SERI/TP-257-4019
UC Category: 261
DE91002113

A Discussion of the Results of an In-Situ Comparison of Three Full-Vector Anemometers

N. D. Kelley
G. N. Scott
J. S. Allread
Wind Energy Research Branch
Solar Energy Research Institute
Golden, Colorado 80401

October 1990

prepared for the
7th Symposium on Meteorological
Observations and Instrumentation
American Meteorological Society
71st Annual Meeting
New Orleans, Louisiana
13-18 January 1991

Prepared under Task No. WE118001

Solar Energy Research Institute
A Division of Midwest Research Institute

1617 Cole Boulevard
Golden, Colorado 80401-3393

Prepared for the
U.S. Department of Energy
Contract No. DE-AC02-83CH10093

Printed in the United States of America
Available from:
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161

Price: Microfiche A01
Printed Copy A02

Codes are used for pricing all publications. The code is determined by the number of pages in the publication. Information pertaining to the pricing codes can be found in the current issue of the following publications which are generally available in most libraries: *Energy Research Abstracts (ERA); Government Reports Announcements* and Index (*GRA* and I); *Scientific and Technical Abstract Reports (STAR);* and publication NTIS-PR-360 available from NTIS at the above address.

A DISCUSSION OF THE RESULTS OF AN IN-SITU COMPARISON OF THREE, FULL-VECTOR ANEMOMETERS

N.D. Kelley
G.N. Scott
J.S. Allread

Wind Energy Research Branch
Solar Energy Research Institute
Golden, Colorado

1. INTRODUCTION

Extensive field measurements and the numerical modeling of dynamic responses associated with wind turbine rotor blades have pointed to strong interactions with coherent turbulent structures in the turbine inflow. These interactions are thought to be a major source of high-cycle fatigue in the primary structural components of wind turbines. The sources of such turbulent structures are not only natural terrain features but also the wakes from upwind turbines. Many unsteady aerodynamic processes are excited by turbulent eddies ranging in size from several rotor diameters down to the dimensions of the mean blade chord. These processes are responsible for inducing large, fluctuating loads on the turbine rotor blades. For the wind turbine generators now in use, this encompasses a spatial range of about 0.1 to 300 m.

To assess our ability to measure the coherent properties of inflow turbulence over such a wide range of spatial range, we performed a study to compare three full-vector anemometers. We believe that to identify the dominant fluid dynamic properties of such flows, the instrumentation used must be capable of good fidelity measurements over the desired spatial range. The sonic anemometer is a primary candidate; we also wanted to compare the results associated with a well-designed mechanical instrument which is available at considerably less cost. Two sonic designs and a propeller-bivane were exposed to turbulent flows downstream of both extremely complex and moderately rolling terrain. This paper discusses some of the results of these comparisons with an emphasis on the measurements of turbulent fluctuations.

2. EXPERIMENTAL SETUP, DATA ACQUISITION AND PROCESSING

The experiment was conducted at the Wind Energy Test Center (WETC) operated by the Solar Energy Research Institute (SERI). The WETC is located 13 km south of Boulder, Colorado. The site is dominated by flows from the WNW which have previously traversed the eastern slope of the Colorado Rockies and as a result are quite turbulent. The upwind fetch associated with flows coming from the opposite direction (ESE) consists of the moderately rolling terrain associated with the high plains of Colorado. A 50-m micrometeorological tower containing four measurement levels is located 200 m towards the west and slightly south of the comparison installation.

2.1 Instruments Compared

The two sonic anemometer designs compared were a Kaijo-Denki (K-D) Model DA-200 with a Model TR-61B measuring head and an Applied Technologies, Inc. (ATI) Model SWS-211/3K Kaimal-design. The K-D anemometer operates at 100 KHz and uses three 20-cm measuring paths mounted at 120^{0} intervals and inclined 45^{o} to the horizontal. It is capable of sensing a maximum wind speed of 60 ms^{-1} with a minimum resolution of .005 ms^{-1}. It operates at a nominal measurement rate of 20 readings per second.

The ATI anemometer is a 200-KHz device consisting of three mutually orthogonal 20-cm measuring paths. It is normally operated with the one of the paths aligned to the local vertical. The instrument is designed to provide a range of ±20 ms^{-1} for the two horizontal channels and ±5 ms^{-1} for the vertical. The minimum resolution is .01 m at 10 readings per second. Internal transducer-shadow compensation is applied to the two horizontal measurement paths but not to the vertical.

The mechanical instrument compared was an R.M. Young (RMY) Model 21003/08274 Gill propeller-bivane. This instrument uses a direct current (dc) generator as the speed transducer and linear potentiometers for the elevation and azimuth angle pickoffs. The propeller and tail fin were made of polystyrene. The propeller pitch was 22 cm x 30 cm. The dimensions of the tail fin were 23 cm x 23 cm. The instrument is designed to provide a distance constant of 1.0 m and a vane damping ratio of 0.53.

2.2 Instrument Exposure and Data Recording

The three instruments were mounted on a horizontal bar at a height of 10 m above the local terrain. The horizontal separation between instruments was 1.8 m. The bar was oriented perpendicular to an axis parallel with the two most prevalent local wind directions. Figure 1 depicts the plan arrangement. The ATI anemometer was mounted with its horizontal axes at a 45^{o} angle to the orientation of the mounting bar. As is shown in Figure 1, this also place its sampling region slightly upstream of the other anemometers. The orientation was chosen to minimize any residual transducer shadow effects not accounted for by the internal correction.

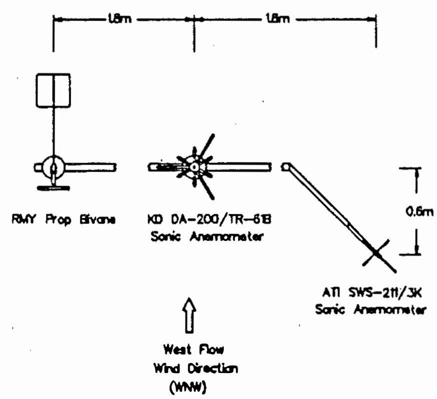

Fig. 1. Truncated plan view of instrument exposure.

The raw data from each of the three anemometers was recorded on a personal-computer-based data collection system. This system incorporates a NEFF Instrument Corp. System 470 acquisition unit which provides a data conversion resolution of 15 bits (one part in 32,768) plus sign. It also supports a multiple input gain capability to individually optimize the conversion process for each measurement channel. Digitally programmable, pre-sampling low-pass filters were provided for each measurement channel. Data was recorded only when a control anemometer, mounted below the level of the instruments being compared, indicated that the 100-second mean wind vector was within 45^{o} of the bar perpendicular and above a desired speed threshold. Data was continuously collected for 20 minutes at a sampling rate of 50 samples per second on each channel. One series of measurements was made with the pre-sampling filters set at 1.25 Hz and another at 12.5 Hz. The sampled data were subsequently stored on an optical disk for final processing. Information from the upwind micrometeorological tower was collected simultaneously on a separate recording system.

The data collected with 1.25-and 12.5-Hz bandwidths were processed with final data rates of 6.25 and 50 samples per second respectively. The processed data was then stratified into west and east flow cases of either high or low data rate. Coordinate transformations were applied to the data from each instrument to establish a common reference aligned with the mounting bar. Flow incidence angles and total speed magnitudes were computed from each of the two sonic anemometers. This allowed direct comparisons with the fundamental variables of the propeller-bivane. The fluctuating component velocities were derived by aligning the coordinate with the streamwise direction and removing the mean values. Further smoothing of 1 and 12 seconds was subsequently applied to the low-rate data sets. This allowed us to isolate instrument-to-instrument biases and establish observed variability levels.

3. RESULTS

3.1 Frequency/Spatial Response

One of the primary goals of this comparison was to establish the frequency and spatial resolution capabilities of the ATI sonic and RMY bivane anemometers relative to the more sensitive and responsive K-D sonic. These capabilities are particularly important to wind energy research because coherent turbulent structures must be resolved at space scales at or smaller than the rotor diameters of current wind turbine designs. A series of nine high-rate (50 samples per second) cases of flow from the west were used to make these comparisons. Table 1 lists the conditions associated with these cases.

Table 1

Mean Wind Dirctn@ (deg)	Mean Wind Speed (ms^{-1})	Wind Speed σ (ms^{-1})	u_* (ms^{-1})	z/L
-0.64	15.95	2.91	1.278	0.005
1.73	14.82	2.50	1.292	0.007
-4.57	11.01	2.18	1.036	0.012
2.81	10.42	1.72	0.725	0.008
-0.37	8.02	1.77	0.543	0.014
3.00	7.95	1.86	0.740	0.000
-0.13	6.16	1.62	0.506	0.019
-3.14	3.67	0.76	0.202	-1.176
4.72	3.06	0.85	0.466	1.135

@relative to the mounting bar perpendicular (292^{o} with respect to true north)

Bivane Propeller

The high-frequency or small-scale turbulence information associated with the RMY bivane is determined by the response characteristics of the propeller. The measured response is plotted in Figure 2. Both the frequency and spatial response can be seen using the dual abscissas provided. This figure shows that one can expect this instrument to indicate only 63% of the available turbulent energy at a space scale of 20 m and 90% or more at wavelengths greater than 130 m.

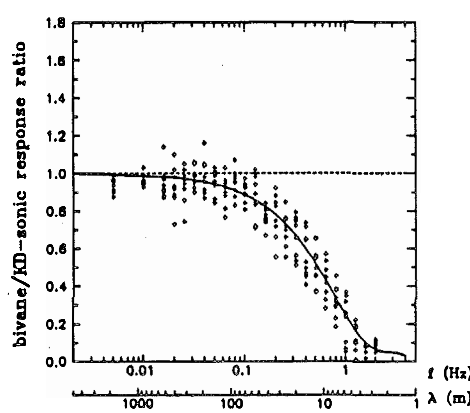

Fig. 2. Measured response of RMY bivane total speed magnitude relative to K-D sonic.

Fluctuating Components

The observed root-mean-square (rms) responses of the ATI and RMY anemometers in coordinates aligned with the mean flow are summarized in Figure 3.

The horizontal components in both instruments have similar response characteristics but there is considerable overshoot in the bivane vertical component. This is a result of the underdamped response of the bivane elevation angle. The elevation response is driven by gyroscopic moments associated with the propeller/turbulence interaction. Figure 4 presents the elevation response curve, which is similar to the w'-component response of Figure 3c.

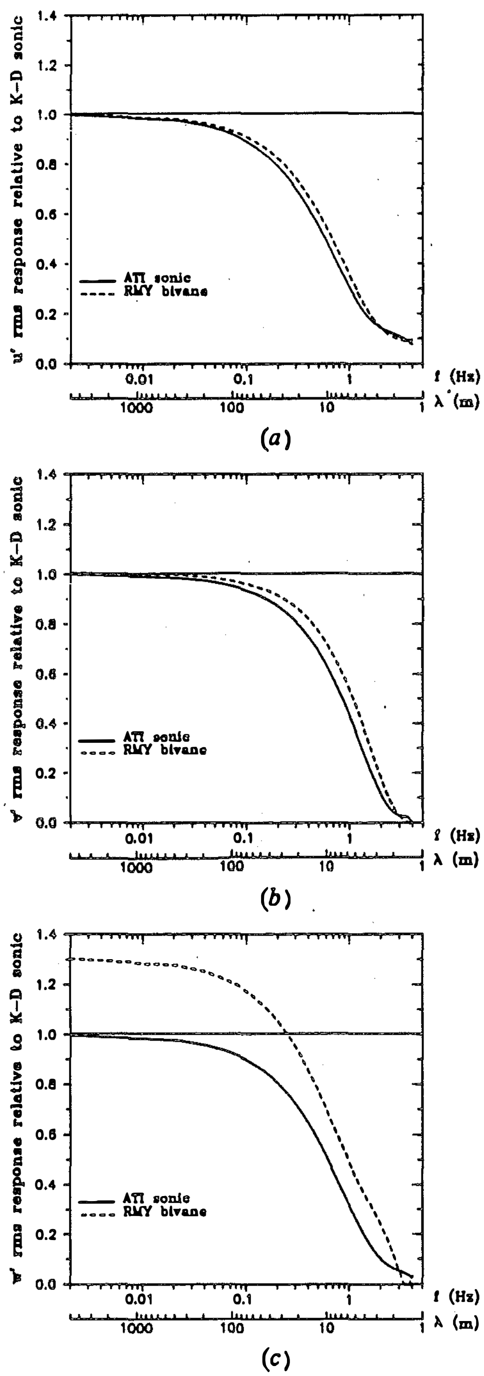

Fig. 3. Measured fluctuating component response of ATI and RMY anemometers relative to K-D sonic, (a) u'-component, (b) v'-component, (c) w'-component.

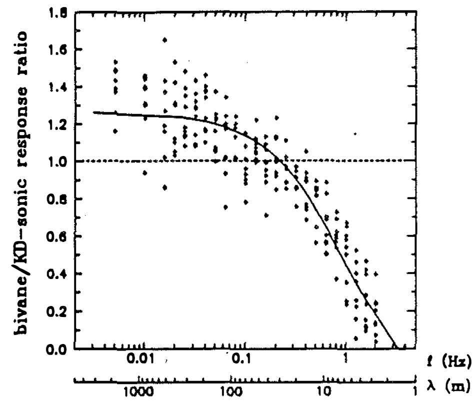

Fig. 4. Observed rms response of bivane elevation angle relative to K-D sonic.

The ATI response curves of Figure 3 show that the spatial sensitivity of this instrument, as implemented here, is essentially equivalent to the horizontal component performance of the bivane. Though a low-pass smoothing filter was incorporated in the ATI digital-to-analog conve ter used to record this data, it is likely that a 10-point block averaging process used to smooth the original inst ument sampling dominates the final response. Figure 5 compa es the measured with the expected response for such a smoothing process. To achieve increased spatial sensitivity, it will be necessary to alter this internal smoothing process. This tradeoff will probably result in some loss of accuracy.

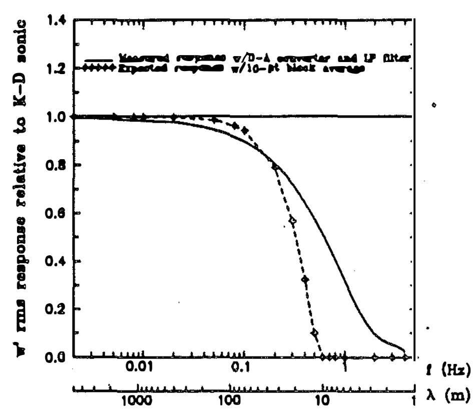

Fig. 5. Comparison of observed (*solid*) ATI spatial response with that predicted (*dashed*) for a 10-point block averaging process.

Reynolds Stresses

One important fluid dynamic property that 3-D anemometers measure is the cross-axis correlations or Reynolds stress components (u'w', u'v', and v'w'). These stresses also represent the local flux of momentum and are related to the vorticity. Because of the lack of response displayed in Figure 3, we used six low-rate cases (1.25-Hz bandwidth) to compare the Reynolds stress component responses of the ATI and RMY bivane with the K-D sonic. Figure 6 presents these comparisons. This figure clearly demonstrates that the underdamped elevation response of the bivane is responsible for considerable overestimation of the vertical momentum flux (u'w'). The figure also shows that both instruments underestimate the flux contributions at scales

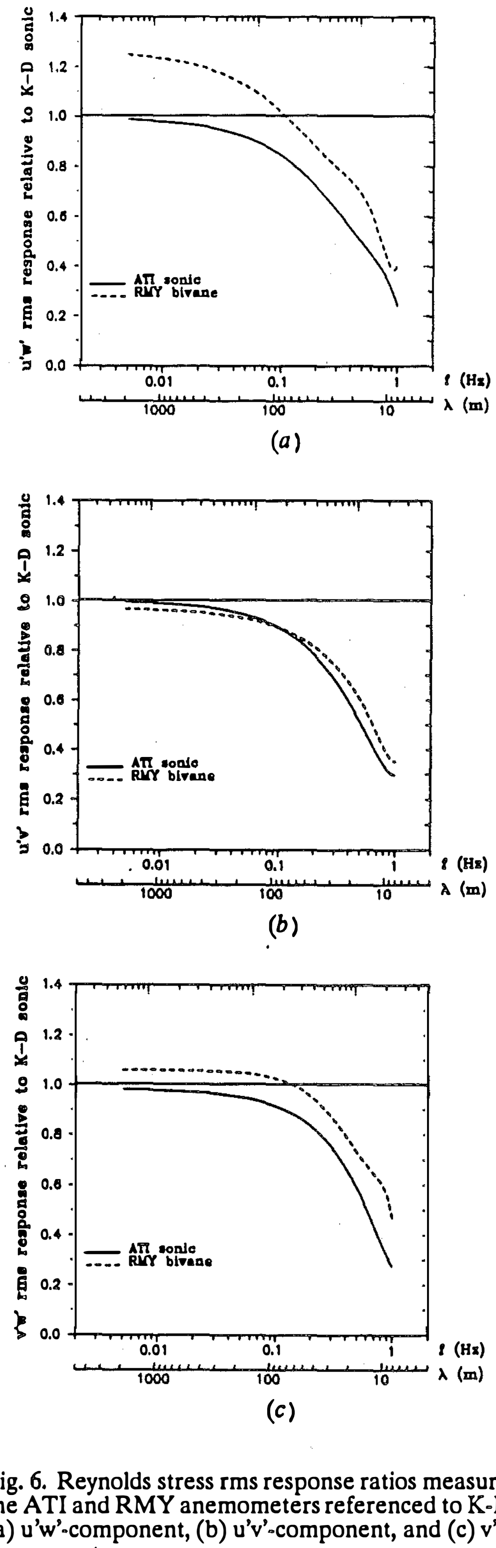

Fig. 6. Reynolds stress rms response ratios measured by the ATI and RMY anemometers referenced to K-D sonic; (a) u'w'-component, (b) u'v'-component, and (c) v'w'-component.

smaller than about 100 m. This is a region of particular interest to wind energy research.

3.2 Statistical Comparisons

Wind energy researchers are principally interested in the fluctuating aerodynamic forces created by the ingestion of turbulent fields over time scales of less than 100 seconds. Thus, a comparison of the higher statistical moments of the fluctuating velocity components aligned with the mean wind vector for each anemometer would be useful. To make sure we gave no extra advantage to the K-D anemometer, we applied an additional smoothing over one second to the low-rate data sets. We then calculated the corresponding statistical moments as a function of approach mean wind speed. A total of 57 west flow cases were available, compared with 31 from the east. The bulk of the west flow cases exhibited near-neutral to slightly positive stabilities while the those from the east ranged from unstable to convectively unstable.

Cartesian Components

A comparison of the standard deviation of each of the turbulent components as a function of wind speed is summarized in Figure 7. There is excellent agreement for the along-the-wind component with biases present in the lateral components. Again, the effect of the bivane underdamped elevation response is apparent in Figure 7c. The comparison of the third statistical moment is plotted in Figure 8 as the skewness coefficient.

The agreement between the three anemometers is quite good for the horizontal components for both flow directions. However, considerable disagreement exists in the ATI sonic and to a lesser extent for the bivane (as would be expected) in the vertical component. This discrepancy is even more pronounced in the fourth statistical moment expressed as the kurtosis coefficient shown in Figure 9. After discussions with the manufacturer, it was decided the transducer shadow correction needs to be applied to the vertical as well as the horizontal channels. This conclusion is borne out in Figures 8 and 9, which indicate a predominance of negative excursions in this channel.

Momentum Flux Comparisons

Figure 10 summarizes the first four statistical moments of the momentum flux or surface stress (u'w') associated with the west flow cases. Figure 10a indicates that for low velocity, unstable flow conditions all three anemometers sense essentially the same value for the mean flux. However as the velocity and stability increase, the disagreement also increases. As would be expected, the greatest disagreement is with the bivane. However, the problems pointed out above with the ATI vertical component are clearly evident. Again, these are most obvious in the third and fourth statistical moments plotted in Figures 10c and 10d.

4. CONCLUSIONS

Neither the ATI sonic, as presently supplied, or the RMY bivane provide adequate spatial sensitivity to develop a full understanding of the unsteady aerodynamic processes associated with wind turbine rotors. Both have similar horizontal response characteristics; i.e., full response at turbulent scales larger than 200 m. The response of the vertical component is identical to the horizontal for the ATI sonic. The RMY bivane overestimates the vertical component by more than 30% at scales larger than 200 m due to an underdamped elevation angle response. Similar statements can be made

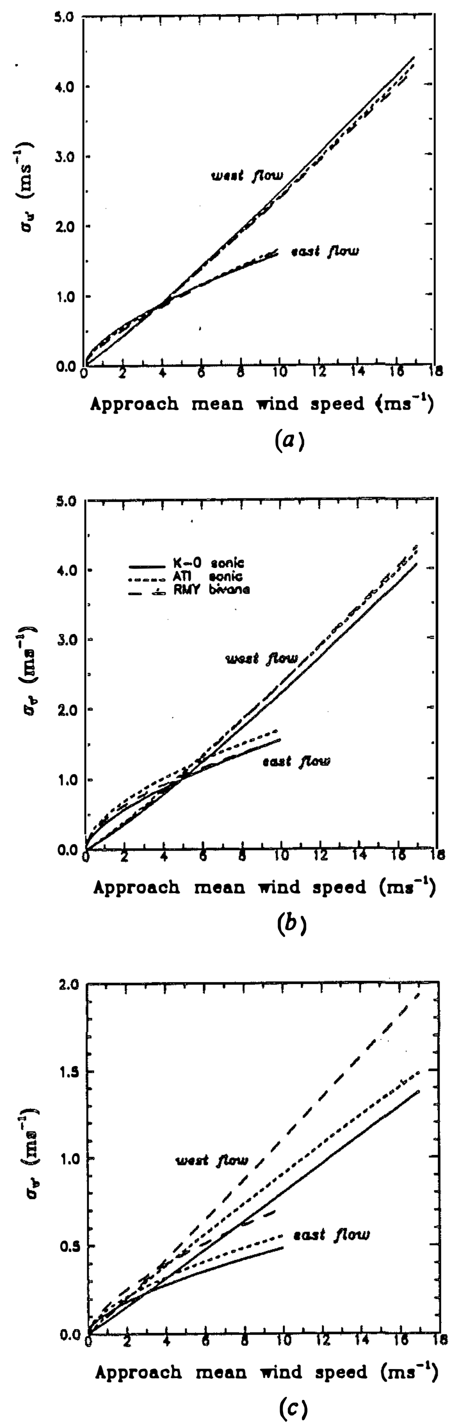

Fig. 7. Comparison of fluctuating velocity component standard deviations as a function of approach wind speed; (a) $\sigma_{u'}$, (b) $\sigma_{v'}$, and (c) $\sigma_{w'}$.

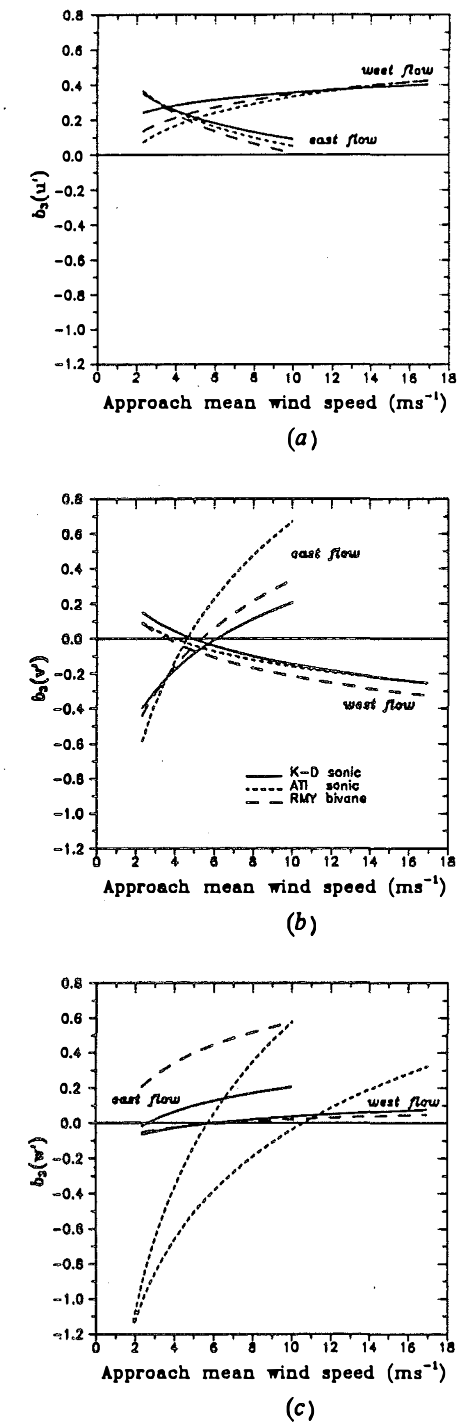

Fig. 8. Comparison of skewness coefficients of fluctuating velocity components; (*a*) u', (*b*) v', and (*c*) w'.

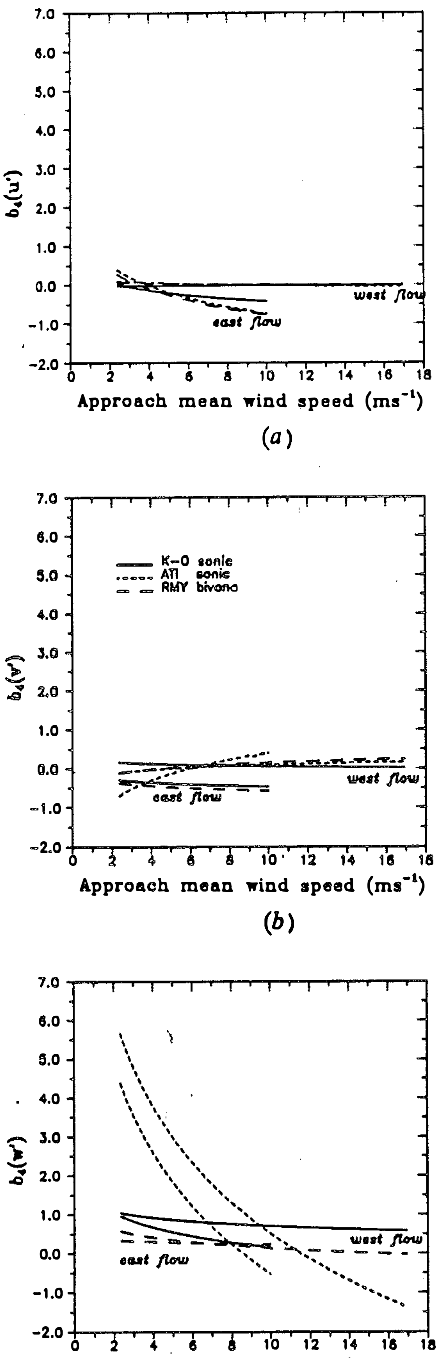

Fig. 9. Comparison of kurtosis coefficients of fluctuating velocity components; (a) u', (b) v', and (c) w'.

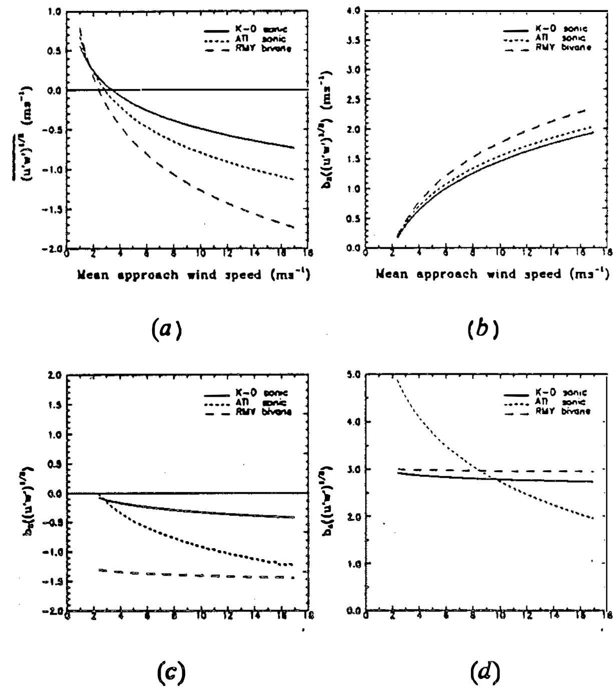

Fig. 10. Comparisons of the first four statistical moments of the momentum flux (u'w') for west flows; (a) mean, (b) standard deviation, (c) skewness, and (d) kurtosis.

about the rms Reynolds stress responses. The ATI and K-D sonics agree quite well at scales larger than 100 m. The RMY bivane over estimates the u'w' momentum flux in this range by more than 20%. The ATI provides a full contribution to the u'w' flux at scales larger than about 100 m.

Comparisons of the second, third, and fourth statistical moments of the fluctuating horizontal velocity components as a function of wind speed indicate close agreement between the three anemometers. The vertical component measured by the RMY bivane agrees well with the K-D sonic for all but the second moment or variance. An apparent transducer wake or shadowing error in the ATI vertical channel creates signal dropouts of short duration. This problem can be solved by including a shadow correction. As would be expected, discrepancies exist among the anemometers in the first four statistical moments of the momentum flux, u'w'. The smallest discrepancy occurs among the instruments in the second moment or variance of u'w'.

5. ACKNOWLEDGEMENTS

This work has been supported by the U.S. Department of Energy under contract no. DE-AC02-83CH10093. The results presented here could not have been possible without the dedicated assistance of Bob Keller and Tom Richards of Sugarloaf Enterprises, Inc., and Ed McKenna, Rich Osgood, Doyle Selix, Dave Jager, and Jim Pruitt of SERI. Helpful discussions with Herb and Gary Zimmerman of Applied Technologies, Inc. are gratefully acknowledged.