EURAMET project No. 1450

# Comparison of low air speed calibration facilities

## Final report


**Coordinator**

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# Contents

# 1 Introduction

This report describes a supplementary interlaboratory comparison between European low air speed calibration facilities. Two thermal anemometers have been used as transfer standards and circulated between five participants. The transfer standards selection was based on stable behaviour and sensitivity at very low air speeds. The first anemometer was calibrated by the participants at nominal velocities from 0.05 m/s to 1.0 m/s. The second anemometer was calibrated at nominal velocities from 0.15 m/s to 1 m/s.

# 2 Participants

Participating laboratories, their contact details, measurement principles and air speed ranges are summarised in Tab. 1. Time schedule of the calibrations is summarised in Tab. 2.

| Laboratory | Address | Facility | Range | CMC uncertainty (k = 2) |
|---|---|---|---|---|
| **CMI**<br>(Czech Republic) | **CMI** (Jan Sluse)<br>Okruzni 31, 63800 Brno,<br>Czech Republic | tow tank<br>wind tunnel | 0.05 m/s to 0.5 m/s<br>0.3 m/s to 50 m/s | 0.005 m/s + 0.005*v<br>0.01 m/s + 0.003*v (for v ≤ 5 m/s)<br>0.005*v (for v > 5 m/s) |
| **BEV/E+E Elektronik**<br>(Austria) | **BEV/E+E Elektronik**<br>(Dietmar Pachinger)<br>Langwiesen 7, A-4209<br>Engerwitzdorf, Austria | wind tunnel | 0.04 m/s to 2 m/s | 0.004 m/s + 0.0047*v |
| **CETIAT**<br>(France) | **CETIAT** (Isabelle Care)<br>Laboratoire Anémométrie<br>Domaine Scientifique de la Doua<br>54, boulevard Niels Bohr<br>69100 VILLEURBANNE, France | wind tunnel | 0.05 m/s to 2 m/s | 0.006 m/s + 0.006*v |
| **DTI**<br>(Denmark) | **DTI** (Søren Haack)<br>Installation og Kalibrering,<br>Bygning 14, Teknologiparken,<br>Kongsvang Allé 29,<br>8000 Arhus C, Denmark | tow tank | 0.05 m/s to 0.7 m/s | 0.02 m/s |
| **METAS**<br>(Switzerland) | **METAS** (Marc de Huu)<br>Laboratory for Flow and Hydrometry<br>Lindenweg 50, 3084 Wabern,<br>Switzerland | wind tunnel | 0.1 m/s to 30 m/s | 0.02 m/s (for v ≤ 1 m/s)<br>0.02*v (for v > 1 m/s) |

Tab. 1 List of participants and parameters of their facilities.

| | 2018 | | | | |
|---|---|---|---|---|---|
| | **January** | **February** | **March** | **April** | **May** |
| **CMI** | | | | | |
| **DTI** | | | | | |
| **CMI** | | | | | |
| **BEV/E+E** | | | | | |
| **METAS** | | | | | |
| **CETIAT** | | | | | |
| **CMI** | | | | | |

Tab. 2 Time schedule

# 3 Description of transfer standards

Two transfer standards were used. Both of them use the same control unit Ahlborn Almemo 25904S (see Fig. 2) which can be connected by USB cable to a computer.

## 3.1 Transfer standard *1*

The probe of the transfer standard *1* is an omnidirectional thermal sensor Schiltknecht type FV A605 TA1O (see Fig. 1). The sensor includes special wire frame as a protective cover. To avoid any possible flow disturbances due to the frame the calibrations were performed with the frame removed. The sensor itself is very small and therefore there is no significant blockage effect. The anemometer does not contain any barometric pressure sensor and a fixed value of the pressure 1013 hPa was set in the control unit during calibrations in all the laboratories. Therefore, a pressure compensation correction was applied by the pilot lab within the data evaluation.

**Transfer standard *1***

**Probe:**

| | |
|---|---|
| Manufacturer: | Schiltknecht |
| Type: | FV A605 TA1O (or f.443.6/64) |
| Serial number: | 84070 |
| Sensor size: | length 310 mm; diameter 15 mm |
| Sensor weight: | approximately 240g |
| Range: | (0.01 – 1) m/s |
| Resolution: | 0,001 m/s |
| Accuracy: | ±1.0% of final value and ±1.5% of measuring value |

**Control unit:**

| | |
|---|---|
| Manufacturer: | Ahlborn |
| Type: | Almemo 25904S |
| Serial number: | H13121064 |

Fig. 1 Probe Schiltknecht FV A605 TA1O (or f.443.6/64)

**Installation of the probe**

The tip is defined as omnidirectional but in fact it indicates slightly different velocities for different wind directions. The reason is that the thermal sensor is not axially symmetric (Fig. 3). The probe included a dot for definition of the direction of wind (Fig. 4). The participants were instructed that the dot should face upstream the air flow during the calibration. Cable connections are described in Fig. 5.


Fig. 2 Control unit – Ahlborn, Almemo 25904S

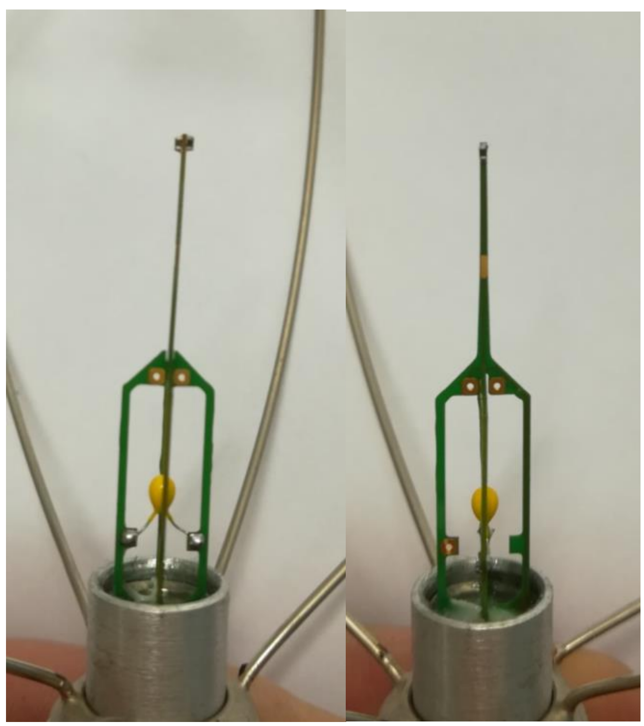

Fig. 3 Two orthogonal views of the probe tip

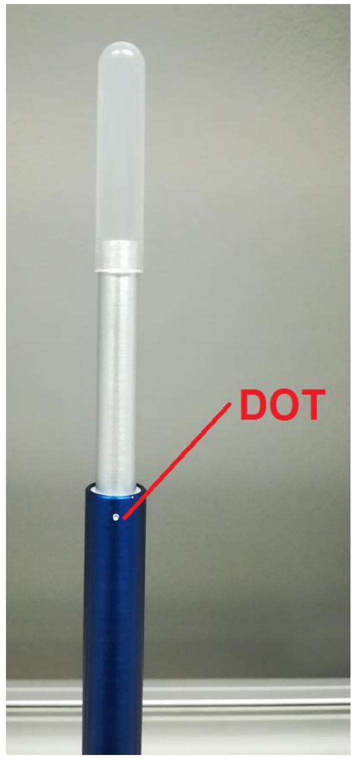


Fig. 4 The dot on the probe of the transfer standard *1*

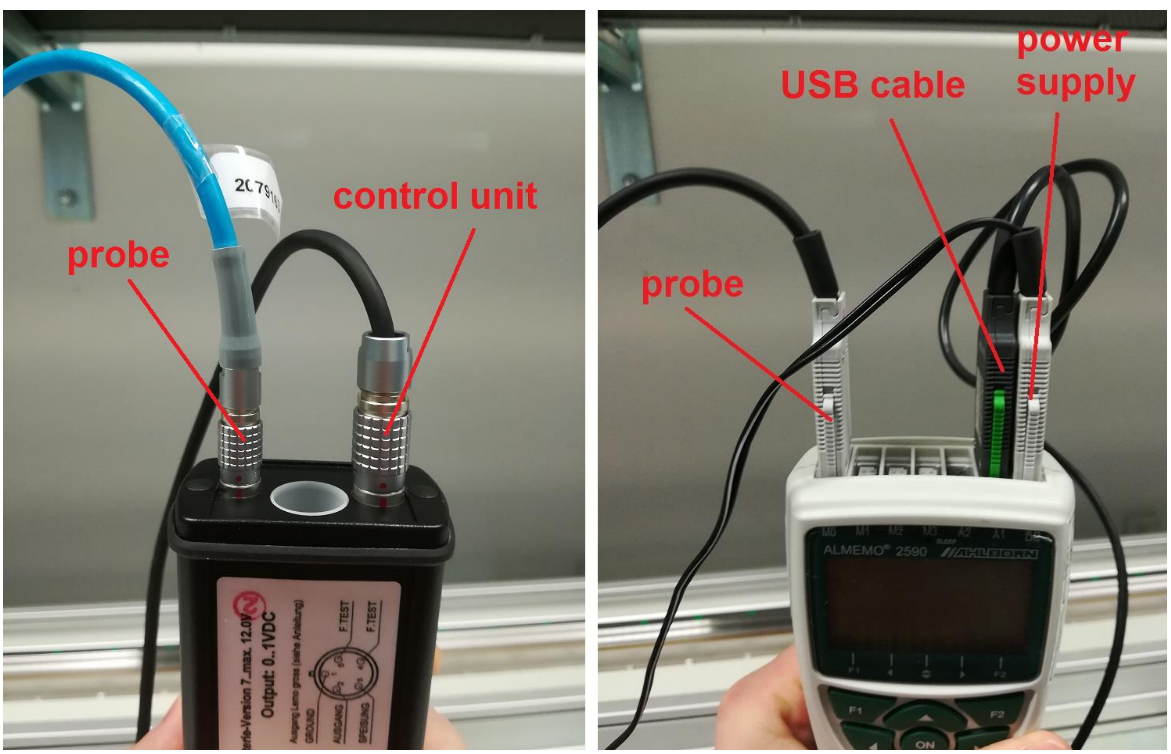


Fig. 5 Cable connections of the transfer standard *1*

## 3.2 Transfer standard *2*

The probe of the transfer standard *2* is a bidirectional thermal sensor Ahlborn type FVAD 35 TH4 (see Fig. 6). The sensitivity of this probe is smaller than for the transfer standard *1*. The lower air speed range of this probe declared by the manufacturer is 0.08 m/s. The connector at the end of the probe's cable contains a sensor of barometric pressure and the anemometer indicates velocity values compensated for ambient conditions. Therefore, no further corrections were applied.

**Transfer standard *2***

**Probe:**

| | |
|---|---|
| Manufacturer: | Ahlborn |
| Type: | FVAD 35 TH4 |
| Serial number: | 17050107 |
| Sensor size: | length 210 mm; diameter 6 mm |
| Sensor weight: | approximately 240g |
| Range: | (0.08 – 2) m/s |
| Resolution: | 0.001 m/s |
| Accuracy: | ±(0.04 m/s + 1.0 % of measuring value) |

**Control unit:**

| | |
|---|---|
| Manufacturer: | Ahlborn |
| Type: | Almemo 25904S |
| Serial number: | H13121064 |

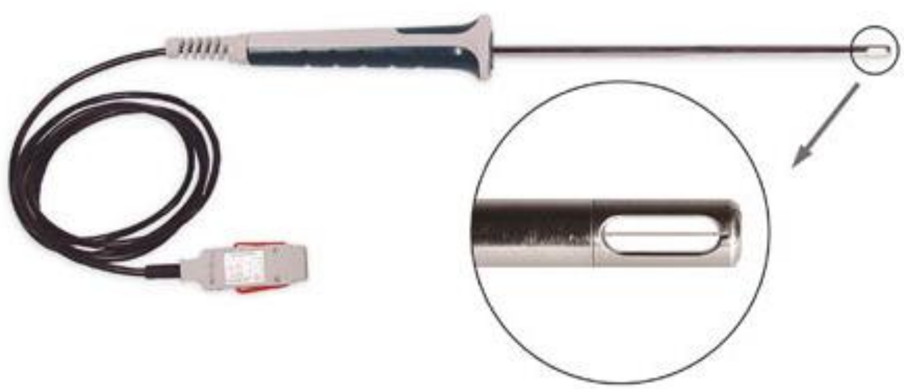

Fig. 6 Probe Ahlborn FVAD 35 TH4

Again, the probe was installed in a predefined direction such that a dot on the probe faced upstream. Cable connections were the same as shown in the right part of Fig. 5.

# 4 Measurement procedure

Each participating laboratory calibrated both transfer standards and evaluated the uncertainty of the calibration according to its standard procedure.

The calibrations were performed for nominal velocities as listed in Tab. 3. Laboratories which could not reach the full velocity range from 0.05 m/s up to 1.0 m/s limited their measurements to the velocity range they can realize. The velocities were set starting from the lowest one and continuing to the highest one.

| **Transfer standard** | **Tested velocities (m/s)** |
|---|---|
| *1* | 0.05; 0.1; 0.2; 0.3; 0.4; 0.5; 0.7; 1.0 |
| *2* | 0.15; 0.2; 0.3; 0.4, 0.5; 0.7; 1.0 |

Tab. 3 The testing velocities for each transfer standard

The meters were temperature stabilised to the laboratory temperature at least for three hours before the start of the measurement. The ambient conditions were kept in the ranges as defined in Tab. 4.

| | |
|---|---|
| Temperature | (18 – 24) °C |
| Relative humidity | (30 – 60) % |

Tab. 4 Ambient condition during the calibrations

The control unit was connected to an external power supply, i.e. no batteries were used. The meters have been zeroed before the start of the calibration process according to a procedure described in the technical protocol.

# 5 Data from participating laboratories

## 5.1 Transfer standard *1*

The velocity indication of transfer standard *1* is automatically corrected just for the air temperature but not for the pressure. A fixed value of standard barometric pressure 1013 hPa was set in the control unit of the instrument for all calibrations and a correction of the indicated velocity to the actual pressure in the calibration facility was performed by the pilot laboratory. The pressure in a calibration facility was assumed to be equal to the ambient pressure in a laboratory which is true for the used low air speeds with a sufficient accuracy. The correction for barometric pressure was calculated according to the formula

$$v_{i,cor} = v_i \frac{p_s}{p_i}$$

where:

$v_i$ - value measured by MUT,
$v_{i,cor}$ - value corrected on standard barometric pressure,
$p_i$ - barometric pressure during test in laboratories,
$p_s$ - standard barometric pressure (1013 hPa).

The tables below contain the calibration data submitted by the participants for the transfer standard *1*. In case of CMI two calibration facilities have been used – tow tank (CMI-TT) and wind tunnel (CMI-WT). Tab. 5 contains the barometric pressures in particular laboratories during the calibration of the transfer standard *1* which are then used for the pressure correction of the indicated velocities. Tab. 6 contains reference velocities, measurement errors without the pressure correction, measurement errors calculated from the pressure corrected velocity indication by the pilot laboratory and expanded (k = 2) uncertainties of the errors. The pressure corrected errors are then plotted in Fig. 7.

| | CMI-TT | BEV/E+E | METAS | Cetiat | DTI | CMI-WT |
|---|---|---|---|---|---|---|
| **$p_i$ (hPa)** | 981.0/969.0 | 965.0 | 947.7 | 995.5 | 1005.4 | 982.0 |

Tab. 5 Barometric pressure during the calibration in each laboratory. For CMI-TT the pressures for two repeated measurements are included.

| **$v_{nom}$ (m/s)** | | CMI-TT | BEV/E+E | METAS | Cetiat | DTI | CMI-WT |
|---|---|---|---|---|---|---|---|
| **0.05** | $v_{ref}$ (m/s) | 0.0500 | | | 0.0499 | 0.050 | |
| | E (m/s) | | | | -0.0099 | -0.009 | |
| | $E_{cor}$ (m/s) | -0.0020 | | | -0.0092 | -0.008 | |
| | U (m/s) | 0.0050 | | | 0.0063 | 0.021 | |
| **0.10** | $v_{ref}$ (m/s) | 0.1000 | 0.1137 | | 0.1009 | 0.101 | |
| | E (m/s) | | -0.0129 | | -0.0114 | -0.014 | |
| | $E_{cor}$ (m/s) | -0.0105 | -0.0079 | | -0.0098 | -0.013 | |
| | U (m/s) | 0.0056 | 0.0045 | | 0.0067 | 0.021 | |
| **0.20** | $v_{ref}$ (m/s) | 0.2000 | 0.2011 | 0.230 | 0.2007 | 0.202 | 0.233 |
| | E (m/s) | | -0.0161 | -0.015 | -0.0061 | -0.006 | -0.002 |
| | $E_{cor}$ (m/s) | -0.0090 | -0.0069 | 0.000 | -0.0027 | -0.005 | 0.005 |
| | U (m/s) | 0.0055 | 0.0050 | 0.020 | 0.0073 | 0.021 | 0.011 |
| **0.30** | $v_{ref}$ (m/s) | 0.3000 | 0.2906 | 0.300 | 0.3002 | 0.303 | 0.312 |
| | E (m/s) | | -0.0182 | -0.019 | -0.0032 | -0.003 | -0.005 |
| | $E_{cor}$ (m/s) | -0.0006 | -0.0047 | 0.000 | 0.0020 | -0.001 | 0.005 |
| | U (m/s) | 0.0060 | 0.0054 | 0.020 | 0.0081 | 0.021 | 0.011 |
| **0.40** | $v_{ref}$ (m/s) | 0.4000 | 0.3824 | 0.400 | 0.4014 | 0.403 | 0.393 |
| | E (m/s) | | -0.0145 | -0.025 | 0.0025 | 0.002 | -0.004 |
| | $E_{cor}$ (m/s) | 0.0072 | 0.0038 | 0.001 | 0.0095 | 0.005 | 0.009 |
| | U (m/s) | 0.0060 | 0.0058 | 0.020 | 0.0086 | 0.021 | 0.011 |
| **0.50** | $v_{ref}$ (m/s) | 0.5000 | 0.4805 | 0.500 | 0.5008 | 0.504 | 0.478 |
| | E (m/s) | | -0.0106 | -0.020 | 0.0093 | 0.003 | -0.002 |
| | $E_{cor}$ (m/s) | 0.0189 | 0.0128 | 0.013 | 0.0183 | 0.007 | 0.013 |
| | U (m/s) | 0.0076 | 0.0063 | 0.020 | 0.0097 | 0.021 | 0.011 |
| **0.70** | $v_{ref}$ (m/s) | | 0.6638 | 0.700 | 0.701 | 0.706 | 0.723 |
| | E (m/s) | | -0.0015 | -0.004 | 0.022 | 0.020 | 0.007 |
| | $E_{cor}$ (m/s) | | 0.0314 | 0.044 | 0.035 | 0.026 | 0.030 |
| | U (m/s) | | 0.0077 | 0.020 | 0.011 | 0.023 | 0.012 |
| **1.00** | $v_{ref}$ (m/s) | | 0.9596 | 0.990 | 1.002 | | 0.980 |
| | E (m/s) | | 0.0004 | -0.005 | 0.002 | | 0.006 |
| | $E_{cor}$ (m/s) | | 0.0481 | 0.063 | 0.020 | | 0.038 |
| | U (m/s) | | 0.0101 | 0.020 | 0.013 | | 0.013 |

Tab. 6 Calibration data for the transfer standard *1*: "$v_{ref}$" is the reference velocity, "E" is the anemometer error without air pressure correction, "$E_{cor}$" is the anemometer error with air pressure correction and "U" is the expanded uncertainty (k=2) of the error. For CMI-TT average of pressure corrected errors from two repeated measurements is included (for details see Tab. 8).

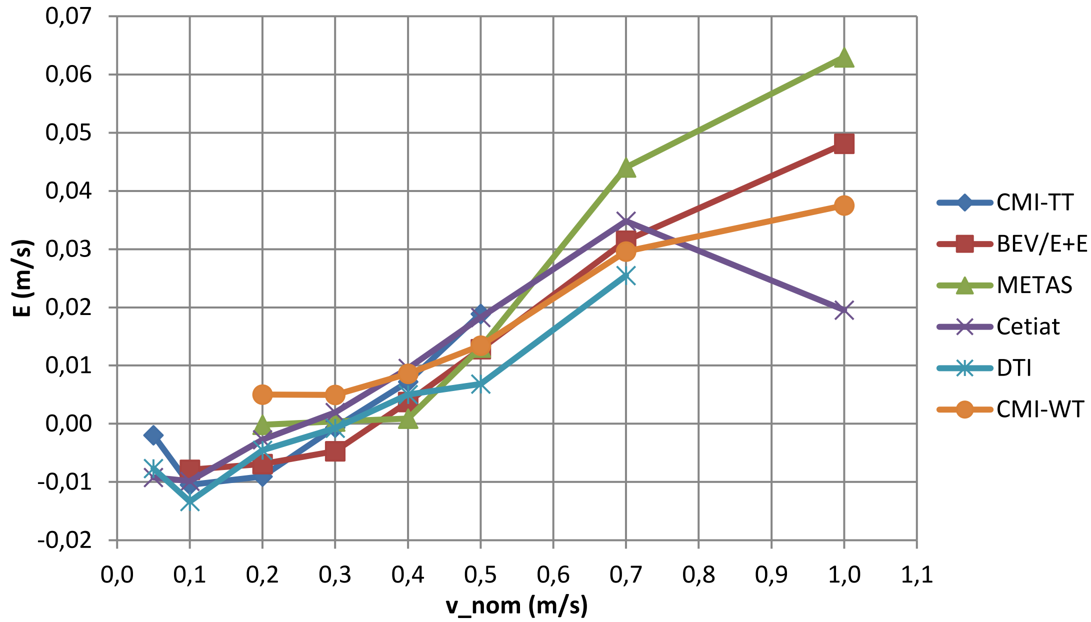


Fig. 7 Measurement error of the transfer standard *1* as a function of nominal velocity

## 5.2 Transfer standard *2*

The transfer standard *2* automatically corrects the indicated velocity to actual temperature and barometric pressure. Therefore, data from participants can be directly compared without further corrections. Tab. 7 contains the reference velocities, measurement errors and the corresponding expanded (k=2) uncertainties for the transfer standard *2*. The measurement errors are plotted in Fig. 8.

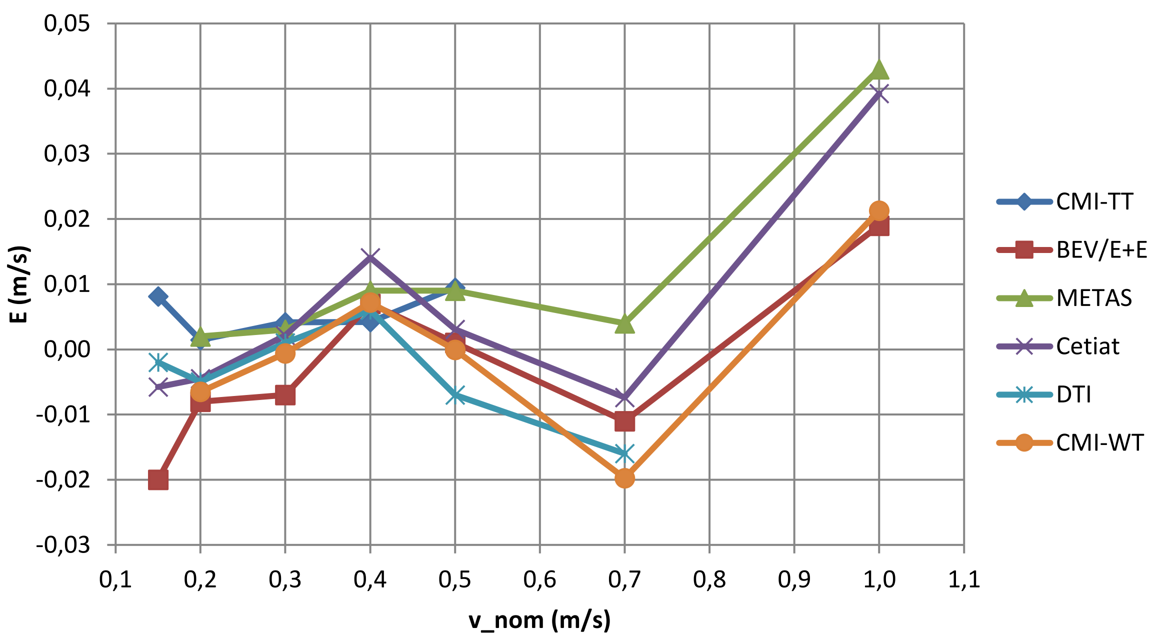


Fig. 8 Measurement error of the transfer standard *2* as a function of nominal velocity

| $v_{nom}$ (m/s) | | CMI-TT | BEV/E+E | METAS | Cetiat | DTI | CMI-WT |
|---|---|---|---|---|---|---|---|
| **0.15** | $v_{ref}$ (m/s) | 0.1500 | 0.1550 | | 0.1497 | 0.151 | |
| | E (m/s) | 0.0081 | -0.0200 | | -0.0058 | -0.002 | |
| | U (m/s) | 0.0073 | 0.0050 | | 0.0070 | 0.020 | |
| **0.20** | $v_{ref}$ (m/s) | 0.2000 | 0.2010 | 0.190 | 0.2003 | 0.202 | 0.223 |
| | E (m/s) | 0.0014 | -0.0080 | 0.002 | -0.0045 | -0.005 | -0.006 |
| | U (m/s) | 0.0069 | 0.0050 | 0.020 | 0.0073 | 0.020 | 0.011 |
| **0.30** | $v_{ref}$ (m/s) | 0.3000 | 0.2910 | 0.290 | 0.3009 | 0.303 | 0.303 |
| | E (m/s) | 0.0042 | -0.0070 | 0.003 | 0.0022 | 0.001 | -0.001 |
| | U (m/s) | 0.0069 | 0.0060 | 0.020 | 0.0079 | 0.020 | 0.011 |
| **0.40** | $v_{ref}$ (m/s) | 0.4000 | 0.3820 | 0.390 | 0.4006 | 0.403 | 0.386 |
| | E (m/s) | 0.0042 | 0.0070 | 0.009 | 0.0140 | 0.006 | 0.007 |
| | U (m/s) | 0.0089 | 0.0060 | 0.020 | 0.0086 | 0.020 | 0.011 |
| **0.50** | $v_{ref}$ (m/s) | 0.5000 | 0.4810 | 0.490 | 0.5017 | 0.504 | 0.470 |
| | E (m/s) | 0.0095 | 0.0010 | 0.009 | 0.0031 | -0.007 | 0.000 |
| | U (m/s) | 0.0089 | 0.0070 | 0.020 | 0.0094 | 0.020 | 0.011 |
| **0.70** | $v_{ref}$ (m/s) | | 0.6640 | 0.700 | 0.700 | 0.706 | 0.720 |
| | E (m/s) | | -0.0110 | 0.004 | -0.007 | -0.016 | -0.020 |
| | U (m/s) | | 0.0080 | 0.020 | 0.011 | 0.021 | 0.012 |
| **1.00** | $v_{ref}$ (m/s) | | 0.9580 | 1.010 | 1.003 | | 0.987 |
| | E (m/s) | | 0.0190 | 0.043 | 0.039 | | 0.021 |
| | U (m/s) | | 0.0100 | 0.021 | 0.020 | | 0.013 |

Tab. 7 Calibration data for the transfer standard *2*: "$v_{ref}$" is the reference velocity, "E" is the anemometer error and "U" is the expanded uncertainty (k=2) of the error. For CMI-TT average of errors from two repeated measurements is included (for details see Tab. 18).

# 6 Evaluation of the results

The results were evaluated according to the procedure published by Cox [2,3]. The procedure was applied for each velocity and for each anemometer separately.

**Comparison reference value (CRV) and its uncertainty**

A reference value $y$ is calculated as weighted mean error

$$y = \frac{\frac{x_1}{u^2(x_1)} + \cdots + \frac{x_N}{u^2(x_N)}}{\frac{1}{u^2(x_1)} + \cdots + \frac{1}{u^2(x_N)}}$$

where

$x_i$ - input quantities to the evaluation (errors measured by participants),
$u(x_i)$ - standard uncertainties associated with these values,
$i$ - identifies the participating institutes,
$N$ - number of participating laboratories.

The drift of the sensor element over the whole time period is added to the whole uncertainty budget. Denoting $E_{min}$ and $E_{max}$ the minimal and maximal errors obtained during repeated calibrations of an instrument in the pilot laboratory the corresponding standard uncertainty component is calculated as

$$u_{drift} = \frac{(E_{max} - E_{min})}{2\sqrt{3}}.$$

The standard uncertainties of the error including the uncertainty caused by instability of the anemometer are then calculated as

$$u(x_i) = \sqrt{\left(\frac{U(x_i)}{2}\right)^2 + u_{drift}{}^2}.$$

The standard deviation of the reference value $u(y)$ is calculated according to the formula

$$\frac{1}{u^2(y)} = \frac{1}{u^2(x_1)} + \cdots + \frac{1}{u^2(x_N)}.$$

The expanded uncertainty of the reference value then is $U(y) = 2 \cdot u_y$.
The chi-squared test will be applied to carry out an overall consistency check of the results. The result is considered inconsistent if the value of $\chi^2_{obs}$ calculated as

$$\chi^2_{obs} = \frac{(x_1 - y)^2}{u^2(x_1)} + \cdots + \frac{(x_N - y)^2}{u^2(x_N)}$$

satisfies

$$\Pr\{\chi^2(\nu) > \chi^2_{obs}\} < 0.05$$

with $\nu = N - 1$ being the degrees of freedom. If the results pass the consistency check the value of $y$ is accepted as the comparison reference value (CRV) and denoted as $x_{ref}$ and $u(y)$ is accepted as its standard uncertainty $u(x_{ref})$. If the result does not pass the consistency check, laboratories causing the inconsistency are identified and removed from the CRV calculation. The CRV is then calculated from the reduced set of the laboratories.

**Degrees of equivalence**

To establish differences between the participating laboratories and the CRV we calculate

$$d_i = x_i - x_{ref}, \qquad d_{ij} = x_i - x_j$$

and the degrees of equivalence are then given as

$$D_i = \left|\frac{d_i}{2u(d_i)}\right|, \qquad D_{ij} = \left|\frac{d_{ij}}{2u(d_{ij})}\right|$$

where for the laboratories included in the CRV calculation we have

$$u^2(d_i) = u^2(x_i) - u^2(x_{ref})$$

and for the laboratories excluded from CRV calculation by the chi-squared test we have

$$u^2(d_i) = u^2(x_i) + u^2(x_{ref}).$$

The $u(d_{ij})$ value is in any case given by

$$u^2(d_{ij}) = u^2(x_i) + u^2(x_j).$$

## 6.1 Transfer standard *1*

Long-time stability of the transfer standards has been checked by two repeated calibrations in the tow tank facility of CMI. The first calibration took place at the beginning of the measurement campaign and the second at the end. The results for CMI tow tank reported in Tab. 6 and Tab. 7 are averages from the two repeated measurements. Since the upper velocity range of the CMI tow tank is 0.5 m/s, the long-time stability has been tested up to this velocity only. For higher velocities it was neglected. Results of the two repeated measurements for the transfer standard *1* including the values of $u_{drift}$ are shown in Tab. 8 and in Fig. 9.

| | 1st measurement ($p_i$ = 981 hPa) | | | 2nd measurement ($p_i$ = 969 hPa) | | | |
|---|---|---|---|---|---|---|---|
| **$v_{ref}$ (m/s)** | E (m/s) | $E_{cor}$ (m/s) | U(E) (m/s) | E (m/s) | $E_{cor}$ (m/s) | U(E) (m/s) | u_drift (m/s) |
| **0.0500** | -0.0027 | -0.0012 | 0.0050 | -0.0048 | -0.0027 | 0.0050 | 0.00045 |
| **0.1000** | -0.0130 | -0.0102 | 0.0056 | -0.0146 | -0.0107 | 0.0056 | 0.00014 |
| **0.2000** | -0.0145 | -0.0085 | 0.0055 | -0.0179 | -0.0096 | 0.0055 | 0.00032 |
| **0.3000** | -0.0108 | -0.0014 | 0.0060 | -0.0128 | 0.0002 | 0.0060 | 0.00046 |
| **0.4000** | -0.0060 | 0.0069 | 0.0060 | -0.0102 | 0.0075 | 0.0060 | 0.00018 |
| **0.5000** | 0.0035 | 0.0199 | 0.0076 | -0.0046 | 0.0179 | 0.0076 | 0.00058 |
| **0.7** | | | | | | | 0.00000 |
| **1.0** | | | | | | | 0.00000 |

Tab. 8 Stability of the transfer standard *1*; “E” is the anemometer error without air pressure correction, “$E_{cor}$” is the anemometer error with air pressure correction and “U” is its expanded uncertainty (k=2).

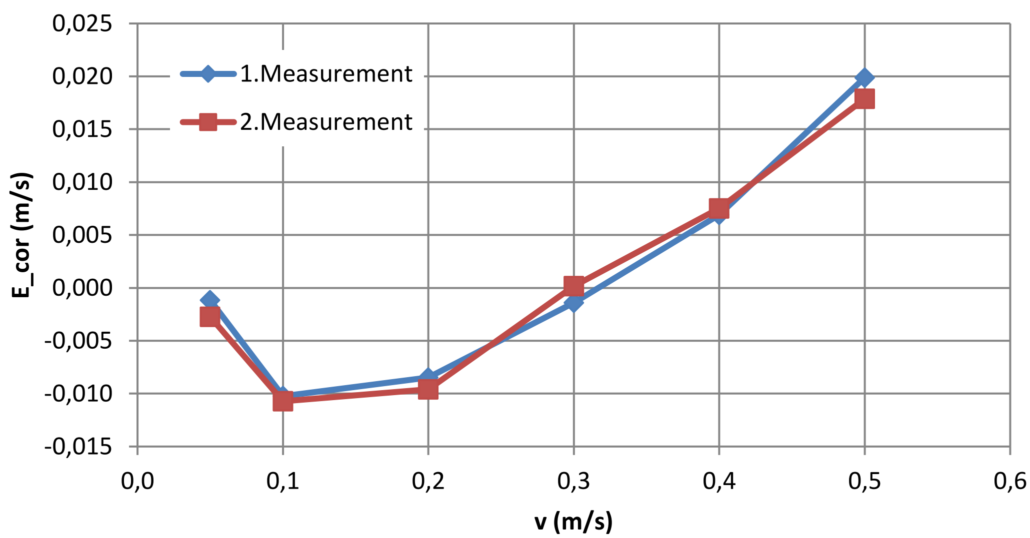


Fig. 9 Stability of the transfer standard *1*

The comparison reference values and results of the chi-squared test performed on the full set of data for the transfer standard *1* are shown in Tab. 9. The $\chi^2$(0.05, n-1) value is the maximal value of $\chi^2_{obs}$ for which the result is considered as consistent. We see that inconsistent result was obtained for the largest air speed of 1 m/s only. Consistency is achieved if the Cetiat laboratory is excluded for this air speed and in that case we obtain the CRV value given in Tab. 10.

| $v_{nom}$ (m/s) | CRV (m/s) | U(CRV) (m/s) | $\chi^2$obs | n-1 | $\chi^2$ (0.05, n-1) | Result |
|---|---|---|---|---|---|---|
| **0.05** | -0.0048 | 0.0039 | 3.35 | 2 | 5.99 | passed |
| **0.10** | -0.0092 | 0.0031 | 0.73 | 3 | 7.81 | passed |
| **0.20** | -0.0057 | 0.0031 | 6.72 | 5 | 11.07 | passed |
| **0.30** | -0.0012 | 0.0033 | 3.64 | 5 | 11.07 | passed |
| **0.40** | 0.0062 | 0.0035 | 1.89 | 5 | 11.07 | passed |
| **0.50** | 0.0152 | 0.0039 | 2.69 | 5 | 11.07 | passed |
| **0.70** | 0.0324 | 0.0053 | 2.13 | 4 | 9.49 | passed |
| **1.00** | 0.0402 | 0.0065 | 17.54 | 3 | 7.81 | failed |

Tab. 9 CRV values and results of the chi-squared test on the complete data set

| $v_{nom}$ (m/s) | CRV (m/s) | U(CRV) (m/s) | $\chi^2$obs | n-1 | $\chi^2$ (0.05, n-1) | Result |
|---|---|---|---|---|---|---|
| **1.00** | 0.0467 | 0.0074 | 2.21 | 2 | 5.99 | passed |

Tab. 10 CRV value and result of the chi-squared test for 1 m/s with Cetiat excluded

The degrees of equivalence $D_i$ with respect to the CRV for the transfer standard *1* are shown in Tab. 11 and in Fig. 10.

| $v_{nom}$ (m/s) | CMI-TT | BEV/E+E | METAS | Cetiat | DTI | CMI-WT |
|---|---|---|---|---|---|---|
| **0.05** | 0.63 | | | 0.73 | 0.14 | |
| **0.10** | 0.24 | 0.31 | | 0.10 | 0.20 | |
| **0.20** | 0.64 | 0.26 | 0.27 | 0.41 | 0.05 | 1.01 |
| **0.30** | 0.10 | 0.69 | 0.08 | 0.40 | 0.02 | 0.57 |
| **0.40** | 0.17 | 0.45 | 0.27 | 0.39 | 0.06 | 0.21 |
| **0.50** | 0.50 | 0.40 | 0.10 | 0.33 | 0.40 | 0.15 |
| **0.70** | | 0.13 | 0.58 | 0.23 | 0.30 | 0.24 |
| **1.00** | | 0.15 | 0.83 | 1.98 | | 0.74 |

Tab. 11 Degrees of equivalence with respect to the CRV – transfer standard *1*

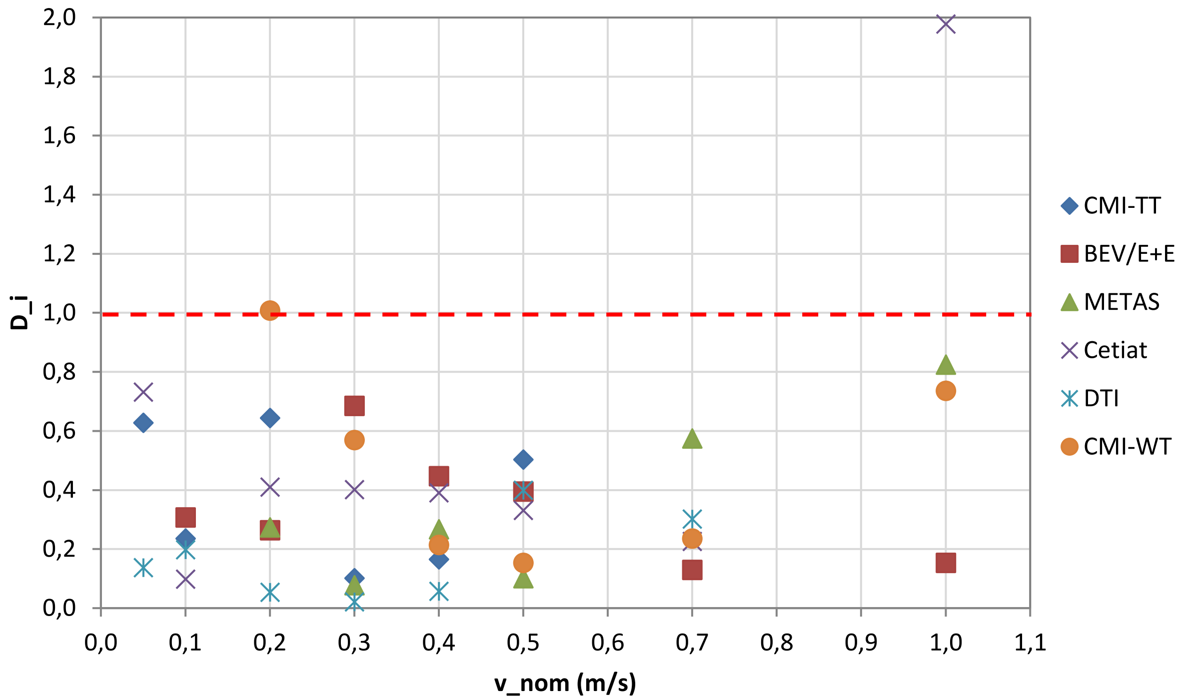


Fig. 10 Degrees of equivalence with respect to the CRV – transfer standard *1*

The lab to lab degrees of equivalence $D_{ij}$ for the transfer standard *1* are listed in Tabs. 12 to 17. Each of the tables represents the degrees of equivalence of one laboratory to all of the remaining laboratories.

| $v_{nom}$ (m/s) | BEV/E+E | METAS | Cetiat | DTI | CMI-WT |
|---|---|---|---|---|---|
| **0.05** | | | 0.90 | 0.27 | |
| **0.10** | 0.36 | | 0.07 | 0.13 | |
| **0.20** | 0.29 | 0.43 | 0.69 | 0.21 | 1.17 |
| **0.30** | 0.51 | 0.05 | 0.26 | 0.01 | 0.45 |
| **0.40** | 0.41 | 0.30 | 0.22 | 0.10 | 0.11 |
| **0.50** | 0.61 | 0.27 | 0.05 | 0.54 | 0.40 |

Tab. 12 Lab to CMI-TT equivalence degrees

| $v_{nom}$ (m/s) | CMI-TT | METAS | Cetiat | DTI | CMI-WT |
|---|---|---|---|---|---|
| **0.10** | 0.36 | | 0.24 | 0.25 | |
| **0.20** | 0.29 | 0.33 | 0.47 | 0.11 | 1.01 |
| **0.30** | 0.51 | 0.24 | 0.69 | 0.18 | 0.79 |
| **0.40** | 0.41 | 0.14 | 0.56 | 0.06 | 0.38 |
| **0.50** | 0.61 | 0.01 | 0.48 | 0.27 | 0.05 |
| **0.70** | | 0.58 | 0.25 | 0.25 | 0.13 |
| **1.00** | | 0.66 | 1.72 | | 0.64 |

Tab. 13 Lab to BEV/E+E equivalence degrees

| $v_{nom}$ (m/s) | CMI-TT | BEV/E+E | Cetiat | DTI | CMI-WT |
|---|---|---|---|---|---|
| **0.20** | 0.43 | 0.33 | 0.12 | 0.15 | 0.23 |
| **0.30** | 0.05 | 0.24 | 0.07 | 0.04 | 0.20 |
| **0.40** | 0.30 | 0.14 | 0.40 | 0.14 | 0.34 |
| **0.50** | 0.27 | 0.01 | 0.23 | 0.22 | 0.01 |
| **0.70** | | 0.58 | 0.40 | 0.60 | 0.61 |
| **1.00** | | 0.66 | 1.80 | | 1.06 |

Tab. 14 Lab to METAS equivalence degrees

| $v_{nom}$ (m/s) | CMI-TT | BEV/E+E | METAS | DTI | CMI-WT |
|---|---|---|---|---|---|
| **0.05** | 0.90 | | | 0.07 | |
| **0.10** | 0.07 | 0.24 | | 0.16 | |
| **0.20** | 0.69 | 0.47 | 0.12 | 0.08 | 0.60 |
| **0.30** | 0.26 | 0.69 | 0.07 | 0.12 | 0.22 |
| **0.40** | 0.22 | 0.56 | 0.40 | 0.20 | 0.07 |
| **0.50** | 0.05 | 0.48 | 0.23 | 0.50 | 0.32 |
| **0.70** | | 0.25 | 0.40 | 0.37 | 0.32 |
| **1.00** | | 1.72 | 1.80 | | 0.97 |

Tab. 15 Lab to Cetiat equivalence degrees

| $v_{nom}$ (m/s) | CMI-TT | BEV/E+E | METAS | Cetiat | CMI-WT |
|---|---|---|---|---|---|
| **0.05** | 0.27 | | | 0.07 | |
| **0.10** | 0.13 | 0.25 | | 0.16 | |
| **0.20** | 0.21 | 0.11 | 0.15 | 0.08 | 0.41 |
| **0.30** | 0.01 | 0.18 | 0.04 | 0.12 | 0.24 |
| **0.40** | 0.10 | 0.06 | 0.14 | 0.20 | 0.15 |
| **0.50** | 0.54 | 0.27 | 0.22 | 0.50 | 0.28 |
| **0.70** | | 0.25 | 0.60 | 0.37 | 0.16 |

Tab. 16 Lab to DTI equivalence degrees

| $v_{nom}$ (m/s) | CMI-TT | BEV/E+E | METAS | Cetiat | DTI |
|---|---|---|---|---|---|
| **0.20** | 1.17 | 1.01 | 0.23 | 0.60 | 0.41 |
| **0.30** | 0.45 | 0.79 | 0.20 | 0.22 | 0.24 |
| **0.40** | 0.11 | 0.38 | 0.34 | 0.07 | 0.15 |
| **0.50** | 0.40 | 0.05 | 0.01 | 0.32 | 0.28 |
| **0.70** | | 0.13 | 0.61 | 0.32 | 0.16 |
| **1.00** | | 0.64 | 1.06 | 0.97 | |

Tab. 17 Lab to CMI-WT equivalence degrees

## 6.2 Transfer standard *2*

Results of the two repeated measurements for the transfer standard *2* including the values of $u_{drift}$ are shown in Tab. 18 and in Fig. 11.

| | 1st measurement | | 2nd measurement | | |
|---|---|---|---|---|---|
| **$v_{ref}$ (m/s)** | E (m/s) | U(E) (m/s) | E (m/s) | U(E) (m/s) | u_drift (m/s) |
| **0.1500** | 0.0082 | 0.0073 | 0.0081 | 0.0073 | 0.00002 |
| **0.2000** | 0.0000 | 0.0069 | 0.0028 | 0.0069 | 0.00081 |
| **0.3000** | 0.0037 | 0.0069 | 0.0046 | 0.0069 | 0.00026 |
| **0.4000** | 0.0023 | 0.0089 | 0.0061 | 0.0089 | 0.00109 |
| **0.5000** | 0.0110 | 0.0089 | 0.0079 | 0.0089 | 0.00088 |
| **0.7** | | | | | 0.00000 |
| **1.0** | | | | | 0.00000 |

Tab. 18 Stability of the transfer standard *2*; "E" is the anemometer error and "U" is its expanded uncertainty (k=2).

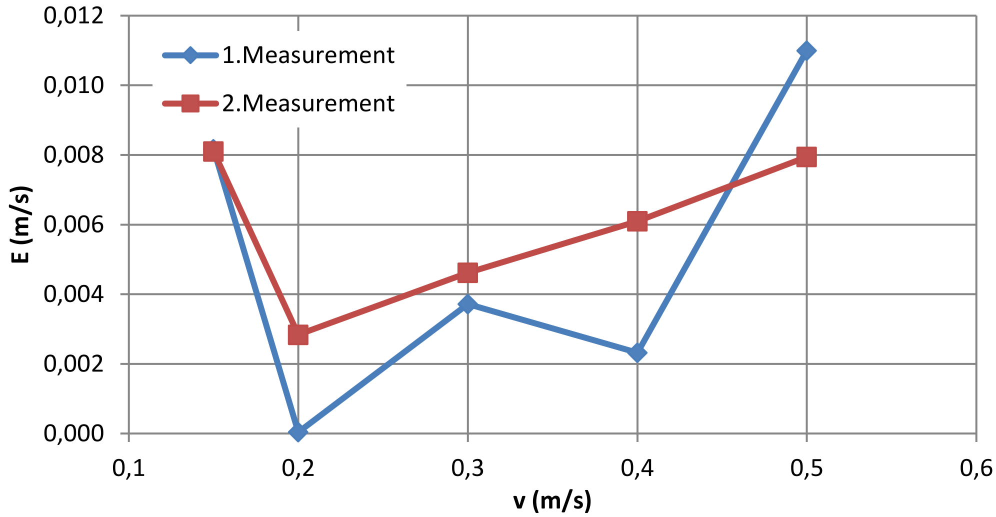

Fig. 11 Stability of the transfer standard *2*

The comparison reference values and results of the chi-square test performed on the full set of data for the transfer standard *2* are shown in Tab. 19. The $\chi^2$(0.05, n-1) value is again the maximal value of $\chi^2_{obs}$ for which the result is considered as consistent. We see that now an inconsistent result was obtained for the lowest air speed of 0.15 m/s only. Consistency is achieved if the CMI-TT and BEV/E+E laboratories are excluded for this air speed and in that case we obtain the CRV value given in Tab. 20.

| $v_{nom}$ (m/s) | CRV (m/s) | U(CRV) (m/s) | $\chi^2$obs | n-1 | $\chi^2$ (0.05, n-1) | Result |
|---|---|---|---|---|---|---|
| **0.15** | -0.0094 | 0.0035 | 42.64 | 3 | 7.81 | failed |
| **0.20** | -0.0047 | 0.0034 | 5.47 | 5 | 11.07 | passed |
| **0.30** | -0.0009 | 0.0036 | 7.09 | 5 | 11.07 | passed |
| **0.40** | 0.0080 | 0.0040 | 2.90 | 5 | 11.07 | passed |
| **0.50** | 0.0031 | 0.0043 | 4.07 | 5 | 11.07 | passed |
| **0.70** | -0.0111 | 0.0053 | 4.92 | 4 | 9.49 | passed |
| **1.00** | 0.0250 | 0.0069 | 7.07 | 3 | 7.81 | passed |

Tab. 19 CRV values and results of the chi-square test on the complete data set

| $v_{nom}$ (m/s) | CRV (m/s) | U(CRV) (m/s) | $\chi^2$obs | n-1 | $\chi^2$ (0.05, n-1) | Result |
|---|---|---|---|---|---|---|
| **0.15** | -0.0054 | 0.0066 | 0.13 | 1 | 3.84 | passed |

Tab. 20 CRV value and result of the chi-square test for 0.15 m/s with CMI-TT and BEV/E+E excluded

The degrees of equivalence $D_i$ with respect to the CRV for the transfer standard *2* are shown in Tab. 21 and in Fig. 12.

| $v_{nom}$ (m/s) | CMI-TT | BEV/E+E | METAS | Cetiat | DTI | CMI-WT |
|---|---|---|---|---|---|---|
| **0.15** | 1.69 | 2.44 | | 0.07 | 0.17 | |
| **0.20** | 0.92 | 0.70 | | 0.03 | 0.02 | 0.17 |
| **0.30** | 0.76 | 1.07 | 0.19 | 0.39 | 0.09 | 0.02 |
| **0.40** | 0.43 | 0.17 | 0.05 | 0.73 | 0.10 | 0.07 |
| **0.50** | 0.73 | 0.32 | 0.29 | 0.01 | 0.51 | 0.28 |
| **0.70** | | 0.01 | 0.74 | 0.36 | 0.24 | 0.73 |
| **1.00** | | 0.64 | 0.91 | 0.74 | | 0.29 |

Tab. 21 Degrees of equivalence with respect to the CRV – transfer standard *2*

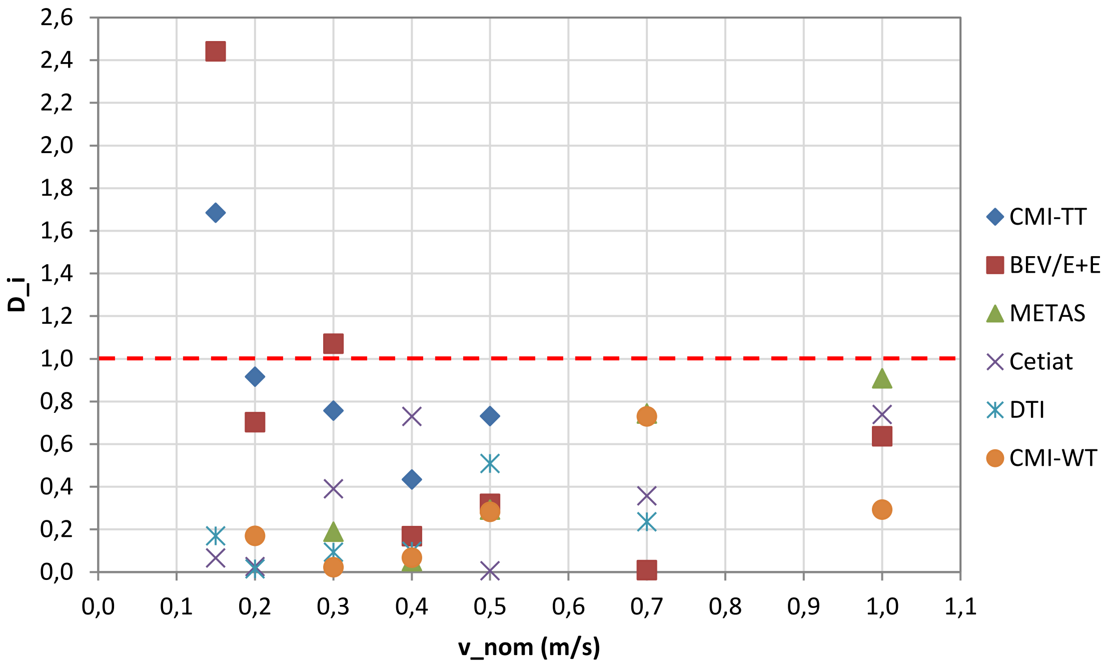


Fig. 12 Degrees of equivalence with respect to the CRV – transfer standard *2*

The lab to lab degrees of equivalence $D_{ij}$ for the transfer standard *2* are listed in Tabs. 22 to 27. Each of the tables represents the degrees of equivalence of one laboratory to all of the remaining laboratories.

| $v_{nom}$ (m/s) | BEV/E+E | METAS | Cetiat | DTI | CMI-WT |
|---|---|---|---|---|---|
| **0.15** | 3.18 | | 1.38 | 0.48 | |
| **0.20** | 1.11 | 0.03 | 0.59 | 0.30 | 0.62 |
| **0.30** | 1.22 | 0.05 | 0.19 | 0.15 | 0.37 |
| **0.40** | 0.26 | 0.22 | 0.80 | 0.08 | 0.21 |
| **0.50** | 0.75 | 0.02 | 0.49 | 0.75 | 0.66 |

Tab. 22 Lab to CMI-TT equivalence degrees

| $v_{nom}$ (m/s) | CMI-TT | METAS | Cetiat | DTI | CMI-WT |
|---|---|---|---|---|---|
| **0.15** | 3.18 | | 1.65 | 0.87 | |
| **0.20** | 1.11 | 0.48 | 0.40 | 0.15 | 0.13 |
| **0.30** | 1.22 | 0.47 | 0.92 | 0.38 | 0.51 |
| **0.40** | 0.26 | 0.10 | 0.67 | 0.05 | 0.02 |
| **0.50** | 0.75 | 0.38 | 0.18 | 0.38 | 0.08 |
| **0.70** | | 0.68 | 0.27 | 0.22 | 0.60 |
| **1.00** | | 1.07 | 0.92 | | 0.14 |

Tab. 23 Lab to BEV/E+E equivalence degrees

| $v_{nom}$ (m/s) | CMI-TT | BEV/E+E | Cetiat | DTI | CMI-WT |
|---|---|---|---|---|---|
| **0.20** | 0.03 | 0.48 | 0.30 | 0.25 | 0.37 |
| **0.30** | 0.05 | 0.47 | 0.04 | 0.07 | 0.16 |
| **0.40** | 0.22 | 0.10 | 0.23 | 0.11 | 0.08 |
| **0.50** | 0.02 | 0.38 | 0.27 | 0.56 | 0.39 |
| **0.70** | | 0.68 | 0.49 | 0.68 | 1.00 |
| **1.00** | | 1.07 | 0.13 | | 0.91 |

Tab. 24 Lab to METAS equivalence degrees

| $v_{nom}$ (m/s) | CMI-TT | BEV/E+E | METAS | DTI | CMI-WT |
|---|---|---|---|---|---|
| **0.15** | 1.38 | 1.65 | | 0.18 | |
| **0.20** | 0.59 | 0.40 | 0.30 | 0.02 | 0.15 |
| **0.30** | 0.19 | 0.92 | 0.04 | 0.05 | 0.20 |
| **0.40** | 0.80 | 0.67 | 0.23 | 0.37 | 0.49 |
| **0.50** | 0.49 | 0.18 | 0.27 | 0.46 | 0.21 |
| **0.70** | | 0.27 | 0.49 | 0.37 | 0.77 |
| **1.00** | | 0.92 | 0.13 | | 0.76 |

Tab. 25 Lab to Cetiat equivalence degrees

| $v_{nom}$ (m/s) | CMI-TT | BEV/E+E | METAS | Cetiat | CMI-WT |
|---|---|---|---|---|---|
| **0.15** | 0.48 | 0.87 | | 0.18 | |
| **0.20** | 0.30 | 0.15 | 0.25 | 0.02 | 0.07 |
| **0.30** | 0.15 | 0.38 | 0.07 | 0.05 | 0.07 |
| **0.40** | 0.08 | 0.05 | 0.11 | 0.37 | 0.05 |
| **0.50** | 0.75 | 0.38 | 0.56 | 0.46 | 0.30 |
| **0.70** | | 0.22 | 0.68 | 0.37 | 0.15 |

Tab. 26 Lab to DTI equivalence degrees

| $v_{nom}$ (m/s) | CMI-TT | BEV/E+E | METAS | Cetiat | DTI |
|---|---|---|---|---|---|
| **0.20** | 0.62 | 0.13 | 0.37 | 0.15 | 0.07 |
| **0.30** | 0.37 | 0.51 | 0.16 | 0.20 | 0.07 |
| **0.40** | 0.21 | 0.02 | 0.08 | 0.49 | 0.05 |
| **0.50** | 0.66 | 0.08 | 0.39 | 0.21 | 0.30 |
| **0.70** | | 0.60 | 1.00 | 0.77 | 0.15 |
| **1.00** | | 0.14 | 0.91 | 0.76 | |

Tab. 27 Lab to CMI-WT equivalence degrees

# 7 Discussion and conclusions

In the supplementary Euramet comparison F1450 calibration procedures and CMCs of 5 European NMIs or DIs were successfully validated for air speeds from a range of (0.05 to 1) m/s or from a part of this range in which the particular laboratories performed their measurements.

For the transfer standard Schiltknecht FV A605 TA1O with measurement range of (0.01 to 1) m/s consistent results have been obtained for all tested air speeds starting at 0.05 m/s besides the largest one of 1 m/s where one laboratory (out of four labs testing this air speed) had to be excluded to obtain a consistent chi-squared test. Similarly for the second transfer standard Ahlborn FVAD 35 TH4 with measurement range of (0.08 to 2) m/s consistent results have been obtained for all tested air speeds besides the smallest one of 0.15 m/s where two (out of four labs testing this air speed) had to be excluded to obtain the consistency in terms of the chi-squared test. Both of the problematic points are near to the measurement range limits of the transfer standards. At the same time, if inconsistent result is obtained for one of the transfer standards, consistency and equivalence degrees below 1 are obtained for the second transfer standard near the same air speed. This indicates that the cause of the few observed inconsistencies should be assigned to the transfer standards' behaviour near their air speed limits rather than to the calibration facilities.

The transfer standards instability as expressed by the $u_{drift}$ uncertainties in Tab. 8 and Tab. 18 was much smaller than the declared standard calibration uncertainties of the participants. Namely, for the first transfer standard Schiltknecht FV A605 TA1O the $u_{drift}$ is in the worst case 5 times smaller than the smallest declared standard calibration uncertainty. For the second transfer standard Ahlborn FVAD 35 TH4 it is in the worst case 3 times smaller than the smallest declared standard calibration uncertainty. Therefore, the results can be considered as conclusive.

# References

[1] Guidelines for CIPM key comparisons

[2] Cox, M. G., The Evaluation of Key Comparison Data, Metrologia 39, 589-595, 2002.

[3] Cox, M. G., The evaluation of key comparison data: determining the largest consistent subset, Metrologia 44, 187 - 200, 2007.

[4] 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, France, October, 1999.

[5] NMi – VSL, Draft B Report of Euromet.M.FF-K3 Euromet Key Comparison for Airspeed Measurements.