Anemometer Calibration Requirements for Wind Energy Applications

***Presented By*:**

Rachael V Ishaya

Bryza Wind Lab, Inc., Fairfield, California

American Meteorological Society

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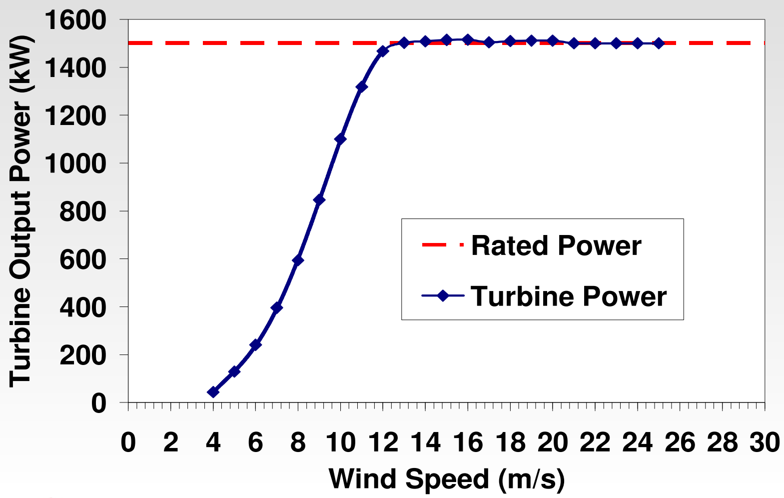
Outline

- Importance of Wind Sensors in Wind Energy
- Wind Sensors Used in Wind Power
- Basic Anemometer Calibration
- Applicable Test Standards
- Test Facility Requirements
- Facility Performance Evaluation
- Calibration Uncertainty
- Summary

Rachael V Ishaya, President
rvishaya@bryzawindlab.com

Importance of Wind Sensors in Wind Energy

- **Wind Plant Operations**
  - Validate wind turbine power output
  - Control start-up and shut-down
- **Wind Turbine Performance Evaluations**
  - Power curve (wind turbine power output as a function of wind speed)
- **Wind Energy Site Assessments**
  - Use power curves and wind distributions to estimate annual energy production for power purchase agreements



Sample Turbine Power Curve

- 1.5 MW rated power reached at ~12 m/s
- Power estimated at lower wind speeds can be as much as 30% error depending on curve

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Rachael V Ishaya, President
rvishaya@bryzawindlab.com

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Wind Sensors Used in Wind Power

Cup Anemometers

Propeller Anemometers

Ultra-Sonic Anemometers

- *Wind turbines are designed to generate power from direct incoming flow*
- *Key measure from a wind sensor is the magnitude of the horizontal wind speed component*

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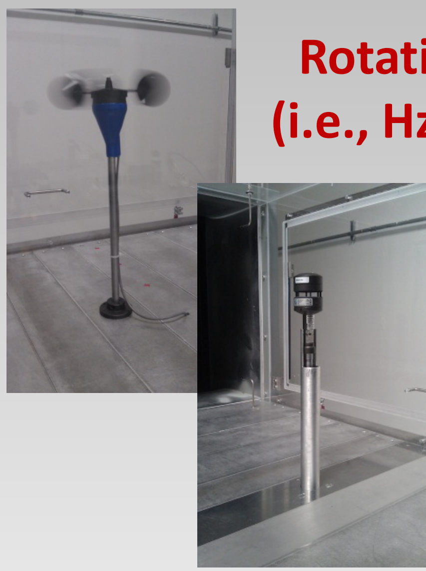
rvishaya@bryzawindlab.com

Basic Anemometer Calibration

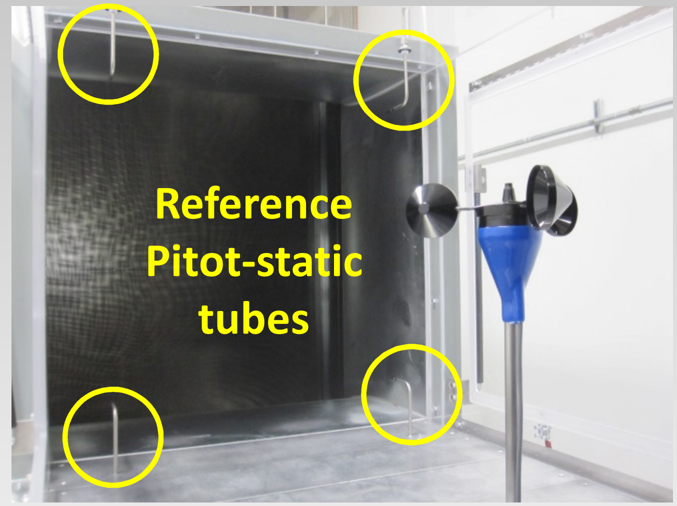
Anemometer Output ⇔ Controlled Reference Speed

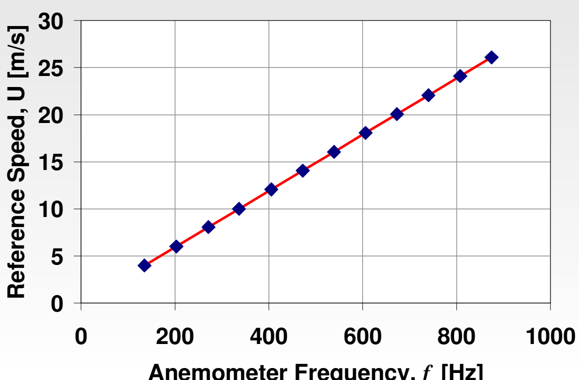


Rotation rate (i.e., Hz or rpm)

Analog voltage or conditioned digital signal

Wind generated from a controlled wind tunnel





Anemometers are designed to be linear instruments

Perform a Least Squares Fit

⇒ ***Linear Transfer Function***

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Applicable Test Standards

- **ASTM D5096-02, "Standard test method for determining the performance of a cup anemometer or propeller anemometer"**
- **ASTM D6011-96, "Standard test method for determining the performance of a sonic anemometer/thermometer"**
- **ISO 17713-1, "Meteorology – Wind measurements Part 1: Wind tunnel test methods for rotating anemometer performance"**
- **ISO 16622, "Meteorology – Sonic anemometers/thermometers – Acceptance test methods for mean wind measurements"**
- **IEC 61400-12-1, "Wind turbines – Part 12-1: Power performance measurements of electricity producing wind turbines"**
- **IEC 61400-12-2, "Wind turbines – Part 12-2: Power performance of electricity producing wind turbines using nacelle anemometry"**

General requirement is to perform anemometer calibrations in a *uniform-flow, low-turbulence wind tunnel*

Test Facility Requirements

Wind Tunnel Characteristic	Standards Requirements
Speed Range	IEC 61400-12-1 (4-16 m/s); Others based on % of application speed
Flow Uniformity	IEC 61400-12-1 (<0.2%); Others (<1%)
Wind Gradient	IEC 61400-12-1 (<0.2%)
Turbulence Intensity	IEC 61400-12-1 (<2%); Others (<1%)
Density Uniformity	ASTM D5096-2, ISO 17713-1 (<3%)
Data Acquisition	Resolution 0.02 m/s, minimum sampling 10 Hz, duration 30-100 sec
Model Blockage	10% max for open test sections, 5% max for closed test sections
Repeatability	IEC 61400-12-1 (<0.5% at 10 m/s test speed)
Interlaboratory Comparison	IEC 61400-12-1 (within 1% in 4-16 m/s test speed range)

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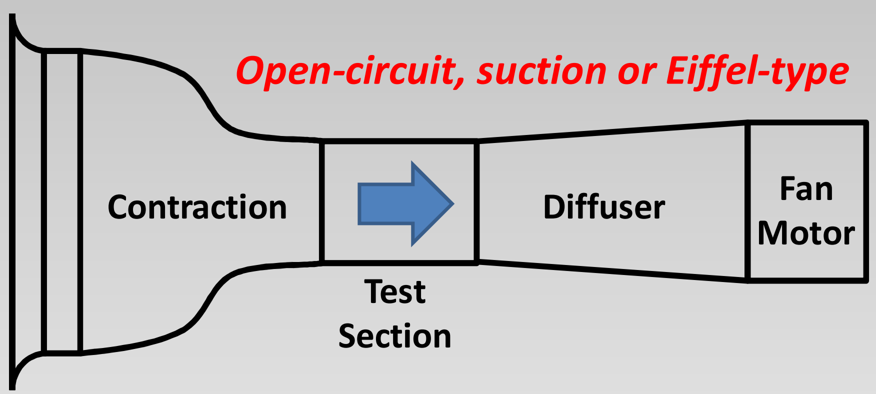
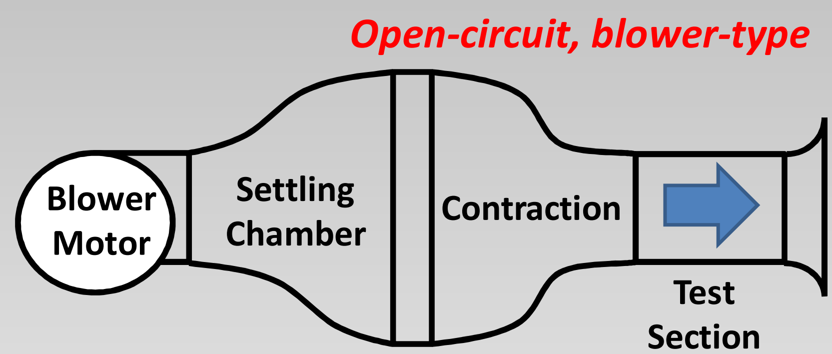
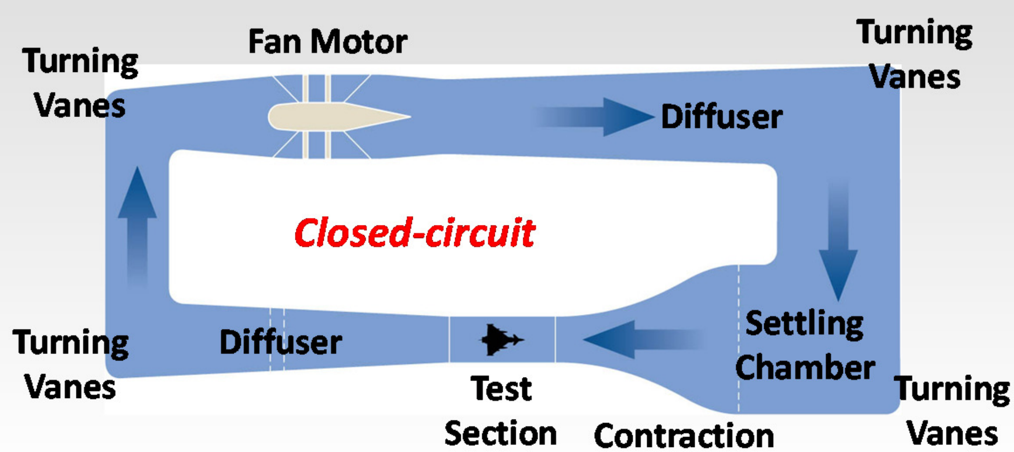
rvishaya@bryzawindlab.com

Test Facility Requirements

Common Wind Tunnel Configurations







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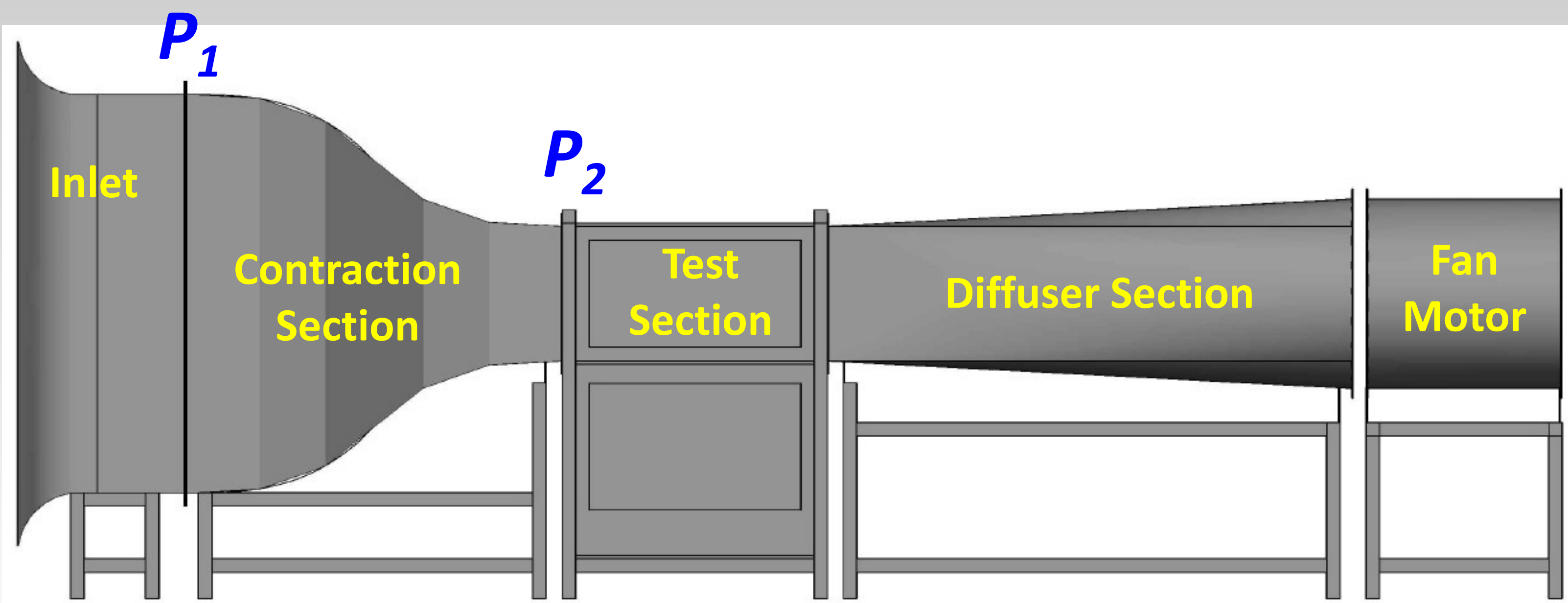
rvishaya@bryzawindlab.com

Facility Performance Evaluation

AIAA R-093-2003, “Calibration of Subsonic and Transonic Wind Tunnels”

General concept is to define dynamic pressure in test section according to the pressure drop generated by the wind tunnel contraction section.



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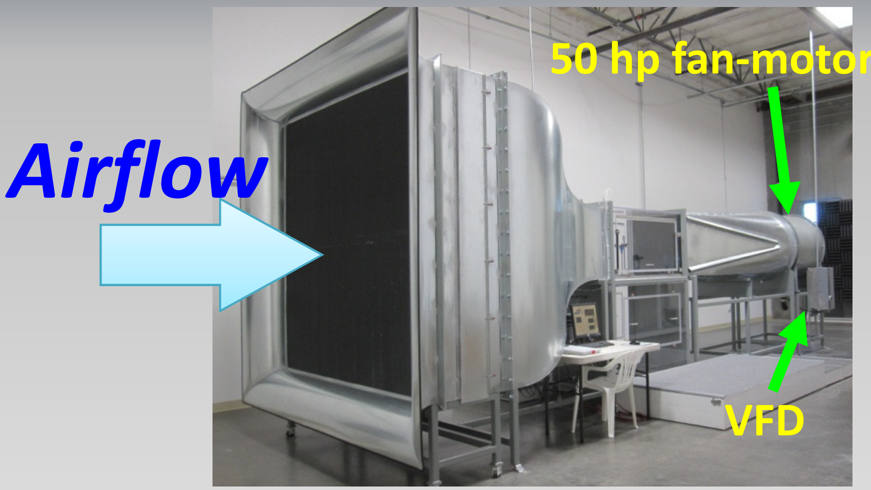
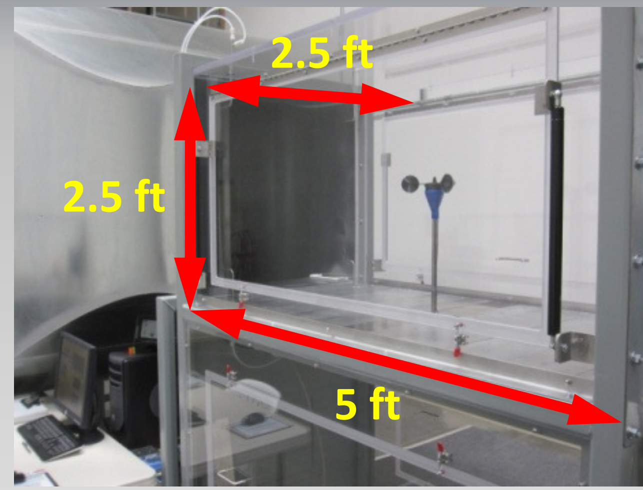
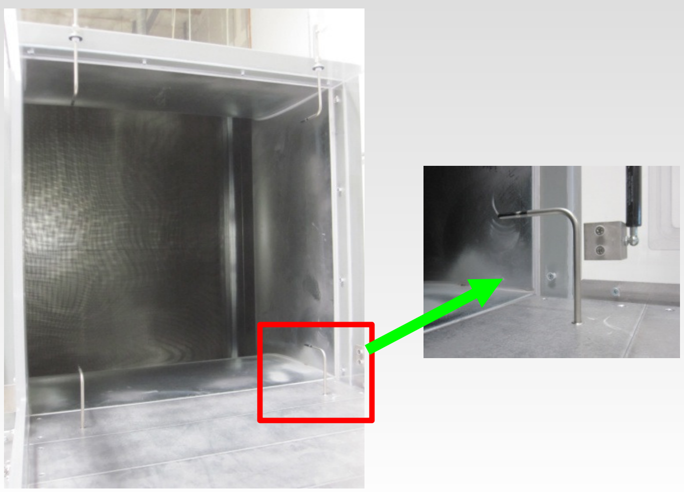
Facility Performance Evaluation







Reference speed measurement:

Pitot-static tube system

(as defined by IEC 61400-12-1)

Four Pitot tubes with sensing tips positioned at test section inlet where total and reference ports connected to an MKS 120AD transducer.

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rvishaya@bryzawindlab.com

Facility Performance Evaluation

Pitot-Static Tube System
General Velocity Equation

$$V = \sqrt{\frac{2\Delta p}{\rho}}$$

Differential pressure from Pitot-static tube (Δp)

Density of humid air (ρ)

$$\rho = \frac{1}{R * T}\left[PM_{air} - 2.05\times 10^{-7}\phi e^{0.0631846T}\left(M_{air} - M_{w}\right)\right]$$

Ambient temperature (T)

Ambient pressure (P)

Relative humidity (ϕ)

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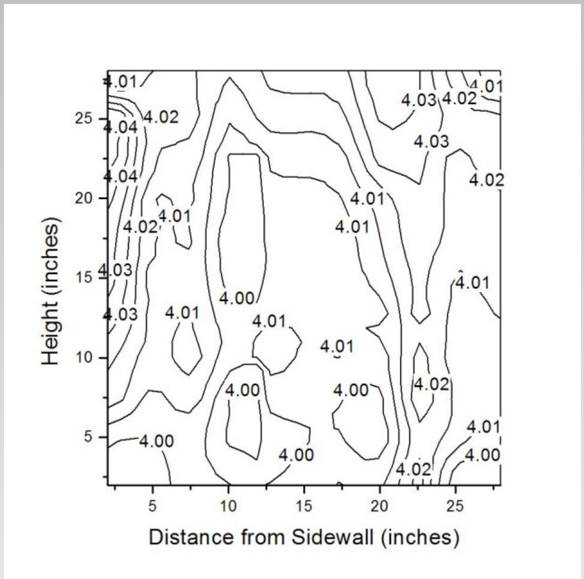
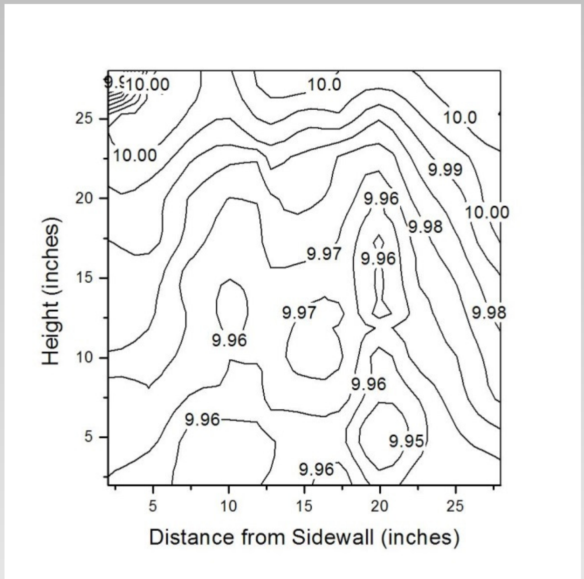
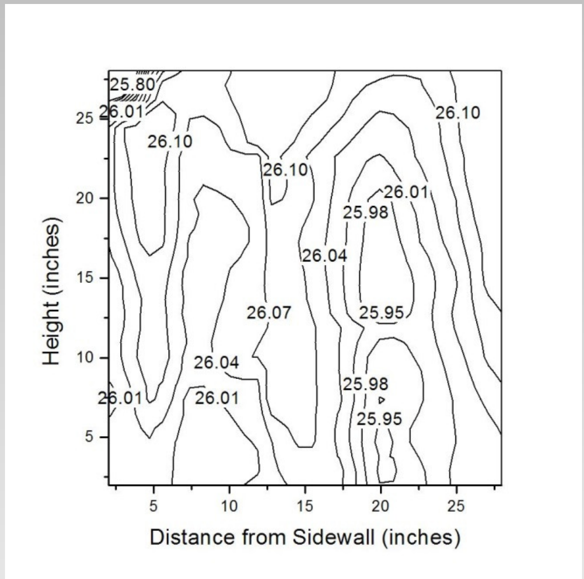
rvishaya@bryzawindlab.com

Facility Performance Evaluation

Velocity profiles at center of test section from traversed Pitot tube.







1) Profiles mean speed settings from 4 to 26 m/s showed an average test section uniformity within +/-0.2%.

2) Preliminary indication of less than 0.2% turbulence.

3) Difference in wind speed between center of test section to reference Pitot-static tubes at inlet averages to +0.014%.

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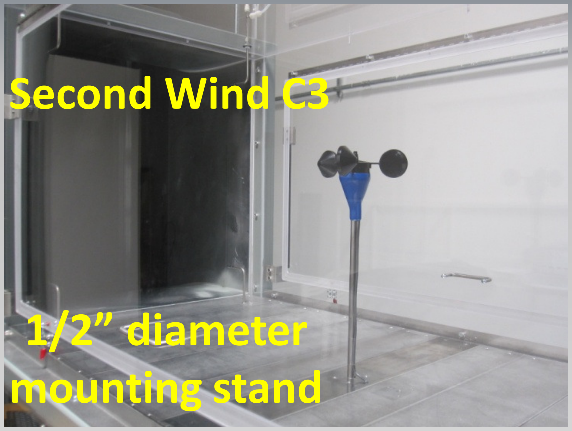
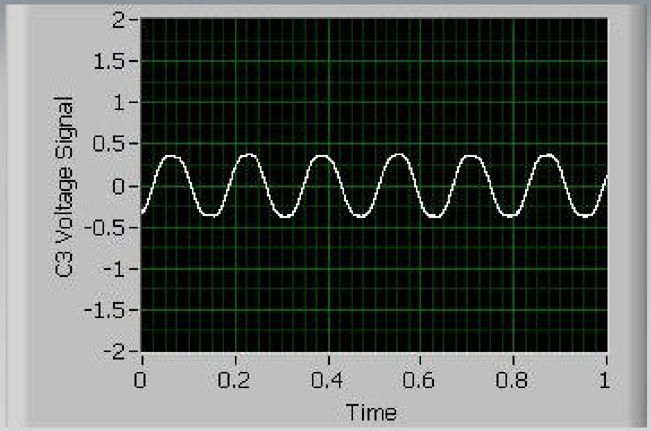
Facility Performance Evaluation





Blockage Ratio $\frac{A_{C3}}{A_{TS}} \leq 2\%$ ⇒ **Empirical Blockage Correction** $k_b = 1 + \frac{1}{4}\frac{A_{C3}}{A_{TS}} = 1.005$

Test performance requirements according to IEC 61400-12-1

- **Calibration test speeds: 4 to 16 m/s at 1 m/s increments**
- **Repeatability (<0.5% at 10 m/s) $\Rightarrow$ within 0.2% for 5 repeated tests**
- **Interlaboratory Comparison (+/-1% at 4-16 m/s) $\Rightarrow$ 1% average variation in comparison to an accredited wind tunnel laboratory in Denmark**

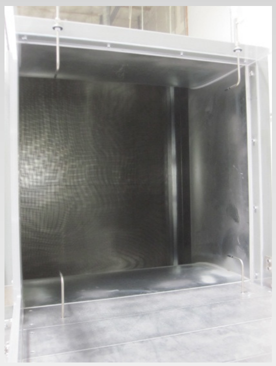
Rachael V Ishaya, President
rvishaya@bryzawindlab.com

Calibration Uncertainty

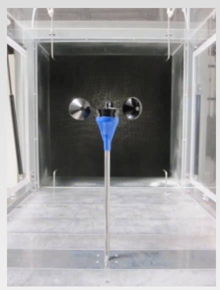
Anemometer calibration uncertainty consists of the propagation of errors from three general areas

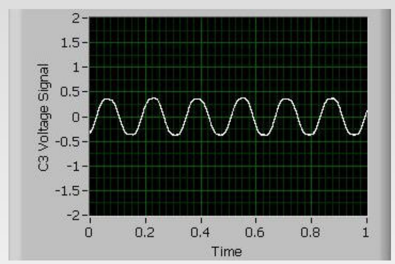
$$U_{cal} = \sqrt{(U_V)^2 + (U_{IUT})^2 + (U_{LR})^2}$$

Reference wind speed

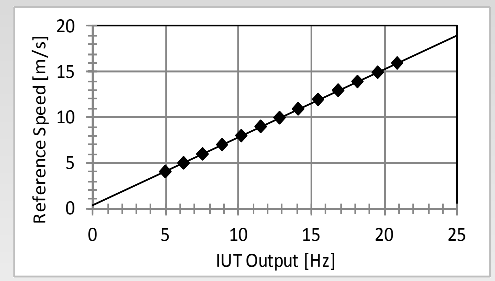


Test sensor output





Calibration linearity



Uncertainty in each area includes systematic or Type B errors (B_i) and random or Type A errors (S_i)

$$U_i = \sqrt{B_i^2 + (tS_i)^2}$$

Coverage factor at 95% confidence

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Rachael V Ishaya, President
rvishaya@bryzawindlab.com

Calibration Uncertainty

Uncertainty in reference wind speed

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

Analyzed from Pitot-static tube velocity equation

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

$$\rho = \frac{1}{R^* T}\left[PM_{air} - 2.05\times10^{-7}\phi e^{0.0631846T}(M_{air} - M_w)\right]$$

$$V = f(M_{air}, M_w, k_b, k_c, C_h, R^*, P, T_K, \Delta p, \phi)$$

Rachael V Ishaya, President
rvishaya@bryzawindlab.com

Calibration Uncertainty

Uncertainty in reference wind speed

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

INDEPENDENT VARIABLES
(exact values defined by NIST)

M_{air} and M_w

DEPENDENT VARIABLES

Measured

$P, T, \phi, \Delta p$

Analyzed

k_b, k_c, C_h, R^*

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

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

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rvishaya@bryzawindlab.com

Calibration Uncertainty

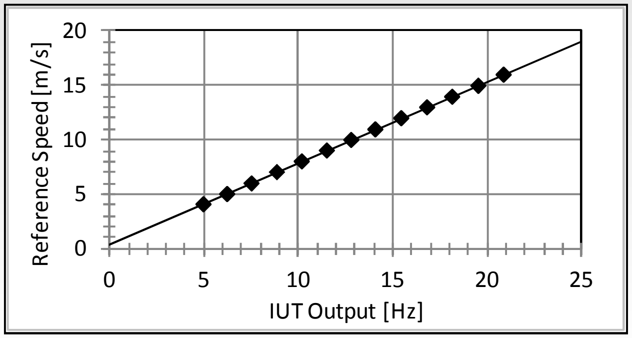
Uncertainty in test sensor output

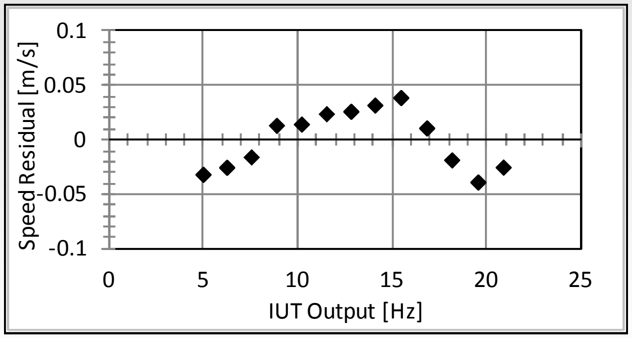
$$U_{IUT} = \sqrt{B_{IUT}^2 + (tS_{IUT})^2}$$

- Type B errors are acquired from data acquisition system.
- Type A errors are quantified by the standard deviations in the test sensor reading.

Uncertainty in calibration linearity

$$U_{LR} = \sqrt{(tV_{res})^2}$$





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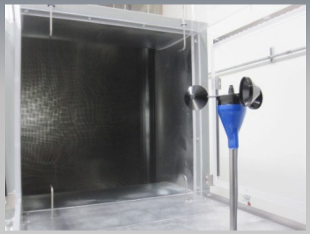
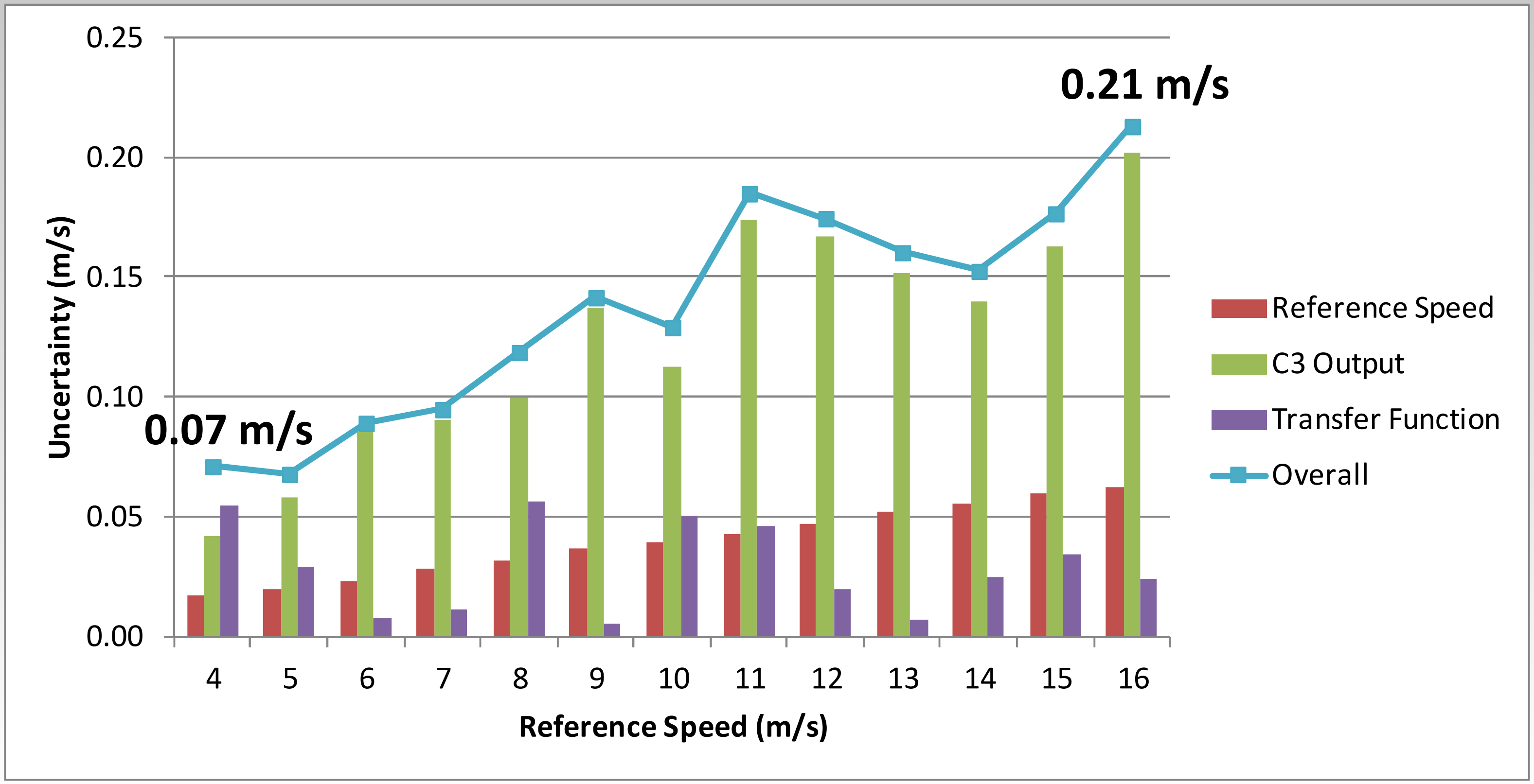
rvishaya@bryzawindlab.com

Calibration Uncertainty

Calibration Uncertainty for the C3 Anemometer





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Summary

Key Considerations for an Anemometer Calibration Program

1) **Perform tests in a controlled, uniform-flow, low-turbulence wind tunnel as required by test standards**
2) **Verify wind tunnel performance through velocity surveys**
3) **Qualify ability to perform wind sensor calibrations**
   - **Blockage evaluation**
   - **Test repeatability**
   - **Interlaboratory comparison**
4) **Document the uncertainty analysis**

For more information:
rvishaya@bryzawindlab.com

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