EURAMET project No. F 1515
Intercomparison of air speed in the range of (1- 40) m/s

Final Report

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Table of Content

1. Introduction

The F1515 comparison was organized for the purpose of determination of the degree of equivalence of the national standards for air speed over the range 1 m/s to 40 m/s. Nine countries participated in the comparison. This comparison covers the air speed range (1-40) m/s and is intended to be a Supplementary Comparison for CIPM Air Speed Key Comparison (CCM.FF-K3.2011). Two types of anemometers were used as transfer standards; an ultrasonic anemometer and a pitot tube. Each transfer standard was tested separately at air speeds of 1.0, 3.0, 5.0, 10.0, 15.0, 20.0, 30.0, 40.0 m/s.

Three participants of this project France (CETIAT), Germany (PTB) and Austria (BEV/E+E) were also participants in the CIPM key comparison CCM.FF-K3.2011 which covers air speeds from 0,5 m/s to 40 m/s. Exactly the same type of ultrasonic anemometer which is manufactured by SONIC CORPORATION is also used in this comparison.

The present report is written according to the guidelines for CIPM key comparison [1] and to the comparison protocol organization for EURAMET TC flow [2].

2. Participants

The participants are listed in table 1 and comparison timetable in table 2.

Table 1. List of participants

TÜBİTAK UME	**TÜBİTAK UME** Akışkanlar Laboratuarları TÜBİTAK Gebze Yerleşkesi Barış Mah. Dr.Zeki Acar Cad. No:1 41470 Gebze / KOCAELİ TURKEY	Hakan KAYKISIZLI hakan.kaykisizli@tubitak.gov.tr +90 262 679 500 00
CETIAT	**CETIAT** Laboratoire Anémométrie Domaine scientifique de la Doua 54, avenue Niels Bohr 69100 Villeurbanne/France	Isabelle CARE isabelle.care@cetiat.fr +33 4 72 44 49 92
METAS	**Federal Institute of Metrology METAS** Laboratory Flow and Hydrometry	Marc DE HUU marc.dehuu@metas.ch Tel. +41 58 387 02 67
RISE	**RISE Research Institutes of Sweden AB** Inspection and Calibration Brinellgatan 4 SE-504 62 Borås,Sweden	Per JACOBSSON per.jacobsson@ri.se +46 10 516 56 63
LEI	**LEI** Lithuanian Energy Institute (LEI) Laboratory of heat equipment research and testing Breslaujos str. 3 44403 Kaunas Lithuania	Agne BERTASIENE agne.bertasiene@lei.lt +37061301728
BEV/E+E	**BEV/E+E Elektronik** Designated Laboratory Langwiesen 7 A-4209 Engerwitzdorf	Dietmar PACHINGER dietmar.pachinger@epluse.at +43 7235 605 275
DTI	**Danish Technological Institute** Installation and Calibration Technology Teknologiparken Kongsvang Allé 29 - DK-8000 Aarhus C – Denmark	Søren HAACK sorh@teknologisk.dk +45 72 20 23 38
PTB	**PTB** Fachbereich Gase 1.4 Bundesallee 100 38116 Braunschweig/Germany	Jessica KAMPE Jessica.Kampe@ptb.de +49 531 592 1316
CMI	**CMI** Czech Metrology Institute Okruzni 31, 63800 Brno Czech Republic	Jan Geršl jgersl@cmi.cz +420 545 555 718

Table 2. Comparison timetable

	2021											
	1	2	3	4	5	6	7	8	9	10	11	12
Turkey TÜBİTAK UME	Pilot											
France CETIAT		Pilot										
Switzerland METAS												
France CETIAT				Pilot								
Sweden RISE												
Lithuania LEI												
Austria BEV/E+E												
France CETIAT								Pilot				
Denmark DTI												
Germany PTB												
Czech Republic CMI												
Turkey TÜBİTAK UME												Pilot
France CETIAT												Pilot

3. Description of transfer standards

Two types of anemometers were used in this comparison; static pitot tube and ultrasonic anemometer. Some technical specifications are listed in table 3.

Table 3. Technical specifications of the transfer anemometers

Measuring instrument	**Ultrasonic Anemometer**	**Pitot Tube**
Indication	Digital display	Digital display
Manufacturer	KAIJO Sonic	Fluke
Type	DA-650/TR-92	Fluke 922
Measuring range:	1 m/s – 50 m/s	1 m/s – 40 m/s
Sensor Size	120 mm L x 60 mm Φ	30 mm L x 6 mm Φ
Resolution	0,01 m/s	0,01 m/s

Figure 1. *Fluke 922 Pitot tube*

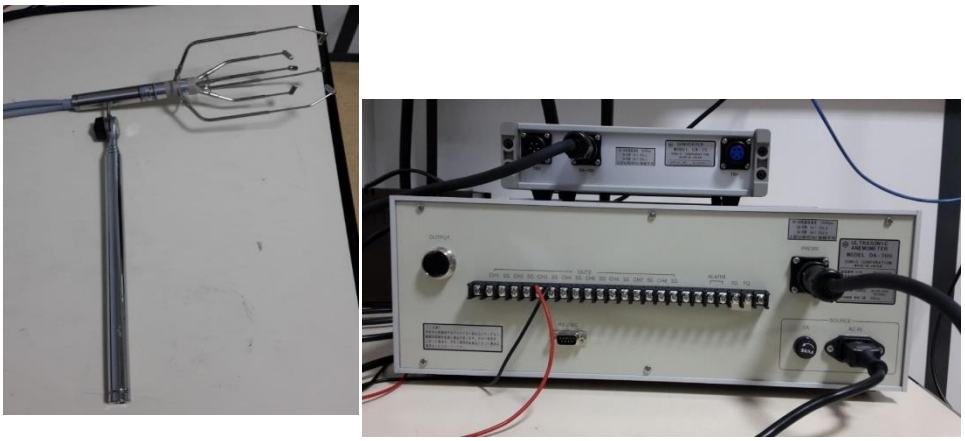


Figure 2. *Ultrasonic anemometer*

The ultrasonic anemometer used in this SC is manufactured by KAIJO 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.

The arrangement of the instrument is such that the flow reach the sensor along its main axis. 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 should be 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, test rooms of at least 30 cm diameter (or 30 cm minimum transverse direction for square/rectangular section wind tunnels) are recommended to be used.

The Pitot Tube uses standard conditions (temperature =21.1 °C, barometric pressure = 1013 mbar, 45 %relative humidity), to approximate actual velocity and flow.

4. Description of the used calibration method

Two types of anemometer have been calibrated by 9 laboratories and results have been analyzed. Each participating lab have calibrated the two transfer standards and evaluated the uncertainty of the calibration results as per their own quality system. The calibration of the transfer standards in the tunnel facilities was performed for the following air speeds;

Table 4. Measurement points

#	**Air speed**
1	1.0 m/s
2	3.0 m/s
3	5.0 m/s
4	10.0 m/s
5	15.0 m/s
6	20.0 m/s
7	30.0 m/s
8	40.0 m/s

At each speed repeated measurements have been recorded according to the procedure of each laboratory.

Since the pitot tube velocity reading is at standard conditions (temperature =21.1 °C, barometric pressure = 1013 mbar), laboratories have used their own procedures to correct the readings for actual conditions.

The data for the two instruments should be recorded to measurement file. In measurement file there are two pages; one for ultrasonic anemometer and the other for pitot tube.

Laboratory Reference values have been adjusted within the ± 5 % of the target air speeds.

The data for the two instruments have been recorded to a measurement file.

Laboratories have used their own procedures to calculate the error and uncertainties of the transfer meters. The drift of the anemometers have been calculated by the pilot laboratory and added to the laboratory uncertainty values.

5. The stability determination of the transfer meters

The ultrasonic anemometer has been recalibrated by the CETIAT five times in order to check its stability during the comparison. Due to the shift after first measurement at TUBITAK UME, the drift was calculated only for the other four stability measurements of ultrasonic anemometer during the comparison as shown in figure 3. TUBITAK UME measurements are not included in ultrasonic anemometer comparison.

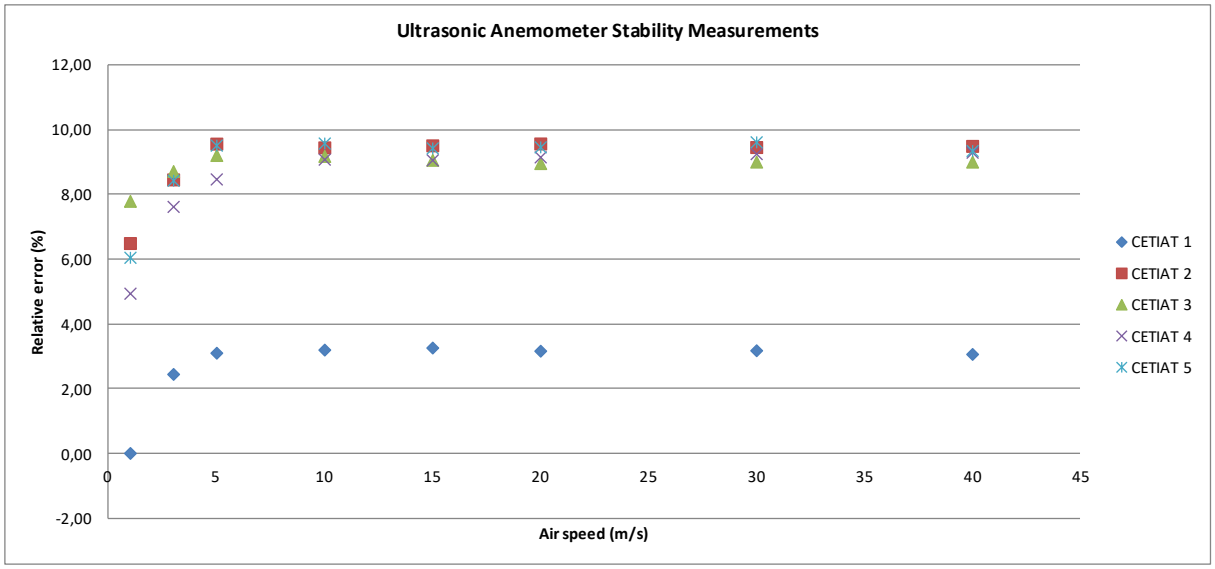


Figure 3. *Stability measurement results for ultrasonic anemometer by CETIAT*

The relative error and related uncertainties corresponding to each stability measurements are given in table 5 with calculated drift values.

The drift of the transfer meters are calculated according to the equation (1) as follows;

$$u_{drift} = \frac{E_{\max} - E_{\min}}{2\sqrt{3}} \qquad (1)$$

The expanded relative uncertainty of the reference value is added to calibration measurement uncertainty as follows;

$$U = k\sqrt{\left[\frac{U(x_i)}{2}\right]^2 + u^2{}_{drift}} \qquad (2)$$

where $U(x_i)$ is the expanded combined uncertainty ($k=2$) determined by laboratory and presented in results of laboratory.

Table 5. Stability data and calculated drift uncertainty for ultrasonic anemometer

Air speed (m/s)	CETIAT 2		CETIAT 3		CETIAT 4		CETIAT 5		u_{drift}
	E (%)	U(k=2)	E (%)	U(k=2)	E (%)	U(k=2)	E (%)	U(k=2)	%
1	6,49	2,81	7,80	2,75	4,94	2,73	6,05	2,26	0,82
3	8,46	1,78	8,72	1,13	7,63	1,44	8,43	1,14	0,32
5	9,56	0,85	9,21	1,01	8,47	0,99	9,52	0,85	0,31
10	9,45	0,77	9,18	0,81	9,09	0,74	9,58	0,77	0,14
15	9,51	0,83	9,06	0,81	9,06	0,82	9,43	0,89	0,13
20	9,57	0,79	8,96	0,83	9,16	0,80	9,46	0,85	0,17
30	9,46	0,69	9,01	0,83	9,26	0,96	9,62	0,85	0,18
40	9,49	0,74	9,01	0,85	9,30	0,94	9,35	1,11	0,14

The pitot tube has been calibrated before and after the comparison four times for stability check and drift calculations. The results are shown in figure 4.

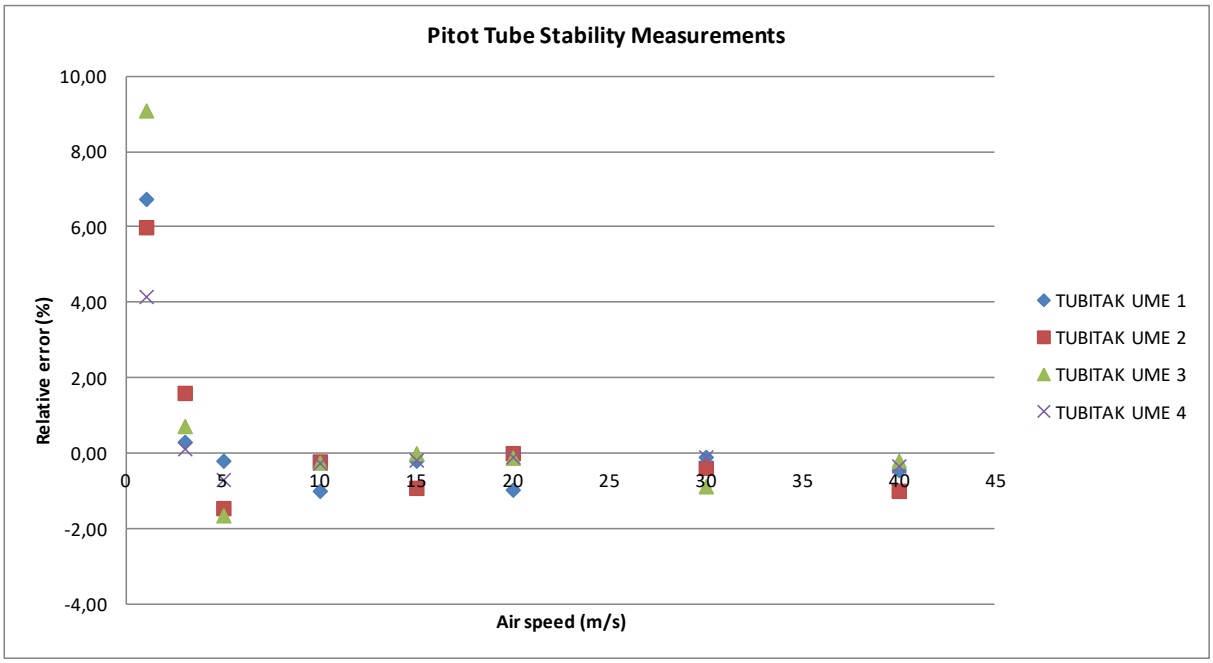


Figure 4. *Stability measurement results for pitot tube anemometer by TUBITAK UME*

The relative error and related uncertainties corresponding to each stability measurements are given in table 6 with calculated drift values.

Table 6. Stability data calculated drift uncertainty for pitot tube anemometer

Air speed (m/s)	TUBITAK UME 1		TUBITAK UME 2		TUBITAK UME 3		TUBITAK UME 4		u_{drift}
	E (%)	U(k=2)	E (%)	U(k=2)	E (%)	U(k=2)	E (%)	U(k=2)	%
1	6,75	2,02	6,00	2,00	9,10	2,02	4,16	2,04	1,43
3	0,30	1,48	1,60	1,42	0,72	1,50	0,12	1,44	0,43
5	-0,20	0,91	-1,46	0,90	-1,65	0,93	-0,70	0,94	0,42
10	-1,00	0,92	-0,22	0,92	-0,25	0,91	-0,26	0,92	0,23
15	-0,20	0,93	-0,92	0,92	0,00	0,92	-0,18	0,92	0,27
20	-0,97	0,92	0,00	0,92	-0,12	0,92	-0,10	0,92	0,28
30	-0,10	0,93	-0,39	0,92	-0,88	0,91	-0,10	0,92	0,23
40	-0,45	0,92	-1,00	0,92	-0,20	0,93	-0,34	0,92	0,23

6. The Calculation of the Comparison Reference Value (CRV)

The reference value was determined in each air speed separately. The method of determination of the reference value in each air speed corresponds to the procedure presented by M.G.Cox [3].

The determination of the CRV will include a consistency check according to [4].

The reference value *y* will be calculated as weighted mean error (WME):

$$y = \frac{\frac{x_1}{u_{x1}^2} + \frac{x_2}{u_{x2}^2} + \ldots\ldots\ldots \frac{x_n}{u_{xn}^2}}{\frac{1}{u_{x1}^2} + \frac{1}{u_{x2}^2} + \ldots\ldots\ldots \frac{1}{u_{xn}^2}} \qquad (3)$$

where $x_1, x_2, \ldots\ldots x_n$ are errors of the anemometer in one air speed in different laboratories $1,2, \ldots\ldots n$

$u_{x1}, u_{x2}, \ldots\ldots u_{xn}$ are standard uncertainties (not expanded) of the error in laboratories $1,2, \ldots\ldots n$ including the uncertainty caused by stability of the anemometer.

The standard uncertainty of the reference value u_y is given by

$$\frac{1}{u_y^2} = \frac{1}{u_{x1}^2} + \frac{1}{u_{x2}^2} + \ldots\ldots\ldots \frac{1}{u_{xn}^2} \qquad (4)$$

The expanded uncertainty of the reference value *U(y)* is

$$U(y) = 2.u_y \qquad (5)$$

The chi-squared test for consistency check was performed using values of errors of the anemometer in each air speed. At first the chi-squared value χ^2_{obs} was calculated by

$$\chi^2_{obs} = \frac{(x_1 - y)^2}{u^2_{x1}} + \frac{(x_2 - y)^2}{u^2_{x2}} + ... \frac{(x_n - y)^2}{u^2_{xn}} \quad (6)$$

The degrees of freedom ν was assigned

$$\nu = n - 1 \quad (7)$$

where n is the number of evaluated laboratories.

The consistency check was failing if

$$Pr\{\chi^2_\nu > \chi^2_{obs}\} < 0{,}05 \quad (8)$$

(The function *CHIINV(0,05; ν)* in MS Excel was used. The consistency check was failing if *CHIINV(0,05; ν)*< χ^2_{obs})

If the consistency check does not fail, then *y* was accepted as the comparison reference value x_{ref} and *U(y)* was accepted as the expanded uncertainty of the comparison reference value $U(x_{ref})$.

If the consistency check fails then the laboratory with the highest value of $\frac{(x_i - y)^2}{u^2_{xi}}$ was excluded for the next round of evaluation and the new reference value *y* (WME), the new standard uncertainty of the reference value u_y and the chi-squared value χ^2_{obs} was calculated again without the values of excluded laboratory. The consistency check was calculated again, too. This procedure was repeated ones till the consistency check has passed.

7. The determination of the differences “Lab to CRV” and “Lab to Lab”

When the CRV was determined, the differences between the participating laboratories and the CRV was calculated according to

$$di = x_i - x_{ref} \quad (9)$$

$$dij = x_i - x_j \quad (10)$$

Based on these differences, the Degree of Equivalence (*DoE*) was calculated according to:

$$Ei = \left| \frac{di}{U(di)} \right| \qquad (11)$$

and $$Eij = \left| \frac{dij}{U(dij)} \right| \quad \text{respectively.} \qquad (12)$$

The *DoE* is a measure for the equivalence of the results of any laboratory with the CRV or with any other laboratory, respectively:

The results of a laboratory is equivalent (passed) if |Ei| or |Eij|≤1.

- The laboratory was determined as not equivalent (failed) if |Ei| or |Eij| >1.2.

- For values of DoE in the range 1 < |Ei| or |Eij| ≤ 1.2 we define "warning level" were actions to check is recommended to the laboratory.

The calculation of the *DoE* needs the information about the uncertainty of the differences *di* and *dij* (equations (9) and (10)).

The covariance between the result of a laboratory and the CRV is the variance of the CRV itself.

$$u(di) = \sqrt{u_{xi}^2 - u_{xref}^2} \qquad (13)$$

There is no covariance between two independent laboratories so;

$$u(dij) = \sqrt{u_{xi}^2 + u_{xj}^2} \qquad (14)$$

The equations (13 and 14) use the standard uncertainties. The expanded uncertainties *U(di)* and *U(dij)* (see equations (15), (16)) are determined by

$$U(di) = 2.u(di) \qquad (15)$$

$$U(dij) = 2.u(dij) \qquad (16)$$

Therefore the only case in this comparison is the "independent laboratories with contribution to the CRV"; the covariance between the result of a laboratory (with contribution to the CRV)
and the CRV is the variance of the CRV itself.

$$u(di) = \sqrt{u_{xi}^2 + u_{xref}^2 - 2.u_{xref}^2} = \sqrt{u_{xi}^2 - u_{xref}^2} \qquad (17)$$

8. Evaluation of the Measurement Results

All data collected from the participating laboratories are summarized in following tables and figures. PTB has results for their two different wind tunnels; PTB-A and PTB-B.

Table 7. Relative errors (%) of the participating laboratories-**Pitot Tube**

Air speed(m/s)	UME	CETIAT	METAS	RISE	LEI	DTI	PTB-A	PTB-B	CMI
1	6.50	6.53	4.95	4.10	1.41	-3.92	-1.08	2.33	6.52
3	0.69	0.39	0.00	0.45	0.36	-0.56	0.89	-0.51	-0.39
5	-1.00	-0.09	0.00	-0.22	-0.04	-0.17	-0.10	-0.72	-0.86
10	-0.43	-0.54	-0.50	-0.07	-0.37	-0.05	-0.46	-0.71	-0.95
15	-0.33	-0.64	0.40	-0.12	-0.22	-0.21	-0.49	-0.69	-0.85
20	-0.30	-0.74	0.50	-0.34	-0.24	0.04	-0.62	-0.79	-0.77
30	-0.37	-0.68	0.60	0.18	-0.19	-0.42	-0.54	-0.80	-0.57
40	-0.50	-0.69		0.57			-0.47		-0.46

Table 8. Expanded uncertainties (%) of measurements reported by participating laboratories-**Pitot Tube**

Air speed(m/s)	UME	CETIAT	METAS	RISE	LEI	DTI	PTB-A	PTB-B	CMI
1	5.00	1.87	2.97	5.00	1.90	5.02	0.85	4.39	5.15
3	1.46	0.85	2.33	5.00	1.10	1.79	0.55	0.55	0.66
5	0.92	0.73	2.20	3.80	0.81	1.00	0.45	0.51	0.50
10	0.92	0.63	2.09	3.80	0.55	0.51	0.40	0.44	0.50
15	0.92	0.62	2.07	3.80	0.45	0.51	0.40	0.42	0.50
20	0.92	0.61	2.05	3.80	0.45	0.51	0.40	0.41	0.50
30	0.92	0.58	2.03	3.80	0.45	0.52	0.40	0.40	0.50
40	0.92	0.57		3.80			0.40		0.50

Table 9. Calculated expanded uncertainties (%) including drift of the **Pitot Tube**

Air speed(m/s)	UME	CETIAT	METAS	RISE	LEI	DTI	PTB-A	PTB-B	CMI
1	5,76	3,42	4,12	5,76	3,43	5,78	2,98	5,24	5,89
3	1,70	1,21	2,48	5,07	1,40	1,99	1,02	1,02	1,08
5	1,25	1,11	2,35	3,89	1,17	1,31	0,95	0,98	0,98
10	1,03	0,78	2,14	3,83	0,72	0,69	0,61	0,64	0,68
15	1,07	0,82	2,14	3,84	0,70	0,74	0,67	0,68	0,74
20	1,08	0,83	2,13	3,84	0,72	0,76	0,69	0,69	0,75
30	1,03	0,74	2,08	3,83	0,64	0,70	0,61	0,61	0,68
40	1,03	0,74		3,83			0,61		0,68

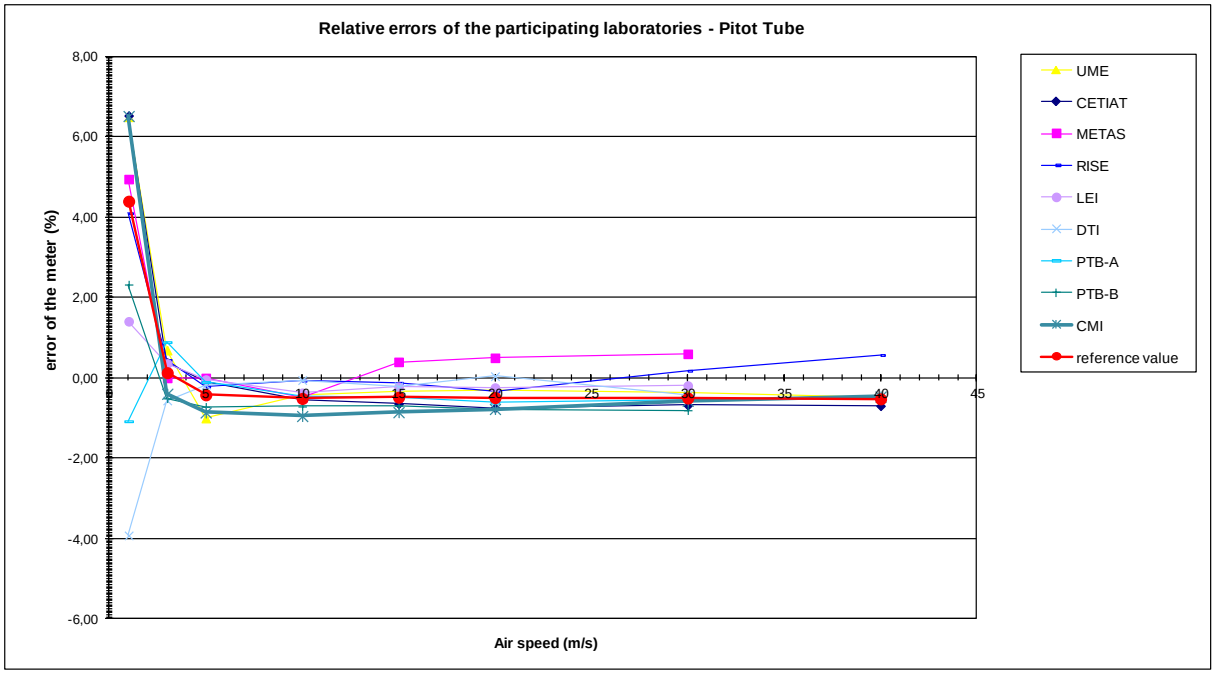


Figure 5. *Relative errors (%) of the participating laboratories – Pitot Tube*

Table 10. Relative errors (%) of the participating laboratories-**Ultrasonic Anemometer**

Air speed(m/s)	CETIAT	METAS	RISE	LEI	BEV/E+E	DTI	PTB-A	PTB-B	CMI
1	6.32	7.00	8.52	8.04	8.54	9.82	6.31	2.33	7.09
3	8.31	7.69	7.36	8.12	9.21	10.93	8.36	-0.51	7.95
5	9.19	7.82	10.11	8.69	10.11	11.21	9.08	-0.72	8.76
10	9.33	7.71	9.54	8.57	9.74	10.88	8.92	-0.71	8.79
15	9.27	10.11	10.06	8.94	9.62	10.31	8.81	-0.69	8.84
20	9.29	9.98	10.39	9.05	9.60	10.10	8.81	-0.79	8.66
30	9.34	10.25	10.28	9.20	9.55	9.88	8.87	-0.80	8.86
40	9.29		11.43		9.72		9.19		8.98

Table 11. Expanded uncertainties (%) of measurements reported by participating laboratories-**Ultrasonic Anemometer**

Air speed(m/s)	CETIAT	METAS	RISE	LEI	BEV/E+E	DTI	PTB-A	PTB-B	CMI
1	2.64	2.80	7.70	1.90	1.88	5.40	2.36	0.96	1.33
3	1.37	2.38	5.30	1.10	1.49	1.83	0.99	0.56	0.63
5	0.92	2.23	3.90	0.81	1.46	1.34	0.45	0.49	0.50
10	0.77	2.20	3.80	0.55	1.39	0.76	0.40	0.45	0.50
15	0.84	2.15	3.80	0.45	1.40	0.92	0.73	0.43	0.50
20	0.82	2.36	3.80	0.45	1.41	1.25	0.60	0.42	0.50
30	0.83	2.42	3.80	0.45	1.38	0.92	0.92	0.42	0.50
40	0.91		4.10		1.40		0.89		0.51

Table 12. Calculated expanded uncertainties (%) including drift of the **Ultrasonic Anemometer**

Air speed(m/s)	CETIAT	METAS	RISE	LEI	BEV/E+E	DTI	PTB-A	PTB-B	CMI
1	3,11	3,24	7,87	2,51	2,49	5,64	2,87	1,90	2,11
3	1,51	2,46	5,34	1,27	1,62	1,94	1,18	0,85	0,90
5	1,11	2,31	3,95	1,02	1,59	1,48	0,77	0,79	0,80
10	0,82	2,22	3,81	0,62	1,41	0,81	0,49	0,53	0,57
15	0,88	2,17	3,81	0,52	1,42	0,96	0,77	0,50	0,56
20	0,88	2,38	3,82	0,56	1,45	1,30	0,69	0,54	0,60
30	0,91	2,45	3,82	0,58	1,43	0,98	0,99	0,55	0,62
40	0,95		4,11		1,43		0,93		0,58

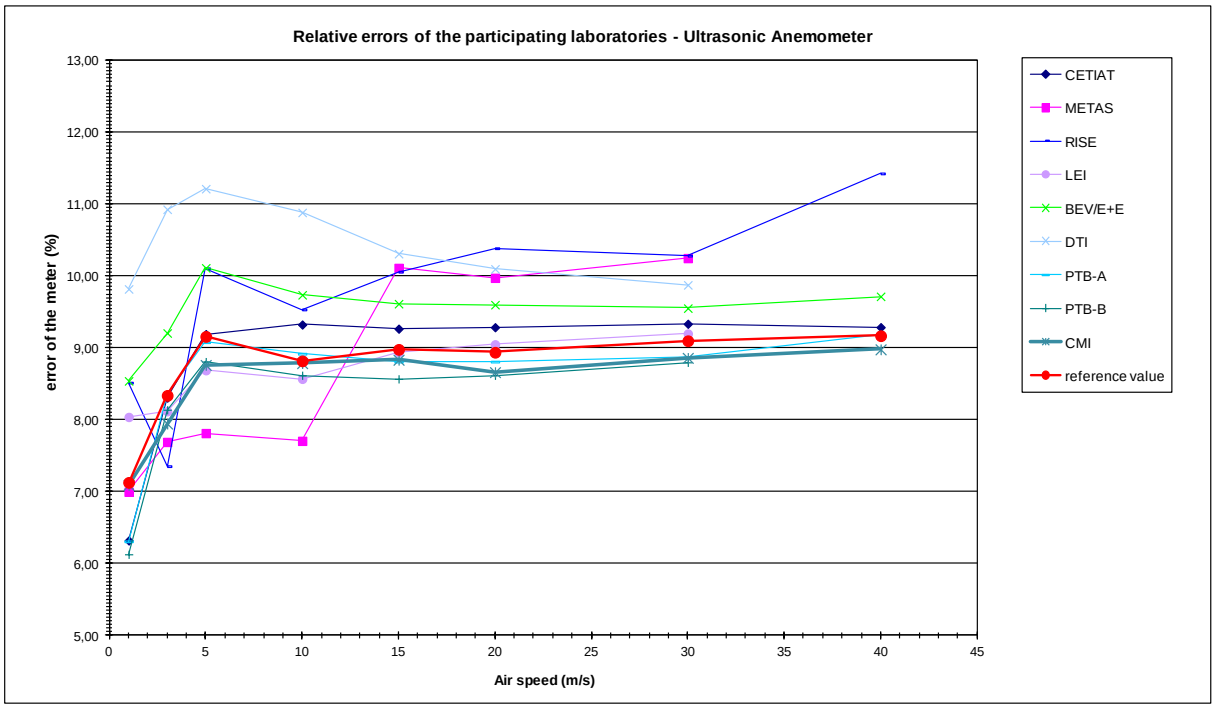


Figure 6. *Relative errors (%) of the participating laboratories – Ultrasonic Anemometer*

The degree of Equivalence "Lab to CRV"

The number of independent laboratories is eight based on the laboratory declarations. Only BEV/E+E declared that their laboratory is dependent laboratory.

For each participating laboratory the degree of equivalence was calculated and presented in the following tables for pitot tube and ultrasonic anemometer.

Table 12. The degree of equivalence **"Lab to CRV"** for **pitot tube** measurements.

Air speed (m/s)	UME	CETIAT	METAS	RISE	LEI	DTI	PTB-A	PTB-B	CMI
	Ei	*Ei*	*Ei*	*Ei*	*Ei*	*Ei*	*Ei*	*Ei*	*Ei*
1	0,38	0,72	0,15	0,05	1,00	1,51	2,23	0,42	0,38
3	0,34	0,23	0,05	0,06	0,17	0,36	0,84	0,70	0,54
5	0,49	0,32	0,18	0,05	0,35	0,20	0,37	0,33	0,49
10	0,08	0,04	0,01	0,12	0,21	0,72	0,10	0,35	0,71
15	0,15	0,21	0,42	0,09	0,41	0,40	0,01	0,34	0,55
20	0,18	0,33	0,47	0,04	0,38	0,76	0,20	0,47	0,00
30	0,13	0,26	0,53	0,18	0,53	0,13	0,08	0,56	0,11
40	0,02	0,27		0,29			0,10		0,10

Table 13. The degree of equivalence **"Lab to CRV"** for **ultrasonic anemometer** measurements.

Air speed (m/s)	CETIAT	METAS	RISE	LEI	BEV/E+E	DTI	PTB-A	PTB-B	CMI
	Ei	*Ei*	*Ei*	*Ei*	*Ei*	*Ei*	*Ei*	*Ei*	*Ei*
1	0,27	0,04	0,18	0,39	0,61	0,48	0,30	0,60	0,02
3	0,02	0,27	0,19	0,18	0,56	1,37	0,02	0,28	0,50
5	0,11	0,55	0,26	0,41	0,67	1,48	0,00	0,38	0,44
10	0,64	0,50	0,19	0,44	0,66	2,66	0,24	0,42	0,06
15	0,34	0,53	0,28	0,09	0,45	1,44	0,23	0,94	0,29
20	0,41	0,44	0,38	0,22	0,46	0,91	0,20	0,67	0,00
30	0,27	0,47	0,31	0,20	0,33	0,83	0,24	0,64	0,44
40	0,14		0,55		0,40		0,02		0,47

The final evaluation of the countries is given in the below tables

Table 14. Pitot tube results

Air speed (m/s)	UME	CETIAT	METAS	RISE	LEI	DTI	PTB-A	PTB-B	CMI
	Ei	*Ei*	*Ei*	*Ei*	*Ei*	*Ei*	*Ei*	*Ei*	*Ei*
1	passed	passed	passed	passed	passed	failed	failed	passed	passed
3	passed	passed	passed	passed	passed	passed	passed	passed	passed
5	passed	passed	passed	passed	passed	passed	passed	passed	passed
10	passed	passed	passed	passed	passed	passed	passed	passed	passed
15	passed	passed	passed	passed	passed	passed	passed	passed	passed
20	passed	passed	passed	passed	passed	passed	passed	passed	passed
30	passed	passed	passed	passed	passed	passed	passed	passed	passed
40	passed	passed		passed			passed		passed

Table 15. Ultrasonic anemometer results

Air speed (m/s)	CETIAT *Ei*	METAS *Ei*	RISE *Ei*	LEI *Ei*	BEV/E+E *Ei*	DTI *Ei*	PTB-A *Ei*	PTB-B *Ei*	CMI *Ei*
1	passed	passed	passed	passed	passed	passed	passed	passed	passed
3	passed	passed	passed	passed	passed	failed	passed	passed	passed
5	passed	passed	passed	passed	passed	failed	passed	passed	passed
10	passed	passed	passed	passed	passed	failed	passed	passed	passed
15	passed	passed	passed	passed	passed	failed	passed	passed	passed
20	passed	passed	passed	passed	passed	passed	passed	passed	passed
30	passed	passed	passed	passed	passed	passed	passed	passed	passed
40	passed		passed		passed		passed		passed

The degree of Equivalence "Lab to Lab"

For each participating laboratory the degree of equivalence "lab to lab" was calculated and presented in the following tables for pitot tube and ultrasonic anemometer.

Table 16. The degree of equivalence "lab to lab" tables for pitot tube for all air speeds.

Air speed 1 m/s	UME *Eij*	CETIAT *Eij*	METAS *Eij*	RISE *Eij*	LEI *Eij*	DTI *Eij*	PTB-A *Eij*	PTB-B *Eij*	CMI *Eij*
UME									
CETIAT	0,005								
METAS	0,219	0,296							
RISE	0,295	0,363	0,120						
LEI	0,760	1,060	0,661	0,402					
DTI	1,278	1,558	1,250	0,984	0,794				
PTB-A	1,169	1,682	1,186	0,799	0,548	0,437			
PTB-B	0,536	0,673	0,394	0,228	0,146	0,801	0,565		
CMI	0,002	0,002	0,218	0,294	0,750	1,266	1,152	0,533	

Air speed 3 m/s	UME *Eij*	CETIAT *Eij*	METAS *Eij*	RISE *Eij*	LEI *Eij*	DTI *Eij*	PTB-A *Eij*	PTB-B *Eij*	CMI *Eij*
UME									
CETIAT	0,147								
METAS	0,230	0,140							
RISE	0,046	0,012	0,079						
LEI	0,151	0,014	0,126	0,016					
DTI	0,480	0,407	0,176	0,185	0,379				
PTB-A	0,101	0,321	0,332	0,086	0,308	0,651			
PTB-B	0,607	0,566	0,189	0,184	0,503	0,024	0,973		
CMI	0,541	0,482	0,146	0,162	0,428	0,073	0,868	0,076	

Air speed 5 m/s	UME *Eij*	CETIAT *Eij*	METAS *Eij*	RISE *Eij*	LEI *Eij*	DTI *Eij*	PTB-A *Eij*	PTB-B *Eij*	CMI *Eij*
UME									
CETIAT	0,544								
METAS	0,376	0,035							
RISE	0,192	0,030	0,047						
LEI	0,563	0,032	0,015	0,043					
DTI	0,459	0,046	0,064	0,011	0,075				
PTB-A	0,574	0,006	0,040	0,028	0,041	0,043			
PTB-B	0,179	0,422	0,281	0,125	0,445	0,334	0,451		
CMI	0,090	0,519	0,337	0,160	0,539	0,421	0,556	0,102	

Air speed 10 m/s	UME *Eij*	CETIAT *Eij*	METAS *Eij*	RISE *Eij*	LEI *Eij*	DTI *Eij*	PTB-A *Eij*	PTB-B *Eij*	CMI *Eij*
UME									
CETIAT	0,086								
METAS	0,028	0,019							
RISE	0,091	0,121	0,098						
LEI	0,048	0,162	0,057	0,078					
DTI	0,306	0,471	0,198	0,004	0,321				
PTB-A	0,024	0,084	0,018	0,101	0,095	0,444			
PTB-B	0,233	0,170	0,095	0,166	0,358	0,707	0,289		
CMI	0,423	0,397	0,201	0,227	0,591	0,934	1,152	0,259	

Air speed 15 m/s	UME *Eij*	CETIAT *Eij*	METAS *Eij*	RISE *Eij*	LEI *Eij*	DTI *Eij*	PTB-A *Eij*	PTB-B *Eij*	CMI *Eij*
UME									
CETIAT	0,235								
METAS	0,304	0,455							
RISE	0,052	0,133	0,118						
LEI	0,084	0,393	0,276	0,026					
DTI	0,092	0,395	0,269	0,022	0,012				
PTB-A	0,129	0,146	0,397	0,095	0,279	0,284			
PTB-B	0,289	0,046	0,487	0,147	0,485	0,484	0,214		
CMI	0,407	0,190	0,554	0,187	0,625	0,622	0,367	0,160	

Air speed 20 m/s	UME *Eij*	CETIAT *Eij*	METAS *Eij*	RISE *Eij*	LEI *Eij*	DTI *Eij*	PTB-A *Eij*	PTB-B *Eij*	CMI *Eij*
UME									
CETIAT	0,326								
METAS	0,336	0,545							
RISE	0,009	0,103	0,191						
LEI	0,046	0,458	0,330	0,025					
DTI	0,260	0,698	0,203	0,097	0,271				
PTB-A	0,247	0,118	0,500	0,071	0,377	0,642			
PTB-B	0,380	0,040	0,576	0,115	0,547	0,806	0,175		
CMI	0,361	0,027	0,565	0,111	0,513	0,764	0,155	0,013	

Air speed 30 m/s	UME	CETIAT	METAS	RISE	LEI	DTI	PTB-A	PTB-B	CMI
	Eij	*Eij*	*Eij*	*Eij*	*Eij*	*Eij*	*Eij*	*Eij*	*Eij*
UME									
CETIAT	0,245								
METAS	0,418	0,580							
RISE	0,139	0,221	0,096						
LEI	0,149	0,503	0,363	0,095					
DTI	0,038	0,260	0,464	0,154	0,242				
PTB-A	0,145	0,144	0,528	0,187	0,402	0,137			
PTB-B	0,365	0,131	0,648	0,254	0,700	0,422	0,306		
CMI	0,160	0,114	0,534	0,192	0,406	0,155	0,026	0,263	

Air speed 40 m/s	UME	CETIAT	METAS	RISE	LEI	DTI	PTB-A	PTB-B	CMI
	Eij	*Eij*	*Eij*	*Eij*	*Eij*	*Eij*	*Eij*	*Eij*	*Eij*
UME									
CETIAT	0,153								
METAS									
RISE	0,270	0,325							
LEI									
DTI									
PTB-A	0,024	0,233		0,269					
PTB-B									
CMI	0,029	0,230		0,266			0,008		

Table 17. The degree of equivalence “lab to lab” tables for ultrasonic anemometer for all air speeds

Air speed 1 m/s	CETIAT	METAS	RISE	LEI	BEV/E+E	DTI	PTB-A	PTB-B	CMI
	Eij	*Eij*	*Eij*	*Eij*	*Eij*	*Eij*	*Eij*	*Eij*	*Eij*
CETIAT									
METAS	0,151								
RISE	0,259	0,178							
LEI	0,429	0,253	0,058						
BEV/E+E	0,556	0,376	0,003	0,142					
DTI	0,543	0,433	0,135	0,288	0,207				
PTB-A	0,003	0,159	0,263	0,453	0,586	0,554			
PTB-B	0,053	0,231	0,295	0,605	0,768	0,619	0,052		
CMI	0,205	0,024	0,174	0,288	0,442	0,452	0,220	0,338	

Air speed 3 m/s	CETIAT	METAS	RISE	LEI	BEV/E+E	DTI	PTB-A	PTB-B	CMI
	Eij	*Eij*	*Eij*	*Eij*	*Eij*	*Eij*	*Eij*	*Eij*	*Eij*
CETIAT									
METAS	0,214								
RISE	0,172	0,057							
LEI	0,096	0,146	0,139						
BEV/E+	0,406	0,514	0,332	0,529					
DTI	1,066	1,033	0,629	1,213	0,682				
PTB-A	0,027	0,245	0,184	0,139	0,424	1,134			
PTB-B	0,098	0,172	0,145	0,013	0,585	1,319	0,152		
CMI	0,206	0,097	0,109	0,111	0,682	1,397	0,280	0,157	

Air speed 5 m/s	CETIAT	METAS	RISE	LEI	BEV/E+E	DTI	PTB-A	PTB-B	CMI
	Eij	*Eij*	*Eij*	*Eij*	*Eij*	*Eij*	*Eij*	*Eij*	*Eij*
CETIAT									
METAS	0,535								
RISE	0,223	0,501							
LEI	0,331	0,345	0,348						
BEV/E+	0,474	0,818	0,001	0,752					
DTI	1,088	1,235	0,262	1,400	0,506				
PTB-A	0,083	0,518	0,255	0,303	0,585	1,276			
PTB-B	0,278	0,406	0,322	0,092	0,733	1,428	0,243		
CMI	0,312	0,386	0,334	0,056	0,758	1,453	0,284	0,041	

Air speed 10 m/s	CETIAT	METAS	RISE	LEI	BEV/E+E	DTI	PTB-A	PTB-B	CMI
	Eij	*Eij*	*Eij*	*Eij*	*Eij*	*Eij*	*Eij*	*Eij*	*Eij*
CETIAT									
METAS	0,683								
RISE	0,054	0,414							
LEI	0,731	0,374	0,414						
BEV/E+	0,252	2,430	0,374	0,756					
DTI	1,344	1,344	1,344	2,259	0,701				
PTB-A	0,422	0,533	0,533	0,442	0,546	2,063			
PTB-B	0,717	0,400	0,400	0,061	0,739	2,324	0,413		
CMI	0,534	0,471	0,471	0,257	0,622	2,100	0,220	0,214	

Air speed 15 m/s	CETIAT	METAS	RISE	LEI	BEV/E+E	DTI	PTB-A	PTB-B	CMI
	Eij	*Eij*	*Eij*	*Eij*	*Eij*	*Eij*	*Eij*	*Eij*	*Eij*
CETIAT									
METAS	0,362								
RISE	0,203	0,012							
LEI	0,322	0,527	0,291						
BEV/E+	0,208	0,192	0,110	0,446					
DTI	0,804	0,083	0,064	1,260	0,406				
PTB-A	0,392	0,567	0,322	0,139	0,497	1,219			
PTB-B	0,691	0,694	0,388	0,512	0,692	1,612	0,260		
CMI	0,415	0,571	0,318	0,137	0,509	1,330	0,027	0,352	

Air speed 20 m/s	CETIAT	METAS	RISE	LEI	BEV/E+E	DTI	PTB-A	PTB-B	CMI
	Eij	*Eij*	*Eij*	*Eij*	*Eij*	*Eij*	*Eij*	*Eij*	*Eij*
CETIAT									
METAS	0,270								
RISE	0,281	0,092							
LEI	0,226	0,377	0,347						
BEV/E+	0,184	0,134	0,192	0,353					
DTI	0,515	0,046	0,071	0,739	0,256				
PTB-A	0,424	0,469	0,407	0,267	0,491	0,874			
PTB-B	0,641	0,554	0,458	0,544	0,632	1,048	0,215		
CMI	0,581	0,533	0,446	0,464	0,596	1,000	0,159	0,052	

Air speed 30 m/s	CETIAT	METAS	RISE	LEI	BEV/E+E	DTI	PTB-A	PTB-B	CMI
	Eij	*Eij*	*Eij*	*Eij*	*Eij*	*Eij*	*Eij*	*Eij*	*Eij*
CETIAT									
METAS	0,351								
RISE	0,242	0,008							
LEI	0,127	0,418	0,281						
BEV/E+	0,129	0,246	0,179	0,231					
DTI	0,406	0,141	0,103	0,596	0,187				
PTB-A	0,348	0,523	0,359	0,290	0,395	0,724			
PTB-B	0,507	0,578	0,385	0,505	0,494	0,958	0,062		
CMI	0,434	0,550	0,368	0,404	0,446	0,877	0,007	0,076	

Air speed 40 m/s	CETIAT	METAS	RISE	LEI	BEV/E+E	DTI	PTB-A	PTB-B	CMI
	Eij	*Eij*	*Eij*	*Eij*	*Eij*	*Eij*	*Eij*	*Eij*	*Eij*
CETIAT									
METAS									
RISE	0,507								
LEI									
BEV/E+	0,249		0,393						
DTI									
PTB-A	0,074		0,531		0,309				
PTB-B									
CMI	0,275		0,589		0,477		0,190		

9. Conclusions

The EURAMET comparison F 1515 - Intercomparison of air speed in the range of 1 m/s – 40 m/s has been successfully completed. It was carried out with two transfer standards; pitot tube and ultrasonic anemometer. Nine countries took part in the comparison.

The results of measurements were evaluated by standard methods following the works of Cox. The performance of the transfer standards and their stability in time was evaluated by TUBITAK UME and CETIAT.

All the laboratories participated in the comparison are independent laboratories.

BEV/E+E has withdrawn the measurement results of pitot tube due to shift in zero adjustment and TUBITAK UME has withdrawn the results of ultrasonic anemometer due to shift in calibration value of transfer standard.

PTB participated with two wind tunnels in the comparison as PTB-A and PTB-B which the details of the wind tunnels are given in the appendix A.

All labs measured up to 30 m/s but only five laboratories measured 40 m/s air speed.

The consistency of the results in the sense of chi-square test was satisfactory. 3 % of the “lab to CRV” (CRV = comparison reference value) equivalence degrees values were out of the satisfactory range (larger than one) for pitot comparison and 6 % for the ultrasonic anemometer comparison results.

References

[1] Measurement Comparisons in the CIPM MRA, January 2021.

[2] CCM Guidelines for approval and publication of the final reports of key and supplementary comparisons, 24 February 2022.

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

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

[5] Müller H., Care I.,Final Report on CCM.FF-K3.2011 CIPM Key Comparison of Air Speed 0,5 m/s to 40 m/s, BIPM KCDB Database, March 2017

[6] Pachinger D.,Euramet Final Report on the Project No.1225 Intercomparison of very low air speed standard facilities (0,05-1m/s), October 2016

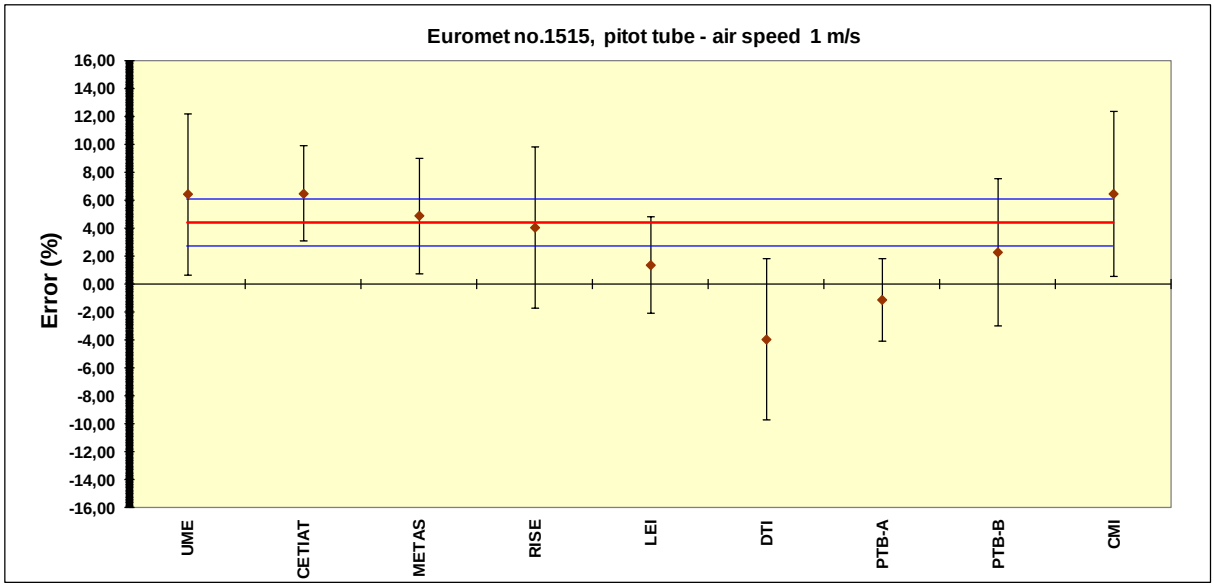
Appendix A– Laboratory information

Participant	Tunnel Type	Range	Uncertainty	Reference

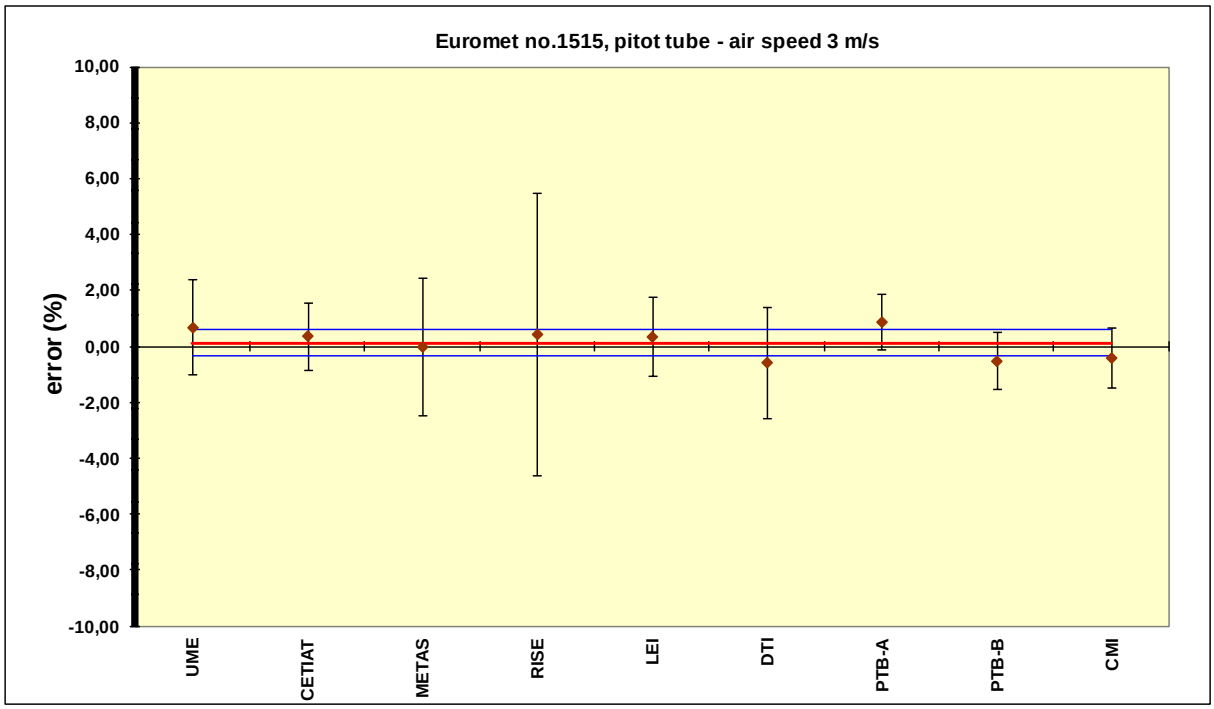
TÜBİTAK UME	Open type	(0,5-40) m/s	For (0,5<v<1,0) m/s
			% 1,86
			For (1,0≤v<3,0) m/s
			% 1,44
			For (3,0≤v<40,0) m/s
			% 0,63
				LDA

CETIAT	Göttingen type	(0.15 – 40) m/s	0,008 m/s + 0,0051.V	LDA
METAS	Göttingen type	(0.1 - 40) m/s	0.015 m/s, v <= 0.5 m/s 0.020 m/s, v = (0.5-1) m/s 2 %, v > 1 m/s	Tow tank and Pitot
RISE	Own production	(0,3 – 37) m/s	For 0,3-0,6 m/s ±0,03m/s For 0,6-4,0 m/s ±4,9% For 4,0-37 m/s ±3,7%	Prandtl (4-37 m/s) and a low speed rig (0,1-4,0 m/s) transmitted with a hot wire anemometer
LEI	Göttingen type	(0,05 – 60) m/s	For: (0.05 - 0.15) m/s [(0,23 / v) + 3,4] % For: > 0.15 m/s to 1 m/s [(0,52 / v) + 1,4] % For: > 1 m/s to 60 m/s [(1,51 / v) + 0,41] %	LDV
BEV/E+E	Göttingen type	(0.3 – 40) m/s	(0.004 m/s + 0.0047 *v)	LDA
DTI	Open type, Closed measurement section 50x50 cm	(0,3 – 30) m/s	0-10 m/s: 0,05 m/s 10-30 m/s: v x 0,005 m/s	LDA
PTB - A	Göttingen type WKR008 Nozzle diameter: 32 cm Open test section Test section length: approx. 45 cm	(1-60) m/s	reference uncertainty: 0.14 % Measurement uncertainty: 0,005 m/s + 0,0035 *U (U = wind speed in m/s)	LDA
PTB - B	Göttingen type WKCCW Nozzle cross section: 50 cm x 50 cm Open test section Test section length: 75 cm	(1-28) m/s	reference uncertainty: 0.18 % Measurement uncertainty: 0,005 m/s + 0,0035 *U (U = wind speed in m/s)	LDA
CMI	Göttingen type	(0.3 - 50) m/s	for (0.3 - 5) m/s 0.01 m/s + 0.3% of measured value; for [5 - 50] m/s 0.5 % of measured value	LDA

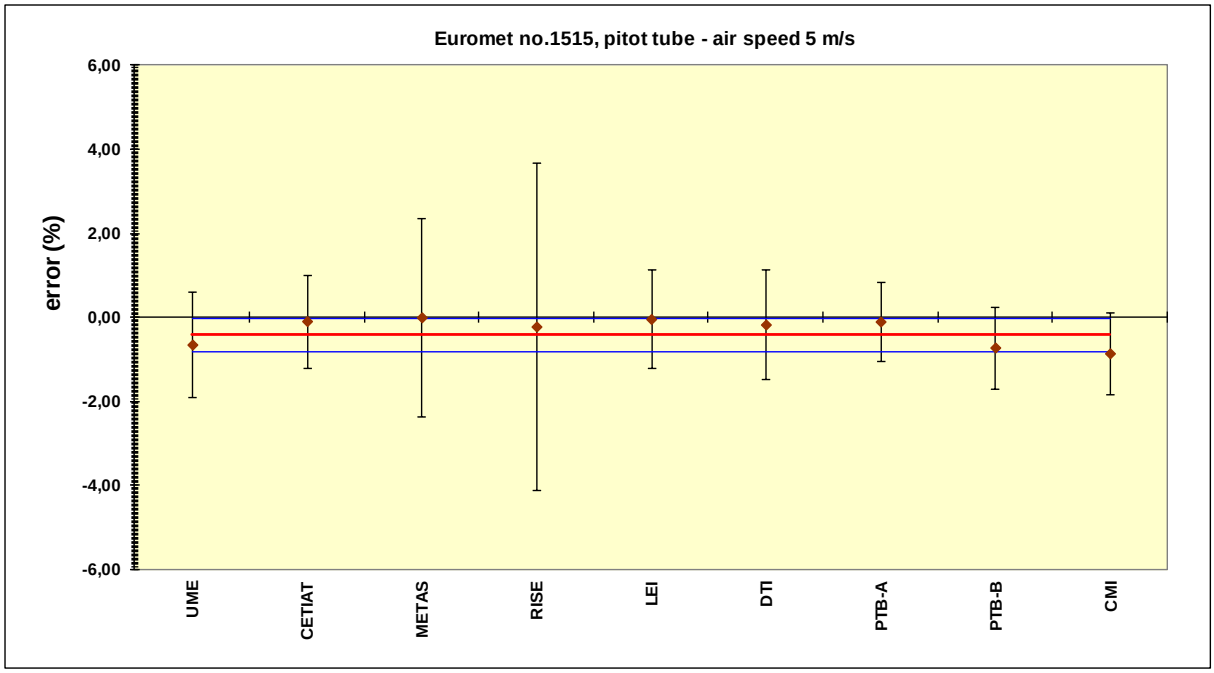
Appendix B– Graphical representation of errors E and uncertainties U for Pitot Tube



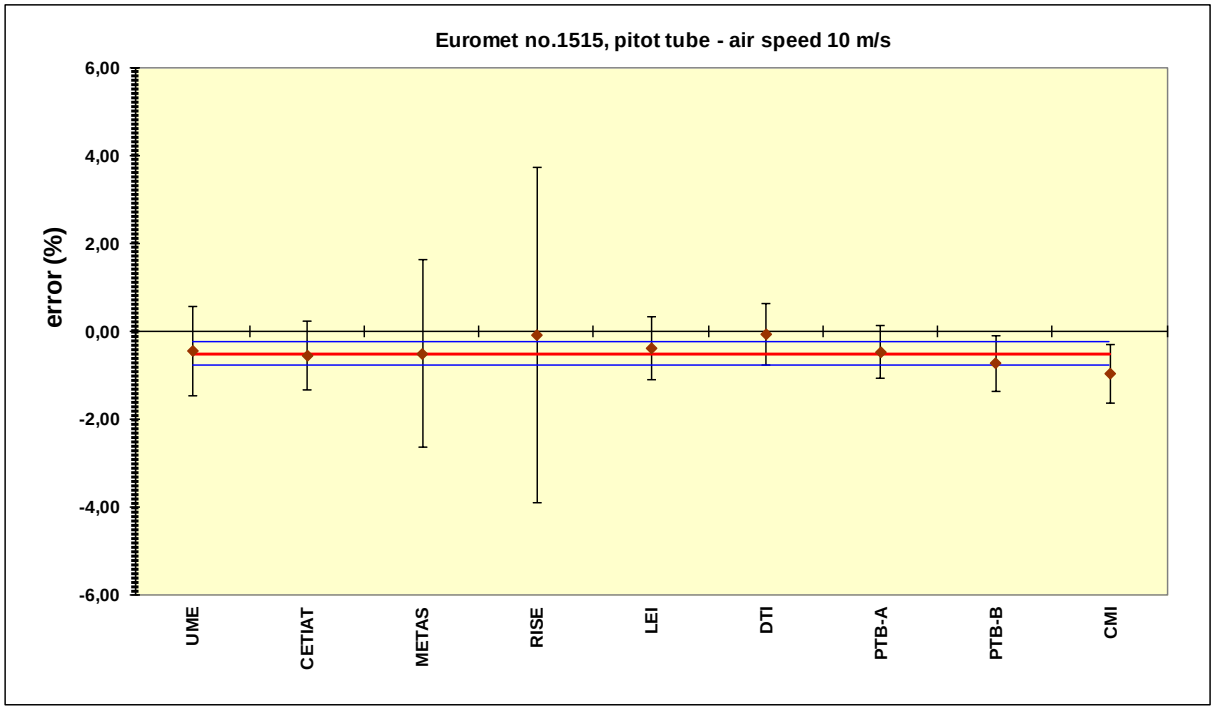
x_{ref} =	4,40
u_{xref}=	1,68



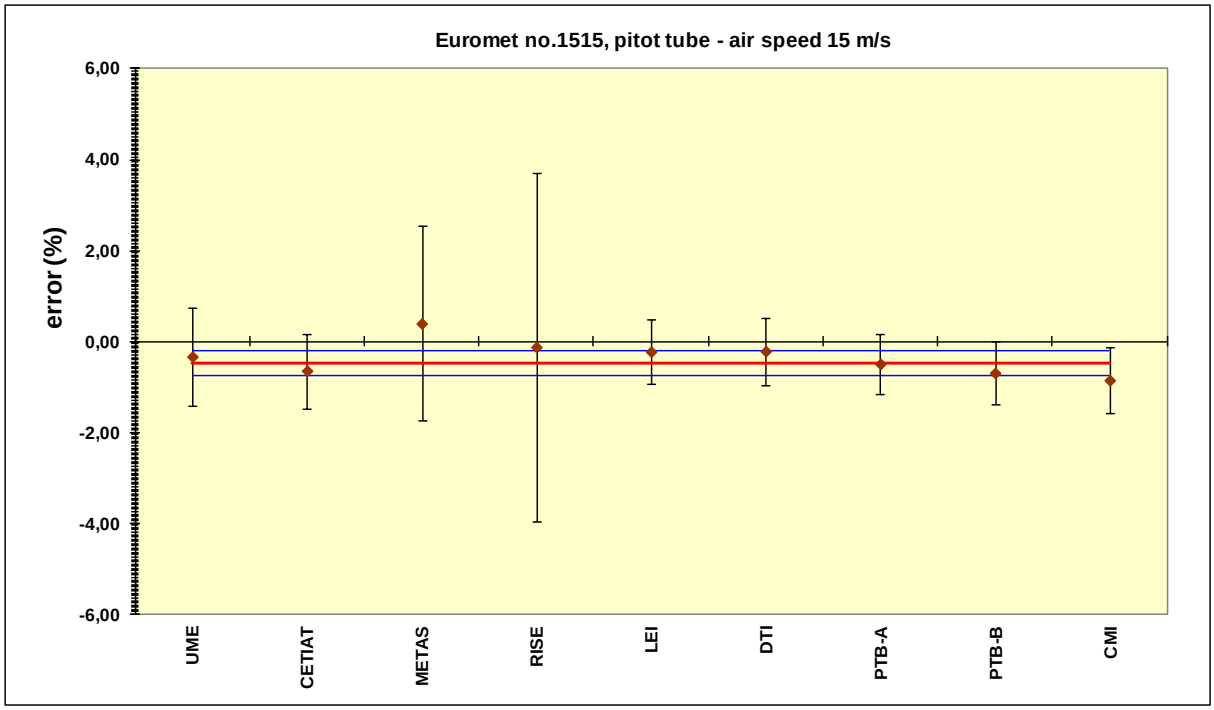
x_{ref} =	0,13
u_{xref}=	0,46



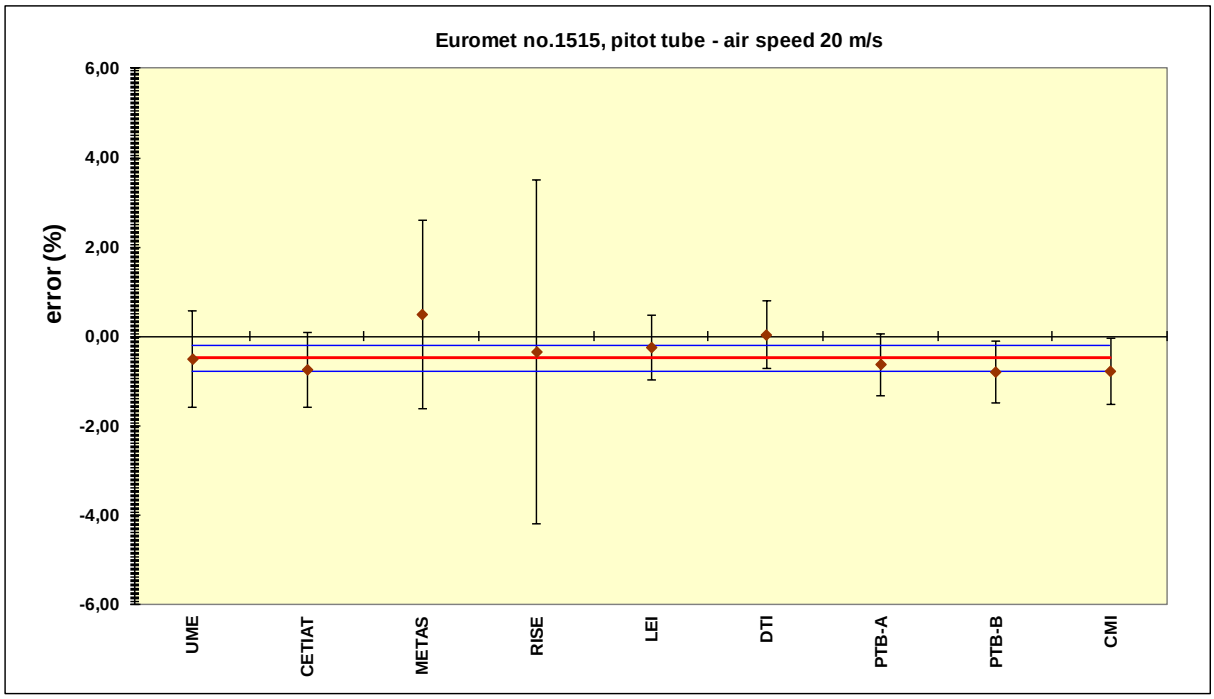
x_{ref} =	-0,42
u_{xref}=	0,40



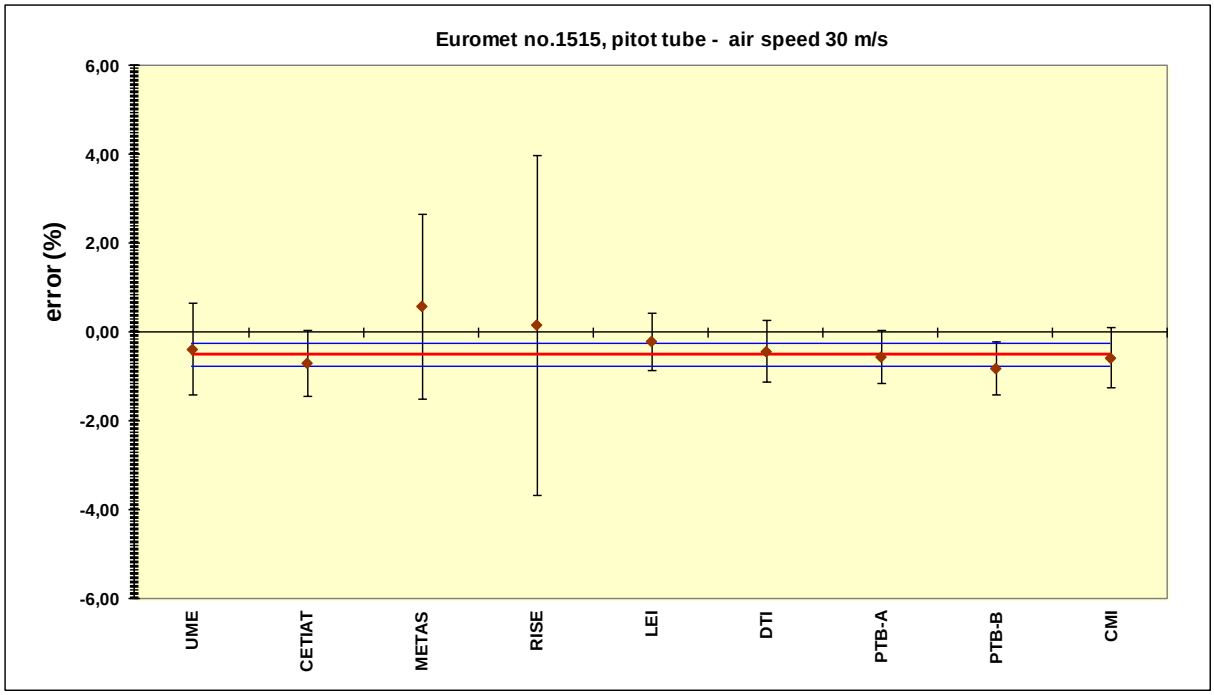
x_{ref} =	-0,51
u_{xref}=	0,26



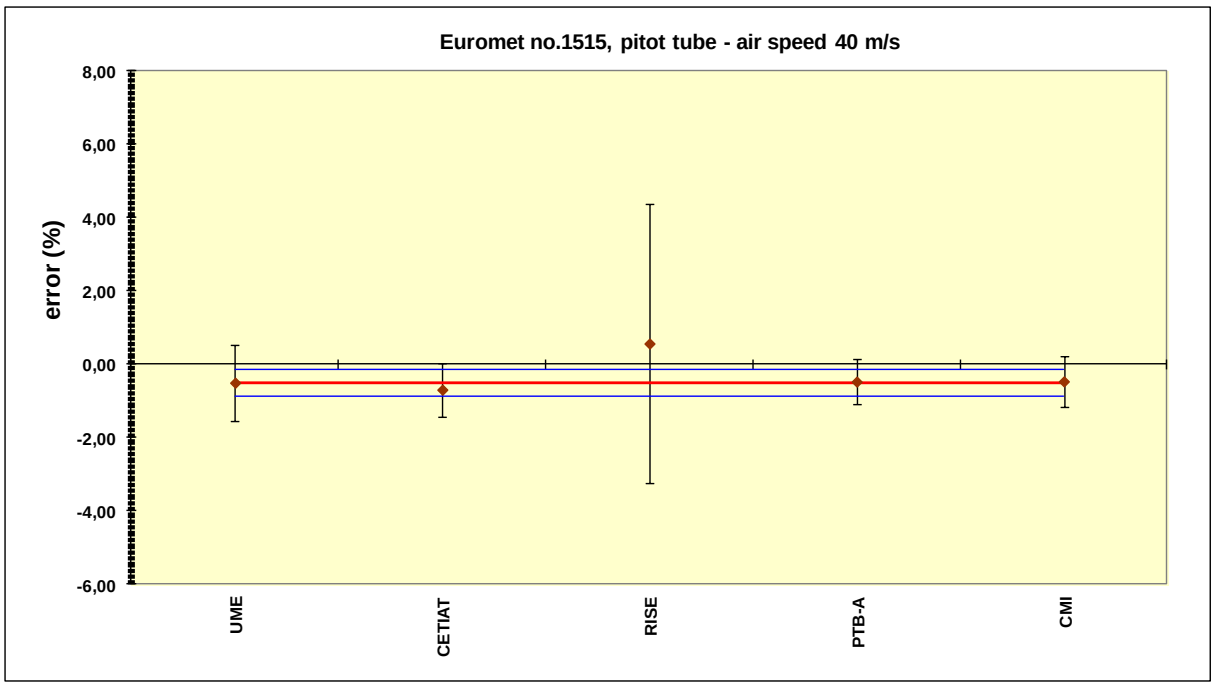
x_{ref} =	-0,48
u_{xref}=	0,28



x_{ref} =	-0,49
u_{xref}=	0,29

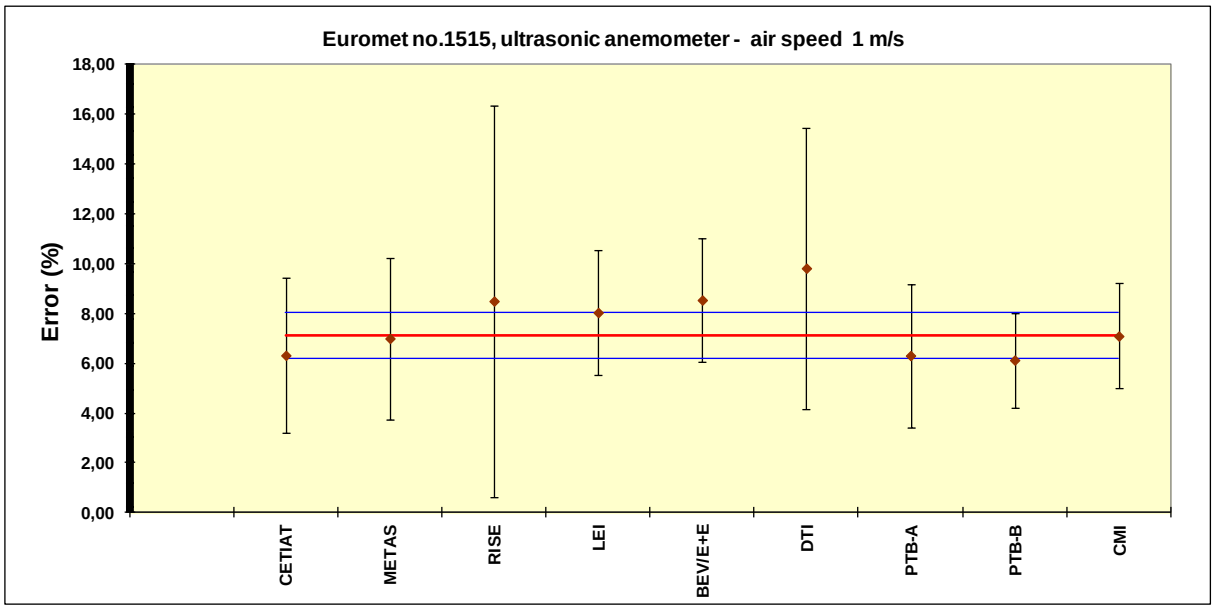


x_{ref} =	-0,50
u_{xref}=	0,26

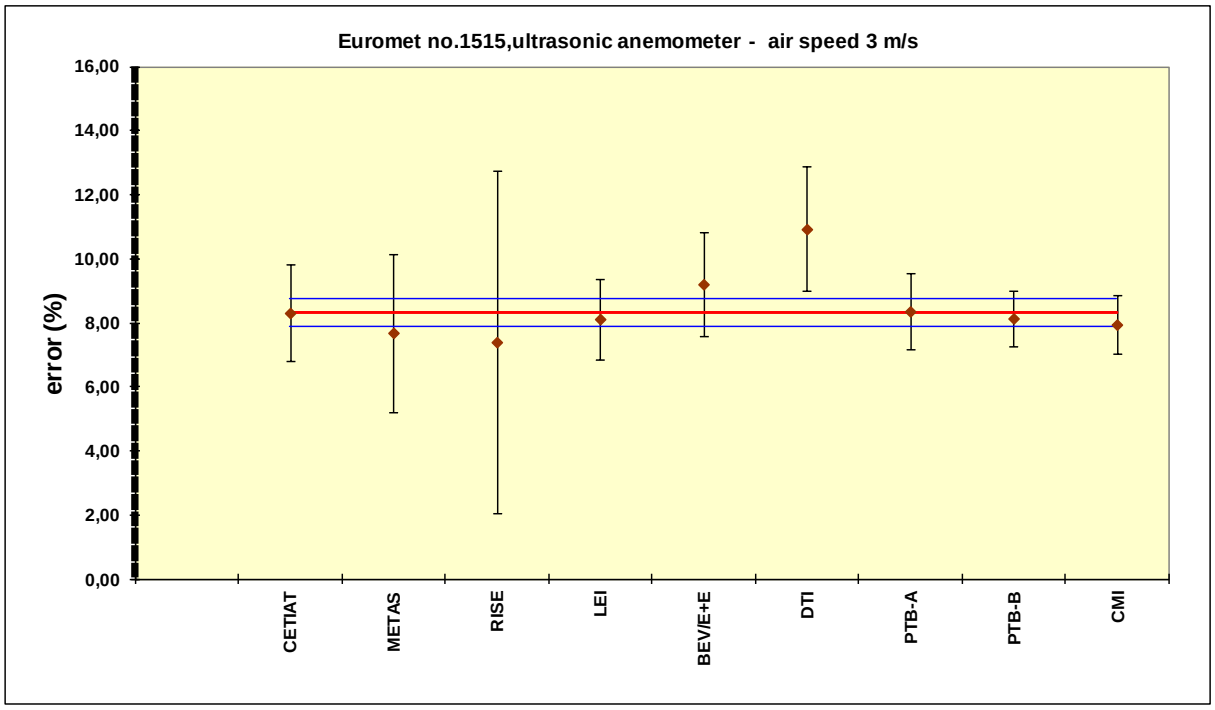


x_{ref} =	-0,52
u_{xref}=	0,36

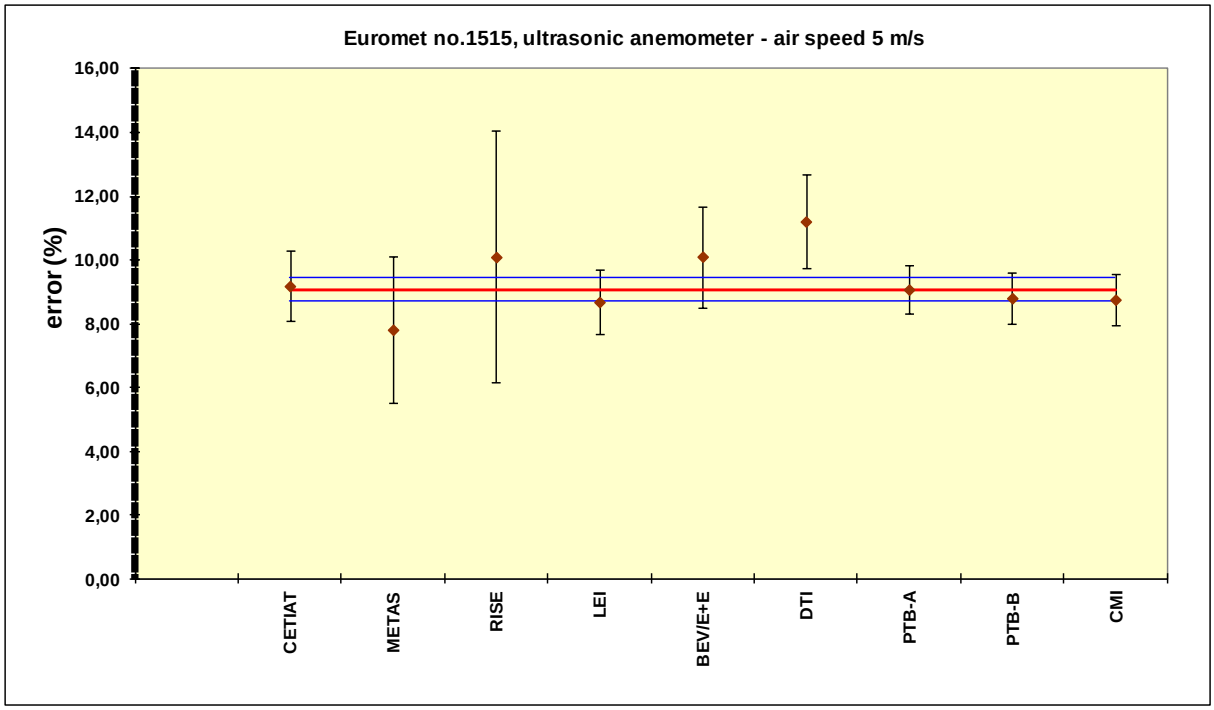
Appendix C– Graphical representation of errors E and uncertainties U for Ultrasonic Anemometer Results



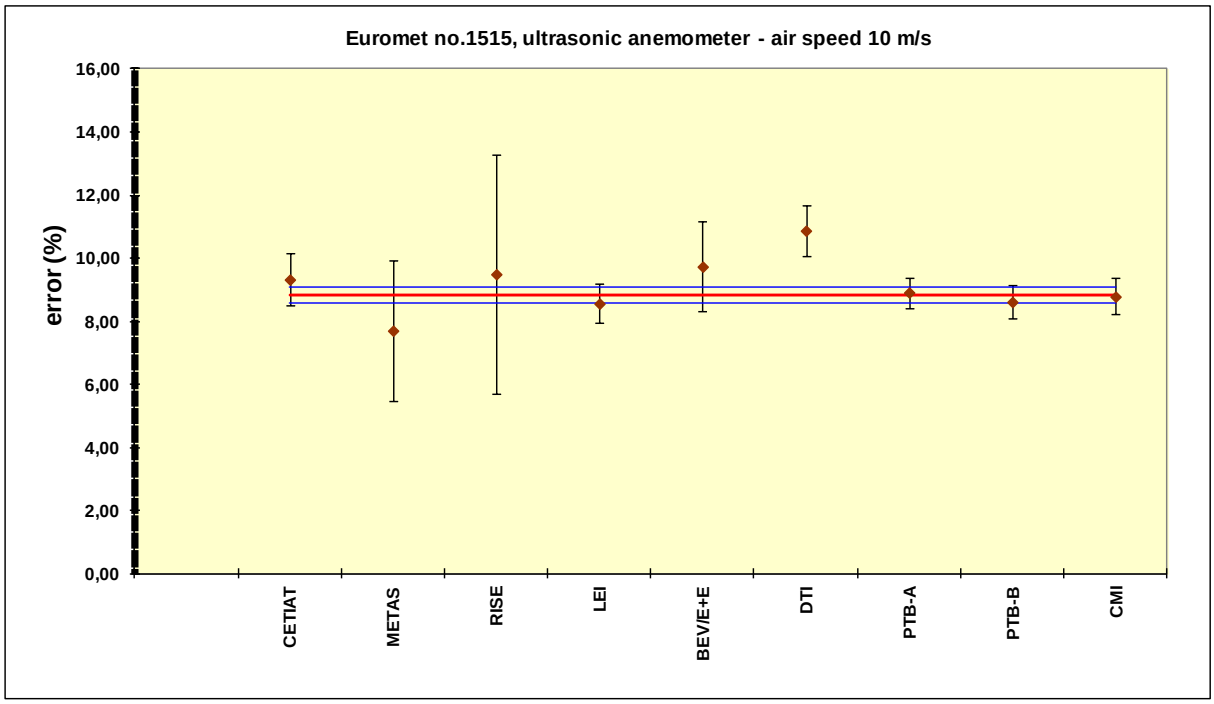
x_{ref} =	7,13
u_{xref}=	0,92



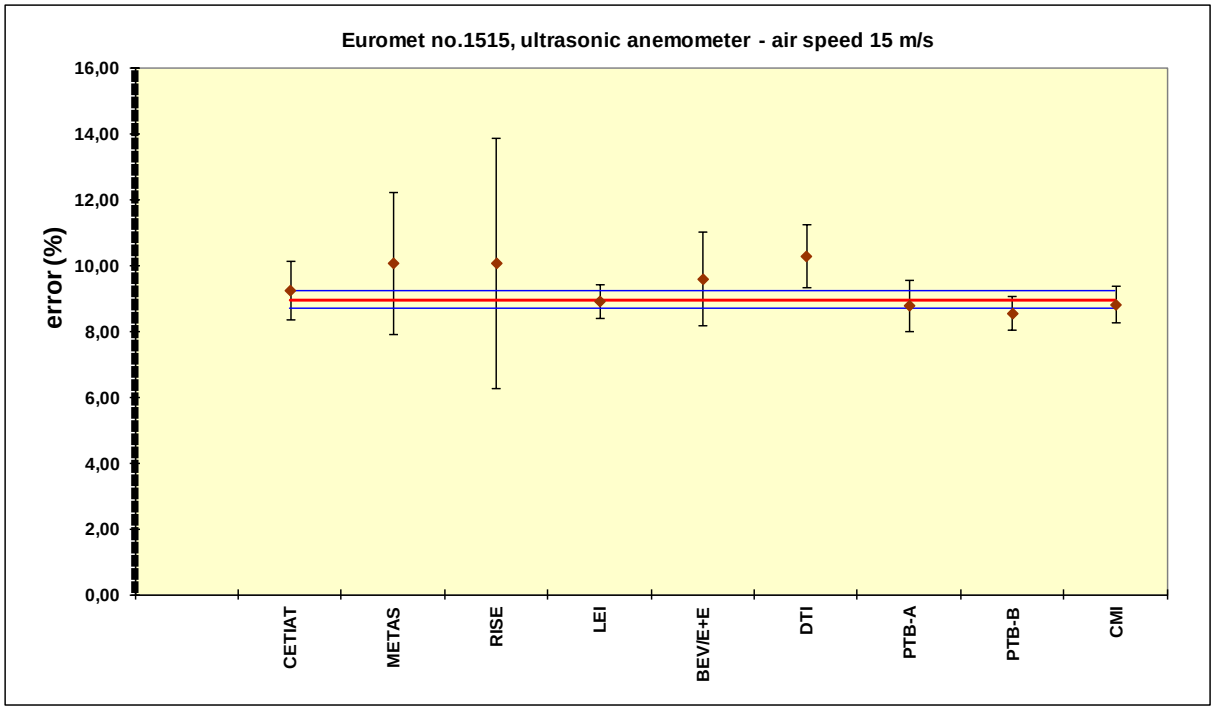
x_{ref} =	8,34
u_{xref}=	0,44



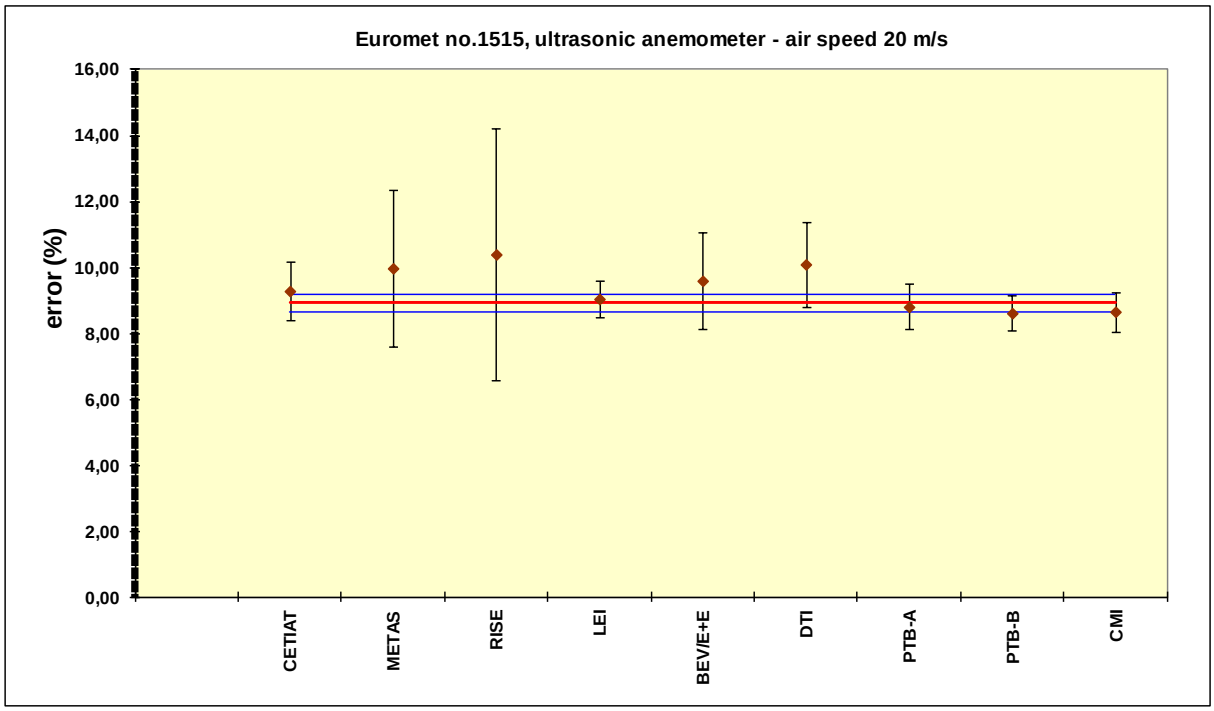
x_{ref} =	9,08
u_{xref}=	0,36



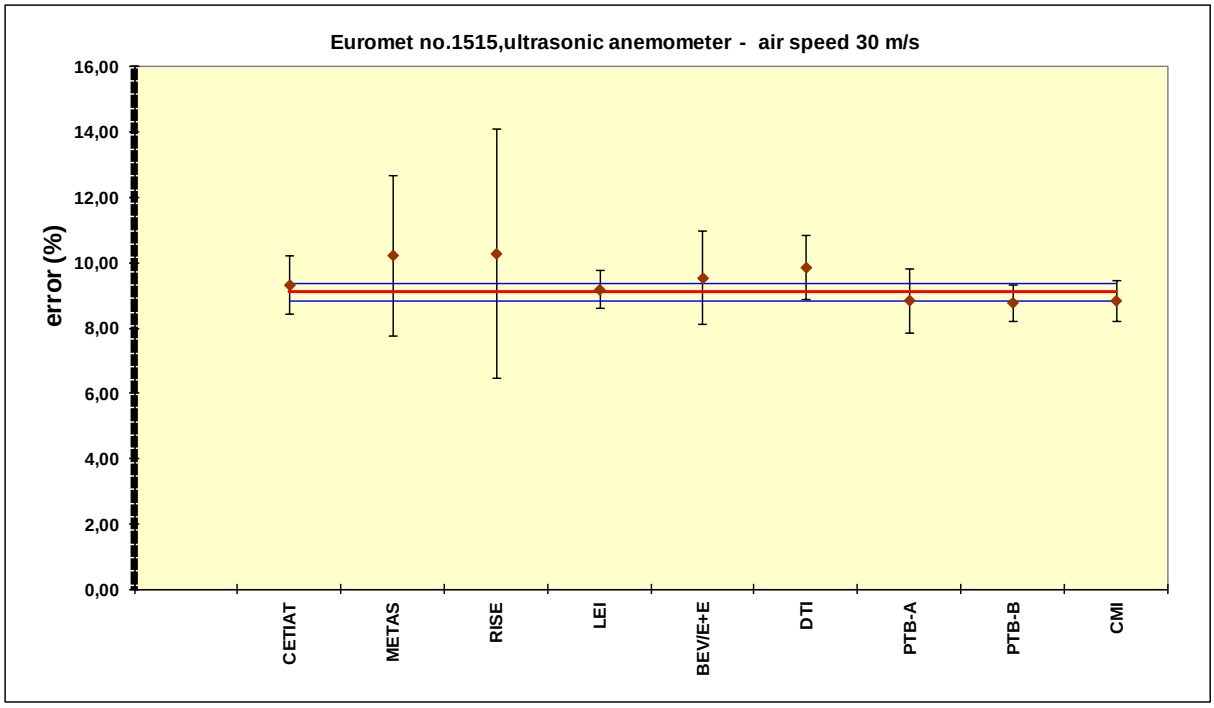
x_{ref} =	8,82
u_{xref}=	0,25



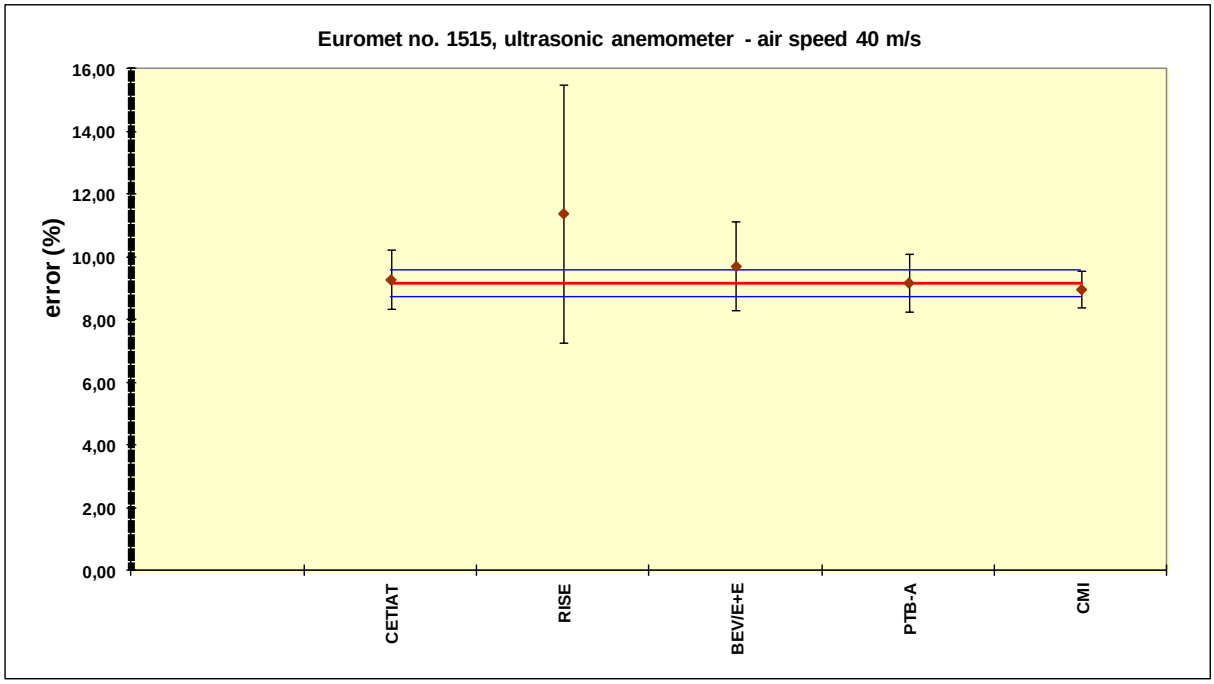
x_{ref} =	8,98
u_{xref}=	0,25



x_{ref} =	8,94
u_{xref}=	0,27



x_{ref} =	9,10
u_{xref}=	0,28



x_{ref} =	9,17
u_{xref}=	0,42