	1220–1320	22	NNW	2.6–3.9	Slightly unstable
	10/06/88	0220–0320	22	NNW	1.6–2.6	Slightly stable
3	04/12/89	1420–1520	22	NNW	1.7–2.3	Unstable
	04/12/89	1700–2140	22	NNW	1.1–5.2	Neutral
	04/12/89–04/13/89	2200–0210	22	NNW	1.6–4.4	Stable
	04/13/89	0540–0840	22	NNW	1.4–3.8	Slightly stable to neutral
	04/14/89	1000–1100	22	NNW	2.0–2.9	Unstable
	04/13/89	1720–2140	22	NNW	2.9–5.8	Stable

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