# CCM.FF-K3.2011.1

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

## Final Report


**Pilots**

Harald Müller – PTB, Germany

Isabelle Caré – LNE-CETIAT, France

**Participants**

Harald Müller – PTB, Germany

Konstantin Popov – VNIIM, Russia


**April, 2019**

## Abstract

The bilateral key comparison between PTB and VNIIM (CCM.FF-K3.2011.1) was performed as direct follow-up of the CIPM Air speed Key Comparison (CCM.FF-K3.2011) which was organized to determine the degree of equivalence of the national standards for air speed covering the range 0.5 m/s to 40 m/s under ambient conditions. An ultrasonic anemometer and a laser Doppler anemometer were used as transfer standards. The measurement procedures in the technical protocol as well as the transfer standards for the bilateral key comparison (CCM.FF-K3.2011.1) were identical to the CIPM Key Comparison (CCM.FF-K3.2011) with nine participants from three RMOs. Thus, the measurement results were directly linked to the key comparison reference values published in the final report of the (CCM.FF-K3.2011) for each standard and each air speed separately. The degree of equivalence of each result with the key comparison reference value (KCRV) was calculated. All reported results of the bilateral key comparison were consistent with the KCRV results of the (CCM.FF-K3.2011).

## Graphical summary of results

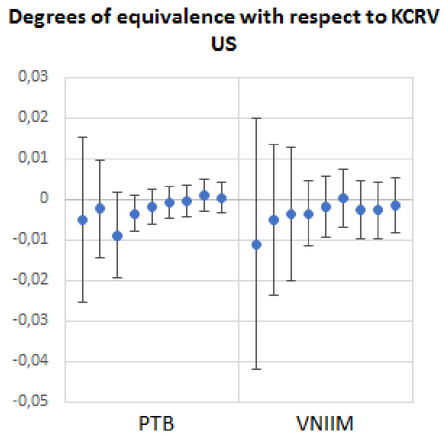



**Figure 1 – Degrees of equivalence with respect to KCRV (CCM.FF-K3.2011) of PTB and VNIIM for the ultrasonic anemometer at the different air speeds. The error bars show the expanded uncertainty of the degree of equivalence for each calibrated value.**

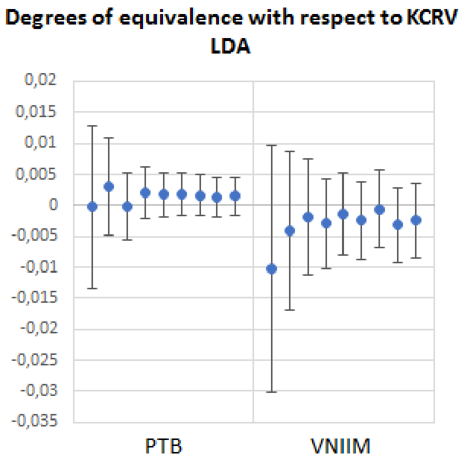



**Figure 2 – Degrees of equivalence with respect to KCRV (CCM.FF-K3.2011) of PTB and VNIIM for the laser Doppler anemometer at the different air speeds. The error bars show the expanded uncertainty of the degree of equivalence for each calibrated value.**

# CONTENTS

# 1. Introduction

The Key Comparison CCM.FF.K3.2011 for air speed and its follow-up, the bilateral key comparison CCM.FF.K.2011.1 between VNIIM and PTB, have been undertaken by CCM (Consultative Committee for Mass and related quantities) Working Group for Fluid Flow (WGFF) and were 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 the one used in the Key Comparison CCM.FF-K3 [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 avoid unintentional changes of the LDA operating parameters by the laboratories during the calibration.

The objective of the key comparisons 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 participants calibrated the transfer standards and compared the calibration results.

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

# 2. PARTICIPANTS AND ORGANIZATION OF THE COMPARISON

## 2.1. Participants

The participants are listed in table 1.

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

| Participant<br>(Country) | Type of reference standard | Date of tests | Independent traceability? |
|---|---|---|---|
| PTB<br>(Germany) | LDA standard | Test period:<br>July 2013,<br>…<br>October 2016, …<br>February 2017 | Yes |
| VNIIM<br>(Russia) | LDA standard | January 2017 | Yes |

## 2.2. Organization of the comparison

According to the technical protocol (CCM.FF-K3.2011.1) and the corresponding contract between PTB and VNIIM from October 2016, the shipping of the transfer standards, the assumption of costs due to the transportation costs, custom clearance and delivery affairs were conjointly arranged.

## 2.3. Unexpected events

Thanks to the meticulous assistance of VNIIM concerning an unobstructed custom clearance and delivery, no unexpected events occurred. No influence on the stability of the travelling standards was observed.

# 3. TRAVELLING STANDARDS

## 3.1. Ultrasonic anemometer

The ultrasonic anemometer which has been used in this key comparison (KC) was 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.

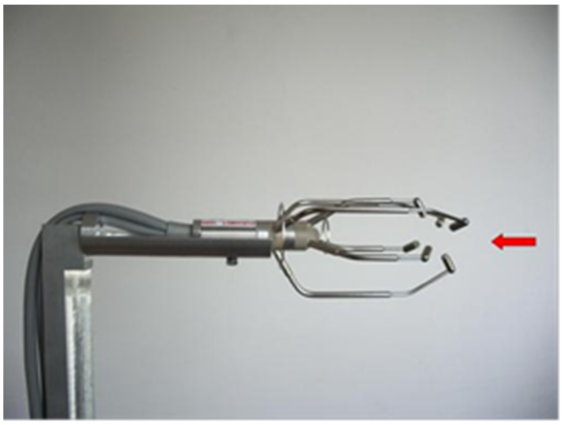


**Figure 3 - Ultrasonic Anemometer sensing element; the arrow indicates the flow direction**

The arrangement of the instrument is such that the flow reaches the sensor along its main axis as shown in Figure 3. 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 was 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.

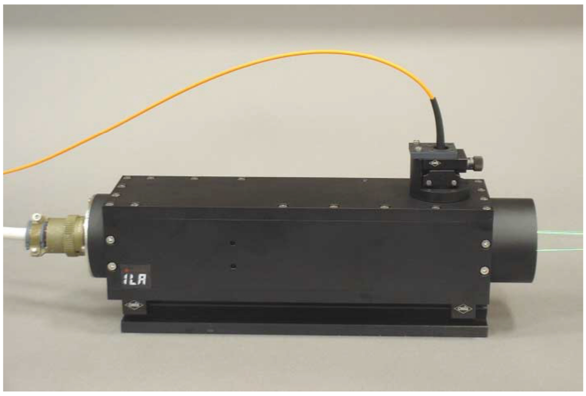



**Figure 4 - Laser Doppler Anemometer probe; power 75 mW, wavelength 532 nm**

The LDA system includes the controller, the signal processing unit and the software specially developed to ensure an 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 could be 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:

$$K = \frac{V_{ref}}{V_{ts}} \quad (1)$$

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 |
| VNIIM (Russia) | Aerodynamic facility: loop tube, open test section | LDA calibrated |

# 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 5 for the ultrasonic anemometer over a time period from July 2013 to February 2017.

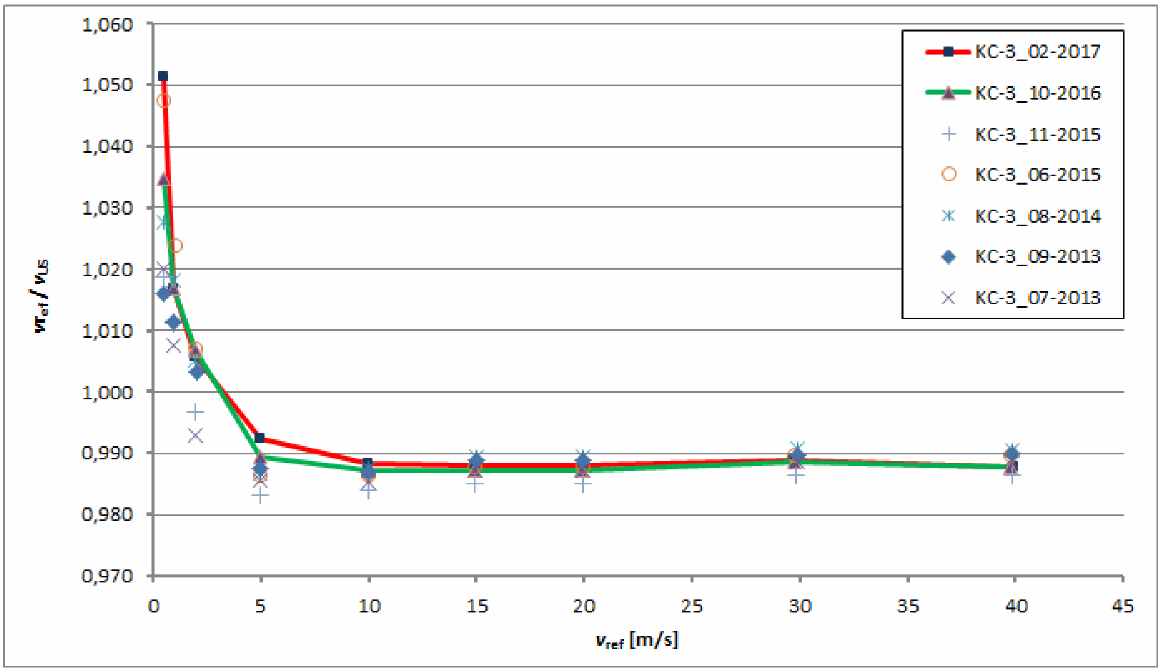



**Figure 5 – *K* factor for the different calibrations at PTB for the ultrasonic anemometer**

Five of the seven calibrations were performed at PTB between June 2013 and November 2015 and used in the CCM.FF.K3.2011 evaluation to calculate the stability of the transfer standard for each velocity and expressed 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 was calculated, considering a rectangular law, as the observed maximum deviation divided by the square root of 12.

The subsequent calibrations, one before (Fig. 6: green line) and one after (Fig. 6: red line) the bilateral comparison with VNIIM, are consistent with the data for the ultrasonic anemometer stability tests during the CCM.FF.K3.2011. Hence the standard uncertainty for the stability contribution was taken according to table 3 identical to the CCM.FF.K3.2011.

Considering the results obtained at PTB, this additional contribution of uncertainty due to the stability of the transfer standard was included when calculating the degree of equivalence with the KCRV from the CCM.FF.K3.2011.

**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.

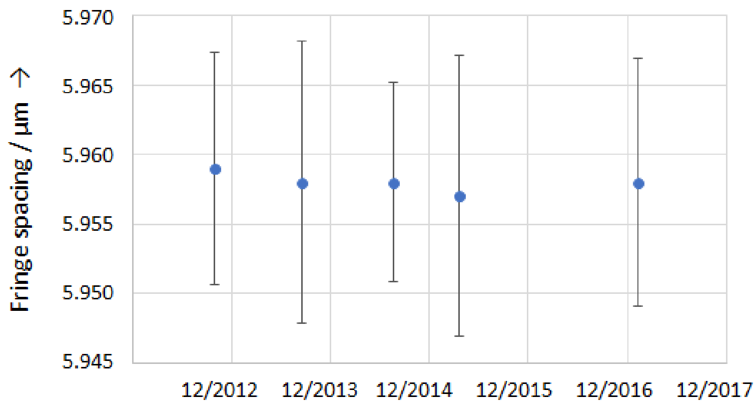



**Figure 6 – Calibration of the fringe spacing at PTB over the duration of K3**

With an analysis similar to the one performed for the ultrasonic anemometer an additional contribution of uncertainty due to the stability of the transfer standard has been 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 DEGREE OF EQUIVALENCE TO THE KCRV

### 7.1. Results of the participants

#### 7.1.1. Ultrasonic anemometer

**Measurement results of PTB**

The PTB measurement results were taken from the key comparison as the stability of both transfer standards was checked by PTB before and after the bilateral comparison with VNIIM and proven to be as stable as documented in the CCM.FF-K3.2011 final report.

**Table 4 – PTB results for the ultrasonic anemometer**

| AVERAGE DATA | | | | | |
|---|---|---|---|---|---|
| | Institute 's results - US anemometer | | | | |
| Nominal airspeed $V$nom [m/s] | Reference air speed $V_{\text{ref}}$ [m/s] | Indicated air speed $V_{\text{US}}$ [m/s] | Standard deviation air speed [m/s] | Calibration result $V_{\text{ref}}/V_{\text{US}}$ | Lab Uncertainty $U(V_{ref}/V_{US})$ |
| 0,5 | 0,5014 | 0,492 | 0,001 | 1,0201 | 0,0136 |
| 1 | 0,9984 | 0,991 | 0,006 | 1,0076 | 0,0085 |
| 2 | 1,9821 | 1,996 | 0,005 | 0,9930 | 0,0060 |
| 5 | 5,0075 | 5,081 | 0,002 | 0,9855 | 0,0045 |
| 10 | 9,9997 | 10,148 | 0,009 | 0,9854 | 0,0040 |
| 15 | 14,9615 | 15,154 | 0,040 | 0,9873 | 0,0038 |
| 20 | 19,9419 | 20,171 | 0,005 | 0,9886 | 0,0038 |
| 30 | 29,8843 | 30,224 | 0,007 | 0,9887 | 0,0037 |
| 40 | 39,8130 | 40,238 | 0,005 | 0,9894 | 0,0036 |

**Measurement results of VNIIM**

**Table 5 – VNIIM results for the ultrasonic anemometer**

| AVERAGE DATA | | | | | |
|---|---|---|---|---|---|
| | Institute 's results - US anemometer | | | | |
| Nominal airspeed $V_{\text{nom}}$ [m/s] | Reference air speed $V_{\text{ref}}$ [m/s] | Indicated air speed $V_{\text{US}}$ [m/s] | Standard deviation air speed [m/s] | Calibration result $V_{\text{ref}}/V_{\text{US}}$ | Lab Uncertainty $U(V_{ref}/V_{US})$ |
| 0,5 | 0,5343 | 0,527 | 0,014 | 1,0143 | 0,0144 |
| 1 | 0,9819 | 0,977 | 0,024 | 1,0049 | 0,0101 |
| 2 | 2,0492 | 2,053 | 0,023 | 0,9983 | 0,0074 |
| 5 | 5,0021 | 5,076 | 0,029 | 0,9854 | 0,0060 |
| 10 | 9,9713 | 10,120 | 0,055 | 0,9853 | 0,0055 |
| 15 | 14,8045 | 14,978 | 0,082 | 0,9884 | 0,0053 |
| 20 | 19,7311 | 20,003 | 0,107 | 0,9864 | 0,0053 |
| 30 | 30,6018 | 31,063 | 0,170 | 0,9852 | 0,0052 |
| 40 | 40,7300 | 41,247 | 0,245 | 0,9875 | 0,0051 |

### 7.1.2. Laser Doppler anemometer

**Measurement results of PTB**

The PTB measurement results were taken from the key comparison as the stability of both transfer standards was checked by PTB before and after the bilateral comparison with VNIIM and proven to be as stable as documented in the CCM.FF-K3.2011 final report.

**Table 6 – PTB results for the laser Doppler anemometer**

| AVERAGE DATA | | | | | |
|---|---|---|---|---|---|
| | Institute 's results - Laser Doppler anemometer | | | | |
| Nominal airspeed $V$nom [m/s] | Reference air speed $V_{\text{ref}}$ [m/s] | Indicated air speed $V_{\text{LDA}}$ [m/s] | Standard deviation air speed [m/s] | Calibration result $V_{\text{ref}}/V_{\text{LDA}}$ | Lab Uncertainty $U(V_{ref}/V_{LDA})$ |
| 0,5 | 0,4904 | 0,491 | 0,011 | 0,9990 | 0,0136 |
| 1 | 0,9954 | 0,992 | 0,003 | 1,0030 | 0,0085 |
| 2 | 1,9991 | 1,997 | 0,001 | 1,0011 | 0,0060 |
| 5 | 4,9936 | 4,980 | 0,004 | 1,0027 | 0,0045 |
| 10 | 9,9975 | 9,965 | 0,007 | 1,0033 | 0,0040 |
| 15 | 14,9865 | 14,937 | 0,007 | 1,0033 | 0,0038 |
| 20 | 19,9487 | 19,885 | 0,006 | 1,0032 | 0,0037 |
| 30 | 29,8838 | 29,806 | 0,012 | 1,0026 | 0,0037 |
| 40 | 39,8588 | 39,774 | 0,010 | 1,0021 | 0,0036 |

**Measurement results of VNIIM**

**Table 7 – VNIIM results for the laser Doppler anemometer**

| AVERAGE DATA | | | | | |
|---|---|---|---|---|---|
| | Institute 's results - Laser Doppler anemometer | | | | |
| Nominal airspeed $V$nom [m/s] | Reference air speed $V_{\text{ref}}$ [m/s] | Indicated air speed $V_{\text{LDA}}$ [m/s] | Standard deviation air speed [m/s] | Calibration result $V_{\text{ref}}/V_{\text{LDA}}$ | Lab Uncertainty $U(V_{ref}/V_{LDA})$ |
| 0,5 | 0,5003 | 0,506 | 0,004 | 0,9890 | 0,0150 |
| 1 | 0,9862 | 0,990 | 0,003 | 0,9959 | 0,0101 |
| 2 | 1,9980 | 1,999 | 0,001 | 0,9994 | 0,0075 |
| 5 | 4,9383 | 4,950 | 0,008 | 0,9977 | 0,0060 |
| 10 | 9,8276 | 9,825 | 0,004 | 1,0003 | 0,0055 |
| 15 | 15,0527 | 15,066 | 0,009 | 0,9991 | 0,0053 |
| 20 | 20,0500 | 20,030 | 0,014 | 1,0010 | 0,0052 |
| 30 | 29,9162 | 29,976 | 0,042 | 0,9980 | 0,0052 |
| 40 | 40,1341 | 40,207 | 0,052 | 0,9982 | 0,0051 |

## 7.2. Input data considering the stability of the transfer standards

The tables 8 - 11 show the input data of PTB and VNIIM considering the uncertainty contribution related to the stability of the transfer standards. The PTB data were the input data for the calculation of the *KCRV* (CCM.FF-K3.2011) and the VNIIM data for the calculation of the degree of equivalence of the VNIIM results to the *KCRV* (CCM.FF-K3.2011) (see chapter 7.3). The expanded uncertainties including the stability of the transfer standards (see chapter 6) are and listed in the tables in the columns "Pilot calculation" according to:

$$U(K)_{\mathrm{PC}} = \sqrt{U^2(K)\text{"}Lab\ Uncertainty\text{"} + U^2(transfer\ standard)} \quad (3)$$

### 7.2.1. Ultrasonic anemometer

**Table 8 – PTB data set**

| | Institute 's results - Ultrasonic anemometer | | | | | Pilot calculation |
|---|---|---|---|---|---|---|
| Nominal airspeed $V_{\mathrm{nom}}$ [m/s] | Reference air speed $V_{\mathrm{ref}}$ [m/s] | Indicated air speed $V_{\mathrm{US}}$ [m/s] | Standard deviation air speed [m/s] | Calibration result $V_{\mathrm{ref}}/V_{\mathrm{US}}$ | Lab Uncertainty $U(K)$ | Expanded Uncertainty $U(K)_{\mathrm{PC}}$ |
| 0,5 | 0,5014 | 0,492 | 0,001 | 1,0201 | 0,0136 | 0,0229 |
| 1,0 | 0,9984 | 0,991 | 0,006 | 1,0076 | 0,0085 | 0,0132 |
| 2,0 | 1,9821 | 1,996 | 0,005 | 0,9930 | 0,0060 | 0,0116 |
| 5,0 | 5,0075 | 5,081 | 0,002 | 0,9855 | 0,0045 | 0,0052 |
| 10,0 | 9,9997 | 10,148 | 0,009 | 0,9854 | 0,0040 | 0,0047 |
| 15,0 | 14,9615 | 15,154 | 0,040 | 0,9873 | 0,0038 | 0,0046 |
| 20,0 | 19,9419 | 20,171 | 0,005 | 0,9886 | 0,0038 | 0,0045 |
| 30,0 | 29,8843 | 30,224 | 0,007 | 0,9887 | 0,0037 | 0,0045 |
| 40,0 | 39,8130 | 40,238 | 0,005 | 0,9894 | 0,0036 | 0,0044 |

**Table 9 – VNIIM data set**

| | Institute 's results - Ultrasonic anemometer | | | | | Pilot calculation |
|---|---|---|---|---|---|---|
| Nominal airspeed $V_{\mathrm{nom}}$ [m/s] | Reference air speed $V_{\mathrm{ref}}$ [m/s] | Indicated air speed $V_{\mathrm{US}}$ [m/s] | Standard deviation air speed [m/s] | Calibration result $V_{\mathrm{ref}}/V_{\mathrm{US}}$ | Lab Uncertainty $U(K)$ | Expanded Uncertainty $U(K)_{\mathrm{PC}}$ |
| 0,5 | 0,5343 | 0,527 | 0,014 | 1,0143 | 0,0144 | 0,0232 |
| 1,0 | 0,9819 | 0,977 | 0,024 | 1,0049 | 0,0101 | 0,0142 |
| 2,0 | 2,0492 | 2,053 | 0,023 | 0,9983 | 0,0074 | 0,0125 |
| 5,0 | 5,0021 | 5,076 | 0,029 | 0,9854 | 0,0060 | 0,0065 |
| 10,0 | 9,9713 | 10,120 | 0,055 | 0,9853 | 0,0055 | 0,0061 |
| 15,0 | 14,8045 | 14,978 | 0,082 | 0,9884 | 0,0053 | 0,0059 |
| 20,0 | 19,7311 | 20,003 | 0,107 | 0,9864 | 0,0053 | 0,0058 |
| 30,0 | 30,6018 | 31,063 | 0,170 | 0,9852 | 0,0052 | 0,0058 |
| 40,0 | 40,7300 | 41,247 | 0,245 | 0,9875 | 0,0051 | 0,0057 |

### 7.2.2. Laser Doppler anemometer

**Table 10 – PTB data set**

| | 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 $K=V_{ref}/V_{LDA}$ | Lab Uncertainty $U(K)$ | Expanded Uncertainty $U(K)_{PC}$ |
| 0,5 | 0,4904 | 0,491 | 0,011 | 0,9990 | 0,0136 | 0,0136 |
| 1,0 | 0,9954 | 0,992 | 0,003 | 1,0030 | 0,0085 | 0,0085 |
| 2,0 | 1,9991 | 1,997 | 0,001 | 1,0011 | 0,0060 | 0,0060 |
| 5,0 | 4,9936 | 4,980 | 0,004 | 1,0027 | 0,0045 | 0,0045 |
| 10,0 | 9,9975 | 9,965 | 0,007 | 1,0033 | 0,0040 | 0,0040 |
| 15,0 | 14,9865 | 14,937 | 0,007 | 1,0033 | 0,0038 | 0,0038 |
| 20,0 | 19,9487 | 19,885 | 0,006 | 1,0032 | 0,0037 | 0,0038 |
| 30,0 | 29,8838 | 29,806 | 0,012 | 1,0026 | 0,0037 | 0,0037 |
| 40,0 | 39,8588 | 39,774 | 0,010 | 1,0021 | 0,0036 | 0,0036 |

**Table 11 – VNIIM data set**

| | 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 $K=V_{ref}/V_{LDA}$ | Lab Uncertainty $U(K)$ | Expanded Uncertainty $U(K)_{PC}$ |
| 0,5 | 0,5003 | 0,506 | 0,004 | 0,9890 | 0,0150 | 0,0150 |
| 1,0 | 0,9862 | 0,990 | 0,003 | 0,9959 | 0,0101 | 0,0101 |
| 2,0 | 1,9980 | 1,999 | 0,001 | 0,9994 | 0,0075 | 0,0075 |
| 5,0 | 4,9383 | 4,950 | 0,008 | 0,9977 | 0,0060 | 0,0060 |
| 10,0 | 9,8276 | 9,825 | 0,004 | 1,0003 | 0,0055 | 0,0055 |
| 15,0 | 15,0527 | 15,066 | 0,009 | 0,9991 | 0,0053 | 0,0053 |
| 20,0 | 20,0500 | 20,030 | 0,014 | 1,0010 | 0,0052 | 0,0053 |
| 30,0 | 29,9162 | 29,976 | 0,042 | 0,9980 | 0,0052 | 0,0052 |
| 40,0 | 40,1341 | 40,207 | 0,052 | 0,9982 | 0,0051 | 0,0051 |

## 7.3. Degree of equivalence and linkage to the KCRV

The degree of equivalence of VNIIM to the *KCRV* is given by the degree of equivalence $d_{\mathrm{PTB}}$ as the PTB deviation from the key comparison reference value *KCRV* (CCM.FF-K3.2011) at each velocity point according to:

$$d_{\mathrm{PTB,\,KCRV}} = K_{\mathrm{PTB}} - KCRV \tag{4}$$

with the uncertainty of the deviation at 95 % level of confidence:

$$U(d_{\mathrm{PTB,\,KCRV}}) = 2 \times u(d) \quad \text{and} \quad u(d) = \sqrt{u^2(K) - u^2(KCRV)} \tag{5}$$

(see final report CCM.FF-K3.2011, table 6 and 7)

and the VNIIM deviation from PTB:

$$d_{\mathrm{VNIIM,\,PTB}} = K_{\mathrm{VNIIM}} - K_{\mathrm{PTB}} \tag{6}$$

resulting in:

$$d_{\mathrm{VNIIM,\,KCRV}} = d_{\mathrm{PTB,\,KCRV}} + d_{\mathrm{VNIIM,\,PTB}} \tag{7}$$

with:

$$U(d_{\mathrm{VNIIM,\,KCRV}}) = \sqrt{U^2\left(d_{\mathrm{PTB,\ KCRV}}\right) + U^2(d_{\mathrm{VNIIM}})} \tag{8}$$

and:

$$U(d_{\mathrm{VNIIM}}) = U(K_{\mathrm{VNIIM}})_{\mathrm{PC}} \qquad \text{according to (3)} \tag{9}$$

Taking the key comparison result KCRV(CCM.FF-K3.2011) values for PTB, the bilateral comparison results from VNIIM and considering that $U(d_{\mathrm{VNIIM;PTB}}) = U_{\mathrm{VNIIM,"Pilot\ calculation"}}$ including the transfer standard stability the normalized error $E_{\mathrm{n}}$ expressed as

$$E_{\mathrm{n}} = \left|\frac{d_{\mathrm{VNIIM,KCRV}}}{U(d_{\mathrm{VNIIM,KCRV}})}\right| \tag{10}$$

describes the degree of equivalence of VNIIM related to the KCRV. The results are considered as consistent with the KCRV if $E_{\mathrm{n}} \leq 1$.

### 7.3.1. Ultrasonic anemometer

The degree of equivalence with respect to the KCRV of CCM.FF-K3.2011 at each velocity for the ultrasonic anemometer is shown in Table 12.

**Table 12 – Degree of equivalence of PTB and VNIIM with respect to the KCRV**

| AVERAGE DATA | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| US | | | | | | | | | | |
| Nominal air speed $V_{nom}$ [m/s] | *KKCRV* | $U$(KKCRV) | PTB | | VNIIM | Calibration result $V_{ref}/US$ | Calibration result $V_{ref}/US$ | | | |
| | | | $d_{i,PTB,KCRV}$ | $U(d_{i,PTB,KCRV})$ | $U(d_{i,VNIIM})$ | PTB | VNIIM | $d_{i,VNIIM,PTB}$ | $d_{i,VNIIM,KCRV}$ | $U(d_{i,VNIIM,KCRV})$ | $E_{i,VNIIM,KCRV}$ |
| 0,5 | 1,0253 | 0,0103 | -0,0051 | 0,0204 | 0,0232 | 1,0201 | 1,0143 | -0,0058 | -0,0109 | 0,0309 | 0,35 |
| 1,0 | 1,0099 | 0,0056 | -0,0023 | 0,0120 | 0,0142 | 1,0076 | 1,0049 | -0,0027 | -0,0050 | 0,0186 | 0,27 |
| 2,0 | 1,0018 | 0,0046 | -0,0088 | 0,0106 | 0,0125 | 0,9930 | 0,9983 | 0,0053 | -0,0036 | 0,0164 | 0,22 |
| 5,0 | 0,9890 | 0,0024 | -0,0034 | 0,0046 | 0,0065 | 0,9855 | 0,9854 | -0,0001 | -0,0035 | 0,0080 | 0,44 |
| 10,0 | 0,9871 | 0,0022 | -0,0018 | 0,0042 | 0,0061 | 0,9854 | 0,9853 | 0,0000 | -0,0018 | 0,0074 | 0,24 |
| 15,0 | 0,9881 | 0,0022 | -0,0008 | 0,0041 | 0,0059 | 0,9873 | 0,9884 | 0,0011 | 0,0003 | 0,0072 | 0,04 |
| 20,0 | 0,9890 | 0,0022 | -0,0004 | 0,0040 | 0,0058 | 0,9886 | 0,9864 | -0,0022 | -0,0026 | 0,0071 | 0,36 |
| 30,0 | 0,9878 | 0,0023 | 0,0009 | 0,0039 | 0,0058 | 0,9887 | 0,9852 | -0,0036 | -0,0027 | 0,0069 | 0,38 |
| 40,0 | 0,9895 | 0,0025 | 0,0000 | 0,0037 | 0,0057 | 0,9894 | 0,9875 | -0,0020 | -0,0020 | 0,0068 | 0,29 |

### 7.3.2. Laser Doppler anemometer

The degree of equivalence with respect to the KCRV of CCM.FF-K3.2011 at each velocity for the laser Doppler anemometer is shown in Table 13.

**Table 13 – Degree of equivalence of PTB and VNIIM with respect to the KCRV**

| AVERAGE DATA | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| LDA | | | | | | | | | | | |
| Nominal air speed $V_{nom}$ [m/s] | *KKCRV* | $U$(KKCRV) | PTB | | VNIIM | Calibration result $V_{ref}/V_{LDA}$ | Calibration result $V_{ref}/V_{LDA}$ | | | | |
| | | | $d_{i,PTB,KCRV}$ | $U(d_{i,PTB,KCRV})$ | $U(d_{i,VNIIM})$ | PTB | VNIIM | $d_{i,VNIIM,PTB}$ | $d_{i,VNIIM,KCRV}$ | $U(d_{i,VNIIM,KCRV})$ | $E_{i,VNIIM,KCRV}$ |
| 0,5 | 0,9993 | 0,0034 | -0,0003 | 0,0132 | 0,0150 | 0,9990 | 0,9890 | -0,0100 | -0,0103 | 0,0200 | 0,51 |
| 1,0 | 1,0000 | 0,0032 | 0,0030 | 0,0079 | 0,0101 | 1,0030 | 0,9959 | -0,0071 | -0,0041 | 0,0128 | 0,32 |
| 2,0 | 1,0013 | 0,0024 | -0,0002 | 0,0055 | 0,0075 | 1,0011 | 0,9994 | -0,0017 | -0,0019 | 0,0093 | 0,20 |
| 5,0 | 1,0006 | 0,0018 | 0,0021 | 0,0041 | 0,0060 | 1,0027 | 0,9977 | -0,0050 | -0,0029 | 0,0073 | 0,40 |
| 10,0 | 1,0016 | 0,0017 | 0,0017 | 0,0036 | 0,0055 | 1,0033 | 1,0003 | -0,0031 | -0,0013 | 0,0066 | 0,20 |
| 15,0 | 1,0016 | 0,0018 | 0,0018 | 0,0034 | 0,0053 | 1,0033 | 0,9991 | -0,0042 | -0,0024 | 0,0063 | 0,39 |
| 20,0 | 1,0016 | 0,0017 | 0,0017 | 0,0034 | 0,0053 | 1,0032 | 1,0010 | -0,0022 | -0,0006 | 0,0062 | 0,09 |
| 30,0 | 1,0012 | 0,0019 | 0,0014 | 0,0032 | 0,0052 | 1,0026 | 0,9980 | -0,0046 | -0,0032 | 0,0061 | 0,53 |
| 40,0 | 1,0009 | 0,0019 | 0,0012 | 0,0031 | 0,0051 | 1,0021 | 0,9982 | -0,0039 | -0,0027 | 0,0060 | 0,46 |

## 7.4. Discussion

As both transfer standards - the ultrasonic anemometer and the laser Doppler anemometer - had shown a high stability during the term of both key comparisons CCM.FF-K3.2011 and CCM.FF-K3.2011.1, the comparison results of PTB were taken from CCM.FF-K3.2011 to allow a direct linkage of the VNIIM results to the KCRV-(CCM.FF-K3.2011)-values.

The resulting $E_n$-values according to (10) show that all VNIIM results are consistent to the KCRV-values.

## 8. Optional LDA calibration with a primary standard

Optionally, a calibration of the LDA with a primary standard was proposed but was not subject of the bilateral key comparison CCM.FF-K3.2011.1.

## 9. Summary and conclusions

The bilateral key comparison CCM.FF-K3.2011.1 between VNIIM and PTB followed up the CCM.FF-K3.2011 key comparison and its protocol with identical transfer standards. As the stability of the transfer standards has been proven by measurements at PTB before and after the bilateral comparison and the data during the key comparison, a direct linkage between the VNIIM-results and the key comparison reference values via PTB's data from the key comparison was possible.

The VNIIM data for both transfer standards and all velocity values are consistent with the KCRV of the CCM.FF-K3.2011.

Nine institutes took part in 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 following table 14 checks the compliance of the results obtained by each participating laboratory to its claimed CMCs.

**Table 44 – Comparison of the results with the declared CMCs for the calibration of an anemometer**

| Country<br>NMI | Range<br>as declared in CMCs tables | Expanded uncertainty<br>as declared in CMCs tables | Result |
|---|---|---|---|
| Germany<br>PTB | 0.5 m/s to 40 m/s | (0.005 m/s + 0.0035*v*),<br>*v* speed in m/s | In accordance |
| Russian Federation<br>VNIIM | 0.5 m/s to 25 m/s | 0.5 % | In accordance |
| | 10 m/s to 100 m/s | 0.55 % to 1.0 % | In accordance |

## 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* (-) |
| $E_n$ | 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

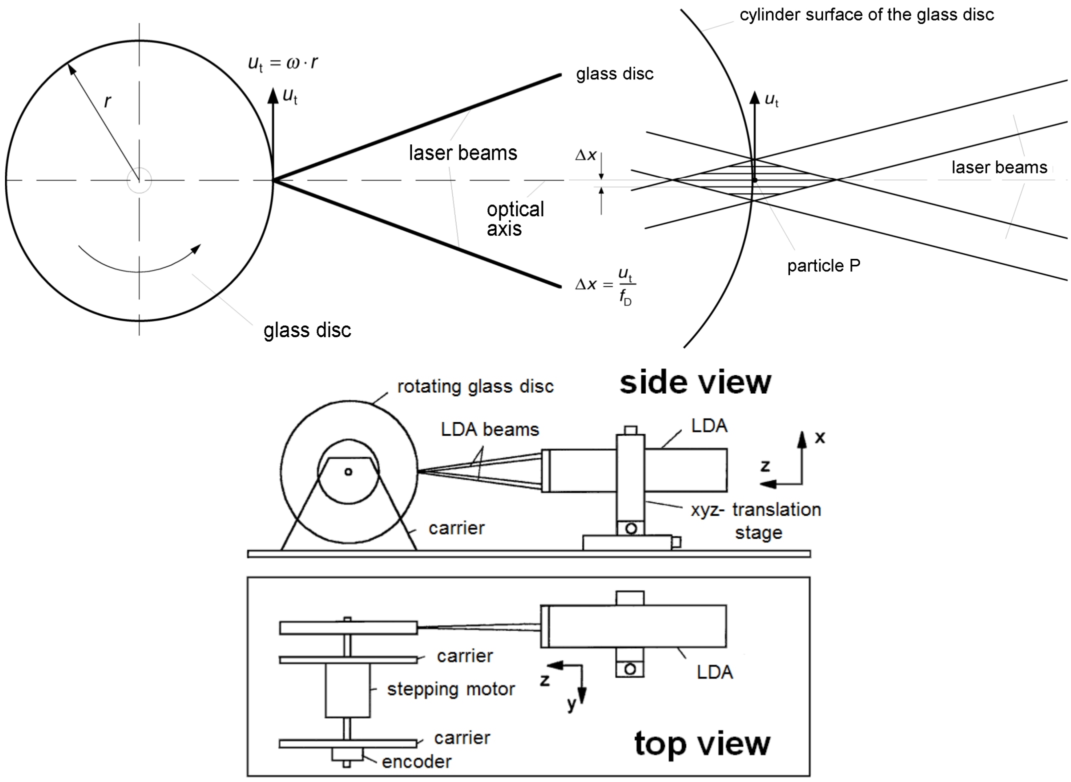
[8] CCM.FF-K3.2011: Final report for the CIPM key comparison of air speed, 0.5 m/s to 40 m/s, Metrologia, Volume 54, Issue 1A, pp. 07013 (2017).

# APPENDIX – DESCRIPTION OF THE FACILITIES

## PTB

### 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 $\omega$ 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.

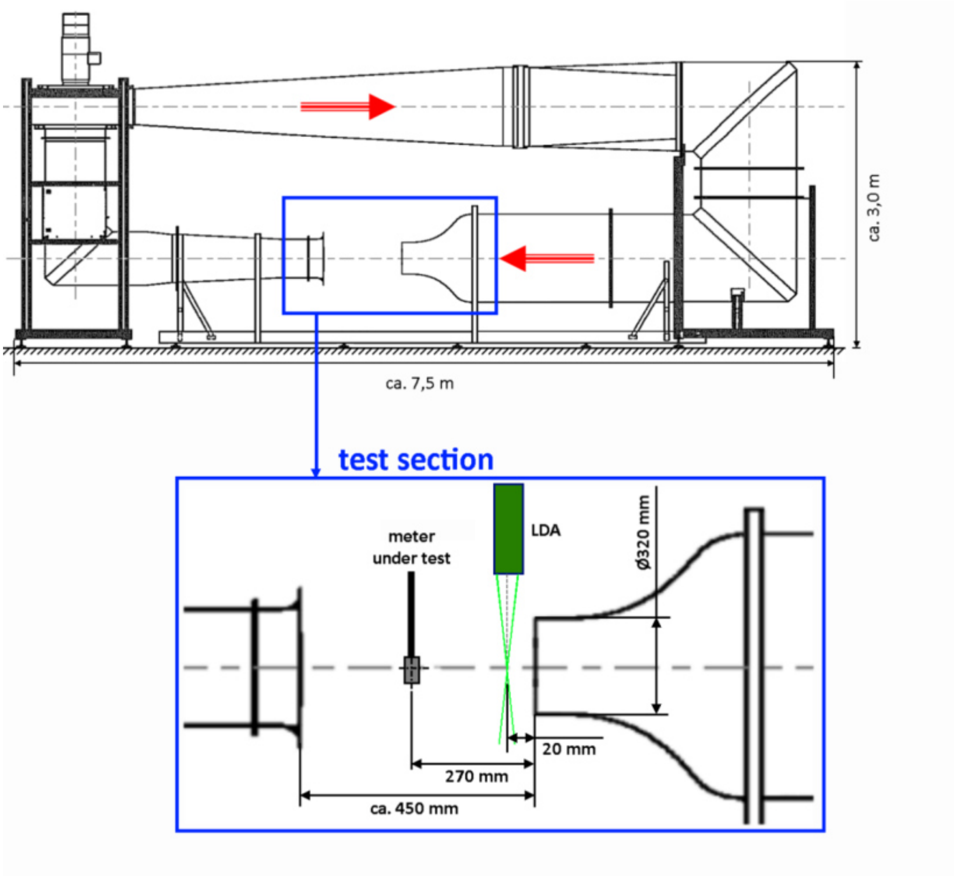
with relative expanded uncertainties ($k$ = 2) for the calibration (best available DUT) according to the CMCs:

*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*
*NMI service identifier: DE39*

*Flow speed. Laser Doppler Velocimeter (LDV), 1 µm to 15 µm*
*Relative expanded uncertainty (k = 2, level of confidence 95%) in %: 0.05*
*NMI service identifier: DE42*

## 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).




**Setup of the Göttingen type wind tunnel at PTB**

**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<br>test section length: 450 mm |
| Reference: | LDA |
| Traceability: | PTB,<br>rotating glass wheel surface for fringe calibration, frequency standard |

## VNIIM

### Facility and uncertainty budget for the calibration of anemometers

Calibration of transfer standard – ultrasonic anemometer – has been performed by measuring the anemometer indicated speed and the VNIIM standard reading simultaneously. Measurements accomplished at aerodynamic facility: loop tube with open test section. Nozzle diameter is 700 mm, range 0.05 – 100 m/s. Means of air speed measuring:

| | |
|---|---|
| 0.1 – 20 m/s | LDA |
| 5 - 100 m/s | Pitot static tube with differential manometer. |

Distance between nozzle exit plane and ultrasonic anemometer sensors was 70 mm.

While using LDA air speed determined as

$$V_s = K_l * K_b * K_d * V_l, \text{ [m/s]} \quad (1)$$

$K_l$ – LDA calibration factor
$K_b$ – correction factor due to duct blockage
$K_d$ – correction factor due to velocity distribution across the duct
$V_l$ – air speed indicated by LDA, [m/s]

The relative uncertainty

$$\frac{u_c(V_s)}{V_s} = \left(\left(\frac{u(K_l)}{K_l}\right)^2 + \left(\frac{u(K_b)}{K_b}\right)^2 + \left(\frac{u(K_d)}{K_d}\right)^2\right)^{1/2} \quad (2)$$

Expanded uncertainty sources and values

| Sourses | | $u(X_i)/X_i$, % |
|---|---|---|
| LDA calibration factor | $\left(\frac{u(K_l)}{K_l}\right)$ | 0.05 |
| Correction factor due to duct blockage | $\left(\frac{u(K_b)}{K_b}\right)$ | 0.10 |
| Correction factor due to velocity distribution across the duct | $\left(\frac{u(K_d)}{K_d}\right)$ | 0.25 |
| Combined standard uncertainty | $\frac{u_c(V_s)}{V_s}$ | 0.27 |
| | $k$ | 2 |
| Expanded uncertainty | | 0.54 |