CCM.FF-K3.2011

CIPM Key Comparison of Air Speed, 0.5 m/s to 40 m/s

Final Report

Pilots

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Abstract

The CCM.FF-K3.2011 comparison was organized for the purpose of determination of the degree of equivalence of the national standards for air speed over the range 0.5 m/s to 40 m/s. An ultrasonic anemometer and a Laser Doppler anemometer were used as transfer standards. Nine laboratories from three RMOs participated between July 2013 and July 2015 – EURAMET: PTB, Germany; LNE-CETIAT, France; INRIM, Italy; VSL, The Netherlands; E+E, Austria; SIM: NIST, USA; APMP: NMIJ/AIST, Japan; NIM, China; CMS/ITRI, Chinese Taipei. The measurements were provided at ambient conditions. All results of independent participants were used in the determination of the key comparison reference value (KCRV) and the uncertainty of the KCRV. The reference value was determined at each air speed separately following "procedure A" presented by M.G. Cox [7]. The degree of equivalence with the KCRV was calculated for each air speed and laboratory. Almost all reported results were consistent with the KCRV.

Graphical summary of results

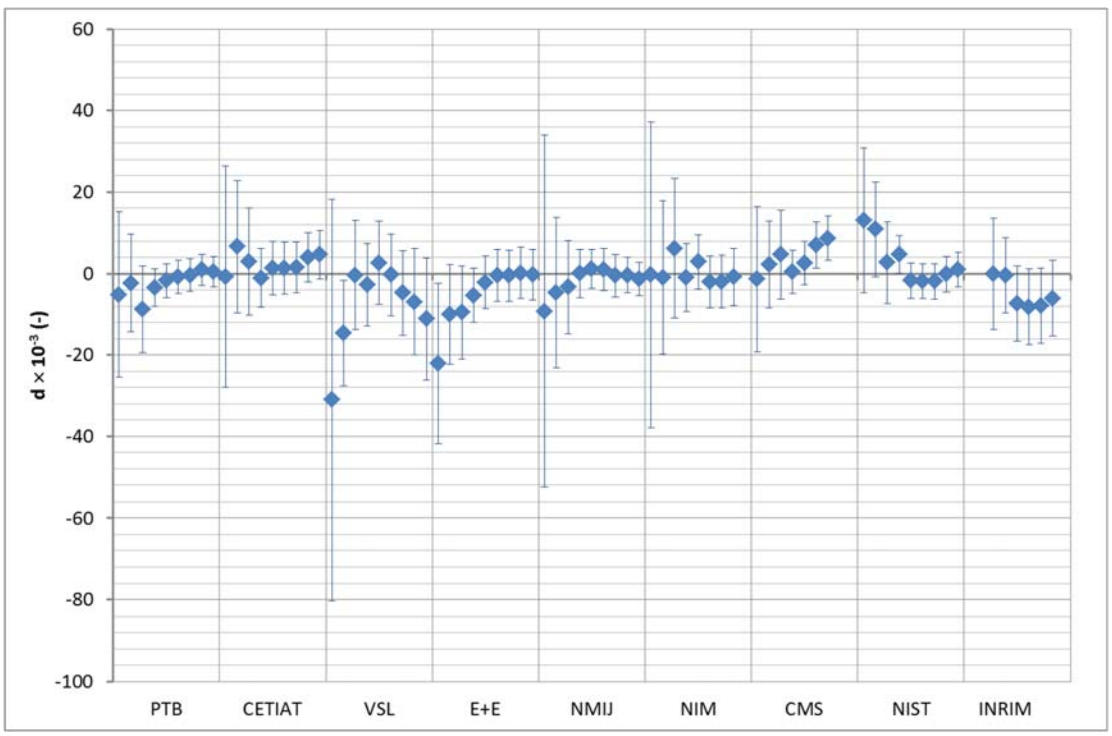


Figure 1 – Degrees of equivalence with respect to KCRV of each laboratory for the ultrasonic anemometer at the different air speeds. The error bars show the expanded uncertainty of the degree of equivalence for each calibrated value.

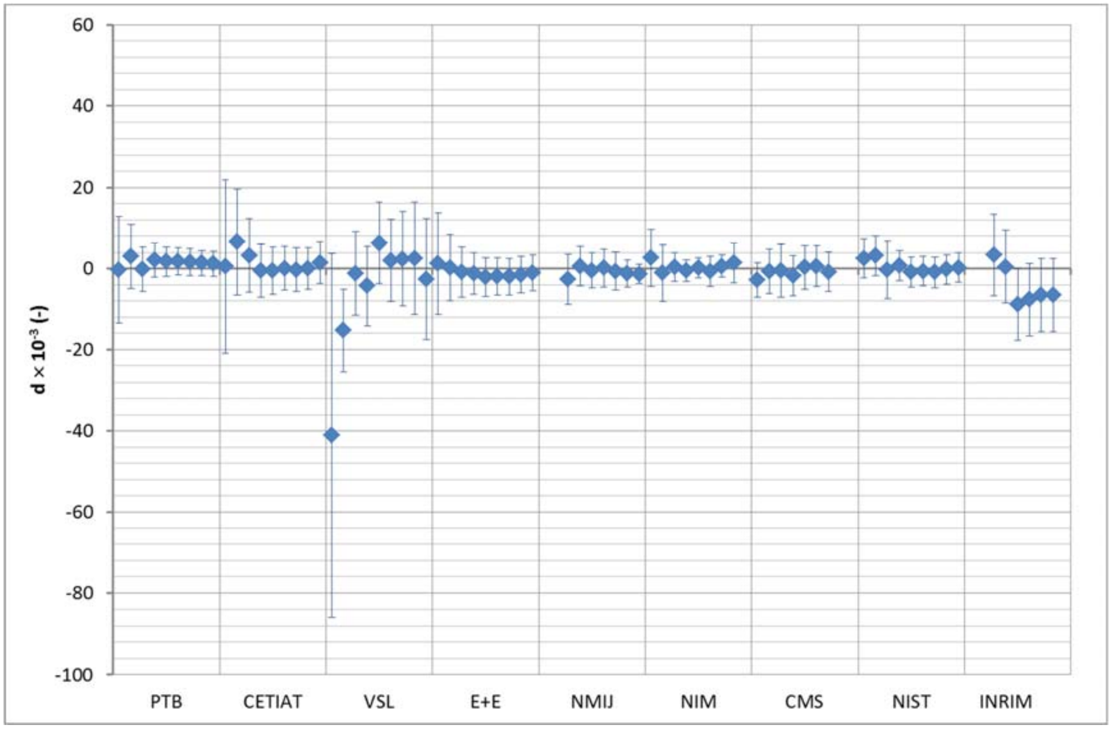


Figure 2 – Degrees of equivalence with respect to KCRV of each laboratory for the Laser Doppler anemometer at the different air speeds. The error bars show the expanded uncertainty of the degree of equivalence for each calibrated value.

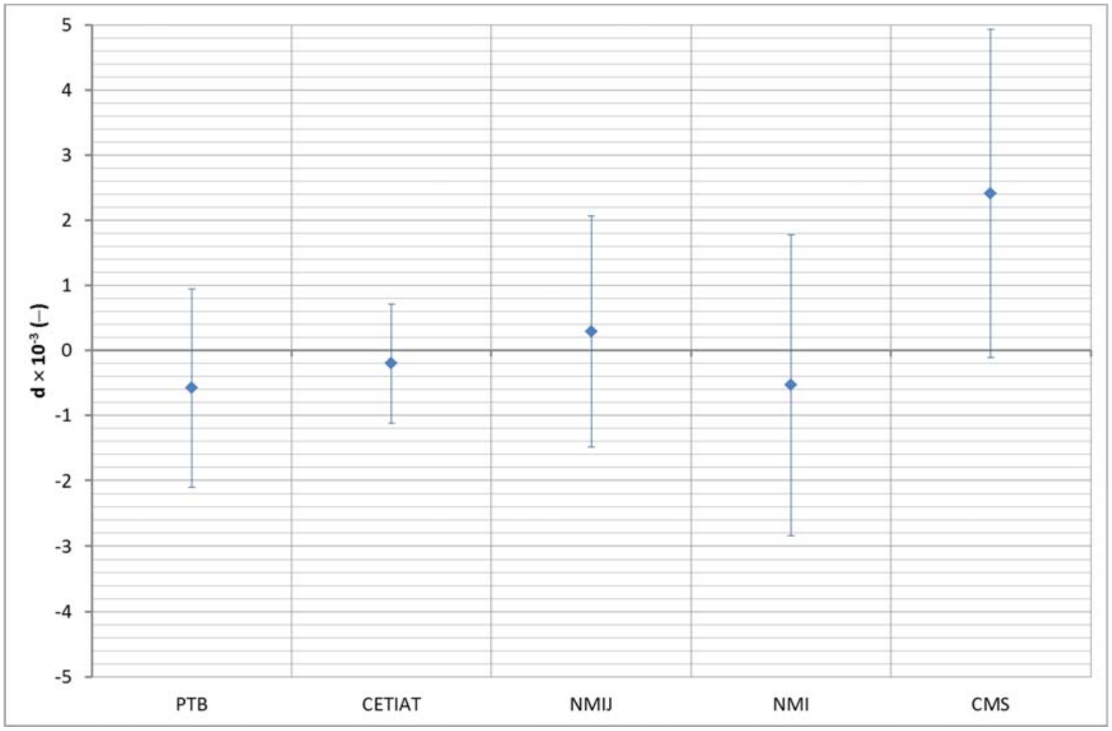


Figure 3 –Degrees of equivalence with respect to KCRV of each laboratory for the Laser Doppler anemometer calibrated with a primary standard. The error bars show the expanded uncertainty of the degree of equivalence for each calibrated value.

CONTENTS

1. INTRODUCTION

This second round of the Key Comparison, CCM.FF.K3.2011 for air speed, has been undertaken by CCM (Consultative Committee for Mass and related quantities) Working Group for Fluid Flow (WGFF) and was piloted by PTB (National Metrology Institute of Germany) and LNE-CETIAT (Designated Institute for Air Speed of France). Two transfer standards were used. The first one was an ultrasonic anemometer similar to those used during the first run in 2005 [1]. The second one was a Laser Doppler anemometer, known as the best transfer standard in the field which had already shown its interest during the EURAMET comparison 827 [2]. It was especially designed to limit the changes in the parameters by the laboratories during the calibration.

The objective of the 2^{nd} round of this key comparison is to determine the key comparison reference values (KCRVs) for air speed measurement and to demonstrate the degree of equivalence among the participating National Metrology Institutes (NMIs) and Designated Institutes (DIs). The participating NMIs/DIs calibrated transfer standards and compared their calibration results.

This report was prepared in accordance with some guidelines [3 – 7].

2. Participants and organization of the comparison

2.1. List of participants

The participants are listed in table 1.

Table 1 - List of the participating NMIs/DIs, facilities used, dates of test and independence of the participant's traceability from other participants

Participant (Country)	Type of reference standard	Date of tests	Independent traceability?
PTB (Germany)	LDA standard	July 2013	Yes
LNE-CETIAT (France)	LDA standard	July 2013	Yes
VSL (Netherlands)	Flow rate standard	August 2013	Yes
E+E (Austria)	LDA standard	August 2013	No, PTB
NMIJ/AIST (Japan)	LDA standard Linear displacement	December 2013	Yes
NIM (China)	LDA standard	May 2014	Yes
CMS/ITRI (Chinese Taipei)	LDA standard	July 2014	Yes
NIST (USA)	LDA standard	October 2014	Yes
INRIM (Italy)	LDA standard	March 2015	Yes

2.2. Organization of the comparison

A single internationally acting company (Westfacht Spezialverkehre International GmbH) was charged to handle the transportation including all the formalities concerning documents and customs and managed by PTB.

According to the technical protocol chapter 7 “shipping the transfer standard” from June 2013 the global costs due to transportation are to be shared equally between all participating laboratories. An invoice taking into account the real costs is sent to the partners at the end of the comparison.

2.3. Unexpected events

Several unexpected events occurred during the comparison which caused some delays and changes of the initial time schedule:

- September, 2013: US government shutdown. Adjustment of the schedule needed.
- January, 2014: air freight confusion on the road back from Japan leading to delay.
- May, 2014 to June, 2014: transportation procedure not respected leading to customs clearance problems and delay.
- November, 2014: Asbestos removal in Italy leading to delay.
- November 2015 to June, 2016: Customs clearance problems with Russia. Conclusion of the comparison in agreement with the WGFF chairperson.
  VNIIM will participate in a separate bilateral comparison with PTB in the near future (registered comparison CCM.FF-K3.2011.1).

3. Travelling standards

3.1. Ultrasonic anemometer

The ultrasonic anemometer to be used in this key comparison (KC) is manufactured by SONIC CORPORATION. The probe has three pairs of ultrasonic transducers and measures the three dimensional velocity vector derived from the time of the ultrasonic waves between pairs of transducers. The projected area of the probe is 1287 mm^2 and a photo is shown below.

Figure 4 - Ultrasonic Anemometer sensing element; the arrow indicates the flow direction

The arrangement of the instrument is such that the flow reaches the sensor along its main axis as shown in Figure 4. This way, the disturbance of the instrument to the flow is minimized; also, no influence of the emitters' supports on the measurements is noticeable.

Although the overall blockage effect of the instrument is quite reduced, the overall dimension of the sensor implies a diameter of about 10 cm. In order to minimize the effects of wall interaction, it is recommended to have any walls at a distance of at least 10 cm from the instrument. Therefore, only test sections of at least 30 cm diameter (or 30 cm minimum transverse direction for square/rectangular section wind tunnels) should be used.

3.2. Laser Doppler anemometer

The laser Doppler anemometer system is manufactured by ILA GmbH. The focal lens allows a working distance of approximately 500 mm. The distance between the two beams at the front lens of the LDA probe is 45 mm.

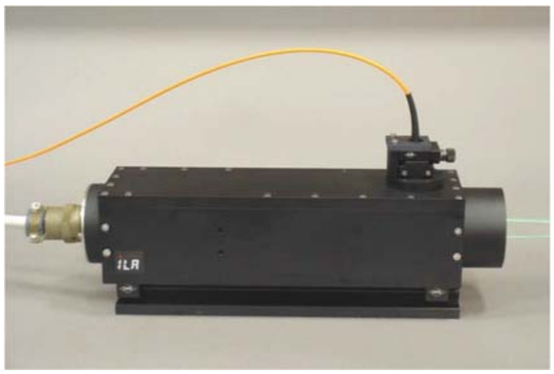


Figure 5 - Laser Doppler Anemometer probe; power 75 mW, wavelength 532 nm

The LDA system includes the controller, the signal processing unit and the software specially developed to ensure a uniform operation. A portable measurement PC specified as signal processing unit is also enclosed in the LDA-transportation box to record the data from the laser Doppler anemometer as well as from the ultrasonic anemometer.

4. Measurement instructions

The measurements had to be performed at ambient conditions.

The participants performed the calibration of the transfer standards for the velocities 0.5 m/s, 1.0 m/s, 2.0 m/s , 5.0 m/s 10.0 m/s 15.0 m/s, 20.0 m/s, 30.0 m/s and 40.0 m/s or within their own velocity range if the full range of set points is not possible.

At each speed, five repeated measurements were recorded according to the procedure of each laboratory. Both transfer standards were completely calibrated separately as two different meters under test.

Additionally, if possible, the Laser Doppler anemometer was calibrated with a primary standard according to the measurement possibility of each partner.

The participants calculated *K* factors at each velocity and for the both instruments, expressed as:

$$K = \frac{V_{ref}}{V_{ts}} \tag{1}$$

With:

- V_{ref}, the reference velocity measured by the participant (m/s)
- V_{ts}, the reading of the transfer standard (m/s)

5. Methods of measurement

A summary of the calibration methods used by the participants is presented in Table 2.

Table 2 – Calibration method

Participant Lab (Country)	Calibration method	Reference standard
PTB (Germany)	Wind tunnel: closed loop, open test section	LDA calibrated with a rotating disk
LNE-CETIAT (France)	Closed wind tunnel with a square test section	LDA calibrated with a rotating disk
VSL (Netherlands)	Free jet nozzle flow	Flow rate standard
E+E (Austria)	Wind tunnel: closed wind tunnel with a round open test section	LDA calibrated with a rotating disk
NMIJ/AIST (Japan)	Tow carriage Closed wind tunnel with a square test section	Laser interferometer and frequency counter LDA calibrated with a rotating disk
NIM (China)	Open wind tunnel	LDA calibrated with a rotating disk
CMS/ITRI (Chinese Taipei)	Open wind tunnel	LDA calibrated with a rotating disk
NIST (USA)	Closed wind tunnel with a square test section	LDA calibrated against spinning disk
INRIM (Italy)	Closed loop/closed chamber wind tunnel Open loop/semi-open chamber wind tunnel	Pitot static tube traceable to LDA (Large wind tunnel) LDA (small wind tunnel)

6. UNCERTAINTY DUE TO THE TRANSFER STANDARDS

From the measurements at the pilot institute, PTB, the stability and reproducibility of the transfer standards were evaluated.

6.1. Ultrasonic anemometer

The stability of the *K* factor for each velocity is shown in Figure 6 for the ultrasonic anemometer.

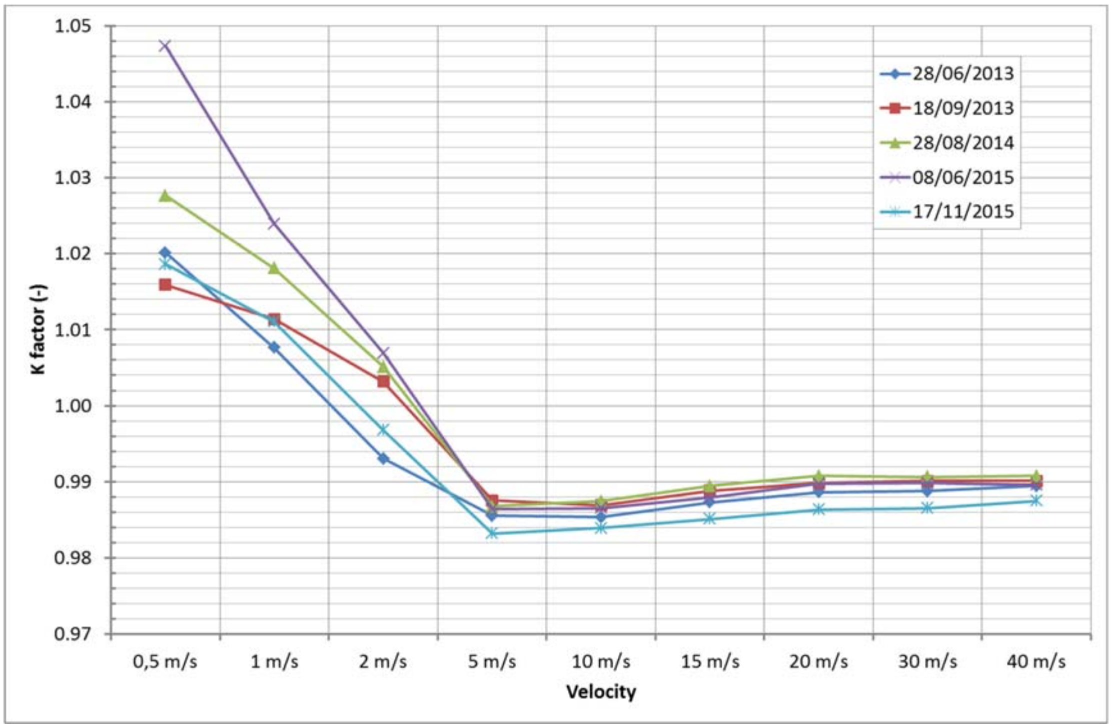


Figure 6 - *K* factor for the different calibrations at PTB for the ultrasonic anemometer

Five calibrations were performed at PTB between June 2013 and November 2015. The stability of the transfer standard is calculated and is expressed for each velocity as:

$$\frac{Max(K_i) - Min(K_i)}{K_{mean}} \times 100\ (\%) \tag{2}$$

With:

- K_i, the *K* factor obtained by PTB at the date *i*
- K_{mean}, the mean *K* factor obtained by PTB considering all the performed calibrations.

Furthermore, the standard uncertainty at each velocity is calculated, considering a rectangular law, as the observed maximum deviation divided by the square root of 12.

Considering the results obtained at PTB, an additional contribution of uncertainty due to the stability of the transfer standard will be included when calculating the uncertainty of the KCRV as followed:

Table 3 – Standard uncertainty of the ultrasonic anemometer

Nominal air speed (m/s)	Standard uncertainty for the transfer standard (%)
0.5	0.9
1	0.5
2	0.5
5	0.13
10	0.13
15	0.13
20	0.13
30	0.13
40	0.13

6.2. Laser Doppler Anemometer

The stability of the Laser Doppler anemometer has been evaluated through the recalibration of the fringe spacing against the rotating wheel facility at PTB.

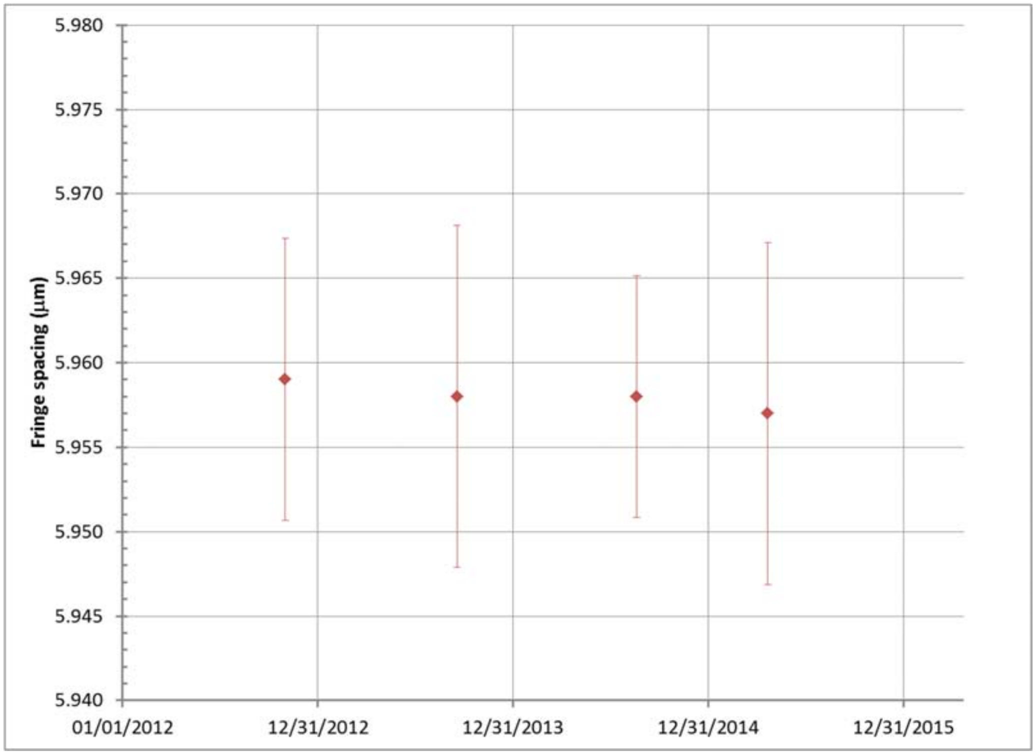


Figure 7 – Calibration of the fringe spacing at PTB over the duration of K3

With an analysis similar to the one performed for the ultrasonic anemometer, considering the results obtained at PTB, an additional contribution of uncertainty due to the stability of the transfer standard will be included when calculating the uncertainty of the KCRV. The value of this standard uncertainty is 0.01% over the whole range of velocity.

7. DATA PROCESSING AND COMPUTATION OF THE KCRV

7.1. Results of the participating institutes

7.1.1. Ultrasonic anemometer

The *K* factor from all participants is shown in Figure 8. All of the reported values are listed in Appendix A.

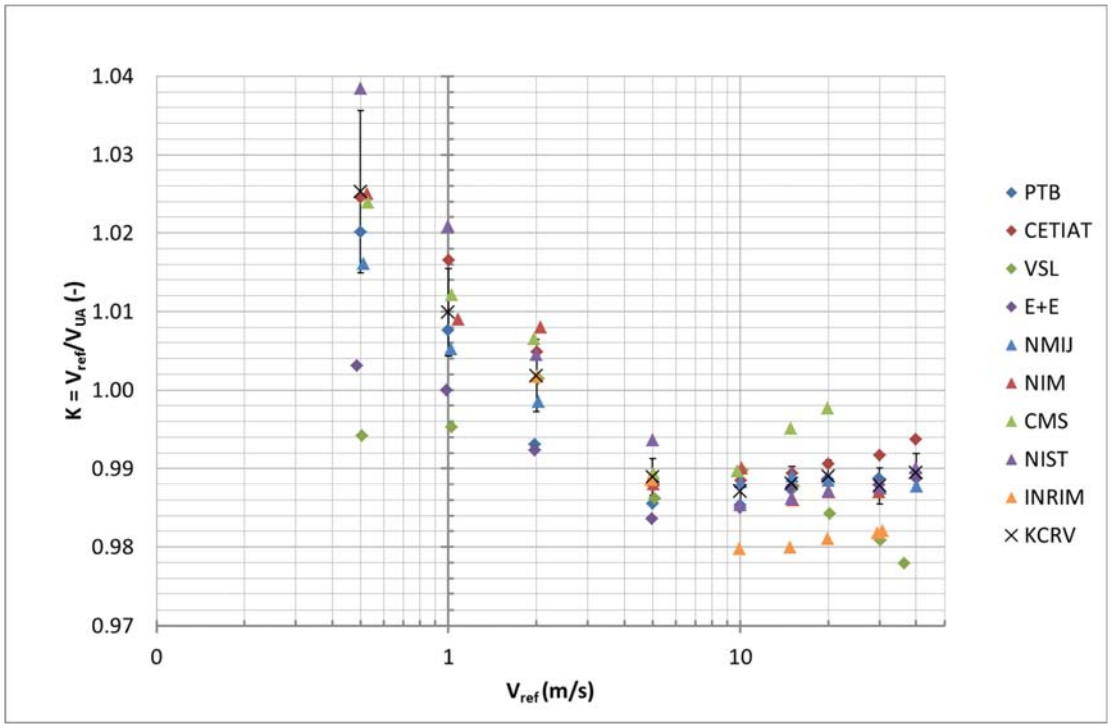


Figure 8 - ***K*** **factor obtained by all the participants for the ultrasonic anemometer**

7.1.2. Laser Doppler anemometer

The *K* factor from all participants is shown in Figure 9. All of the reported values are listed in Appendix A.

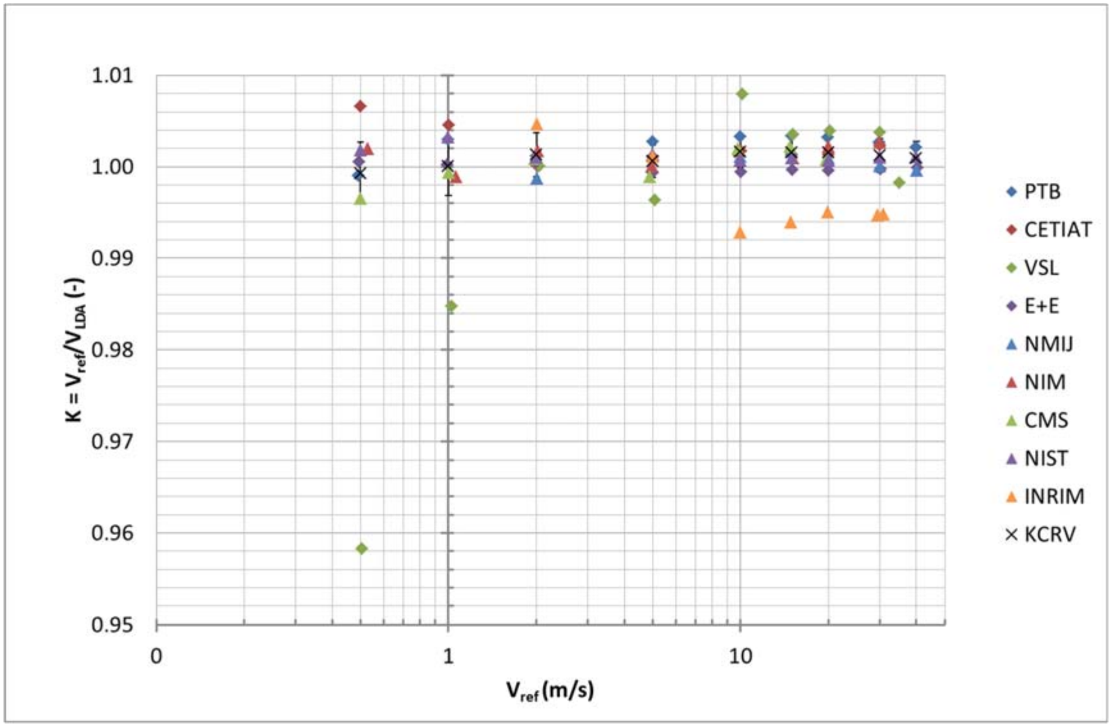


Figure 9 - ***K*** **factor obtained by all the participants for the Laser Doppler anemometer**

7.2. Calculation of the reference value and its uncertainty

The analysis of the results was carried out according to the method specified by Cox [6, 7].

According to the Cox procedure, the KCRV is calculated only considering institutes' measurements which are realized independently of the other institutes' measurements in the key comparison (condition 2 of the Cox procedure). As a consequence, since E+E has its LDA traceability by PTB, the measurements of this institute were not considered for the calculation of the KCRV.

7.2.1. Ultrasonic anemometer

The KCRVs for the ultrasonic anemometer were calculated by applying the "weighted mean" method (procedure A).

Table 4 shows the result of the chi-square consistency test performed on the full set of data:

Table 4 - Results of the chi square consistency test on the overall data set

Nominal airspeed V_{nom} [m/s]	*KCRV*	U(KCRV)	χ^2_{obs}	n-1	Test $\chi^2_{0.05,\ n-1}$	Result
0.5	1.0253	0.0103	3.56	6	12.59	Pass
1	1.0099	0.0056	8.23	6	12.59	Pass
2	1.0018	0.0046	4.13	7	14.07	Pass
5	0.9890	0.0024	5.47	7	14.07	Pass
10	0.9871	0.0022	5.53	7	14.07	Pass
15	0.9881	0.0022	9.79	7	14.07	Pass
20	0.9890	0.0022	13.67	7	14.07	Pass
30	0.9878	0.0023	4.43	6	12.59	Pass
40	0.9895	0.0025	6.39	4	9.49	Pass

The test passed for the overall set. All the data are mutually consistent.

Detailed results from each participant are presented in Appendix A. A comparison with the KCRV is presented in Figures below for each air speed.

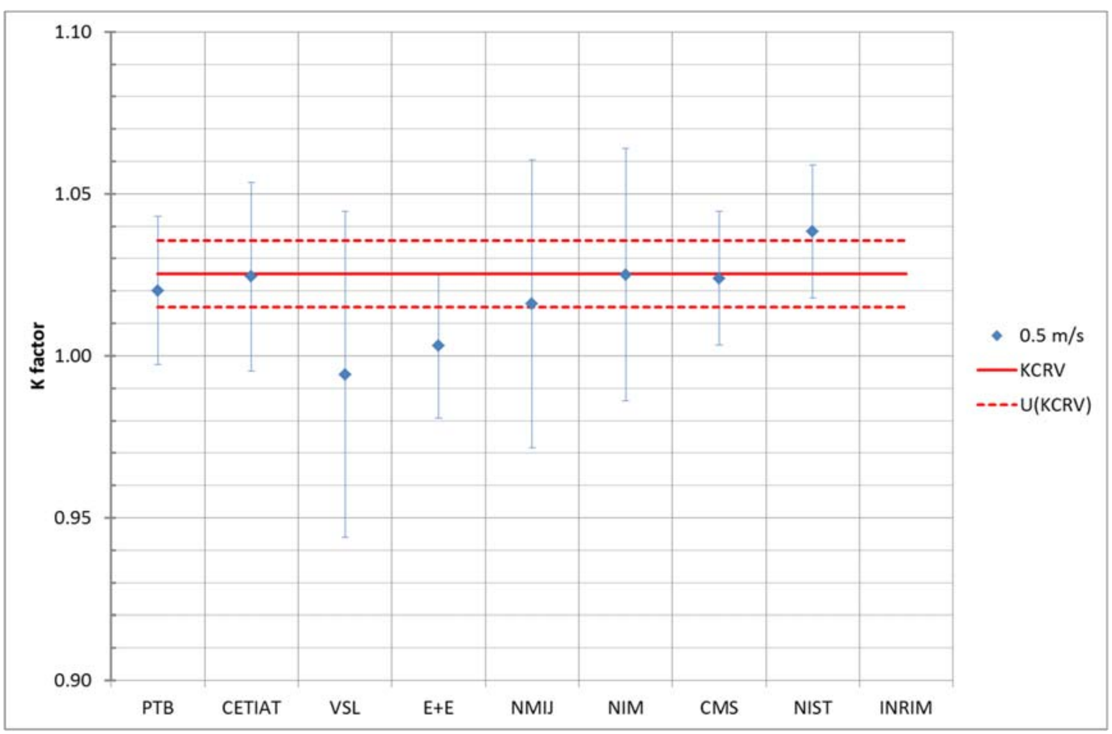


Figure 10 - Measurement results of the ultrasonic anemometer at 0.5 m/s

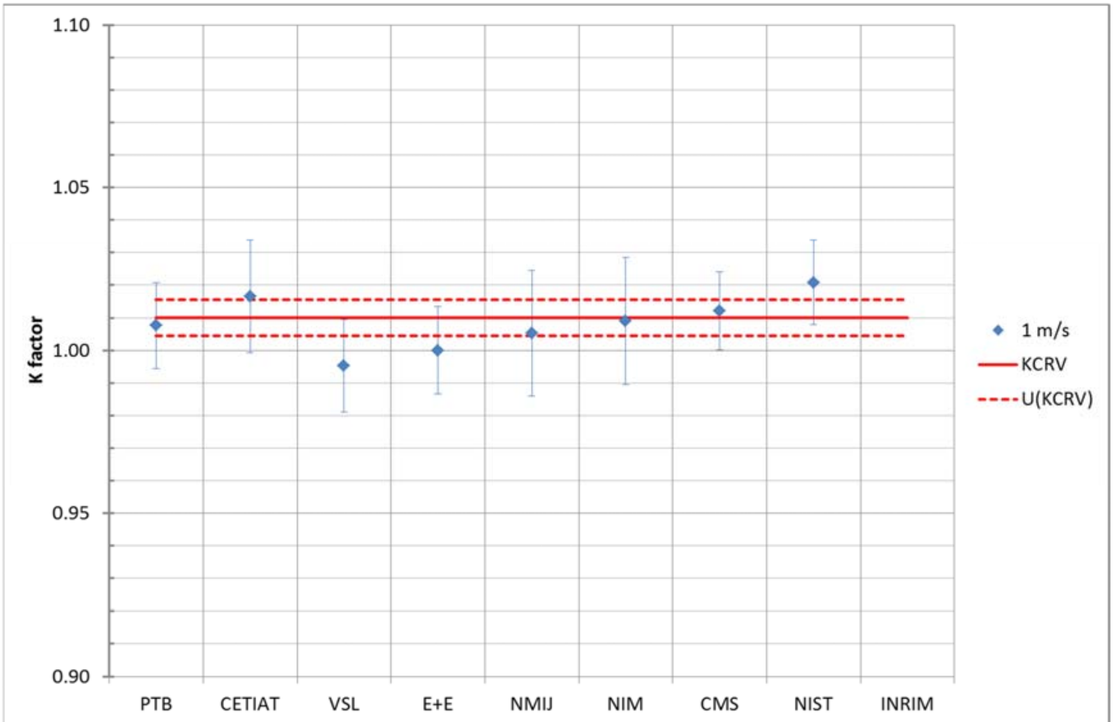


Figure 11 – Measurement results of the ultrasonic anemometer at 1 m/s

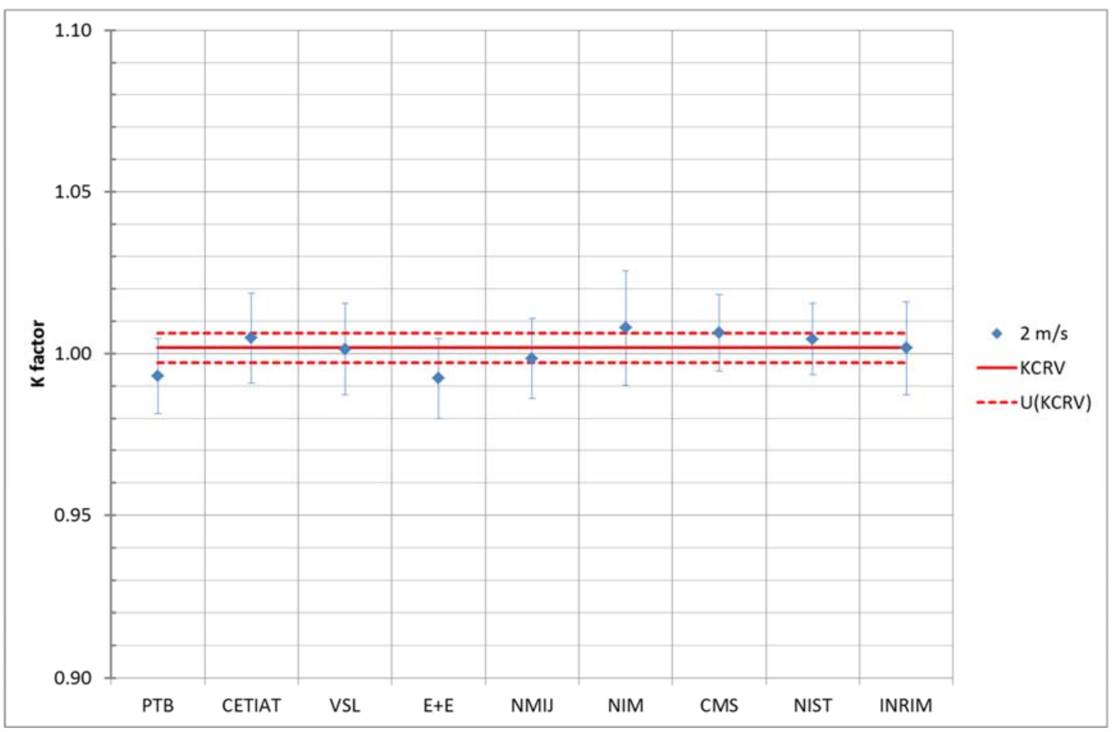


Figure 12 – Measurement results of the ultrasonic anemometer at 2 m/s

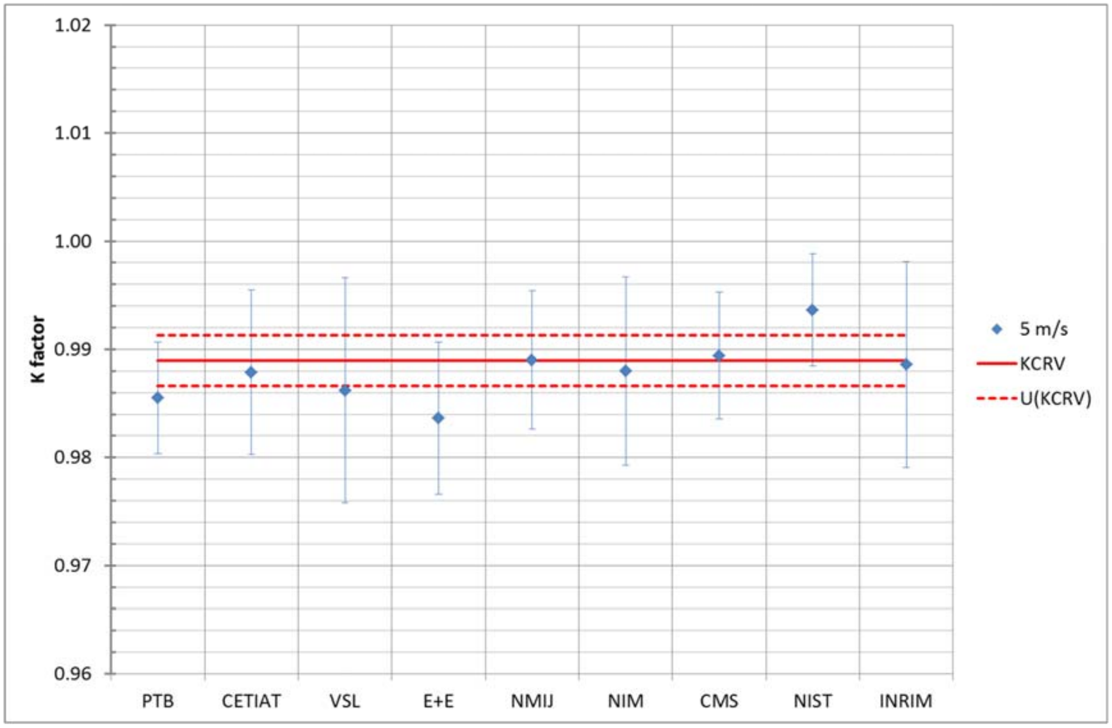


Figure 13 – Measurement results of the ultrasonic anemometer at 5 m/s

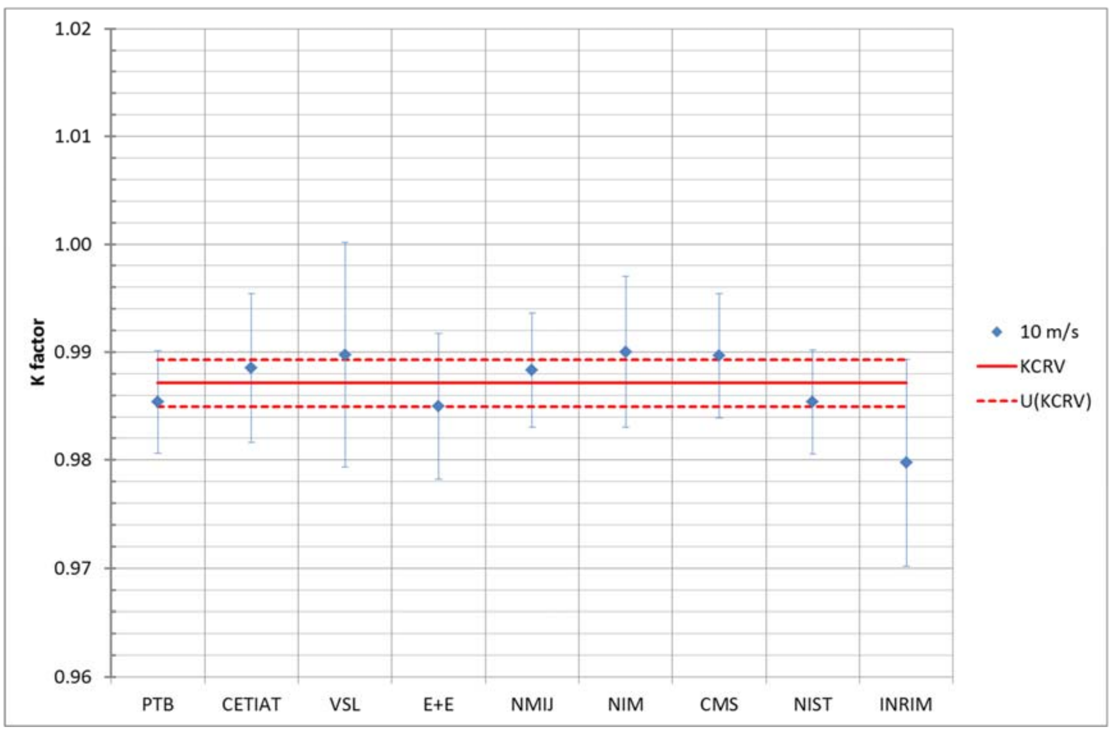


Figure 14 – Measurement results of the ultrasonic anemometer at 10 m/s

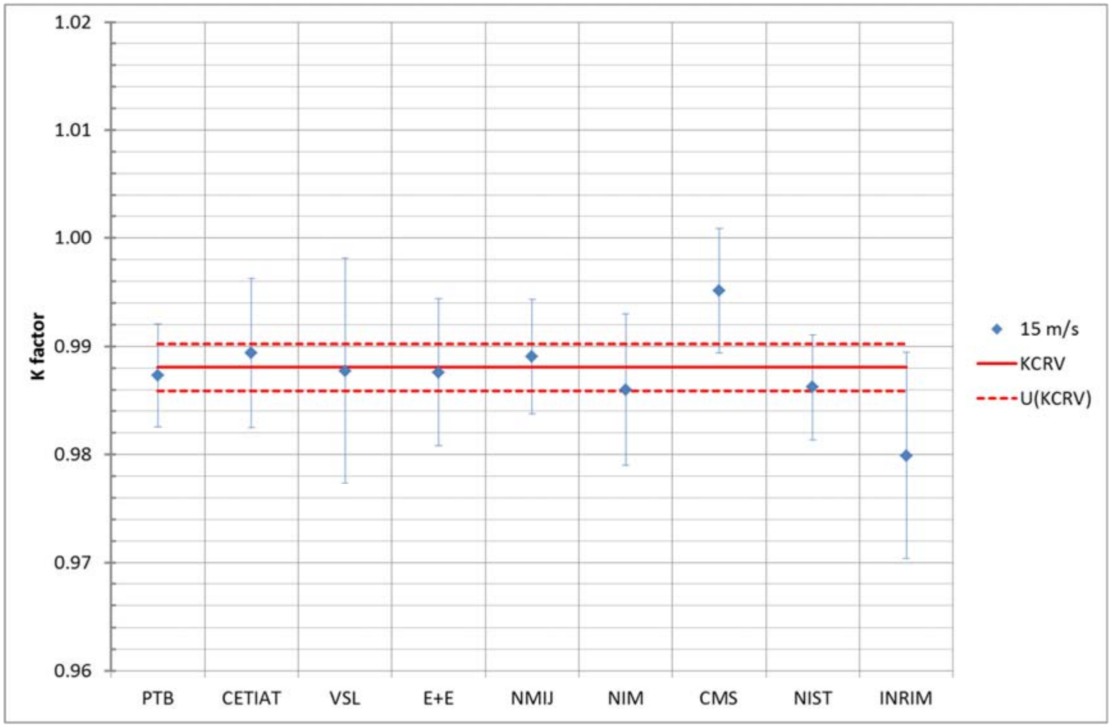


Figure 15 - Measurement results of the ultrasonic anemometer at 15 m/s

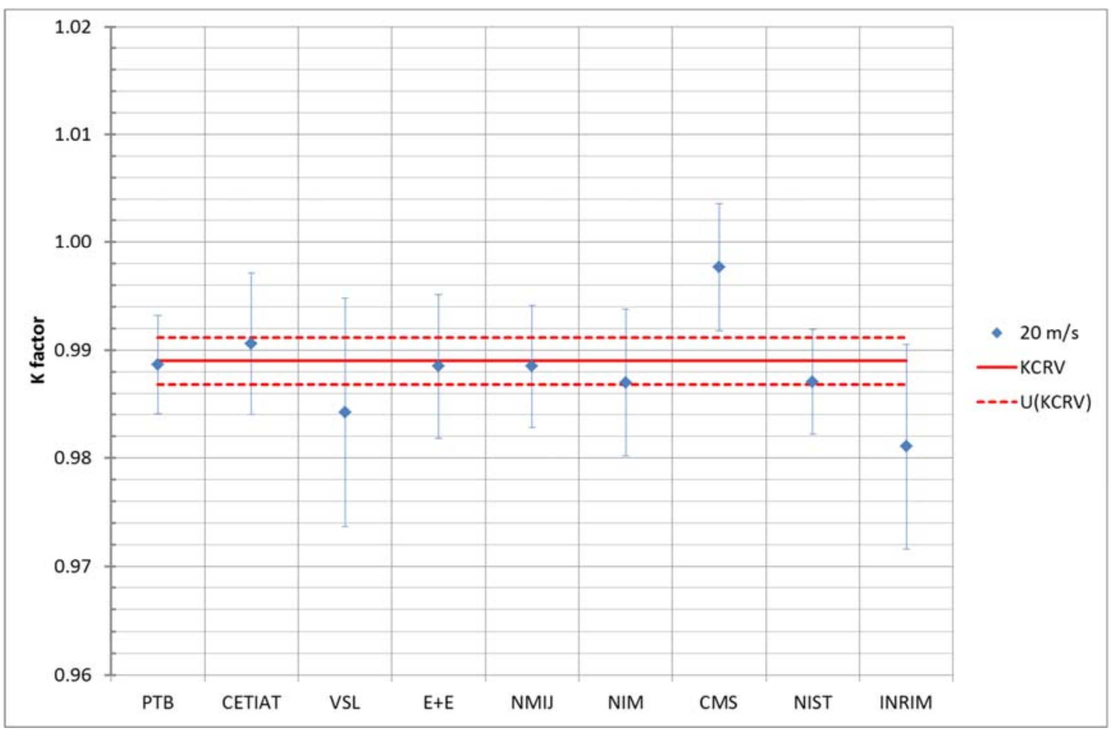


Figure 16 - Measurement results of the ultrasonic anemometer at 20 m/s

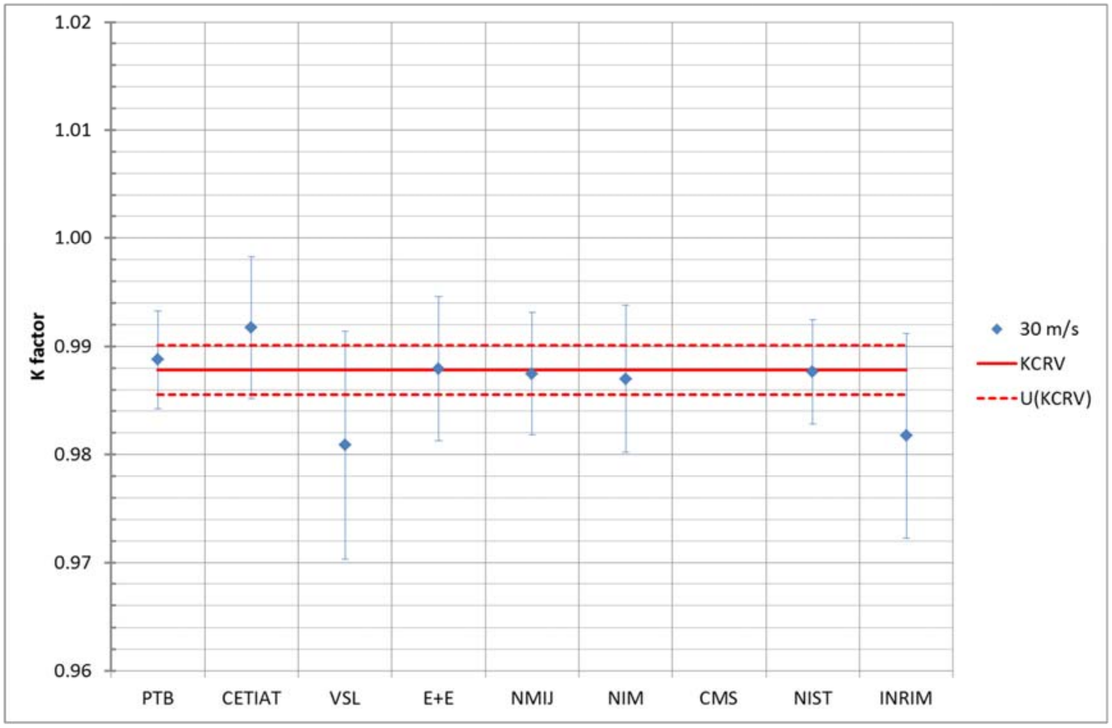


Figure 17 - Measurement results of the ultrasonic anemometer at 30 m/s

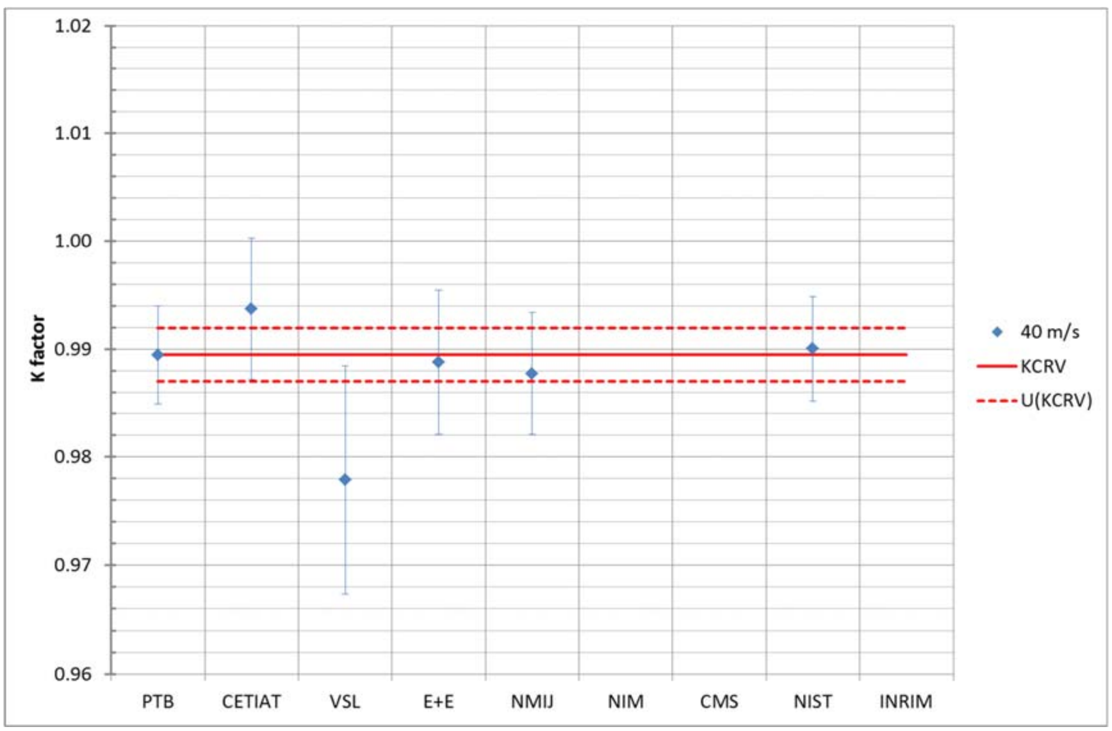


Figure 18 - Measurement results of the ultrasonic anemometer at 40 m/s

7.2.2. Laser Doppler anemometer

The KCRVs for the ultrasonic anemometer were calculated by applying the "weighted mean" method (procedure A).

Table 5 shows the result of the chi-square consistency test performed on the full set of data:

Table 5 - Results of the chi square consistency test on the overall data set

Nominal airspeed V_{nom} [m/s]	*KCRV*	U(*KCRV*)	χ^2_{obs}	n-1	Test $\chi^2_{0.05,\ n-1}$	Result
0.5	0.9993	0.0034	5.528	5	11.07	Pass
1	1.0000	0.0032	10.985	5	11.07	Pass
2	1.0013	0.0024	1.611	7	14.07	Pass
5	1.0006	0.0018	2.371	7	14.07	Pass
10	1.0016	0.0017	6.391	7	14.07	Pass
15	1.0016	0.0018	4.026	7	14.07	Pass
20	1.0016	0.0017	3.453	7	14.07	Pass
30	1.0012	0.0019	3.427	6	12.59	Pass
40	1.0009	0.0019	1.609	4	9.49	Pass

The test passed for the overall set. All the data are mutually consistent.

Detailed results from each participant are presented in Appendix A. A comparison with the KCRV is presented in Figures below for each air speed.

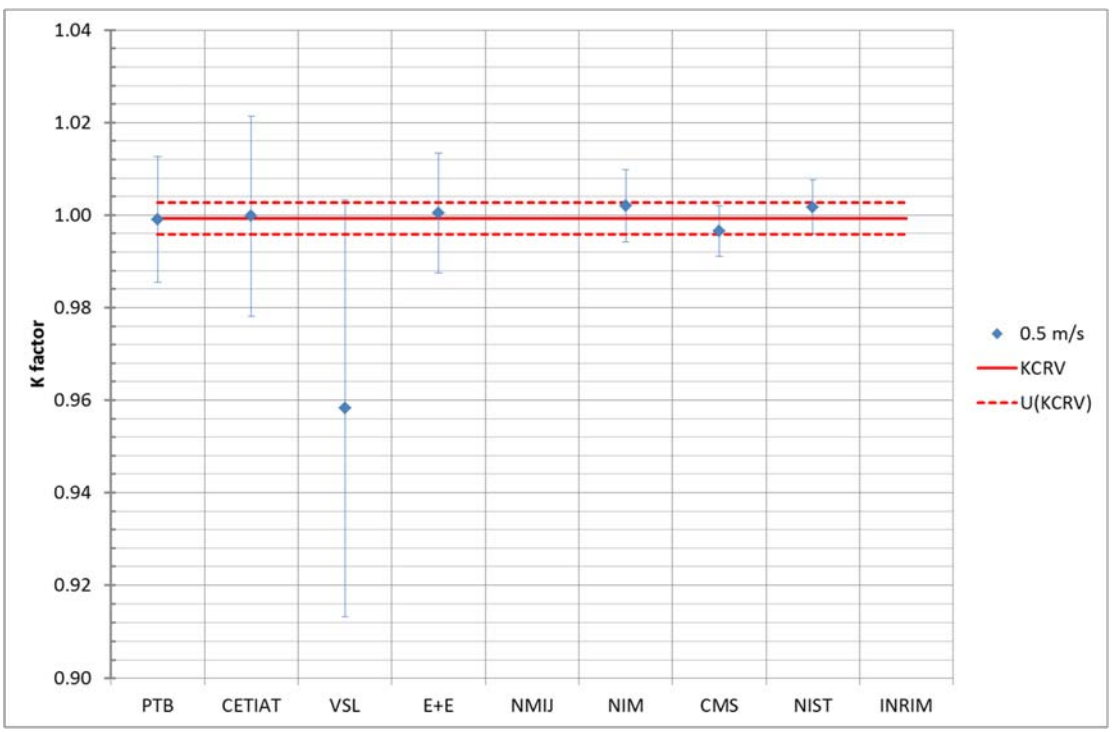


Figure 19 - Measurement results of the Laser Doppler anemometer at 0.5 m/s

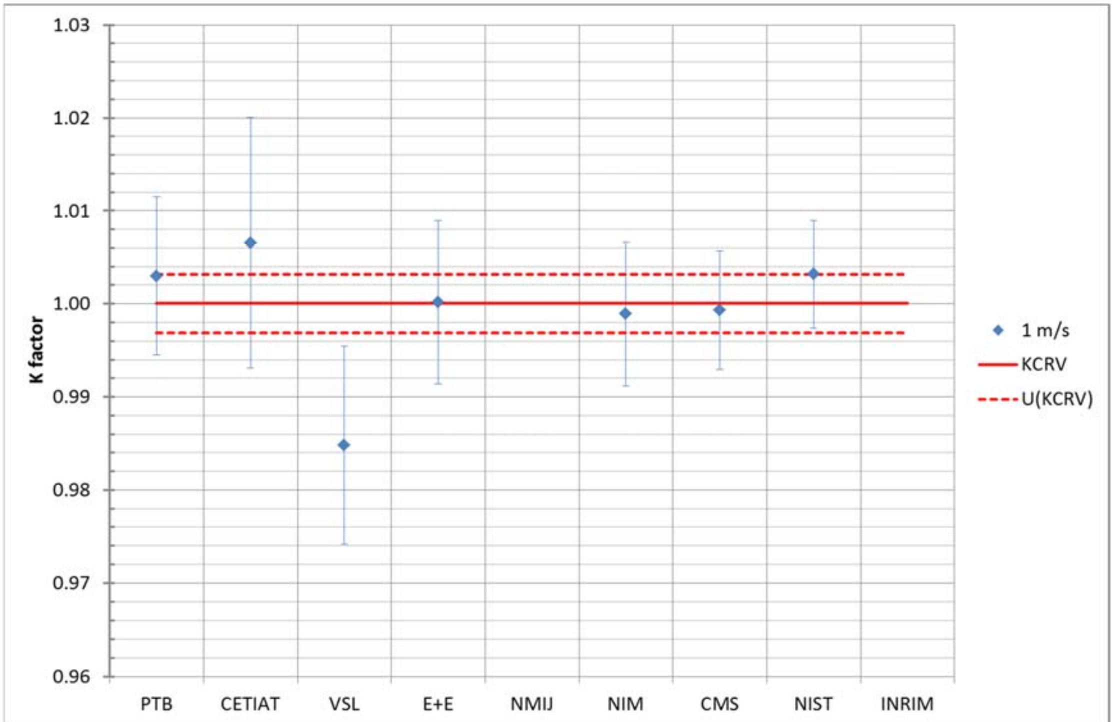


Figure 20 – Measurement results of the Laser Doppler anemometer at 1 m/s

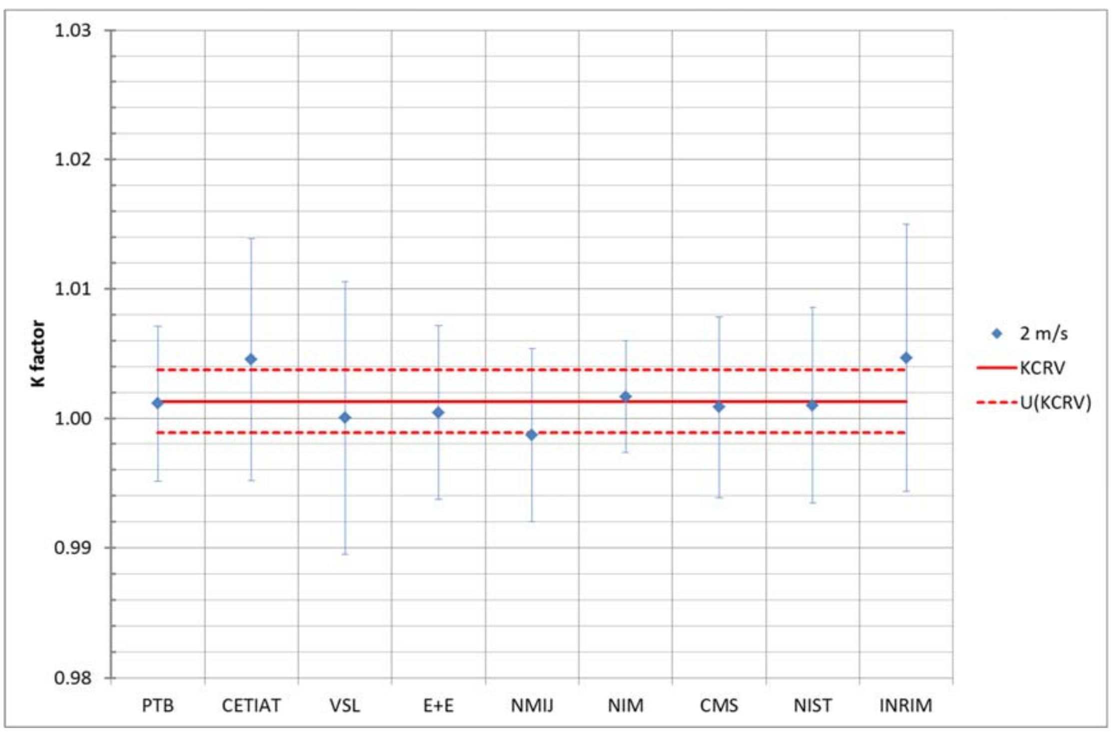


Figure 21 – Measurement results of the Laser Doppler anemometer at 2 m/s

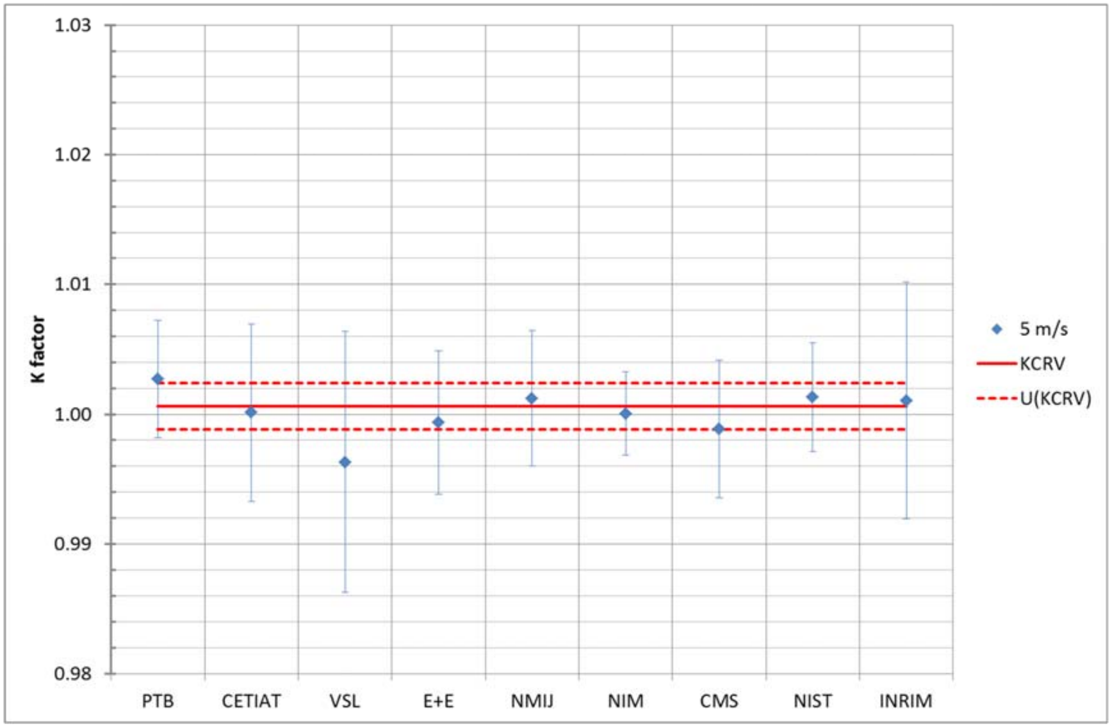


Figure 22 – Measurement results of the Laser Doppler anemometer at 5 m/s

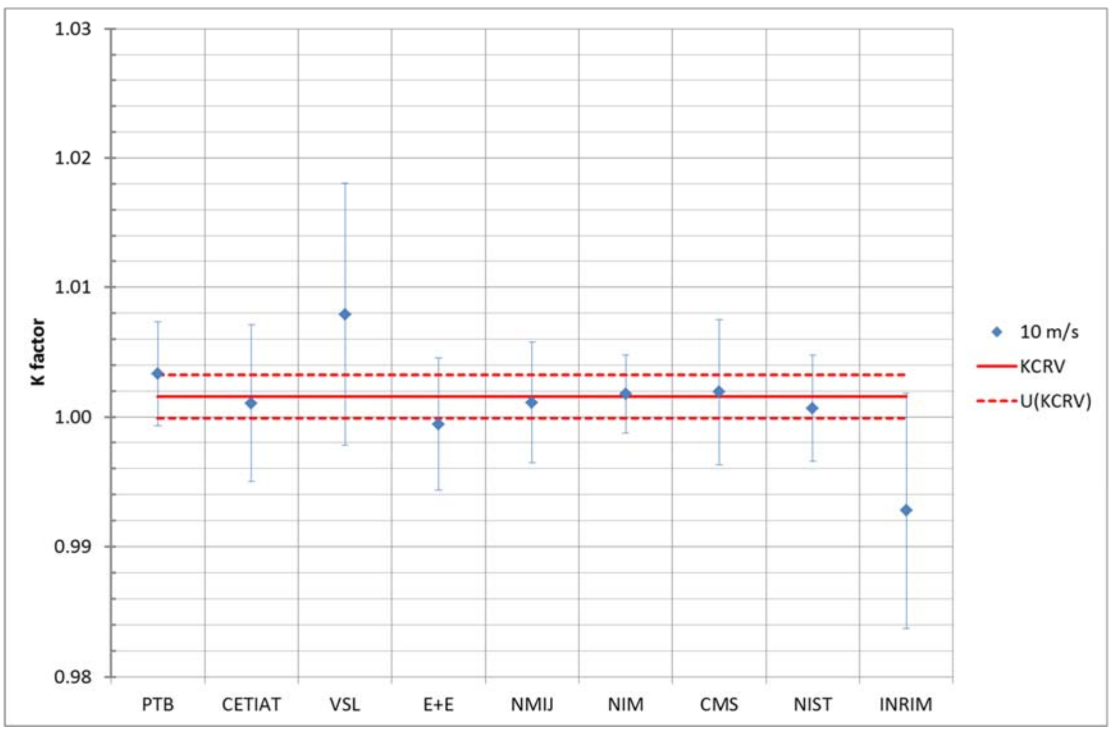


Figure 23 – Measurement results of the Laser Doppler anemometer at 10 m/s

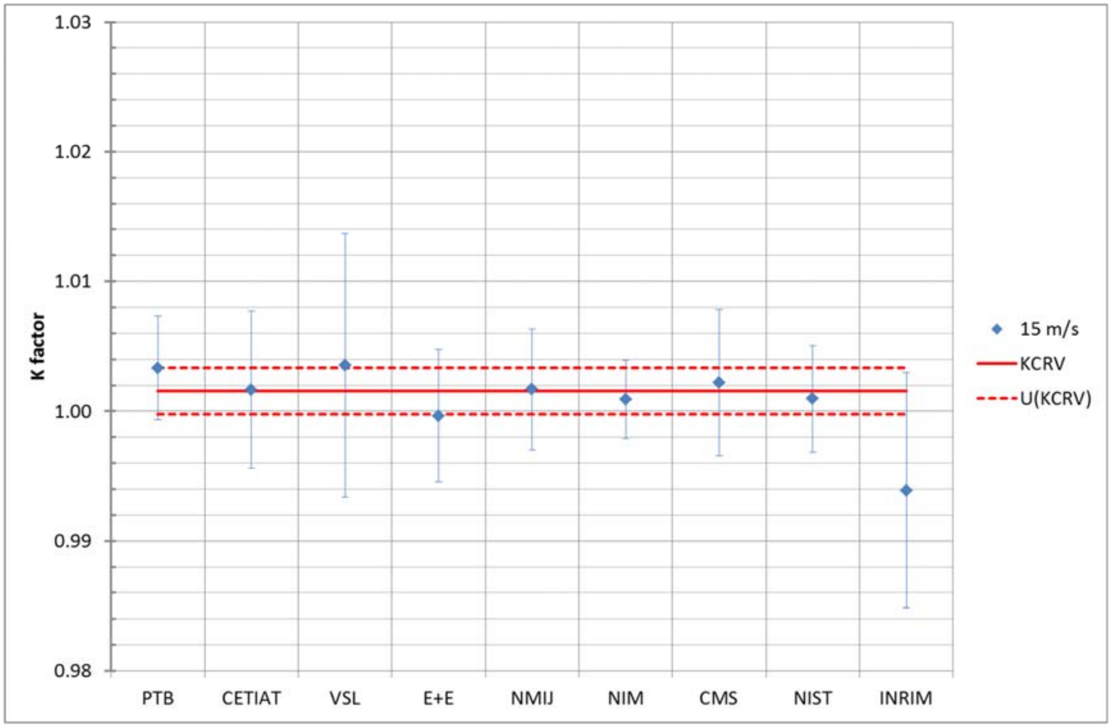


Figure 24 – Measurement results of the Laser Doppler anemometer at 15 m/s

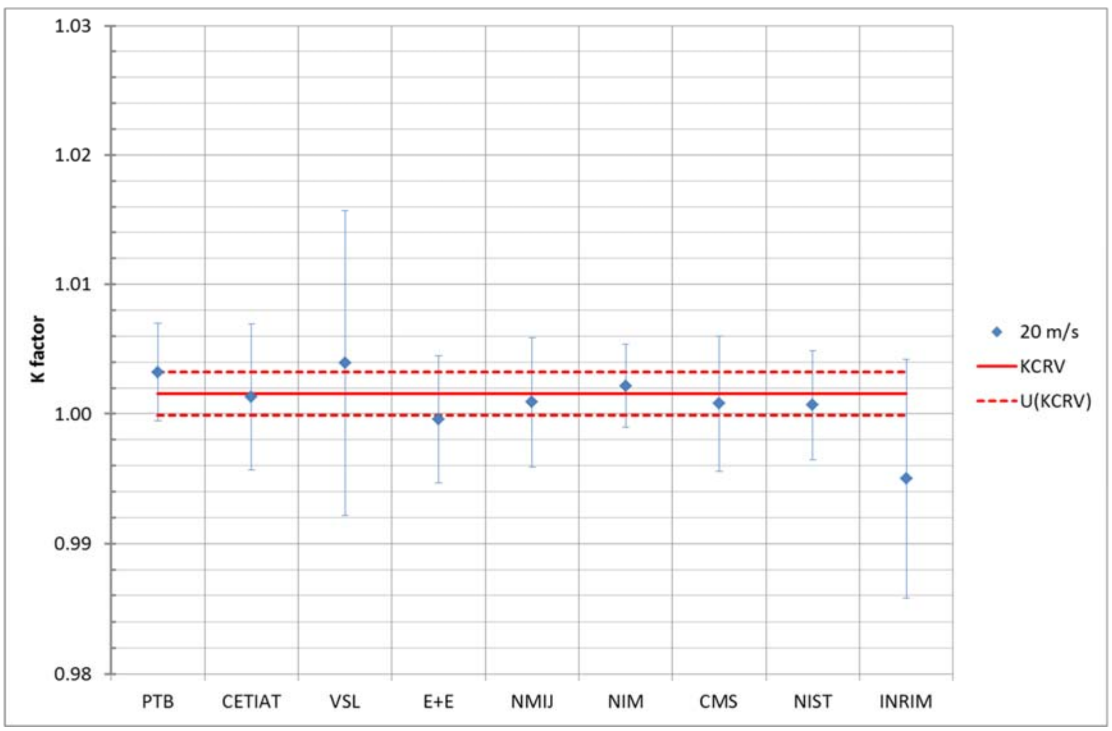


Figure 25 – Measurement results of the Laser Doppler anemometer at 20 m/s

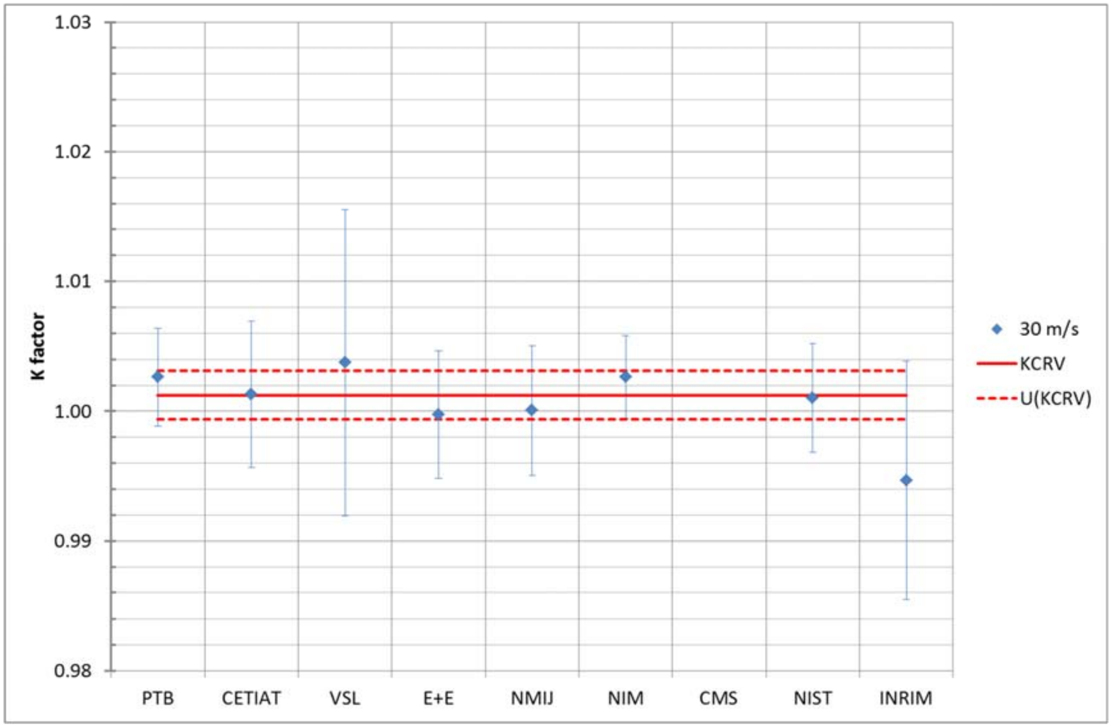


Figure 26 – Measurement results of the Laser Doppler anemometer at 30 m/s

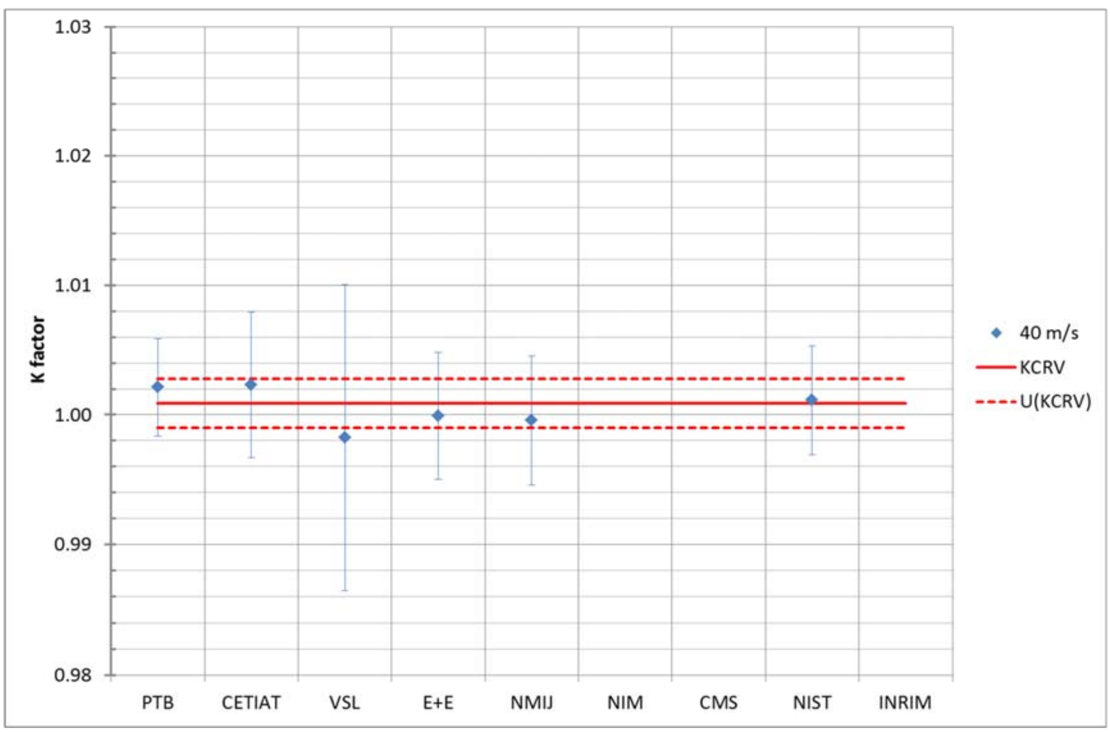


Figure 27 – Measurement results of the Laser Doppler anemometer at 40 m/s

7.3. Degree of equivalence

The degree of equivalence (*d*) of each of the participating institutes is expressed quantitatively as the deviation from the comparison value KCRV at each velocity point according to the procedure A specified by Cox [7] as:

$$d = K - KCRV \tag{9}$$

The uncertainty of this deviation is given at a 95% level of confidence as:

$$U(d) = 2 \times u(d) \tag{10}$$

where

$$u(d) = \sqrt{u^2(K) - u^2(KCRV)} \tag{11}$$

Note that the air speed reference of E+E has traceability to PTB and therefore the E+E results were not used during calculation of the KCRV. Equation 11 still applies to E+E because there is strong covariance between E+E and the KCRV via the PTB traceability path.

The normalized error, *En*, describes the degree of equivalence of a laboratory related to the KCRV. This value is expressed as:

$$En = \left|\frac{d}{U(d)}\right| \tag{12}$$

The results of an institute:

- are considered as consistent with the KCRV if *En* ≤ 1
- are considered as inconsistent with the KCRV if *En* > 1.2 (red colored values)
- are recommended to be carefully checked if 1 < *En* ≤ 1.2 (orange colored values)

7.3.1. Ultrasonic anemometer

The degree of equivalence between the KCRV of CCM.FF-K3.2011 at each velocity for the ultrasonic anemometer is shown in Table 6 and Figure 28.

Table 6 – Degree of equivalence of each participating institute with respect to the KCRV

	US anemometer										
Nominal airspeed V_{nom} [m/s]	KCRV	U(KCRV)	PTB			CETIAT			VSL		
			d	U(d)	En	d	U(d)	En	d	U(d)	En
0.5	1.025	0.010	-0.005	0.020	0.25	-0.001	0.027	0.03	-0.031	0.049	0.63
1	1.010	0.006	-0.002	0.012	0.19	0.007	0.016	0.41	-0.015	0.013	1.13
2	1.002	0.005	-0.009	0.011	0.83	0.003	0.013	0.23	0.000	0.013	0.03
5	0.9890	0.0024	-0.0034	0.0046	0.75	-0.0011	0.0072	0.15	-0.003	0.010	0.27
10	0.9871	0.0022	-0.0018	0.0042	0.41	0.0014	0.0066	0.21	0.003	0.010	0.26
15	0.9881	0.0022	-0.0008	0.0041	0.19	0.0013	0.0063	0.21	0.000	0.010	0.03
20	0.9890	0.0022	-0.0004	0.0040	0.09	0.0016	0.0062	0.26	-0.005	0.010	0.46
30	0.9878	0.0023	0.0009	0.0039	0.25	0.0039	0.0060	0.65	-0.007	0.013	0.53
40	0.9895	0.0025	0.0000	0.0037	0.00	0.0043	0.0059	0.72	-0.012	0.015	0.77

Nominal airspeed V_{nom} [m/s]	KCRV	U(KCRV)	E+E			NMIJ			NIM		
			d	U(d)	En	d	U(d)	En	d	U(d)	En
0.5	1.025	0.010	-0.022	0.020	1.12	-0.009	0.043	0.21	0.000	0.038	0.01
1	1.010	0.006	-0.010	0.012	0.82	-0.005	0.018	0.26	-0.001	0.019	0.05
2	1.002	0.005	-0.010	0.011	0.83	-0.003	0.011	0.29	0.006	0.017	0.36
5	0.9890	0.0024	-0.0053	0.0066	0.81	0.0001	0.0059	0.01	-0.0010	0.0084	0.11
10	0.9871	0.0022	-0.0021	0.0064	0.33	0.0012	0.0048	0.25	0.0029	0.0066	0.43
15	0.9881	0.0022	-0.0005	0.0064	0.07	0.0010	0.0052	0.19	-0.0021	0.0064	0.32
20	0.9890	0.0022	-0.0005	0.0063	0.08	-0.0005	0.0052	0.10	-0.0020	0.0065	0.31
30	0.9878	0.0023	0.0001	0.0063	0.02	-0.0003	0.0044	0.08	-0.0008	0.0070	0.11
40	0.9895	0.0025	-0.0007	0.0061	0.11	-0.0017	0.0041	0.42			

Nominal airspeed V_{nom} [m/s]	KCRV	U(KCRV)	CMS			NIST			INRIM		
			d	U(d)	En	d	U(d)	En	d	U(d)	En
0.5	1.025	0.010	-0.001	0.018	0.08	0.013	0.018	0.74			
1	1.010	0.006	0.002	0.011	0.20	0.011	0.012	0.93			
2	1.002	0.005	0.005	0.011	0.43	0.003	0.010	0.27	0.000	0.014	0.01
5	0.9890	0.0024	0.0005	0.0054	0.09	0.0047	0.0046	1.02	-0.0004	0.0092	0.04
10	0.9871	0.0022	0.0026	0.0053	0.48	-0.0017	0.0043	0.40	-0.0074	0.0093	0.79
15	0.9881	0.0022	0.0071	0.0056	1.25	-0.0019	0.0043	0.43	-0.0082	0.0093	0.88
20	0.9890	0.0022	0.0087	0.0055	1.59	-0.0019	0.0043	0.45	-0.0079	0.0092	0.86
30	0.9878	0.0023				-0.0002	0.0043	0.04	-0.0061	0.0093	0.65
40	0.9895	0.0025				0.0006	0.0042	0.13			

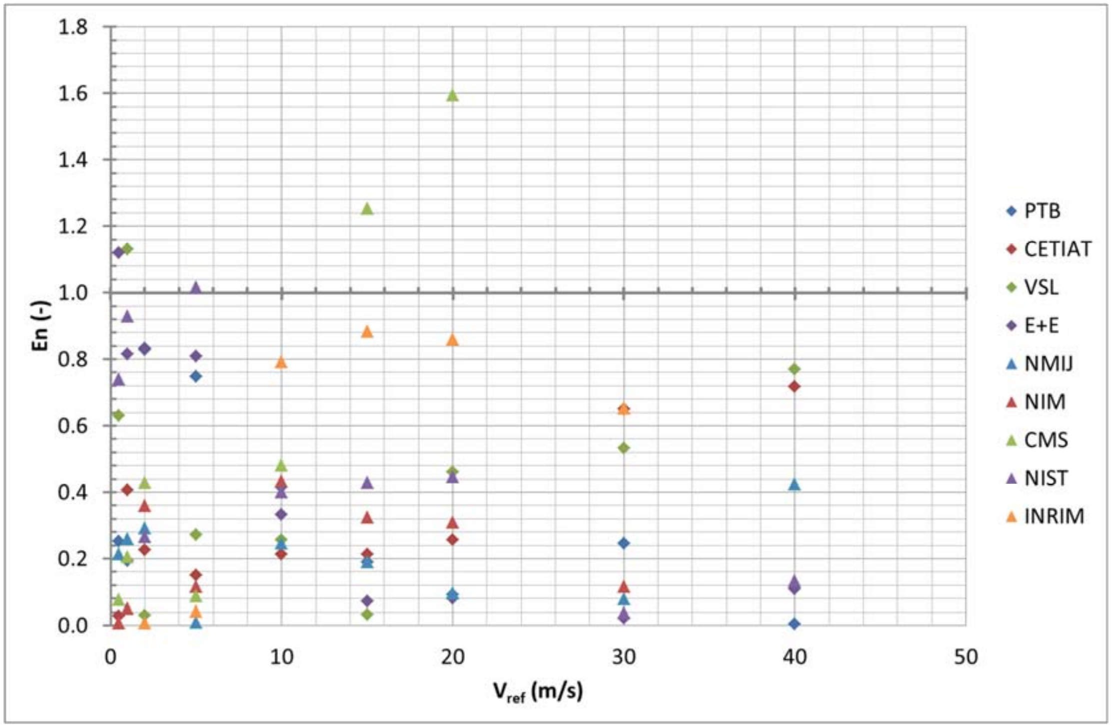


Figure 28 – Normalized error of each participating institute with respect to the KCRV

7.3.2. Laser Doppler anemometer

The degree of equivalence between the KCRV of CCM.FF-K3.2011 at each velocity for the Laser Doppler anemometer is shown in Table 7 and Figure 29.

Table 7 – Degree of equivalence of each participating institute with respect to the KCRV

	LDA anemometer										
Nominal airspeed V_{nom} [m/s]	KCRV	U(KCRV)	PTB			CETIAT			VSL		
			d	U(d)	En	d	U(d)	En	d	U(d)	En
0.5	0.9993	0.0034	0.000	0.013	0.02	0.000	0.021	0.02	-0.041	0.045	0.92
1	1.0000	0.0032	0.003	0.008	0.38	0.007	0.013	0.50	-0.015	0.010	1.50
2	1.0013	0.0024	0.000	0.005	0.03	0.003	0.009	0.36	-0.001	0.010	0.12
5	1.0006	0.0018	0.0021	0.0041	0.51	-0.0005	0.0066	0.07	-0.004	0.010	0.43
10	1.0016	0.0017	0.0017	0.0036	0.47	-0.0005	0.0058	0.09	0.006	0.010	0.63
15	1.0016	0.0018	0.0018	0.0034	0.52	0.0001	0.0055	0.02	0.002	0.010	0.19
20	1.0016	0.0017	0.0017	0.0034	0.49	-0.0003	0.0054	0.05	0.002	0.012	0.20
30	1.0012	0.0019	0.0014	0.0032	0.44	0.0001	0.0052	0.01	0.003	0.014	0.18
40	1.0009	0.0019	0.0012	0.0031	0.40	0.0014	0.0052	0.27	-0.003	0.015	0.18

Nominal airspeed V_{nom} [m/s]	KCRV	U(KCRV)	E+E			NMIJ			NIM		
			d	U(d)	En	d	U(d)	En	d	U(d)	En
0.5	0.9993	0.0034	0.001	0.013	0.09				0.003	0.007	0.37
1	1.0000	0.0032	0.000	0.008	0.02				-0.001	0.007	0.16
2	1.0013	0.0024	-0.001	0.006	0.14	-0.003	0.006	0.42	0.000	0.004	0.11
5	1.0006	0.0018	-0.0012	0.0052	0.24	0.0006	0.0049	0.12	-0.0006	0.0027	0.22
10	1.0016	0.0017	-0.0022	0.0048	0.45	-0.0005	0.0044	0.11	0.0002	0.0025	0.07
15	1.0016	0.0018	-0.0019	0.0046	0.41	0.0001	0.0047	0.02	-0.0007	0.0037	0.18
20	1.0016	0.0017	-0.0020	0.0046	0.44	-0.0007	0.0047	0.14	0.0006	0.0027	0.22
30	1.0012	0.0019	-0.0015	0.0045	0.34	-0.0012	0.0034	0.35	0.0014	0.0049	0.29
40	1.0009	0.0019	-0.0010	0.0044	0.22	-0.0013	0.0024	0.55			

Nominal airspeed V_{nom} [m/s]	KCRV	U(KCRV)	CMS			NIST			INRIM		
			d	U(d)	En	d	U(d)	En	d	U(d)	En
0.5	0.9993	0.0034	-0.003	0.004	0.65	0.002	0.005	0.51			
1	1.0000	0.0032	-0.001	0.006	0.13	0.003	0.005	0.65			
2	1.0013	0.0024	0.000	0.007	0.07	0.000	0.007	0.04	0.003	0.010	0.33
5	1.0006	0.0018	-0.0018	0.0050	0.35	0.001	0.004	0.19	0.0004	0.0089	0.05
10	1.0016	0.0017	0.0003	0.0054	0.06	-0.0009	0.0038	0.24	-0.0088	0.0089	0.99
15	1.0016	0.0018	0.0006	0.0051	0.12	-0.0006	0.0037	0.17	-0.0077	0.0090	0.85
20	1.0016	0.0017	-0.0008	0.0050	0.16	-0.0009	0.0038	0.23	-0.0066	0.0091	0.72
30	1.0012	0.0019				-0.0002	0.0037	0.06	-0.0066	0.0090	0.73
40	1.0009	0.0019				0.0002	0.0037	0.06			

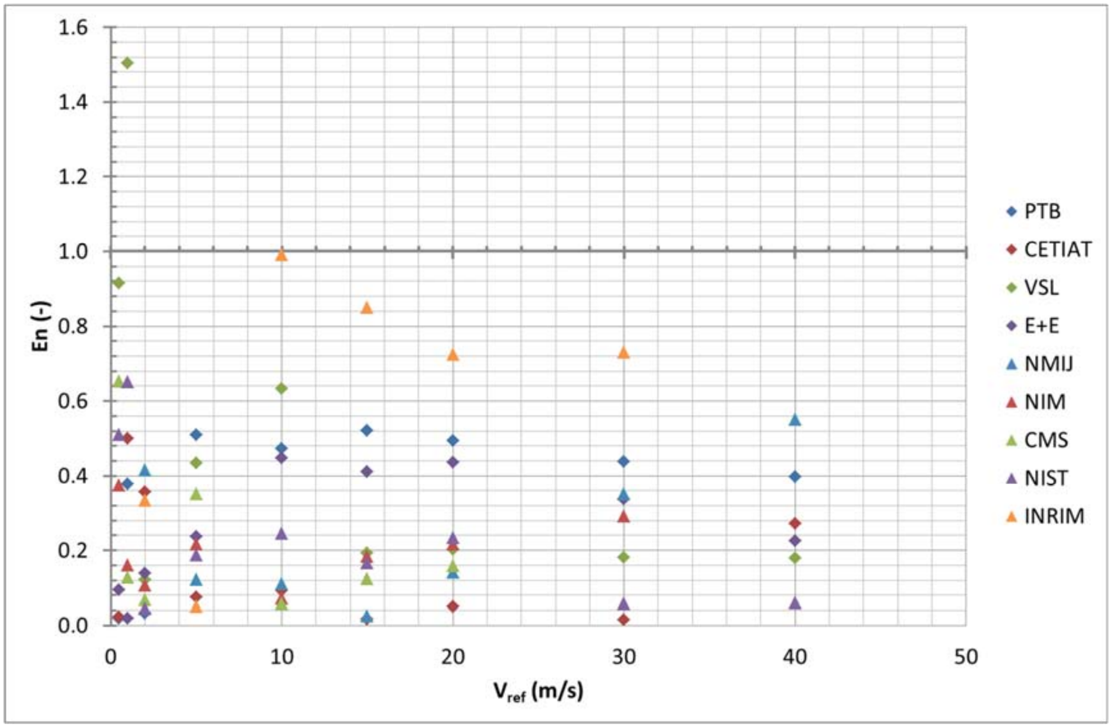


Figure 29 – Normalized error of each participating institute with respect to the KCRV

7.4. Discussion

The ultrasonic anemometer was of that type used as transfer standard for the 1st round of the K3 comparison.

The Laser Doppler Anemometer has shown its value as a transfer standard because of its stability in time and the fact that it generates no disturbances in the flow.

As a consequence, the Laser Doppler anemometer led to more consistent calibration results with lower calibration uncertainties in all participating institutes than the ultrasonic one.

However, even if the comparison results are satisfactory for the Best Existing Device (the one for which the CMCs are claimed), the uncertainty values reported in customer calibration reports may be underestimated if the disturbance due to the instrument in the flow is poorly taken into account. The interest of the use of the ultrasonic anemometer is the ability of the participating laboratories to assess how to take potential disturbances into account.

8. Optional LDA calibration with a primary standard

Optionally, a calibration of the LDA with a primary standard was proposed. Each institute was invited to use its own procedure. Five partners provided measurement data resulting from rotating wheel (or spinning disk) facilities and covering different velocity ranges. Provided data were the reference wheel speed and the indicated LDA velocity, as well as the associated calibration uncertainty.

8.1. Measurements results

The ratio between the wheel speed and the indicated LDA velocity is presented in Figure 30. All of the reported values are listed in Appendix A.

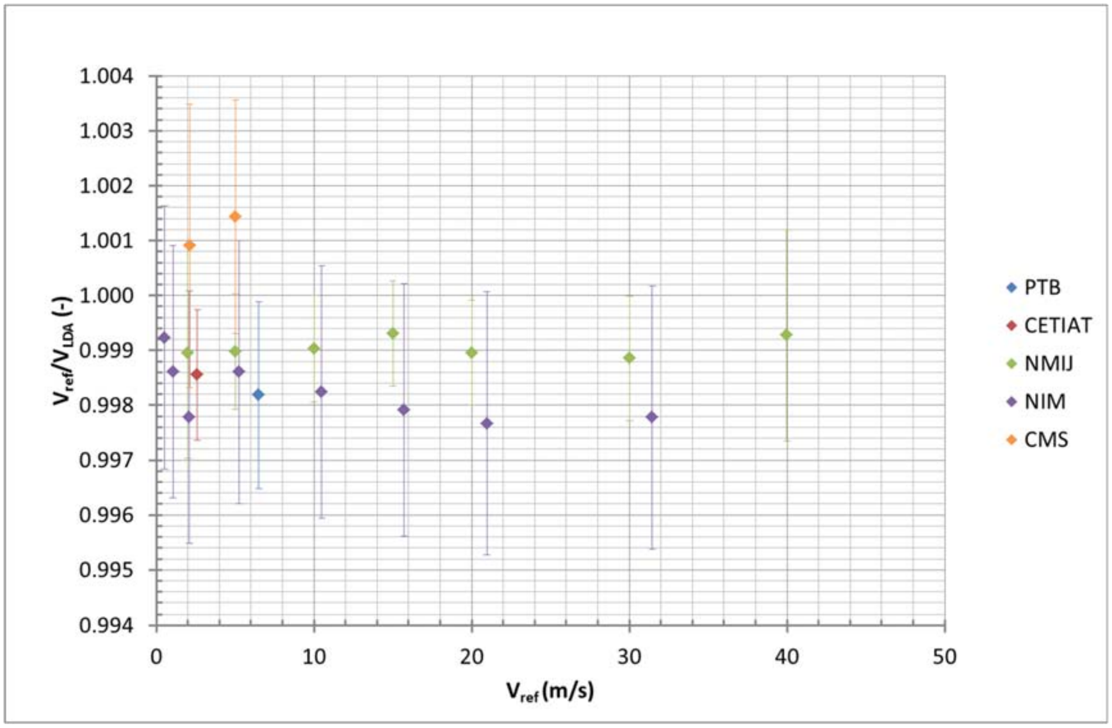


Figure 30 - Results obtained by all the participants for the calibration of the Laser Doppler anemometer with a primary standard

A KCRV is calculating using Cox procedure as already described in the previous section. For this calculation, the contribution of the transfer standard was chosen according to the analysis of the LDA stability (see section 6.2). For institutes which provided values over a velocity range (see Appendix A), a mean value was considered and the expanded uncertainty took also into account the deviation of the reported values around this mean value and the maximum of the calibration uncertainty.

Table 8 – Results of the chi square test on the overall data set

KCRV	U(KCRV)	χ^2_{obs}	n-1	Test $\chi^2_{0.05,\ n-1}$	Result
0.9988	0.0008	3.73	4	9.49	Pass

The test passed for the overall set. All the data are mutually consistent.

The degree of equivalence and the normalized error were calculated for each institute and presented in the table below:

Table 9 – Degree of equivalence of each participating institute with respect to the KCRV

KCRV	U(KCRV)	PTB			CETIAT			NMIJ		
		d	U(d)	En	d	U(d)	En	d	U(d)	En
0.9988	0.0008	-0.0006	0.0015	0.38	-0.00020	0.00091	0.22	0.0003	0.0018	0.16

NIM			CMS		
d	U(d)	En	d	U(d)	En
-0.0005	0.0023	0.23	0.0024	0.0025	0.96

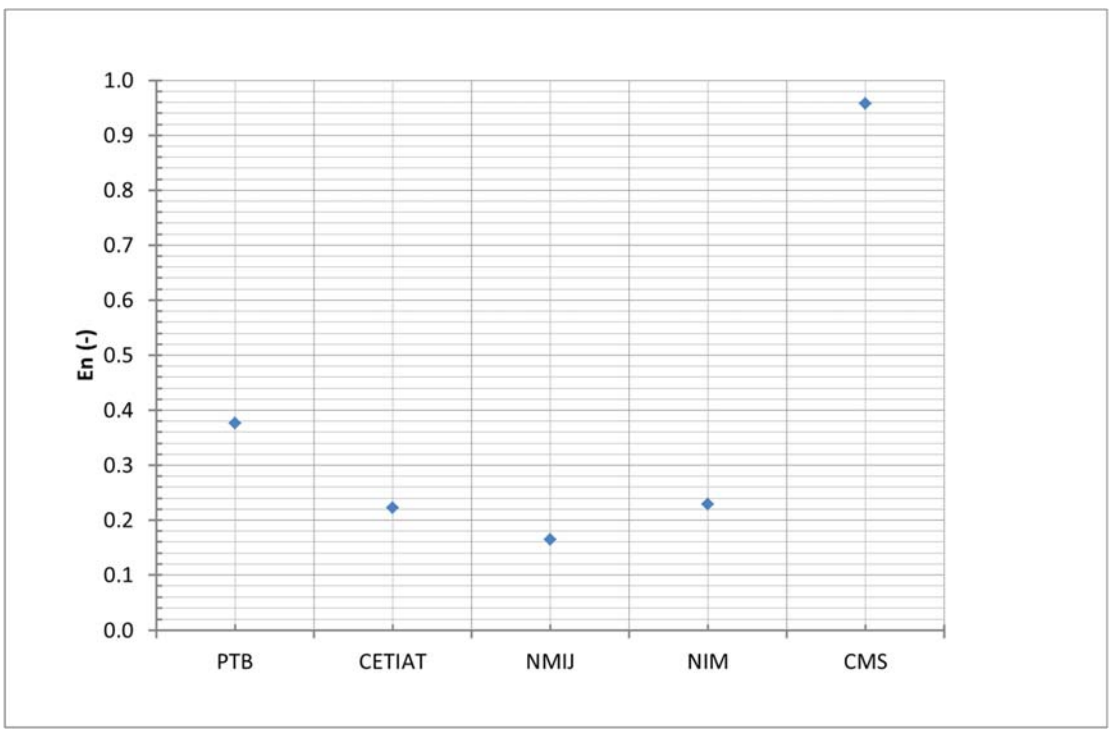


Figure 31 – Normalized error of each participating institute with respect to the KCRV

8.2. Discussion

Different procedures were used by the laboratories for the calibration of the LDA with a primary standard. Some of them considered it as a black box (including the fringe spacing of the LDA and the signal processing system) and performed the calibration over an air speed range. Some others, considering the LDA as an instrument composed of a signal processing system and a Laser probe, performed the calibration at only one value of air speed for the calculation of the fringe spacing. Considering this latter case, access to the signal processing or the Doppler frequency measurement is needed.

In this first evaluation, we assume the signal processing had no influence on the results since the LDA constant is the fringe spacing, which is theoretically independent of the velocity. Observed fluctuations of v_{ref}/v_{LDA} over the velocity range probably are due to effects of the rotating wheel facility as the signal processing influence normally can be neglected. For each of the participants, the mean value over the covered air speed range was considered.

Considering the results of the comparison, this assumption concerning the negligible impact of the signal processing error on the LDA constant measurement is validated for the used LDA.

9. SUMMARY AND CONCLUSIONS

Nine institutes took part in the second run of the key comparison CCM.FF-K3-2011 for air speed measurement. Two transfer standards were used. The first one was an ultrasonic anemometer similar to the one used during the first run in 2005. The second one was a laser Doppler anemometer, known as the best transfer standard in the field which had already shown its interest during the EURAMET comparison 827.

The performance of the transfer standards and their stability in time was evaluated from the measurement of one of the pilot institutes, PTB. The transfer standards showed good stability since the uncertainty due to the transfer standards was less than the quoted uncertainties of the participants.

However, the Laser Doppler anemometer showed better performances in all the participating institutes than the ultrasonic one with lower calibration uncertainties.

The chi-square consistency test showed that for the two transfer standards, for the overall velocity range, the data were mutually consistent. The KCRVs were then obtained as the weighted mean of the calibration results.

The calculated degree of equivalence and E_n values show a high consistency between the calibration results and the calculated KCRVs with

- less than 3% of the values with a normalized error greater than 1.2 and less than 4% of the values within the warning zone, for the ultrasonic anemometer,
- one value with a normalized error greater than 1.2 for the Laser Doppler anemometer.

The results obtained for the optional calibration of the Laser Doppler anemometer against a primary standard show also a high consistency even if the used procedures are not exactly equivalent.

The following tables check the compliance of the results obtained by each participating laboratory to its claimed CMCs, when available.

As the CMCs are usually declared for the “Best Existing Device” (BED), this comparison is performed first for the LDA transfer standard. However, as the ultrasonic anemometer was considered in the past, and more especially during the first round of the K3 comparison, as the BED despite its disturbing impact on the flow, the comparison is also performed with it.

Table 10 is related to the comparison measurements with the two transfer standards in the air speed range between 0.5 m/s and 40 m/s whereas table 11 shows the impact on the CMC claims related to the optionally proposed calibration of the LDA with a spinning disc as primary standard.

Table 10 – Comparison of the results with the declared CMCs for the calibration of an anemometer

Country NMI	Range (as declared in CMCs tables)	Expanded uncertainty (as declared in CMCs tables)	Result
Germany PTB	0.5 m/s to 40 m/s	(0.005 m/s + 0.0035v), v speed in m/s	In accordance
France CETIAT	0.15 m/s to 40 m/s	0.009 m/s to 0.28 m/s	In accordance
Netherlands VSL	1 m/s to 35 m/s	1 %	In accordance[1])
Austria BEV-E+E	0.3 m/s to 40 m/s	(0.4/v_{ref} + 0.47), v_{ref} speed in m/s	In accordance
Japan NMIJ	1.3 m/s to 27.5 m/s	[0.297 + 0.27/(v^2 - 0.77v)] v speed in m/s	In accordance
	27.5 m/s to 40 m/s	[-0.0001185v^3 + 0.01157v^2 - 0.3677v + 4.124] v speed in m/s	In accordance
China NIM			No CMCs
Chinese Taipei CMS	0.5 m/s to 25 m/s	0.5 %	In accordance [2])
United States NIST	0.15 m/s to 75 m/s	[0.42 + 0.0039exp(1.22/v)] v speed in m/s	In accordance
Italy INRIM			No CMCs

[1]) The results of K3 support CMCs except for the value at 1 m/s.

[2]) The results of K3 support CMCs for the best existing device (LDA) but E_n values greater than 1.2 for the ultrasonic anemometer transfer standard at 15 m/s and 20 m/s suggest that, for this device under test, the calibration procedure may not be appropriate, or the uncertainty values given in customer calibration reports are underestimated.

Table 11 – Comparison of the results with the declared CMCs for the calibration of LDA with a spinning disc

Country NMI	Range	Expanded uncertainty	Result
	as declared in CMCs tables		
Germany PTB	0.1 m/s to 15 m/s	0.1 %	In accordance
France CETIAT	1 µm to 15 µm	0.05 %	In accordance
Japan NMIJ	1.3 m/s to 27.5 m/s	$[0.091 + 0.22/(v^2 - 0.9v)]$ % v air speed in m/s	In accordance
	27.5 m/s to 40 m/s	$[-0.0002386v^3 + 0.02331v^2 - 0.7409v + 7.801]$ % v air speed in m/s	In accordance
China NIM			No CMCs
Chinese Taipei CMS			No CMCs

10. Nomenclature

V_{ref}	Reference air speed measurement (m/s)
V_{ts} (V_{UA}, V_{LDA})	Transfer standard (Ultrasonic anemometer, Laser Doppler anemometer) measurement (m/s)
K	Ratio between the reference air speed and the transfer standard measurements (-)
KCRV	Comparison reference value (-)
u(X)	Standard uncertainty of the mesurand *X*
U(X)	Expanded uncertainty of the mesurand *X* with approximately 95% confidence level
d	Degree of equivalence = *K* – *KCRV* (-)
En	Standardized degree of equivalence between a lab and the key comparison reference value, =| *d*/2u(*d*) |

11. References

[1] TERAO Y., VAN DER BEEK M., YEH T.T., MÜLLER H., Final report on the CIPM air speed key comparison (CCM.FF-K3), BIPM KCDB Database, October 2007

[2] MÜLLER H., Final Report on LDA-based intercomparison of anemometers (EURAMET 827), EURAMET.M.FF.S5, BIPM KCDB Database, February 2012

[3] Comité International des Poids et Mesures (CIPM), Mutual recognition of national measurement standards and of calibration and measurement certificates issued by national metrology institutes, Paris, 14 October 1999

[4] CCM-WGS, CCM Guidelines for approval and publication of the final reports of key and supplementary comparisons, 30 June 2016

[5] CCEM, CCEM Guidelines for planning, organizing, conducting and reporting key, supplementary and pilot comparisons, 21 March 2007

[6] CCQM Guidance note: Estimation of a consensus KCRV and associated Degrees of Equivalence, 12 April 2013

[7] COX M.G., The evaluation of key comparison data, Metrologia **(39)**, pp 589-595, 2002

APPENDIX A - TABLE OF RESULTS

A.1. PTB

	Institute 's results - Ultrasonic anemometer					Pilot calculation
Nominal airspeed V_{nom} [m/s]	Reference air speed V_{ref} [m/s]	Indicated air speed V_{US} [m/s]	Standard deviation air speed [m/s]	Calibration result V_{ref}/V_{US}	Lab Uncertainty $U(V_{ref}/V_{US})$	Expanded Uncertainty $U(V_{ref}/V_{US})$
0.5	0.5014	0.492	0.001	1.0201	0.0136	0.0229
1	0.9984	0.991	0.006	1.0076	0.0085	0.0132
2	1.9821	1.996	0.005	0.9930	0.0060	0.0116
5	5.0075	5.081	0.002	0.9855	0.0045	0.0052
10	9.9997	10.148	0.009	0.9854	0.0040	0.0047
15	14.9615	15.154	0.040	0.9873	0.0038	0.0046
20	19.9419	20.171	0.005	0.9886	0.0038	0.0045
30	29.8843	30.224	0.007	0.9887	0.0037	0.0045
40	39.8130	40.238	0.005	0.9894	0.0036	0.0044

	Institute 's results - Laser Doppler anemometer					Pilot calculation
Nominal airspeed V_{nom} [m/s]	Reference air speed V_{ref} [m/s]	Indicated air speed V_{LDA} [m/s]	Standard deviation air speed [m/s]	Calibration result V_{ref}/V_{LDA}	Lab Uncertainty $U(V_{ref}/V_{LDA})$	Expanded Uncertainty $U(V_{ref}/V_{LDA})$
0.5	0.4904	0.491	0.011	0.9990	0.0136	0.0136
1	0.9954	0.992	0.003	1.0030	0.0085	0.0085
2	1.9991	1.997	0.001	1.0011	0.0060	0.0060
5	4.9936	4.980	0.004	1.0027	0.0045	0.0045
10	9.9975	9.965	0.007	1.0033	0.0040	0.0040
15	14.9865	14.937	0.007	1.0033	0.0038	0.0038
20	19.9487	19.885	0.006	1.0032	0.0037	0.0038
30	29.8838	29.806	0.012	1.0026	0.0037	0.0037
40	39.8588	39.774	0.010	1.0021	0.0036	0.0036

	Institute 's results - LDA vs Rotating wheel				Pilot calculation
Reference wheel speed V_{ref} [m/s]	Indicated air speed V_{LDA} [m/s]	Standard deviation air speed [m/s]	Calibration result V_{ref}/V_{LDA}	Lab Uncertainty $U(V_{ref}/V_{LDA})$	Expanded Uncertainty $U(V_{ref}/V_{US})$
6.4950	6.507	0.001	0.9982	0.0017	0.0017

A.2. CETIAT

	Institute 's results - Ultrasonic anemometer					Pilot calculation
Nominal airspeed V_{nom} [m/s]	Reference air speed V_{ref} [m/s]	Indicated air speed V_{US} [m/s]	Standard deviation air speed [m/s]	Calibration result V_{ref}/V_{US}	Lab Uncertainty $U(V_{ref}/V_{US})$	Expanded Uncertainty $U(V_{ref}/V_{US})$
0.5	0.5012	0.487	0.014	1.0245	0.0225	0.0291
1	1.0024	0.981	0.014	1.0166	0.0139	0.0172
2	2.0145	1.995	0.014	1.0048	0.0097	0.0139
5	5.0245	5.062	0.016	0.9879	0.0072	0.0076
10	10.0276	10.095	0.024	0.9885	0.0064	0.0069
15	15.0343	15.122	0.042	0.9894	0.0062	0.0067
20	20.0379	20.131	0.061	0.9906	0.0060	0.0066
30	30.0698	30.175	0.114	0.9917	0.0059	0.0065
40	39.8573	39.917	0.165	0.9937	0.0059	0.0064

	Institute 's results - Laser Doppler anemometer					Pilot calculation
Nominal airspeed V_{nom} [m/s]	Reference air speed V_{ref} [m/s]	Indicated air speed V_{LDA} [m/s]	Standard deviation air speed [m/s]	Calibration result V_{ref}/V_{LDA}	Lab Uncertainty $U(V_{ref}/V_{LDA})$	Expanded Uncertainty $U(V_{ref}/V_{LDA})$
0.5	0.4995	0.500	0.002	0.9998	0.0216	0.0216
1	1.0003	0.994	0.004	1.0066	0.0135	0.0135
2	2.0094	2.000	0.004	1.0045	0.0093	0.0093
5	5.0107	5.010	0.008	1.0001	0.0068	0.0068
10	10.0136	10.003	0.016	1.0011	0.0060	0.0060
15	15.0020	14.977	0.027	1.0017	0.0058	0.0058
20	19.9971	19.971	0.040	1.0013	0.0056	0.0056
30	29.9864	29.947	0.063	1.0013	0.0055	0.0055
40	39.9518	39.860	0.124	1.0023	0.0055	0.0055

	Institute 's results - LDA vs Rotating wheel				Pilot calculation
Reference wheel speed V_{ref} [m/s]	Indicated air speed V_{LDA} [m/s]	Standard deviation air speed [m/s]	Calibration result V_{ref}/V_{LDA}	Lab Uncertainty $U(V_{ref}/V_{LDA})$	Expanded Uncertainty $U(V_{ref}/V_{US})$
2.6026	2.606	0.001	0.9986	0.0012	0.0012

A.3. VSL

	Institute 's results - Ultrasonic anemometer					Pilot calculation
Nominal airspeed V_{nom} [m/s]	Reference air speed V_{ref} [m/s]	Indicated air speed V_{US} [m/s]	Standard deviation air speed [m/s]	Calibration result V_{ref}/V_{US}	Lab Uncertainty $U(V_{ref}/V_{US})$	Expanded Uncertainty $U(V_{ref}/V_{US})$
0.5	0.5045	0.507	0.018	0.9942	0.0470	0.0503
1	1.0244	1.029	0.016	0.9953	0.0100	0.0141
2	2.0345	2.032	0.027	1.0014	0.0100	0.0142
5	5.0854	5.157	0.051	0.9862	0.0101	0.0104
10	10.1450	10.250	0.187	0.9897	0.0101	0.0104
15	15.2249	15.414	0.295	0.9877	0.0100	0.0103
20	20.2132	20.537	0.432	0.9842	0.0102	0.0105
30	30.1164	30.704	0.785	0.9809	0.0130	0.0132
40	36.4939	37.318	0.963	0.9779	0.0150	0.0152

	Institute 's results - Laser Doppler anemometer					Pilot calculation
Nominal airspeed V_{nom} [m/s]	Reference air speed V_{ref} [m/s]	Indicated air speed V_{LDA} [m/s]	Standard deviation air speed [m/s]	Calibration result V_{ref}/V_{LDA}	Lab Uncertainty $U(V_{ref}/V_{LDA})$	Expanded Uncertainty $U(V_{ref}/V_{LDA})$
0.5	0.5069	0.529		0.9582	0.0450	0.0450
1	1.0236	1.039		0.9848	0.0106	0.0106
2	2.0407	2.041		1.0001	0.0105	0.0105
5	5.0991	5.118		0.9963	0.0101	0.0101
10	10.1676	10.088		1.0079	0.0101	0.0101
15	15.1627	15.109		1.0035	0.0103	0.0103
20	20.2925	20.213		1.0039	0.0118	0.0118
30	29.9684	29.857		1.0037	0.0140	0.0140
40	35.0228	35.085		0.9982	0.0150	0.0150

A.4. E+E

	Institute 's results - Ultrasonic anemometer					Pilot calculation
Nominal airspeed V_{nom} [m/s]	Reference air speed V_{ref} [m/s]	Indicated air speed V_{US} [m/s]	Standard deviation air speed [m/s]	Calibration result V_{ref}/V_{US}	Lab Uncertainty $U(V_{ref}/V_{US})$	Expanded Uncertainty $U(V_{ref}/V_{US})$
0.5	0.4853	0.484	0.001	1.0031	0.0131	0.0223
1	0.9837	0.984	0.001	1.0000	0.0090	0.0134
2	1.9767	1.992	0.001	0.9923	0.0074	0.0123
5	4.9757	5.059	0.001	0.9836	0.0065	0.0070
10	9.9655	10.117	0.001	0.9850	0.0063	0.0068
15	14.9728	15.161	0.002	0.9876	0.0062	0.0067
20	19.9336	20.166	0.005	0.9885	0.0062	0.0067
30	29.9191	30.284	0.017	0.9879	0.0062	0.0067
40	40.2110	40.667	0.008	0.9888	0.0061	0.0066

	Institute 's results - Laser Doppler anemometer					Pilot calculation
Nominal airspeed V_{nom} [m/s]	Reference air speed V_{ref} [m/s]	Indicated air speed V_{LDA} [m/s]	Standard deviation air speed [m/s]	Calibration result V_{ref}/V_{LDA}	Lab Uncertainty $U(V_{ref}/V_{LDA})$	Expanded Uncertainty $U(V_{ref}/V_{LDA})$
0.5	0.4934	0.493	0.000	1.0005	0.0130	0.0130
1	0.9936	0.993	0.000	1.0002	0.0088	0.0088
2	1.9954	1.995	0.000	1.0004	0.0067	0.0067
5	5.0180	5.021	0.001	0.9994	0.0055	0.0055
10	10.0405	10.046	0.002	0.9994	0.0051	0.0051
15	15.0871	15.092	0.002	0.9997	0.0050	0.0050
20	20.0697	20.079	0.001	0.9996	0.0049	0.0049
30	30.1362	30.144	0.005	0.9997	0.0048	0.0048
40	40.4431	40.447	0.006	0.9999	0.0048	0.0048

A.5. NMIJ

	Institute 's results - Ultrasonic anemometer					Pilot calculation
Nominal airspeed V_{nom} [m/s]	Reference air speed V_{ref} [m/s]	Indicated air speed V_{US} [m/s]	Standard deviation air speed [m/s]	Calibration result V_{ref}/V_{US}	Lab Uncertainty $U(V_{ref}/V_{US})$	Expanded Uncertainty $U(V_{ref}/V_{US})$
0.5	0.5121	0.504	0.005	1.0160	0.0406	0.0445
1	1.0177	1.013	0.004	1.0052	0.0165	0.0193
2	2.0299	2.033	0.001	0.9985	0.0073	0.0123
5	5.0326	5.089	0.001	0.9890	0.0058	0.0064
10	10.0327	10.151	0.000	0.9883	0.0046	0.0053
15	15.0505	15.217	0.002	0.9890	0.0050	0.0056
20	20.0572	20.291	0.003	0.9885	0.0051	0.0057
30	30.1021	30.484	0.003	0.9875	0.0042	0.0049
40	40.1303	40.629	0.007	0.9877	0.0040	0.0048

	Institute 's results - Laser Doppler anemometer					Pilot calculation
Nominal airspeed V_{nom} [m/s]	Reference air speed V_{ref} [m/s]	Indicated air speed V_{LDA} [m/s]	Standard deviation air speed [m/s]	Calibration result V_{ref}/V_{LDA}	Lab Uncertainty $U(V_{ref}/V_{LDA})$	Expanded Uncertainty $U(V_{ref}/V_{LDA})$
0.5						
1						
2	2.0134	2.016	0.001	0.9987	0.0067	0.0067
5	5.0201	5.014	0.000	1.0012	0.0052	0.0052
10	9.9993	9.988	0.000	1.0011	0.0047	0.0047
15	15.0047	14.979	0.002	1.0017	0.0050	0.0050
20	19.9988	19.981	0.001	1.0009	0.0050	0.0050
30	29.9948	29.993	0.002	1.0001	0.0038	0.0038
40	40.0199	40.038	0.008	0.9996	0.0031	0.0031

	Institute 's results - LDA vs Rotating wheel				Pilot calculation
Reference wheel speed V_{ref} [m/s]	Indicated air speed V_{LDA} [m/s]	Standard deviation air speed [m/s]	Calibration result V_{ref}/V_{LDA}	Lab Uncertainty $U(V_{ref}/V_{LDA})$	Expanded Uncertainty $U(V_{ref}/V_{US})$
1.9987	2.001	0.000	0.9990	0.0019	
4.9987	5.004	0.000	0.9990	0.0011	
10.0017	10.011	0.000	0.9990	0.0010	
14.9984	15.009	0.001	0.9993	0.0010	
19.9991	20.020	0.002	0.9990	0.0010	
30.0103	30.045	0.003	0.9989	0.0011	
39.9932	40.022	0.005	0.9993	0.0019	
Pilot calculation			0.9991		0.0019

A.6. NIM

	Institute 's results - Ultrasonic anemometer					Pilot calculation
Nominal airspeed V_{nom} [m/s]	Reference air speed V_{ref} [m/s]	Indicated air speed V_{US} [m/s]	Standard deviation air speed [m/s]	Calibration result V_{ref}/V_{US}	Lab Uncertainty $U(V_{ref}/V_{US})$	Expanded Uncertainty $U(V_{ref}/V_{US})$
0.5	0.5267	0.508	0.002	1.0250	0.0343	0.0389
1	1.0804	1.055	0.002	1.0090	0.0168	0.0196
2	2.0681	2.048	0.002	1.0080	0.0146	0.0177
5	5.0222	4.991	0.005	0.9880	0.0083	0.0087
10	10.1183	10.093	0.007	0.9900	0.0065	0.0070
15	15.1331	15.103	0.009	0.9860	0.0062	0.0067
20	20.1673	20.103	0.004	0.9870	0.0063	0.0068
30	29.8872	29.822	0.021	0.9870	0.0069	0.0074
40						

	Institute 's results - Laser Doppler anemometer					Pilot calculation
Nominal airspeed V_{nom} [m/s]	Reference air speed V_{ref} [m/s]	Indicated air speed V_{LDA} [m/s]	Standard deviation air speed [m/s]	Calibration result V_{ref}/V_{LDA}	Lab Uncertainty $U(V_{ref}/V_{LDA})$	Expanded Uncertainty $U(V_{ref}/V_{LDA})$
0.5	0.5291	0.528	0.008	1.0019	0.0078	0.0078
1	1.0589	1.060	0.009	0.9989	0.0077	0.0077
2	2.0274	2.024	0.020	1.0017	0.0043	0.0043
5	4.9896	4.989	0.041	1.0000	0.0032	0.0032
10	9.9273	9.910	0.073	1.0018	0.0030	0.0030
15	15.1297	15.116	0.103	1.0009	0.0041	0.0041
20	20.0664	20.023	0.143	1.0022	0.0032	0.0032
30	29.9718	29.893	0.214	1.0026	0.0052	0.0052
40						

	Institute 's results - LDA vs Rotating wheel				Pilot calculation
Reference wheel speed V_{ref} [m/s]	Indicated air speed V_{LDA} [m/s]	Standard deviation air speed [m/s]	Calibration result V_{ref}/V_{LDA}	Lab Uncertainty $U(V_{ref}/V_{LDA})$	Expanded Uncertainty $U(V_{ref}/V_{US})$
0.5240	0.524	0.000	0.9992	0.0024	
1.0483	1.050	0.000	0.9986	0.0023	
2.0967	2.101	0.000	0.9978	0.0023	
5.2415	5.249	0.001	0.9986	0.0024	
10.4833	10.502	0.000	0.9982	0.0023	
15.7250	15.758	0.001	0.9979	0.0023	
20.9667	21.016	0.002	0.9977	0.0024	
31.4500	31.520	0.005	0.9978	0.0024	
Pilot calculation			0.9982		0.0024

A.7. CMS

	Institute 's results - Ultrasonic anemometer					Pilot calculation
Nominal airspeed V_{nom} [m/s]	Reference air speed V_{ref} [m/s]	Indicated air speed V_{US} [m/s]	Standard deviation air speed [m/s]	Calibration result V_{ref}/V_{US}	Lab Uncertainty $U(V_{ref}/V_{US})$	Expanded Uncertainty $U(V_{ref}/V_{US})$
0.5	0.5281	0.516	0.021	1.0239	0.0093	0.0207
1	1.0259	1.014	0.020	1.0121	0.0065	0.0120
2	1.9666	1.954	0.031	1.0065	0.0063	0.0118
5	5.0247	5.078	0.043	0.9894	0.0053	0.0059
10	9.7678	9.870	0.058	0.9897	0.0051	0.0057
15	14.8520	14.925	0.096	0.9951	0.0055	0.0060
20	19.9143	19.961	0.126	0.9977	0.0053	0.0059
30						
40						

	Institute 's results - Laser Doppler anemometer					Pilot calculation
Nominal airspeed V_{nom} [m/s]	Reference air speed V_{ref} [m/s]	Indicated air speed V_{LDA} [m/s]	Standard deviation air speed [m/s]	Calibration result V_{ref}/V_{LDA}	Lab Uncertainty $U(V_{ref}/V_{LDA})$	Expanded Uncertainty $U(V_{ref}/V_{LDA})$
0.5	0.5006	0.502	0.014	0.9965	0.0055	0.0055
1	1.0019	1.003	0.012	0.9993	0.0064	0.0064
2	1.9787	1.977	0.019	1.0009	0.0070	0.0070
5	4.8904	4.893	0.031	0.9989	0.0053	0.0053
10	9.8411	9.822	0.060	1.0019	0.0056	0.0056
15	14.8325	14.800	0.089	1.0022	0.0054	0.0054
20	19.6378	19.623	0.126	1.0008	0.0052	0.0052
30						
40						

	Institute 's results - LDA vs Rotating wheel				Pilot calculation
Reference wheel speed V_{ref} [m/s]	Indicated air speed V_{LDA} [m/s]	Standard deviation air speed [m/s]	Calibration result V_{ref}/V_{LDA}	Lab Uncertainty $U(V_{ref}/V_{LDA})$	Expanded Uncertainty $U(V_{ref}/V_{US})$
2.1027	2.101	0.012	1.0009	0.0026	
5.0258	5.019	0.005	1.0014	0.0021	
Pilot calculation			1.0012		0.0026

A.8. NIST

	Institute 's results - Ultrasonic anemometer					Pilot calculation
Nominal airspeed V_{nom} [m/s]	Reference air speed V_{ref} [m/s]	Indicated air speed V_{US} [m/s]	Standard deviation air speed [m/s]	Calibration result V_{ref}/V_{US}	Lab Uncertainty $U(V_{ref}/V_{US})$	Expanded Uncertainty $U(V_{ref}/V_{US})$
0.5	0.5009	0.482	0.003	1.0384	0.0086	0.0206
1	0.9998	0.979	0.006	1.0208	0.0080	0.0130
2	2.0000	1.991	0.003	1.0045	0.0046	0.0111
5	5.0004	5.033	0.004	0.9936	0.0045	0.0052
10	9.9994	10.148	0.001	0.9854	0.0041	0.0048
15	14.9985	15.208	0.002	0.9862	0.0041	0.0048
20	19.9988	20.261	0.002	0.9871	0.0041	0.0048
30	29.9973	30.373	0.005	0.9876	0.0041	0.0049
40	39.9917	40.395	0.008	0.9900	0.0041	0.0048

	Institute 's results - Laser Doppler anemometer					Pilot calculation
Nominal airspeed V_{nom} [m/s]	Reference air speed V_{ref} [m/s]	Indicated air speed V_{LDA} [m/s]	Standard deviation air speed [m/s]	Calibration result V_{ref}/V_{LDA}	Lab Uncertainty $U(V_{ref}/V_{LDA})$	Expanded Uncertainty $U(V_{ref}/V_{LDA})$
0.5	0.5009	0.500	0.003	1.0017	0.0059	0.0059
1	0.9998	0.997	0.006	1.0032	0.0058	0.0058
2	2.0000	1.998	0.006	1.0010	0.0075	0.0075
5	5.0004	4.994	0.002	1.0013	0.0042	0.0042
10	9.9994	9.993	0.001	1.0007	0.0041	0.0041
15	14.9985	14.984	0.002	1.0010	0.0041	0.0041
20	19.9988	19.985	0.009	1.0007	0.0042	0.0042
30	29.9973	29.967	0.001	1.0010	0.0041	0.0041
40	39.9917	39.947	0.010	1.0011	0.0041	0.0041

A.9. INRIM

	Institute 's results - Ultrasonic anemometer					Pilot calculation
Nominal airspeed V_{nom} [m/s]	Reference air speed V_{ref} [m/s]	Indicated air speed V_{US} [m/s]	Standard deviation air speed [m/s]	Calibration result V_{ref}/V_{US}	Lab Uncertainty $U(V_{ref}/V_{US})$	Expanded Uncertainty $U(V_{ref}/V_{US})$
0.5						
1						
2	2.0057	2.002	0.000	1.0017	0.0103	0.0144
5	4.9627	5.020	0.002	0.9886	0.0092	0.0095
10	9.9095	10.114	0.008	0.9798	0.0092	0.0096
15	14.8222	15.126	0.019	0.9799	0.0092	0.0095
20	19.8577	20.241	0.035	0.9811	0.0091	0.0095
30	29.4831	30.032	0.081	0.9817	0.0093	0.0096
32	30.7363	31.298	0.088	0.9820	0.0094	0.0098

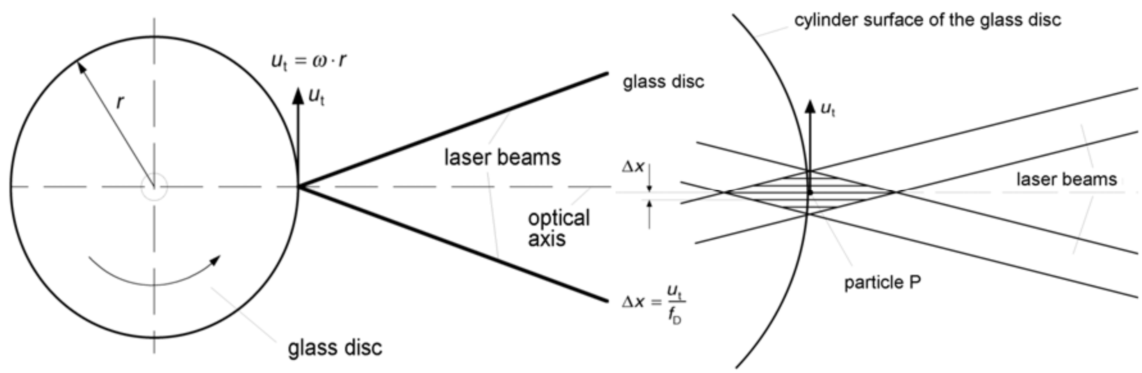
	Institute 's results - Laser Doppler anemometer					Pilot calculation
Nominal airspeed V_{nom} [m/s]	Reference air speed V_{ref} [m/s]	Indicated air speed V_{LDA} [m/s]	Standard deviation air speed [m/s]	Calibration result V_{ref}/V_{LDA}	Lab Uncertainty $U(V_{ref}/V_{LDA})$	Expanded Uncertainty $U(V_{ref}/V_{LDA})$
0.5						
1						
2	2.0135	2.004	0.011	1.0047	0.0103	0.0103
5	4.9975	4.992	0.034	1.0011	0.0091	0.0091
10	9.9721	10.045	0.073	0.9928	0.0090	0.0090
15	14.8975	14.989	0.113	0.9939	0.0092	0.0092
20	19.9156	20.016	0.169	0.9950	0.0092	0.0092
30	29.5341	29.693	0.244	0.9947	0.0092	0.0092
32	30.8065	30.970	0.268	0.9947	0.0094	0.0094

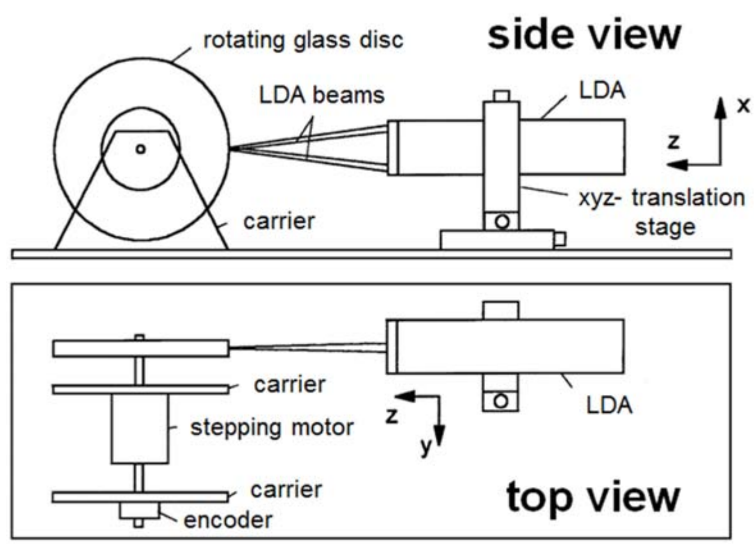
APPENDIX B – DESCRIPTION OF THE FACILITIES

B.1. PTB

a. PTB velocity primary standard for LDA

At PTB´s LDA calibration facility the velocity of a set of single scattering particles adhered to the lateral surface of a polished glass cylinder represents the "standard" velocity u_t which is given by the angular speed ω and the radius r of a rotating glass disc ($2r$ = 184 mm).





Principle: LDA calibration via particle velocities u_t generated by a rotating glass disc.

Calibration results are provided in two different formats:

- as LDA measuring head specific calibration constant represented by the fringe spacing,
- as LDA calibration factor derived from the standard velocity of the rotating disc facility and the indicated LDA velocity of the associated LDA signal processing unit.

For both formats the relative expanded uncertainty (k = 2) for the calibration (best available DUT) is 0.1 % according to the CMC in the KCDB:

Flow speed. Laser Doppler Velocimeter (LDV), 0.1 m/s to 15 m/s

Relative expanded uncertainty (k = 2, level of confidence 95%) in %: 0.1

LDV

Particle speed: rotating glass wheel surface for fringe calibration

Approved on 16 November 2012

Internal NMI service identifier: DE39

b. PTB calibration facility for air speed anemometers

Calibrations of air speed anemometers according to the PTB service identifier DE41 are performed in the Göttingen type wind tunnel at PTB. The reference velocity v_{ref} is determined by the use of a Laser Doppler Anemometer as reference standard and represents the velocity at the position of the probe in the measurement section of the wind tunnel (see figure and table below).

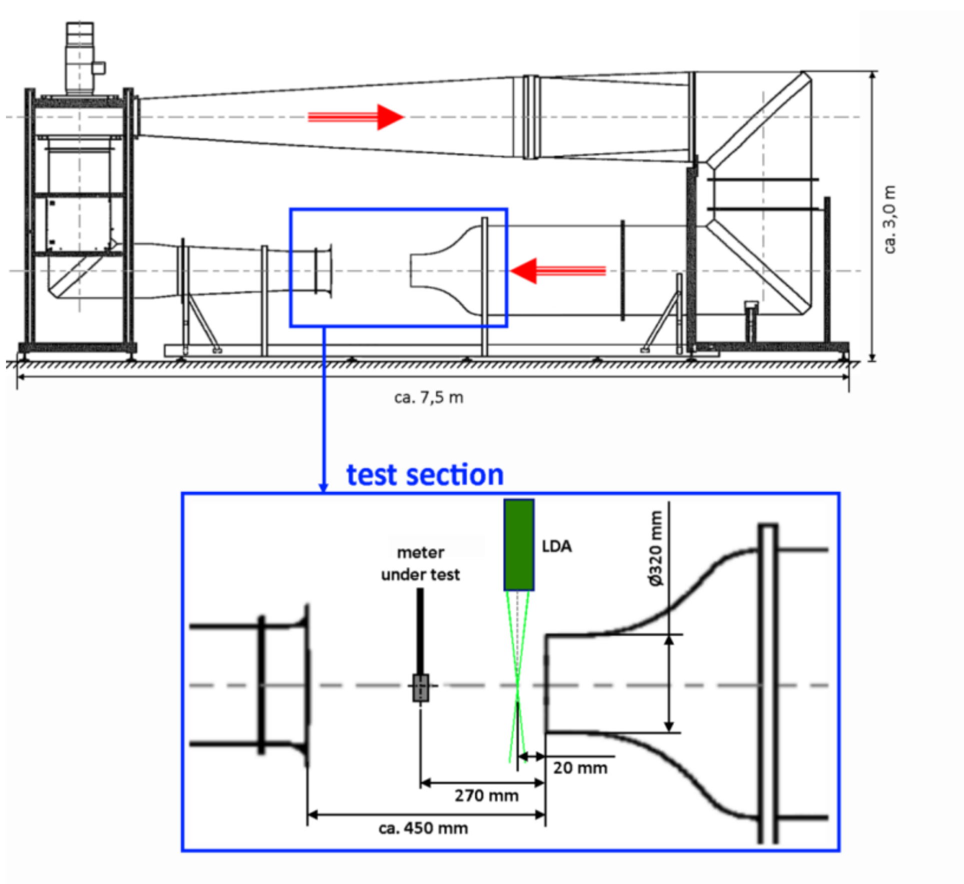


Figure 1 - Setup of the Göttingen type wind tunnel at PTB

Table 1 - Data for anemometer's calibration in the Göttingen type wind tunnel at PTB

Type:	Göttingen, open test section
Range:	0.5, ..., 65 m/s
Uncertainty:	(0.005 + 0.0035 · *U*), *U* speed in m/s
Dimensions measuring section:	nozzle diameter: Ø 320 mm test section length: 450 mm
Reference:	LDA
Traceability:	PTB, rotating glass wheel surface for fringe calibration, frequency standard

B.2. CETIAT

a. Facilities for the calibration of anemometers

CETIAT has 2 wind tunnels allowing the calibration of anemometers:

	High Speed Wind tunnel	Low Speed Wind tunnel
Type	Göttingen type, closed test section in square shape	closed loop, closed test section in square shape
Range	0.15 – 40 m/s	0.05 – 2 m/s
Uncertainty (k=2)	(0.008 + 0.0051×U), U in m/s	(0.006 + 0.006×U), U in m/s
Dimensions of the measuring section	Width: 500 mm Height: 500 mm Length: 1000 mm	Width: 125 mm Height: 125 mm Length: 300 mm
Temperature	10 – 40°C	10 – 50°C
Humidity	ambient	10% - 90%
Pressure	ambient	ambient
Direction	Horizontal	Horizontal, Vertical upward, Vertical downward
Reference measurement	LDA	LDA
Traceability	CETIAT(fringe spacing calibration, frequency)	CETIAT(fringe spacing calibration, frequency)

Only the High Speed Wind tunnel has been used during the K3 comparison for the calibration of the ultrasonic anemometer and the LDA.

Figure 1 - High Speed wind tunnel

b. Primary standard for the calibration of LDA

A rotating wheel is available for the calibration of LDA. The reference speed is given by the product of the rotation speed of a glass cylinder by its radius. This reference value is compared to the value measured by the LDA when its measurement volume focuses on the side of the disc.

The relative expanded uncertainty (k = 2) for the calibration is 0.05% according to the CMC in the KCDB.

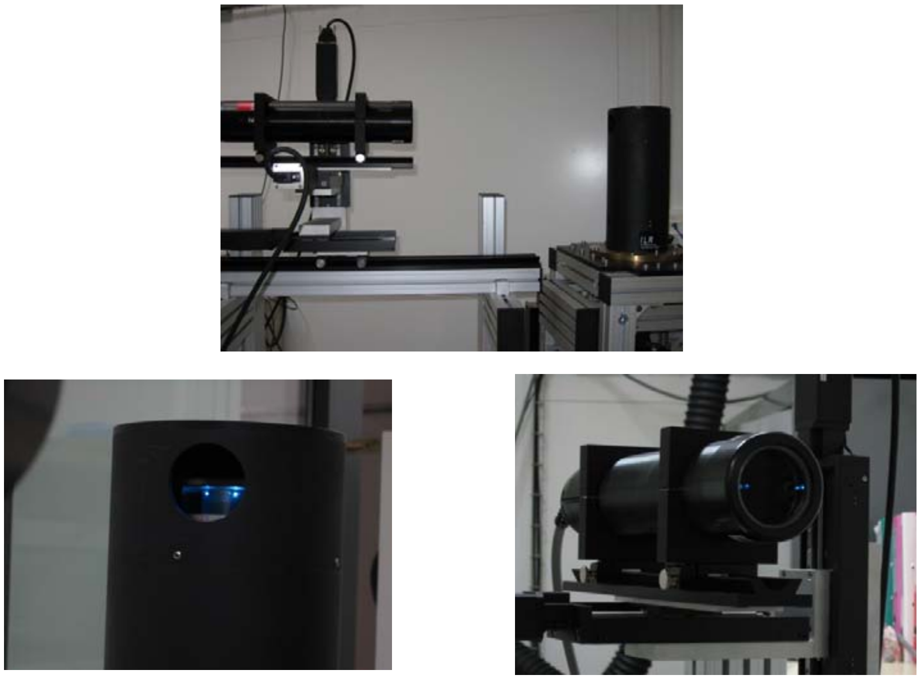


Figure 2 - Primary standard for the calibration of LDA (rotating wheel)

B.3. VSL

The VSL anemometer test bench consists of a test facility for atmospheric flow rates (15 - 15000 m^3/h) coupled to an open, blowing circular wind duct with a diameter of 380 mm. The flow characteristics are enhanced by means of a number of parallel 5mm hexagonal channels (honeycomb plates of 1.2 diameter, L = 50 mm). The traceability is realized by means of an iterative calibration process, starting with the known actual reference flow rate at the position of the anemometer. The position of the measuring body is always in the centerline and plane of the free-outlet of the duct.

B.4. E+E

a. Accreditation Range

Designated laboratory for air speed (BEV/E+E) in the range of:

- Air velocity: 0.3 - 40 m/s
- Temperature range: 5 - 80°C

A closed loop wind tunnel with an open test section (Figure 1) delivers a defined homogeneous air flow profile. There is a limitation of the dimensions of the test devices due to the dimensions of the measurement section.

b. System Description

- Reference Instrument:
  - Laser Doppler-Anemometer: ILA Flowpoint 550
- Wind tunnel:
  - Type: Göttingen (closed loop) with an open test section
  - Contraction ratio: 4
  - Contraction Length-Diameter ratio: 1
  - Test section: round, diameter: 0.255 m; length 0.30 m
  - Turbulence: TU=0.15-0.4%
- Further components of the system:
  - Humidity-/Temperature measurement (Typ EE31 E+E Elektronik) as a reference
  - Pressure-Reference: Keller pressure transmitter (Typ 33x)
  - Measurement devices (current, voltage, pulse, digital,..) for the output signals of the test devices

The temperature in the wind tunnel can be controlled in a range between 5 and 80 °C

Figure 1 - Closed loop wind tunnel with an open test section

c. Best measurement capability

With respect to all measurement uncertainties of the system one can calculate the best measurement capability as followed (k=2 for 95% confidence level):

Air velocity, v:

- Range: v =0.3 to 40 m/s
- 0.004 m/s + 0.0047 × v

d. Calibration of references

The Laser Doppler Anemometer (LDA) is calibrated every 3 years at the Physikalisch-Technische Bundesanstalt (PTB) in Braunschweig. The actual calibration of the distance of the interference fringes is used for the determination of the air velocity.

Measurement devices for the state variables (pressure, temperature and humidity) are calibrated once a year and any deviations are considered.

B.5. NMIJ

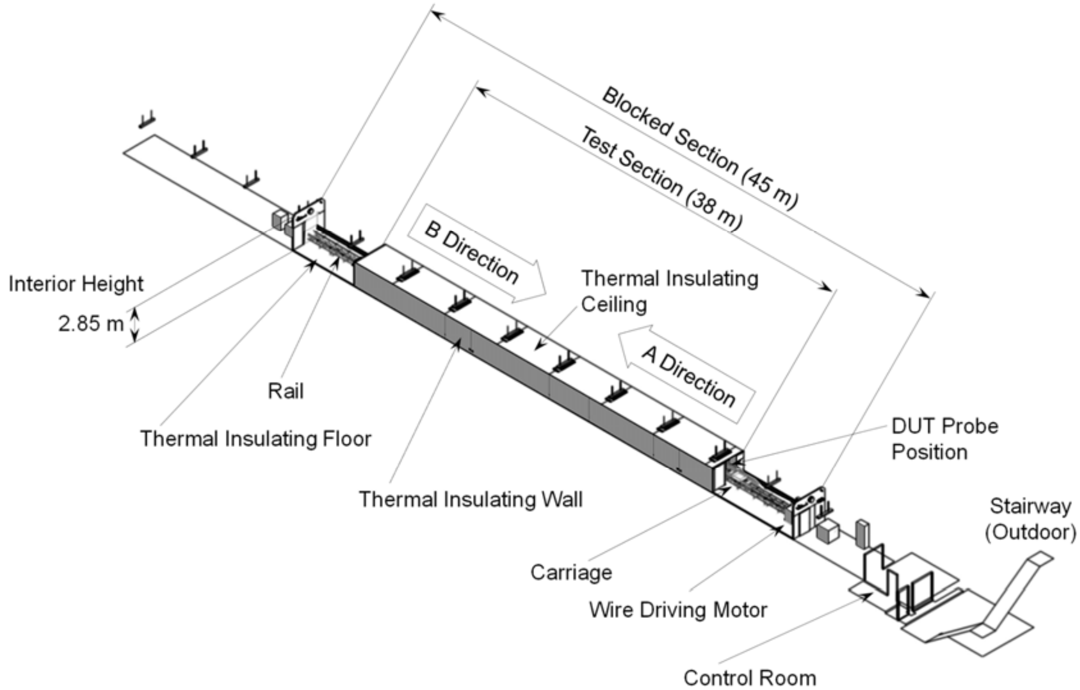
a. Used calibration facility

NMIJ has 3 categories of air speed standard segmented by range now, however, the highest range (40 m/s - 90 m/s) was not provided yet at the key comparison performed in 2013. Figure 1 shows schematics of standard facilities used for the key comparison.

For calibration points less than 1.3 m/s, tow carriage system of low air speed standard was used. The tow carriage travels along the rail trough static air in underground tunnel, and outputs from the DUT is compared with the reference traveling speed determined by laser interferometer. The carriage runs 4 times for each calibration point. To calm the air, the carriage waits 30 minutes for 0.5 m/s and 45 minutes for 1.0 m/s. The carriage runs for opposite directions represented as A and B in Figure 1 (i) to avoid the error caused by background flow through the tunnel.

For other calibration points up to 40 m/s, wind tunnel was used for both transfer anemometers. The wind tunnel of NMIJ is Gottingen type, and has closed test section in square shape. Double pass ultrasonic flow meter fixed just upstream of the measuring point is used as a reference anemometer of the wind tunnel. For LDA measurement, enlarged incense smoke particles were seeded in wind tunnel to detect the scattered light from the air flow.

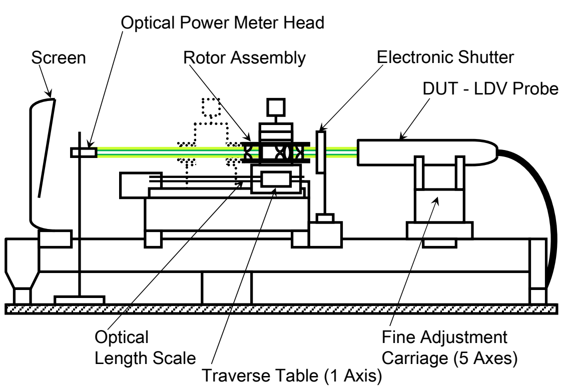
According to the recommendation in protocol, spinning disc system is also used for the LDA calibration. The spinning disk has 5 μm tungsten wire to simulate the seeding particle. To avoid the error caused by wire bending, the wire orbit diameter is measured by observing the burst signal amplitude with traversing rotor assembly at each calibration speed just before the Doppler frequency measurement. This spinning disc system generates various speeds to treat the whole LDA setup as a black box to include the frequency dependence of the signal processor for calibration result.



Primary standard: Tow carriage

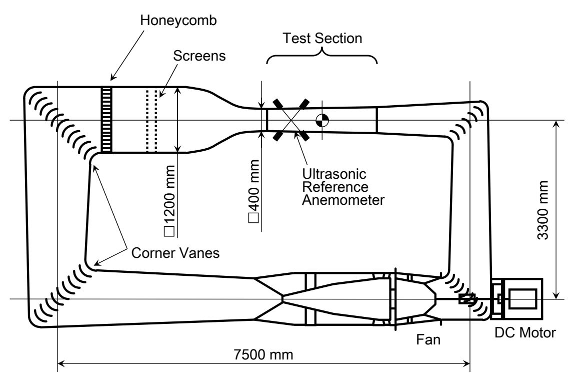
Expanded uncertainty 6.9 mm/s - 8.7 mm/s

(i) Low air speed (0.05 m/s - 1.5 m/s)



Primary standard: Spinning disc

Expanded uncertainty 0.063 % - 0.50 %



Working standard: Wind tunnel

Expanded uncertainty 0.29 % - 0.67 %

(ii) Medium air speed (1.3 m/s - 40 m/s)

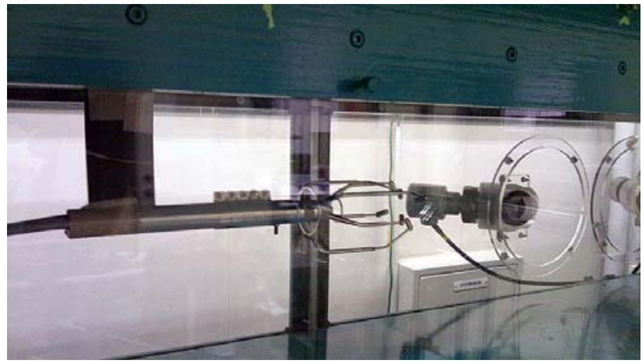
Figure 1 Air speed standard facility of NMIJ

b. Procedure

i. Ultrasonic anemometer calibration

Figure 2 shows the overview of ultrasonic anemometer calibration using the wind tunnel (2 m/s - 4 m/s) and the tow carriage (0.5 m/s and 1.0 m/s) with or without item A-5 support provided for the DUT probe. The measurement results were compared to validate the effect of the support shape, and little differences were found between them.

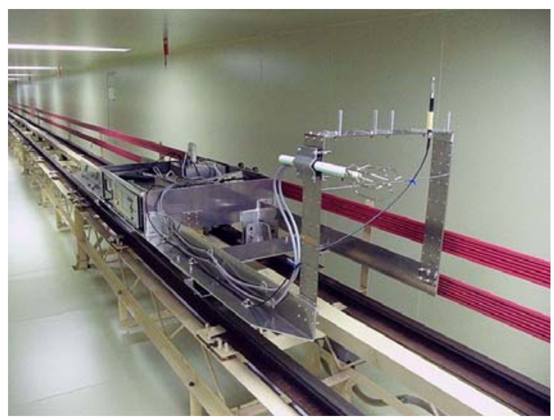
a. Holding the probe with item A-5



b. Holding the probe with own device

(i) Using wind tunnel (2 m/s - 40 m/s)

a. Holding the probe with item A-5



b. Holding the probe with own device

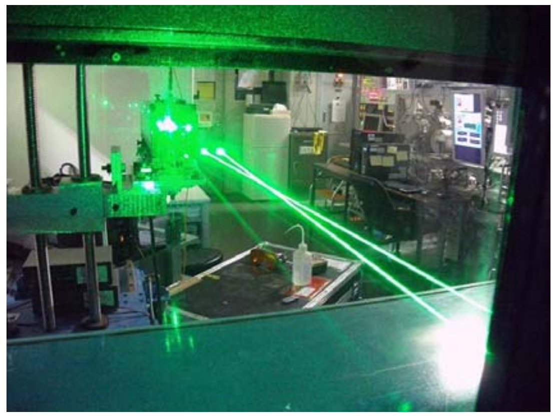
(ii) Using tow carriage (0.5 m/s and 1.0 m/s)

Figure 2 Overview of ultrasonic anemometer calibration

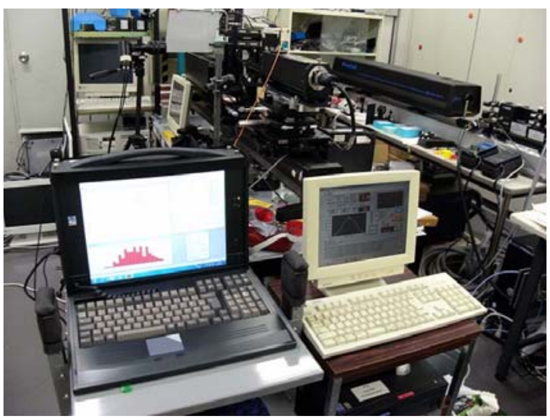
ii. LDA calibration

Figure 3 shows the overview of the LDA calibration using the wind tunnel and the spinning disc. Generally, the acquisition of burst signals seems to be easier than LDA owned by NMIJ (60X probe with beam expander and BSA F60 setup, Dantec Dynamics) for the smoke particles seeded in wind tunnel. At spinning disc, system evaluation at various speeds and fringe spacing evaluation were done. As shown in Figure 4, the fringe spacing distribution was quite flat and the length of the measuring control volume was quite long compare to the LDA owned by NMIJ.

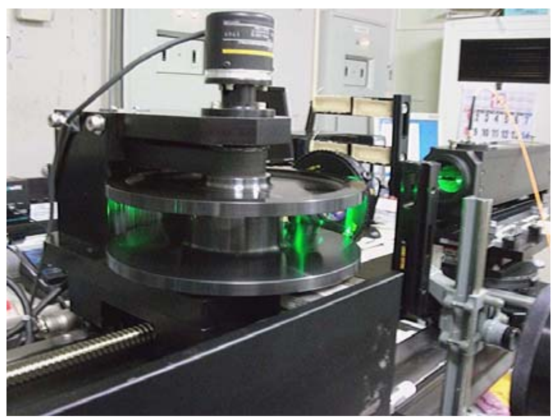
To validate the measurement result, the calibration result of LDA at the spinning disc was used to correct the indication of LDA observed at the wind tunnel. There found good agreement with the correction factor achieved at in-house calibration result for wind tunnel.



(i) Using wind tunnel (2 m/s - 40 m/s)



a. System evaluation at various speeds



b. Fringe spacing evaluation

(ii) Using spinning disc (2 m/s - 40 m/s)

Figure 3 Overview of LDA calibration

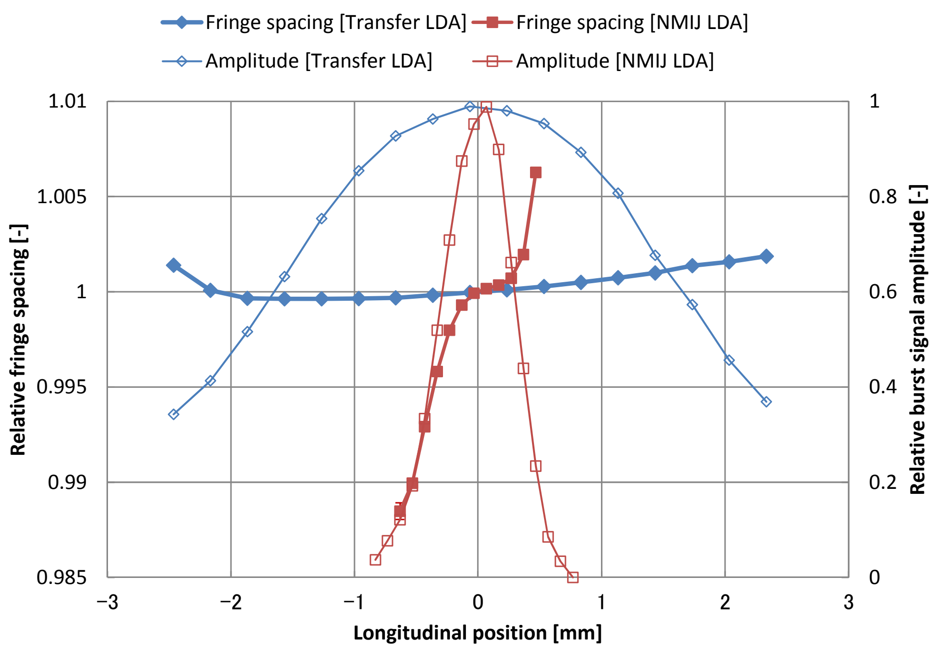


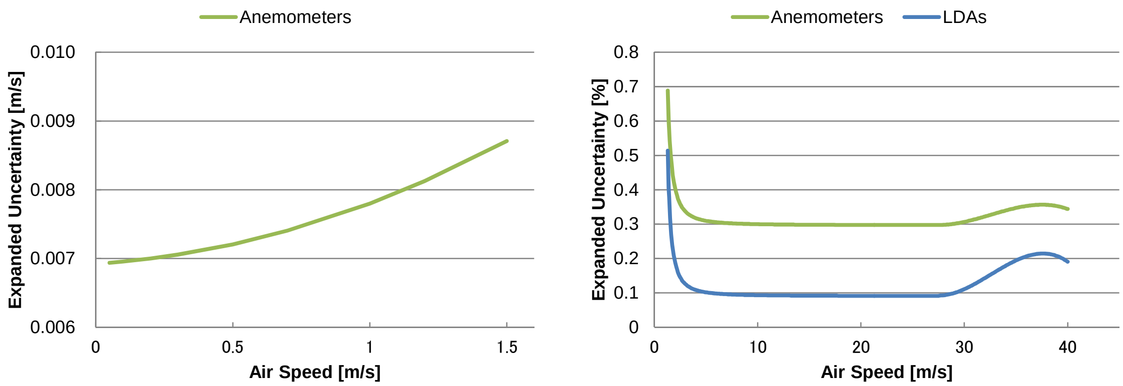
Figure 4 Relative fringe spacing distribution evaluated at NMIJ

c. Standard

Table 1 shows CMC for anemometers and LDAs of NMIJ. These expanded uncertainties are also plotted in Figure 5 by air speed.

Table 1 - CMC for anemometers and LDAs

Instrument	Range	Expanded Uncertainty (k =2)
Anemometers	0.05 m/s ≤ v ≤ 1.5 m/s	[0.0069+(0.025v+0.005) ^{2}] m/s
LDVs	1.3 m/s ≤ v ≤ 27.5 m/s	[0.091+0.22/(v^2-0.9v)] %
	27.5 m/s < v ≤ 40 m/s	[-0.0002386v^3+0.02331v^2-0.7409v+7.801] %
Anemometers	1.3 m/s ≤ v ≤ 27.5 m/s	[0.297+0.27/(v^2-0.77v)] %
	27.5 m/s < v ≤ 40 m/s	[-0.0001185v^3+0.01157v^2-0.3677v+4.124] %



(i) Low air speed (0.05 m/s - 1.5 m/s) (ii) Medium air speed (1.3 m/s - 40 m/s)

Figure 5 CMC plot for anemometers and LDAs

B.6. NIM

a. The standard facilities at NIM

The air velocity standard facility was developed at 2009, which locates in the new campus of NIM. The wind tunnel, LDV and spinning-disc facility are taken to make experiments of K3.

i. Wind tunnel

The type of wind tunnel at NIM is open-jet. The specification and facility are shown as Table 1 and the Figure 1.

Table 1 - The specification of wind tunnel

Velocity range	(0.2~30）m/s
Radius of nozzle	R=100mm
Core region	R=70mm
Uniformity of profile	0.35%
Stability of flow	0.35%
Contraction	9 : 1
Diameter of settling chamber	600mm
Size of test section	Length1000mm,Width 800mm, Height 800mm
Diameter of diffuser	300mm
Type of fan	Axial fan

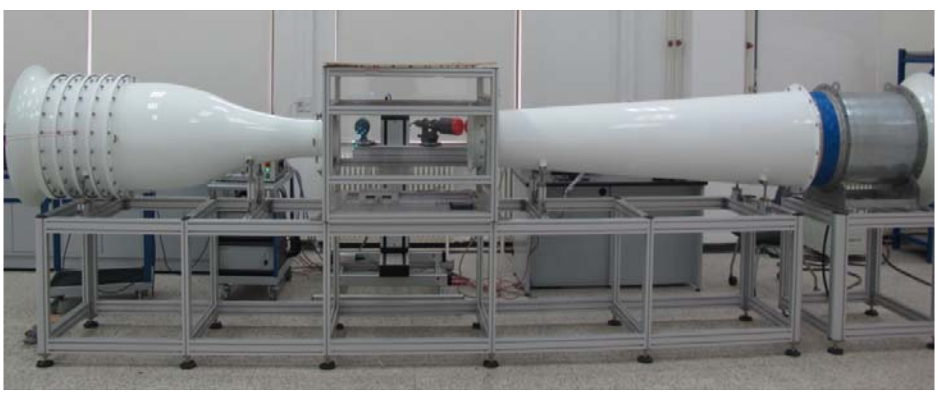


Figure 1 - Wind tunnel

ii. LDV

The LDV for K3 is manufactured by Dantec. The specification is shown as Table 2.

Table 2 - LDV specification

Wave length	514.5 nm
Diameter of front lens	60 mm
Beam distance	39.07 mm
Focus length	800 mm
expander	E=1.98
Scatter particles	DEHS
Diameter of particles	5 μm
Expanded uncertainty	0.24%，k=2

iii. Spinning-disc facility

The spinning-disc for K3 is developed by NIM. The specification and facility are shown as Table 3 and Figure 2.

Table 3 - Specification of spinning-disc facility

Diameter of spinning-disc	200.2848 mm
Velocity range	（0.1~30） m/s
Diameter of wire	5 μm

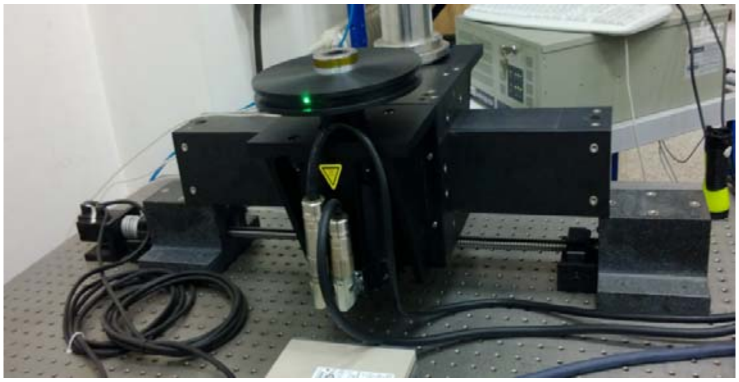


Figure 2 - Spinning-disc facility

b. Measurement procedure

i. US meter calibration

(1) The US meter for comparison is mounted at the position of 170mm away from nozzle outlet and the air velocity at 20mm position in the flow axial is measured by LDV. The size of wind tunnel is described as table 1. The 8 velocity points including 0.5 m/s, 1 m/s, 2 m/s, 5 m/s, 10 m/s, 15 m/s, 20 m/s, 30 m/s are taken. The experiment is shown as figure 3.

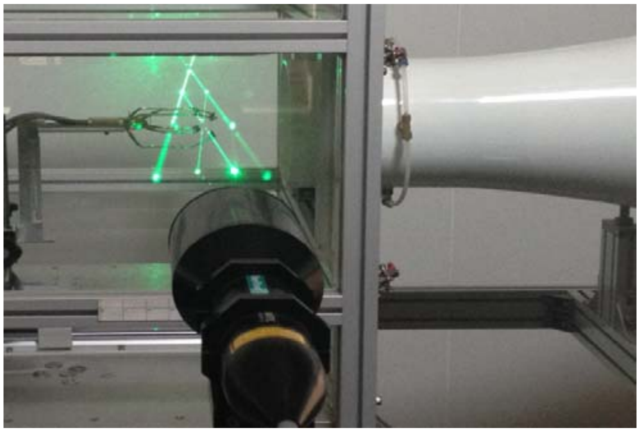


Figure 3 - US meter calibration

(2) Calculation

$$C_{US} = \frac{V_{LDV}}{V_{US}} \frac{V_{170}}{V_{20}} \qquad (1)^*$$

*No blockage correction is done for formula (1).

(3) Uncertainty evaluation

The uncertainty of US meter is evaluated according to formula (1). The standard uncertainty of reference LDV is 0.12%. The uncertainty of US includes the standard deviation for 5 measurements, turbulence and display resolution.

Table 4 - Uncertainty budget of US meter calibration

V(m/s)		0.5	1	2	5	10	15	20	30
$u(V_{ref})$	B(%)	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
$u(V_{US})$	A(%)	0.25	0.22	0.31	0.08	0.01	0.05	0.03	0.04
	B(%)	1.69	0.8	0.65	0.39	0.3	0.28	0.29	0.32
	B(%)	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
u_{rel} (%)		1.72	0.85	0.75	0.45	0.36	0.35	0.35	0.38
U_{rel} (%), k=2		3.43	1.68	1.46	0.83	0.65	0.62	0.63	0.69

ii. LDV calibration

(1) It is difficult to measure the velocity at the same position by both 2 LDVs. However there is some deviation at different positions. To reduce this deviation the 20mm and 170mm positions at axial are measured by reference LDV and transfer LDV at the same time. Then the procedure is repeated but the positions of 2 LDVs are exchanged. The calibration result is calculated by formula (2). The 8 velocity points including 0.5 m/s, 1 m/s, 2 m/s, 5 m/s, 10 m/s, 15 m/s, 20 m/s, 30 m/s are taken. The experiment is shown as figure 5.

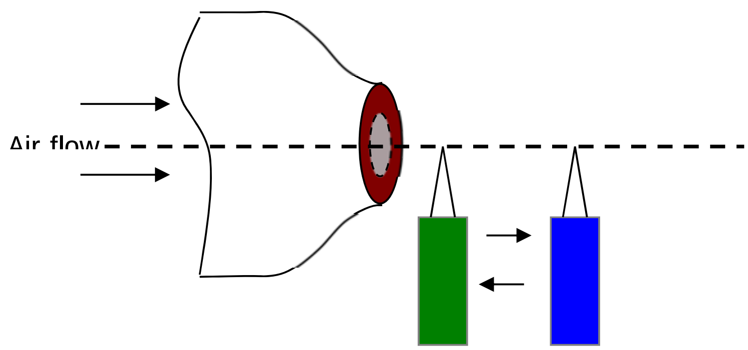


Figure 4 - LDV calibration procedure

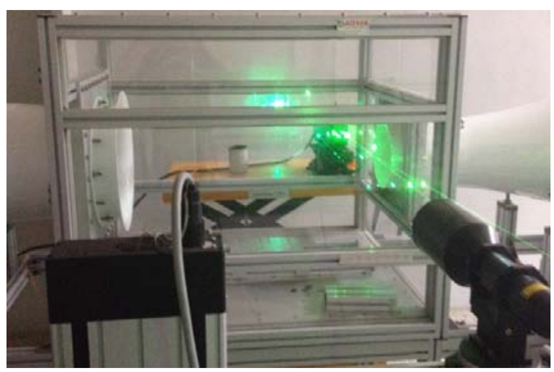


Figure 5 The photo picture of LDV calibration

(2) Calculation

$$C_{LDV} = \frac{V_{ref-20} + V_{ref-100}}{V_{LDV-20} + V_{LDV-100}} \quad (2)$$

Where C_{LDV} is calibration coefficient for transfer LDV; V_{ref-20}, $V_{ref-100}$ are measurement results by reference LDV at 20 mm, 100 mm separately band V_{LDV-20}, $V_{LDV-100}$ are measurement results by transfer LDV at 20 mm, 100 mm separately.

*To prove the formula (2) is valid, the measurement results of reference LDV and transfer LDV are defined as $V_{ref}(20,t_1)$, $V_{ref}(100,t_2)$, $V_{LDV}(100,t_1)$, $V_{LDV}(20,t_2)$. 20 or 100 mean different measurement position and t_1 or t_2 mean different measurement time. The velocity deviation along flow axial is considered to be ΔV_P and the velocity stability for time is considered to be ΔV_t, then:

$$V_{ref}(20,t_1) = V_{ref}(20,t_1)$$

$$V_{ref}(100,t_2) = V_{ref}(20,t_1) + \Delta V_P + \Delta V_t$$

$$V_{LDV}(20,t_2) = V_{ref}(20,t_1) + \Delta V_t$$

$$V_{LDV}(100,t_1) = V_{LDV}(20,t_1) + \Delta V_P$$

Then the formula (2) can be expressed by：

$$C_{LDV} = \frac{2V_{ref}(20,t_1) + \Delta V_P + \Delta V_t}{2V_{LDV}(20,t_1) + \Delta V_P + \Delta V_t} = \frac{C_{theory} + \dfrac{\Delta V_P + \Delta V_t}{2V_{LDV}(20,t_1)}}{1 + \dfrac{\Delta V_P + \Delta V_t}{2V_{LDV}(20,t_1)}},$$

$\frac{\Delta V_P + \Delta V_t}{2V_{LDV}(20,t_1)} = \delta$, the specification tested by experiments of wind tunnel suggests $\delta \le 0.3\%$；

Then：$C_{LDV} = \frac{C_{theory} + \delta}{1+\delta}$, namely, $C_{LDV} - C_{theory} = \delta(1 - C_{LDV})$,

The calibration results of C_{LDV} suggest $(1 - C_{LDV}) \le 0.3\%$, then $C_{LDV} - C_{theory} < 0.1\%$。

(4)Uncertainty evaluation

The uncertainty is evaluated according to formula (3):

$$C_{LDV} = \frac{V_{reference}}{V_{LDV}} \quad (3)$$

$$u_{rel}(C_{LDV}) = (u_{rel}^2(V_{reference}) + u_{rel}^2(V_{LDV}))^{1/2} \quad (4)$$

The standard uncertainty of reference LDV is 0.12%. The uncertainty of transfer LDV includes the standard deviation for 5 measurements, turbulence and display resolution.

Table 6 - Uncertainty budget of transfer LDV calibration

v(m/s)	Type	0.5	1	2	5	10	15	20	30
$u(V_{ref})$	B(%)	0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
$u(V_{LDV})$	A(%)	0.35	0.34	0.17	0.07	0.04	0.14	0.07	0.23
	B(%)	0.124	0.14	0.04	0.076	0.077	0.087	0.077	0.032
	B(%)	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
u_{rel} (%)		0.42	0.42	0.27	0.23	0.22	0.26	0.23	0.31
U_{rel} (%), k=2		0.78	0.77	0.43	0.32	0.30	0.41	0.32	0.52

iii. LDV calibration by spinning-disc

(1) The layout to calibrate transfer LDV by spinning-disc is shown as Figure 6. The wolfram wire of 5μ diameter is stick on the edge of spinning disc. The 8 velocity points including 0.5 m/s, 1 m/s, 2 m/s, 5 m/s, 10 m/s, 15 m/s, 20 m/s, 30 m/s are taken. The experiment is shown as Figure 7.

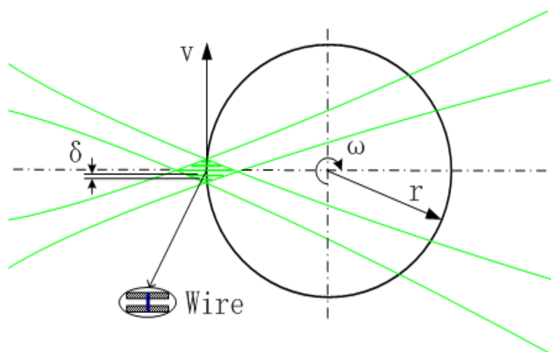


Figure 6 - the calibration layout for LDA

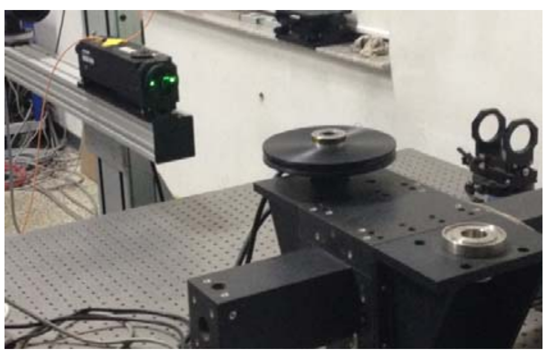


Figure 7 Photo picture of LDV calibration by spinning-disc

(2) Calculation

$$C_{LDV} = \frac{V_{disc}}{V_{LDV}} \tag{5}$$

Where V_{disc} is linear velocity of spinning-disc.

(4) Uncertainty evaluation

The uncertainty is evaluated according to formula (5).

$$u_{rel}(C_{LDV}) = (u_{rel}^2(V_{disc}) + u_{rel}^2(V_{LDV}))^{1/2} \tag{6}$$

Where V_{disc} can be expressed by:

$$V_{disc} = \pi \cdot f \cdot d \tag{7}$$

Then the formula (6) is expressed by:

$$u_{rel}(C_{LDV}) = (u_{rel}^2(f) + u_{rel}^2(d) + u_{rel}^2(V_{LDV}))^{1/2} \tag{8}$$

Where, f is spinning frequency. The rotation stability is 0.05%, and the standard deviation is 0.025%. d is diameter of spinning disc. The roundness, the gap of bearing and the distortion of wire are estimated to be 0.2 mm, namely the standard uncertainty is 0.1%. The uncertainty of transfer LDV includes the standard deviation for 5 measurements, turbulence and display resolution.

Table 9 - Uncertainty budget of transfer LDV calibration by spinning-disc

v(m/s)		0.5	1	2	5	10	15	20	30
u(f)	B (%)	0.05	0.05	0.05	0.05	0.05	0.05	0.05	0.05
	B (%)	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025
u(d)	B (%)	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1
u(v)	A (%)	0.0200	0.0000	0.0000	0.0100	0.0000	0.0100	0.0200	0.0100
	B (%)	0.0212	0.0070	0.0035	0.0170	0.0155	0.0131	0.0166	0.0218
	B (%)	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02
u_{rel} (%)		0.12	0.12	0.12	0.12	0.12	0.12	0.12	0.12
U_{rel} (%), k=2		0.24	0.23	0.23	0.24	0.23	0.23	0.24	0.24

B.7. CMS

a. The Air Speed Calibration System at CMS (Chinese Taipei)

The air speed calibration system at CMS consists of the wind tunnel and transfer standard Laser Doppler Velocimetry (LDV) as shown in Figure 1.The wind tunnel is an open loop design with total length of 6 m and an inlet diameter of 0.6 m, a 9:1 contraction ratio, a nozzle diameter of 200 mm and test chamber of 800 mm by 800 mm. The air speed range is from 0.2 m/s to 25 m/s in the test section at the exit of the contraction section. An inverter is used to control the fan for proper air speed generation.

The velocity standard used is an LDV placed on a three-axis traversing system, manufactured by TSI, model IFA 655 with a fringe spacing of 1.9145 µm and a laser wavelength of 514.5 nm.
In order to trace air speed measurement to the International System of Units (SI), a spinning disk is used as the velocity standard, as shown in Figure 2. Based on measurements and analyses on the flow characteristics of the wind tunnel, the uncertainties for air speed measurement are as follows. u_{base} = 0.249 %, u_{BED} = 0.04 %, U_{CMC} = 0.52 % (k = 2.06), with the best existing device (BED) being an LDV.

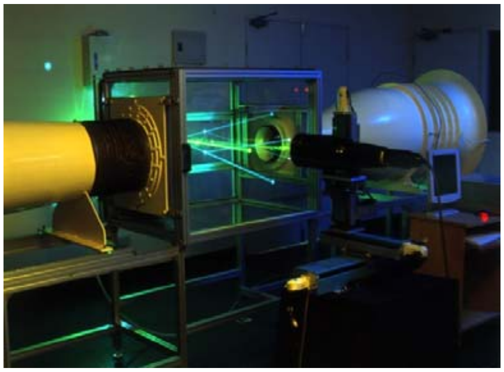


Figure 1 - The air speed calibration system

Figure 2 - The spinning disk

b. Uncertainty budget of the CMS air speed standards

The real air speed at the anemometry position in the wind tunnel can be expressed as

$$V_{tunnel} = V_{ldv} \times \delta \times \varepsilon \qquad (1)$$

where:

- V_{ldv} : Air speed measured by using LDV
- V_{tunnel} : Real air speed at the position of anemometry
- δ : Correction factor for flow characteristic of the wind tunnel
- ε : Correction factor for wind-tunnel performance

According to equation (1), the uncertainty of the standard air speed in the wind tunnel (ubase) can be expressed as

$$u_C^2(V_{tunnel}) = \left[\frac{\partial f}{\partial V_{ldv}} u(V_{ldv})\right]^2 + \left[\frac{\partial f}{\partial \delta} u(\delta)\right]^2 + \left[\frac{\partial f}{\partial \varepsilon} u(\varepsilon)\right]^2$$

$$= [c_1 u(V_{ldv})]^2 + [c_2 u(\delta)]^2 + [c_3 u(\varepsilon)]^2 \quad (2)$$

where

- c_1: sensitivity coefficient of the variable V_{ldv}
- c_2: sensitivity coefficient of the variable δ
- c_3: sensitivity coefficient of the variable ε

The uncertainty of air speed in the measurement zone can be expressed as

$$\frac{u(V_{tunnel})}{V_{tunnel}} = ((\frac{u(V_{ldv})}{V_{ldv}})^2 + (\frac{u(\delta)}{\delta})^2 + (\frac{u(\varepsilon)}{\varepsilon})^2)^{1/2} \quad (3)$$

The uncertainty budget of the air speed measurement system is shown in Table 1.

Table 1 - Uncertainty budget of air speed measurement by the LDV system

Symbol	Uncertainty Source		$u(x_i)/x_i$ (%)	v_x
$[\frac{u(V_{ldv})}{V_{ldv}}]$	LDV system		0.075	46
	1	LDV calibration	0.046	10
	2	Long term stability	0.06	50
$[\frac{u(\delta)}{\delta}]$	Flow and particle influences on LDV measurement		0.056	1067
	1	Particle lag	0	∞
	2	Velocity bias	0.010	∞
	3	Turbulence intensity	0.055	999
	4	Fringe bias	0	∞
$[\frac{u(\varepsilon)}{\varepsilon}]$	Flow velocity distribution in the wind tunnel		0.230	8
	1	Along vertical direction	0.141	14
	2	Along horizontal direction	0.129	7
	3	Axial velocity direction	0.128	9
$[\frac{u_c(V_{tunnel})}{V_{tunnel}}]$	Combined relative standard uncertainty		0.249	25
k	Coverage factor		2.06	25
$[\frac{U(V_{tunnel})}{V_{tunnel}}]$	Relative expanded uncertainty		0.51	25

The fringe spacing of the LDV system was calibrated by the spinning disk facility, and the measurement equation can be expressed as follows.

$$d_f = r \times \omega / f_D \times \cos\beta + \zeta \tag{4}$$

where

- d_f : fringe spacing (μm)
- β : angle deviated from the optical axis to the normal direction of the side surface
- f_D : Doppler frequency of LDV measurement (MHz)
- V_{disc} : tangential speed of the rotating disc (m/s)
- V_{ldv} : particle velocity measured by LDV (m/s)
- r : radius of the disc (m)

- ω : rotational speed (rad/s)
- ζ : correction factor due to stability of laser wavelength and rotating disc (μm)

From Eq. (4), the uncertainty of the fringe spacing d_f in the measuring volume can be expressed as, it is

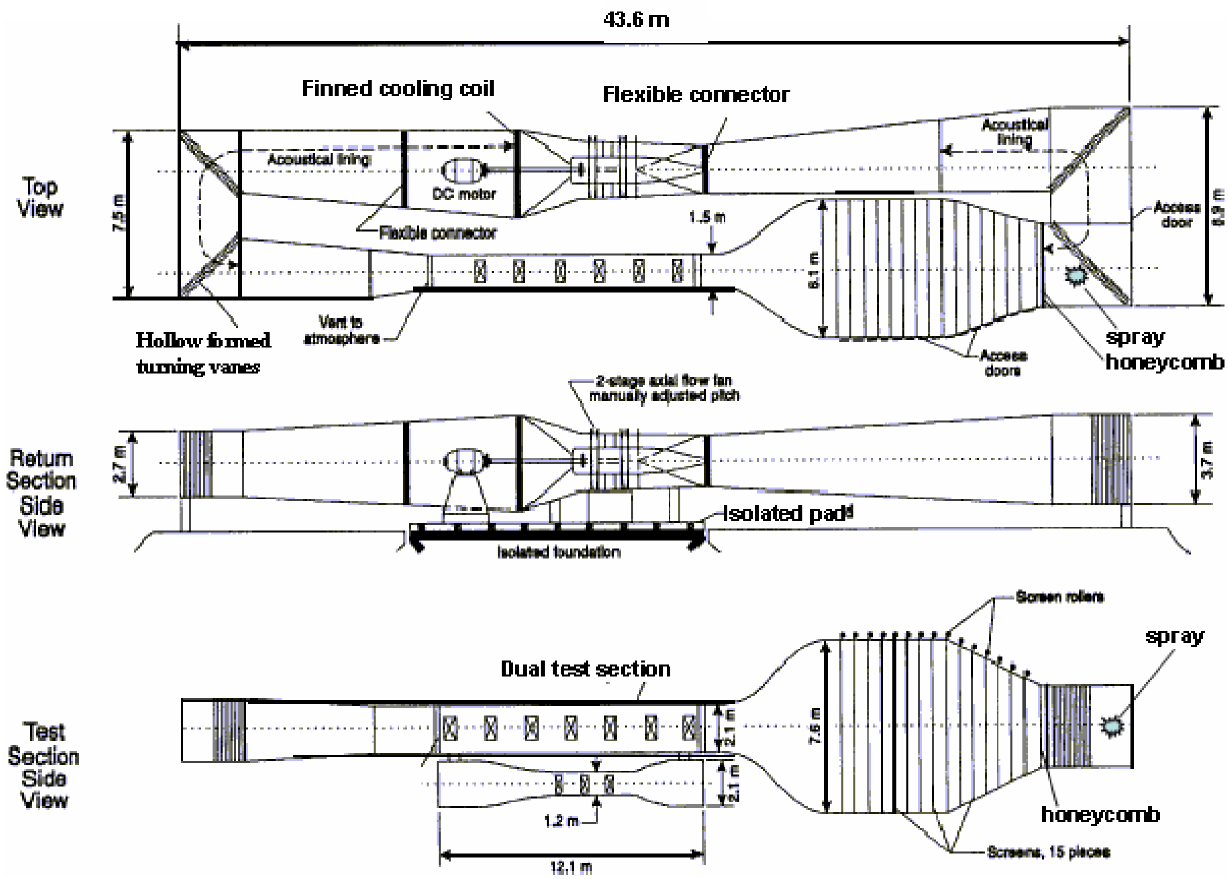
$$u(d_f) = \sqrt{\left(\frac{\cos\beta}{f_D}\times\omega\times u(r)\right)^2 + \left(\frac{\cos\beta}{f_D}\times r\times u(\omega)\right)^2 + \left(\frac{-r\times\omega}{f_D}\times \sin(\beta)\times u(\beta)\right)^2 + \left(\frac{-r\times\omega\times\cos\beta}{f_D{}^2}\times u(f_D)\right)^2 + (u(\varsigma))^2} \quad (5)$$

The uncertainty budget for the measurement of the fringe spacing of LDV system is shown in Table 2. The maximum uncertainty occurs at disc rotational speed of 600 rpm.

Table 2 - Uncertainty budget of the fringe spacing for LDV system

Uncertainty Source	Type	x_i	Standard uncertainty $u(x_i)$	Sensitivity $c(x_i)$	$u(x_i) \times c(x_i)$	Degrees of freedom v_x
LDV Doppler frequency f_D (MHz)	A	3.28959	0.00066	-0.58424	0.00038	4
Disc radius r (m)	B	0.09997	0.000015	19.22435	0.00029	163805
Disk rotation speed ω (rad /s)	A	63.24979	0.00302	0.03039	0.00009	4
LDV and disk angle β (degree)	B	1	0.00504	-0.03355	0.00017	∞
Correction factor ζ (μm)	A	0	0.0007	1	0.0007	5
Combined standard uncertainty (μm)	0.00087					10
Average fringe spacing (μm)	1.9145					
Relative standard uncertainty (%)	0.046					10
Coverage factor	2.23					
Relative expanded uncertainty (%)	0.10					

B.8. NIST



NIST Wind tunnel for the air speed calibration service

The air flow in the NIST wind tunnel is generated by a two stage axial fan that is powered by a variable speed 300 kW DC motor. The fan speed is controlled by a feedback loop that stabilizes the rotation rate within ± 0.1 %. Turbulence and swirl induced by the fan are mitigated by a large-cross-section "settling" chamber upstream of the test section where air speed measurements are made. The settling chamber contains flow-conditioning devices including several arrays of honeycomb meshes followed by a contracting section that smoothly attaches to the test section. The contraction accelerates the flow and produces a nearly uniform velocity profile in the rectangular test section that is 1.2 m high by 1.5 m wide and is 2 m in length. This large cross section reduces disturbances in the air flow from the tunnel's walls and from flow blockage effects attributed to instrumentation installed in the test section [1]. We calibrate customer wind speed instruments against NIST air speed standards in a well-characterized measurement zone near the center of the test section where velocity surveys have shown that the air speed is nearly independent of position [2].

NIST air speed measurements are traceable to SI derived unit of velocity via length and time. We establish traceability by calibrating our Laser Doppler Anemometer (LDA) working standard against a spinning disk. The spinning disk method for calibrating an LDA system is described in several references [2, 3, 4, 5]. For quality assurance NIST also uses an L-shaped pitot probe check standard along with the LDA measurements. The test section is equipped with an actuated probe mount that allows testing of sensors at various pitch and yaw angles.

[1] Yeh, T. T., Hall, J. M., *Air Speed Calibration Service*, NIST Special Publication 250-79, National Institute of Standards and Technology, Gaithersburg, Maryland, 2006.

[2] Shinder, I. I., Crowley, C. J., Filla, B. J., Moldover, M. R., *Improvements to NIST's Air Speed Calibration Service*, 16th International Flow Measurement Conference, Flomeko 2013, Paris, France September 24-26, 2013.

[3] Shinder, I. I., Crowley, C. J., Filla, B. J., Moldover, M. R., *Improvements to NIST's Air Speed Calibration Service*, Flow Measurement and Instrumentation, Vol. 44, pp. 19–26, 2015.

[4] Yeh, T. T., Hall, J. M., *An Uncertainty Analysis of the NIST Airspeed Standards*, ASME Paper FEDSM2007-37560, ASME/JSME 5th Joint Fluids Engineering Conference, pp. 135-142, San Diego, California, USA, 2007.

[5] Yeh, T. T. and Hall, J. M. *Uncertainty of NIST Airspeed Calibrations*, Technical document of Fluid Flow Group, NIST, Gaithersburg, Maryland, USA, 2008.

B.9. INRIM

The test rig we used is an open-circuit-semi-open test chamber wind tunnel, called GVP (for Galleria del Vento Piccola, i.e. Small Wind Tunnel).

The test chamber is an open jet with a starting diameter of 40 cm enclosed in a closed box which is a cube of approx. 90 cm side; the useful length of the jet is of about 50 cm.

The fan is downstream of the test chamber and has therefore no direct influence on the flow swirl.

The convergent has an area ratio of about 3:1, and is provided with screens and a coarse honeycomb.

The maximum speed is of about 35 m/s.

Traceability is obtained indirectly through an LDA, meaning that our LDA was used to calibrate the differential pressure through the convergent; this pressure is then used for current use of the tunnel.