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## Calibration Procedures and Uncertainty in Wind Power Anemometers

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### ABSTRACT

Accurate wind measurements are critical in evaluating wind turbine power performance and site assessment. In a turbine power performance evaluation, wind speed readings are matched with corresponding turbine power measurements to produce a power curve for the turbine. For site assessment, the distribution of measured wind speed is used to determine the predicted annual energy production from the wind. Since wind power is proportional to the cube of the wind speed, a small error in the wind measurement could translate to a much greater error in the predicted wind power, which emphasizes the importance of having accurate wind speed readings. To acquire such precision in wind data, it is recommended that individually calibrated anemometers be employed. With these calibrations, it is also recommended that the uncertainty in the calibration be reported so that it may be used not only in the overall uncertainty for turbine power curves and site assessments, but also in improving the performance of an anemometer. A method of presenting calibration uncertainty is defined in the standard IEC 61400-12-1. However, the standard only refers to the measurement uncertainty of the reference wind speed from the particular test facility. It does not include the uncertainty in the anemometer linear transfer function and the errors directly made by the anemometer signal. This paper will discuss: 1) the details of uncertainty reporting as defined by IEC 61400-12-1, 2) a method of extending the uncertainty to include the errors when using the linear transfer function, and 3) a qualitative description of how to determine the uncertainty in a wind speed measurement in the field.

### I. INTRODUCTION

Energy production estimates for wind turbine sites are determined based on two sources: 1) wind resource assessment and 2) wind turbine power production<sup>(9)</sup>. In both of these sources, wind speed is one of the critical measures that require a detailed uncertainty analysis. Part of the protocols in site assessment is to conduct field measurements of local wind speeds, which are then used to estimate the potential wind power available at a particular site. Turbine power production may be predicted based on the turbine power curve where the measured turbine power is a function of measured wind speed (see Figure 1).

A common question from end users is whether to use uncalibrated or calibrated anemometers to conduct wind measurements. With uncalibrated anemometers, a customary

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protocol is to incorporate the manufacturer's published transfer function to convert the anemometer output to wind speed. This, however, elevates the uncertainty in the field measured wind allowing the inclusion of not only the propagation of errors in the anemometer manufacturer's design specifications, its output, data acquisition, and installation, but also the uncertainty in the published transfer function itself and in manufacturing control of a particular anemometer. Typically, public transfer functions are produced based on initial anemometer design performance and on the consensus from a population distribution of anemometer calibrations. Thus, the published transfer function does have a degree of uncertainty which essentially adds to the bias of any same model anemometer. From the manufacturer's specification, a level of accuracy is also assigned to the anemometer; however, this value also only applies as a bias error. A calibrated anemometer, on the other hand, is provided with a unique transfer function that essentially eliminates the errors associated with the use of a published transfer function and with manufacturing control. Uncertainty analysis in calibrated anemometer also investigates not only test facility and manufacturer bias errors but also unique precision errors, which are related to the repeatability of a particular wind measurement. It is possible that significant precision errors would be revealed during calibration. Thus, in order to gain a better understanding of the uncertainty in the wind speed, calibrated anemometers should be employed using its unique transfer function since error sources in its measurement performance would be accounted for.

In IEC 61400-12-1, a sample uncertainty calculation is provided for a wind tunnel facility that uses a Pitot tube system to measure the reference wind speed. This paper investigates the uncertainty analysis for anemometer calibration testing as defined in the IEC. In this standard anemometer calibration uncertainty is only defined through the propagation of errors in the reference wind speed. It does not account for errors generated from the anemometer output itself. Nonetheless, uncertainty in the reference wind speed is an appropriate starting point to the total uncertainty in the calibration. Thus, this paper proposes an expanded uncertainty analysis, which would incorporate additional sources of error, including the uncertainty in the output of the anemometer and particularly in the use of the linear transfer equation calculated from the anemometer calibration.

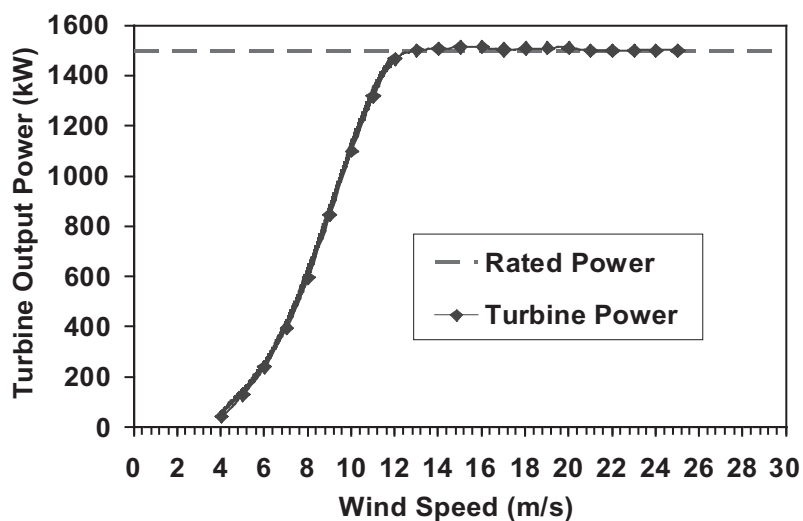


Figure 1. Sample wind turbine power curve.

## 2. ANEMOMETER CALIBRATION STANDARDS

Anemometer calibration is performed to determine the relationship between the output of the anemometer, whether a voltage or TTL signal (i.e., Hz or RPM), and the measurement of the reference wind speed. During a calibration test, anemometer output is collected for a range of wind speed settings. With this data a regression analysis is conducted to determine a calibration transfer function. Ideally, this relationship is linear (see Figure 2). The wind speed residuals can also be determined by finding the difference between the calculated wind speed based on the linear regression equation and the measured reference speed. A sample wind speed residual graph is presented in Figure 3. From the linear regression analysis, two statistical measures, the correlation coefficient (R-value) and the standard error of the estimate (STE), are calculated and used to represent the degree of linearity between the anemometer output and corresponding wind speed readings.

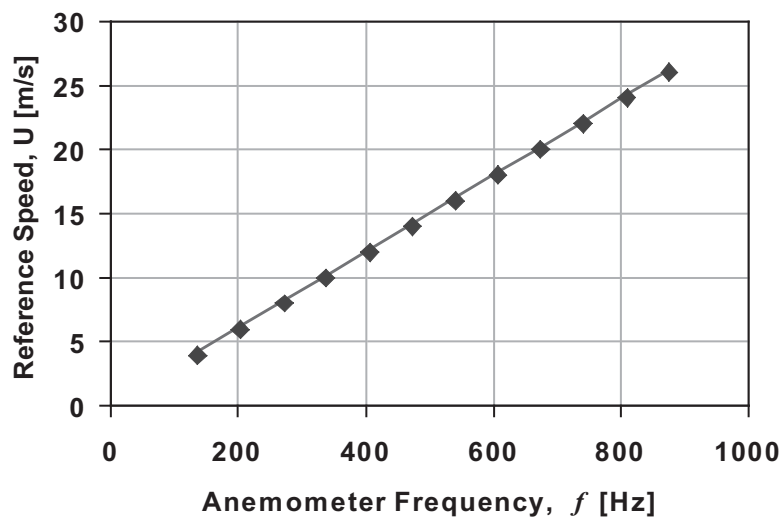


Figure 2. Sample calibration result with linear regression line.

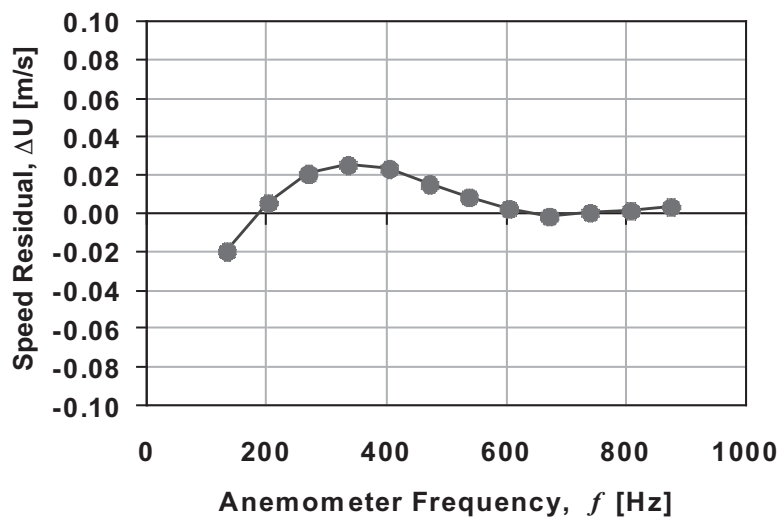


Figure 3. Sample wind speed residual graph of an anemometer calibration.

Several techniques of anemometer calibration have been attempted including using a moving vehicle where the anemometer under test is moved through the air. A more controlled test methodology is done using a wind tunnel where air is moved across the anemometer under test. Some facilities test one anemometer at a time while there are also those that test multiple anemometers during one calibration cycle. In order to reduce the biases, it is recommended that anemometer calibration test standards be complied. In the wind energy industry, the most commonly referred publication for anemometer calibration is IEC 61400-12-1, released in December 2005. This particular document provides calibration procedures for cup anemometers used in turbine power performance evaluation. A calibration protocol for both cup and propeller anemometers is also provided in ASTM D 5096-02, originally published in 1990. This particular standard applies to anemometers used for general meteorology applications including wind resource assessment. In May 2007, ISO 17713-1 was released, which is an international standard for calibration and performance testing of rotating anemometers. This ISO standard is essentially an updated version of ASTM D 5096-02 and refers to ISO 5725-1 and ISO 5725-2 as a guideline for calculating measurement uncertainty. Although details in these standards differ in some ways, a common requirement for anemometer calibration and performance evaluation is that tests are to be conducted under controlled conditions using a low turbulence, uniform-flow wind tunnel.

### 3. INTRODUCTION TO UNCERTAINTY

From its basic definition, uncertainty is an estimate of the errors in a measured variable. It defines the propagation of bias,  $\beta$ , and precision,  $\sigma$ , errors that surround a particular measurement as shown in Figure 4. Here,  $X_{true}$  is the true value for a particular variable, such as wind speed.  $\bar{X}$  is a measured variable from a certain instrument system, such as a wind tunnel Pitot-static tube system. The bias error,  $\beta$ , is the fixed error that defines the offset of  $\bar{X}$  from  $X_{true}$ . Some references identify the bias as systematic errors or Type B errors according to NIST. With multiple readings of  $\bar{X}$ , precision errors, based on the variability of the readings at a particular statistical confidence interval, define repeatability or variability of  $\bar{X}$ . Precision errors are also known as random errors or Type A errors according to NIST.

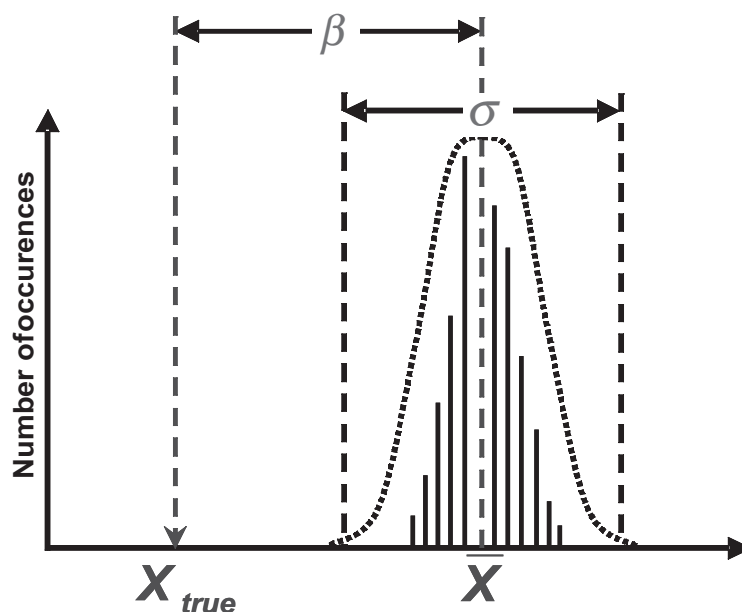


Figure 4. Bias and random error contributions to uncertainty,  $\beta$  and  $\sigma$  respectively.

Uncertainty is of great importance and can be a powerful tool in the wind energy industry such that it could be used to define whether or not a wind farm project is successful. For developers and finance institutions, the feasibility of a project and the degree of financial risks and returns are predicted partly by wind power uncertainty estimates. For wind energy consultants, an uncertainty analysis can be used to track down sources that generate errors in a wind energy estimate so that recommendations may be made to improve the system. Unfortunately, uncertainty can also be made misleading when presented based on incomplete analysis in error propagation or for incorrect use of terminology. At times uncertainty is referred to as a measure of accuracy when, on the contrary, accuracy is a form of bias error,  $\beta$ , that is a partial role in uncertainty. By definition, accuracy is a closeness of agreement between a measured,  $\bar{X}$ , and a true value,  $X_{true}$ .

#### 4. IEC 61400-12-1 UNCERTAINTY ANALYSIS METHOD

There are several references providing methods in determining the uncertainty of an anemometer calibration. For the wind energy industry, the most widely referred standard is IEC 61400-12-1, first edition, 2005-12: "Power Performance Measurements of Electricity Producing Wind Turbines". This particular document provides the steps in conducting a field evaluation of a wind turbine producing a power curve. The evaluation includes site measurements of the local wind speed. Within the appendices of this standard are procedures in performing a cup anemometer calibration transfer function test along with the various tests that would evaluate the instrument's sensitivity to certain terrain and atmospheric conditions. The standard also specifies that one should conduct cup anemometer calibration using a wind tunnel test facility that incorporates a Pitot-static tube system to measure the reference wind speed. As a note, some test facilities choose to incorporate other methods to measure the reference speed such as hot wire anemometry, laser Doppler velocimetry, or even propeller or other types of dynamic anemometers. In the IEC standard, however, uncertainty analysis is conducted based on the errors accumulated in the reference wind speed measurement from a Pitot-static tube system.

In a test protocol where an anemometer is calibrated to the wind speed measurement sensed by the Pitot-static tube system, the IEC standard suggests that the uncertainty in the calibration is defined by the uncertainty in the reference wind speed,  $V$ , defined in Equation (1).

$$V = k_b \sqrt{\frac{2k_c \Delta p}{C_h \rho}} \quad (1)$$

Here,  $\Delta p$  is the differential pressure reading from the Pitot-static tube,  $C_h$  is the Pitot-static tube head coefficient,  $\rho$  is the density,  $k_c$  is the wind tunnel calibration factor, and  $k_b$  is the blockage correction. In more detail, the density can be defined in terms of the ambient pressure,  $P$ , the ambient temperature,  $T$ , the relative humidity,  $\phi$ , vapor pressure,  $P_w$ , the gas constant for air,  $R_{air}$ , and the gas constant for water,  $R_w$ , as defined in Equation (2).

$$\rho = \frac{1}{T} \left[ \frac{P}{R_{air}} - 0.01\phi P_w \left( \frac{1}{R_{air}} - \frac{1}{R_w} \right) \right] \quad (2)$$

Vapor pressure and gas constants for air and water are then defined as follows:

$$P_w = 0.0000205 \exp(0.0631846T) \quad (3)$$

$$R_{air} = \frac{R}{M_{air}} \quad (4)$$

$$R_w = \frac{R}{M_w} \quad (5)$$

Here,  $R$  is the universal gas constant.  $M_{air}$  and  $M_w$  are the molecular weights for air and water, respectively. Using the terms listed above, the reference wind speed measured from a Pitot-static tube system previously defined in Equation (1) can be expanded as follows.

$$V = k_b \sqrt{\frac{2k_c \Delta p R T}{C_h [P M_{air} - 2.05 \times 10^{-7} \phi \exp(0.0631846T)(M_{air} - M_w)]}} \quad (6)$$

This form of the wind speed equation allows a more direct identification of the variables that are most sensitive to the calculation. From Equation (6), the independent variables, terms with exact values as defined in NIST, are found to be  $M_{air}$  and  $M_w$ . Since independent variables have no systematic or random errors, further sensitivity analysis are not required. Dependent variables are essentially measured or pre-calculated parameters which do require further analysis. Thus, from Equation (6), uncertainty in the reference wind speed measured by a Pitot-static tube system is a function of  $k_b$ ,  $k_c$ ,  $C_h$ ,  $R$ ,  $P$ ,  $T$ ,  $\Delta p$ , and  $\phi$  and is then defined as:

$$U_V = \sqrt{(B_V)^2 + (tS_V)^2} \quad (7)$$

Here,  $B_V$  represents the propagation of systematic or bias error contributions and is a function of all the dependent variables found in Equation (6). Thus, the propagation of systematic errors is defined as:

$$B_V = \sqrt{\left( \frac{\delta V}{\delta k_b} B_{k_b} \right)^2 + \left( \frac{\delta V}{\delta k_c} B_{k_c} \right)^2 + \left( \frac{\delta V}{\delta C_h} B_{C_h} \right)^2 + \left( \frac{\delta V}{\delta R} B_R \right)^2 + \left( \frac{\delta V}{\delta P} B_P \right)^2 + \left( \frac{\delta V}{\delta T} B_T \right)^2 + \left( \frac{\delta V}{\delta \Delta p} B_{\Delta p} \right)^2 + \left( \frac{\delta V}{\delta \phi} B_\phi \right)^2} \quad (8)$$

In Equation (8),  $B_{k_b}$ ,  $B_{k_c}$ ,  $B_{C_h}$ ,  $B_R$ ,  $B_P$ ,  $B_T$ ,  $B_{\Delta p}$ , and  $B_\phi$  are the bias errors from each of the dependent variables. For the measured variables,  $P$ ,  $T$ ,  $\Delta p$ , and  $\phi$ , bias errors can be found from data acquisition, signal conditioning, and instrument performance such as linearity or accuracy. For the assigned or property variables,  $k_b$ ,  $k_c$ ,  $C_h$ , and  $R$ , "fossilized" errors are generally applied, representing both the random and systematic errors in the determination of such variables.

From Equation (7),  $S_V$  signifies the propagation of random or precision error contributions which originate only from the measured dependent variables,  $P$ ,  $T$ ,  $\Delta p$ , and  $\phi$ . The value of  $t$  for 95% confidence at  $\infty$  degrees of freedom is 1.96<sup>(3)</sup>. The propagation of random errors is defined according to the following equation.

$$S_V = \sqrt{\left( \frac{\delta V}{\delta P} S_P \right)^2 + \left( \frac{\delta V}{\delta T} S_T \right)^2 + \left( \frac{\delta V}{\delta \Delta p} S_{\Delta p} \right)^2 + \left( \frac{\delta V}{\delta \phi} S_\phi \right)^2} \quad (9)$$

Random errors are the variability in the measured variables. Thus,  $S_P$ ,  $S_T$ ,  $S_{\Delta p}$  and  $S_\phi$  are simply the standard deviations of the mean values from the corresponding measured variables. For both Equations (8) and (9), the partial differentials in front of each term are the

corresponding sensitivity coefficients of each dependent variable. These partial differentials are essentially derived from the expanded reference wind speed, Equation (6). Below displays a table of the sensitivity equations for the reference wind speed calculation.

Table 1. Sensitivity coefficients for each dependent variable.		
Dependent Variable	Sensitivity Coefficient Equation	Equation Number
Blockage Coefficient	$\frac{\delta V}{\delta k_b} = \sqrt{\frac{2\Delta pRT}{C_h[PM_{air} - 2.05 \times 10^{-7} \phi \exp(0.0631846T_K)(M_{air} - M_w)]}} = \frac{V}{k_b}$	Eq. (10)
Pitot-static Tube Head Coefficient	$\frac{\delta V}{\delta C_h} = -\frac{1}{2} \frac{k_b}{C_h^{3/2}} \sqrt{\frac{2\Delta pRT}{PM_{air} - 2.05 \times 10^{-7} \phi \exp(0.0631846T)(M_{air} - M_w)}} = -\frac{1}{2} \frac{V}{C_h}$	Eq. (11)
Universal Gas Constant	$\frac{\delta V}{\delta R} = \frac{1}{2} k_b \sqrt{\frac{2\Delta pT}{RC_h[PM_{air} - 2.05 \times 10^{-7} \phi \exp(0.0631846T)(M_{air} - M_w)]}} = \frac{1}{2} \frac{V}{R}$	Eq. (12)
Ambient Pressure	$\frac{V}{P} = -\frac{1}{2} \frac{VM_{air}}{PM_{air} - 2.05 \times 10^{-7} \exp(0.0631846T)(M_{air} - M_w)}$	Eq. (13)
Ambient Temperature	$\frac{V}{T_K} = \frac{1}{2} V \frac{1}{T} + \frac{1.295 \times 10^{-8} \exp(0.0631846T)(M_{air} - M_w)}{PM_{air} - 2.05 \times 10^{-7} \exp(0.0631846T)(M_{air} - M_w)}$	Eq. (14)
Differential Pressure	$\frac{\delta V}{\delta \Delta p} = \frac{1}{2} k_b \sqrt{\frac{2RT}{\Delta p C_h [PM_{air} - 2.05 \times 10^{-7} \phi \exp(0.0631846T)(M_{air} - M_w)]}} = \frac{1}{2} \frac{V}{\Delta p}$	Eq. (15)
Relative Humidity	$\frac{V}{RH} = \frac{1}{2} \frac{V[-2.05 \times 10^{-7} \exp(0.0631846T)(M_{air} - M_w)]}{PM_{air} - 2.05 \times 10^{-7} \exp(0.0631846T)(M_{air} - M_w)}$	Eq. (16)

An uncertainty analysis using the IEC 61400-12-1 methodology was conducted for the Otech Engineering Wind Tunnel Facility. This facility is a uniform-flow, low-turbulence wind tunnel which uses a Pitot-static tube system to measure the reference wind speed (see Figure 5 and Figure 6). A sample calibration report is presented in Figure 7.



Figure 5. Otech Engineering Wind Tunnel Facility located at Davis, CA.

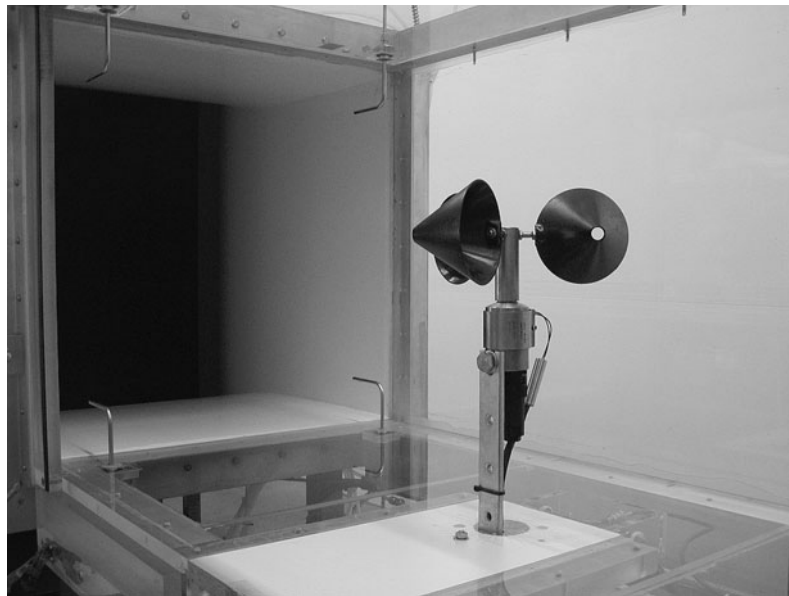


Figure 6. Anemometer calibration testing using a Pitot-static tube system.

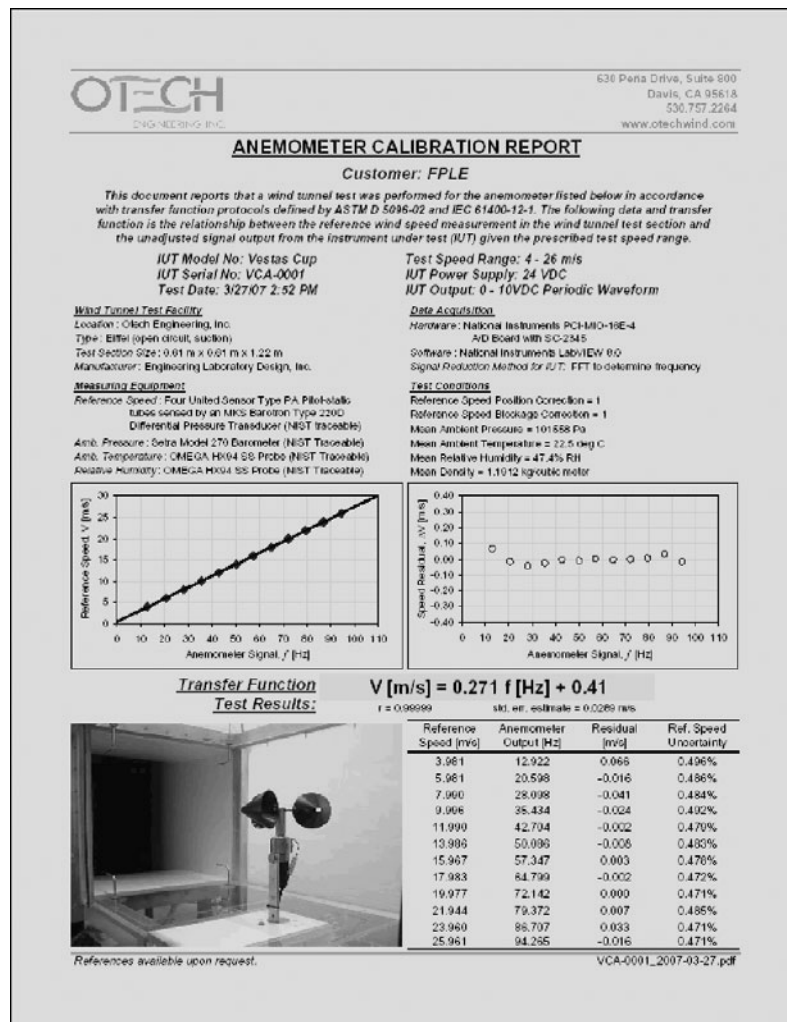


Figure 7. Sample anemometer calibration report generated at Otech Engineering.

In the sample calibration report above, specifications of both the anemometer under test and the wind tunnel facility are first presented, including a list of the instruments used to measure the wind tunnel speed and corresponding local conditions (i.e. ambient pressure, temperature, and relative humidity). Results from the test are also reported, which includes the measured local conditions. From the table of test speeds and corresponding anemometer output measurements, a column of the corresponding uncertainty for each wind speed is also presented. According to IEC 61400-12-1 guidelines, the average uncertainty in the reference wind speed measurement in the Otech Wind Tunnel Facility for test speeds ranging from 4 to 26 m/s is approximately 0.5%.

## 5. EXPANDED UNCERTAINTY ANALYSIS FOR ANEMOMETER CALIBRATION

In the previous section, a method of uncertainty presentation of an anemometer calibration was conducted using the uncertainty analysis in the reference wind speed measurement as defined in IEC 61400-12-1. However, this uncertainty may only apply if you use the calibration tables as a “look-up” table to convert the anemometer signal output into wind speed. In addition, since anemometer calibration relies on the output of the anemometer itself, an uncertainty analysis of the anemometer signal must also be investigated. If the linear regression equation of the calibration tables is used, the uncertainty in the regression should also be accounted for in the anemometer calibration. Thus, an expanded uncertainty of the anemometer calibration,  $U_{cal}$  would be the sum of the squares of the uncertainty in the reference wind speed measurement as defined in IEC 61400-12-1,  $U_V$ , the uncertainty in the output of the anemometer under test,  $U_{IUT}$ , and the uncertainty in the linear regression fit,  $U_{LR}$ .

$$U_{cal} = \sqrt{(U_V)^2 + (U_{IUT})^2 + (U_{LR})^2} \quad (17)$$

Uncertainty in the output of the test anemometer,  $U_{IUT}$ , is essentially the propagation of inherent bias errors,  $B_{IUT}$ , and precision errors generated during the calibration test,  $S_{IUT}$  (see Equation 18). Bias errors in the anemometer output are primarily from the data acquisition system and, for the pulse output anemometer, the methodology of calculating for rate of rotation whether in Hz or rpm. The precision errors are accounted for in the standard deviation of anemometer output reading during the duration of the data collection. Again, the value of  $t$  for 95% confidence at  $\infty$  degrees of freedom is 1.96<sup>(3)</sup>. Bias errors are typically dominated by the method of determining the anemometer’s rate of rotation. For instance, with a pulse count method, a bias error is associated with the least significant count. Precision errors may vary largely based on the standard deviations in the anemometer output at each wind speed. Thus, typically the range in the anemometer output uncertainty could vary from 0.5% to 1.5%.

$$U_{IUT} = \sqrt{B_{IUT}^2 + (tS_{IUT})^2} \quad (18)$$

Linear regression uncertainty,  $U_{LR}$ , may be approached in one of two options. First is the classical method, which then can also be done in one of two ways. One is by applying the standard error of estimate in the linear fit ( $STE_V$ ) as shown in Equation 19, where  $STE_V$  is defined in Equation 20.

$$U_{LR} = \sum_{i=1}^N t \frac{STE_V}{V_i} \quad (19)$$

$$STE_V = \sqrt{\frac{\sum_{i=1}^N (V_i - mf_i - b)^2}{N - 2}} \quad (20)$$

Defining the uncertainty in the linear regression using Equation 19 is more applicable from most anemometer calibration reports which report the  $STE_V$ . However, if the standard error in the slope ( $STE_m$ ) and the offset ( $STE_b$ ) are calculated and readily available, then the uncertainty in the linear regression analysis would be based on the propagation of such errors as shown in Equation 21, where  $STE_m$  and  $STE_b$  are defined in equations 22 and 23.

$$U_{LR} = \sqrt{\left(t \frac{STE_m}{V_i} f_i\right)^2 + \left(t \frac{STE_b}{V_i}\right)^2} \quad (21)$$

$$STE_m = \sqrt{\frac{STE_V^2}{SS_f}} \quad (22)$$

$$STE_b = \sqrt{STE_V^2 \left(\frac{1}{N} + \frac{\bar{f}^2}{SS_f}\right)} \quad (23)$$

Here, the term  $SS_f$  is the sum of the squares of the anemometer readings measured at each wind speed. This is calculated according to the following Equation 24.

$$SS_f = \sum_{i=1}^N f_i^2 - \frac{\left(\sum_{i=1}^N f_i\right)^2}{N} \quad (24)$$

At Otech, values of the  $STE_V$  for various types of anemometers could range from 0.02 m/s to as much as 0.15 m/s for a test range of 4 to 26 m/s. Thus, using Equation 19, the linear regression uncertainty could vary from 0.2% to 5.0% depending on the  $STE_V$ . For the most part,  $STE_m$  and  $STE_b$  are smaller compared to  $STE_V$ , however, when combined in the propagation of uncertainty as defined in Equation 21, the linear regression uncertainty can vary from 0.2% to 5.0% similar to the results from Equation 19. For the second method, the dominant error source is generally the standard error in the offset.

Using Equation 19 or 21 requires that all the random errors in determining the linear transfer function only originate from the wind speed reading; however, in reality, during a calibration the reading from the anemometer output is also measured. Thus, random errors in the anemometer output should also be accounted for. A second option in defining the uncertainty in the linear regression involves a more comprehensive expression for  $U_{LR}$ , which assumes that random errors in both the reference wind speed and the anemometer output dominate the analysis. For this case,  $U_{LR}$  is defined as follows.

$$U_{LR} = \sqrt{U_m^2 + U_b^2} \quad (25)$$

Here,  $U_m$  and  $U_b$  are the uncertainty values for the slope,  $m$ , and offset,  $b$ , respectively. In a linear regression analysis, the slope and offset are a function of the two variables to be related. For the case of anemometer calibration, the two variables are wind speed and anemometer output. Below are the equations for the slope and offset in an anemometer calibration linear regression analysis.

$$m = \frac{N \sum_{i=1}^N f_i V_i - \sum_{i=1}^N f_i \sum_{i=1}^N (f_i V_i)}{N \sum_{i=1}^N (f_i^2) - \left(\sum_{i=1}^N f_i\right)^2} \quad (26)$$

$$b = \frac{\sum_{i=1}^N (f_i^2) \sum_{i=1}^N V_i - \sum_{i=1}^N f_i \sum_{i=1}^N (f_i V_i)}{N \sum_{i=1}^N (f_i^2) - \left( \sum_{i=1}^N f_i \right)^2} \tag{27}$$

As shown in Equations 24 and 25, the slope and offset are both a function of the reference wind speed,  $V_i$  and the anemometer output,  $f_i$ . Thus, the general comprehensive expressions for the uncertainty in the slope and offset are as follows, which includes the bias error propagation of the correlated variables.

$$U_m^2 = \sum_{i=1}^N \left( \frac{\delta m}{\delta V_i} \right)^2 S_{V_i}^2 + \sum_{i=1}^N \left( \frac{\delta m}{\delta f_i} \right)^2 S_{f_i}^2 + \sum_{i=1}^N \left( \frac{\delta m}{\delta V_i} \right)^2 B_{V_i}^2 + 2 \sum_{i=1}^{N-1} \sum_{k=i+1}^N \left( \frac{\delta m}{\delta V_i} \right)^2 \left( \frac{\delta m}{\delta V_k} \right)^2 B_{V_i V_k} + \sum_{i=1}^N \left( \frac{\delta m}{\delta f_i} \right)^2 B_{f_i}^2 + 2 \sum_{i=1}^{N-1} \sum_{k=i+1}^N \left( \frac{\delta m}{\delta f_i} \right)^2 \left( \frac{\delta m}{\delta f_k} \right)^2 B_{f_i f_k} + 2 \sum_{i=1}^{N-1} \sum_{k=1}^N \left( \frac{\delta m}{\delta f_i} \right)^2 \left( \frac{\delta m}{\delta V_k} \right)^2 B_{f_i V_k} \tag{28}$$

$$U_b^2 = \sum_{i=1}^N \left( \frac{\delta b}{\delta V_i} \right)^2 S_{V_i}^2 + \sum_{i=1}^N \left( \frac{\delta b}{\delta f_i} \right)^2 S_{f_i}^2 + \sum_{i=1}^N \left( \frac{\delta b}{\delta V_i} \right)^2 B_{V_i}^2 + 2 \sum_{i=1}^{N-1} \sum_{k=i+1}^N \left( \frac{\delta b}{\delta V_i} \right)^2 \left( \frac{\delta b}{\delta V_k} \right)^2 B_{V_i V_k} + \sum_{i=1}^N \left( \frac{\delta b}{\delta f_i} \right)^2 B_{f_i}^2 + 2 \sum_{i=1}^{N-1} \sum_{k=i+1}^N \left( \frac{\delta b}{\delta f_i} \right)^2 \left( \frac{\delta b}{\delta f_k} \right)^2 B_{f_i f_k} + 2 \sum_{i=1}^{N-1} \sum_{k=1}^N \left( \frac{\delta b}{\delta f_i} \right)^2 \left( \frac{\delta b}{\delta V_k} \right)^2 B_{f_i V_k} \tag{29}$$

In Equations 26 and 27,  $B_{V_i}$  and  $B_{f_i}$  are the propagation of the corresponding bias errors, respectively. The fourth and sixth terms in Equations 26 and 27 accounts for the self-correlated bias errors for both the wind speed and anemometer output measurements for a range of  $N$  test speeds. The last term in both Equations 26 and 27 defines the correlated bias errors between the wind speed and the anemometer output readings at each test speed. If there are no common sources of error such as a similar data acquisition system, then the last term goes to zero. The variables  $S_{V_i}$  and  $S_{f_i}$  are the propagation of precision errors in the wind speed and the anemometer output, respectively. For each test speed, a standard deviation in the wind speed and anemometer reading is determined for data collected during a particular acquisition time. This standard deviation at 95% confidence is generally used to determine the precision of the measurement.

More investigation is required in the comprehensive analysis for the linear regression uncertainty, particularly in the sensitivity coefficients. Further research would determine whether a comprehensive analysis would be required or whether using the classical expression (Equation 19) would provide a valid representation for linear regression fit uncertainty. Another key note would be that if the calibration results were used as a “look up” table to determine the wind speed reading for a particular anemometer output in the field, the uncertainty in the anemometer calibration would be directly related only to the uncertainty in the reference wind speed and in the output of the anemometer in the test facility. However, the most common practice is to use the calibration equation. In this case, the uncertainty should also reflect the uncertainty contribution from the linear regression fit. Table 1 is a summary of the equations required for an expanded uncertainty analysis using the classical expression for linear regression uncertainty. Since the standard error in the linear regression is most commonly provided in calibration reports, Case 1 in the table below would provide an applicable expression for linear regression uncertainty.

Anemometer Calibration Uncertainty	$U_{cal} = \sqrt{(U_V)^2 + (U_{IUT})^2 + (U_{LR})^2}$	~ 0.7% to 5.2%
Reference Wind Speed Uncertainty	$U_V = \sqrt{(B_V)^2 + (tS_V)^2}$	~ 0.5%
Anemometer Output Uncertainty	$U_{IUT} = \sqrt{B_{IUT}^2 + (tS_{IUT})^2}$	~ 0.5% to 1.5%
Linear Regression Uncertainty (Case 1)	$U_{LR} = \sum_{i=1}^N t \frac{STE_V}{V_i}$	~ 0.2% to 5.0 %
Linear Regression Uncertainty (Case 2)	$U_{LR} = \sqrt{\left(t \frac{STE_m}{V_i} f_i\right)^2 + \left(t \frac{STE_b}{V_i}\right)^2}$	~ 0.2% to 5.0 %

An expanded uncertainty analysis was conducted using the data presented in the sample calibration report shown in Figure 7. For this analysis, the linear regression uncertainty was calculated based on the presentation of the standard error of estimate in the linear fit. From this sample calibration case, the standard error of estimate was 0.0289 m/s revealing a highly linear sensor. A lower standard error value generally corresponds to a more linear anemometer. The bias uncertainty in the anemometer output measurement was essentially based on the errors in the data acquisition system. In the following Table 3, the lower right-hand results table portion from the calibration report in Figure 7 is presented along with columns of the calculated values of anemometer output uncertainty, regression uncertainty, and the calibration uncertainty for each test speed. From this sample analysis, the average anemometer calibration uncertainty for a test speed range of 4 to 26 m/s was found to be 1.2%.

Reference Speed [m/s]	Anemometer Output [Hz]	Residual [m/s]	Ref. Speed Uncertainty, $U_V$	Anem. Output Uncertainty, $U_{IUT}$	Regression Uncertainty, $U_{LR}$	Calibration Uncertainty, $U_{cal}$
3.981	12.922	0.066	0.496%	1.467%	1.425%	2.104%
5.981	20.598	-0.016	0.486%	1.030%	0.949%	1.482%
7.990	28.098	-0.041	0.484%	0.981%	0.710%	1.304%
9.996	35.434	-0.024	0.492%	0.780%	0.567%	1.083%
11.990	42.704	-0.002	0.479%	0.818%	0.473%	1.059%
13.986	50.086	-0.008	0.483%	0.954%	0.406%	1.144%
15.967	57.347	0.003	0.478%	0.715%	0.355%	0.930%
17.983	64.799	-0.002	0.472%	0.785%	0.315%	0.969%
19.977	72.142	0.000	0.471%	0.802%	0.284%	0.973%
21.944	79.372	0.007	0.485%	0.938%	0.259%	1.087%
23.960	86.707	0.033	0.471%	1.071%	0.237%	1.194%
25.961	94.265	-0.016	0.471%	1.086%	0.219%	1.204%
<b>Average Uncertainties</b>			<b>0.5%</b>	<b>1.0%</b>	<b>0.5%</b>	<b>1.2%</b>

## 6. WIND POWER ANEMOMETER UNCERTAINTY IN FIELD MEASUREMENTS

Contributions to the uncertainty in wind energy estimates may originate from several sources of error such as wind variability at a selected site, resource modeling, or field measurements of wind. Field measurements are essentially conducted using anemometer towers. Typically, the most common protocol in field anemometry is to program a calibration transfer function by entering the calibration slope and offset values into data loggers or other forms of data acquisition system to convert the output signal from an anemometer into a wind speed reading. Thus, the equation used to conduct uncertainty analysis in a field measured wind speed is as follows:

$$V_{field} = mf_{field} + b \quad (30)$$

Here,  $V_{field}$  is the measured wind speed at a particular site,  $f_{field}$  is the on-site raw

anemometer output in voltage, pulse counts, or rotation rate,  $m$  and  $b$  are the slope and offset, respectively, from the linear regression of the anemometer calibration. Based on this equation, the uncertainty in the field measured wind speed is a function of  $m$ ,  $b$ , and  $f_{field}$ . Assuming that the anemometer readings during its calibration have no random errors, the classical uncertainty expression in the anemometer calibration, examined in the previous section and defined in Equation 19 and 21, may be used to define the combined uncertainty in the use of the calibration slope and offset. Thus, the uncertainty in the field measured wind speed,  $U_{V_{field}}$  is a function of the uncertainty in the anemometer calibration,  $U_{cab}$  as defined in Equation 17, and uncertainty in the field measured raw output from the anemometer,  $U_{f_{field}}$

$$U_{V_{field}} = \sqrt{(U_{cal})^2 + (U_{f_{field}})^2} \quad (31)$$

Anemometer calibration uncertainty,  $U_{cab}$  was quantified based on an expanded uncertainty analysis method presented in the previous section. To complete the uncertainty analysis of the wind speed measured in the field,  $U_{V_{field}}$  it is necessary to review of the sources of uncertainty in the anemometer raw output measured in the field,  $U_{f_{field}}$ . When installed in the field, a rotating anemometer rotation signal can be influenced by several error sources such as: 1) incoming flow distortions from tower shadow and boom mounting position and angularities, 2) flow distortions due to turbulence generated from terrain complexities and atmospheric stability, 3) mechanical wear on the anemometer bearings, shaft and or electronics, and 4) aliasing and data acquisition limitations. For anemometers mounted on turbine nacelles, the anemometer raw output could be affected by flow disturbances from the rotors, turbine nacelle, and any other objects nearby. Rotating anemometers are typically designed to sense horizontal flow. When subjected to vertical flow disturbances, drag on the cups or propellers may increase or decrease depending on its aerodynamic design threshold, which allows the anemometer to spin slower or faster regardless of the magnitude of the incoming horizontal wind. For the scope of this paper, only a qualitative discussion on anemometer output field measurements is provided. A critical deduction from this section is that anemometer calibration is only a portion of the sources of uncertainty in the field measured wind speed. Based on the list of possible sources of error that could impact the raw output from the anemometer, uncertainty in the anemometer calibration would seem to generate the least sensitivities since procedures and standards have generally rendered a much more controlled calibration system. Thus, further investigation is highly recommended in anemometer field installation.

## 7. CONCLUSION

Under current standards (IEC 61400-12-1), anemometer calibration uncertainty is based only on the uncertainty of the reference wind speed measured at the test facility. For field applications, a more useful value would be an expanded uncertainty analysis of the anemometer calibration which not only includes the test facility wind speed uncertainty but also the uncertainty in the anemometer output measured in the test facility and, if applied, the uncertainty in the use of the calibration linear transfer function equation. The uncertainty in the linear transfer function would not be required if the calibration results were applied as a "look up" table. Common field practice uses the linear regression equation. This paper presented versions of the classical and comprehensive approach in the uncertainty analysis of the linear regression equation. The comprehensive approach required further investigation in the sensitivity coefficients to determine whether it would be necessary to use a comprehensive uncertainty analysis or just to apply the classical approach. However, it was also determined that the classical approach does provide a valid estimate of the uncertainty

in the linear regression fit. Thus, the expanded anemometer calibration uncertainty is the propagation of errors from the reference wind speed measurement at the test facility and includes contributions from the linear regression. When applied to the field, the anemometer calibration is only one of many sources of uncertainty in the field measured wind speed. For this case, the uncertainty in the anemometer output due to installation and to sensitivities to environmental conditions should be accounted for.

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