# Accuracy of the Collocated Transfer Standard Method for Wind Instrument Auditing

THOMAS J. LOCKHART

*Meteorological Standards Institute, Fox Island, Washington*

20 June 1988 and 19 January 1989

ABSTRACT

The application of collocated data collection for the purpose of estimating the accuracy of an operating wind instrument requires some baseline demonstrating the best agreement which can be expected. A series of data were carefully taken in 1982 from six different collocated wind instruments. The published reports of these data suggest that the best agreement from averaged wind speed measurements will be between 0.3 and 0.5 m s$^{-1}$ and for wind direction will be 4 to 6 degrees.

A new analysis of the same data reduces the best expected agreement to about 0.2 m s$^{-1}$ and 2 degrees. The several reasons for claiming the better potential accuracy for collocated measurement (auditing) with calibrated transfer standard instruments are discussed.

## 1. Introduction

The collocated transfer standard (CTS) method for wind instrument auditing is based on the assumption that the difference between data from the CTS and data from the subject instrument will describe the error of the subject instrument plus or minus some uncertainty. The uncertainty can be estimated by using the ASTM Standard Practice for determining the operational comparability of meteorological measurements (ASTM 1984). This practice specifies how the data from two instruments, mounted near each other, can be expressed in terms of the difference between them. The root-mean-square (rms) of the sample differences is called operational comparability ($C$) and the systematic difference ($d$) is the bias. The estimated standard deviation of the difference ($s$) about the systematic difference or bias describes the dynamic performance of one sensor versus the other. The bias describes the calibration difference for wind speed instruments and primarily the orientation difference for wind direction instruments. A field program in Boulder, Colorado in 1982 gathered data in a way which can be used to estimate the uncertanity of a CTS audit. An analysis of these data has been reported in Finkelstein et al. (1986) and Kaimal et al. (1984). While this field program had as its main goal a test of the suitability of conventional instruments for measuring second moments (variance), the inclusion of the mean values in these reports and papers could lead to an underestimation of the accuracy of the CTS method for auditing.

In this paper an analysis of the same raw data finds significantly smaller uncertainties than those published in the above references. The reasons for the differences are partially explained. One reason is that two dissimilar periods with different instruments were combined in the original analysis into a single data period. Another reason is that samples from the standard of comparison (a sonic anemometer) used in the original analysis contained instrument errors which added to the natural variability expected in surface layer monitoring.

The published values of $C$ and $d$ (called $c$ and $b$ in the references) suggest too large an uncertainty in the method to support the use of a CTS to verify that a wind instrument is accurate to the required 0.5 mps and 5 degrees of arc for air quality applications. This

TABLE 1. Hypothetical audit of wind direction $\theta$.

| Sample (No.) | $b$ (deg) | $a_1$ (deg) | $a_2$ (deg) | $a_1 - b$ (deg) | $a_2 - b$ (deg) |
|---|---|---|---|---|---|
| 1 | 31 | 20 | 40 | −11 | 9 |
| 2 | 34 | 25 | 23 | −9 | −11 |
| 3 | 31 | 20 | 40 | −11 | 9 |
| · | 34 | 25 | 23 | −9 | −11 |
| · | 31 | 20 | 40 | −11 | 9 |
| 1000 | 34 | 25 | 23 | −9 | −11 |
| Average $\bar{\theta}$ | 32.5 | 22.5 | 31.5 | | |
| $\sigma_\theta$ | 1.5 | 2.5 | 8.5 | | |
| From (1) | | | | $C$ = 10.05 | 10.05 |
| From (2) | | | | $d$ = −10.00 | −1.00 |
| From (3) | | | | $s$ = 1.00 | 10.00 |

*Corresponding author address:* Mr. Thomas J. Lockhart, Meteorological Standards Institute, 841 Seventh Lane, P.O. Box 26, Fox Island, WA 98333.

© 1989 American Meteorological Society

Unauthenticated | Downloaded 10/07/22 12:19 PM UTC

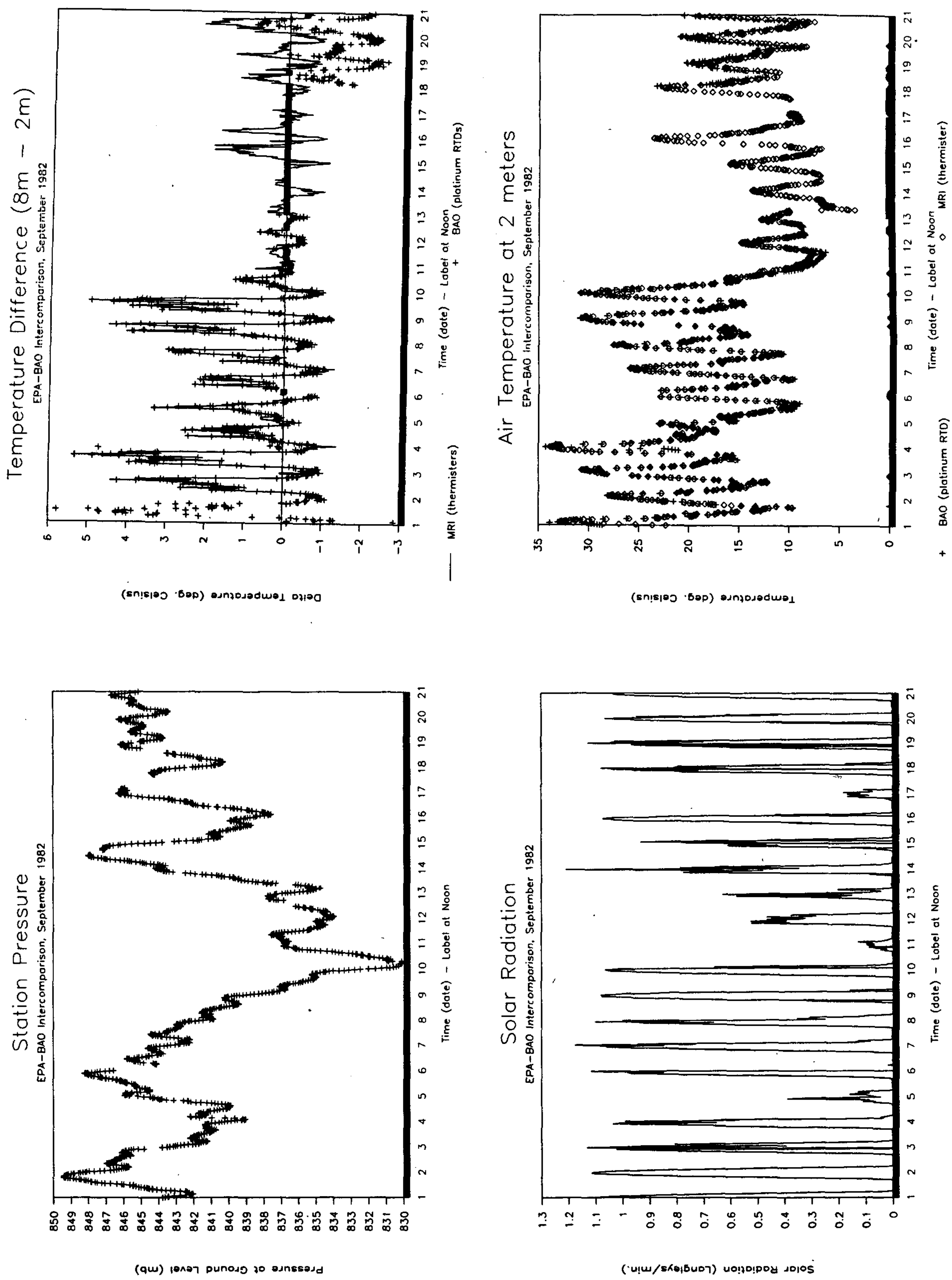


FIG. 1. Background data.

Unauthenticated | Downloaded 10/07/22 12:19 PM UTC

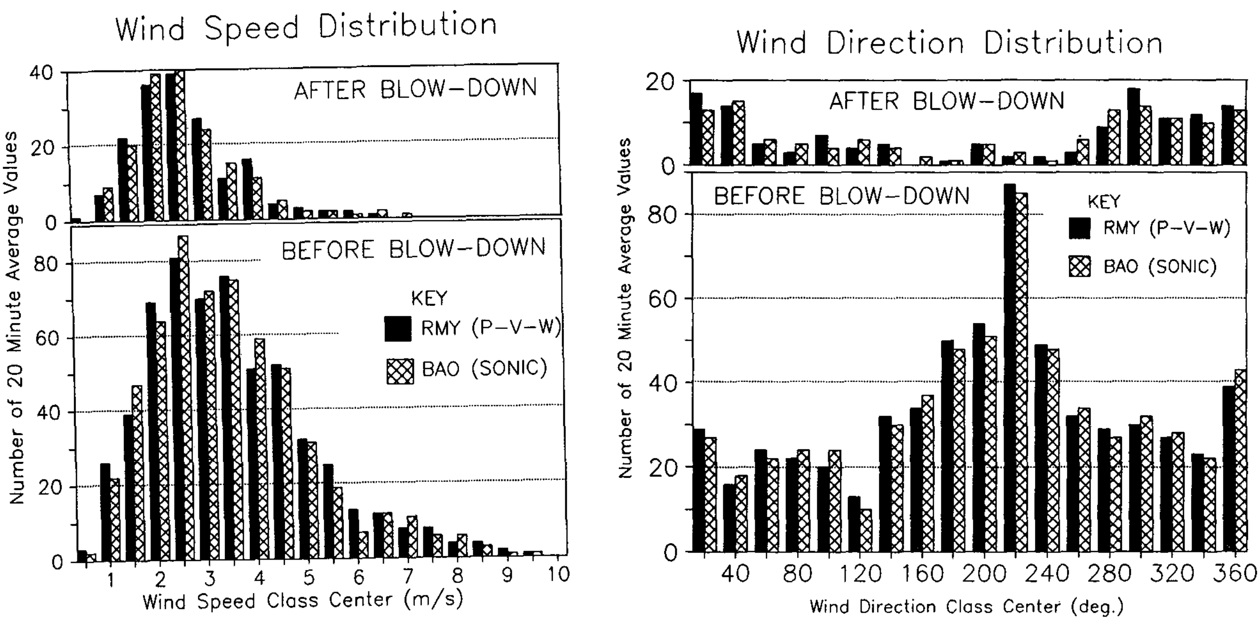


FIG. 2. Wind speed and wind direction distributions for BAO sonic anemometer (SONIC) and R. M. Young propeller-vane (P-V-W).

further analysis of the same data shows that the CTS method can be used for that purpose.

## 2. Data collection, reduction and summarization

Six entirely different instrument systems for measuring wind in three dimensions were collocated near the base of the Boulder Atmospheric Observatory (BAO) tower. The horizontal wind speed and wind direction will be considered here. Each instrument system was mounted atop a 10 m tower. The six 10 m towers were in a line oriented 094 to 274 degrees with a separation distance of about 5 m. Going from east to west, they were:

1 U-V-W fixed propeller array (R. M. Young)
2 C-BIV bivane and cup (MRI 1074 cup and bivane)
3 P-BIV Gill propeller bivane (R. M. Young)
4 SONIC sonic anemometer (Applied Technology)
5 C-V-W cup and vane (Climatronics F-460)
6 P-V-W propeller vane (R. M. Young)

The orientation of the SONIC was the same as those on the BAO tower with the structure containing the *w* sensors pointing toward the SSE. The orientation of the fixed propeller array was one toward south and one toward west. The BAO tower was about 25 m east of tower 1.

All wind sensors were sampled 10 times per second by the standard BAO data system (Kaimal and Gaynor 1983). Each 10 seconds the mean, variance and one instantaneous "grab sample" were recorded. The data were combined into 20 minute means and variances for both the continuous data (12 000 samples per 20 minutes) and the grab sample data (120 samples per 20 minutes). The 20 minute data were calculated as scalar values with speed and direction handled independently. The 10 second averages were either resultant vectors or scalar averages depending upon the instrument. To assure consistency and avoid data handling bias, the instantaneous 10 second grab samples were used to convert from orthogonal to polar coordinates, where necessary, before averaging. Some editing of the data was done by BAO. These edited 20 minute values were supplied to the Environmental Protection Agency (EPA) for further editing and analysis. The dataset provided EPA and the dataset edited by EPA were made available to the author for this further analysis.

TABLE 2. Comparability and bias for wind direction using SONIC as standard of comparison.

| Instrument | $c'$* (deg) | $C$** (deg) | $b'$ (deg) | $d$ (deg) | $N'$ | $N$ |
|---|---|---|---|---|---|---|
| U-V-W | 5.40 | 5.40 | −1.47 | −1.48 | 1035 | 1035 |
| C-BIV | 5.54 | 5.54 | −2.69 | −2.69 | 1057 | 1057 |
| P-BIV | 4.61 | 4.61 | −0.16 | −0.16 | 1055 | 1055 |
| C-V-W | 4.48 | 4.48 | 1.44 | 1.44 | 819 | 819 |
| P-V-W | 4.03 | 4.05 | −0.31 | −0.27 | 897 | 897 |

* $c'$, $b'$ and $N'$ are the published values.
** $C$, $d$ and $N$ are the new analysis values.

Unauthenticated | Downloaded 10/07/22 12:19 PM UTC

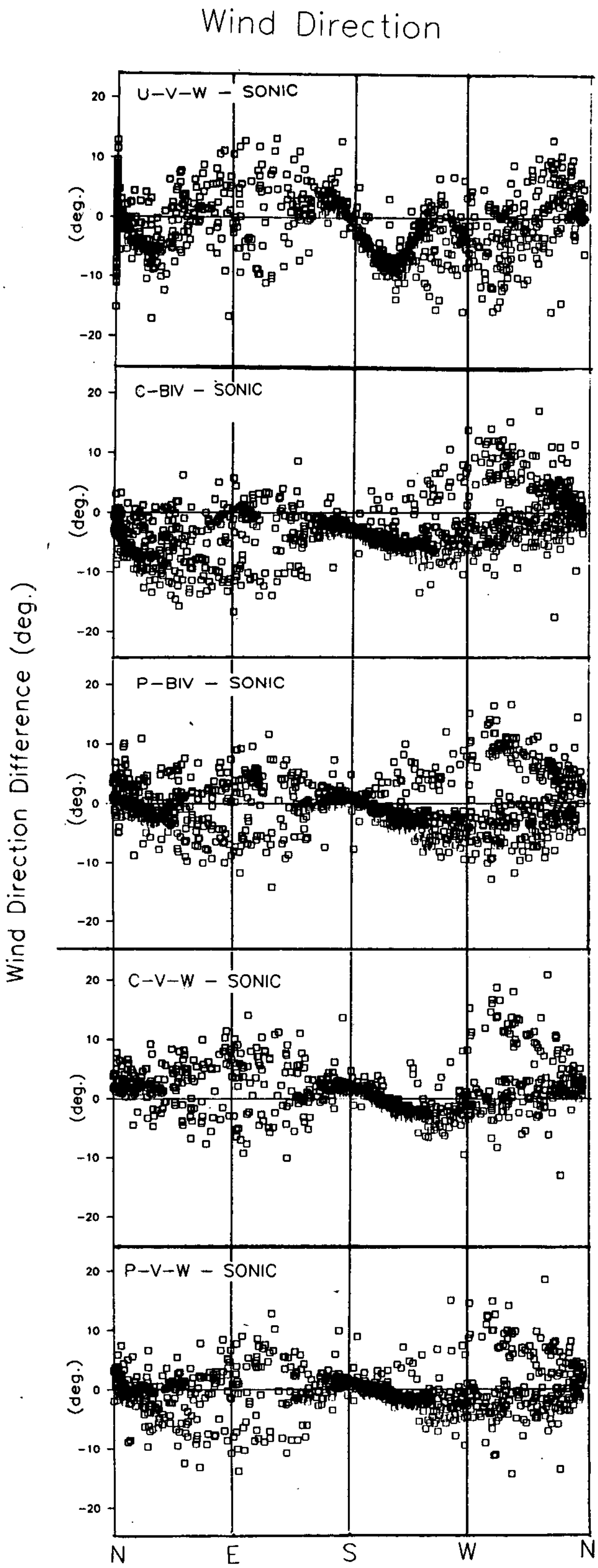


FIG. 3. Wind direction difference from SONIC for all data.

*a. The comparability method*

The comparability statistics were calculated in accordance with ASTM (1984) as follows:

$$C = \pm\left[\frac{1}{N} \sum (X_{a_i} - X_{b_i})^2\right]^{1/2} \quad (1)$$

$$d = \frac{1}{N} \sum (X_{a_i} - X_{b_i}) \quad (2)$$

$$s = \pm\sqrt{C^2 - d^2} \quad (3)$$

where:

$X_{a_i}$ $i$th measurement made by one system
$X_{b_i}$ $i$th simultaneous measurement made by another system, and
$N$ number of samples used.

Consider two performance audits of hypothetical wind vanes. Vane $b$ is the CTS. Vanes $a_1$ and $a_2$ are to be audited by the CTS method. A series of 1000 samples are represented in Table 1 with statistics from (1), (2) and (3). A few comments about this hypothetical audit are made in section 4.

*b. General conditions*

The measurements of surface pressure and solar radiation are plotted in Fig. 1 as general background information. Two differential temperature systems were deployed as a part of the comparison program. One set was a pair of BAO platinum transducers mounted in Young aspirated radiation shields. They were mounted at 2 m and 8 m on tower 4. The other set was a pair of linearized thermisters (YSI) in MRI aspirated radiation shields, very much like the Young shields. These were mounted at 2 m and 8 m on tower 3. The data from the temperature comparison have not been published or discussed. They are plotted in Fig. 1 as background data.

It is useful to have a background distribution of wind speed and wind direction to get a feel for the conditions which prevailed during the experiment. Figure 2 is a histogram of speed (0.5 m s$^{-1}$ bin size) and direction (20 degree bin size) from both the instruments

TABLE 3. Comparability and bias for wind direction using SONIC as standard of comparison.

| Instrument | $c$ Before (deg) | $c'$ After (deg) | $b$ Before (deg) | $b'$ After (deg) | $N$ Before | $N'$ After |
|---|---|---|---|---|---|---|
| U-V-W | 5.52 | 5.29 | −2.12 | −0.74 | 661 | 150 |
| C-BIV | 4.60 | 7.85 | −3.50 | −1.57 | 679 | 155 |
| P-BIV | 3.75 | 6.81 | −1.29 | 2.52 | 672 | 157 |
| C-V-W | 3.52 | 7.39 | 0.90 | 3.87 | 670 | 149 |
| P-V-W | 3.25 | 6.57 | −0.63 | 0.62 | 680 | 153 |

Unauthenticated | Downloaded 10/07/22 12:19 PM UTC

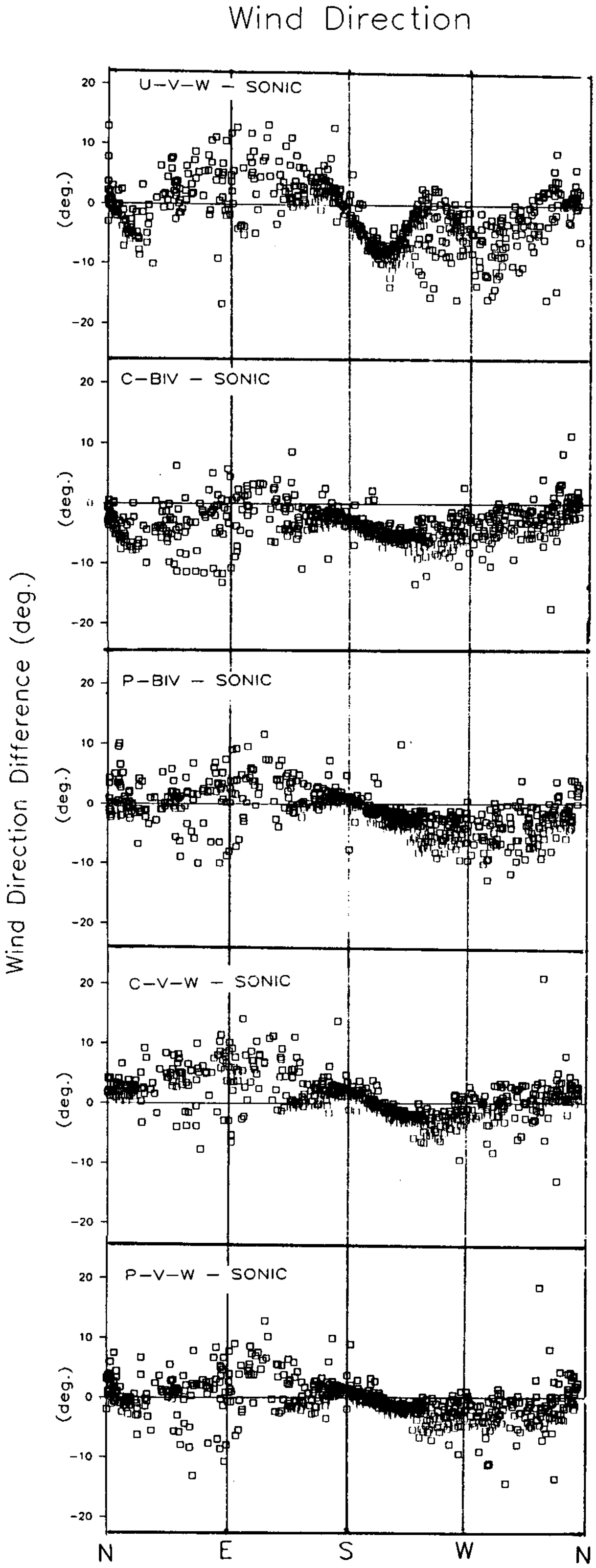


FIG. 4. Wind direction difference from SONIC for data before blow-down accident.

which have been used as standards of comparison, the sonic anemometer (SONIC) and the propeller vane (P-V-W). These data describe the final complete database both before and after the blow-down accident as described in 2c.

### c. *Wind direction*

Using the edited EPA data, an attempt was made to reproduce the published values. Table 2 shows the published data (Finkelstein et al. 1986, Table 3) and the new analysis. It is clear that the dataset is the same. Figure 3 is a plot of all of the difference values vs wind direction (SONIC) used in the Table 2 statistics.

On the 13 September, a strong wind in combination with rain-soaked soil blew tower 4 over toward the west. Tower 4 knocked down tower 5, which in turn knocked down tower 6. The SONIC on tower 4 was replaced with another sensor. The cups, vanes and propellers on towers 5 and 6 were replaced with new ones. All six towers were operational on the 16th. To test the consequence of combining the periods into a single dataset, the analysis was run on the same dataset divided into the appropriate two parts. Table 3 shows the comparability and bias for each period. Figure 4 is a plot of all the difference values vs wind direction for the period before the blow-down.

It was somewhat unsettling to have different sample sizes for different comparisons. Before testing the effect of the chosen "standard of comparison," a solid database was constructed by eliminating any 20 minute period with missing direction data for any sensor. Between 32 and 51 partially complete periods were deleted (5%–8%). The propeller vane (P-V-W) on tower 6 was chosen as the new standard of comparison. Table 4 documents the lower comparability found when the new standard of comparison was compared to the other instruments, particularly the vanes. The difference between (P-V-W)-(SONIC) and (SONIC)-(P-V-W) is a result of the times deleted because of some missing data. Table 4 also shows the SONIC problem with the replacement sensor. Figure 5 is a plot of all the difference values vs wind direction for the period before the blow-down.

TABLE 4. Comparability and bias for wind direction using P-V-W as standard of comparison (before and after the blow-down).

| Instrument | $C'$* Before (deg) | $C'$** After (deg) | $s$* Before (deg) | $s'$** After (deg) | $d$* Before (deg) | $d'$** After (deg) |
|---|---|---|---|---|---|---|
| U-V-W | 4.27 | 5.19 | 3.98 | 5.03 | −1.55 | −1.26 |
| C-BIV | 3.60 | 3.33 | 2.10 | 2.76 | −2.92 | −1.87 |
| P-BIV | 1.78 | 2.52 | 1.66 | 1.46 | −0.64 | 2.05 |
| SONIC | 2.86 | 6.67 | 2.80 | 6.64 | 0.59 | −0.61 |
| C-V-W | 2.26 | 3.88 | 1.70 | 1.38 | 1.48 | 3.63 |

* ($N$ = 610).
** ($N$ = 132).

Unauthenticated | Downloaded 10/07/22 12:19 PM UTC

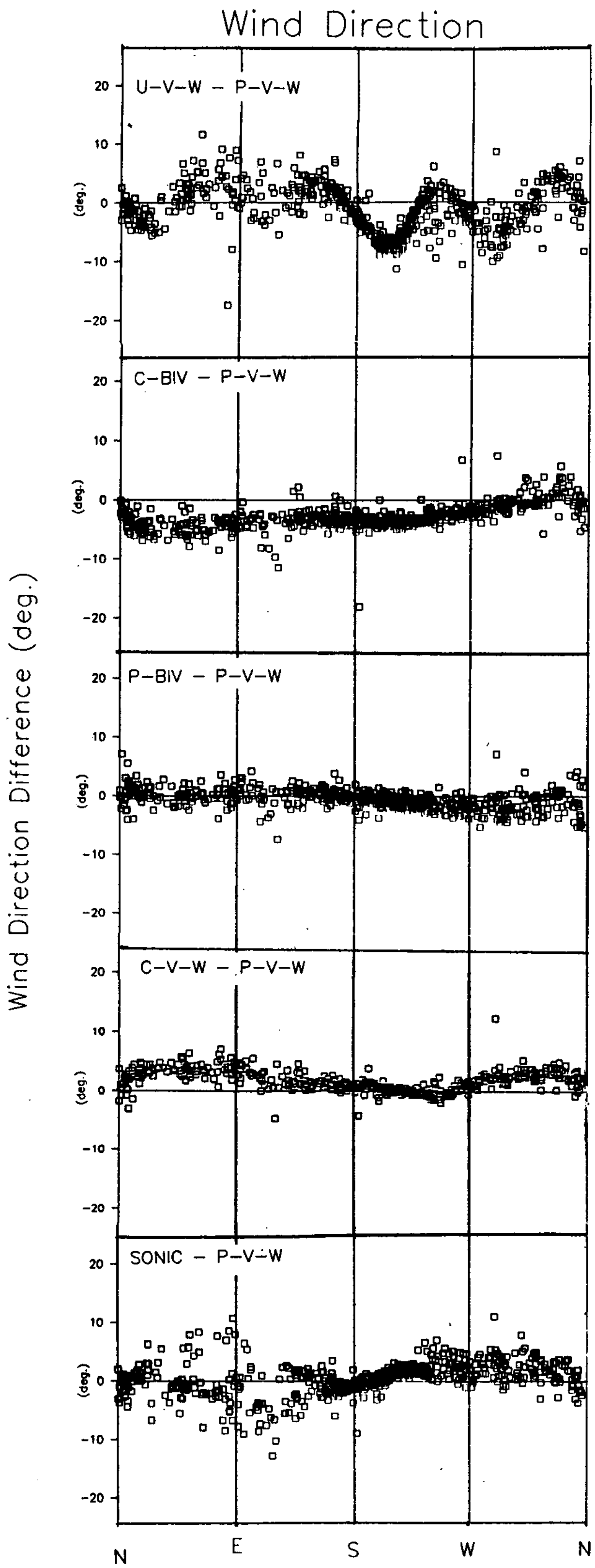


FIG. 5. Wind direction difference from propeller-vane for data before blow-down accident.

TABLE 5. Comparability and bias for wind speed using SONIC as standard of comparison.

| Instrument | $c'$* (m s$^{-1}$) | $C$** (m s$^{-1}$) | $b'$ (m s$^{-1}$) | $d$ (m s$^{-1}$) | $N'$ | $N$ |
|---|---|---|---|---|---|---|
| U-V-W | 0.53 | 0.53 | −0.43 | −0.43 | 1279 | 1279 |
| C-BIV | 0.35 | 0.22 | −0.13 | −0.05 | 760 | 800 |
| P-BIV | 0.48 | 0.30 | 0.33 | 0.13 | 760 | 1272 |
| C-V-W | 0.36 | 0.20 | −0.13 | −0.05 | 760 | 739 |
| P-V-W | 0.34 | 0.21 | −0.16 | 0.00 | 760 | 1092 |

* $c'$, $b'$ and $N'$ are the published values.
** $C$, $d$ and $N$ are the new analysis values.

### *d. Wind speed*

A similar analysis was attempted for wind speed. The initial step of reproducing the published values was not successful. There was no single file with all the speed data as there was for direction. A file was constructed by merging the grab sample data for towers 1, 3 and 4 with the average data for towers 2, 5 and 6. The latter three required no coordinate changes for scalar values and it is not known if a grab sample database was delivered to EPA for these sensors. Table 5 compares the published data (Finkelstein et al. 1986, Table 2) with the data from the combined database.

Since the published data could not be duplicated, the analysis moved directly to the solid database with no missing data and the use of the propeller vane (P-V-W) as the standard of comparison. Table 6 shows these data before and after the blow-down incident. Figure 6 is a plot of all the difference values vs wind speed from P-V-W. Different symbols are used for before and after the blow-down.

## 3. Analysis

### *a. Wind direction and $\sigma_\theta$*

Looking at Figs. 3, 4 and 5 it is clear that much of the variability is related to the SONIC instrument, particularly the one used AFTER the blow-down. Note also the difference in comparability for the SONIC in Table 4. The differences shown in Fig. 5 between the three vane instruments and the P-V-W propeller vane represent a more accurate picture of the potential uncertainty for collocated data. Vanes agree with vanes, but will a vane give a true measure of turbulent flow given the response window of a vane which excludes small eddy sizes and the second order response which adds vane movement which is not atmospheric? One way to look at this question for the 20 minute mean time period is to examine the standard deviation of the samples during the 20 minutes, namely $\sigma_\theta$.

Unauthenticated | Downloaded 10/07/22 12:19 PM UTC

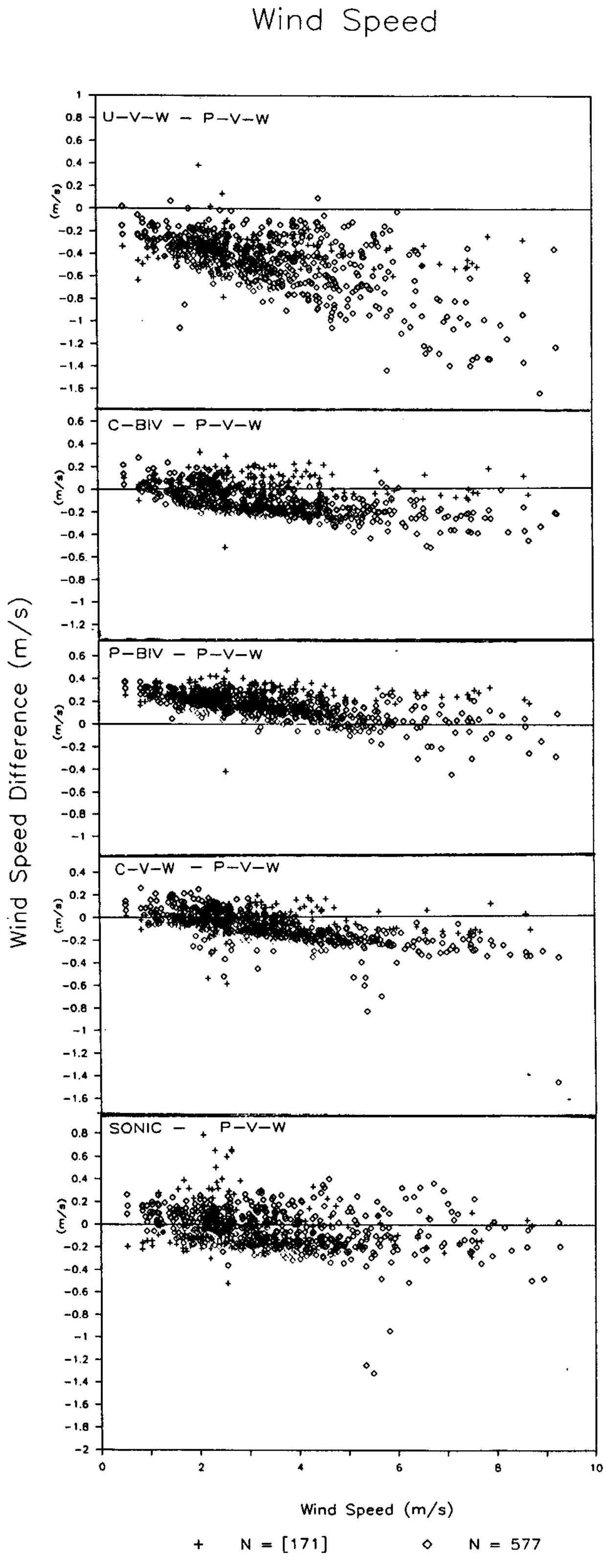


FIG. 6. Wind speed difference from propeller-vane for data before blow-down accident.

TABLE 6. Comparability and bias for wind speed using P-V-W as standard of comparison (before and after the blow-down).

| Instrument | $C$* Before (m $s^{-1}$) | $C'$** After (m $s^{-1}$) | $s$* Before (m $s^{-1}$) | $s'$** After (m $s^{-1}$) | $d$* Before (m $s^{-1}$) | $d'$** After (m $s^{-1}$) |
|---|---|---|---|---|---|---|
| U-V-W | 0.54 | 0.38 | 0.25 | 0.14 | −0.48 | −0.36 |
| C-BIV | 0.18 | 0.11 | 0.12 | 0.10 | −0.13 | 0.05 |
| P-BIV | 0.17 | 0.28 | 0.02 | 0.08 | 0.14 | 0.27 |
| SONIC | 0.18 | 0.20 | 0.17 | 0.20 | −0.05 | −0.02 |
| C-V-W | 0.18 | 0.11 | 0.14 | 0.10 | −0.10 | −0.03 |

* ($N$ = 577).
** ($N$ = 171).

To examine the difference in $\sigma_\theta$ for the six sensors, a database was combined from the edited data. It includes 590 samples from before the blow-down for each of six $\sigma_\theta$ (grab sample) channels, four $\sigma_\theta$ (average data) channels, one wind direction and one wind speed channel. The data were sorted by wind direction so that a subset between 150 and 250 degrees could be examined. This is the range where the SONIC seemed to have the least scatter (see Fig. 5). This subset was further sorted by wind speed to find a second subset within the direction window and above 2 m $s^{-1}$. Table 7 is a summary of the differences between each $\sigma_\theta$ minus the tower 6 $\sigma_\theta$ for the grab samples. If the direction changes from small eddies, which SONIC can measure but vanes cannot, are important for a 20 minute average, the $\sigma_\theta$ will be larger for SONIC than for the vanes and the average difference ($d$, SONIC–P-V-W) will be positive. This is the same consequence of apparent direction changes from SONIC instrument error. If the direction changes from the overshoot of a moving vane are important for a 20 minute average, the average difference will be negative. Since the average differences are quite small and both positive and negative, it seems they are not important at 20 minutes.

## b. *Sample size*

Most of the analysis is based on grab sample data limiting the sample size to 120 for each 20-minute value. The edited EPA database also provided the "average" data (12 000 samples per 20-minute value) for $\sigma_\theta$ and $\bar{\theta}$ for the four vane sensors. On-Site Meteorological Program Guidance for Regulatory Modeling Applications (EPA 1987, 6–11) stipulates that at least 60 samples of direction be taken to estimate the mean and at least 360 samples of direction be taken to estimate the standard deviation to about 5%–10% of the true value. To test the impact of a small sample size on $\sigma_\theta$ estimates, a combined dataset of average and grab sample statistics was compiled. Letting the average data represent the true values, the comparability and bias were calculated from the differences found by subtracting the average $\sigma_\theta$ from the grab sample $\sigma_\theta$. A sub-

Unauthenticated | Downloaded 10/07/22 12:19 PM UTC

TABLE 7. Comparability and bias for $\sigma_\theta$ using P-V-W as standard of comparison.

| Instrument | C* (deg) | C'** (deg) | C"† (deg) | d (deg) | d' (deg) | d" (deg) |
|---|---|---|---|---|---|---|
| U-V-W | 3.64 | 2.52 | 2.25 | −0.34 | −0.09 | 0.03 |
| C-BIV | 2.65 | 1.06 | 1.03 | −0.86 | −0.35 | −0.36 |
| P-BIV | 2.12 | 0.80 | 0.77 | 0.21 | −0.12 | −0.12 |
| SONIC | 2.29 | 1.28 | 1.19 | −0.29 | 0.38 | 0.27 |
| C-V-W | 2.02 | 0.75 | 0.71 | −0.35 | −0.22 | −0.28 |

* C and d are for all the data ($N$ = 590).
** C' and d' are for 150–250 deg. ($N$ = 273).
† C" and d" are for >2 m s$^{-1}$ ($N$ = 249).

TABLE 9. Comparability and bias for $\sigma_\theta$ grab sample data and average data.

| Instrument | C* (deg) | C'** (deg) | C"† (deg) | d (deg) | d' (deg) | d" (deg) |
|---|---|---|---|---|---|---|
| C-BIV | 1.24 | 0.57 | 1.08 | 0.68 | 0.35 | 0.59 |
| P-BIV | 1.81 | 0.99 | 1.69 | 1.33 | 0.66 | 1.36 |
| C-V-W | 1.72 | 0.93 | 1.64 | 1.22 | 0.57 | 1.30 |
| P-V-W | 1.70 | 1.05 | 1.72 | 1.29 | 0.69 | 1.34 |
| Ave. | 1.62 | 0.88 | 1.53 | 1.13 | 0.57 | 1.15 |
| Percent†† | 48 | 12 | 10 | 34 | 8 | 8 |

* C and d for $\sigma_\theta$ 1.7–5 deg. ($N$ = 100).
** C' and d' for $\sigma_\theta$ 5–10 deg. ($N$ = 190).
† C" and d" for $\sigma_\theta$ 10–20 deg. ($N$ = 116).
†† Percent ' is with respect to the interval midpoint.

set of these data was compiled to isolate any mutual or large tower interference by limiting the directions to between 150 and 250 degrees (184 degrees being perpendicular to the tower line). A second subset assured the speed to be greater than 2 m s$^{-1}$. Table 8 lists the results of this analysis. The small sample size may have introduced a bias in $\sigma_\theta$ of about one degree. Listed also in Table 8 is a comparison of the average and grab sample average directions for (P-V-W). As might be expected, the average direction is accurately estimated by the grab samples with no significant bias.

To test the sample size recommendations in EPA (1987) stated above, the data shown in Table 8 were resorted by size of $\sigma_\theta$ as measured by P-V-W. Table 9 shows these data for three ranges of $\sigma_\theta$. Both the bias and the comparability are consistantly lower in the 5–10 degree range.

These data support the guidance that 120 samples is too small to estimate the standard deviation within 5%–10%.

## 4. Conclusions

This further analysis of the 1982 Boulder comparative data for in situ sensors shows that cups and vanes or a vane with a front-mounted propeller may be used as a CTS to audit wind instruments. Consider the hypothetical audit described in 2a. The systematic difference ($d$) with respect to the CTS describes the bias error in the data from the challenged instrument. For $a_1$, the wind directions contain a −10 degree orientation bias (see Table 1). If the two sensors are operating properly and sited properly, the standard deviation of the difference ($s$) will be 2 degrees or less (see C-V-W in Table 4). Sensor $a_1$ qualifies and the accuracy of the average direction can be stated as −10 ± 2 degrees. The average data could be corrected by adding 10 degrees leaving an uncertainty of about 2 degrees . The ASTM method cannot be applied to $\sigma_\theta$ unless each difference contains enough samples to be representative. For $a_2$, the standard deviation of the difference is outside the limit for proper operation and siting. Further analysis would be necessary to find the apparent problem with $a^2$.

The variable uncertainty, or irreducible nonbias uncertainty, for collocated wind direction data is estimated from Table 4 C-V-W as 2 degrees. For wind speed, this value is estimated from Table 6 C-V-W as 0.2 m s$^{-1}$.

The CTS anemometer should be calibrated in a suitable wind tunnel to an accuracy (with respect to the wind tunnel) of 0.1 m s$^{-1}$ over a range of 2–10 m s$^{-1}$. The CTS vane should be calibrated by a circle divider to an accuracy (with respect to the vane base) of 2 degrees and oriented to true north to an accuracy of 2 degrees.

The standard deviation ($s$) of the differences observed in the CTS audit method provides a measure of the quality of the test data. If it is greater than 0.2 m s$^{-1}$ for speed or 2 degrees for direction, look for one of the following problems:

- a malfunctioning sensor (bearings or damage)
- wind speed samples less than 1 m s$^{-1}$
- exposure interference
- a data logging problem (software or hardware)

If the test data are within the expected variability, the average difference, bias or systematic difference from the CTS method audit data is the error of the challenged

TABLE 8. Comparability and bias for $\sigma_\theta$ and $\theta$—grab sample data and average data ($\sigma_\theta$ is sigma theta and $\bar{\theta}$ is average direction.)

| Instrument | N | C* (deg) | C'** (deg) | C"† (deg) | d (deg) | d' (deg) | d" (deg) |
|---|---|---|---|---|---|---|---|
| $\sigma_\theta$ C-BIV | 576 | 1.20 | 0.80 | 0.80 | 0.42 | 0.40 | 0.41 |
| $\sigma_\theta$ P-BIV | 494 | 2.14 | 1.22 | 1.23 | 0.80 | 0.84 | 0.86 |
| $\sigma_\theta$ C-V-W | 542 | 1.36 | 1.12 | 1.11 | 0.99 | 0.76 | 0.75 |
| $\sigma_\theta$ P-V-W | 501 | 1.77 | 1.31 | 1.31 | 0.82 | 0.90 | 0.92 |
| $\bar{\theta}$ P-V-W | 504 | 1.25 | 0.33 | 0.32 | −0.06 | 0.04 | 0.04 |

* C and d are for all the data.
** C' and d' are for 150–250 deg. ($N$ = 273).
† C" and d" are for >2 m s$^{-1}$ ($N$ = 429).

Unauthenticated | Downloaded 10/07/22 12:19 PM UTC

instrument. The uncertainty of the estimate of speed error is the CTS calibration uncertainty, 0.2 m $s^{-1}$, and for direction it is 2 degrees. If the standard deviation ($s$) of the direction difference data meets the criteria, all the direction error can be considered orientation error. An error larger than 2 degrees should be considered reason to reorient the challenged instrument.

The sample size should be large enough to make the data representative. The ASTM practice requires the number of samples ($N$) to be greater than the square of three standard deviations ($s$) of the difference samples divided by the increment of resolution ($r$) used either in sampling or reporting the results, or $N > (3s/r)$.

*Acknowledgments.* This analysis would have not been possible without the help and cooperation of the Environmental Monitoring Systems Laboratory of EPA, Research Triangle Park, North Carolina. Special thanks to Mr. M. E. Graves and Mr. J. Wu of Northrop Services, Inc. who provided the data on floppy disks. The analysis of the data was sponsored by Meteorological Standards Institute.

## REFERENCES

ASTM, 1984: Standard practice for determining the operational comparability of meteorological measurements. D 4430-84. American Society for Testing and Materials, Philadelphia, PA.

EPA, 1987: On-Site Meteorological Program Guidance for Regulatory Modeling Applications. EPA-450/4-87-013, Office of Air Quality Planning and Standards, Research Triangle Park, NC.

Finkelstein, P. L., J. C. Kaimal, J. E. Gaynor, M. E. Graves and T. J. Lockhart, 1986: Comparison of wind monitoring systems. Part I: In situ sensors. *J. Atmos. Oceanic Technol.*, **3**, 583–593.

Kaimal, J. C., and J. E. Gaynor, 1983: The Boulder Atmospheric Observatory. *J. Appl. Meteor.*, **22**, 863–880.

——, ——, P. L. Finkelstein, M. E. Graves and T. J. Lockhart, 1984: A field comparison of in situ meteorological sensors. NOAA/BAO Report No. 6.

Unauthenticated | Downloaded 10/07/22 12:19 PM UTC