Application Note

#40C Anemometer Uncertainty

Introduction

Renewable NRG Systems receives many questions regarding anemometer accuracy, uncertainty and performance. This application note addresses uncertainty and measurement, anemometer classification number and calibration uncertainty.

Uncertainty and measurement

Uncertainty is an estimation of the errors in a measured variable such as the wind speed. As depicted in Figure 1, uncertainty estimates include the bias or systematic error and the precision or random errors associated with the measurement. In this figure, X_{true} represents the true value (e.g., the true wind speed) or measurand; $\overline{X}$ represents the measured wind speed using an anemometer, for example. $\overline{X}$ is comprised of the bias or systematic errors plus random or precision errors.

Any real measurement is an approximation of the true value, so a recorded measurement is complete only when it includes an estimate of its uncertainty. Uncertainty components are frequently classified as Type A for random errors and Type B for systematic errors. Statistical methods are used to quantify Type A uncertainty components. Type B uncertainty components are evaluated using other means, including accuracy estimates from manufacturer specification sheets.

Most methods and procedures used to quantify uncertainty are based on the groundwork included in the ISO Guide to the Expression of Uncertainty in Measurement (ISO, 1993).

In mathematical terms, uncertainty is the root sum of the squares (RSS) of the systematic plus precision errors, and takes the following form:

$$Uncertainty := \sqrt{\beta^2 + \sigma^2} \quad (1)$$

Where:

$$\beta := systematic\ bias$$

$$\sigma := precision\ error$$

Graphically, uncertainty is defined as:

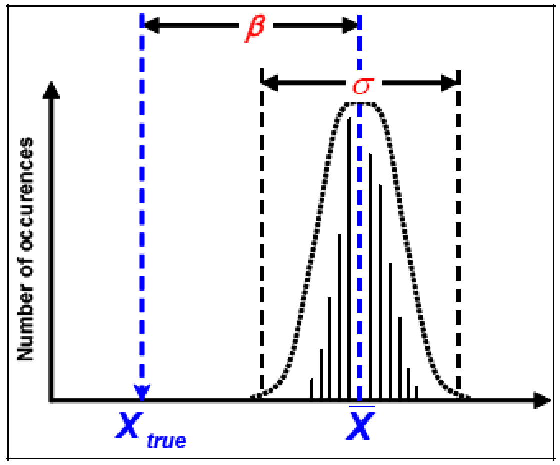

Figure 1 Definition of Uncertainty

Where:

$$X_{true} := true\ value$$

$$\bar{X} := measured\ value\ from\ anemometer$$

Anemometer Classification Number

The random and systematic uncertainty of an anemometer can be characterized by the classification number. The classification number of an anemometer is an index representing the maximum anemometer error, derived from experimental and modeling methods. The classification number is dimensionless. It is based on the combined percent and absolute errors but it is not as sensitive to the bias errors normally associated with percent error or absolute error specifications. Use of only absolute error underestimates the uncertainty at high wind speeds, and use of only percent error underestimates the uncertainty at low wind speeds.

To assign a classification number, anemometer dynamic effects, angular characteristics, and bearing friction are measured under laboratory-controlled conditions. These measurements are the inputs to a dynamic model of the anemometer which is used to bound the error of the anemometer, subject to influence parameters including turbulence intensity, off-axis wind, and ambient temperature. The assigned classification number for the Renewable NRG Systems #40 anemometer can be found in the report published by RISO National Laboratory under the Accuwind research project (T.F. Pedersen, 2006) and an excerpt from this report is included in Table 1 below.

Table 1 Classification of Five Cup Anemometers

Classification IEC 61400-12-1 Model: TRTC + DEWI tilt response + with friction				
Cup Anemometer	Horizontal Wind Speed Definition		Vector Wind Speed Definition	
	Class A	Class B	Class A	Class B
NRG #40	2.4	7.7	2.8	4.8
RISO P2546	1.9	8.0	2.4	12.0
Thies FC	1.5	2.9	1.9	6.3
Vaisala WAA151	1.7	11.1	1.2	5.5
Vector L100	1.8	4.5	1.7	4.0

Class A and B are defined according to the operational ranges reported in Table 2 below.

Table 2 Class A and B Operational Ranges

Classification Category	Class A Ideal flat terrain sites		Class B Non-ideal complex terrain sites	
	Min	Max	Min	Max
Wind speed range (m/s)	4	16	4	16
Turbulence Intensity	0.03	0.12 + 0.48/V	0.03	0.12 + 0.96/V
Turbulence Structure $\sigma_u/\sigma_v/\sigma_w$	1/0.8/0.5 Non-isotropic turbulence Kaimal wind spectrum with a longitudinal turbulence scale of 350m		1/1/1 Isotropic turbulence Von Karman wind spectrum with a longitudinal turbulence length scale of 170m	
Air Temperature (°C)	0	40	-10	40
Air Density (kg/m3)	0.9	1.35	0.9	1.35
Average flow inclination (°)	-3	3	-15	15

Maximum Deviation

Using the classification index listed in Table 1, the bounded error of the Renewable NRG Systems #40 anemometer is shown in Figure 2. For example, for Class A 4 m/s horizontal wind speed, the maximum predicted deviation (error) of the NRG #40 anemometer is ± 0.168 m/s.

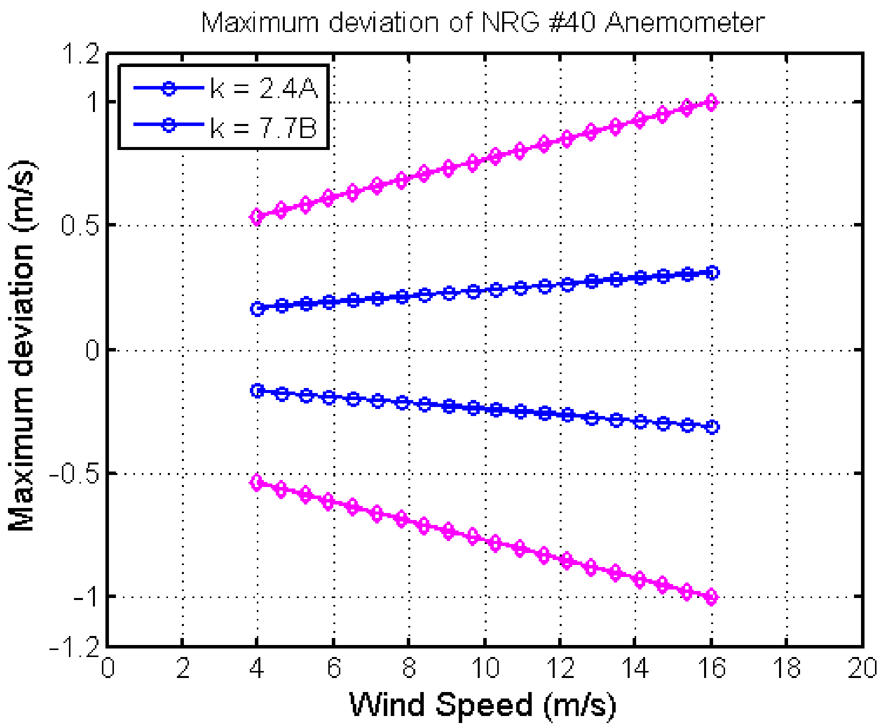

Figure 2 Maximum deviation of NRG #40 anemometer

Operational Standard Uncertainty

For wind power assessment applications, the Operational Standard Uncertainty associated with the Renewable NRG Systems #40 can then be derived from the Anemometer Classification number. The method is defined in International Standard IEC 61400-12-1 *Wind Turbines- Power performance measurements of electricity producing machines* (IEC, 2005). Specifically, Equation (2) gives the operational standard uncertainty:

$$u_i = \left(0.05m/s + 0.005 * U_i\right) * \frac{k}{\sqrt{3}} \qquad (2)$$

as a function of wind speed bin (U_i) and classification number (k). Plotted, this equation yields the following Class A and B operational standard uncertainty for the NRG #40 anemometer under the horizontal wind speed definition as shown in Figure 3.

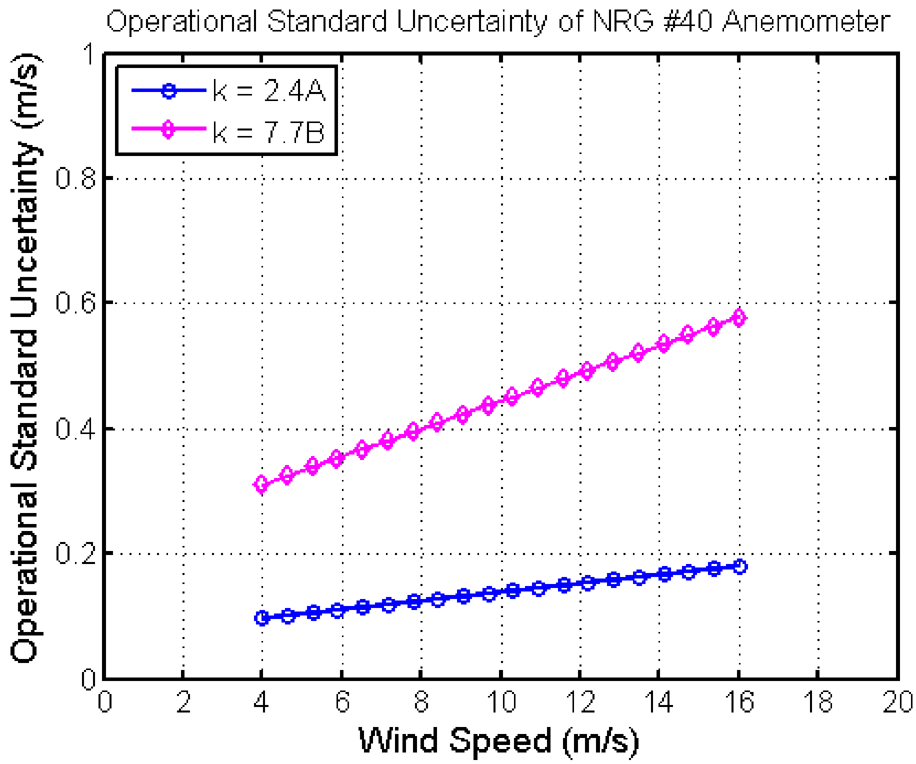

Figure 3 Operational Standard Uncertainty of NRG #40 Anemometer

Class A operational standard uncertainty under the horizontal wind speed definition for five (5) anemometers is shown in Figure 4 (Note scale change on the Y-Axis).

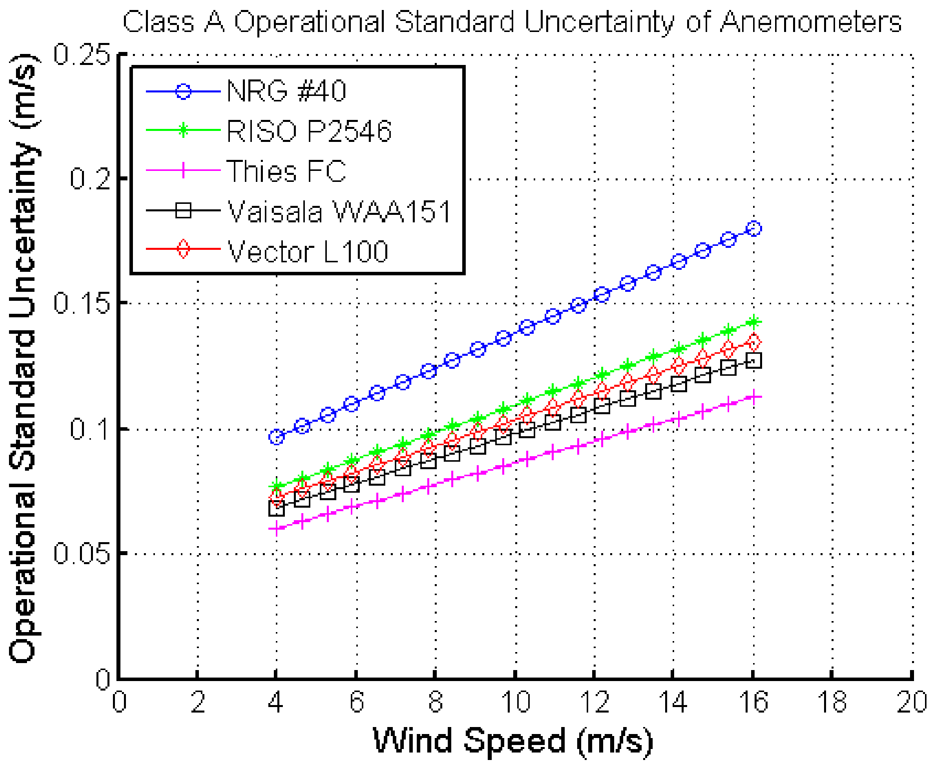

Figure 4 Class A Operational Standard Uncertainty of Five Anemometers (Note change of scale on Y-axis)

Class B operational standard uncertainty under the horizontal wind speed definition for five (5) anemometers is shown below in Figure 5.

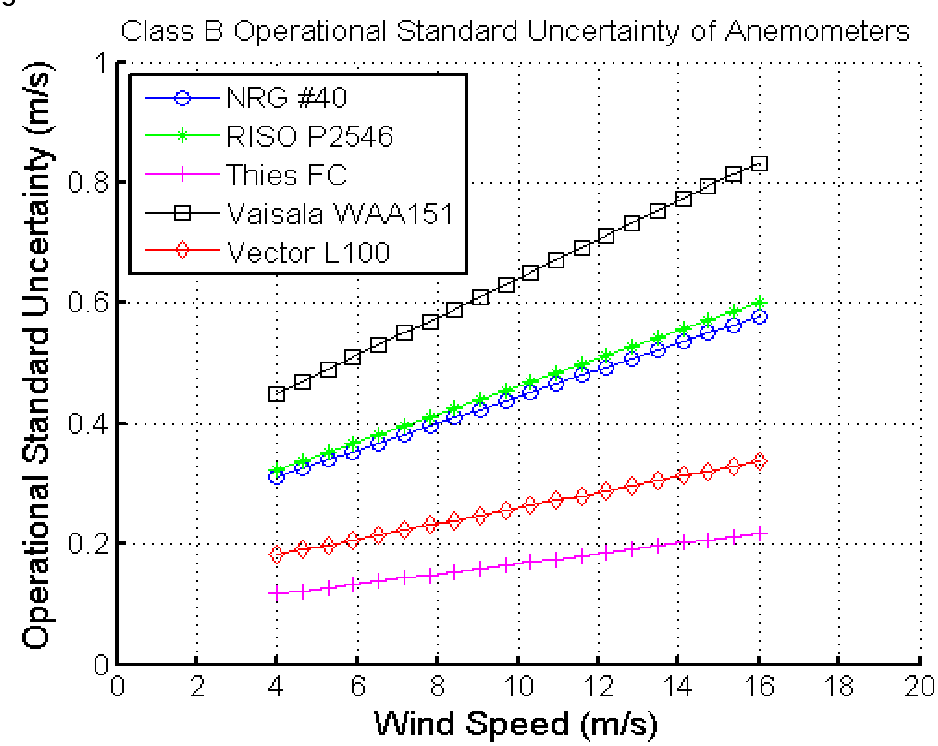

Figure 5 Class B Operational Standard Uncertainty of Five Anemometers

The Operational Standard Uncertainty computed from the Accuwind-derived classification number and Equation (2) is used in the equations listed in the IEC specification (IEC, 2005) to estimate the combined uncertainty associated with a wind turbine annual energy production (AEP) estimate.

The work performed under the Accuwind study quantified uncertainty associated with the operation of the anemometer. Operational uncertainty includes dynamic effects from turbulence over-speeding, angular characteristics or errors due to off-axis response, and bearing friction. In addition to operational uncertainty, there is also uncertainty associated with the calibration of the anemometer.

Calibration Uncertainty

OTECH Engineering, Inc. has quantified the calibration uncertainty of a number of anemometers including the Renewable NRG Systems #40 sensor (Coquilla, 2008). The calibration uncertainty includes the combined uncertainty associated with the reference wind speed (U_{cal}) the uncertainty in the test anemometer output signal (U_{IUT}) and the level of linearity of the anemometer relative to the reference wind speed, (U_{LR}). The calibration uncertainty of the Renewable NRG Systems #40 anemometer is 1.48% and is summarized in the chart below along with several other anemometers. Considering calibration uncertainty only, this estimate is interpreted as follows: there is a 95% statistical confidence the true value is within ±1.48% of the reading reported by the Renewable NRG Systems #40 anemometer.

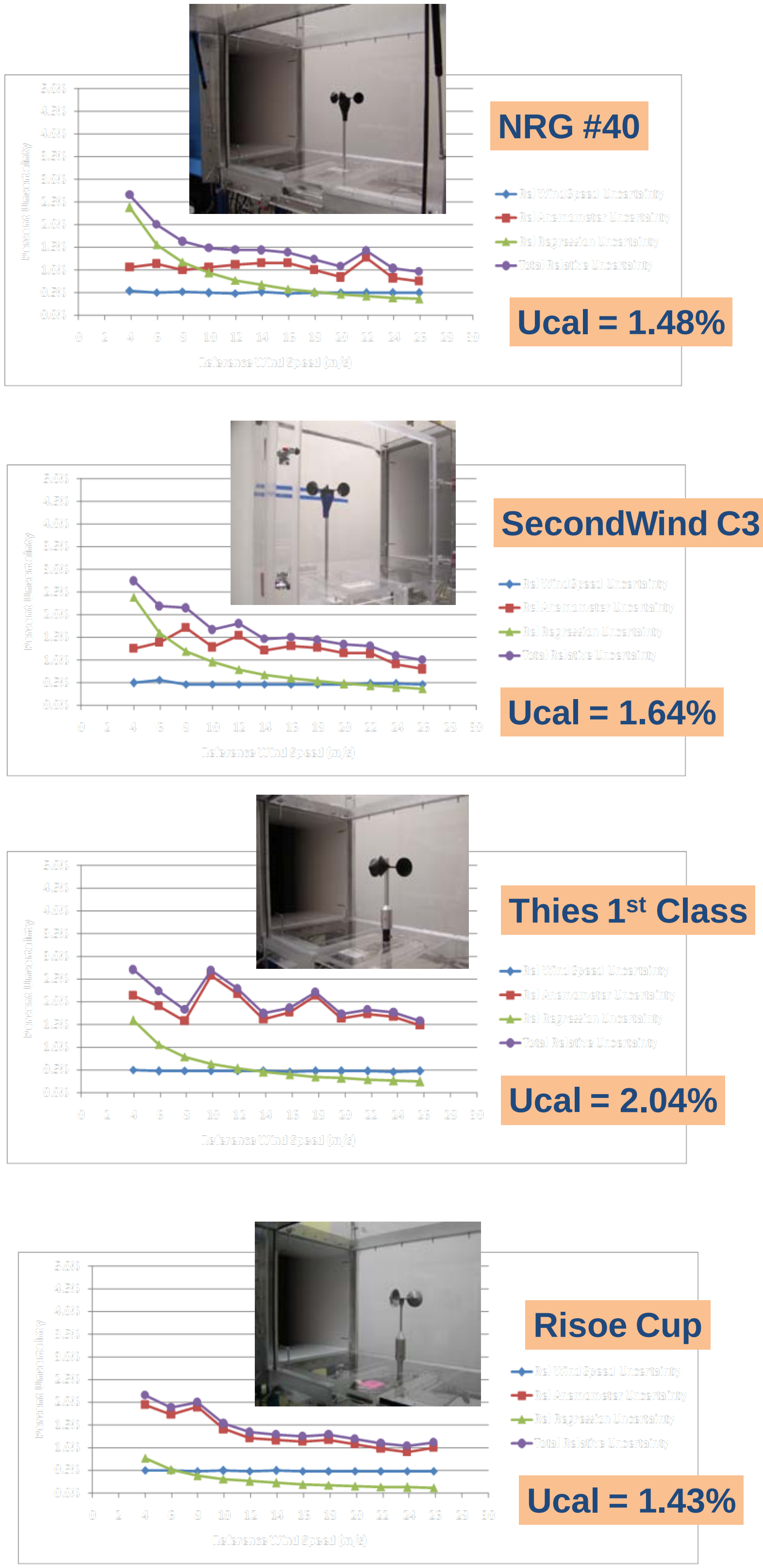

Figure 6 Summary of OTECH Calibration Uncertainty

Works Cited

ISO. (1993). *Guide to the Expression of Uncertainty in Measurement.* Switzerland: International Organization for Standardization.

T.F. Pedersen, J. D. (2006). *ACCUWIND - Classification of Five Cup Anemometers According to IEC61400-12-1.* Roskilde: Riso National Laboratory.

IEC. (2005). *Wind Turbines - Part 12-1: Power performance measurements of electricity producing wind turbines.* Geneva: International Electrotechnical Commission.

Coquilla, R. (2008). Calibration Uncertainty Between Various Anemometers. *AWEA Windpower 2008.* Houston: AWEA.