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Calibration Data for Improved Correction of UVW Propeller Anemometers

**J. R. Connell
V. R. Morris**

October 1991

**Prepared for the U.S. Department of Energy
under Contract DE-AC06-76RLO 1830**

**Pacific Northwest Laboratory
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CORRECTION OF UVW PROPELLER ANEMOMETERS

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Pacific Northwest Laboratory
Richland, Washington 99352

(a) Colorado State University
Fort Collins, Colorado

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SUMMARY

Wind turbine test programs sponsored by the U.S. Department of Energy in the late 1980s called for measurement of three-dimensional turbulent wind with an accuracy not previously required. The Pacific Northwest Laboratory (PNL) identified the need for more complete, more highly resolved, and more accurate calibrations to provide the new level of measurement capability. The most understood anemometer and the "workhorse" of the program, the uvw propeller anemometer, became the object of a unique calibration effort at a large wind tunnel at Colorado State University.

A uvw anemometer, with all three propellers active, was installed in the wind tunnel on a digitally stepped two-axis rotary platform placed just below the tunnel floor. The azimuth and elevation of the anemometer in a steady wind at each of a selected set of speeds was stepped through a complete test program using a digital computer as controller and a digital data acquisition system to sample and filter the data. Tests were run using polypropylene and carbon fiber propellers. In addition, the effects of attaching "shaft extensions" to the polypropylene propellers were measured.

Calibrations for the polypropylene four-blade propeller provide an improved level of detail and repeatability. The uvw propeller anemometer is quite accurate at all wind angles and speeds to be experienced in wind energy studies, including winds blowing at right angles to the axis of rotation of a propeller. The new correction factors derived from these data eliminate previous difficulties in accuracy and speed of data reduction from voltages to wind speed components.

Calibration data for a carbon-fiber thermoplastic propeller are presented with resolution similar to that for the polypropylene propellers. A few differences from a polypropylene propeller in the details of the calibration curve are noted. Corresponding correction factors for the carbon-fiber propeller are included in the table with those for the polypropylene propeller.

Comparisons of the new calibrations are made with those available in previous publications with the result that the new calibrations are recommended.

Special tests clarify the effect of attaching shaft extensions to each propeller hub with the purpose of making the propeller response symmetric about a wind direction of 90° to the shaft. It is shown that the extender is not needed to get the maximum accuracy possible at any wind angle; instead, accurate and detailed anemometer calibration provides improved correction factors for winds directed perpendicular to the axis of propeller rotation.

The calibration curves derived from measurements made in nonturbulent wind are shown to require a small simplification at angles near 90° , after which they apply better to turbulent wind conditions. Accurate tests of propeller anemometer calibration characteristics using turbulent winds remain to be done.

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1.0 INTRODUCTION

A need for accurate measurement of the three vector components of strong winds as part of wind turbine testing led us to make computer-controlled calibrations of uvw propeller anemometers with a resolution not previously achieved. This report discusses calibration data for polypropylene and carbon fiber propellers and gives correction factors in the form in which the data are most commonly used in computer programs that correct u, v, and w velocity estimates derived from the corresponding sensor output voltages.

Traditionally, the error caused by deviation of the individual propellers of the three-dimensional (3-d), mutually orthogonal propeller anemometer from cosine wind direction response have been reduced using an iteration method of computational correction of the measurements, if high accuracy is required for all three components of turbulent wind (Horst 1973). Particular difficulties exist if accurate measurement is required for a component of wind fluctuation that is nearly normal to the total wind direction and nearly perpendicular to the axis of rotation of the measuring propeller (Hicks 1972). For example, the axis of a vertical wind speed propeller is often at nearly 90° to the wind and the w propeller experiences very small forces of rotation. Most w-propeller calibrations for this wind angle range have been in substantial error. Large calibration anomalies also exist if the wind is blowing nearly 180° to the incoming axis of the propeller or if one of the propellers is approximately upwind of another.

Our first objective was to determine how accurate the uvw propeller anemometer can be at each wind angle and for wind speeds from 10 to 30 m/s. After reviewing the existing literature for calibration and correction information, the most current available to us being that by Bowen and Tenissen (1986), we initiated a calibration program using a large wind tunnel. The results of the wind tunnel calibrations of uvw propeller anemometers are in kind no different than other recent calibrations, but they have detail, demonstrated repeatability, and completeness that make them a useful addition to the anemometry literature.

Section 2.0 describes the method and equipment used to calibrate the anemometers, including a two-axis, digitally stepped, rotary platform to

orient the 3-d anemometer. Section 3.0 presents graphs of the new calibration data. Section 4.0 presents new correction factors for polypropylene and carbon-fiber propellers. In Section 5.0, the new data are compared with other calibration data presented in the literature. Section 6.0 shows the improved accuracy obtained in using the new calibrations in the computational correction scheme for transforming uvw sensor output into 3-d velocity components.

2.0 THE CALIBRATION METHOD

Two types of propellers, constructed of molded polypropylene and carbon fiber thermoplastic, were calibrated. The polypropylene propeller was calibrated with and without a shaft extension. The propellers were calibrated in a large wind tunnel at Colorado State University. The data were collected using a unique system composed of a computer, a digital multiplexer, and a computer-controlled, two-axis rotary platform.

2.1 THE PROPELLER ANEMOMETERS

The primary calibrations were made using model 8234 "high resolution" polypropylene, 4-blade, 18-cm diameter, 30-cm pitch propellers installed on a model 27005 Gill UVW Anemometer manufactured by R. M. Young Company. The propeller's mass is 31 g. A calibration was also made for the polypropylene propeller and a Model 27160 Propeller Extension (or more properly, "shaft housing extension"). A third calibration was made with the new model 8254 carbon fiber thermoplastic, 4-blade propeller installed on the same anemometer. This propeller, except in having a 20-cm diameter, has the same geometric specifications as given above for the polypropylene propeller. However, its blades are thinner and its mass, 29 g, is slightly less than the mass of the polypropylene propeller. The signal generators provided a nominal output of 500 millivolts dc at 1800 rpm. The blower providing positive flow through the bearings was operated in most tests. There appeared to be no difference in calibration with or without the blower operating.

2.2 THE WIND TUNNEL TEST SECTION

The anemometers were calibrated in the upwind end of the test section of the meteorological wind tunnel at Colorado State University. The tunnel has a cross section of 1.83 m x 1.83 m. We performed calibrations at nominal speeds of 10, 20, and 30 m/s. The spatial and temporal variations of mean wind speed and turbulence in a planar cross-tunnel section were measured at the beginning of the test program to assure that the propellers being calibrated remained in a nearly constant ambient wind velocity field in all tests.

The complete three-axis anemometer was installed in this section of the tunnel to simulate, in calibration, the field measurement configuration.

Figure 1 illustrates the anemometer configuration in the wind tunnel. The propeller of primary interest in a particular calibration remained in the center location of the test section and the rest of the anemometer structure moved around it when the orienting platform was rotated to cause a wind direction change relative to the anemometer. Thus, the effect of interaction of the three propellers with the airflow modified by the anemometer body and each propeller is included in the calibration.

Reference static atmospheric pressure, pitot-static pressure difference, and temperature measurements were used in a calculation of the actual wind tunnel speed as a function of time. The slight variation in wind tunnel speed thus measured was used to adjust the output signals of the anemometer to those for nominal wind speed.

FIGURE 1. Configuration of the Anemometer. A downward view showing the v propeller of the anemometer located in the center of the wind tunnel over the axis of azimuth rotation of the anemometer.

2.3 THE DATA ACQUISITION SYSTEM

The data acquisition system was composed of a digital computer, a digital multiplexer, and a computer-controlled rotary platform. A major factor in the success of the calibrations was the high resolution of the digitizer and the unique, computer-controlled anemometer orientation.

All data were recorded digitally with a DEC MicroVAX computer system. The voltages from the sensors were filtered, amplified, multiplexed, and digitized with 16-bit resolution using a NEFF Model 620 analog-to-digital conversion system. The low-pass signal filters on all channels were set to 1 Hz and the amplifier gains on individual channels were set to optimize the sensitivity for each sensor's expected signal range. The analog signals were sampled 10 times per second for 1 minute at each calibration step, allowing time for the anemometer to reach its new orientation and the propeller rotation rate to reach steady state and still provide a 30-s signal to be averaged in later analysis. The total measurement period was controlled by the digital computer.

Anemometer orientation was established by a digitally stepped, two-axis, rotary platform. The axes of rotation of the two rotary platforms were mutually orthogonal. They were driven by stepping motors under computer control and installed below the wind tunnel floor. The anemometer support pipe extended into the working section of the tunnel. Use of the MicroVAX-controlled rotary platform allowed fast, continuous acquisition of large calibration data sets. The angle stepping was performed with a resolution and repeatability of 0.01° . The absolute value of the angle was known to better than 0.5° relative to the tunnel wind direction.

3.0 CALIBRATION CURVES

3.1 THE POLYPROPYLENE PROPELLER CALIBRATION DATA

3.1.1 The Effect of Shaft Extenders on the Polypropylene Propeller Calibration

The primary calibrations presented in this report are for two identically made, new anemometers using propellers without "shaft extenders." Our finding is that the extenders primarily move the center of the wind-angle band spanning the region of zero rotation rate of the propeller (i.e., the "dead band") closer to 90° from the axis of rotation of the propeller. [Deyer et al. (1967) reported that use of the shaft extender also reduced the dead band to half its original width and made the curve more symmetric around the axis of zero rotation rate. Bowen and Teunissen (1986) drew a similar conclusion.] Without the extender, the propeller zero-rotation point occurs at about 88° , rather than the ideal 90° . A few examples of calibration with and without the use of extenders are included to clarify their effect in Figure 2. As shown in Figure 2a for the u propeller, at wind directions within $\pm 20^\circ$ of the plane of rotation, there is a 10% or greater difference between calibration curves with and without the shaft housing extender. If, however, a calibration curve for any component propeller is sufficiently resolving for all angles and speeds, it appears that the extender is not needed to allow accurate measurement of this component of the wind.

Indeed, if the free-stream wind being estimated has no component parallel to the axis of rotation of, say, the vertical wind propeller, the propeller without an extender will be rotating and giving an unambiguous measure. In other words, used with an accurate calibration curve, it will show that the free-stream vertical velocity is zero. Further, there will be no dead band spanning the vertical direction. Without an extender in place, the (ambiguous) region (in which, under static wind conditions, the propeller will not rotate) is shifted to a band surrounding 88° . Whether or not to use an extender is a matter of the quality of the anemometer, its calibration, and the small angles of most importance to the user, among other factors. The effect of the magnitude of the wind speed as well as the extender on the measurement of vertical velocity, when the wind direction is nearly orthogonal to the axis of the vertical propeller, is shown in Figure 2b. At 20 m/s there is less difference

FIGURE 2. Comparison of Angle Calibration With and Without "Shaft Extenders". (a) The u propeller at a wind speed of 10 m/s, $(u_s - u)/u$, where u_s is the indicated wind speed with shaft extender, (b) the w , or vertical-axis, propeller at wind speeds of 10 and 20 m/s, $(w_s - w)/w$.

between calibrations of propellers with and without the shaft housing extender than at 10 m/s. Hicks (1972) has shown that the accuracy of measurement with the extender in place is a function of total wind speed.

3.1.2 Detailed Discussion of Calibration for Propeller Without Shaft Extender

The calibration curves for the u and the v propellers are found to be nearly identical, with the exception of a reversal of the wind-angle asymmetry caused by the wake of the other propeller (near 225° in Figure 3). There are also differences in the curves at wind angles within $\pm 10^\circ$ of orthogonal to the axis of rotation. This is shown in Figure 3 in which the sequence of wind angles for the u propeller calibration curve was reversed to provide the same asymmetry as the v propeller curve before calculating the difference between the two curves. The repeatability of calibration for a single anemometer (see Figure 4a) and the consistency of it to an identically manufactured

FIGURE 3. Fractional Difference of the Calibration Curves for the u Propeller and the v Propeller on the uvw Anemometer at a Wind Speed of 10 m/s, $[(u(360^\circ - \theta_u) - v(\theta_v))/u]$, where θ is the Wind Azimuth Measured Relative to the Specific Propeller Axis. The wind angle is measured relative to the axis of the individual propellers, at zero angle the axis points directly into the wind. The u curve has been flipped about the 180° point to make the wake asymmetry match that of the v curve before computing their difference.

FIGURE 4. Fractional Difference in Angle Calibrations of (a) the Same New u Propeller Anemometer From Two Tests and (b) Two New u Propeller Anemometers of the Same Manufacture. The wind speed was 10 m/s.

anemometer (see Figure 4b) is shown in Figure 4 for a 10 m/s wind speed. As was shown in Figure 3 for u and v propellers, the difference in calibration for two u sensors is seen to be greater than 10% when the wind direction is within $\pm 10^\circ$ of orthogonal to the shaft. If maximum accuracy of measurement of 3-d turbulence is needed, especially for wind near 90° to the axis of rotation of one or two propellers, separate calibrations must be done for each of the u, v, and w sensors of the anemometer. Figure 5 shows the changes in calibration data that occur for a horizontal-component anemometer if a constant updraft is changed from 20° to 1° . This graph reinforces the conclusion that there is a need for a correction scheme that incorporates data from all three axes for reducing 3-d wind data.

The calibration for the vertical propeller was obtained only for wind directions between $+20^\circ$ and -20° from normal to the axis of the w propeller. This w propeller calibration is compared with the u propeller calibration in Figure 6. The calibration for the w propeller is well enough represented by the u propeller calibration if 10% accuracy is acceptable or if up and down-draft angles are greater than $\pm 5^\circ$.

FIGURE 5. Comparison of the u Output Voltage Versus Wind Azimuth for a Steady Wind Updraft Angle of $+20^\circ$ and for a Steady Updraft Angle of $+1^\circ$. The wind speed was 10 m/s.

FIGURE 6. The Fractional Difference Between Angle Calibration Curves for the u Propeller and the w Propeller on the uvw Anemometer, $[u(\theta) - w(\phi)]/u(\theta)$, where θ and ϕ are the Same-Valued Wind Angles Relative to the u and w Propeller Axes, Respectively. At zero wind direction the axis would point directly into the wind. Only directions from 70° to 110° are compared because of limits imposed by our apparatus on the range of angles possible for the w measurement. The wind speed was 10 m/s.

The difference in angle calibration for constant nominal wind speeds of 10, 20, and 30 m/s is shown in Figure 7. Before calculating differences of pairs of calibrations at different wind speeds, we normalized all of the data to a wind speed of 10 m/s. This was done by multiplying signal voltages for a given nominal wind speed by the ratio of 10 m/s to the measured tunnel wind speed. For example, at a nominal value of 20 m/s the measured wind speed might be 19.5 m/s. The angle calibration curve for the 20 m/s speed would be multiplied by $(10 \text{ m/s})/(19.5 \text{ m/s}) = 0.512$. This is like a calibration at 10 m/s in which the anemometer has the characteristics of a propeller in 20 m/s winds. The results show that there is little difference in calibration curve characteristics at wind speeds of 10 and 20 m/s. At these speeds the primary differences are at angles where there are narrow dead bands in rotation near

FIGURE 7. A Comparison of Angle Calibration Curve Characteristics of a u Propeller for Different Fixed Wind Speeds. (a) Fractional differences for 10 m/s and 20 m/s and (b) fractional differences for 10 m/s and 30 m/s. The anemometer output values are normalized to those for a nominal speed of 10 m/s before computing their difference.

90 and 270°. At 30 m/s the calibration curve shape changes noticeably around 90° and 270° and also near 45°, 135°, 180°, 225°, and 315°.

The details of the calibration curves for angles near 90° are compared in Figure 8 for wind speeds of 10 and 20 m/s. No 30 m/s wind speed data were recorded at these wind angles. Note that the graph in Figure 8 is plotted using a ratio of signals at two wind speeds, both normalized to 10 m/s values. The normalization provides a more direct measure of the universality of the calibration curve near 90° wind angles. Ten percent errors may be expected in wind components near 90° if one calibration curve is taken to apply to all wind speeds. Similarly, Figure 9 shows the fractional difference of calibration curves for the propeller in the wake of the anemometer structure at 10 and 20 m/s. The calibration curves are identical throughout the 170° to 190° region. For wind directions at which a propeller is in the wake of part of the anemometer, mean winds may be expected to be estimated accurately in the

FIGURE 8. Comparison of Details Near $\theta = 90^\circ$ of Angle Calibration Curve Characteristics for Nominal Wind Speeds of 10 m/s and 20 m/s, $[u_{10}(\theta) - u_{20}(\theta)]/u_{10}(\theta)$. This plot includes the wind angles at which the propeller does not rotate because of too little wind normal to the plane of rotation and the bearing friction. All signals were normalized to nominal 10 m/s values before computing the difference.

FIGURE 9. Comparison of Details Near $\theta = 180^\circ$ (in the Wake of the Anemometer Housing) of Angle Calibration Curve Characteristics for Nominal Wind Speeds of 10 m/s and 20 m/s, as in Figures 7 and 8.

normal ranges of atmospheric turbulence if the calibration is done well. Insufficient data are in hand to demonstrate that turbulence time series are estimated as accurately at the wind directions for which wake influence occurs as at others. It is reasonable to assume that the wake-affected time series will not be as accurate for time scales less than several seconds.

3.2 THE CARBON-FIBER THERMOPLASTIC PROPELLER CALIBRATION DATA

Calibrations for carbon-fiber propellers installed on a Gill uvw anemometer are different in some details from those of the polypropylene propeller. Figure 10 shows the fractional difference in angle calibration curves at 10 m/s between the carbon-fiber and the polypropylene propellers. The data that were accumulated for the carbon-fiber propeller in a brief calibration program used techniques and apparatus identical to those used for the polypropylene propellers.

The differences between the calibration curves of the polypropylene propeller and the carbon-fiber propeller indicate some substantial differences

FIGURE 10. A Comparison of Angle Calibrations for Carbon-Fiber Thermoplastic and Polypropylene Propellers at 10 m/s Wind Speed, $[u_p(\theta) - u_c(\theta)]/u_p(\theta)$

in the aerodynamics for the two types of blades. The thinness and the sharpness of the edges of the carbon-fiber blade might be a source of the improvement in characteristics in the free stream. This improvement is apparent in the discussion of the correction factors derived from the calibration curves, which are provided in Section 4.0. The carbon-fiber propeller provides a more ideal measurement of wind angles whose cosine is positive, while the polypropylene propeller is more ideal at wind angles whose cosine is negative.

4.0 CORRECTION FACTORS FOR PROPELLER RESPONSE TO WIND ANGLE

New multiplication factors for correcting the non-cosine response of the Gill uvw propeller anemometer have been derived for three variations of the anemometer tested in the meteorological wind tunnel at Colorado State University. The three variations were 1) with molded polypropylene propellers (MPP), 2) with molded polypropylene propellers and propeller extensions (MPPx), better described as shaft housing extensions, and 3) with carbon-fiber thermoplastic (CFT) propellers without shaft extensions. In every calibration of a single sensor, the complete uvw anemometer was installed in the wind tunnel as described in Section 2.2.

The correction factor, cor , computed from the calibration data is defined as:

$$cor(\theta) = \frac{e(0^\circ)\cos \theta}{e(\theta)} \quad (1)$$

where $e(0^\circ)$ is the sensor output voltage at zero incidence to the tunnel wind, θ is the angle between the wind and the propeller axis of rotation, and $e(\theta)$ is the axial sensor output voltage indicated by the propeller at angle θ . Correction factors were calculated for each angle to which the anemometer was positioned from 0° to 360° azimuth and -20° to $+20^\circ$ tilt of the vertical axis of the uvw anemometer. The azimuth-related calibrations were reduced to a smaller set by averaging all values with the same sign and magnitude of cosine of the azimuth. In the computation that uses Equation (1), the correction factors are indefinite at the angles for which the sensor output, e , equals zero. The correction factors assigned to those angles were obtained by linear interpolation of factors at angles adjacent to both sides of the region where the factors are undefined. The correction factors for non-cosine angular response of each type of propeller are plotted as a function of the cosine of the angle between the wind vector and the axis of rotation of the propeller in Figure 11. The correction factors for all three propeller configurations of the uvw anemometer are also tabulated in Table 1, using the traditional uniform increment of cosine of the wind angle of 0.02 introduced by Horst (1973).

FIGURE 11. Plots of Correction Factor Versus the Cosine of Wind Azimuth for Three Types of Propellers on a uvw Anemometer: Molded Polypropylene Propeller (MPP), Polypropylene Propeller Used with a Shaft Extension (MPPx), and Carbon-fiber Thermoplastic (CFT) Propeller. The data are for a wind speed of 10 m/s.

TABLE 1. Correction Factors as a Function of the Cosine of the Wind Angle for Gill Propeller Anemometers. Factors are tabulated for molded polypropylene propeller (R. M. Young Model 8234), molded polypropylene propeller with shaft extension (RMY Model 8234x), and the carbon-fiber thermoplastic propeller (RMY Model 8254). In all cases the data are for three propellers mounted on a Gill uvw Anemometer (RMY Model 27005).

Cos θ	08234	08234x	08254	Cos θ	08234	08234x	08254
-1.00	1.07	1.09	1.13	0.00	0.00	0.00	0.00
-0.98	1.03	1.03	1.08	0.02	0.97	0.49	-0.95
-0.96	1.01	1.01	1.05	0.04	2.79	1.56	1.86
-0.94	1.01	1.01	1.04	0.06	2.18	1.05	2.35
-0.92	1.01	1.01	1.04	0.08	1.65	1.04	1.37
-0.90	1.02	1.02	1.05	0.10	1.41	1.06	1.29
-0.88	1.03	1.03	1.06	0.12	1.35	1.08	1.28
-0.86	1.04	1.04	1.07	0.14	1.30	1.09	1.24
-0.84	1.06	1.05	1.08	0.16	1.29	1.06	1.19
-0.82	1.07	1.07	1.09	0.18	1.28	1.06	1.21
-0.80	1.08	1.08	1.10	0.20	1.26	1.11	1.20
-0.78	1.10	1.09	1.11	0.22	1.24	1.14	1.17
-0.76	1.11	1.11	1.12	0.24	1.23	1.16	1.19
-0.74	1.12	1.12	1.14	0.26	1.23	1.17	1.21
-0.72	1.14	1.14	1.17	0.28	1.24	1.18	1.24
-0.70	1.16	1.15	1.19	0.30	1.25	1.19	1.25
-0.68	1.17	1.16	1.20	0.32	1.26	1.21	1.25
-0.66	1.17	1.17	1.21	0.34	1.27	1.22	1.26
-0.64	1.17	1.17	1.20	0.36	1.28	1.21	1.27
-0.62	1.18	1.17	1.20	0.38	1.28	1.20	1.27
-0.60	1.18	1.17	1.19	0.40	1.28	1.17	1.27
-0.58	1.18	1.18	1.19	0.42	1.27	1.16	1.24
-0.56	1.18	1.18	1.19	0.44	1.25	1.16	1.20
-0.54	1.17	1.17	1.18	0.46	1.21	1.17	1.20
-0.52	1.16	1.16	1.17	0.48	1.19	1.18	1.21
-0.50	1.14	1.15	1.16	0.50	1.19	1.19	1.21
-0.48	1.12	1.13	1.15	0.52	1.21	1.21	1.22
-0.46	1.11	1.11	1.13	0.54	1.22	1.23	1.22
-0.44	1.09	1.09	1.12	0.56	1.24	1.25	1.23
-0.42	1.08	1.08	1.10	0.58	1.24	1.25	1.22
-0.40	1.06	1.07	1.09	0.60	1.24	1.25	1.22
-0.38	1.04	1.06	1.08	0.62	1.23	1.25	1.22
-0.36	1.03	1.05	1.06	0.64	1.23	1.24	1.21
-0.34	1.03	1.05	1.04	0.66	1.22	1.23	1.21
-0.32	1.02	1.06	1.03	0.68	1.22	1.22	1.20
-0.30	1.02	1.07	1.02	0.70	1.22	1.21	1.20
-0.28	1.01	1.06	1.01	0.72	1.22	1.20	1.18
-0.26	0.98	1.03	0.99	0.74	1.21	1.18	1.17
-0.24	0.96	1.01	0.97	0.76	1.19	1.17	1.15
-0.22	0.93	0.99	0.94	0.78	1.17	1.15	1.13
-0.20	0.92	0.96	0.92	0.80	1.15	1.13	1.12
-0.18	0.91	0.93	0.89	0.82	1.12	1.11	1.10
-0.16	0.87	0.89	0.87	0.84	1.10	1.10	1.09
-0.14	0.83	0.85	0.83	0.86	1.08	1.08	1.07
-0.12	0.76	0.81	0.76	0.88	1.07	1.06	1.06
-0.10	0.70	0.75	0.70	0.90	1.05	1.05	1.05
-0.08	0.65	0.69	0.67	0.92	1.04	1.04	1.04
-0.06	0.59	0.61	0.62	0.94	1.03	1.03	1.03
-0.04	0.46	0.50	0.50	0.96	1.02	1.02	1.02
-0.02	0.28	0.32	0.32	0.98	1.01	1.01	1.01
				1.00	1.00	1.00	1.00

The base of data from which the correction factors were calculated is as follows. For the polypropylene propellers without shaft extenders, the set was a composite from

- 1) one set of measurements at 2° increments from 0° to 360° for both the u propeller and the v propeller
- 2) two sets of measurements at 0.2° increments for the u propeller from 85° to 95° and another two sets from 265° to 275° .

For the polypropylene propellers with shaft extenders, the set was a composite from a program of measurements identical to that without the shaft extension.

For the carbon-fiber propellers without shaft extenders, the set was a composite from

- 1) two sets of measurements at 2° increments from 0° to 360° for the u propeller
- 2) one set of measurements at 0.1° increments from 250° to 290° for the u propeller
- 3) one set of measurements at 0.5° increments from 150° to 210° for the u propeller.

All of the data used in producing the correction factor table were collected at a wind tunnel speed of 10 m/s.

5.0 COMPARISON OF THE NEW CALIBRATIONS WITH OLDER RESULTS

A variety of calibrations have been published, including some relatively new ones by Bowen and Teunissen (1986). There are similarities and differences among them. Three of the greatest discrepancies are in the

- 1) symmetry of the calibration across adjacent quadrants
- 2) wake region near 180°
- 3) band of wind directions surrounding the angles of no propeller rotation.

These discrepancies appear in the comparisons made in Figure 12. Figure 12a shows the response manifest in our new data, the recent data of Bowen and Teunissen (1986), and the data of R. M. Young Company (Gill 1975). The data of Bowen and Teunissen and those of this report compare generally quite well (see Figure 12c). The techniques of calibration and the anemometers used were similar in the two tests.

The assumptions of symmetry, both about the along-wind axis and about the no-rotation wind directions at 90° and 270° in the R. M. Young (Gill 1975) data table, are shown to be too much in error for use in 3-d precision measurement of turbulence. (See the comparison of PNL and RMY data in Figure 12b.) Use of our new calibration data eliminates some serious problems encountered in reducing uvw anemometer component data having large angles to the total wind in some wind turbine tests. How rapidly the calibration spanning the dead band changes with anemometer wear has yet to be learned.

In summary, our new calibrations, generally confirmed in comparison with the recent previous measurements by Bowen and Teunissen, are proposed as the most detailed and reliable for use with the Gill anemometers at this time. They are certainly recommended for winds in which a component nearly normal to the mean wind is measured along the axis of a sensor.

FIGURE 12. A Comparison Between the New Data of This Report, the 1986 Data of Bowen and Teunissen (AES), and the 1975 Data of R. M. Young (RMY) (Gill 1975) for the Polypropylene Propeller. (a) Voltage output as a function of wind direction, normalized to give 100% at $\theta = 0^\circ$; (b) $[u_{PNL}(\theta) - u_{RMY}(\theta)]/u_{PNL}(\theta)$; (c) $[u_{PNL}(\theta) - u_{AES}(\theta)]/u_{PNL}(\theta)$.

6.0 EXAMPLE OF THE NEW CALIBRATION DATA USED IN AN ITERATIVE CORRECTION SCHEME

6.1 A COMPARISON OF TWO PROPELLER ANEMOMETER CORRECTION SCHEMES

An iteration algorithm, written by Horst (1973) and based upon a method developed by Drinkrow (1972), is the core of the computer code that we have used for recent 3-d wind data reduction. The modified code is discussed in Section 6.2. The accuracy of the corrected estimates of wind speed vs. wind direction using the new correction factors presented in this paper are compared in Figure 13 with that of estimates using the R. M. Young (Gill 1975) correction factors previously used by PNL and others. The corrections are made on measurements from our wind tunnel tests, where the actual speed and direction are independently known. It is clear that our correction factors result in an improvement at all angles.

The number of iterations required to obtain our result is no greater than two at nearly all wind angles. Figure 14 shows the number of iterations required for the program to converge acceptably. In the few wind directions where convergence criteria had not been met after ten iterations, no improvement over the value at three iterations was achieved. The iteration corrections of one set of u,v,w measurements requires about 1 millisecond on the MicroVAX computer using the Morris modification of the Horst iteration correction program. In an earlier modification of the Horst algorithm, George (George and Connell 1984) discovered that when the turbulent wind was mostly along the u direction, but there was a small v component, the Horst iteration scheme would not converge. George made an adjustment of the correction factor curve near 90° that allowed convergence without benefitting from new calibration measurements. We have added the required additional measurements near wind angles of 90° that eliminate this problem.

FIGURE 13. Comparison of the Accuracy of uvw Data Correction Using One Iteration Scheme and Two Correction Factors, One From the Manufacturer (RMY) and One From the New Wind Tunnel Calibrations (PNL). (a) Plots of corrected sensor output using each of RMY and PNL correction factors, a plot of the ideal response, and a plot of the uncorrected measurements. (b) Fractional differences from the ideal output of the data (1) uncorrected, (2) corrected using RMY factors, and (3) corrected using PNL factors.

FIGURE 14. Number of Iterations Required for Each u, v, and w Wind Speed Data Set to Achieve Acceptable Convergence in a Computational Correction Scheme Using Correction Factors from the Manufacturer (RMY) and Those from the New Wind Tunnel Calibration (PNL). The data were corrected at each available wind azimuth angle from 0° to 360° as indicated on the plot.

6.2 A COMPUTER CODE FOR ITERATIVE CORRECTION OF THE UVW ORTHOGONAL-PROPELLER ANEMOMETER

The subroutine used for correcting the non-cosine response of the Gill uvw anemometer applies the correction factors in an iterative scheme that simultaneously corrects the u, v, and w components as a function of their direction cosine.

The code presented in this section is our most current variation of the original Horst (1973) code. It differs primarily in the way it is structured and in its convergence criteria, which are based on the difference in actual cosine values rather than integer subscript values, allowing the criteria to be twice as stringent.

The algorithm first computes the total wind speed and the direction cosines of the three velocity components using the independent estimates derived from output voltages from the sensors. Each of these first estimates of wind speed components is uncorrected for angle-induced errors in sensor response. The direction cosines are used to select correction factor values from an array of factors for the velocity component parallel to the axis of rotation of each sensor.

Using the adjusted components of the indicated wind velocity derived from use of the correction factors, the algorithm computes new values of the direction cosines and compares them with the previous values. The process of determining a new set of correction factors, applying them to the original measures of velocity components, and computing new direction cosines is allowed to continue until either the difference in direction cosines from one iteration to the next is less than or equal to 0.01, or four iterations have occurred. The resultant wind velocity components are then computed using correction factors based on the last set of cosine values.

The iterative correction subroutine, UVWCOR, is printed in Figure 15. When used with the VAX computer to correct the data taken with a uvw anemometer in the known wind of the wind tunnel, the program takes about 1 millisecond to correct each set of u, v, and w values. The computation takes about 0.01 of the time it took to measure and record the data. Many of the computers used in data acquisition are capable of correcting such data as they are being measured in the field and providing real-time readouts of the wind speed and direction.

6.3 AVAILABILITY OF MORE COMPLETE CORRECTION FACTOR TABLES

It is recognized that users of our calibration data may not wish to be constrained to using the abbreviated "standard form" of correction factor table or this code, which uses data representing the equal intervals of 0.02 of the cosine of wind angles relative to the propeller axes. The original calibration data are more finely resolved and in terms of wind angles rather than their cosine as tabulated in the "standard" correction factors given in this paper. A more detailed printout of correction factors, about 6 pages in length, is available.

```

      SUBROUTINE UVWCOR(U,V,W)
C
C*****
C
C   This subroutine corrects the non-cosine response of a
C   Gill UVW Anemometer using an algorithm written by T. Horst
C   for an iterative method developed by R. Drinkow.
C   Author: V. Morris, December 1988.
C*****
C
C      REAL COR(101)

C   initialize direction cosines
      S = SQRT(U*U + V*V + W*W)
      IF (S .EQ. 0.0) RETURN
      COSU = U/S
      COSV = V/S
      COSW = -W/S

      DO 10, N = 0, 3
C   determine correction factor index
          I = NINT(50.*COSU) + 51
          J = NINT(50.*COSV) + 51
          K = NINT(50.*COSW) + 51
C   correct data for non-cosine response
          UC = U * COR(I)
          VC = V * COR(J)
          WC = W * COR(K)
C   compute new direction cosines
          S = SQRT(UC*UC + VC*VC + WC*WC)
          IF (S .EQ. 0.0) RETURN
          COSUC = UC/S
          COSVC = VC/S
          COSWC = -WC/S
C   compare new direction cosine with previous and
C   iterate if greater than .01
          IF (ABS(COSUC-COSU) .LE. .01 .AND.
1             ABS(COSVC-COSV) .LE. .01 .AND.
2             ABS(COSWC-COSW) .LE. .01) GOTO 20
          COSU = COSUC
          COSV = COSVC
          COSW = COSWC
10  CONTINUE

C   replace wind speed values with cosine-corrected values
20  I = NINT(50.*COSUC) + 51
      J = NINT(50.*COSVC) + 51
      K = NINT(50.*COSWC) + 51
      U = U * COR(I)
      V = V * COR(J)
      W = W * COR(K)
      RETURN
      END

```

FIGURE 15. Listing of UVWCOR, a Fortran Subroutine for Correcting the Output from a Gill uvw Anemometer for Its Non-cosine Angle Response. Array COR used in the subroutine contains the correction factors printed in Table 1 for the appropriate propeller.

7.0 CONCLUSIONS

With detailed angle calibration data such as those reported in this paper, turbulent wind measurements by 3-d mutually orthogonal propeller anemometers are shown to be very accurate at all angles, at least for total wind speeds of 10 to 30 m/s. For greatest accuracy, individual calibration data must be obtained for each of the three sensors, and the calibrations must be done with all three propellers installed on the complete anemometer. For more ordinary requirements on 3-d wind measurement accuracy, a single calibration adequately represents the response of all three sensors on the 3-d propeller anemometer, as long as the major anomalies, such as deviations near 90°, are well resolved.

The new calibrations are particularly detailed in accurately accounting for deviations from the exact cosine angular response for sensors of wind components that are nearly orthogonal to the total wind. They also accurately represent the anomalies in calibration caused when a propeller is in the influence of the wake of another propeller, of a shaft housing, or of the main body of the anemometer.

Although the new data are mostly for four-blade polypropylene propellers mounted on a Gill anemometer, an important contribution is made by providing the equivalent quality and resolution of calibration for the carbon-fiber thermoplastic propeller. Comparison of calibrations of the two types of propellers indicates that there are substantial differences to be considered in achieving uvw measurements of high precision.

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