Infrastructure Commission (INFCOM)

Standing Committee on Measurements, Instrumentation and Traceability (SC-MINT)

Expert Team on Quality, Traceability and Calibration (ET-QTC)

Calibration of Wind Instruments

Part-5: Calibration Examples

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Calibration of anemometers

General procedure cup anemometer and ultrasonic anemometer

- calibration must be carried out over a range of values
- calibration must be carried out for both rising and falling wind speeds if hysteresis is to be expected
- the complete anemometer shall be placed in the wind tunnel with the measuring section
- environmental condition of the laboratory should be adjusted according to environmental criteria
- the device under test should last at least 24 hours for acclimatization

Calibration of anemometers

General procedure cup anemometer and ultrasonic anemometer

- device under test is installed at the test point that is decided before
- set up the Wind tunnel 10% Umax and wait approximately 5 min
- set up the Wind tunnel Umax (or max speed value according to capability of the wind tunnel) and wait approximately 5 min
- set up the Wind tunnel to different values (calibration points) and record the values from the reference and device under test
- evaluate the measuring uncertainty of the calibration according to their uncertainty parameters at the each calibration points separately

Calibration of anemometers

Standard	Calibration Test Speeds
ISO 17713-1:2007 Meteorology – Wind measurements – Part 1: Wind Tunnel test methods for rotating anemometer performance (BS ISO 17713-1:2007)	Test speeds cover the range of intended use for the anemometer and the working range of the wind tunnel, which includes five points in the non-linear range of the anemometer (near threshold, U_0). Typical test speeds are: 2 times U_0 — 0.1 times U_{max} — 0.6 times U_{max} 3 times U_0 — 0.2 times U_{max} — 0.7 times U_{max} 4 times U_0 — 0.3 times U_{max} — 0.8 times U_{max} 5 times U_0 — 0.4 times U_{max} — 0.9 times U_{max} 6 times U_0 — 0.5 times U_{max} — U_{max}

- the threshold value U_0 is the speed at which the cup anemometer begins to rotate very slowly
- U_{max} is the maximum speed for which the cup anemometer is designed

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Calibration of anemometers

calibration points on cup anemometer:

Sensor specifications;
Measuring range: 0.4 – 75 m/s Threshold value : 0.5 m/s

Calibration points according to ISO 17713 standard :

2 times U_0	→	1.0 m/s
3 times U_0	→	1.5 m/s
4 times U_0	→	2.0 m/s
5 times U_0	→	2.5 m/s
6 times U_0	→	3.0 m/s
0.1 times U_{max}	→	7.5 m/s
0.2 times U_{max}	→	15.0 m/s
0.3 times U_{max}	→	22.5 m/s
0.4 times U_{max}	→	30.0 m/s
0.5 times U_{max}	→	37.5 m/s
0.6 times U_{max}	→	45.0 m/s
0.7 times U_{max}	→	52.5 m/s
0.8 times U_{max}	→	60.0 m/s
0.9 times U_{max}	→	67.5 m/s
U_{max}	→	75.0 m/s

Calibration points should be selected according to the infrastructure capability of the laboratory, calibration scope of the laboratory and customer demands.

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Calibration of anemometers

uncertainties type A:

- data from the reference for example LDA
- data from other sources like air density (temperature, pressure, humidity)
- data from the calibration object

reference	calibration object
"Row#";"Arrival Time [ms]";"Transit Time [us]";"Velocity U [m/s]";"Arrival Time{G2} [ms]";"Transit Time{G2} [us]";"Velocity V{G2} [m/s]"; 1;19,803;20,9;0,52;24,681;218,5;0,15 2;19,838;16,9;0,56;197,870;218,5;-0,17 3;24,943;436,8;0,49;234,562;10,6;-0,17 4;89,658;6,8;0,48;234,677;218,5;0,46 5;107,822;400,6;0,51;234,862;16,0;-0,01 6;114,413;105,2;0,46;234,874;6,8;0,14 7;114,513;89,2;0,47;234,881;6,9;0,27 8;126,311;436,8;0,46;234,887;3,0;-0,16	05.10.2018;10:43:20.326;6.0Hz 05.10.2018;10:43:20.577;7.0Hz 05.10.2018;10:43:20.827;7.0Hz 05.10.2018;10:43:21.770;6.0Hz 05.10.2018;10:43:21.327;7.0Hz 05.10.2018;10:43:21.577;7.0Hz 05.10.2018;10:43:21.827;6.0Hz 05.10.2018;10:43:22.770;7.0Hz 05.10.2018;10:43:22.311;7.0Hz 05.10.2018;10:43:22.577;6.0Hz 05.10.2018;10:43:22.827;7.0Hz 05.10.2018;10:43:23.770;7.0Hz

Calibration of anemometers

uncertainties type A:

Erfassung- und Auswertesoftware für mechanische Windsensorik: ï»¿Thies Classic Schalensternanemometer

Kalibrierschein

DWD-Nr.: 00182472

Kalibrierdatum: 05.10.2018

Startzeit	Endzeit	nnn	LDA m/s	Stabw m/s	SU m/s	LDA_K m/s	nnn	KG Hz	Stabw Hz	SU Hz	FC m/s	Stabw m/s	SU m/s	Abw m/s	k=1 m/s	
10:43:49.020	10:44:18.987	9396	0,505	0,059	0,001	0,510	120	7,000	0,290	0,026	0,622	0,015	0,001	0,112	0,050	OK
10:47:22.002	10:47:51.998	13855	1,020	0,063	0,001	1,031	120	16,558	0,499	0,046	1,108	0,025	0,002	0,077	0,050	OK
10:52:16.003	10:52:45.997	11284	2,445	0,008	0,000	2,474	120	43,400	0,586	0,053	2,464	0,029	0,003	-0,011	0,050	OK
10:55:11.001	10:55:41.000	14435	4,927	0,014	0,000	4,987	120	91,850	0,682	0,062	4,882	0,034	0,003	-0,105	0,050	OK
10:57:06.001	10:57:35.996	11873	7,285	0,017	0,000	7,376	120	139,942	0,946	0,086	7,250	0,046	0,004	-0,125	0,050	OK
10:59:08.002	10:59:38.000	20413	9,744	0,026	0,000	9,866	120	193,208	0,969	0,088	9,840	0,047	0,004	-0,026	0,059	OK
11:02:05.001	11:02:34.995	12793	12,160	0,025	0,000	12,313	120	245,575	1,105	0,101	12,358	0,053	0,005	0,046	0,074	OK
11:04:07.003	11:04:36.976	12719	14,619	0,032	0,000	14,804	120	299,258	1,338	0,122	14,916	0,063	0,006	0,112	0,089	OK
11:06:28.001	11:06:58.000	11747	19,430	0,045	0,000	19,676	120	405,392	1,440	0,131	19,918	0,067	0,006	0,242	0,118	OK
11:08:32.006	11:09:01.996	11046	29,304	0,067	0,001	29,681	120	620,625	2,162	0,197	29,961	0,101	0,009	0,279	0,178	OK
11:10:18.004	11:10:47.997	16750	39,070	0,108	0,001	39,579	120	830,742	2,779	0,254	39,786	0,131	0,012	0,207	0,237	OK
11:15:40.005	11:16:09.998	18886	48,604	0,127	0,001	49,243	120	1041,050	2,756	0,252	49,744	0,131	0,012	0,501	0,295	OK

Die Abweichung zum Normal liegt unter Einbeziehung der erweiterten Messunsicherheit bei allen Messungen im zulässigen Toleranzbereich.

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Calibration of anemometers

uncertainties type B:

- uncertainty of reference sensor
- annual drift of reference sensor
- environmental effects (temperature, humidity, pressure)
- resolution of reference sensor
- resolution of test sensor
- repeatability of reference sensor
- repeatability of test sensor
- homogeneity of wind tunnel

Calibration of anemometers

uncertainties type B:

- hysteresis
- blockage effect
- turbulence effect
- swirl effect
- power requirements
- not well trained staff
- ..

Calibration of anemometers

uncertainties type B:

- stability of wind tunnel
- source of any other winds especially heating, blower, air conditioner etc…
- opened doors or windows
- carriage, transportation
- vibrations etc

- ….

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Calibration of anemometers – example #1

cup anemometer calibration at ~1 ms^{-1} :

- model:

$$(U)^2 = (U_{ref\_cal})^2 + (U_{drift})^2 + (U_{test\ resolution})^2 + (U_{repeatability})^2 + (U_{stability})^2 + (U_{correction})^2$$

- reference sensor calibration uncertainty → type B normal
- drift of reference sensor → type B rectangular
- test resolution → type B rectangular
- repeatability → type B
- stability → type B
- correction → type B

Calibration of anemometers – example #1

cup anemometer calibration at ~1 ms^{-1} :

- the recordings:

Reference Speed (m/s)	Reference Correction value (m/s)	Corrected Reference Speed (m/s)	Test Speed (m/s)	Test Area Correction Value (m/s)	Corrected Test Speed (m/s)
1,102	0,0224	1,080	1,089	-0,0117	1,077
1,102	0,0224	1,080	1,089	-0,0117	1,077
1,102	0,0224	1,080	1,089	-0,0117	1,077
1,101	0,0224	1,079	1,089	-0,0117	1,077
1,101	0,0224	1,079	1,096	-0,0117	1,084
1,102	0,0224	1,080	1,096	-0,0117	1,084
1,102	0,0224	1,080	1,089	-0,0117	1,077
1,101	0,0224	1,079	1,082	-0,0117	1,070
1,103	0,0224	1,081	1,089	-0,0117	1,077
1,103	0,0224	1,081	1,089	-0,0117	1,077
Arithmetic Mean Speed		**1,079**			**1,078**

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Calibration of anemometers – example #1

cup anemometer calibration at ~1 ms^{-1} :

- the result:

1,0 m/s CALIBRATIO POINT UNCERTAINTY PARAMETERS	ESTIMATED VALUE	DISTRIBUTION	DENOMINATOR	STANDARD UNCERTAINTY	NUMERATOR	PARTIAL VARIANCE
Reference Uncertainty (m/s)	0,01413	normal	2	0,00707	1	4,99488E-05
Drift (m/s)	0,00676	rectangular	1,73	0,00390	1	1,52403E-05
Test resolution (m/s)	0,00100	rectangular	1,73	0,00029	0,5	8,33333E-08
Error Repeatability (m/s)	0,00127	normal	1	0,00127	1	1,61687E-06
System Stability (m/s)	0,00023	normal	1	0,00023	1	5,22512E-08
Test area correction (m/s)	0,00188	normal	1	0,00188	1	3,53440E-06
			Total variance			7,04761E-05
			Standard Uncertainty (m/s)			0,00840
			Expanded Uncertainty (k=2) (m/s)			0,01679
			Relative Uncertainty (%)			**1,56**

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Calibration of anemometers – example #2

cup anemometer calibration at ~50 ms^{-1}:

- model part 1

$$\Delta windspeed = windspeed\_DUT - windspeed\_reference$$

$$\begin{aligned} windspeed\_reference = {} & measurements\_LDA + \\ & \delta calibration\_LDA + \delta calibration\_BSA + \\ & \delta drift\_BSA + \delta resolution\_LDA + \\ & \delta flow\_correction + \delta drift\_LDA + \\ & \delta alignment\_LDA + \delta temperature\_LDA \end{aligned}$$

$$\begin{aligned} windspeed\_DUT = {} & measurements\_DUT + \\ & \delta calibration\_frequency\_counter + \\ & \delta resolution\_frequency\_counter \end{aligned}$$

Calibration of anemometers – example #2

cup anemometer calibration at ~50 ms^{-1}:

- model part 2

Δwindspeed	result (windspeed_DUT - windspeed_reference)
windspeed_DUT	DUT indication of wind speed
windspeed_reference	reference indication of wind speed

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Calibration of anemometers – example #2

cup anemometer calibration at ~50 ms^{-1}:

- uncertainties:

measurements_LDA	measurements of LDA
δcalibration_LDA	calibration of LDA
δcalibration_BSA	calibration of burst spectrum analyzer
δdrift_BSA	drift of BSA
δresolution_LDA	resolution LDA
δflow_correction	flow correction due to the type of DUT
δdrift_LDA	drift of LDA
δalignment_LDA	alignment of LDA
δtemperature_LDA	temperature dependency of LDA

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Calibration of anemometers – example #2

cup anemometer calibration at ~50 ms^{-1}:

- uncertainties

measurements_DUT	measurements of DUT converted from frequency to speed and corrected
δcalibration_frequency_counter	calibration of frequency counter
δresolution_frequency_counter	resolution of frequency counter

Calibration of anemometers – example #2

cup anemometer calibration at ~50 ms^{-1} :

- result:

Quantity	Value	Stand. uncert.	Distribution	DoF	Sensit. coeff.	Uncert. contribution	Rel. contribution	Bar chart
windspeed_DUT	49,57892 m/s	0,02352 m/s						
windspeed_reference	49,7197 m/s	0,2398 m/s						
measurements_LDA	49,719728 m/s	0,001597 m/s	Normal	∞	-1,000	-0,001597 m/s	0,00 %	
δcalibration_LDA	0,0 m/s	0,05469 m/s	Normal	∞	-1,000	-0,05469 m/s	5,15 %	
δcalibrationg_BSA	0,0 m/s	0,01000 m/s	Normal	∞	-1,000	-0,01000 m/s	0,17 %	
δdrift_BSA	0,0 m/s	0,0005774 m/s	Rectangular	∞	-1,000	-0,0005774 m/s	0,00 %	
δresolution_LDA	0,0 m/s	0,002887 m/s	Rectangular	∞	-1,000	-0,002887 m/s	0,01 %	
δflow_correction	0,0 m/s	0,2009 m/s	Rectangular	∞	-1,000	-0,2009 m/s	69,57 %	
δdrift_LDA	0,0 m/s	0,05741 m/s	Rectangular	∞	-1,000	-0,05741 m/s	5,68 %	
δalignment_LDA	0,0 m/s	0,08612 m/s	Rectangular	∞	-1,000	-0,08612 m/s	12,78 %	
δtemperature_LDA	0,0 m/s	0,05741 m/s	Rectangular	∞	-1,000	-0,05741 m/s	5,68 %	
measurements_DUT	49,57892 m/s	0,01285 m/s	Normal	∞	1,000	0,01284 m/s	0,28 %	
δcalibration_frequency_counter	0,0 m/s	0,01400 m/s	Normal	∞	1,000	0,01400 m/s	0,34 %	
δresolution_frequency_counter	0,0 m/s	0,01386 m/s	Rectangular	∞	1,000	0,01386 m/s	0,33 %	
	Value	Comb. stand. uncertainty			Effective degrees of freedom			Sign. digits
Δwindspeed	-0,1408 m/s	0,2409 m/s			∞			4
	Value	Expanded uncertainty			Coverage factor (Probability)		Distribution	Sign. digits
Result	-0,141 m/s	± 0,482 m/s			2,00 (95,45 %)		Normal	3

Δwindspeed = -0,141 ms^{-1} ± 0,482 ms^{-1} (k = 2)

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Calibration of anemometers – example #3

ultrasonic anemometer calibration at ~50 ms^{-1}:

- model part 1

$$\Delta windspeed = windspeed\_DUT - windspeed\_LDA$$

$$windspeed\_LDA = measurements\_LDA + \delta calibration\_LDA + \delta drift\_LDA + \delta calibration\_BSA + \delta drift\_BSA + \delta resolution\_LDA + \delta flow\_correction + \delta alignment\_LDA + \delta temperature\_LDA + \delta reproduceability$$

$$windspeed\_DUT = measurements\_DUT + \delta resolution\_DUT + \delta blocking\_DUT$$

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Calibration of anemometers – example #2

ultrasonic anemometer calibration at ~50 ms^{-1}:

- model part 2

Δwindspeed	result (windspeed_DUT - windspeed_reference)
windspeed_DUT	DUT indication of wind speed
windspeed_reference	reference indication of wind speed

Calibration of anemometers – example #2

ultrasonic anemometer calibration at ~50 ms^{-1}:

- uncertainties:

measurements_DUT	measurements of DUT
δresolution_DUT	resolution DUT
δblocking_DUT	blocking effect / correction of LDA measurements

Calibration of anemometers – example #2

ultrasonic anemometer calibration at ~50 ms^{-1}:

- uncertainties:

measurements_LDA	measurements of LDA
δcalibration_LDA	calibration of LDA
δcalibration_BSA	calibration of burst spectrum analyzer
δdrift_BSA	drift of BSA
δresolution_LDA	resolution LDA
δflow_correction	flow correction due to the type of DUT
δdrift_LDA	drift of LDA
δalignment_LDA	alignment of LDA
δtemperature_LDA	temperature dependency of LDA
δreproduceability	reproduceability of anemometer calibration

Calibration of anemometers – example #3

ultrasonic anemometer calibration at ~50 ms^{-1}:

- result:

Quantity	Value	Stand. uncert.	Distribution	DoF	Sensit. coeff.	Uncert. contribution	Rel. contribution	Bar chart
windspeed_DUT	48,9400 m/s	0,2173 m/s						
windspeed_LDA	48,4340 m/s	0,2562 m/s						
measurements_LDA	48,434000 m/s	0,004000 m/s	Normal	∞	-1,000	-0,004000 m/s	0,01 %	
δcalibration_LDA	0,0 m/s	0,04117 m/s	Normal	∞	-1,000	-0,04117 m/s	1,50 %	
δdrift_LDA	0,0 m/s	0,07746 m/s	Rectangular	∞	-1,000	-0,07746 m/s	5,31 %	
δcalibrationg_BSA	0,0 m/s	0,001732 m/s	Rectangular	∞	-1,000	-0,001732 m/s	0,00 %	
δdrift_BSA	0,0 m/s	0,0005774 m/s	Rectangular	∞	-1,000	-0,0005774 m/s	0,00 %	
δresolution_LDA	0,0 m/s	0,002887 m/s	Rectangular	∞	-1,000	-0,002887 m/s	0,01 %	
δflow_correction	0,0 m/s	0,1678 m/s	Rectangular	∞	-1,000	-0,1678 m/s	24,93 %	
δalignment_LDA	0,0 m/s	0,01398 m/s	Rectangular	∞	-1,000	-0,01398 m/s	0,17 %	
δtemperature_LDA	0,0 m/s	0,02887 m/s	Rectangular	∞	-1,000	-0,02887 m/s	0,74 %	
δreproduceability	0,0 m/s	0,1696 m/s	Rectangular	∞	-1,000	-0,1696 m/s	25,47 %	
measurements_DUT	48,94000 m/s	0,05700 m/s	Normal	∞	1,000	0,05700 m/s	2,88 %	
δresolution_DUT	0,0 m/s	0,002887 m/s	Rectangular	∞	1,000	0,002887 m/s	0,01 %	
δblocking_DUT	0,0 m/s	0,2097 m/s	Rectangular	∞	1,000	0,2097 m/s	38,96 %	
	Value	Comb. stand. uncertainty			Effective degrees of freedom			Sign. digits
Δwindspeed	0,5060 m/s	0,3360 m/s			∞			4
	Value	Expanded uncertainty			Coverage factor (Probability)		Distribution	Sign. digits
Result	0,506 m/s	± 0,672 m/s			2,00 (95,45 %)		Normal	3

Δwindspeed= 0,506 ms^{-1} ± 0,672 ms^{-1} (k=2)

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References and links

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  International Vocabulary of Metrology - Basic and general concepts and associated terms (2012)

  https://www.bipm.org/en/committees/jc/jcgm/publications

- JCGM 100:2008(E) – in English

  Evaluation of measurement data - **Guide to the expression of uncertainty in measurement** (2008)

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References and links

- Guide to Instruments and Methods of Observation (WMO-No. 8)
  https://library.wmo.int/records/item/41650-guide-to-instruments-and-methods-of-observation?offset=4

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  https://www.vdi.de/richtlinien/details/vdi-3650-einrichtungen-zur-sicherung-von- kranen-gegen-abtreiben-durch-wind

- VDI 3786 Part 2 Wind
  https://www.vdi.de/en/home/vdi-standards/details/vdi-3786-blatt-2-environmental-meteorology-meteorological-measurements-wind

References and links

- ISO 16622:2002 Meteorology — Sonic anemometers/thermometers — Acceptance test methods for mean wind measurements

  https://www.iso.org/standard/29291.html

- ISO 17713-1:2007 Meteorology — Wind Measurements Part 1: Wind tunnel test methods for rotating anemometer performance

  https://www.iso.org/standard/31497.html

Calibration of Wind Instruments
End of Part 5

Thank you.

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