# CCM.FF-K3.2011 Intercomparison for airspeed

Isabelle Caré, CETIAT (France)
Harald Müller, PTB (Germany)
Peter Lucas, VSL (The Neherlands)
Dietmar Pachinger, E+E (Austria)
Noboru Kurihara, NMIJ/AIST (Japan)
Cui Lishui, NIM (China)
Chun-Min Su, CMS/ITRI (Chinese Taipei)
Iosif Shinder, NIST (USA)
Pier Giorgio Spazzini, INRIM (Italy)
Corresponding Author: isabelle.care@cetiat.fr

**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. The degree of equivalence with the KCRV was calculated for each air speed and laboratory. Almost all reported results were consistent with the KCRV.

## 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 the one 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 2nd round of this key comparison was 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.

Optionally, a comparison of the Laser Doppler Anemometer with a primary standard was proposed to the participants.

## 2. Participants

The participants are listed in Table 1.

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

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

Because of customs clearance problems, Russia was not able to participate to this comparison. In agreement with all the parties, a separate bilateral comparison with PTB (registered as CCM.FF-K3.2011.1) with the same protocol was organised after the conclusion of this one.

## 3. Travelling standards

### 3.1. Ultrasonic anemometer

The ultrasonic anemometer 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.

***Fig.1.*** 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 Fig.1. 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.

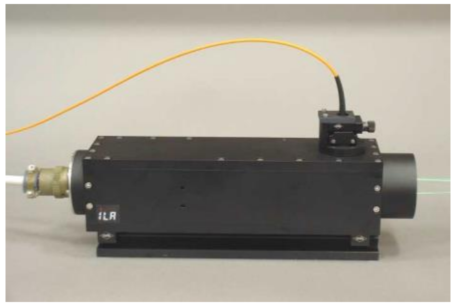


***Fig.2.*** Laser Doppler Anemometer probe (power 75 mW, wavelength 532 mm)

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 was 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 were 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:

$$K = \frac{V_{\mathrm{ref}}}{V_{\mathrm{ts}}} \qquad \textbf{(Eq.1)}$$

With:

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

## 5. Results

### 5.1. Stability of the transfer standards

PTB, as pilot laboratory, tested the instruments several times during the comparison. The stability of the *K* factor for each velocity is shown in Fig.2.

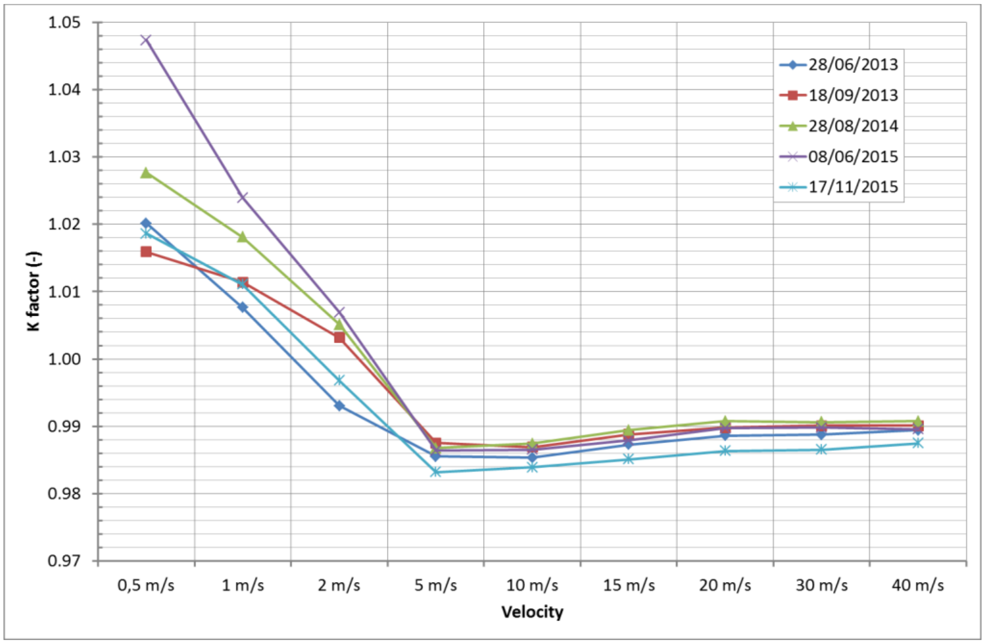


***Fig.3.*** *K* factor of the ultrasonic anemometer for the different calibrations at PTB

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

| **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 |

***Table 2*** Additional standard uncertainty due to the stability of the ultrasonic 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.

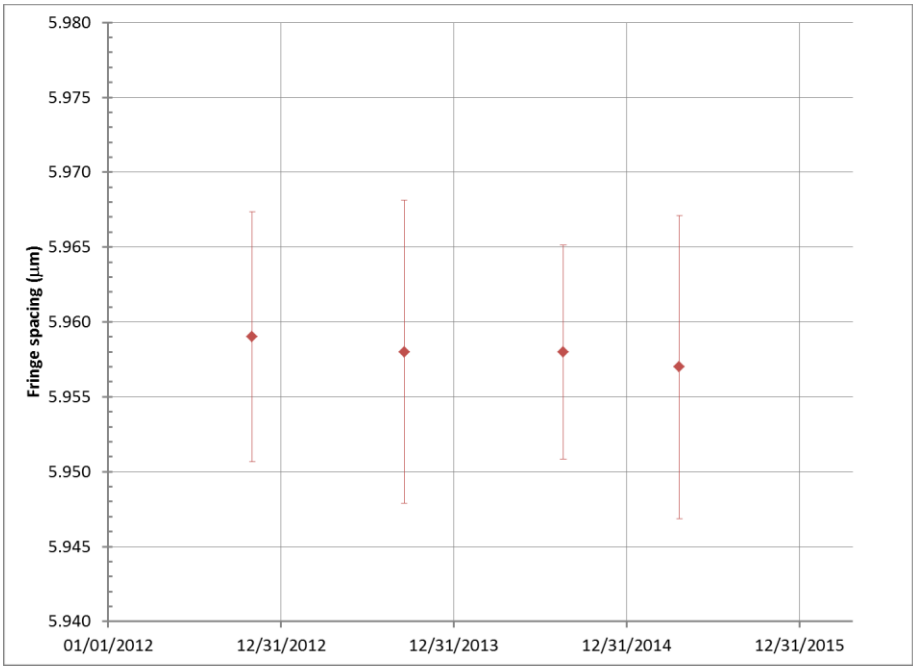


***Fig.4.*** Calibration of the fringe spacing at PB over the duration of K3

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.

### 5.2. Results reported by the participants

The *K* factors from all participants are shown in Fig.4 for the ultrasonic anemometer and Fig.5 for the Laser Doppler anemometer.

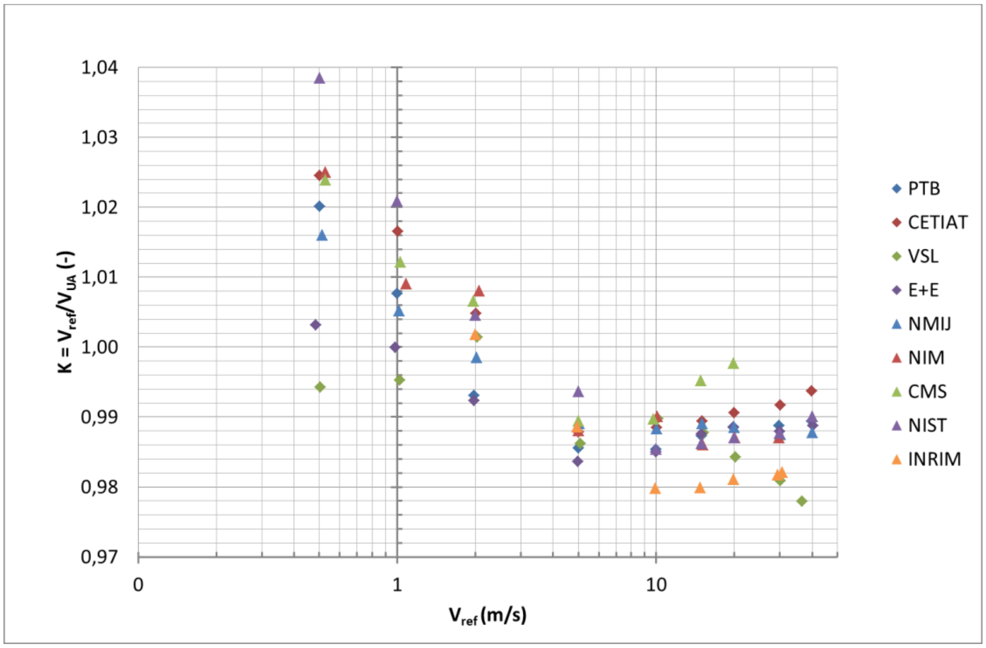


***Fig.5.*** *K* factor obtained by all the participants for the ultrasonic anemometer

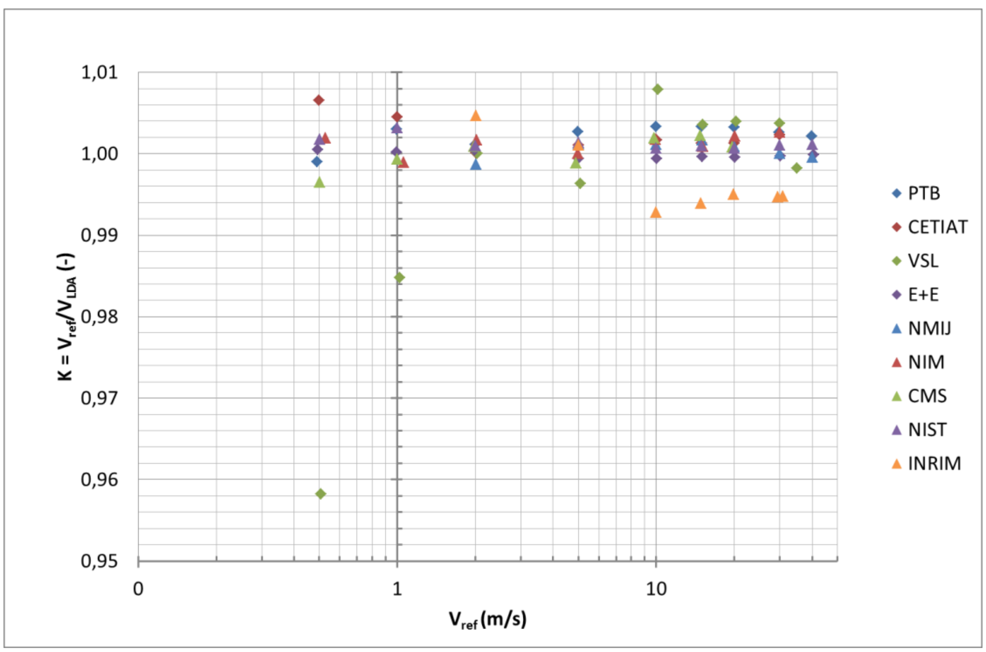


***Fig.6.*** *K* factor obtained by all the participants for the Laser Doppler anemometer

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.

The ratio between the wheel speed and the indicated LDA velocity is presented in Fig.7.

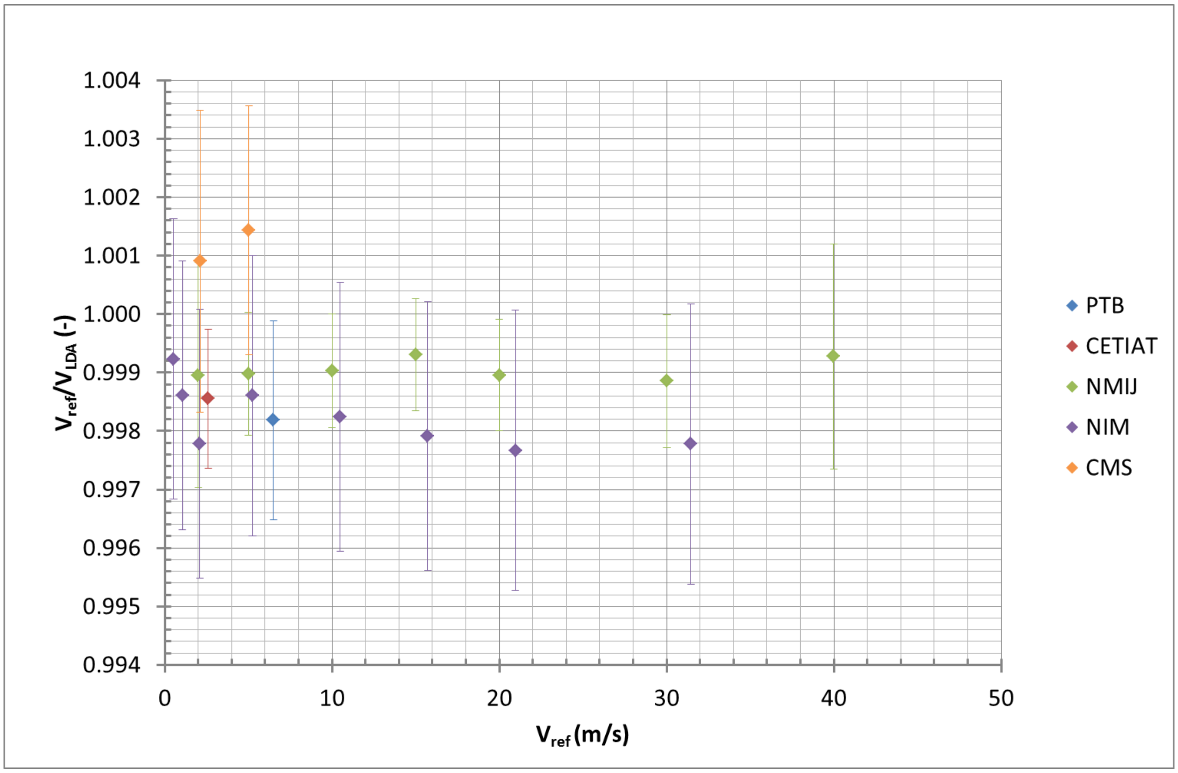


***Fig.7.*** Results obtained by all the participants for the calibration of the Laser Doppler anemometer with a primary standard

**5.3. Calculation of the reference value, its uncertainty and the degree of equivalence**

The analysis of the results was carried out according to the method specified by Cox [3, 4].

According to the Cox procedure, the KCRV was 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.

The KCRVs for the ultrasonic anemometer and the Laser Doppler anemometer were calculated by applying the "weighted mean" method (procedure A).The chi-square consistency test passed for the overall set of data and showed all the data were mutually consistent

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 [4] as:

$$d = K - KCRV \qquad \textbf{(Eq.2)}$$

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

$$U(d) = 2 \times u(d) \qquad \textbf{(Eq.3)}$$

where

$$u(d) = \sqrt{u^2(K) - u^2(KCRV)} \qquad \textbf{(Eq.4)}$$

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. Eq.4 still applies to E+E because there is strong covariance between E+E and the KCRV via the PTB traceability path.

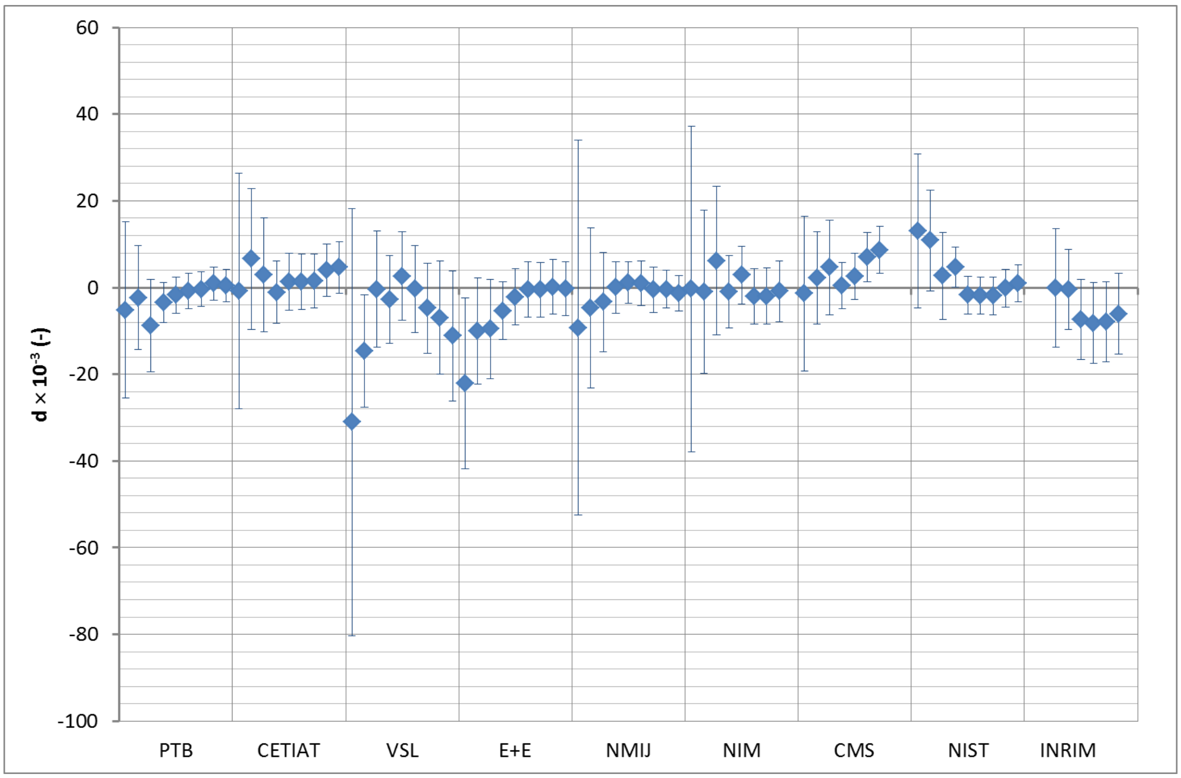


***Fig.8.*** Degrees of equivalence with respect to KCRV of each laboratory for the ultrasonic anemometer at the different air speeds. The error bars show the expanded uncertainty of the degree of equivalence for each calibrated value

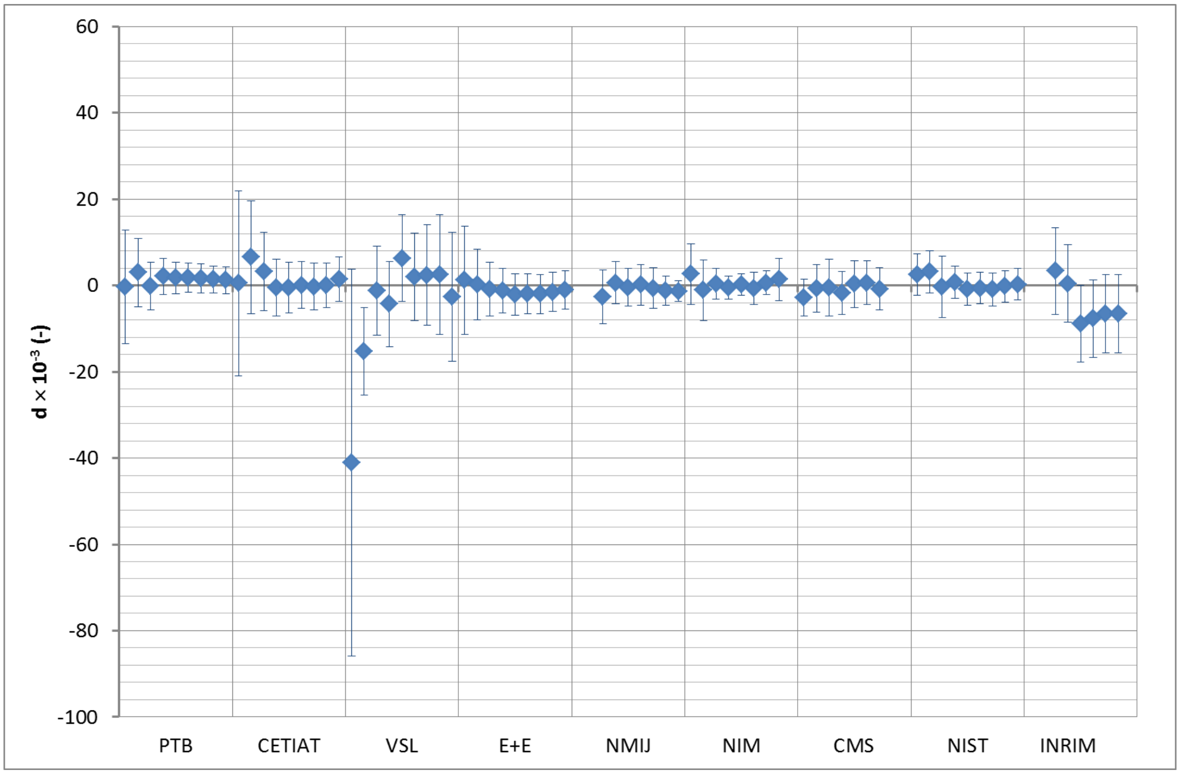


***Fig.9.*** Degrees of equivalence with respect to KCRV of each laboratory for the Laser Doppler anemometer at the different air speeds. The error bars show the expanded uncertainty of the degree of equivalence for each calibrated value

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.

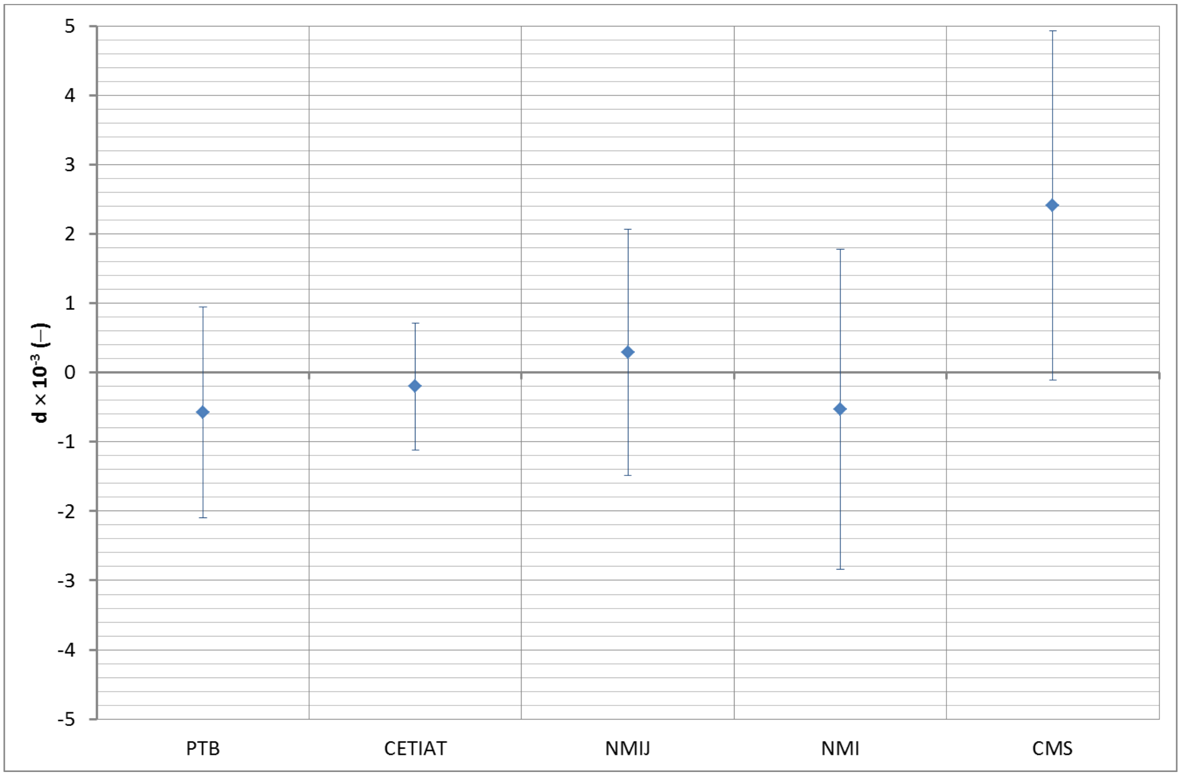


***Fig.10.*** Degrees of equivalence with respect to KCRV of each laboratory for the Laser Doppler anemometer calibrated with a primary standard. The error bars show the expanded uncertainty of the degree of equivalence for each calibrated value

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 can be considered as validated for the used LDA.

## 6. 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 shows 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 comparison allowed checking the compliance of the results obtained by each participant to its claimed CMCs, when available.

[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, 2007
[2] Müller H., *Final Report on LDA-based intercomparison of anemometers (EURAMET 827), EURAMET.M.FF.S5*, BIPM KCDB Database, 2012
[3] CCQM Guidance note, *Estimation of a consensus KCRV and associated Degrees of Equivalence*, 2013
[4] Cox M.G., *The evaluation of key comparison data*, Metrologia (39), pp 589-595, 2002