Comparison of Wind Sensors - Ultrasonic versus Wind Vane/Anemometer

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The Tennessee Valley Authority (TVA) conducted laboratory tests and a side-by-side comparison of an ultrasonic wind sensor with a wind vane/anemometer system on the Browns Ferry Nuclear Plant (BFN) meteorological tower during December 1999-April 2000. This report discusses the background to the comparison, describes the tests conducted, and provides results.

Background

BFN is located on the north side of the Tennessee River in northern Alabama. A 91-meter meteorological tower, located about 1 kilometer east-southeast from the plant, provides meteorological data used for both routine and non-routine applications.

Among the data collected on the tower are wind direction/speed at 10-meters, 46-meters, and tower top. From 1977 to 2000, the wind data were collected using Climet* wind vane/cup anemometer systems. While the existing sensors provide excellent service, they are obsolete with spare parts becoming difficult to obtain. In addition, the existing sensors require routine bearing replacement as part of normal maintenance and have a history of occasional problems due to failure of mechanical components.

Selection of New Sensors

TVA identified two basic requirements for new wind sensors:

1. The sensors shall comply with NRC Regulatory Guide (RG) 1.23 requirements.
    - Wind direction ±5°.
    - Wind speed ±0.5 miles per hour (mph).
2. The sensors should require less maintenance than the existing sensors.

TVA identified a number of wind vane/anemometer systems that satisfied the RG 1.23 requirements, but rejected them because they did not satisfy the requirement for less maintenance. Specifically, while spare parts would be much easier to obtain, the level of maintenance would still be about the same as for the current sensors.

Consequently, TVA selected another option—**sonic wind sensors**—that are all-electronic and require minimal maintenance. While sonic sensor technology has been available for many years in research applications, it has only recently become available at a cost and durability suitable for operational applications. Unfortunately, sonic sensors cannot be substituted directly for the existing sensors in the TVA monitoring systems in analog mode because they are slightly less accurate and would violate the RG 1.23 requirements. Fortunately, sonic wind sensors can transmit digital outputs directly to the data logging computer without the need for wind translators and signal processing equipment required for existing sensors. By removing the intermediate equipment, the overall system error meets the RG 1.23 requirements.

TVA selected the Vaisala* (formerly Handar) 425AH ultrasonic wind sensor as most suitable based on the manufacturer specifications and capabilities for integration into the TVA meteorological monitoring system. Specifically, when the ultrasonic wind sensor digital signal is transmitted directly to the data logging computer, the ultrasonic wind sensor system error meets the RG 1.23 requirements.

	RG 1.23 Requirement	Climet (current)	Vaisala
Wind Direction	**±5°**	±4.6°	**±4.7°**
Wind Speed	**±0.5 mph**	±0.48 mph	**±0.48 mph**

* *Identification of a particular manufacturer or model does not constitute endorsement by TVA.*

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Laboratory Tests

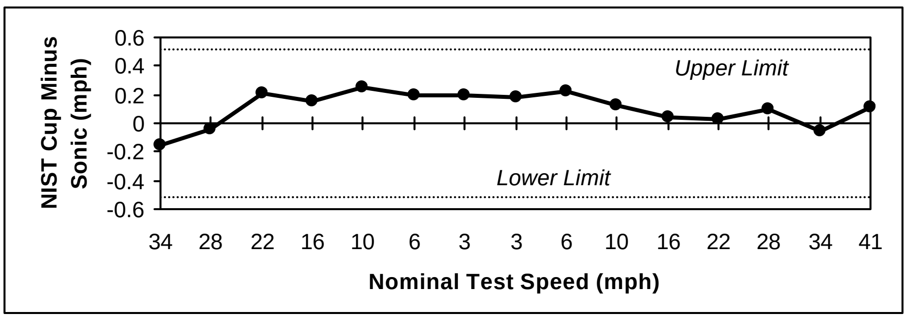
TVA conducted a series of laboratory tests to independently document sensor specifications and quantify characteristics. In performing these tests, two different wind tunnels were used:

1. The TVA Central Laboratories Services wind tunnel in Knoxville, Tennessee.
   - The TVA wind tunnel is used for routine wind speed sensor calibration.
2. The National Oceanic and Atmospheric Administration (NOAA) wind tunnel in Oak Ridge, Tennessee.
   - The NOAA wind tunnel allows testing at higher speeds than the TVA wind tunnel.
   - The NOAA wind tunnel is large enough for side-by-side comparisons of the wind sensors to permit certification of a Vaisala sensor as the certification standard for the TVA wind tunnel.

Appendix A provides a summary of the test objectives, the specific tests conducted, and issues identified related to wind tunnel testing. Tests were conducted on the single ultrasonic sensor certified as the transfer standard. When a comparison standard was required, a Climet anemometer certified by the National Institute for Standards and Technology (NIST) was used. Overall, the wind tunnel tests verified that the ultrasonic sensors work as designed.

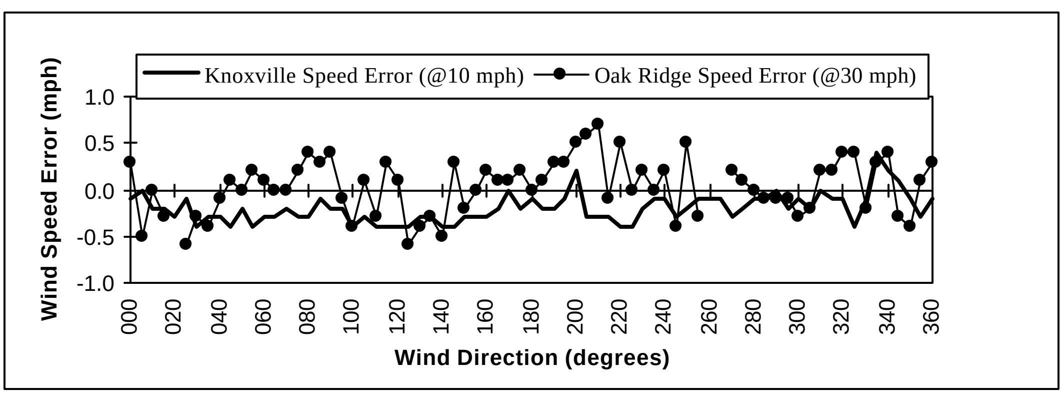
An analysis of the maximum error expected in the NOAA wind tunnel resulted in a value of ±0.51 mph. Figure 1 shows that the resulting errors were well within this amount.

Figure 1. Oak Ridge Calibration Test for Sonic



Unlike an anemometer, the sensing elements of the ultrasonic wind sensor are oriented differently depending on wind direction. This presented a possibility that a wind speed bias might exist based on the direction of the wind. To address this concern, TVA rotated the sensor in 5° increments and measured wind speeds in each position. The resulting samples (12 five-second values) are summarized in Figure 2. No irregularities are evident for any directions.

Figure 2. Anemometer Test Data for 0-360°



Finally, the linearity of the sonic results was tested in the NOAA wind tunnel by comparing results from using both a quadratic and linear equation to calculate the wind speed. The behavior of the resulting wind speed did not reveal any dependence on the speed, so the linear assumption is valid.

Field Installation and Testing

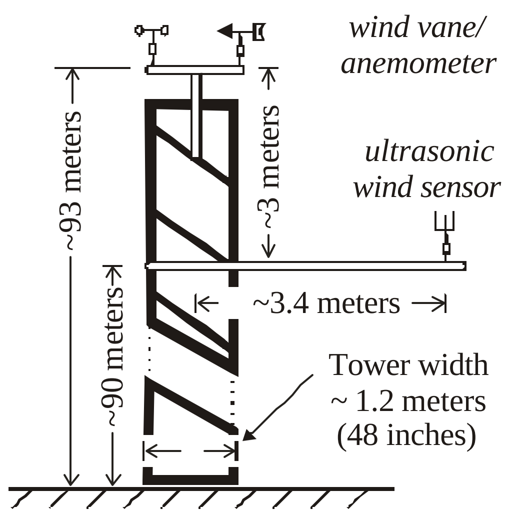
While laboratory tests verified that the ultrasonic wind sensors work as designed, field testing demonstrated that the sensors work correctly in an operating environment. The field test addressed several issues:

- Establish that ultrasonic wind sensor works as expected in the normal sampling environment. This includes showing that the sensor is adequately durable for the expected 6-month operating cycles.
- Document that data collected by the ultrasonic wind sensor are comparable to data collected by the wind vane/anemometer system.
- Verify that software and hardware changes to the data collection and processing system work correctly.
- Provide experience for maintenance personnel with installation and operation of the ultrasonic wind sensor in a non-operational mode.

The tower top elevation on the BFN meteorological tower was selected for the field test. Since the wind vane and anemometer are mounted above the tower top, a mounting arm on the side of the tower toward the northeast was used for the ultrasonic wind sensor.

The critical factor in comparing the two sets of sensors was the need for exposure in the same data regime. The field installation (Figure 3) satisfied ASTM standard D 4430-96 and was within about 3.5 meters horizontal diameter and 0.03 times (i.e., 3/90) the height above the surface.

Figure 3. Field Sampling Configuration



The field test was ultimately successful in demonstrating that the ultrasonic wind sensor will work as a suitable replacement for the wind vane/anemometer combination. Figure 4 and Table 1 illustrate how closely the data collected by the two sensor systems agree based on a total of about 8,700 sets of simultaneous 15-minute data values. Statistical analyses (Appendix B) were performed on about 7,900 sets of data values after adjustments were made for external factors that adversely influenced measurements.

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Figure 4. Wind Rose Plots from Different Sensors Systems

Climet | Vaisala

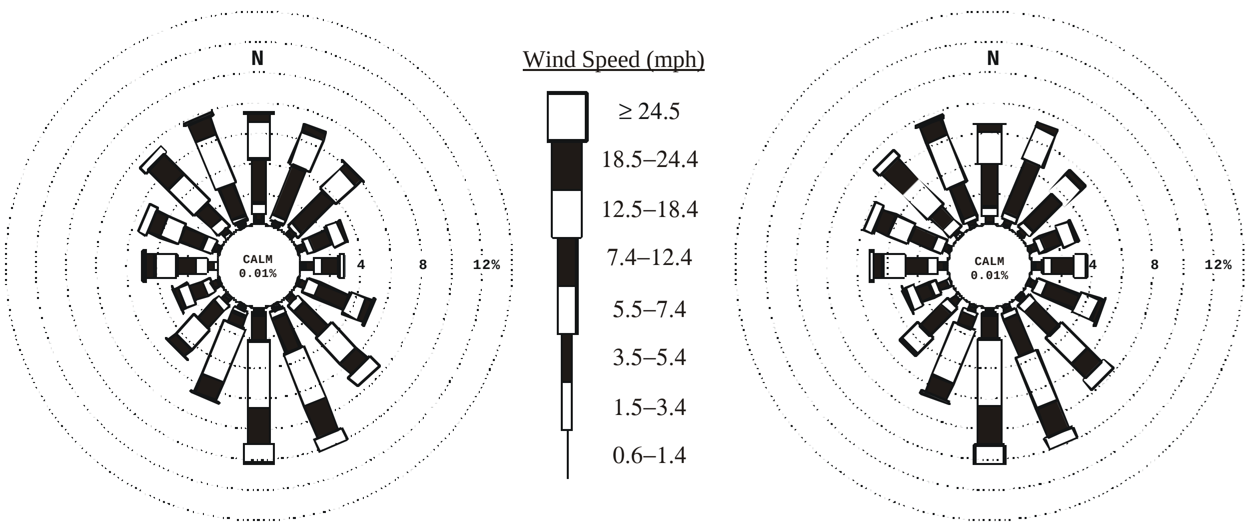

Table 1. Comparison of Wind Direction and Speed Percentages

Wind Direction			
Direction	Climet	Vaisala	Climet - Vaisala
N	7.38	6.61	+0.77
NNE	7.05	7.23	-0.19
NE	6.07	5.53	+0.54
ENE	3.36	3.30	+0.06
E	2.92	3.68	-0.77
ESE	5.16	5.14	+0.02
SE	7.49	7.78	-0.30
SSE	10.09	9.90	+0.19
S	10.25	10.34	-0.09
SSW	6.61	6.72	-0.10
SW	4.95	4.93	+0.02
WSW	3.09	3.14	-0.05
W	4.94	5.16	-0.22
WNW	5.44	5.81	-0.37
NW	7.43	7.13	+0.30
NNW	7.77	7.60	+0.17
		Minimum	**-0.77**
		Average	**±0.00**
		Maximum	**+0.77**

Wind Speed			
Wind Speed Range (mph)	Climet	Vaisala	Climet - Vaisala
Calm	0.01	0.01	±0.00
0.6-1.4	0.15	0.18	-0.03
1.5-3.4	2.57	2.78	-0.21
3.5-5.4	5.24	5.36	-0.12
5.5-7.4	8.29	8.34	-0.05
7.5-12.4	29.99	30.70	-0.71
12.5-18.4	34.13	33.79	+0.34
18.5-24.4	14.83	14.05	+0.78
>=24.5	4.79	4.79	±0.00
		Minimum	**-0.71**
		Average	**±0.00**
		Maximum	**+0.78**

However, during the field test, a number of problems were encountered and handled.

- Software Changes—Since the ultrasonic wind sensor works on a different principle from the wind vane and anemometer, software needed to be developed to properly interrogate the sensor and process the information that was received. During the first few weeks of the comparison, several software errors were identified and corrected.

- Alignment Error—When the ultrasonic wind sensor was initially installed, it was aligned using a compass and not an established orientation point. This resulted in a bias between the wind vane and the ultrasonic wind sensor because the ultrasonic wind sensor was not aligned properly towards north. This was corrected after a survey marker was installed and the sensor was properly aligned.

- Error Handling—During the field test, a suspected random electromagnetic signal caused the ultrasonic wind sensor to change the sampling unit from miles per hour to knots. While similar random signals cannot be prevented, the software was modified to closely examine the data string received from the sensor and take appropriate actions when the data string is not as correct.

- Tower Shadow Effect—A reduction in wind speeds was apparent when the wind was blowing through the tower. A lesser similar impact was noted for the Climet sensors when the wind vane was upwind from the anemometer. The actual magnitude of the reduction depended on both the wind speed and the direction.

Overall Results

Based on the laboratory and field tests, the Vaisala ultrasonic wind sensor is equivalent to the existing Climet wind vane/anemometer system for TVA nuclear plant applications. The ultrasonic wind sensor provides additional benefits during some weather conditions over the wind vane/anemometer system.

- Lower starting threshold—The starting threshold for the wind vane/anemometer system was set at 0.6 mph (anemometer starting threshold). Because there are no moving parts in the ultrasonic sensor, threshold is effectively reduced to 0.1 mph (the lowest non-zero value the data logging system reports).

- Continued functioning during icing conditions—Wind vane/anemometer systems function poorly (or not at all) during freezing rain unless special precautions are taken. The particular model of ultrasonic wind sensor tested included heaters so there was no deterioration of the data from the sensor during two icing events that disabled the wind vane/anemometer system.

In the process of conducting these tests, TVA identified several issues that need to be addressed before ultrasonic sensors can be used in an operational system.

- EMI/RFI potential—Unlike the exiting Climet sensors which provide analog output, the ultrasonic sensor uses two-way digital communications that is much more susceptible to Electromagnetic Interference and Radio Frequency Interference (EMI/RFI). The likely EMI/RFI emissions need to be identified, tests of possible impacts the sensor and related communications should be conducted, and appropriate corrective actions implemented as part of the operational program.

- Uniformity of sensors—TVA obtained sensors from the manufacturer in at least three different batches. While outwardly identical (including the same model number), there were differences in sensor firmware programs among the batches. As a result, not all sensors operated identically, and were not fully interchangeable as required by TVA until after some fixes were implemented.. This emphasizes the need to verify that all sensors are identical within an operational program.

- Changes to operational practices and revision of procedures—Prior operational practices (calibrations, maintenance, data handling and processing, etc.) assume that wind direction and speed are obtained using a wind vane/anemometer system. Appropriate changes need to be made and approved prior to using the new type of sensor in an operational mode. This includes revisions to applicable procedures, FSAR, and training as required.

Operational Configuration and System Changes

The Vaisala ultrasonic wind sensor can be used as a conventional wind vane/anemometer system that gives instantaneous analog readings. This permits the sensor to be substituted for the wind vane/anemometer instruments while still using the existing data processing equipment and software. Unfortunately, when operating in the analog mode, the ultrasonic wind sensor exceeds the allowable error limits. Therefore, several configuration and system changes were needed to allow the Vaisala ultrasonic wind sensor to be used in an operational application.

- Removal of wind translators—The ultrasonic wind sensor provided output in desired wind speed and direction units, so no translator was needed to convert the sensor signal into desired units.

- Connection of ultrasonic wind sensor to data logger computer—Wind vane and anemometer produced electrical signals (after translation) that had to be converted into desired units before processing by the data logger computer. The switch controller allowed the multiple sensors to be polled sequentially by the data logger computer and processed through a single digital voltmeter (DVM). Since the output from the Vaisala ultrasonic sensor was in desired units, there was no need for this intermediate processing. The ultrasonic sensors were connected directly to the data logger computer. The switch controller and DVM were removed from the data stream (also removing the applicable error component).

- Software changes—The data logger computer software was modified to allow direct communication between the data logger computer and the Vaisala sensor and to properly process the sensor outputs into 15-minute and hourly data summaries. For the field test, the new software was operated in parallel with the normal data collection application.

Conclusion

The Vaisala ultrasonic wind sensor meets the accuracy requirements of RG 1.23 and can be used as a replacement for the Climet wind speed/anemometer system.

TVA plans to install the ultrasonic wind sensors at all of its nuclear plants as soon as EMI/RFI testing is completed and applicable documentation (procedures, FSARs, etc.) are updated.

References

ASTM standard D 4430-96, "Standard Practice for Determining Operational Comparability of Meteorological Measurements"

Handar Model 425 Series of Ultrasonic Wind Sensors - User’s Guide, Version 1.6

NRC Regulatory Guide (RG) 1.23, "Onsite Meteorological Programs," Revision 0

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Appendix A
Laboratory Test Summary

Test Objectives:

1. Verify operability for required range of speeds and directions.
2. Verify compliance with required system specifications.
3. Verify repeatability of compliance with calibration limits.
4. Determine linearity of wind speed over required range of speeds.
5. Determine operating characteristics over required range of speeds.
6. Determine wind speed bias for azimuth range.

Tests Performed - NOAA wind tunnel:

Tests Conducted	Objective(s) Addressed					
	1	2	3	4	5	6
Wind speed at threshold, 3, 6, 11, 16, 22, 28, 34, and 40 mph. (Eight 15-second averages of 5-second values)	X	X	X	X	X	
Calibration with NIST standard	X	X		X	X	
Wind directions for range of wind speeds (e.g., 3, 15, and 30 mph) at 5° intervals. Each sample point is made up of several samples (e.g., 12 five-second values).	X					X

Tests Performed - TVA wind tunnel:

Tests Conducted	Objective(s) Addressed					
	1	2	3	4	5	6
Twelve hour check at constant speed and direction (40°, 5 mph)	X				X	
Standard wind speed calibration including test for threshold.	X	X	X		X	
Standard wind direction calibration including test for threshold .		X	X			
Wind directions for range of wind speeds (e.g., 5, and 10 mph) at 5° intervals. Each sample point is made up of several samples (e.g., 12, five-second values).	X					X

Wind Tunnel Issues:

In conducting the wind tunnel tests, the following issues were identified. In all cases, deficiencies were due to the characteristics of the test process rather than any sensor failures. Where necessary, the test process was adjusted so that the full array of tests could be conducted.

- The NOAA wind tunnel was not able to produce speeds greater than 40 mph, so tests could not be conducted for the 45, 60, and 70 mph speeds as planned. Fortunately, tests at lower speeds demonstrated that the sensor response function is linear so the characteristics observed at the lower speeds can be extrapolated to the higher speeds.

- Both wind tunnels reported an excessive number of invalid values for certain wind direction orientations. Subsequent investigation, in conjunction with the manufacturer, determined that this was due to sonic reflections from the wind tunnel walls and would not apply in an ambient sampling environment. The affected directions in the NOAA wind tunnel were 20, 260 and 265°.

- The TVA wind tunnel was designed for calibration of Climet anemometers and is too small to fully contain the Vaisala sensor. Fortunately, the tunnel modifications allowed the sensing elements to be fully immersed inside the air flow. The tunnel modifications are considered acceptable because the NOAA and TVA wind tunnels produce similar results for common wind speed ranges.

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Appendix B
Field Test Summary

The comparison data base consisted of 15-minute data from both the Climet and Vaisala sensors. The Climet sensors produced continuous electronic signals that were sampled every 5 seconds. The Vaisala sensor provided a near-instantaneous wind measurement (0.35 second is required to perform a measurement) when requested every 5 seconds. Since the data logger processing algorithms were identical, any differences can be attributed to sensor differences.

The individual samples were then used by the data logger to calculate values for each 15-minute period:

- **Vector Wind Direction (VWD) - degrees (°)**
- **Vector Wind Speed (VWS) - mph**
- **Average Wind Speed (AWS) - mph**
- **Sigma-Theta (ST) - degrees (°)**

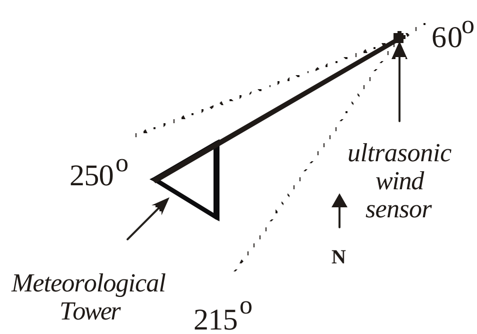
Data Base Preparation

The data base covered the period: **January 1, 2000 (0014 CST) - April 5, 2000 (0659 CST)**.

The following adjustments were made to the raw data base to remove extraneous influences that are not related to differences in the sensor systems:

Maximum possible number of samples (number of 15-minute periods)	**9148**
minus	
Samples with either Climet or Vaisala data were missing (sensor, communications, or computer processing failures)—ALL DATA REMOVED.	**432**
minus	
Invalid comparisons because sensor measurements did not accurately reflect for certain conditions—ALL DATA REMOVED. • [3 samples] Did not compare data when anemometer WS < 1.0 mph (Climet sensor threshold). • [561 samples] Did not compare data when Climet WD = 215-250°. Ultrasonic sensor was influenced by "tower shadow" effect (Figure B-1). • [161 samples] Did not compare data when Climet sensors were affected by icing conditions. Two periods of icing resulted in the Climet sensors not being valid (one about 15 hours long, the other about 25 hours long). In both cases, the heated sonic sensor worked normally.	**725**
equals	
Samples available for comparison	**7991 (87.4%)**

Figure B-1. Wind Sensor Orientation



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After preliminary analyses, the following additional adjustments were made to the database:

- [57 samples] When VWD differences > 180, the ultrasonic wind sensor VWD was adjusted by 360.
- Data that exceeded specified limits were examined individually and selected data were removed when an external factor was adversely influencing measurements or when the two sensing systems did not sample identical conditions due to differences in sampling methodologies or slight differences in the sampling time.
    - 18 VWD comparisons were associated with wind direction changes of more than 25° within 30 minutes. Final data base size = **7973**.
    - 158 VWS comparisons were associated with flow interferences or variability in wind speeds during high wind speed conditions. Final data base size = **7833**.
    - 164 AWS comparisons were associated with flow interferences or variability in wind speeds during high wind speed conditions. Final data base size = **7827**.
    - 15 ST comparisons were associated with wind direction changes of more than 25° within 30 minutes, sigma-theta changes of more than 25° within 30 minutes, or light wind speeds (near sensor threshold) when Climet wind vane was not fully responsive. The two sensing systems did not sample identical conditions due to differences in sampling methodologies and slight differences in the sampling time.
    Final data base size = **7976**.

Data Base Analyses

The following statistical analyses were conducted (ASTM standard D 4430, Standard Practice for Determining the Operational Comparability of Meteorological Measurements"):

Analysis	Purpose
Count (N)	Number of valid pairs compared
Minimum Difference	Extreme minimum difference for information.
Maximum Difference	Extreme maximum difference for information.
Systematic Difference (d)	The mean of the differences. *- low values indicate good agreement with little bias.*
Estimated Standard Deviation of Difference (s)	Same as standard deviation. *- low values indicate close agreement for most of data set.*
Operational Comparability (C)	Root-sum-squared differences. *- low values indicate close agreement for most of data set.*
Skewness (M)	Characterizes the degree of asymmetry of a distribution around its mean *- 0 indicates normal distribution. Non-0 indicates an asymmetric tail.*
Kurtosis (K)	Indicates how high the peak is compared to the normal peak. *- 0 indicates normal peak. Higher numbers indicate very peaked distribution.*
Correlation Coefficient	Indicates how closely two data set agree. *- value near 1.00 indicates close agreement between data sets.*

Analyses Results

	Differences in 15-minute values (Climet minus Vaisala)			
	VWD (°)	VWS (mph)	AWS (mph)	ST (°)
count (N) - nondimentional	7973	7833	7827	7976
minimum difference	-10	-3.8	-3.9	-9
maximum difference	10	1.0	1.0	9
systematic difference (d)	0	0.0	0.0	0
estimated standard deviation of difference (s)	2.4	0.37	0.37	0.9
operational comparability (C)	2.4	0.37	0.37	0.9
skewness (M) - nondimentional	0.2	-1.64	-1.62	-1.4
kurtosis (K) - nondimentional	-0.2	10.90	10.80	24.3
correlation coefficient *- nondimentional*	*1.000*	*0.998*	*0.998*	*0.975*

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Evaluation

ASTM standard D 4430 specifies that the sampling is not complete until a minimum number of samples is collected. The number of samples needed is determined according to the following equation:

$$N_n \geq \left(\frac{3s}{r}\right)^2$$, where: N_n = Number of samples needed

s = estimated standard deviation of difference (from table above)
r = resolution of system (1 for WD and 0.1 for WS)

For the data collected above, the minimum number of samples is:

VWD = 52 VWS = 124 AWS = 124 ST = 8

In all cases, the number of required samples was exceeded by a wide margin.

Results are summarized in the following tables:

VWD	Bias	No bias (systematic difference = 0) within the system resolution.
	Skewness and Kurtosis	Near normal distribution curve.
	Estimated Standard Deviation of Difference and Operational Comparability	Values of 2.4 indicate that more than 96% of the values are within 5° of the mean.
	Correlation Coefficient	Excellent agreement between the two data sets.

VWS AWS	Bias	No bias (systematic difference = 0.0) within the system resolution.
	Skewness and Kurtosis	The peak of distribution curve is about 1.3 times higher than expected with a longer tail into the negative direction. *
	Estimated Standard Deviation of Difference and Operational Comparability	Values of 0.37 indicate that approximately 54% of the values are within 0.5 mph of the mean.
	Correlation Coefficient	Near excellent agreement between the two data sets.

ST	Bias	No bias (systematic difference = 0) within the system resolution.
	Skewness and Kurtosis	The peak of distribution curve is about 1.7 times higher than expected with slightly more negative than positive values. *
	Estimated Standard Deviation of Difference and Operational Comparability	Values of 0.9 indicate that more than 99% of the values are within 5° of the mean.
	Correlation Coefficient	Very good agreement between the two data sets.

* Note: The negative skewness values are likely due to the differences in the sampling methodologies. Due to mechanical friction (i.e., sensor thresholds), the Climet sensors cannot react to changing conditions as quickly as the ultrasonic wind sensor.

Conclusion

The data collected by the two sensor systems are essentially identical.