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PREPRINT

Comparison of In-Situ Data from the Handar Sonic Anemometer and the Met One Cup and Vane

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6.3 COMPARISON OF IN-SITU DATA FROM THE HANDAR SONIC ANEMOMETER AND THE MET ONE CUP AND VANE

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1. INTRODUCTION

A unique 2-dimensional sonic anemometer, designed by Handar, was compared to a conventional cup anemometer and wind vane manufactured by Met One Instruments. This comparison was conducted to assess the ability of the sonic (Handar model 425) to measure the mean and turbulent properties of ambient winds at the standard observing height for surface wind monitoring.

Sonic anemometers are an attractive alternative to the mechanical cup and vane for routine monitoring. Some of the advantages of a sonic include no moving parts, no bearing surfaces, solid-state electronics and small cross-section to the wind. Several instrument manufacturers, such as Climatronics Corp., METEK GmbH, Mesa Systems Company, and Gill-SOLENT, have recently developed rugged and nearly maintenance-free sonic anemometers for routine measurements. These new sonic anemometers are distinguished from the research-grade, 1- and 3-dimensional sonics that are used for measuring sensible heat flux and vertical turbulence, e.g. sensors by Campbell Scientific Inc. and Applied Technologies Inc.

The routine use of sonics brings new challenges to those who maintain and audit meteorological systems. When auditing a system with sonic anemometers, technicians must employ alternatives to the traditional methods used for mechanical wind sensors. A cup anemometer is typically audited by rotating its shaft at known speeds (U.S.EPA 1990). Wind vanes are audited by orientation of the vane to known azimuths. Lacking a rotating shaft and a movable wind vane, the only practical method available for in-situ auditing of a sonic anemometer is by the collocated transfer standard (CTS) method.

A previous study (Finkelstien 1986) describes how data from collocated sensors at the Boulder Atmospheric Observatory (BAO) can be used to estimate the comparability of wind instruments. Another study of the same data set (Lockhart 1989) found smaller values for comparability. These studies employ the CTS method for wind instrument auditing.

Two collocated wind instruments can be compared using methods in ASTM (1984). The data from two instruments, mounted near each other, can be compared to reveal the combination of random and systematic (or instrument) error.

In this study, we duplicate the comparability analysis in Lockhart (1989) where absolute differences are used. We also calculate the normalized or relative differences using the wind speed data. Without an absolute standard wind measurement, our study must be limited to analysis of comparability between two sensors with separate, and not similar, errors. Although our data set is limited in size and range of ambient conditions, it does provide information on the expected values for comparability of these instruments.

We also examine a special case of very low winds. Calm winds are particularly difficult for mechanical sensors. Sonic anemometers lack a starting threshold and therefore have the potential to accurately measure very low winds.

2. DESCRIPTION OF SITE

Our field site is on the grounds of Lawrence Livermore National Laboratory (LLNL) which is located on the eastern side of the Livermore Valley, about 30 miles from Oakland, California. The 40-m meteorological tower used in this study is near the northwest corner of the LLNL site at an elevation of 174 m. The topography slopes up gently towards the southeast with a grade of approximately 12 m in 1 km.

The tower site is exposed to relatively open fetches with surfaces consisting mostly of annual grasses for at least 100 m in all directions. The surface roughness is about 0.15 m and the zero-plane displacement is about 0.5 m (Chapman and Gouveia, 1988). The largest nearby feature is a north to south line of eucalyptus trees about 125 m to the east. A housing development is about 250 m to the west. Commercial buildings are located 220 m to the north.

With an annual average wind speed of 2.6 m/s, LLNL experiences a high frequency of low winds (Gouveia and Chapman, 1989). Based on a 17-year record, 27 percent of the 15-minute average wind speeds are less than 1 m/s and 50 percent are less than 2 m/s.

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Table 1. Manufacturer's wind sensor specifications.

Sensor	Starting Threshold (m/s)	Distance Constant (m)	Damping Ratio	Accuracy	Resolution[c]	Max Speed (m/s)
010C cup	0.3	<1.6	---	V: 0.15 m/s or 1%	0.1 m/s	60
020C vane	0.3	<1.0	>0.4[b]	θ: ±3 deg	1 deg	60
425 sonic[a]	0.0	--	--	V: 0.135 m/s or 3% θ: ±2 deg	0.1 m/s 1 deg	60

[a] Preliminary specifications [b] Estimated using Wang (1979) [c] Includes resolution of logging system

3. METHODS

3.1. Tower Boom and Crossarm set-up

As shown in Figure 1, the wind sets were mounted on a crossarm located at the end of a 2-m long boom on the west side of the tower at 10 m above the ground. The crossarm was oriented north to south with the Met One wind vane on the south end. The Handar sonic was attached close to the center of the crossarm. The sonic's transducers are situated about 0.3 m above the center of the cup and vane.

3.2. Data Acquisition

We connected the Handar and Met One sensors to separate but identical Handar 540 data loggers running similar acquisition programs synchronized to the same clock. Each 540 logger polled the instruments every second and stored 15-minute information. The data were transferred periodically via modem to an Atmospheric Release Advisory Capability (ARAC) Sun workstation. Calibration and maintenance of the Met One system was performed according to U.S. Environmental Protection Agency (EPA) guidance (EPA, 1987 and 1990).

Both loggers recorded the following parameters:

- V, 15-min average horizontal wind speed
- V_m, maximum 1-sec horizontal wind speed
- σ_V, standard deviation of horizontal wind speed
- θ, 15-min average unit-vector wind direction
- σ_θ, standard deviation of wind direction calculated according to Yamartino, 1984

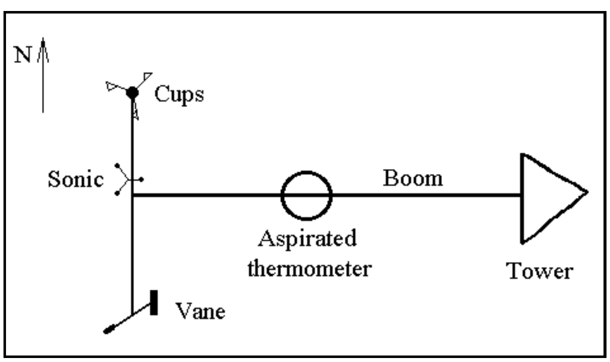


Figure 1. Top view of sensors crossarm, boom and tower layout.

Additionally the logger connected to the Met One system recorded:

- Winds at 40 m
- Temperature at 2, 10 and 40 m
- Precipitation with a tipping bucket rain gauge
- Solar radiation

3.3. Met One Cup and Vane System

Table 1 summarizes the manufacturer's specification for the wind instruments used in this study. The Met One 010C wind speed sensor is a 3-cup design. The 010C uses a slotted chopper disk to produce a pulsed output that is converted to a voltage proportional to wind speed. We verified the calibration of the wind speed sensor by spinning the shaft at constant speed with a tachometer. The Met One 020C vane uses a precision potentiometer to determine wind direction.

3.4. Handar Sonic System

The Handar 425 Ultrasonic wind sensor uses ultrasound to determine the wind speed and direction. Every second a 100-kHz signal is generated by vibrating a cylinder in each of three transducers. The temporal gap between the signal from each transducer is 0.05 seconds. After the third transducer has vibrated, there is a 0.90 second gap until another vibration of the first transducer.

The transit time of the signal is measured once per second in the forward and backward directions by each of the three transducers, which are 120 degrees apart. With wind along the sound path, the upwind transit time increases and the downwind transit time decreases. A sensor micro-controller computes wind speed and direction and reports them to the data logger as analogue voltage signals.

3.5. Systematic difference and operational comparability

Systematic difference (d) and operational comparability (c) are computed following ASTM (1984).

$$d = \frac{1}{N}\sum_{i=1}^{N}\left(S_i - M_i\right) \qquad (1)$$

Table 2. Systematic difference (d) and comparability (c) for all the parameters.

	V (m/s)	V_m (m/s)	σ_V (m/s)	θ (deg)	σ_θ (deg)
All data (N=5170)					
d	-0.026	0.20	0.046	-4.0	1.5
c	0.11	0.40	0.098	14.	8.4
$V \geq 2$ m/s (N=3208)					
d	-0.012	0.31	0.063	-4.0	-0.27
c	0.12	0.49	0.12	4.3	1.5
c for θ with -4.0 deg bias removed				1.6	

$$c = \left[\frac{1}{N} \sum_{i=1}^{N} (S_i - M_i)^2 \right]^{1/2} \quad (2)$$

where N is the number of 15-minute observations, S_i is the ith observation of the sonic, M_i is the ith observation of the Met One sensor.

3.6. Relative systematic difference and relative operational comparability

We also computed the relative difference (d') and relative comparability (c') for the wind speed and gust data.

$$d' = \frac{1}{N} \sum_{i=1}^{N} \left((S_i - M_i) / M_i \right) \quad (3)$$

$$c' = \left[\frac{1}{N} \sum_{i=1}^{N} \left((S_i - M_i) / M_i \right)^2 \right]^{1/2} \quad (4)$$

The EPA states accuracy specifications for anemometers in terms of a percent of the observed speed for speeds greater than 5 m/s (EPA 1987).

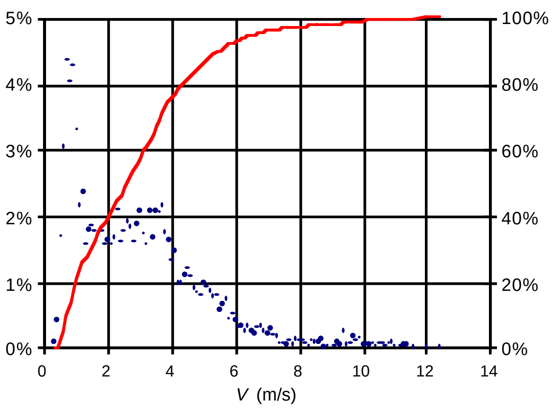
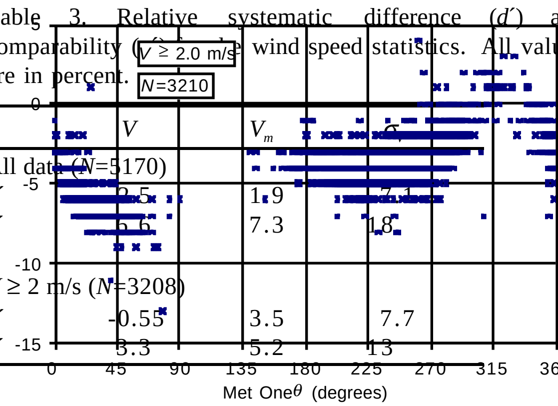


Figure 2. Histogram of V.

Table 3. Relative systematic difference (d') and comparability (c') for the wind speed statistics. All values are in percent.

	V	V_m	σ_V
All data (N=5170)			
d'	2.5	1.9	7.1
c'	6.6	7.3	18.
$V \geq 2$ m/s (N=3208)			
d'	-0.55	3.5	7.7
c'	3.3	5.2	13



4. RESULTS

4.1. Study Period

We collected 5170 fifteen-minute periods from both loggers for 58 contiguous days from 6 March to 2 May, 1997. The weather for the study period was rather atypical for spring at LLNL with stronger than average winds and only one winter storm during the 58-day period. The amount of rain measured during the study period (2.5 mm or 0.10 inches) was abnormally low for LLNL. Based on a 7-year record of rainfall data, LLNL receives an average of 70.6 mm (2.78 inches) of precipitation for March and 18.5 mm (0.73 inches) for April. As measured by the Met One cups, the average wind speed in the predominate wind direction was 3.3 m/s, somewhat stronger than the 2.9 m/s average for the entire study period.

4.2. d, c, d´, and c´

Table 2 summarizes systematic difference and comparability for the entire data period and also for times where the winds were equal to or greater than 2 m/s. These values are generally smaller than previously published values (Lockhart 1989) and are described in more detail later in this paper. The values of d and c are strongly influenced by the ambient conditions at the time of the experiment as illustrated in Figure 2, the histogram of wind speed as measured by the Met One cups. This diagram when compared with Figure 2 in Lockhart (1989) shows that our experiment features a much larger proportion of low winds than the BAO experiment.

Relative difference and relative comparability are computed for the wind speed statistics, V, V_m, and σ_V. The values are presented in Table 3 for the entire set of data and for a subset where $V \geq 2$ m/s.

4.3. V

The least-squares linear regression of the average wind speed data (Equation 5) reveals a very small offset (-0.073 m/s) and slope (1.016). This small deviation from perfect agreement may be due, in part, to very minor systematic errors in the calibration of the sonic or cup anemometer.

$$V(Sonic) = 1016 * V(\text{MetOne}) - 0.073 \text{ m/s} \quad (5)$$

The statistics in Table 2 are somewhat misleading as they are dependent on the frequency distribution of wind speed. We computed *d* and *c* for classes of wind speed with width of 0.5 m/s (Figure 3a). Comparability increases with increasing wind speed class while *d* approaches zero. If we compute the relative systematic difference and relative comparability (Equations 3 and 4) and again plot by wind speed class (Figure 3b) we see that *d´* and *c´* approach 0 and 2%, respectively. The large values of *d* for wind speed greater than 8 m/s occurred during a single episode of strong winds from the north on April 1. These strong winds exhibit some unusual behaviors. We propose several reasons for this spurious data: 1) some incorrect interpretation of persistent north winds by the sonic, 2) incorrect interpretation by the sonic/logger combination, or 3) interference of the wind flow from the wind speed sensor. We considered removing this period from the database and not including it in our analysis. We concluded to keep the strong north wind in the database and interpret the resulting analysis accordingly.

4.4 V_m

The large positive values of *c* and *d* for V_m are likely caused by inertia of the Met One cups. The sonic has no mechanical inertia so it senses very small fluctuations of the wind. The linear regression of the wind gust data (Equation 6) indicates a larger slope (1.064) than the average wind speed regression.

$$V_m(Sonic) = 1064 * V_m(MetOne) - 0.118 \text{ m/s} \quad (6)$$

The systematic differences (*d* and *d´*) and the comparability indexed (c and *c´*) all tend to larger values relative to their counterparts for *V*.

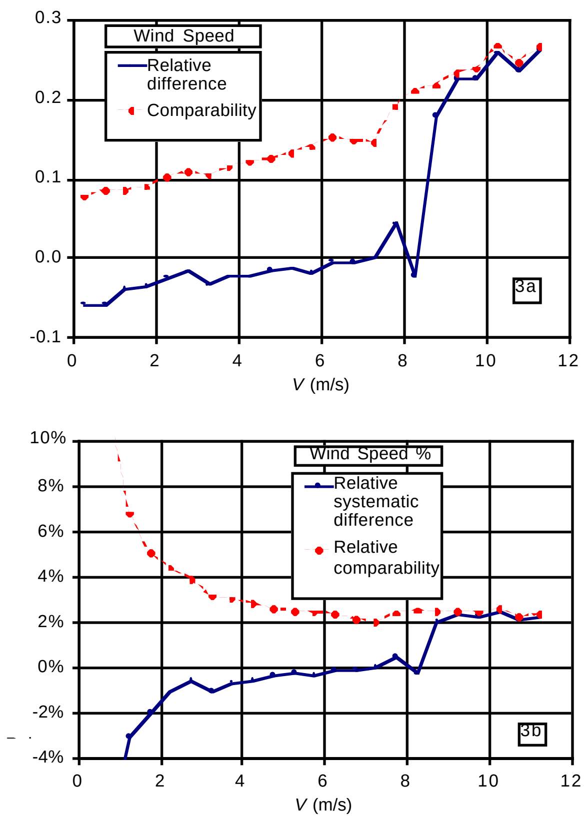


Figure 3. a) *d* and *c* for wind speed, and b) *d´* and *c´* for wind speed plotted by wind speed class.

4.5 σ_v

The sonic did produce wider distributions of wind reports than the cups. The systematic difference of σ_v indicates the sonic returns a value that is 0.046 m/s larger than the cups. Since *d* and *c* for σ_v increase with increasing wind speed, it may be more appropriate to look at *d´* and *c´* (Table 3). The relative difference for σ_v indicates that the sonic returns values that are typically 7% higher than the cups.

Figure 4. Wind direction difference (sonic - vane) versus θ from the vane.

4.6 θ

The systematic difference of the wind direction data indicates a -4.0 degree orientation error between the wind direction sensors. This is obviously caused by the slight misalignment of one or both sensors. With the alignment error mathematically removed in the dataset the comparability of wind direction is reduced to previously published values.

The difference between wind direction reports are plotted in Figure 4 against the wind to direction from the vane for all cases where $V \geq 2$ m/s. The wavy pattern in Figure 4 is due small inaccuracies in the potentiometer of the vane or possibly non-linearity of the sonic response to wind direction. Figure 4 does not indicate an obvious deviation of the wind caused by the open structure of the tower (see Figure 1).

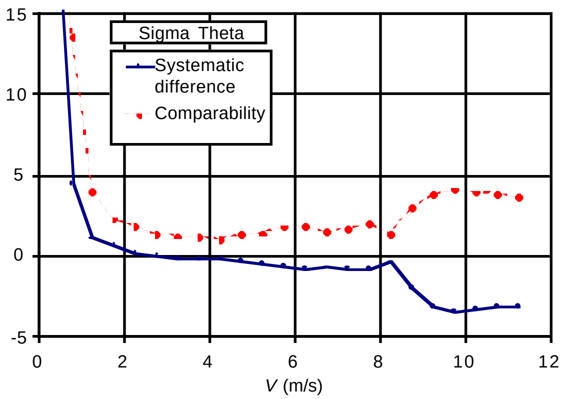


Figure 5. Systematic difference and operational comparability for σ_θ computed for classes of V.

4.7. σ_θ

Figure 5 verifies the values of c and d for σ_θ in Table 2. Both analysis show large differences in σ_θ for small wind speeds. At these light winds the vanes spend increasingly more time experiencing winds less than its starting threshold (0.3 m/s). It is possible for the ambient flow to change azimuth without sufficient torque to alter the position of the vane. During times of light winds, σ_θ from the vane may be an artificially low value.

The same phenomenon is demonstrated in Figure 6a and 6b which are plots of σ_θ against V for each sets of instruments. A bulge in the cloud of data points appears in Fig 6b from the mechanical Met One set.

The vane experienced some enhanced turbulence with north winds due to interference from the other sensors. As stated before, this effect can be seen in Figures 5 and 6 because the only episodes of sustained strong winds (V>8 m/s) came from the north.

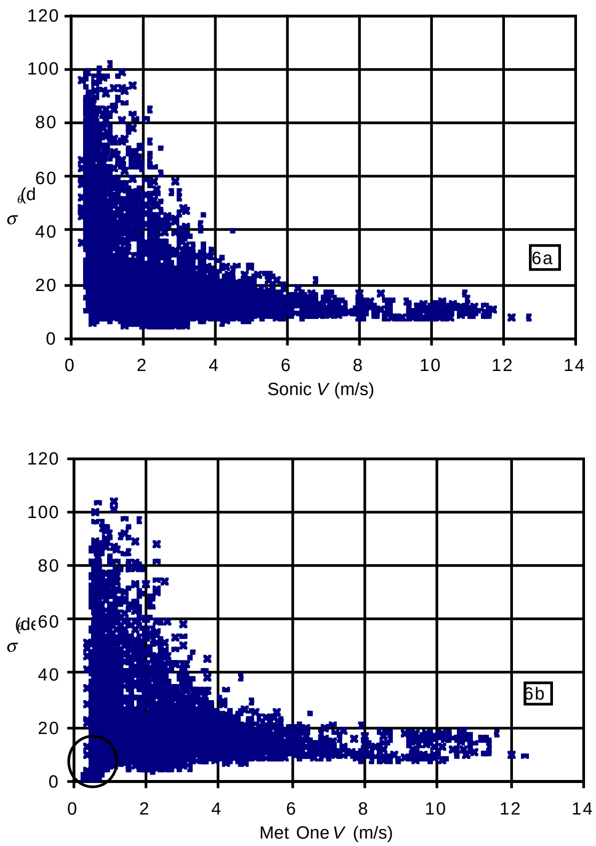


Figure 6. V versus σ_θ for a) the sonic and b) the cup and vane.

4.8. Low Wind Speed Case

A series of three time series diagrams (Figure 7 a, b, c) illustrate how this sonic anemometer performs compared to the mechanical sensors during episodes of very light winds. These diagrams feature data from noon to midnight on the seventh of March. Extremely light winds occurred most notably at 23:00 (3/6) and again at 5:00 (3/7). We interpret the data to mean that at these times the vane remains stationary without even one gust of wind strong enough to alter its position for almost an hour. As a result, θ and σ_θ for the vane deviate from the sonic during extended period of light winds.

5. CONCLUSIONS

The two sensor systems compared in this study, the Handar sonic and the Met One cup and vane, perform almost identically when V is greater than 2 m/s. Comparability values discussed in this paper are similar to values in Lockhart (1989) despite the significant dissimilarities between the datasets. The Handar sonic compares to a cup and vane better than the Applied Technologies sonic manufactured in 1980 that was used in the BAO study.

The sonic responds more naturally than the mechanical sensors under conditions of very light winds. The data from the vane in these conditions are particularly unreliable. It is apparent that progress with microprocessors has moved sonic anemometry into the reliable routine monitoring application.

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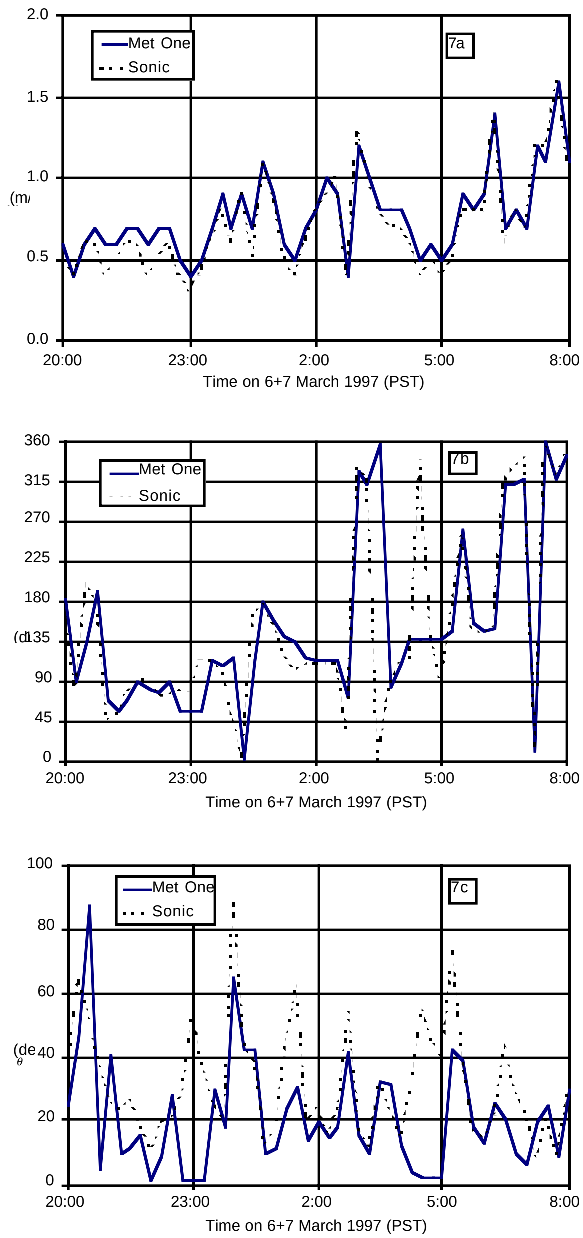

Figure 7. Time series of a) V, b) θ, and c) σ_θ from 7 March 1997.

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