Wind Speeds as Measured by Cup and Sonic Anemometers and Influenced by Tower Structure

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ABSTRACT

Wind tunnel and field experiments have shown that the fast-response three-component sonic anemometer is a highly accurate wind speed sensor. When sonic anemometers were used as reference sensors for wind speed, slower response cup anemometers were found to consistently overestimate the wind speed. Despite measures taken during a field program in Kansas to minimize tower influence on wind measurements, the errors due to the tower effect on the windward side are inferred to be about ±5% of the observed wind speed ratios of cup to sonic anemometers. When the observed speed ratios are compared with the errors due to tower influence, the overspeeding of the cup anemometer is estimated to be about 10% of the reference wind speed.

1. Introduction

It is traditional in micrometeorological field experiments to make wind profile measurements by spacing a number of carefully matched cup anemometers along vertical masts or towers. Based on these cup anemometer measurements, numerous wind profile formulas have been derived to represent the profile as a function of height, to describe its dependence on surface roughness and on thermal stability, and to determine the turbulent flux of momentum and sensible heat. Accurate wind profile measurements are thus essential, particularly in determining shearing stress when direct measurements of stress are not available. However, a basic and underlying problem in analyzing observed wind profiles is to determine the various sources and magnitudes of errors associated with cup anemometry (see MacCready, 1966, and Ramachandran, 1969).

During the summer of 1968 the Boundary Layer Branch, Meteorology Laboratory, Air Force Cambridge Research Laboratories, conducted a micrometeorological field program near Sublette, Kans. Detailed descriptions of the site and of the slow-response instrumentation are provided in a report on an earlier field program by the Boundary Layer Branch (1967). A comprehensive description of the data acquisition system is presented by Kaimal *et al.* (1966). In this field program the wind speed profile measurements from slow-response cup anemometers were supplemented with wind speed measurements from two fast-response sonic anemometers. This paper compares the measured cup and sonic anemometer wind speeds in detail and provides quantitative information on the magnitude of the complicated and inherent errors in cup anemometry.

2. Sonic and cup anemometers

The sonic anemometer used in the experimental program was a three-component sonic anemometer-thermometer (Model PAT 311, Kaijo Denki Co., Tokyo). As described by Kaimal (1969) the anemometer sensing head has three acoustic paths to measure the wind velocity, one for the vertical component and two for the horizontal components. The horizontal paths are set 120° apart to allow for wind directional changes during an observation period. The slow-response wind sensors measured wind speed and wind direction. Wind speeds were obtained with three-cup anemometers (Beckman and Whitley Model 170-41).

Fig. 1. shows the horizontal cross section of the 1.83 m square lattice-type tower with the boom arrangements for the sonic and cup anemometers and the wind vane at the levels of 5.66 and 22.6 m. The boom for the sonic

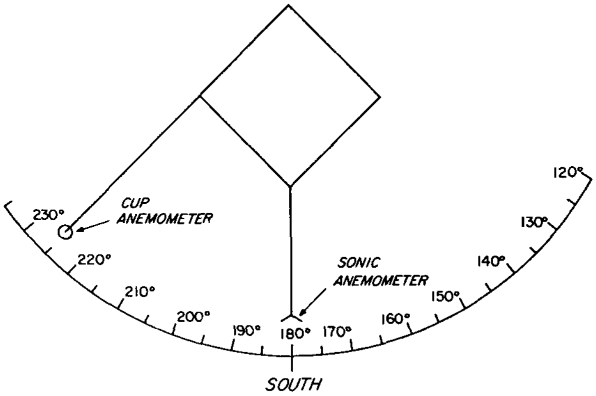

Fig. 1. Horizontal cross section of micrometeorological tower near Sublette, Kans.

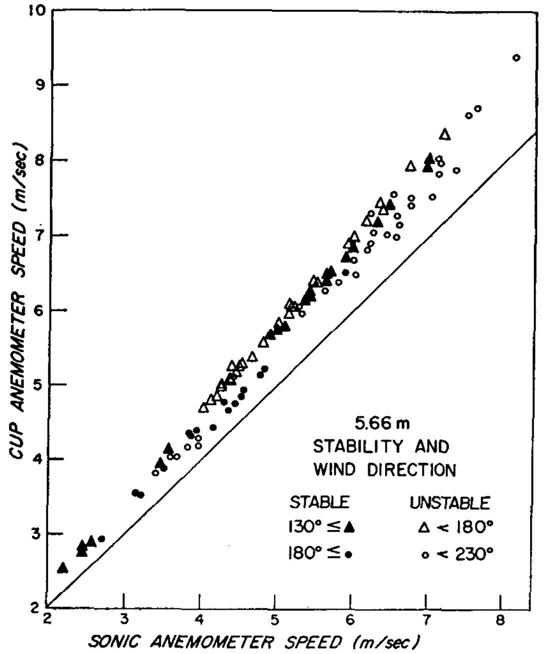

FIG. 2. Comparison of wind speeds measured with cup and sonic anemometers at 5.66 m with data grouped according to wind direction and stability.

anemometer was fixed and extended 1.83 m to the south from the southern corner of the tower. The sonic anemometers were turned into the mean wind before each 1-hr observation period by means of television antenna rotors. The boom for the cup anemometer and wind vane extended 2.74 m to the southwest along the northwestern side of the tower.

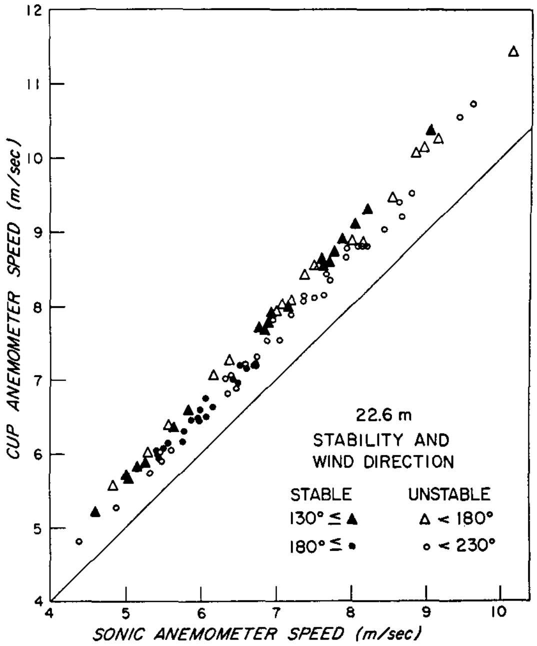

FIG. 3. Comparison of wind speeds measured with cup and sonic anemometers at 22.6 m.

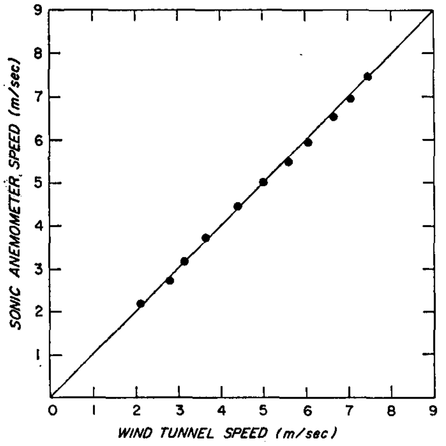

FIG. 4. Wind tunnel calibration of sonic anemometer.

In this paper the sonic anemometer wind speed refers to the 15-min average of the magnitude of the horizontal wind vector measured 20 times a second. The cup anemometer wind speed refers to the 15-min average of the speed measured every second. Any 15-min run with mean wind direction outside the range 130–230° was neglected to avoid distorting influences of the tower structure on the wind sensors and between the sensors themselves. The sonic anemometers were turned into the mean wind, but for reasons described by Kaimal *et al.* (1968) those 15-min runs showing azimuth deviations exceeding the acceptable range of ±45° were deleted from this study. Calibration checks for zero offset and full-scale output were made for the sonic anemometers before and after each 1-hr observation period and any periods showing drifts of over 57 cm sec^{-1} were also neglected in this analysis.

3. Cup and sonic anemometer wind speeds

The cup anemometer wind speed V_c and the sonic anemometer wind speed V_s are compared in Fig. 2 for the 5.66 m level, and in Fig. 3 for the 22.6 m level. The 15-min runs are divided into two groups depending on whether the mean wind was from the SW sector (circles) or from the SE sector (triangles). Furthermore, the runs are identified as to whether they were thermally unstable (open circles and triangles) or stable (closed circles and triangles). The stability is based only on the signs of the potential temperature gradients between 8 and 4 m for the 5.66 m level and between 32 and 16 m for the 22.6 m level. Both figures show that V_c is invariably greater in magnitude than V_s but that there is a difference in the magnitude between the two broad groupings of wind direction and also to some degree between the stabilities. At the 5.66 m level (Fig. 2) V_c averages 15% higher than V_s for the SE sector winds and about 11% for the SW sector winds. For the unstable runs the ratio of V_c to V_s averages ~2% higher than that of the stable runs. At the higher level (Fig. 3) V_c averages 13% higher than V_s for the SE sector winds and 9% for the SW sector winds. These broad groupings of wind data will be discussed in greater detail later.

To confirm the consistently higher readings of the cup anemometer over the sonic anemometer the wind sensors were compared in a daytime experiment at Hanscom Field at a much later date. The same anemometers, i.e., those mounted at the 5.66 m level during the Kansas 1968 Field Program, were used for this experiment. In addition, a DISA hot-wire anemometer was also used. These instruments were mounted on an open lattice-type tower at a height of 6 m above the ground. The booms for the sensors extended 2 m from the tower structure, and, to equalize whatever effect the tower structure had on the sensors, the positions of the instruments were interchanged at frequent intervals. The wind data were sampled at the rate of one per second and the length of each run was confined to 5 min.

Before the experiment the cup anemometer was calibrated in a low-speed wind tunnel. Before and after each series of runs the sonic anemometer was placed in the wind tunnel and its speed reading compared with that of the pitot tube. Results are shown in Fig. 4. Since the two speeds are arrived at independently of one another, Fig. 4 shows that the sonic anemometer is a highly accurate wind speed device. Also, at frequent intervals between runs, the zero and full-scale adjustments in the sonic electronics were checked and readjusted to insure that calibration was maintained. The hot-wire probe was calibrated in the wind tunnel immediately before each series of runs. Calibration points were established over a range of temperatures covering the observed ambient values, and a calibration curve for a temperature was obtained by interpolation. The effect of temperature on the hot-wire calibration is estimated to be about 2% (°C)$^{-1}$. Since the hot-wire anemometer becomes less reliable at low wind speeds, no hot-wire data were made available at wind speeds $\lesssim 3$ m sec^{-1} in this experiment.

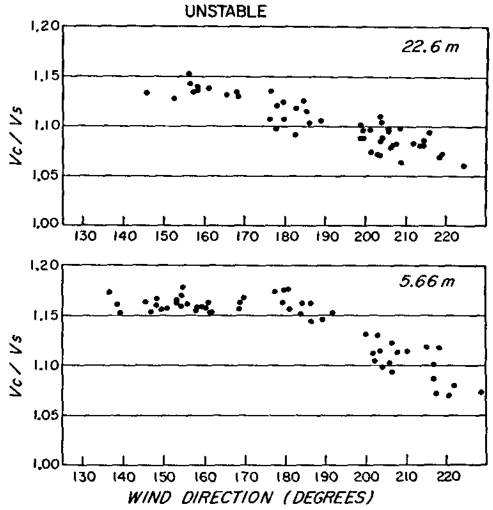

Fig. 6. Wind direction variation of cup to sonic anemometer wind speed ratio at 5.66 and 22.6 m for unstable runs.

The results of the daytime experiment are shown in Fig. 5 which compares the cup and hot-wire anemometer wind speeds with those of the sonic anemometer. In the wind speed range from ~3–4 m sec^{-1} the hot-wire and the sonic anemometers are in good agreement. This verifies the high accuracy of the sonic anemometer as a wind speed sensor. On the other hand, the cup anemometer wind speeds average ~16% higher than the sonic anemometer wind speeds. Although the wind speeds during this experiment were much lower, this percentage is almost the same as that found for those runs with winds from the SE sector shown in Fig. 2 for the 5.66 m level.

Figs. 2, 3 and 5 indicate that the cup anemometer "overspeeds," a well-known effect (Frenzen, 1966) that

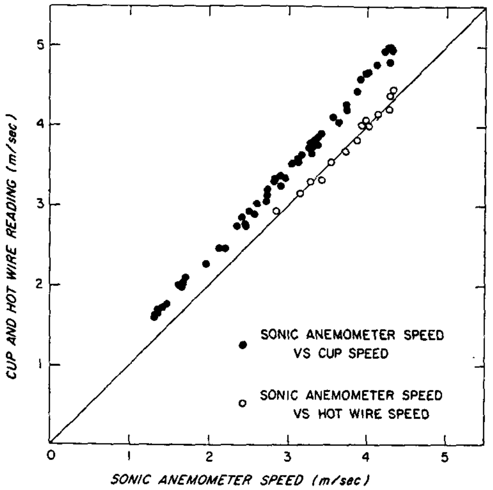

Fig. 5. Comparison of cup and hot-wire anemometer wind speeds with sonic anemometer wind speeds.

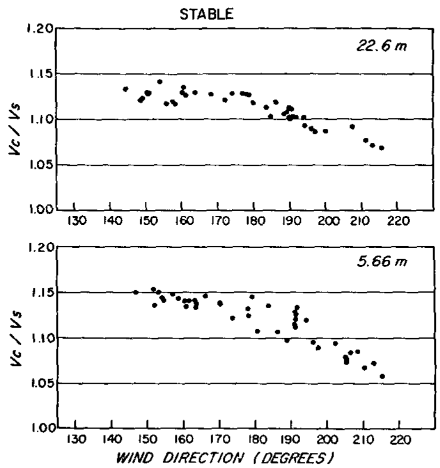

Fig. 7. Wind direction variation of cup to sonic anemometer wind speed ratio at 5.66 and 22.6 m for stable runs.

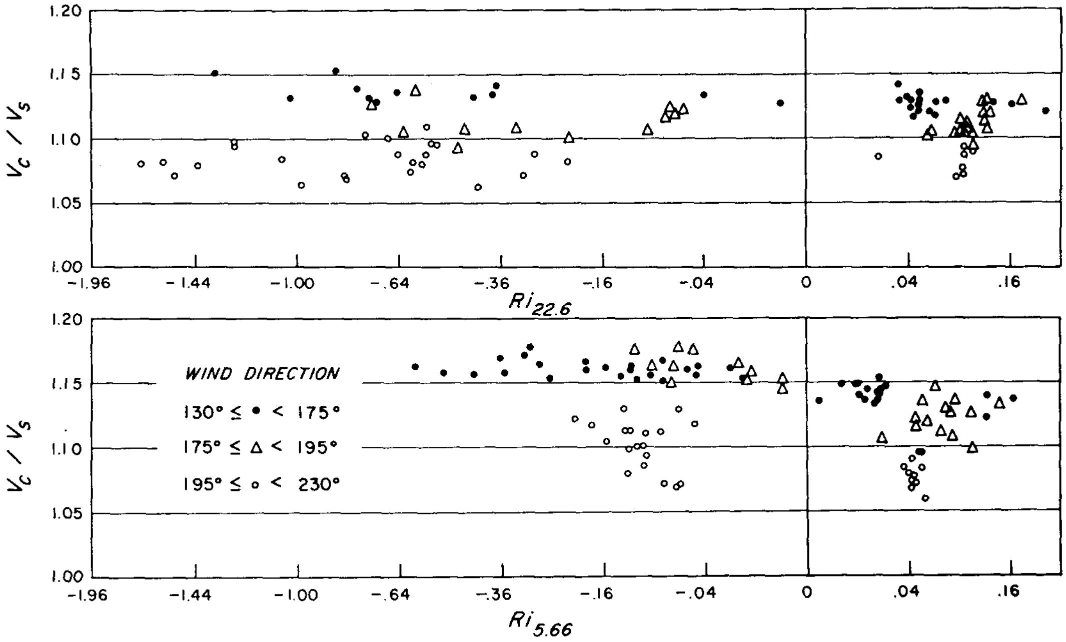

FIG. 8. Variation of cup to sonic anemometer wind speed ratio as a function of Richardson number at 5.66 and 22.6 m.

results from the fact that the cup anemometer speeds up faster than it decelerates in gusty winds. The problem remains as to what is the order of magnitude of the errors in wind speed due to overspeeding of the cup anemometer.

Figs. 2 and 3 showed that the difference between V_c and V_s is dependent on wind direction and to some extent on thermal stability. The variation of the ratios of V_c to V_s with wind direction, as measured by the wind vane, is presented in Figs. 6 and 7. These figures show that, regardless of stability and height, the wind speed ratio is almost constant with wind direction between 130° and 170° or 180° and then steadily decreases as the wind veers from south to south-southwest.

Based on the above figures the ratios, V_c/V_s, were plotted as functions of Richardson number in Fig. 8. The Richardson numbers were obtained from the temperature and wind speed gradients between 8 and 4 m for the 5.66 m level and between 32 and 16 m for the 22.6 m level. The runs are identified by wind direction, using closed circles for those between 130° and 175°, open triangles for those between 175° and 195°, and open circles for those beyond 195°. The figure shows that stability affects the wind speed ratios only for winds from 130° to 175° and that the effect is small.

4. Tower influence on wind speed measurements

The systematic variation of the ratio V_c to V_s with wind direction strongly suggests that the tower influences the wind as measured by the wind sensors on the windward side of the tower. A number of controlled laboratory experiments and environmental experiments have been conducted to study the tower influence on wind measurements. Excellent reviews of these studies are provided by Cermak and Horn (1968) and by Hathorn (1968). Most of these studies were primarily interested in the "shadow" effect of a tower on wind velocity in the lee of the structure, an effect which can be ignored in this paper. However, these studies showed that the tower influence on wind flow depends on the proximity of the sensors to the tower and the direction of the wind with respect to the sensors and the tower. In those investigations that used open lattice-type towers in the laboratory or in the environment, the towers had triangular cross sections, the exception being a tapered square one used by Moses and Daubek (1961). With the wind sensor located at a distance from the tower equal to about half the tower width, they found errors >30% in the measured wind speed when the wind blowing toward the sensor made an angle of 20–40° with respect to the sides of the tower adjacent to the sensor. In view of such large errors on the windward side of a square tower and in view of the lack of quantitative information on influences by a square tower, an attempt was made to obtain some qualitative knowledge of the tower influence on wind flow from available data.

Although what follows may not seem to be directly applicable to the square lattice-type tower with the boom arrangements shown in Fig. 1, the results of controlled wind tunnel experiments by Gill *et al.* (1966) and of the environmental experiments by Hathorn were used to illustrate the tower influence on wind flow on the windward side of the tower. These two studies were selected since they both supplied quantitative information on the magnitude of the tower effect. Both studies used triangular lattice-type structures, with booms for the wind sensors extending from a corner parallel to one side of the tower as shown in Fig. 9. For the wind tunnel experiments (designated as A in Fig. 9) the boom length was equivalent to the length L of one side of the tower, while for the environmental experiments (B in Fig. 9) the boom length was $1.5L$. The average ratios of observed to undisturbed wind speeds from four wind tunnel tests presented by Gill *et al.* were obtained at 15° intervals. The ratios of measured wind speed to a reference wind speed were also obtained at 15° intervals from graphs presented by Hathorn. The variations of wind speed ratios with wind direction are shown in Fig. 9. To make these experimental results compatible with the boom arrangements shown in Fig. 1, the boom orientation in Fig. 9 was first made to read 225° (same as the cup anemometer booms) and the tower was then rotated 45° so that the boom orientation read 180° (same as the sonic anemometer booms). Thus, Fig. 9 has two scales for wind direction, one labelled c for the cup anemometer boom and the other labelled s for the sonic anemometer boom. For the s-scale the wind direction and, in turn, the wind speed ratios are symmetrical about 180°.

Assuming that the mean wind direction for the cup and sonic anemometers are always the same, the ratios of V_c to V_s for A and B as functions of wind direction can be obtained. The results are shown as curves A and B in the lower half of Fig. 9. These two hypothetical curves then represent the wind speed ratios that would be expected due to the influence of a triangular open tower on two similar wind speed sensors that are mounted on booms whose lengths are the same but whose orientations differ by 45°. The two curves differ markedly for wind directions between 120° and 180° but are remarkably similar for wind directions between 180° and 225°. For both curves it can be seen that V_c reads as much as 5% greater or less than V_s due to the tower influence. Referring back to Figs. 6 and 7 we note that the variation of the point distribution of ratios of V_c to V_s with wind direction follows the trend of curve B. For comparison, the speed ratios for the unstable runs at 5.66 m in Fig. 6 were reduced by a constant amount of 0.115 units and plotted in Fig. 9. The reduced ratios fit curve B quite well. In a similar manner the speed ratios of cup to sonic anemometers for the unstable runs at 22.6 m in Fig. 6 were reduced by a constant amount of 0.085 unit, the stable runs at 5.66 m in Fig. 7 by 0.090 unit, and the stable runs at 22.6 m in the same figure by 0.080 unit. The amounts of reduction were again obtained subjectively. These reduced ratios are shown along with curve B in Fig. 10. The figure shows that the reduced speed ratios and curve B are in good agreement in all three cases. Although these results are not conclusive, curve B appears to provide a suitable approximation of the errors in the ratios of V_c to V_s due to the tower influence on cup and sonic anemometers.

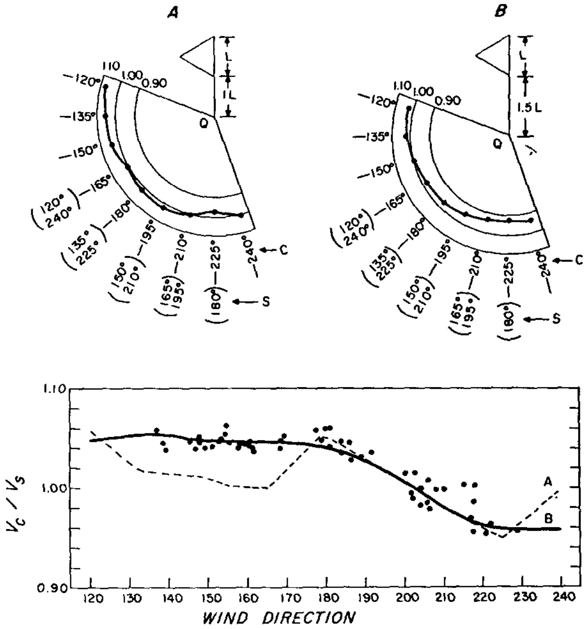

FIG. 9. Ratio of measured wind speed to reference wind speed from wind tunnel experiments (A) by Gill *et al.* (1966) and from environmental experiments (B) by Hathorn (1968).

If the ratio of the measured cup to sonic anemometer wind speeds is considered to be equal to the sum of the ratio due to cup anemometer overspeeding and the ratio due to tower influence on the two wind speed sensors, then the amounts reduced in the above discussion should be the magnitudes of the overspeeding of the cup anemometers. Percentagewise these amount to ~8–12% with the average overspeeding estimated to be ~10%. This is the same percentage quoted by Moses (1968) in discussing MacCready's (1966) paper on errors in cup anemometry.

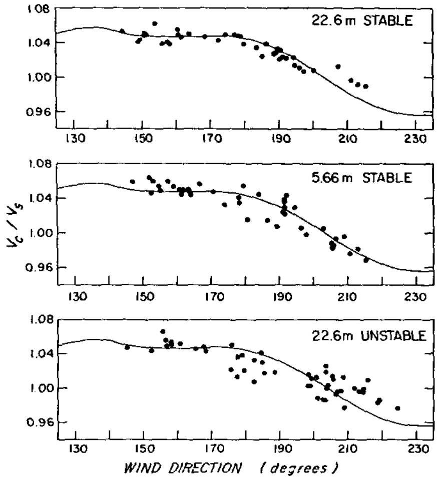

FIG. 10. Reduced ratios of cup to sonic anemometer wind speeds compared with curve B in Fig. 9 for stable runs at 5.66 m and unstable and stable runs at 22.6 m.

5. Conclusions

On the basis of wind tunnel and environmental experiments the fast-response three-component sonic anemometer has been determined to be a highly accurate wind speed sensor. The Kansas 1968 Field Program and the comparison test at Hanscom Field have shown that with the sonic anemometer measurement used as the reference wind speed the slow-response cup anemometer overestimates the wind speed by 8 to as much as 16%. These errors are much too large for the accuracy demanded of wind speed measurements for wind profile and gradient studies in micrometeorology. To minimize these errors the response characteristics of all cup anemometers should be investigated thoroughly. No strong relation was found between the degree of overspeeding and height above the ground surface.

The wind speed measurements by cup anemometers and other types of wind sensors mounted on towers are also subject to errors arising from the distortion to the wind flow by the tower. In the Kansas 1968 Field Program an open lattice-type tower was used as opposed to a solid one, the sensors were mounted on separate booms and were located at distances equal to at least one side of the tower from the corners of the tower, and observations were restricted to a narrow range of wind direction for minimal tower influence. Despite these precautions, errors due to the tower influence on wind sensors are inferred to be as much as ±5% of the observed wind speed ratios of the two sensors. Thus, the magnitude of the errors due to tower influence on wind measurements for that particular tower and that particular boom arrangement must be ascertained. Due to the lack of specific information on the tower effect, the results are inconclusive, but the overspeeding of the cup anemometer used is estimated to be ~10%.

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