Final Report

EURAMET 1050

Euramet Research Comparison for Airspeed Measurements

1. Introduction

A Regional Comparison for Airspeed Standards was performed in recent years for the velocity range 0.2 ï 4.5 m/s (Project EUROMET 514 ï Pilot: NMi-VSL NL), whose results were published in 2008.

Due to the difficulties connected to airspeed measurements, it was decided to limit the span of the Intercomparison to the low-speed range, delaying the analysis of the complementary range of higher speeds to another project.

The project described in the present Protocol aimed at completing the work started with EUROMET 514 by analyzing the complementary range. It was therefore the objective of this project to get insight in the stability, uncertainty and spread of the reference values for airspeed measurements in Europe.

Two anemometers were used as transfer standards, an ultrasonic anemometer (TS #1) and an amplified Pitot tube (TS #2).

Each transfer standard was tested at airspeeds of 2.0; 5.0; 10.0; 15.0; 20.0; 30.0; 40.0; 50.0 m/s.

The ultrasonic anemometer is analogous to the one that was used in the CCM.WGFF-K3 worldwide Key Comparison. This choice of the instrument was done in order to make this Intercomparison analogous to the corresponding KC. Although this comparison is not a Key Comparison but a Research Comparison, it is possible to put it in relation to the CCM.WGFF-K3 through participation of NMi and PTB, which also took part in the CCM.WGFF-K3.

The amplified Pitot is the same that was used during the EUROMET 514 Intercomparison and allows therefore to link the present Intercomparison to that one; indeed, a superposition between the ranges of the two projects was set up to this aim.

2. List of participants and time schedule

The comparison was initially agreed between nine participants. The designated institute of Austria joined the comparison a few weeks before the start of the comparison.

On the other hand, the designated institute of Estonia had to withdraw from the comparison due to an incompatibility of TS #1 with the institute facilities; the exercise was therefore completed by nine participants.

Due to an administrative delay in procurement of the ATA-carnet, the second petal of the exercise (involving the two extra-EU laboratories) started with about a month of delay, and because of the change in scheduling the laboratories required some more time for the measurements. Despite these small problems, the circulation was quite smooth and no major difficulties were encountered.

The pilot lab monitored and updated the circulation timetable; the table below gives the final testing order, together with the indication of the weeks during which the tests were performed.

Participating Laboratory	Shipping Address	Contact person	Test Period (week #)
INRiM, Italy	INRIM C/o DIASP ï PoliTO C.so Duca degli Abruzzi 24 10129 Torino - Italy	Pier Giorgio Spazzini p.spazzini@inrim.it +39 011 0906862	35-36 / 2009
Lithuania	Breslaujos Str. 3 ï 204/1 LK, LT-44403 Heat equipment research and testing laboratory Kaunas - Lithuania	Antanas Pedisius testlab@isag.lei.lt +370 37401863 (or Agne Bertasiene agne@mail.lei.lt)	43-44 / 2009
DTI, Denmark	Danish Technological Institute Installation and Calibration Technology Teknologiparken Kongsvang Allé 29 - DK-8000 Aarhus C - Denmark	John Frederiksen John.Frederiksen@teknologisk.dk +45 7220 1235	47-48 / 2009
VSL, The Netherlands	VSL B.V. Thijsseweg 11 - 2629 JA Delft - The Netherlands	Gerard Blom gblom@vsl.nl +31 15 2691500	1-2 / 2010
CETIAT, France	CETIAT Laboratoire Anémométrie Dom. scientifique de la Doua 54, avenue Niels Bohr - 69100 Villeurbanne - France	Isabelle Care isabelle.care@cetiat.fr	3-4 / 2010
PTB, Germany	Fachbereich Gase 1.4 Physikalisch-Technische Bundesanstalt (PTB) Bundesallee 100 - 38116 Braunschweig - Germany	Harald Mueller harald.mueller@ptb.de +49 531 592 1310	5-6 / 2010
E+E, Austria	BEV/E+E Elektronik Designated Laboratory Langwiesen 7 - A-4209 Engerwitzdorf - Austria	Mathias Rohm mathias.rohm@epluse.at +43/7235-605-275	9-10 / 2010
METAS, Switzerland	Federal Office of Metrology METAS Laboratory Flow and Volume Lindenweg 50 - CH-3003 Bern-Wabern - Switzerland	Hugo Bissig Hugo.Bissig@metas.ch +41 31 32 34 915	22-23 / 2010
TUBITAK-UME Turkey	TUBITAK-UME Anibal Cad. TUBITAK Gebze Yerleskesi PK54 - 41470 Gebze-Kocaeli - Turkey	Vahit Ciftci vahit.ciftci@ume.tubitak.gov.tr +90 262 679 50 00	25-26 / 2010
INRIM, Italy	INRIM C/o DIASP ï PoliTO C.so Duca degli Abruzzi 24 10129 Torino - Italy	Pier Giorgio Spazzini p.spazzini@inrim.it +39 011 0906862	35-36 / 2010

Table 2-1 list of participants and timetable of the measurements performed.

3. Description of the Transfer Standards

3.1. Transfer standard #1

The transfer standard #1 was an ultrasonic anemometer produced by KAIJO Sonic. The instrument is a 3-component ultrasonic anemometer. The sensing element is composed by three couples of ultrasonic emitters/receivers fitted on small but rigid supports and in such positions that the ultrasound path of the three couples are mutually orthogonal (see Fig. 3-1).

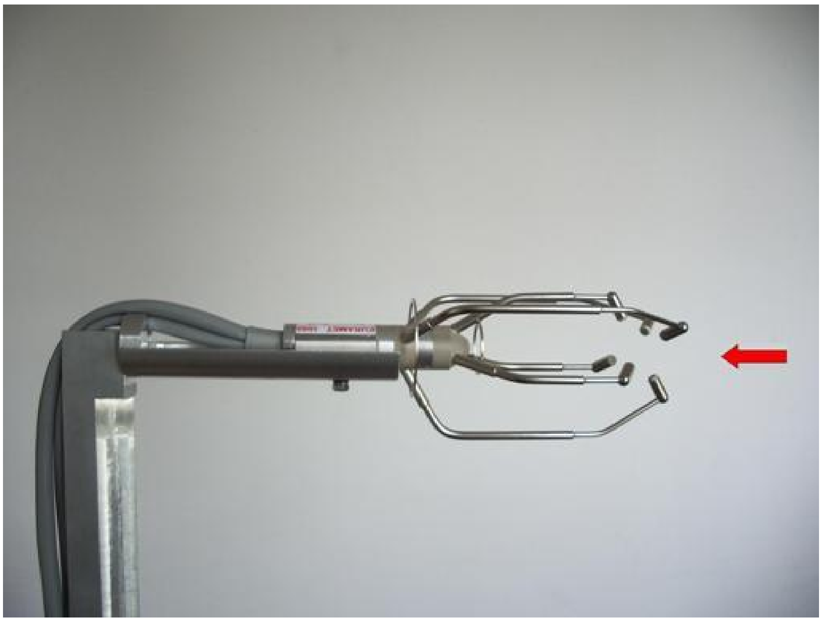


Figure 3-1 Ultrasonic Anemometer sensing element; the arrow indicates the flow direction.

The arrangement of the instrument was such that the flow reached the sensor along its main axis as shown in Fig. 3-1. This way, the disturbance of the instrument to the flow should be minimized; also, no influence of the emittersôsupports on the measurements should be noticeable. This means that recordings of the velocity component named ñWòwere taken.

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

Ultrasonic Anemometer:

Manufacturer: KAIJO Sonic Ltd.

Type: DA-650/TR-92

Sensor size: 120 mm L x 60 mm Φ

Sensor weight: approx. 0.2 kg

Range: 0-50 m/s

3.2. Transfer standard #2

Transfer standard #2 was a Pitot tube with a ñfluid dynamical amplificatorò(see Figure 3-2).

A standard Pitot tube would hardly induce any blockage effect. Though, the presence of the ñamplificatorò, which is meant to induce a larger pressure difference between the static and dynamic pressure, changes the situation; actually, the overall front area of the instrument is brought to about 615 mm^2, and it is a full area. Also in this case, a minimum distance from the walls of about 10 cm was recommended. The Pitot tube was accompanied by a micromanometer (Schiltknecht ManoAir 500, FSR nominal 2000 Pa). Notice that the Pitot tube was the same that had been previously used for Project EURAMET 514, while the micromanometer was changed because of the higher range of the present project.

Pitot tube:

Manufacturer: Acin / NMi-VSL

Micromanometer:

Manufacturer: Schiltknecht Gmbh

Type: ManoAir 500

Serial number: 73294

Range: 0 ï 2000 Pa.

Figure 3-2 Special ñamplifiedòPitot tube (secondary Instrument).

3.3. Equipment List

The transfer package contained the following equipment:

A-1. Case containing items A-2, A-3, A-5, A-7, A-8 and A-10
A-2. Ultrasonic Sensor with cover protection
A-3. Junction Box (s/n 030618903)
A-4. Main Unit (s/n 030617991)
A-5. Support for Ultrasonic Sensor
A-6. Junction Box to Main Unit Cable
A-7. Power Cable for Main Unit
A-8. RS-232 (25-9 pins) cable
A-9. Template for support holes
A-10. Box containing spare fuses, spare screws/washers/nuts and item A-9

B-1. Case containing items B-4, B-5 and B-6
B-2. Box containing items B-3 and B-8
B-3. Pitot tube
B-4. Micromanometer (s/n 73294)
B-5. External power unit for item B-4
B-6. RS-232 (9-9 pins) cable
B-7. Two connection tubes (B-7a red, B-7b blue)
B-8. Optional support for Pitot tube

C-1. Document binder containing copies of the instruments manuals and item C-2

C-2. CD-ROM (includes electronic copy of the protocol, acquisition sheet, acquisition and auxiliary software)
C-3. USB to RS-232 adaptor
C-4. USB cable for downloading acceleration data logger history
C-5. Plastic box containing two spare locks for the transportation box

4. Measurement protocol

The Protocol for the Project included a fully detailed measurement protocol, including procedures for the instruments preparation and installation and instruments operation. Such procedures will not be reported here as they are considered not relevant to this report, while the rest of the protocol will be reported.

4.1. Data Sheet For Recording results

Experimental data gathered during this Comparison were recorded on the data file provided in the CD (directory ñAcquisitionFileò).

This file was to be copied from the CD and renamed by changing the word ñInstituteò with the name of every Institute.

The instructions for the compilation of the various sheets were within the file itself, in the ñNotesò sheet.

The various sheets were organized in accordance to the measurement sequence (see 4.6).

4.2. Facilities

Laboratories which use more than one facility for calibration of anemometers in the range covered by this Comparison could use all these facilities for the Comparison, according to their range; in this case though, for completeness of the results it was required that BOTH anemometers were calibrated in all facilities. No incompatibility between one of the instruments and any facility was reported.

4.3. Recommendations

Each participating lab was expected to calibrate the two transfer standards and evaluate the uncertainty of the calibration results based on its own quality system.

The instruments were required to be in the laboratory at least 12 hours before starting measurements. The Ultrasonic Anemometer and the micromanometer were required to be switched on for at least an hour before starting measurements but preferably longer before. If possible, it was suggested to keep them switched on overnight.

4.4. Velocities table

The velocities to be measured were:

2.0; 5.0; 10.0; 15.0; 20.0; 30.0; 40.0; 50.0 m/s

Laboratories who could not reach the velocity of 50 m/s limited their measurements to the highest velocity they could reach within the required set. This velocity will be from now on indicated as ñmaximum velocityò.

4.5. Data to be Recorded

The data for the two instruments were required to be recorded according to the usual procedure of each laboratory. The reference velocity and ambient conditions were to be recorded according to every Laboratoryõs procedure.

The velocity from the Ultrasonic anemometer and its absolute standard deviation had to be measured through the appropriate software (program "EURAMET_1050_ultrasonic.exe", provided with its manual in the software CD) and recorded on the data file.

The pressure measured by the Pitot had to be measured through the appropriate software (program "EURAMET_1050_pressure.exe", provided with its manual in the software CD), which did not include the calibration of the pressure transducer: the correction was performed by the pilot lab afterwards, in order to be also able to include possible calibration drift effects. The measured pressure average and its absolute standard deviation were to be recorded on the data sheet. The air density for every measurement, computed according to each laboratory's standard procedure, also had to be recorded on the data file.

Both in the case of the Ultrasonic anemometer and of the Pitot/micromanometer, it was required to record the actual output, i.e. no drift correction had to be performed; the Pilot lab took care of this using the initial and final offsets which were also recorded on the data file.

Furthermore, the ambient conditions (ambient pressure, temperature and where available humidity) at the beginning and at the end of each measurement had to be recorded.

4.6. Measurement Sequences

Every velocity was repeated 6 times with the primary instrument (Ultrasonic anemometer) and 3 times with the secondary instrument (Pitot Tube). Each measurement was required to be the average over a period of at least 60 s.

Measurements with the main transfer standard (Ultrasonic anemometer) were organized in sequences (each sequence included one measurement at every one of the selected velocities) as follows:

DAY 1 - Sequences 1U-2U:

- If necessary, perform the zeroing of the instrument;
- record the transfer standard initial offset and initial ambient conditions;
- perform measurements in increasing sequence from minimum to maximum velocity;
- increase the test rig velocity to a value slightly higher than the maximum for at least one minute (this point and the following were necessary for the statistical decorrelation of the two successive measurements at the maximum velocity);
- set the test rig velocity to the maximum again;
- perform measurements in decreasing sequence from maximum to minimum velocity;
- record the transfer standard final offset and final ambient conditions.

DAY 2 - Sequences 3U-4U:

as sequences 1U-2U.

Remark that sequences 1U-2U and 3U-4U had to be performed in two different days.

DAY 3 - Sequence 5U:

- If necessary, perform the zeroing of the instrument;
- Record the transfer standard initial offset and initial ambient conditions;
- Perform measurements at all the selected velocities in random sequence;
- Record the transfer standard final offset and final ambient conditions.

Sequence 6U: as sequence 5U.

Sequences 5U and 6U were permitted to be performed in the same day but a period of at least two hours was required to be allowed between them.

Measurements with the secondary transfer standard (Pitot tube) were organized in sequences (each sequence included one measurement at every one of the selected velocities) corresponding to the sequences 1-2 and 5 of the main transfer standard.

DAY 4 - Sequences 1P-2P:

- If necessary, perform the zeroing of the instrument;
- record the transfer standard initial offset and initial ambient conditions;
- perform measurements in increasing sequence from minimum to maximum velocity;
- increase the test rig velocity to a value slightly higher than the maximum for at least one minute (this point and the following were necessary for the statistical decorrelation of the two successive measurements at the maximum velocity);
- set the test rig velocity to the maximum again;
- perform measurements in decreasing sequence from maximum to minimum velocity;
- Record the transfer standard final offset and final ambient conditions.

Sequence 3P:

- If necessary, perform the zeroing of the instrument;
- record the transfer standard initial offset and initial ambient conditions;
- perform measurements at all the selected velocities in random sequence;
- record the transfer standard final offset and final ambient conditions.

Sequence 3P was permitted to be performed in the same day as sequences 1P-2P but a period of at least two hours had to be allowed between them.

5. Data Treatment

Each laboratory has filled in the form with the results.

Six laboratories limited their tests to 40 m/s, one to 35 m/s and three to 30 m/s[1]. The 35 m/s datum was excluded from the overview because they had no counterparts. As will be discussed in the following, the data were compared with a pointwise method, therefore all data except the cited ones were included in the overview.

Both anemometers have been calibrated at all airspeeds presented by the various laboratories.

The comparison was performed on the ratio of the reference airspeed to the indicated airspeed, $K=U_{ref}/U_{ind}$. In the case of the TS #2, the "indicated airspeed" was the one computed through the straight application of the Bernoulli equation.

The method proposed by Cox[2] was used to analyse the data provided by the participating laboratories. Also the method of Cox[3] to determine the largest consistent subset (LCS) was used to identify inconsistent results and to determine a new RV based upon the remaining results.

5.1. Drawbacks and problems

During the execution of the circulation a few inconveniences happened, which forced to slightly change the forecast of the outcome.

Firstly, a technical problem occurred with the UA TS during the measurement at the Lithuanian laboratory. Unfortunately, this problem was identified only at a later stage and it was solved at the following laboratory in the list. Because of this fact, results obtained at the Lithuanian laboratory with the UA TS are to be considered unreliable and are therefore discarded. Hence, this laboratory participates to the comparison only through the second instrument.

Another drawback happened at the Italian laboratory, where an electrical fault caused the wind tunnel used for the comparison to be out of service for several months, and reduced the maximum available airspeed once the fault was repaired. Because of this, it was not possible to perform the forecast intermediate calibration and the final calibration was performed only up to 30 m/s (present

[1] Actually, INRIM performed measurements up to 50 m/s on the first set of measurements, but due to the wind tunnel failure described later, it was not possible to repeat the higher speed measurements on the last set of measurements, hence it was decided to limit INRIM measurements to 30 m/s, too.

maximum airspeed of the test rig). Luckily, the fault was only on the engine side, thus it did not affect the fluid dynamical behaviour of the wind tunnel.

In the following paragraphs (5.2 to 5.6) the mathematical treatment applied to the data is described. The treatment was performed in the same way on data pertaining to both instruments.

5.2. Determination of the CRV

Since the results of each laboratory are in fact a collection of results the CRV has been determined for each airspeed separately. For this purpose each set of data corresponding to the nominal airspeed has been taken and the weighted average for this nominal airspeed was calculated.

5.2.1. Treatment of the single laboratory data

For every laboratory, laboratory overall values were computed as follows: for the measurement values (reference airspeed, indicated airspeed and *K*), the straight average was considered:

$$x_i = \frac{\sum_{M=1}^{N} x_M}{N} \qquad (2)$$

Where x_i indicates the laboratory overall value for the considered quantity, x_M the result of the Mth measurement and *N* the number of measurements performed at the laboratory.

5.2.2. Treatment of the overall data

The calculated mean for every measurement point was calculated through the weighted average formula:

$$CRV = \frac{\sum_{i=1}^{N} \frac{x_i}{u^2(x_i)}}{\sum_{i=1}^{N} \frac{1}{u^2(x_i)}} \qquad (3)$$

INRIM performed two sets of measurements, but for the calculation of the CRV only the second of these sets have been used. It was decided to use only one set because the use of both them could have caused a bias of the results towards the INRIM results. Also, it was decided to use the second set because it was performed after the wind tunnel fault (see 5.1), i.e. at the present state of the test rig. Notice that all results are considered to be realized independently of the other laboratories.

5.3. Determination of the CRV uncertainty

5.3.1. Treatment of the single laboratory data

The uncertainty assigned to the results obtained at every laboratory was computed keeping into account the uncertainty of every measurement, the repeatability of the measurements and the stability of the transfer standard.

Specifically, the following formula was applied:

$$u(x_i) = \sqrt{\frac{\sum_{M=1}^{N} (x_i - x_M)^2}{N-1} + \frac{1}{\sum_{M=1}^{N} \frac{1}{u^2(x_M)}} + u^2(TS)} \qquad (4)$$

Where *$u(x_i)$* is the overall uncertainty of the laboratory result, *$u(x_M)$* is the uncertainty of the single measurement as reported by the laboratory, *u(TS)* is the long-term uncertainty of the transfer standard (which was computed based on the drift of the measurement results of the pilot lab (INRIM) - see 6.1.1) and the other symbols are as previously.

5.3.2. Treatment of the overall data

The uncertainty associated with the CRV is determined with the following formula (see Cox[2]):

$$u_{CRV} = \frac{1}{\sqrt{\sum_{i=1}^{N} \frac{1}{u^2(x_i)}}} \tag{5}$$

5.4. Determination of a consistent subset

As described in Cox[2], the chi-square test allows to evaluate whether the data are consistent. This test was therefore performed to demonstrate consistency of the data. The formulation of the test is as follows:

$$\chi^2_{obs} = \frac{(x_1 - y)^2}{u^2(x_1)} + \ldots + \frac{(x_n - y)^2}{u^2(x_n)} \tag{6}$$

The consistency check passes when : $\Pr\{\chi^2(\nu) > \chi^2_{obs}\} < 0{,}05$

With $\nu = N - 1$ and N is the number of participating labs for the chi-square test.

In the present case, the actual operation that was performed was the determination of a consistent subset by stepwise removing the largest inconsistency. This approach was chosen, in opposition to the determination of the largest consistent subset, because it is much simpler and, with the present number of participants, who reported uncertainties at comparable levels, the application of the full LCS determination algorithm would not lead to significantly different results.

It occurred that some of the data did not pass the chi-square test. After eliminating the data that were the most extreme a new CRV has been determined and the chi-square test run on them again. This was done until a consistent subset was formed. One has to keep in mind that every test point is considered as a separate set of data. So for every test point this procedure is followed in order to obtain a consistent subset for every test point.

5.5. Degree of equivalence

To establish the degree of equivalence between each laboratory and the CRVs at the various nominal velocities, the following formulae are used (see Cox[2]):

$$d_i = x_i - x_{CRV} \tag{7}$$

and

$$U(d_i) = 2 * u(d_i) \tag{8}$$

With

$$u^2(d_i) = u^2(x_i) ï\ u^2(x_{CRV}) \tag{9}$$

When $U(d_i) < 0{,}8*|d_i|$ the data are considered to be not equivalent; when $0{,}8*|d_i| < U(d_i) < |d_i|$, data are still considered as equivalent but only marginally; finally, when $U(d_i) > |d_i|$, the data are considered to be equivalent.

5.6. E_n-value (Normalized Error)

Another way of evaluating the measurement results is calculating the E_n-value. To do this the following equation is used:

$$E_n = |d_i| / U_i \qquad (10)$$

This is an alternative way of representing the results with respect to the DoE (Degree of Equivalence) representation. Actually, the two forms are redundant. On the other hand, the E_n-value is more appropriate for graphically representing the results, and it will be thus used here.

6. Analysis of the Results

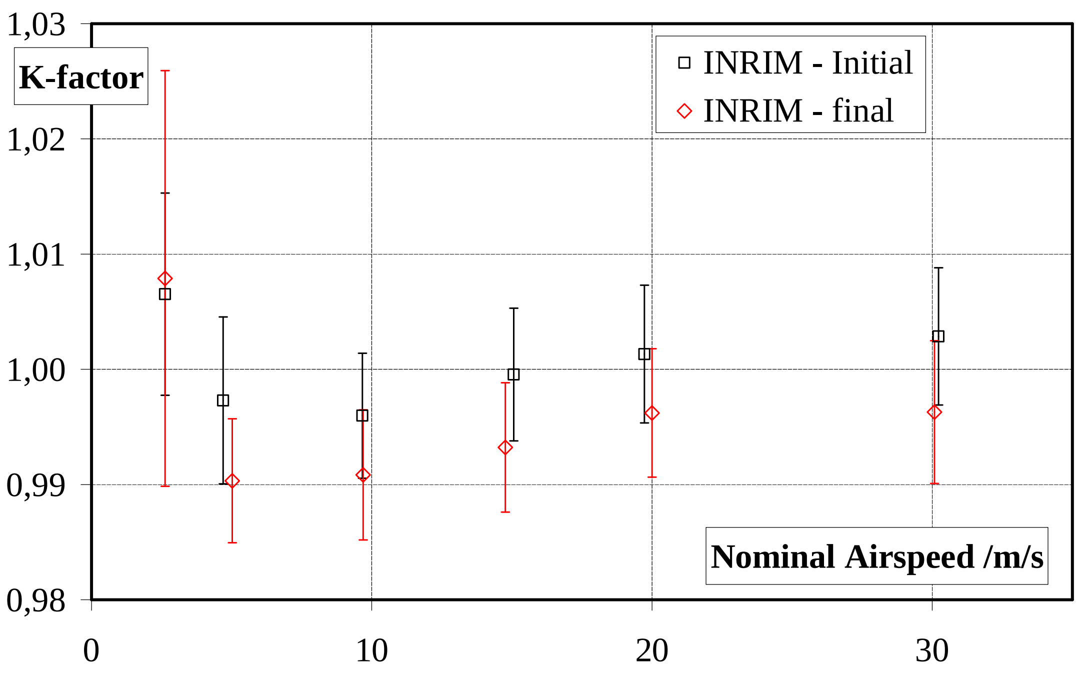
After the final return of the package to Italy the main instrument (UA) was checked for drift. Unfortunately, during the circulation, the INRIM wind tunnel suffered an engine failure and presently is no more able to reach speeds higher than approximately 30 m/s; repairs are under way but they are not expected to be completed before late 2012; the drift test could, therefore, be performed only on the lower velocities. The behaviour of the tunnel is not expected to be altered as the failure concerned only the engine, which is outside of the tunnel; the present setup employs the same fan, only with a different power feed.

Regarding the Micromanometer, it was calibrated at INRIM against the Italian pressure Standard prior to the start of the circulation and at mid-circulation; no appreciable drift effect was observed.

6.1. Measurements repetitions

6.1.1. Reproducibility of the Ultrasonic Anemometer (UA)

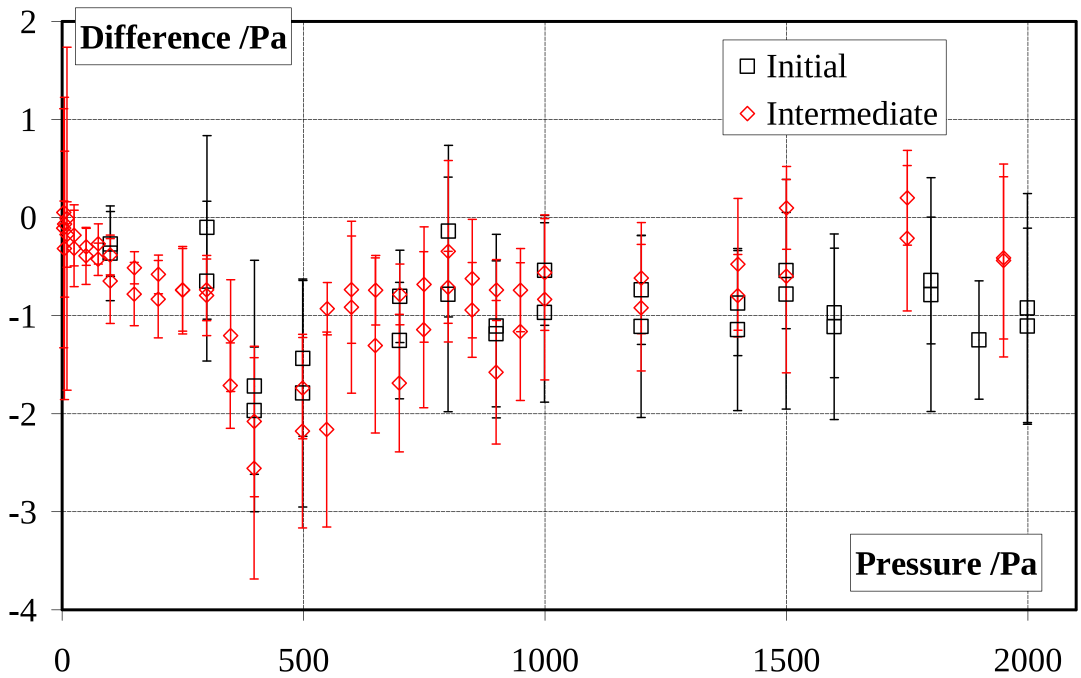
Graph 1 shows the results of the calculation of the K value for the different velocities from the two tests performed by INRIM. It can be observed that all measurement couples are compatible. The conclusion is that the UA in combination with the INRIM test rig reproduces within 0.8 % or better for all airspeeds. Assuming that this value is equally shared between the facility and the instrument, a value of 0.4% can be estimated for the quantity *u(TS).*



Graph 1: reproducibility of the UA at INRIM.

6.1.2. Reproducibility of the Pressure Transducer

Graph 2 shows the results of the two calibrations of the pressure transducer performed at INRIM against the Italian national pressure Standard. Results are presented as the difference between indicated pressure and reference pressure, together with the uncertainty associated to such difference. It can be observed that the two calibrations provided essentially the same results, thus indicating that the drift of the transducer is negligible, therefore in this case *u(TS)* = 0%.

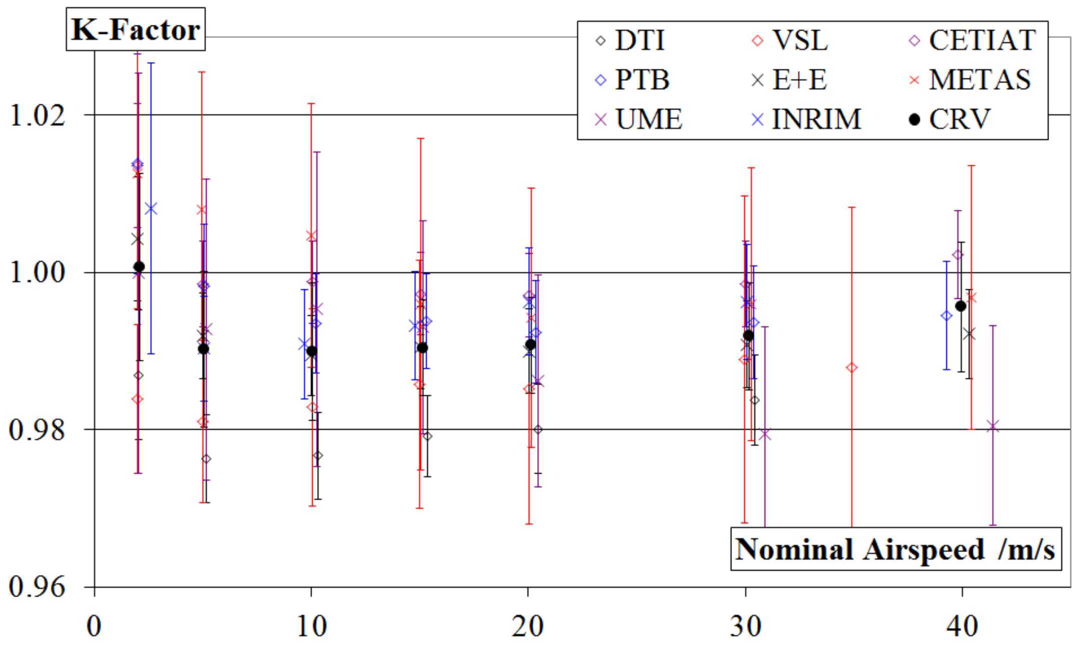


Graph 2: reproducibility of the pressure transducer at INRIM.

6.2. K-factor values of the UA

6.2.1. Consistent Subset

Graph 3 presents the overall data set from the Ultrasonic Anemometer, except data from LEI. The Reference value, computed as described in 5.2, is also plotted. It can be seen that in general data are in quite good agreement.



Graph 3: All data including the Reference Value (CRV)

Table 1 shows the result of the Chi-Squared test performed on the full set of data, as described in 5.4:

Nominal Airspeed Vnom [m/s]	INRIM	DTI	VSL	CETIAT	PTB	E+E	METAS	UME	Σ	Quantile 95%	Pass
2	0.1631	2.8001	3.1352	2.6418	0.8855	0.1973	0.4765	0.0009	10.3006	14,07	YES
5	0.0003	6.2072	0.7990	2.3477	1.0475	0.0951	1.0375	0.0176	11.5519	14,07	YES
10	0.0185	5.7483	0.3145	2.8609	0.3187	0.0075	0.7712	0.0723	10.1119	14,07	YES
15	0.1742	4.6883	0.0876	1.7529	0.3182	0.0001	0.0687	0.0370	7.1270	14,07	YES
20	0.6599	3.5437	0.1047	1.4585	0.0703	0.0181	0.0447	0.1113	6.0112	14,07	YES
30	0.3510	1.9843	0.0195	1.5003	0.0594	0.0357	0.0564	0.8341	4.8407	14,07	YES
40	-----	-----	-----	1.4484	0.0230	0.3621	0.0054	1.4173	3.2561	9,49	YES

Table 1: Results of the Chi squared test on the overall data set

It can be observed that, all the results pass the test; the one presented here is therefore the ñlargest consistent subsetò defined in the sense of Cox[2].

The data of this set, together with the new CRV, are plotted in Graph 4:

6.2.2. Degree of Equivalence

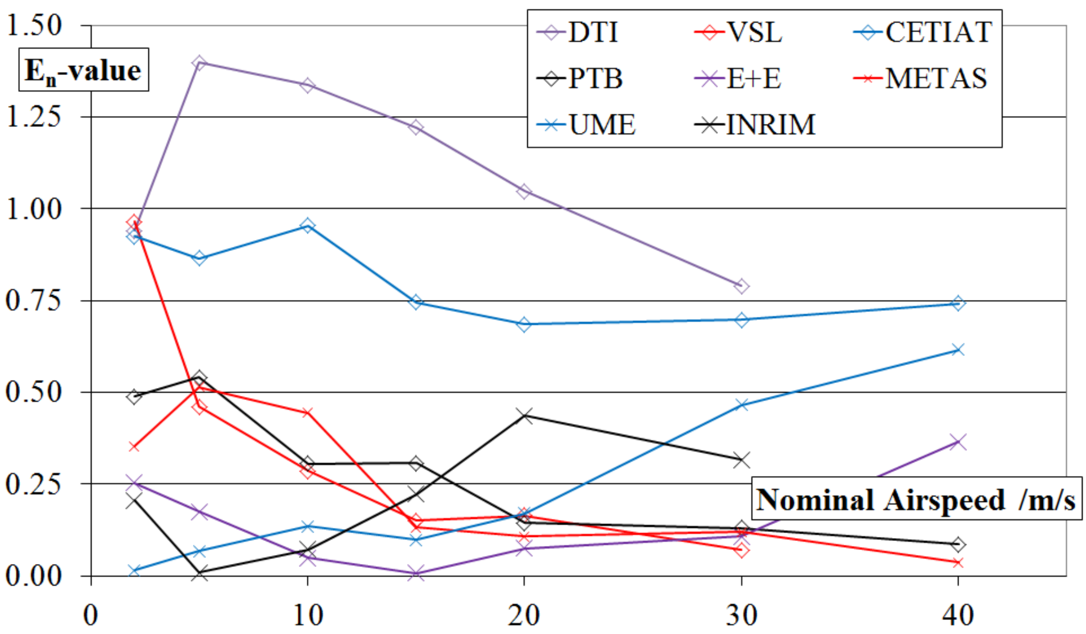
The degrees of equivalence, computed as described in 5.5, are indicated in table 3. Data excluded from the comparison after the Chi-squared test are not reported in this table. The red colour indicates that $U(d_i) < 0,8^*|d_i|$ (not equivalent data), the orange colour indicates that $0,8^*|d_i| < U(d_i) < |d_i|$ (marginally equivalent data).

		INRIM	DTI	VSL	CETIAT	PTB	E+E	METAS	UME
2 m/s	d_i	0.0075	-0.0137	-0.0168	0.0128	0.0132	0.0035	0.0119	-0.0008
	$U(d_i)$	0.0362	0.0146	0.0174	0.0139	0.0269	0.0139	0.0335	0.0503
5 m/s	d_i	0.0001	-0.0139	-0.0092	0.0084	0.0081	0.0017	0.0178	0.0025
	$U(d_i)$	0.0124	0.0099	0.0200	0.0097	0.0150	0.0096	0.0347	0.0380
10 m/s	d_i	0.0009	-0.0132	-0.0071	0.0089	0.0036	-0.0004	0.0148	0.0054
	$U(d_i)$	0.0130	0.0099	0.0247	0.0093	0.0117	0.0090	0.0333	0.0398
15 m/s	d_i	0.0029	-0.0112	-0.0047	0.0069	0.0034	0.0001	0.0055	0.0026
	$U(d_i)$	0.0129	0.0092	0.0312	0.0093	0.0110	0.0093	0.0418	0.0268
20 m/s	d_i	0.0056	-0.0107	-0.0056	0.0064	0.0017	-0.0007	0.0035	-0.0045
	$U(d_i)$	0.0128	0.0102	0.0340	0.0093	0.0120	0.0096	0.0327	0.0265
30 m/s	d_i	0.0044	-0.0081	-0.0029	0.0067	0.0018	-0.0010	0.0041	-0.0124
	$U(d_i)$	0.0138	0.0103	0.0413	0.0096	0.0135	0.0098	0.0342	0.0267
40 m/s	d_i				0.0067	-0.0010	-0.0034	0.0012	-0.0151
	$U(d_i)$				0.0090	0.0122	0.0094	0.0329	0.0245

Table 2: Degrees of equivalence between the labs and the CRV

6.2.3. E_n-value (Normalized Error)

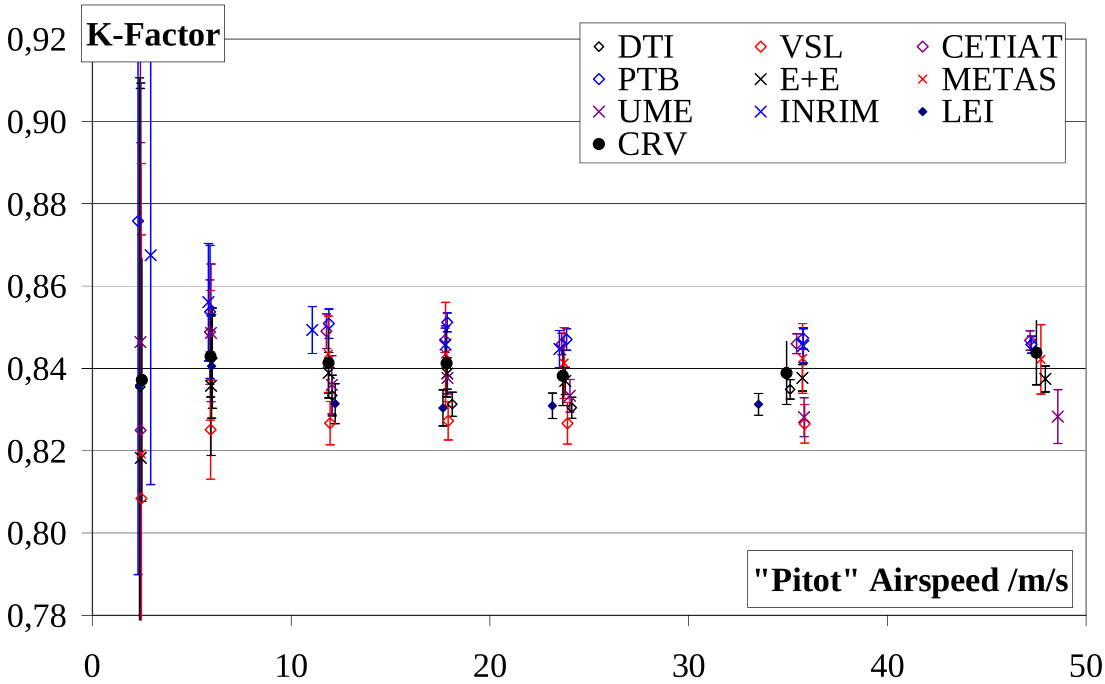
Finally, the normalized error (En-value) was computed, according to what described in 5.6. The results are presented in Graph 4:



Graph 4: En-values (Normalized Errors).

6.3. K-factor values of the Pitot tube

6.3.1. Consistent Subset



Graph 5: All data including the Reference Value (CRV)

Graph 5 presents the overall data set from the Pitot Tube. The X-axis reports the ñPitotò airspeed, i.e. the airspeed computed by direct application of the Bernoulli equation to the measured pressure and air density. The Y-axis reports the K-factor, which in this case is the ratio of the reference airspeed to the ñPitotò airspeed. The Reference value, computed as described in 5.2, is also plotted. It can be seen that in general data are in quite good agreement.

The Chi-Squared test was afterwards performed on the full set of data, as described in 5.4. Table 5 reports the result of this test:

Nominal Airspeed Vnom [m/s]	INRIM	LEI	DTI	VSL	CETIAT	PTB	E+E	METAS	UME	Σ	Quantile 95%	Pass
2	0,2952	0,0003	0,0005	0,2023	0,0306	0,2018	0,0432	0,0649	0,0092	0,8481	15,51	YES
5	0,8564	0,0356	0,0011	2,1759	0,2186	0,4502	0,1752	0,0003	0,1176	4,0310	15,51	YES
10	1,9946	4,1117	2,5220	7,6804	3,3642	7,2606	0,2358	0,0556	0,5584	27,7831	15,51	NO
15	1,0325	6,1254	11,4421	9,0087	3,5599	19,0027	0,4096	0,0325	0,8251	51,4384	15,51	NO
20	2,1088	5,5358	9,1014	5,1905	8,5740	11,8196	0,1373	0,1297	1,4949	44,0921	15,51	NO
30	2,5392	8,1068	2,8537	6,8968	8,7125	10,8080	0,1363	0,1764	5,1724	45,4019	15,51	NO
40	-----	-----	-----	-----	1,6436	0,9409	4,0476	0,0359	5,6211	12,2891	9,49	NO

Table 3: Results of the Chi squared test on the overall data set

As it can be seen, not all the results did pass the test. For every measurement point the result with the highest chi-square value was then eliminated. A new CRV was determined (considering only the remaining values) and the chi-square test performed again, producing the results reported in table 6:

Nominal Airspeed Vnom [m/s]	INRIM	LEI	DTI	VSL	CETIAT	PTB	E+E	METAS	UME	Σ	Quantile 95%	Pass
2	0,2952	0,0003	0,0005	0,2023	0,0306	0,2018	0,0432	0,0649	0,0092	0,8481	15,51	YES
5	0,8564	0,0356	0,0011	2,1759	0,2186	0,4502	0,1752	0,0003	0,1176	4,0310	15,51	YES
10	1,2657	5,5876	3,6786	-----	2,0909	4,9902	0,6678	0,0035	0,9569	19,2412	14,07	NO
15	3,3331	2,6761	4,5319	4,8933	9,7013	-----	0,1058	0,2219	0,0013	25,4648	14,07	NO
20	3,6317	2,8618	4,9373	3,5162	13,6813	-----	0,0587	0,3570	0,5000	29,5439	14,07	NO
30	4,0130	4,8907	0,9305	5,1303	13,3766	-----	0,0261	0,3847	3,6649	32,4168	14,07	NO
40	-----	-----	-----	-----	0,9841	0,4108	4,9555	0,0728	-----	6,4233	7,81	YES

Table 4: Results of the Chi squared test after the first round of data exclusion

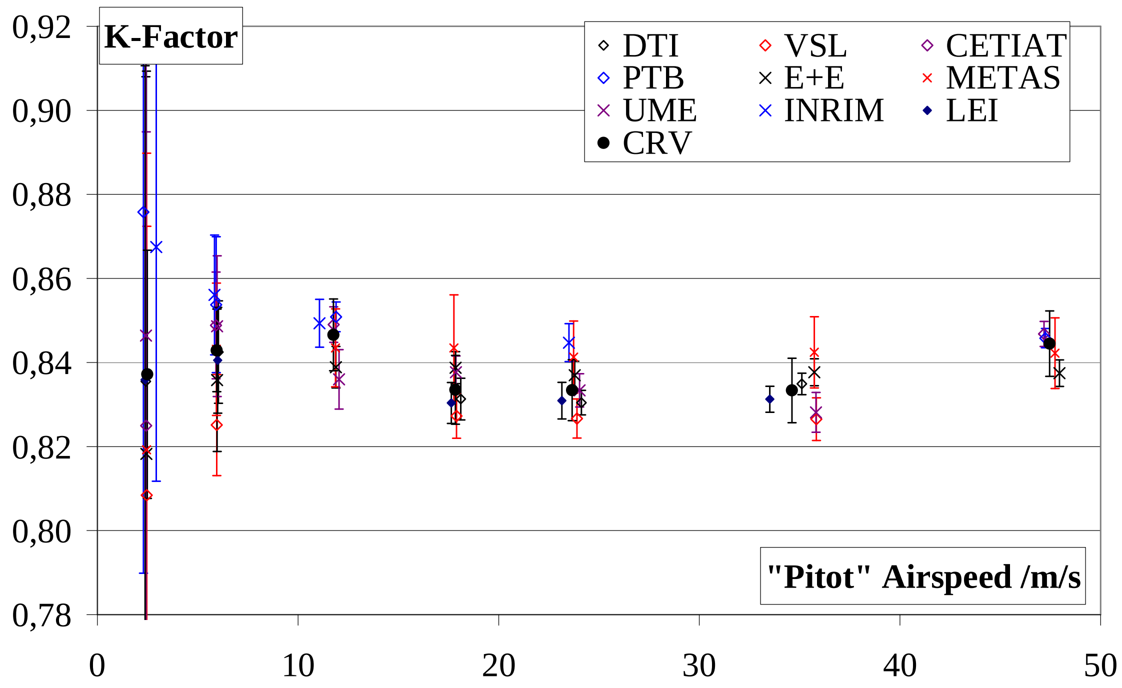
Although the situation was improved, it was still not possible to pass the chi-squared test, so the exclusion process was iterated. After the third pass of data exclusion, it was possible to identify a largest consistent subset of data for every airspeed. Tables 7 and 8 report the results of the successive rounds of data exclusion, while Graph 6 displays the plot of the remaining data after the exclusions, together with the new CRV thus defined.

Nominal Airspeed Vnom [m/s]	INRIM	LEI	DTI	VSL	CETIAT	PTB	E+E	METAS	UME	Σ	Quantile 95%	Pass
2	0,2952	0,0003	0,0005	0,2023	0,0306	0,2018	0,0432	0,0649	0,0092	0,8481	15,51	YES
5	0,8564	0,0356	0,0011	2,1759	0,2186	0,4502	0,1752	0,0003	0,1176	4,0310	15,51	YES
10	0,6727	-----	5,1440	-----	1,0693	3,0450	1,3668	0,0163	1,4964	12,8105	12,59	NO
15	5,7236	1,0993	1,5652	2,7539	-----	-----	1,0022	0,4552	0,4866	13,0860	12,59	NO
20	6,3068	0,6541	1,3468	1,7871	-----	-----	1,1247	0,8360	0,0003	12,0558	12,59	YES
30	6,9339	1,5231	0,0223	2,9234	-----	-----	0,9553	0,8615	1,8527	15,0722	12,59	NO
40	-----	-----	-----	-----	0,9841	0,4108	4,9555	0,0728	-----	6,4233	7,81	YES

Table 5: Results of the Chi squared test after the second round of data exclusion

Nominal Airspeed Vnom [m/s]	INRIM	LEI	DTI	VSL	CETIAT	PTB	E+E	METAS	UME	Σ	Quantile 95%	Pass
2	0,2952	0,0003	0,0005	0,2023	0,0306	0,2018	0,0432	0,0649	0,0092	0,8481	15,51	YES
5	0,8564	0,0356	0,0011	2,1759	0,2186	0,4502	0,1752	0,0003	0,1176	4,0310	15,51	YES
10	0,2345	-----	-----	-----	0,3365	1,4551	2,4240	0,1113	2,2301	6,7916	11,07	YES
15	-----	0,5047	0,5565	1,7996	-----	-----	1,9320	0,6270	1,1622	6,5822	11,07	YES
20	6,3068	0,6541	1,3468	1,7871	-----	-----	1,1247	0,8360	0,0003	12,0558	12,59	YES
30	-----	0,6086	0,4449	2,1080	-----	-----	1,8397	1,1475	1,2191	7,3678	11,07	YES
40	-----	-----	-----	-----	0,9841	0,4108	4,9555	0,0728	-----	6,4233	7,81	YES

Table 6: Results of the Chi squared test after the third round of data exclusion



Graph 5: Consistent Subset data including the Reference Value (CRV)

6.3.2. Degree of Equivalence

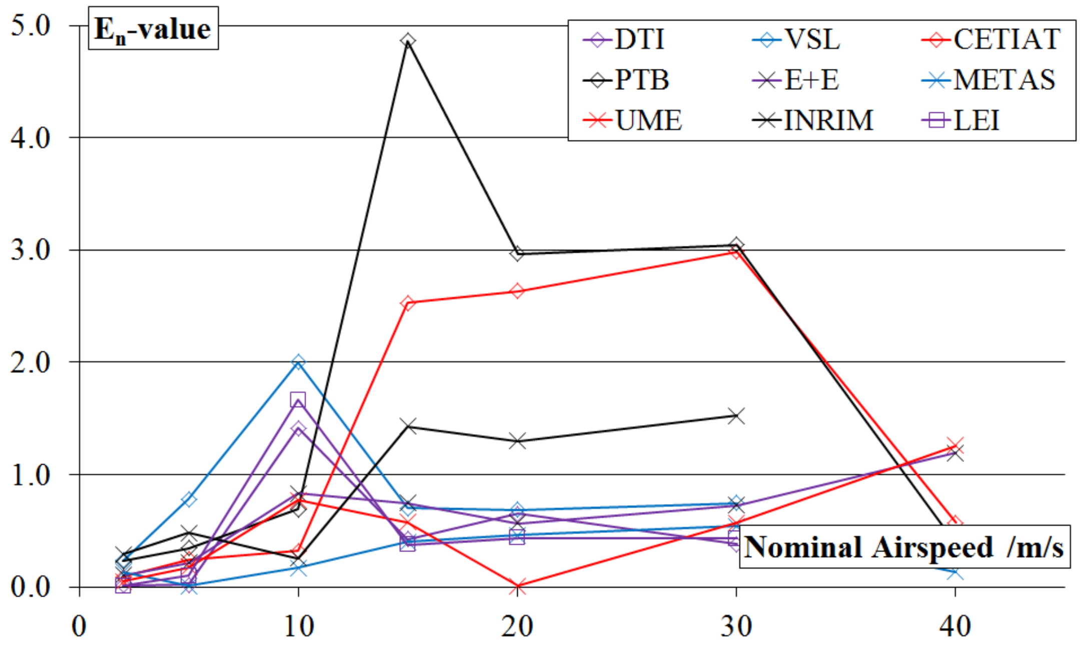
The degrees of equivalence, computed as described in 5.5, are reported in table 9. Data excluded from the comparison after the Chi-squared test are also reported in this table. The red colour indicates that $U(d_i) < 0{,}8^*|d_i|$ (not equivalent data), the orange colour indicates that $0{,}8^*|d_i| < U(d_i) < |d_i|$ (marginally equivalent data).

		INRIM	LEI	DTI	VSL	CETIAT	PTB	E+E	METAS	UME
2 m/s	d_i	0,0303	-0,0013	-0,0017	-0,0288	-0,0122	0,0386	-0,0189	-0,0180	0,0092
	$U(d_i)$	0,1038	0,1438	0,1392	0,1214	0,1338	0,1670	0,1776	0,1352	0,1877
5 m/s	d_i	0,0132	-0,0024	-0,0004	-0,0178	0,0059	0,0109	-0,0071	0,0003	0,0057
	$U(d_i)$	0,0274	0,0239	0,0230	0,0228	0,0241	0,0314	0,0330	0,0305	0,0325
10 m/s	d_i	0,0028	-0,0152	-0,0132	-0,0199	0,0024	0,0043	-0,0077	-0,0031	-0,0106
	$U(d_i)$	0,0109	0,0091	0,0093	0,0099	0,0077	0,0062	0,0092	0,0182	0,0137
15 m/s	d_i	0,0123	-0,0031	-0,0022	-0,0062	0,0133	0,0177	0,0053	0,0100	0,0042
	$U(d_i)$	0,0086	0,0083	0,0051	0,0089	0,0053	0,0036	0,0071	0,0251	0,0072
20 m/s	d_i	0,0113	-0,0025	-0,0030	-0,0068	0,0125	0,0136	0,0035	0,0079	-0,0001
	$U(d_i)$	0,0087	0,0057	0,0046	0,0099	0,0048	0,0046	0,0062	0,0170	0,0076
30 m/s	di	0,0121	-0,0021	0,0016	-0,0068	0,0126	0,0140	0,0043	0,0091	-0,0052
	U(di)	0,0080	0,0048	0,0041	0,0091	0,0042	0,0046	0,0060	0,0168	0,0092
40 m/s	di					0,0023	0,0013	-0,0070	-0,0023	-0,0162
	U(di)					0,0040	0,0034	0,0059	0,0167	0,0129

Table 7: Degrees of equivalence between the labs and the CRV

6.3.3. E_n-value (Normalized Error)

Finally, the normalized error (En-value) was computed, according to what described in 5.6. The results are presented in Graph 6:



Graph 6: En-values (Normalized Errors).

Data excluded from the comparison after the Chi-squared test are also reported in this graph.

7. Conclusion

A very fruitful Regional Comparison was performed. Overall, the outcome of the comparison can be considered a success. Most data, especially in the case of the Ultrasonic Anemometer, were in agreement and allowed to define a reliable Reference Value (CRV). Unfortunately, a technical problem with the instrument did not allow LEI to provide useful data with the UA.

Regarding the Pitot tube (secondary TS), the uncertainties are larger and the correspondence is not as good as with the primary TS, but still satisfactory.

Within this comparison all values of CMC-uncertainties stated by the participants are considered as correct, although the degree of equivalence is not always below 1 (see tables 2 and 7). But all participants could show up with a majority of consistent results out of the total set of measurements. The inconsistencies are probably caused by still unresolved interference effects between the test rigs and the instruments.

Future investigation should reveal the cause of the discrepancies between laboratories and provide tools to eliminate these differences.

8. 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 ï VSL, Draft B Report of Euromet.M.FF-K3 Euromet Key Comparison for Airspeed Measurements.