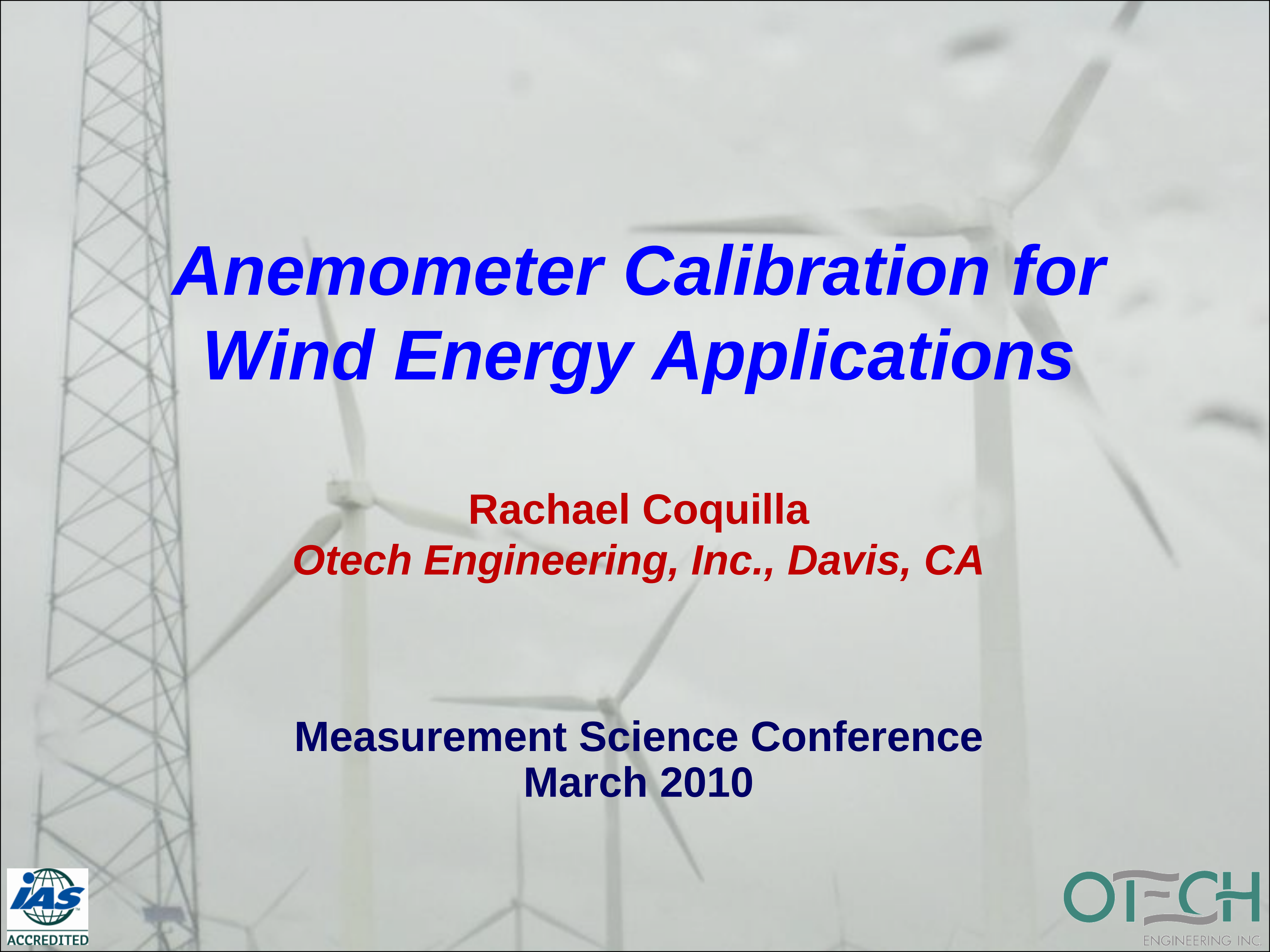
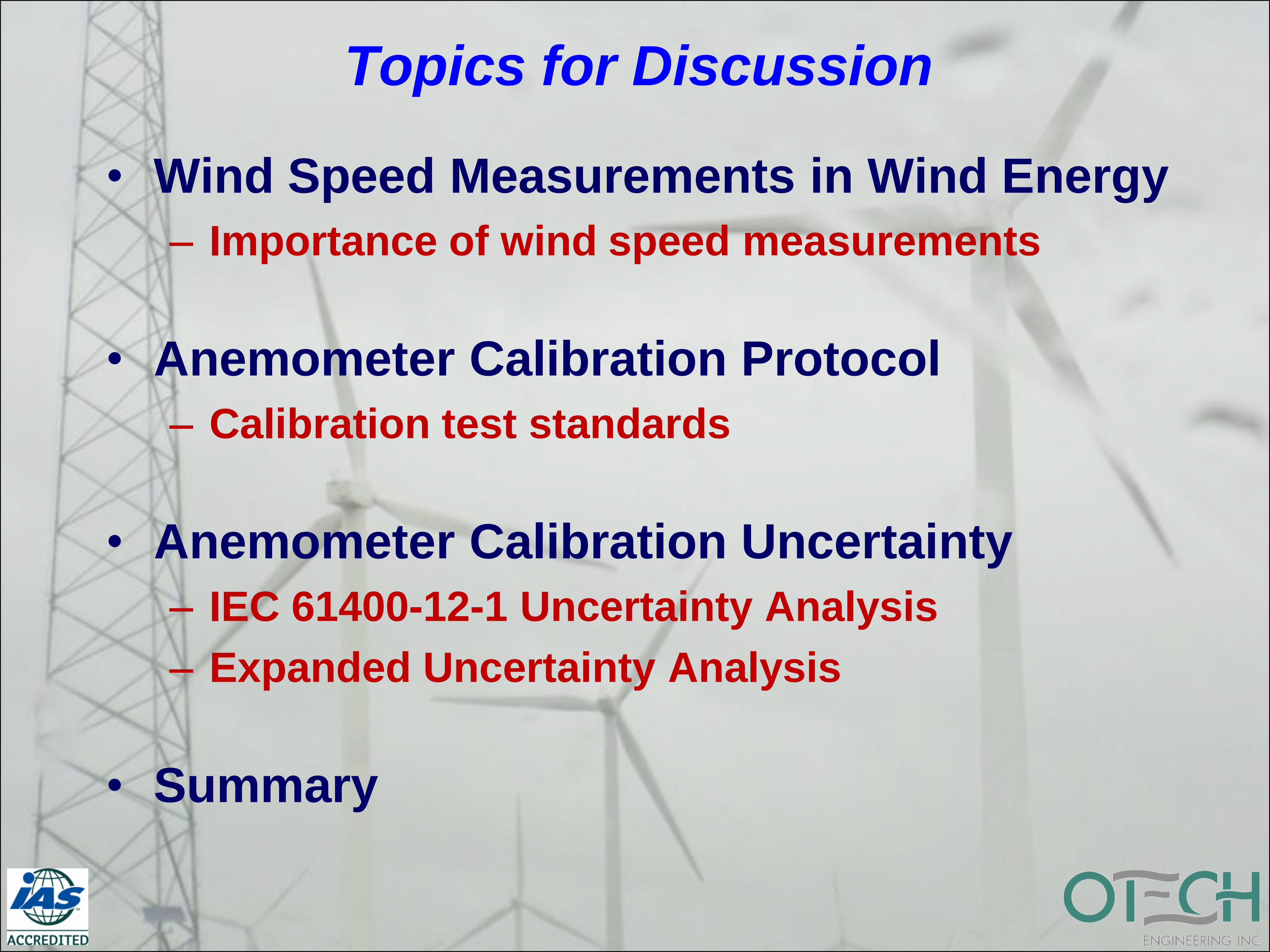


Anemometer Calibration for Wind Energy Applications

Rachael Coquilla
Otech Engineering, Inc., Davis, CA

Measurement Science Conference
March 2010



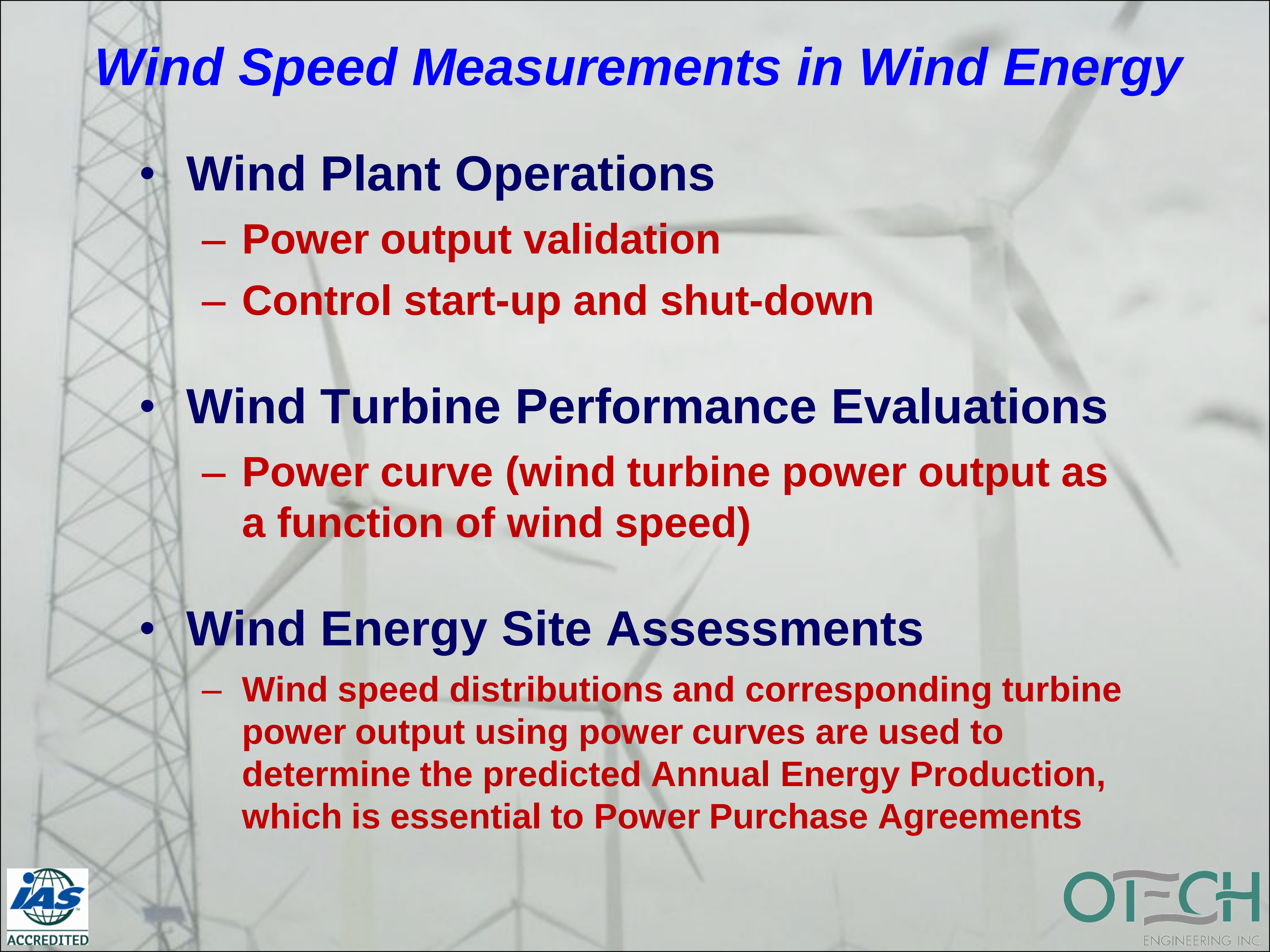
Topics for Discussion

- **Wind Speed Measurements in Wind Energy**
  - **Importance of wind speed measurements**

- **Anemometer Calibration Protocol**
  - **Calibration test standards**

- **Anemometer Calibration Uncertainty**
  - **IEC 61400-12-1 Uncertainty Analysis**
  - **Expanded Uncertainty Analysis**

- **Summary**



Wind Speed Measurements in Wind Energy

- **Wind Plant Operations**
  - **Power output validation**
  - **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**
  - **Wind speed distributions and corresponding turbine power output using power curves are used to determine the predicted Annual Energy Production, which is essential to Power Purchase Agreements**

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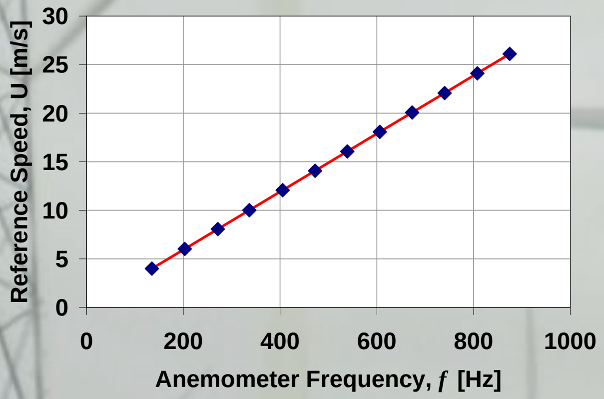
Anemometer Calibration Protocol

Anemometer Output ⇔ Controlled Reference Speed

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

Voltage Signal (Direct or Conditioned)

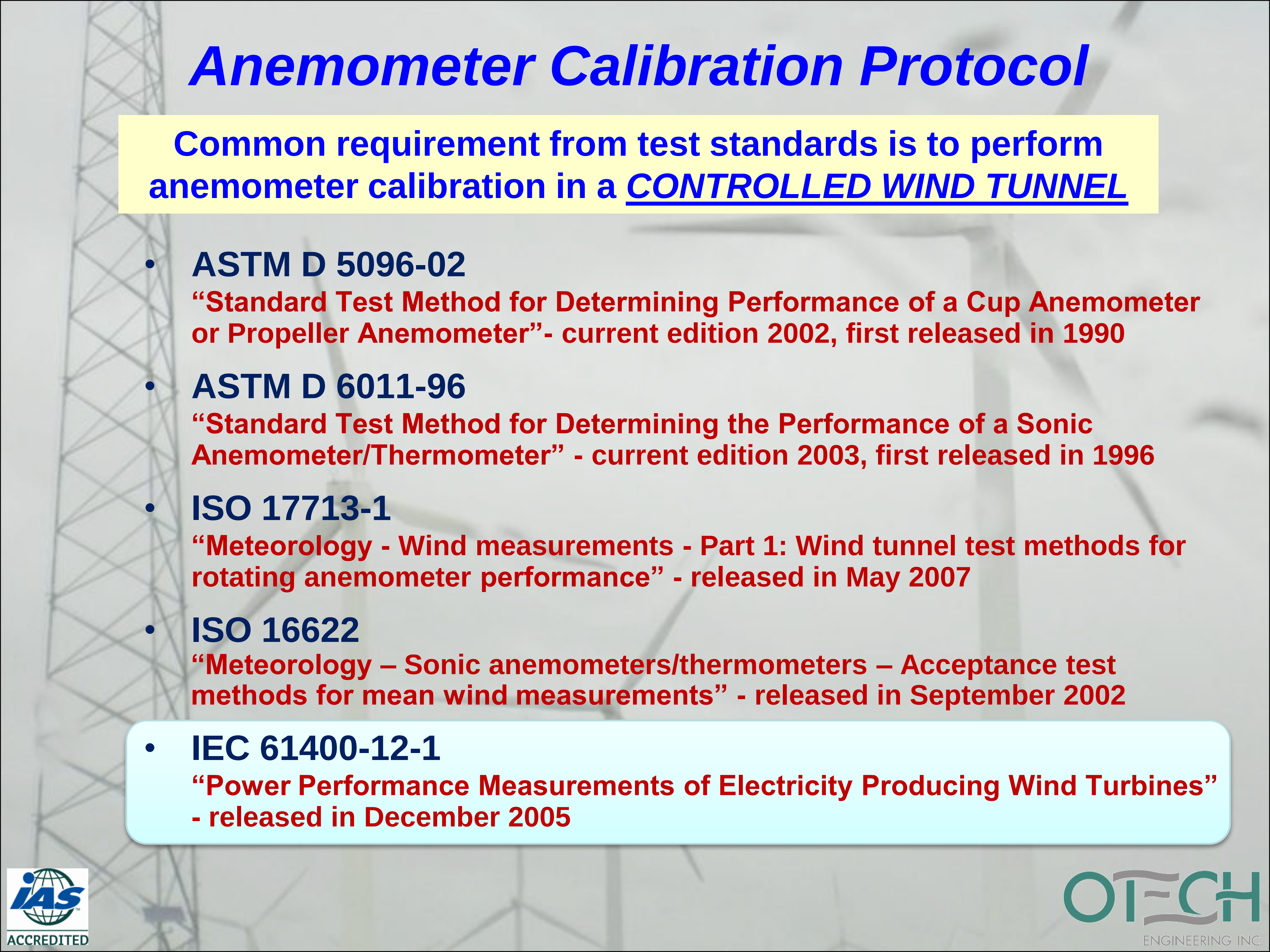
Wind Generated from a Controlled Wind Tunnel



Anemometers are primarily designed to be linear instruments.

Perform a Least Squares Fit

⇒ ***Linear Transfer Function***



Anemometer Calibration Protocol

Common requirement from test standards is to perform anemometer calibration in a *CONTROLLED WIND TUNNEL*

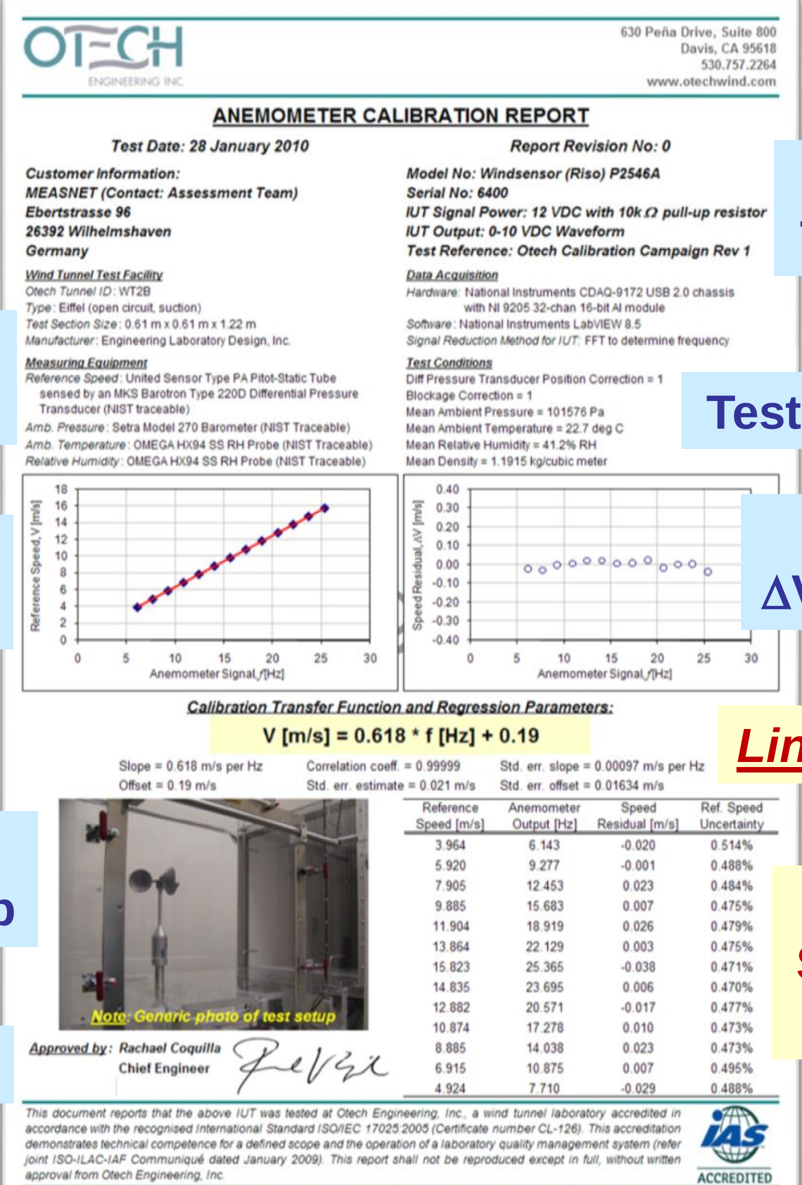
- **ASTM D 5096-02**
  "Standard Test Method for Determining Performance of a Cup Anemometer or Propeller Anemometer"- current edition 2002, first released in 1990
- **ASTM D 6011-96**
  "Standard Test Method for Determining the Performance of a Sonic Anemometer/Thermometer" - current edition 2003, first released in 1996
- **ISO 17713-1**
  "Meteorology - Wind measurements - Part 1: Wind tunnel test methods for rotating anemometer performance" - released in May 2007
- **ISO 16622**
  "Meteorology – Sonic anemometers/thermometers – Acceptance test methods for mean wind measurements" - released in September 2002
- **IEC 61400-12-1**
  "Power Performance Measurements of Electricity Producing Wind Turbines" - released in December 2005

Anemometer Calibration Protocol

Wind Tunnel Characteristic	*Description*	*Minimum Requirements from Standards*
Blockage	Ratio of the test anemometer frontal area over the test section cross-sectional area	IEC 61400-12-1: not to exceed 10% for open test sections and 5% for closed test sections ASTM & ISO: less than 5%, preferably closer to 1%
Flow Uniformity	Wind speed difference within the test section	IEC 61400-12-1: less than 0.2% ASTM & ISO: uniform velocity profile to within 1%
Horizontal Wind Gradient	Pressure difference over area covered by a rotating sensor	IEC 61400-12-1: must be less than 0.2%
Turbulence Intensity	Ratio of the wind speed standard deviation to its mean	IEC 61400-12-1: must be less than 2% ASTM & ISO: must be less than 1%
Air Density Uniformity	Air density difference within the test section	ASTM D 5096-02 & ISO 17713-1: less than 3% difference
Data Acquisition	Method of collecting reference wind speed data	IEC 61400-12-1: maintain resolution of 0.02 m/s at a sampling frequency of at least 1 Hz for 30 sec ASTM & ISO: maintain resolution of 0.02 m/s at a sampling frequency of at least 10 Hz for 30 to 100 sec
Wind Speed Capability	Controlled wind speed range	IEC 61400-12-1: generate controlled speeds from 4 to 16 m/s ASTM D 5096-02, ISO 17713-1: produce speeds at least from 0 to 50% of the test anemometer application range and maintained within +/- 0.2 m/s ASTM D 6011-96: generate speeds of at least 1 to 10 m/s and maintained within +/- 0.1 m/s or better ISO 16622: produce speeds over full application range of the test anemometer and maintained within +/- 0.2 m/s, preferably +/- 0.1 m/s

Anemometer Calibration Protocol

Sample Calibration Report



OTECH
ENGINEERING INC.

630 Peña Drive, Suite 800
Davis, CA 95618
530.757.2264
www.otechwind.com

ANEMOMETER CALIBRATION REPORT

Test Date: 28 January 2010 ***Report Revision No: 0***

Customer Information:
MEASNET (Contact: Assessment Team)
Ebertstrasse 96
26392 Wilhelmshaven
Germany

Model No: Windsensor (Riso) P2546A
Serial No: 6400
IUT Signal Power: 12 VDC with 10k Ω pull-up resistor
IUT Output: 0-10 VDC Waveform
Test Reference: Otech Calibration Campaign Rev 1

Wind Tunnel Test Facility
Otech Tunnel ID: WT2B
Type: Eiffel (open circuit, suction)
Test Section Size: 0.61 m x 0.61 m x 1.22 m
Manufacturer: Engineering Laboratory Design, Inc.

Measuring Equipment
Reference Speed: United Sensor Type PA Pitot-Static Tube sensed by an MKS Barotron Type 220D Differential Pressure Transducer (NIST traceable)
Amb. Pressure: Setra Model 270 Barometer (NIST Traceable)
Amb. Temperature: OMEGA HX94 SS RH Probe (NIST Traceable)
Relative Humidity: OMEGA HX94 SS RH Probe (NIST Traceable)

Data Acquisition
Hardware: National Instruments CDAQ-9172 USB 2.0 chassis with NI 9205 32-chan 16-bit AI module
Software: National Instruments LabVIEW 8.5
Signal Reduction Method for IUT: FFT to determine frequency

Test Conditions
Diff Pressure Transducer Position Correction = 1
Blockage Correction = 1
Mean Ambient Pressure = 101576 Pa
Mean Ambient Temperature = 22.7 deg C
Mean Relative Humidity = 41.2% RH
Mean Density = 1.1915 kg/cubic meter

Calibration Transfer Function and Regression Parameters:

V [m/s] = 0.618 * f [Hz] + 0.19

Slope = 0.618 m/s per Hz
Offset = 0.19 m/s
Correlation coeff. = 0.99999
Std. err. estimate = 0.021 m/s
Std. err. slope = 0.00097 m/s per Hz
Std. err. offset = 0.01634 m/s

Reference Speed [m/s]	Anemometer Output [Hz]	Speed Residual [m/s]	Ref. Speed Uncertainty
3.964	6.143	-0.020	0.514%
5.920	9.277	-0.001	0.488%
7.905	12.453	0.023	0.484%
9.885	15.683	0.007	0.475%
11.904	18.919	0.026	0.479%
13.864	22.129	0.003	0.475%
15.823	25.365	-0.038	0.471%
14.835	23.695	0.006	0.470%
12.882	20.571	-0.017	0.477%
10.874	17.278	0.010	0.473%
8.885	14.038	0.023	0.473%
6.915	10.875	0.007	0.495%
4.924	7.710	-0.029	0.488%

Approved by: ***Rachael Coquilla***
Chief Engineer

This document reports that the above IUT was tested at Otech Engineering, Inc., a wind tunnel laboratory accredited in accordance with the recognised International Standard ISO/IEC 17025:2005 (Certificate number CL-126). This accreditation demonstrates technical competence for a defined scope and the operation of a laboratory quality management system (refer joint ISO-ILAC-IAF Communiqué dated January 2009). This report shall not be reproduced except in full, without written approval from Otech Engineering, Inc.

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References available upon request
Page 1 of 1
WindsensorP2546A_sn6400_2010-01-28.pdf

Description of Test Anemometer

Description of Test Facility

Test Conditions

Plot of Linear Regression

Plot of Residuals
$\Delta V = V_{measured} - V_{calculated}$

Linear Transfer Function

Photo of Test Setup

Test Data with Speed Residuals and *Uncertainty*

Report Signatory

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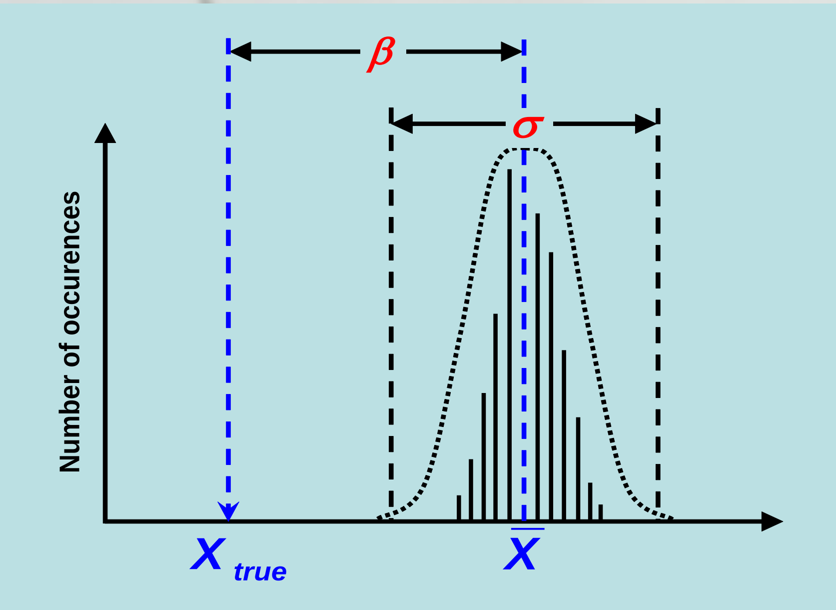
Anemometer Calibration Uncertainty

UNCERTAINTY → an estimated error range for a measured variable



Bias, β
Systematic errors
typically Type B

Precision, σ
Random errors
typically Type A

IMPORTANCE OF UNCERTAINTY

1) Defines the degree of error in a system
2) Identifies the errors in a system

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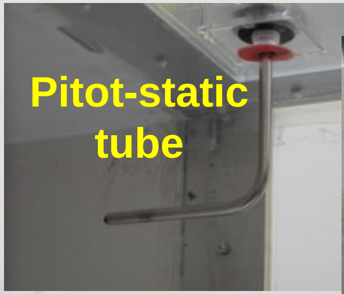
Anemometer Calibration Uncertainty

IEC 61400-12-1

Anemometer Calibration Uncertainty is based on the errors in the calculated reference wind speed from the Pitot-static tube system of a controlled wind tunnel facility.

Controlled Wind Tunnel

Pitot-static Tube System



IEC 61400-12-1 Uncertainty Analysis

Reference Wind Tunnel Speed Equation using a Pitot-static tube system

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

Calculated Variables:

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

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

$$R_{air} = \frac{R}{M_{air}} \qquad R_w = \frac{R}{M_w}$$

Measured Variables:

P, T, ϕ, Δp, k_b, k_c

Defined Variables:

M_{air} and M_w

IEC 61400-12-1 Uncertainty Analysis

Uncertainty in Wind Tunnel Reference Speed

Uncertainty, $U_V \Rightarrow f\,(k_b, k_c, C_h, R, P, T_K, \Delta p, \phi)$

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

Precision or Random Errors (Type A)

Standard deviations in instrument readings

$\Delta p, P, T_K, \phi$

Bias or Systematic Errors (Type B)

- **Instrument manufacturer’s spec**
- **Instrument calibration errors**
- **Data acquisition errors**
- **Correction factor errors**

t-value at 95% confidence

$t = 1.96$ [Coleman & Steele (2009)]

IEC 61400-12-1 Uncertainty Analysis

Reference Speed Error Propagation

Propagation of Bias Errors:

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

Propagation of Precision Errors:

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

IEC 61400-12-1 Uncertainty Analysis

Original Velocity Equation

$$\left.\begin{aligned}
&\rho = \frac{1}{T}\left[\frac{P}{R_{air}} - 0.01\phi P_w\left(\frac{1}{R_{air}} - \frac{1}{R_w}\right)\right] \\
&P_w = 0.0000205\exp(0.0631846T) \\
&R_{air} = \frac{R}{M_{air}} \qquad R_w = \frac{R}{M_w}
\end{aligned}\right\} \quad V = k_b\sqrt{\frac{2k_c}{C_h}\frac{\Delta p}{\rho}}$$

Complete Velocity Equation

$$V = k_b\sqrt{\frac{2k_c\Delta pRT}{C_h\left[PM_{air} - 2.05\times10^{-7}\phi\exp(0.0631846T)(M_{air} - M_w)\right]}}$$

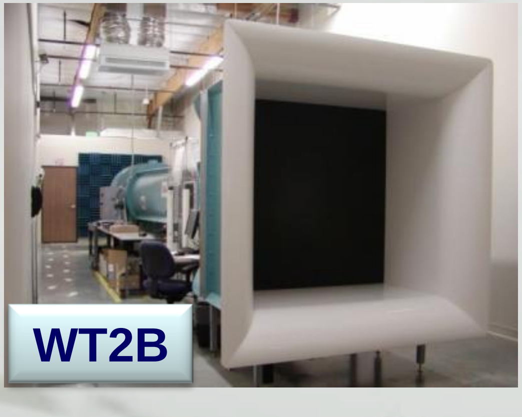
Derive to get the following sensitivity coefficients:

$$\frac{\delta V}{\delta k_b} \quad \frac{\delta V}{\delta k_c} \quad \frac{\delta V}{\delta C_h} \quad \frac{\delta V}{\delta R} \quad \frac{\delta V}{\delta P} \quad \frac{\delta V}{\delta T} \quad \frac{\delta V}{\delta \Delta p} \quad \frac{\delta V}{\delta \phi}$$

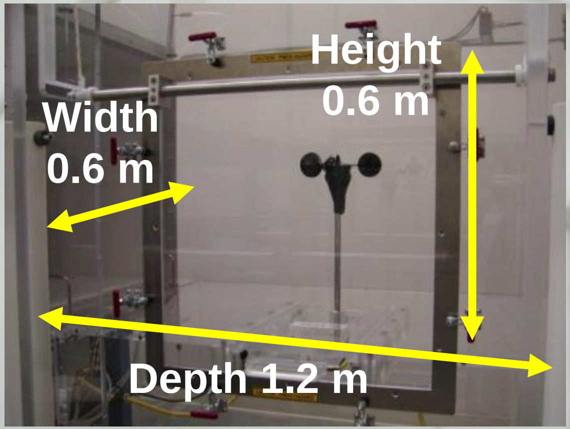
IEC 61400-12-1 Uncertainty Analysis

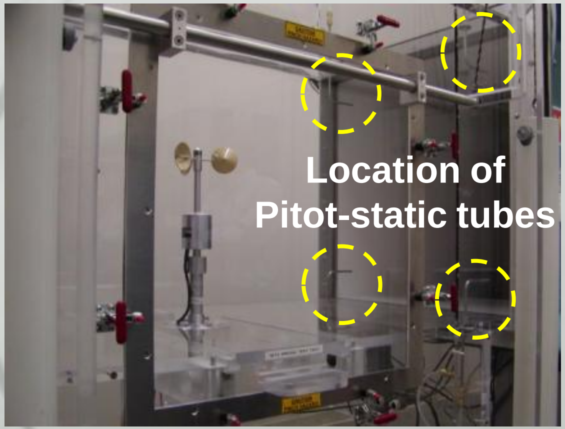
IEC 61400-12-1 Uncertainty Analysis for Otech Engineering Wind Tunnel Facilties


WT1C


WT2B

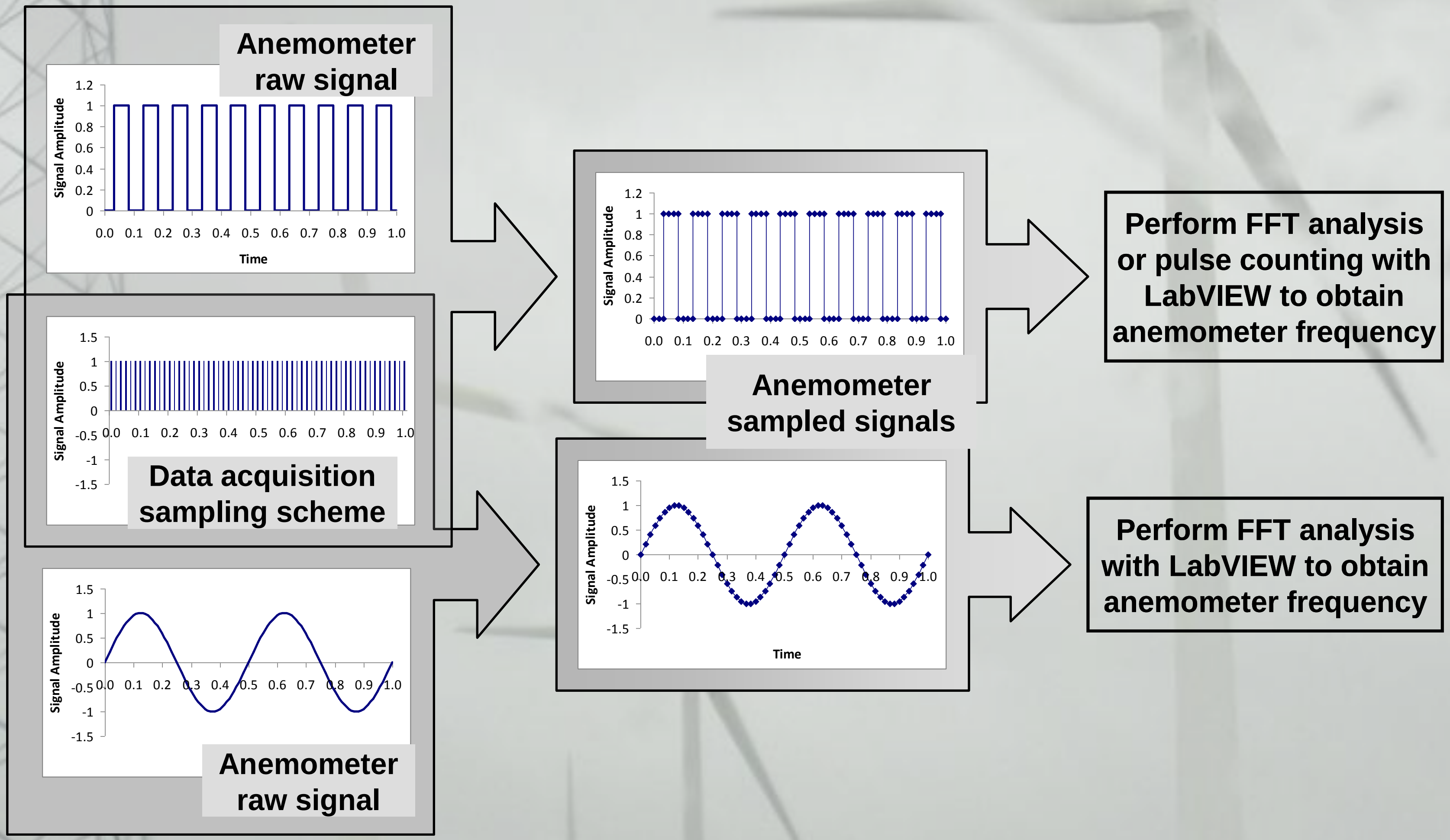

WT3A





IEC 61400-12-1 Uncertainty Analysis

Rotating Anemometer Output Measurement in Otech Engineering Wind Tunnel Facilties



Anemometer raw signal

Data acquisition sampling scheme

Anemometer raw signal

Anemometer sampled signals

Perform FFT analysis or pulse counting with LabVIEW to obtain anemometer frequency

Perform FFT analysis with LabVIEW to obtain anemometer frequency

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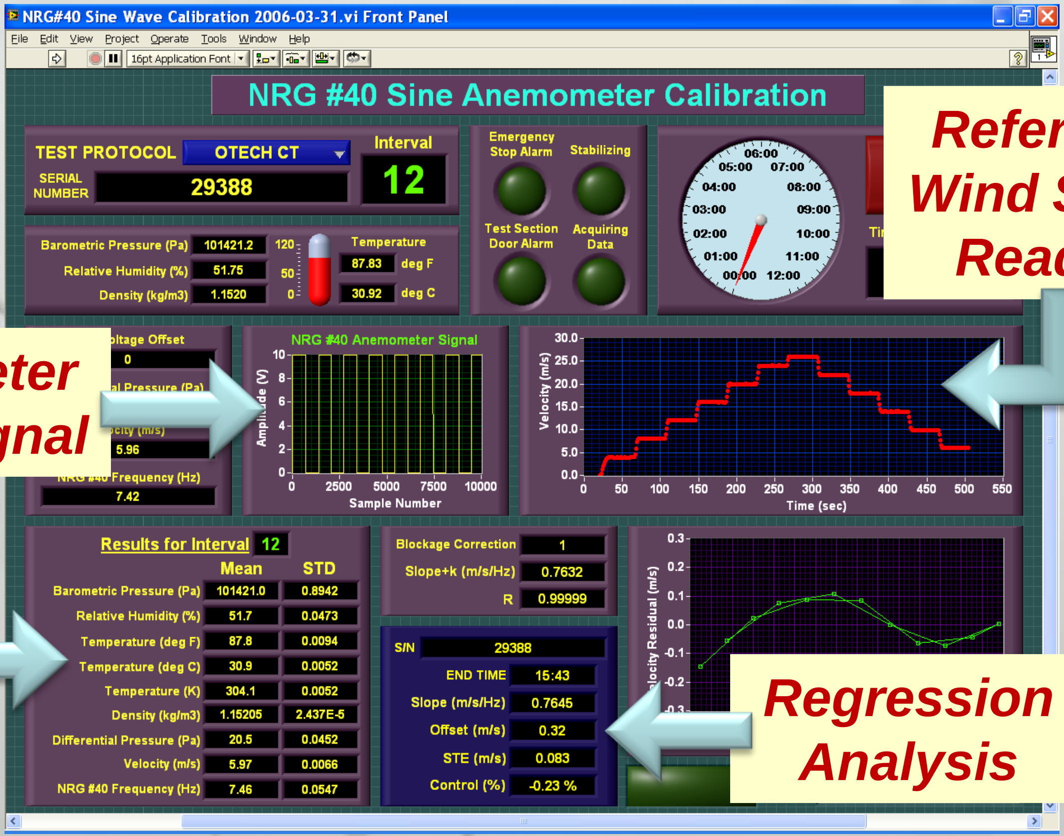
IEC 61400-12-1 Uncertainty Analysis

LabVIEW Data Acquisition System in Otech Engineering Wind Tunnel Facilties



TEST PROTOCOL OTECH CT

SERIAL NUMBER 29388

Interval 12

Barometric Pressure (Pa)	101421.2
Relative Humidity (%)	51.75
Density (kg/m3)	1.1520

Temperature

87.83 deg F

30.92 deg C

...oltage Offset 0

...al Pressure (Pa)

...city (m/s) 5.96

NRG #40 Frequency (Hz) 7.42

Results for Interval 12

	Mean	STD
Barometric Pressure (Pa)	101421.0	0.8942
Relative Humidity (%)	51.7	0.0473
Temperature (deg F)	87.8	0.0094
Temperature (deg C)	30.9	0.0052
Temperature (K)	304.1	0.0052
Density (kg/m3)	1.15205	2.437E-5
Differential Pressure (Pa)	20.5	0.0452
Velocity (m/s)	5.97	0.0066
NRG #40 Frequency (Hz)	7.46	0.0547

Blockage Correction 1

Slope+k (m/s/Hz) 0.7632

R 0.99999

S/N 29388

END TIME 15:43

Slope (m/s/Hz) 0.7645

Offset (m/s) 0.32

STE (m/s) 0.083

Control (%) -0.23 %

Reference Wind Speed Reading

Anemometer Output Signal

Test Conditions

Regression Analysis

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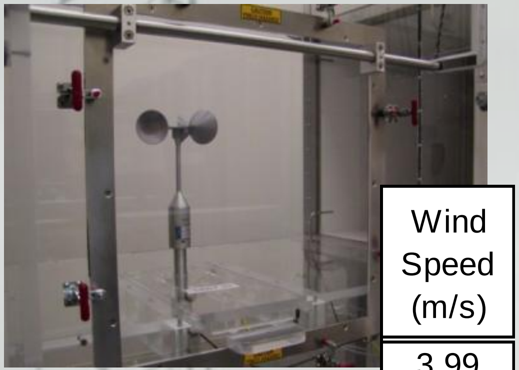
IEC 61400-12-1 Uncertainty Analysis

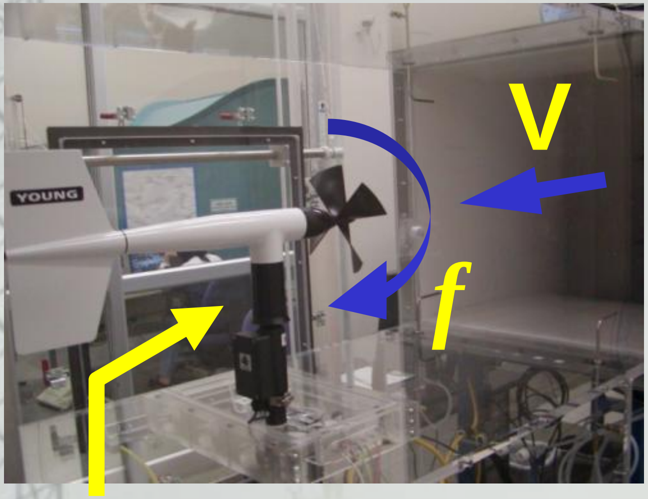
Reference Wind Speed Uncertainty in Otech Engineering Wind Tunnel Facilities



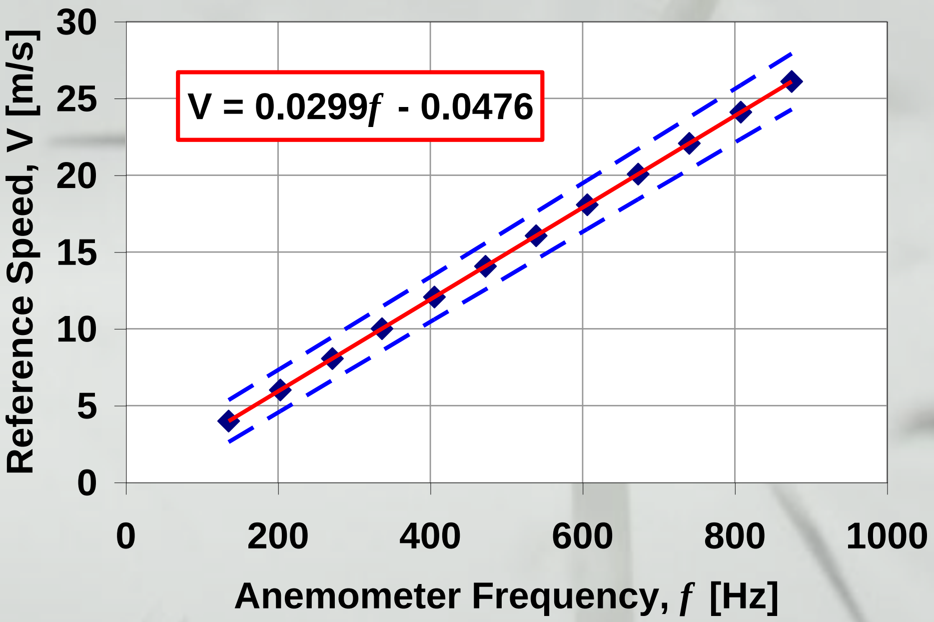
Wind Speed (m/s)	Anemometer Output (Hz)	Wind Speed STD (m/s)	Wind Speed Bias Error (m/s)	Wind Speed Random Error (m/s)	Wind Speed Uncertainty (m/s)	Relative Wind Speed Uncertainty
3.99	6.25	0.003	0.019	0.003	0.020	0.51%
5.97	9.40	0.005	0.028	0.005	0.030	0.50%
7.96	12.59	0.004	0.037	0.004	0.038	0.48%
9.94	15.76	0.007	0.047	0.007	0.049	0.49%
11.92	18.96	0.007	0.056	0.007	0.057	0.48%
13.92	22.23	0.010	0.065	0.010	0.068	0.49%
15.91	25.56	0.011	0.075	0.011	0.078	0.49%
17.90	28.73	0.012	0.084	0.012	0.087	0.49%
19.90	32.02	0.011	0.093	0.011	0.096	0.48%
21.87	35.13	0.012	0.102	0.012	0.105	0.48%
23.87	38.42	0.014	0.112	0.014	0.115	0.48%
25.84	41.53	0.013	0.121	0.013	0.124	0.48%

$$U_V \cong 0.5\%$$

Expanded Uncertainty Analysis



Anemometer Under Test



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

Reference Wind Speed Uncertainty

Anemometer Output Uncertainty

Linear Regression Uncertainty

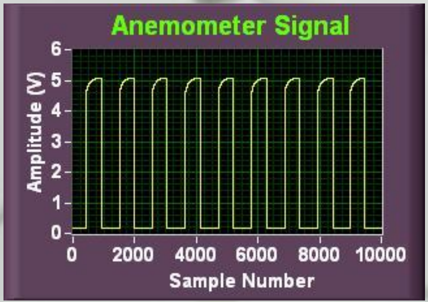
Expanded Uncertainty Analysis

Anemometer Output Uncertainty

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

Bias or Systematic Errors (Type B)

Data acquisition errors (FFT or pulse count method)



Precision or Random Errors (Type A)

Standard deviations in anemometer frequency or voltage output (FFT method)

t-value at 95% confidence

t = 1.96 **[Coleman & Steele (2009)]**

Anemometer Output Uncertainty

$$U_{IUT} \cong 0.5\% - 1.5\%$$

Expanded Uncertainty Analysis

Linear Regression Uncertainty

Case 1

$$U_{LR_{Case1}} = \sqrt{\left(t\,\frac{STE_V}{V_i}\right)^2}$$

Standard Error of Estimate

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

Case 2

$$U_{LR_{Case2}} = \sqrt{\underbrace{\left(t\,\frac{STE_m}{V_i}f_i\right)^2}_{\text{Uncertainty in the Slope}} + \underbrace{\left(t\,\frac{STE_b}{V_i}\right)^2}_{\text{Uncertainty in the Offset}}}$$

Standard Error of Slope

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

Standard Error of Offset

$$STE_m = \sqrt{\frac{STE_V^2}{SS_f}}$$

Sum of the Squares in Anemometer Output

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

Linear Regression Uncertainty (Case 1 or Case 2)

$$\boxed{U_{LR} \cong 0.2\% - 5.0\%}$$

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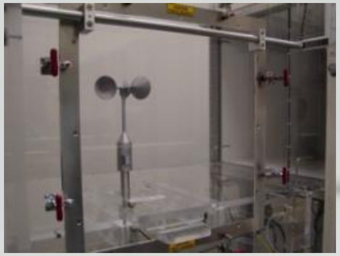
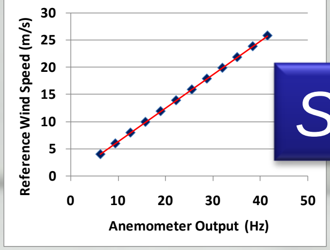
Expanded Uncertainty Analysis

Sample Expanded Uncertainty Analysis





$STE_V = 0.031$ m/s

Wind Speed (m/s)	Wind Speed Uncertainty	Anem. Output (Hz)	Anem. STD (Hz)	Anemometer DAQ Bias Error (Hz)	Anemometer Random Error (Hz)	Anemometer Output Uncertainty	Case 1 Regression Uncertainty	Case 2 Regression Uncertainty	Anemometer Calibration Uncertainty
3.99	0.51%	6.25	0.061	0.00063	0.061	1.94%	1.52%	1.07%	2.52%
5.97	0.50%	9.40	0.082	0.00094	0.082	1.74%	1.02%	0.74%	2.08%
7.96	0.48%	12.59	0.119	0.00126	0.119	1.90%	0.76%	0.58%	2.10%
9.94	0.49%	15.76	0.111	0.00158	0.111	1.41%	0.61%	0.49%	1.62%
11.92	0.48%	18.96	0.116	0.00190	0.116	1.22%	0.51%	0.43%	1.41%
13.92	0.49%	22.23	0.130	0.00222	0.130	1.17%	0.44%	0.39%	1.34%
15.91	0.49%	25.56	0.145	0.00256	0.145	1.13%	0.38%	0.36%	1.29%
17.90	0.49%	28.73	0.169	0.00287	0.169	1.18%	0.34%	0.34%	1.32%
19.90	0.48%	32.02	0.172	0.00320	0.172	1.08%	0.30%	0.33%	1.22%
21.87	0.48%	35.13	0.172	0.00351	0.172	0.98%	0.28%	0.32%	1.13%
23.87	0.48%	38.42	0.174	0.00384	0.174	0.91%	0.25%	0.31%	1.06%
25.84	0.48%	41.53	0.208	0.00415	0.208	1.00%	0.23%	0.30%	1.13%

$U_V \cong 0.5\%$

$U_{IUT} \cong 1.3\%$

$U_{LR} \cong 0.5\%$

$U_{IUT} \cong 1.5\%$

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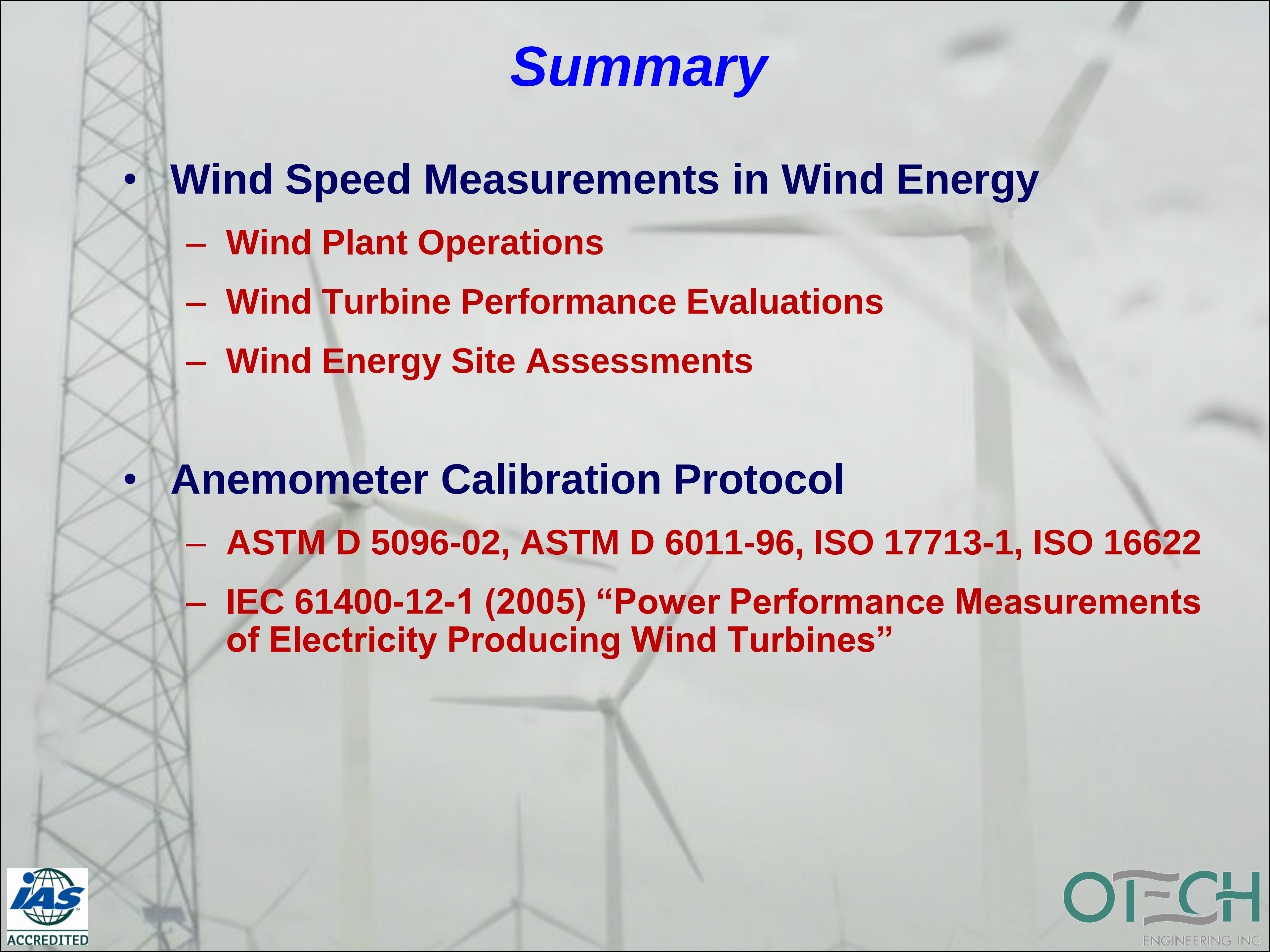

Summary

- **Wind Speed Measurements in Wind Energy**
  - **Wind Plant Operations**
  - **Wind Turbine Performance Evaluations**
  - **Wind Energy Site Assessments**

- **Anemometer Calibration Protocol**
  - **ASTM D 5096-02, ASTM D 6011-96, ISO 17713-1, ISO 16622**
  - **IEC 61400-12-1 (2005) "Power Performance Measurements of Electricity Producing Wind Turbines"**

Summary

- **Anemometer Calibration Uncertainty**
  - **IEC 61400-12-1 Uncertainty Analysis**

$$U_V = \sqrt{B_V^2 + (tS_V)^2} \longrightarrow U_V \cong 0.5\%$$

  - **Expanded Uncertainty Analysis**

$$U_{IUT} = \sqrt{B_{IUT}^2 + (tS_{IUT})^2} \longrightarrow U_{IUT} \cong 0.5\% - 1.5\%$$

$$\left.\begin{aligned} U_{LR_{Case1}} &= \sqrt{\left(t\frac{STE_V}{V_i}\right)^2} \\ U_{LR_{Case2}} &= \sqrt{\left(t\frac{STE_m}{V_i}f_i\right)^2 + \left(t\frac{STE_b}{V_i}\right)^2} \end{aligned}\right\} U_{LR} \cong 0.2\% - 5.0\%$$

$$U_{cal} = \sqrt{(U_V)^2 + (U_{IUT})^2 + (U_{LR})^2} \longrightarrow \boxed{U_{cal} \cong 0.7\% - 5.2\%}$$