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Investigation of the Equivalence of National Dew-Point Temperature Realizations in the −50 °C to +20 °C Range

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Abstract In the field of humidity quantities, the first CIPM key comparison, CCT-K6, is at its end. The corresponding European regional key comparison, EUROMET.T-K6, was completed in early 2008, about 4 years after the starting

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initial measurements in the project. In total, 24 NMIs from different countries took part in the comparison. This number includes 22 EURAMET countries, and Russia and South Africa. The comparison covered the dew-point temperature range from −50 °C to +20 °C. It was carried out in three parallel loops, each with two chilled mirror hygrometers as transfer standards in each loop. The comparison scheme was designed to ensure high quality results with evenly spread workload for the participants. It is shown that the standard uncertainty due to the long-term instability was smaller than 0.008 °C in all loops. The standard uncertainties due to links between the loops were found to be smaller than 0.025 °C at −50 °C and 0.010 °C elsewhere. Conclusions

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on the equivalence of the dew-point temperature standards are drawn on the basis of calculated bilateral degrees of equivalence and deviations from the EURAMET comparison reference values (ERV). Taking into account 16 different primary dew-point realizations and 8 secondary realizations, the results demonstrate the equivalence of a large number of laboratories at an uncertainty level that is better than achieved in other multilateral comparisons so far in the humidity field.

Keywords Degrees of equivalence · Dew-point temperature · Key comparison

1 Introduction

To support worldwide recognition, national metrology institutes (NMIs) regularly investigate the equivalence of the national realizations of SI units by arranging key comparisons. The national standards of a region are compared to each other in regional key comparisons arranged by the relevant regional metrology organization (RMO), e.g., EURAMET in Europe. Regional key comparison results from different regions are linked to each other through CIPM key comparisons.

EUROMET.T-K6 is the European extension of the first CCT key comparison in the field of humidity measurements which will end in year 2010 (the comparison was named before the establishment of EURAMET e.V as the successor of EUROMET.in 2007). The European comparison was executed in years 2004 to 2008. The aim was to obtain high quality data on the equivalence of local dew-point temperature scale realizations in the range from −50 °C to +20 °C. (Note: throughout this article "dew-point temperature" refers to dew-point temperature above 0 °C and frost-point temperature below 0 °C.) The outcomes of the project reported in this article are the deviations of each realization from the EURAMET Comparison Reference Value (ERV) at five nominal measurement points −50 °C, −30 °C, −10 °C, +1 °C, and +20 °C.

This article describes the applied comparison and analysis method and summarizes the results. The full report with the individual results has been published in the Technical Supplement of Metrologia [1].

2 Comparison Method

2.1 Comparison Scheme and Participants

The comparison was carried out in three parallel loops with two chilled mirror hygrometers as transfer standards in each loop. Each NMI calibrated two instruments out of six that were used as transfer standards. In addition, each pair of loops was interlinked through two NMIs that calibrated the transfer standards of the two loops. Before starting the comparison, the pilot laboratories of the loops ran initial tests for the instruments of their loop. They also carried out an additional set of measurements after all other participants of their loops for long-term stability monitoring. This comparison scheme reduced the sensitivity of the final results to the quality of results at individual NMIs. Also, the workload of piloting and establishing links between the loops and to the corresponding CCT comparison was divided to nine NMIs.

Table 1 List of participants

Name of the laboratory	Country	Loop	Type
Central Office of Measures (GUM)	Poland	1, 3	LL
Centre for Metrology and Accreditation (MIKES)	Finland	1	C, P1, LC
Centre Technique des Industries Aérauliques et Thermiques (CETIAT)	France	1, 2	LL
Czech Metrology Institute (CMI)	Czech Republic	3	
D. I. Mendeleyev Institute for Metrology (VNIIM)	Russia	1	LC
DELTA Danish Electronics (DELTA)	Denmark	1	
BEV / E+E ELEKTRONIK (BEV)	Austria	3	
Hellenic Institute of Metrology (EIM)	Greece	2	
Hungarian Trade Licensing Office (MKEH)	Hungary	3	
Instituto Nacional de Técnica Aeroespacial (INTA)	Spain	2, 3	LC, LL
Instituto Português da Qualidade (IPQ)	Portugal	2	
Istituto Nazionale di Ricerca Metrologica (iNRiM)	Italy	2, 3	LC, LL
National Metrology Institute of South Africa (NMISA)	South Africa	1	
National Metrology Laboratory (NML)	Ireland	3	
National Physical Laboratory (NPL)	UK	3	LC
NMi van Swinden Laboratorium (NMi-VSL)	Netherlands	2	P2
Norwegian Metrology Service (JV)	Norway	1	
Physikalisch-Technische Bundesanstalt (PTB)	Germany	1, 2	LL
Slovak Institute of Metrology (SMU)	Slovakia	3	
Swedish National Testing and Research Institute (SP)	Sweden	1	
Swiss Federal Office of Metrology and Accreditation (METAS)	Switzerland	1, 3	P3, LL
Ulusal Metroloji Enstitüsü (UME)	Turkey	2	
University of Ljubljana, Faculty of Electrical Engineering, Laboratory of Metrology and Quality (MIRS/FE-LMK)	Slovenia	2	
University of Zagreb, Faculty of Mechanical Engineering and Naval Architecture, Laboratory for Process Measurements (LPM)	Croatia	2	

Abbreviations used in this report are in parentheses after the laboratory name. Participation types are: *C* coordinator, *P* pilot, *LC* link to the CCT-K6, *LL* link between the EURAMET.T-K6 loops (numbers following P specifies the loop)

Table 1 shows the participating laboratories and their roles in the comparison. Also, NMI acronyms used in this report are listed in the table. In loop 2, the final measurement set was carried out by INTA instead of the pilot laboratory (NMi-VSL) due to a sudden but temporary shortage of human resources at NMi. In loop 3, also NPL carried out two sets of measurements because the pilot laboratory (METAS) reported problems in its measurements.

As shown in Table 2, there were 16 different primary dew-point realizations and 8 secondary realizations to be compared to each other in this comparison. The primary realizations included single pressure (1-P) and two-pressure (2-P) dew-point

Table 2 Summary of the realization methods used by the participating laboratories and the measurement ranges covered in this comparison: *C* coulometric generator, *1-P* single pressure generator, *2-P* two-pressure generator, *S* secondary calibration system; see further details in [1]

Laboratory	Country	Type and covered range
GUM	Poland	1-P (−50 °C to +20 °C)
MIKES	Finland	1-P (−50 °C to +20 °C)
CETIAT	France	1-P (−50 °C to +20 °C)
CMI	Czech Republic	S (−50 °C to +20 °C)
VNIIM	Russia	1-P (−50 °C to +1 °C)
DELTA	Denmark	S (−50 °C to +20 °C)
BEV/E+E	Austria	2-P (−50 °C to +20 °C)
EIM	Greece	1-P (−30 °C to +20 °C)
MKEH	Hungary	S (−50 °C to +20 °C)
INTA	Spain	2-P (−50 °C to +20 °C)
IPQ	Portugal	S (−10 °C to +20 °C)
iNRiM	Italy	1-P (−50 °C to +20 °C)
NMISA	South Africa	S (−50 °C to +20 °C)
NML	Ireland	S (−10 °C to +20 °C)
NPL	UK	1-P (−50 °C to +20 °C)
NMi-VSL	Netherlands	1-P (−50 °C to +20 °C)
JV	Norway	S (−50 °C to +20 °C)
PTB	Germany	2-P (−10 °C to +20 °C) C (−50 °C to −30 °C)
SMU	Slovakia	S (−50 °C to +20 °C)
SP	Sweden	1-P (−50 °C to +1 °C)
METAS	Switzerland	1-P (−50 °C to +20 °C)
UME	Turkey	2-P (−30 °C to +20 °C)
MIRS	Slovenia	1-P (−50 °C to +20 °C)
LPM	Croatia	1-P (−10 °C to +20 °C)

Note: In most cases the operating ranges of the realizations are larger than the ranges covered in this comparison

generators. In the secondary realizations, the reference standards were chilled mirror hygrometers. Detailed information on most of the realizations can be found in [2–16].

At each laboratory, two transfer standards were calibrated in parallel in four full sets of the five nominal measurement points. At each measurement point, the condensate layer on the mirror was reformed.

2.2 Transfer Standards

The transfer standards were MBW373L chilled mirror hygrometers. In each unit, there are two PRTs embedded in the mirror. One of them has direct access for electrical resistance measurement which was used as the primary output. For each nominal measurement point, all participants reported the resistance and the corresponding NMI's reference dew-point temperature value with assigned uncertainties. Also, dew-point readings and flow rate readings displayed by the units were reported as supporting

Table 3 Standard uncertainty due to the long-term instability of the pairs of transfer standards in the loops

t_d (°C)	$u_\mathrm{Stab}(t_\mathrm{d})$		
	Loop1	Loop2	Loop3
−50	0.0071	0.0022	0.0044
−30	0.0062	0.0025	0.0025
−10	0.0047	0.0026	0.0011
1	0.0039	0.0027	0.0004
20	0.0025	0.0029	0.0013

information. Because the integrated flow meters did not work well with slightly pulsating flow, the hygrometers were equipped with additional rotameters.

The stability of the transfer standards were monitored in three ways: by analyzing the difference (1) between the paired hygrometers and (2) between the resistance based temperature and display readings, and (3) by comparing the results obtained by the pilot laboratories in both ends of each loop. In the results of the first two methods, no drift or tendency was identified. In the third method the linearity of the hygrometer response was analyzed for both sets of results. This revealed small shifts in the zero points and slopes of both instruments. The changes, however, are significantly smaller than the associated uncertainties and the deviations of the results at each nominal point. It was concluded that no time-dependent correction due to the long-term instability can be applied but the corresponding uncertainty was added in the analysis. This is supported also by the results of an investigation of the linearity of results reported by other participants: no trend correlating with the changes in the results of the pilot laboratories could be found. The uncertainty (u_Stab) was estimated by comparing the linear fittings (f) to each other at each nominal point:

$$u_\mathrm{Stab}^2(t_\mathrm{d}) = \frac{1}{12}\left\{\left[f_{1,\mathrm{h1}}(t_\mathrm{d}) - f_{2,\mathrm{h1}}(t_\mathrm{d})\right]^2 + \left[f_{1,\mathrm{h2}}(t_\mathrm{d}) - f_{2,\mathrm{h2}}(t_\mathrm{d})\right]^2\right\} \tag{1}$$

where the subscripts specify the measurement set (1 or 2) of the pilot laboratory and the transfer standard of the loop (“h1” or “h2”). Table 3 shows the calculated standard uncertainties.

3 Method for Analyzing the Results

3.1 Overview

The analysis of the results comprises three steps: At first (1), the results reported by a laboratory were combined to a single set of results, i.e., one result for each nominal measurement point. Then (2), the bilateral equivalences between all pairs of laboratories were calculated from the step 1 results. Finally (3), step 2 results were used for calculating the differences between the participating laboratories and corresponding comparison reference values. Conclusions on the equivalence between the laboratories are drawn from the step 3 results.

3.2 Combining the Results of Each Participant

As described above, all participants calibrated two instruments four times at each nominal measurements point. Combining these results, we get the dew-point temperature difference between the laboratory reference and the set of two transfer standards at each point for each laboratory $i\,(\Delta t_{\mathrm{d},i})$. For simplifying equations later in this article, we define $R_i = \Delta t_{\mathrm{d},i}$. Combining was done in the following way: at first, all the mirror resistance values reported by the laboratories were converted to corresponding arbitrary nominal temperature values using the equations presented in [17]. Then, the mean difference $(R_{i,j})$ between the laboratory reference dew-point temperature values ($t_{\mathrm{dR1},i}$ and $t_{\mathrm{dR2},i}$) and the results obtained by the two transfer standards ($t_{\mathrm{dh1},i}$ and $t_{\mathrm{dh2},i}$) was calculated for each measurement set j. Finally, the mean results were calculated from the four repetitions at the measurement point:

$$\begin{aligned}\Delta t_{\mathrm{d},i} = R_i &= \frac{1}{4}\left(\sum_{j=1}^{4} R_{i,j}\right) + \delta_{\mathrm{rep},i}\\ &= \frac{1}{4}\left(\sum_{j=1}^{4} \frac{1}{2}(t_{\mathrm{dR1},j} - t_{\mathrm{dh1},j}) + \frac{1}{2}(t_{\mathrm{dR2},j} - t_{\mathrm{dh2},j})\right) + \delta_{\mathrm{rep},i} \qquad (2)\end{aligned}$$

where δ_{rep} is the correction due to non-ideal reproducibility of the results. Its estimate is zero but its standard uncertainty is estimated by

$$u(\delta_{\mathrm{rep},i}) = \frac{1}{2\sqrt{3}}\left[\max\left(R_{i,j}\right) - \min(R_{i,j})\right] \qquad (3)$$

The uncertainty of the result is calculated from the uncertainties of all initial results, $u(R_{i,j})$:

$$\begin{aligned}u^2(R_i) &= \frac{1}{16}\left[\sum_{j=1}^{4} u^2(R_{i,j})\right] + u^2(\delta_{\mathrm{rep},i})\\ &= \frac{1}{16}\left[\sum_{j=1}^{4} u^2(t_{\mathrm{dR},j}) + \frac{1}{4}\Big(u^2(t_{\mathrm{dh1},j})\right.\\ &\qquad \left.+\,u^2(t_{\mathrm{dh2},j})\Big)\right] + \frac{1}{12}\left[\max(R_{i,j}) - \min(R_{i,j})\right]^2 \qquad (4)\end{aligned}$$

Because the hygrometers were calibrated nominally simultaneously, the uncertainties of the laboratory reference dew-point temperature values $u(t_{\mathrm{dR1},j})$ and $u(t_{\mathrm{dR2},j})$ reduce to a single component $u(t_{\mathrm{dR},j})$ in Eq. 4. The uncertainties of the hygrometer results $u(t_{\mathrm{dh1},j})$ and $u(t_{\mathrm{dh2},j})$ are contributed by the short-term instability and the uncertainty of resistance measurements.

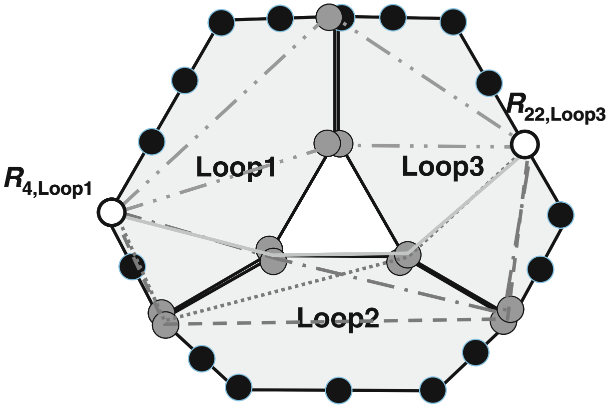

Fig. 1 An example of comparing the results of two laboratories. The laboratories (Nos. 4 and 22) are marked with *white circles*. *Grey circles* represent the link laboratories between the loops. The six possible routes to compare the results are illustrated by the *grey lines* of different types

3.3 Bilateral Equivalence

In principle, the bilateral equivalence analysis for laboratories in the same loop could be carried out in the same way as any single-loop comparison. Bilateral equivalence analysis for laboratories participating in different loops is more complicated. Further complications arise because no laboratory participated in all loops and the linking laboratories are different for each pair of loops.

To maximize the data used in the final analysis (and thus the reliability of the results), results obtained in all three loops are taken into account when calculating the bilateral equivalence of any pair of laboratories. It can easily be shown that all possible different routes for comparing any two laboratories to each other reduce to six routes, because adding laboratories inside a loop does not gain the information about the bilateral equivalence. Figure 1 illustrates the six routes in an example case. The bilateral equivalence is calculated as the weighted mean of the equivalences calculated along the six routes. When studying this in more details, it is found that the bilateral equivalence (D_{ij}) can be presented in a simple form:

$$D_{ij} = R_i - R_j = R_{i,\mathrm{loop}(i)} + B(i,j) - R_{j,\mathrm{loop}(j)} \tag{5}$$

where subscripts i and j identify the laboratories and loop(i) gives the loop number of the laboratory no. i. For link laboratories, loop(i) gives two values, which is discussed further in the end of this section. The discrete function B contains the contributions of the linking laboratories combined in terms of the weighted mean as shown below:

$$\begin{cases} B(i,j) = \sum_{m=1}^{6} [b(i,j,m)] + \delta_B(i,j); \quad \mathrm{loop}(i) \neq \mathrm{loop}(j) \\ B(i,j) = 0; \quad \mathrm{loop}(i) = \mathrm{loop}(j) \end{cases}$$

where

$$\begin{aligned}
b(i,j,m) &= \frac{\frac{P(i,j,m)}{u^2[P(i,j,m)]}}{\sum_{n=1}^{6}\left(u^{-2}[P(i,j,n)]\right)}\\
P(i,j,1) &= -R_{L(i,k,1),\mathrm{loop}(i)} + R_{L(i,k,1),\mathrm{loop}(k)} - R_{L(k,j,1),\mathrm{loop}(k)}\\
&\quad + R_{L(k,j,1),\mathrm{loop}(j)} + \delta_{\mathrm{Stab}}(i,j,1)\\
P(i,j,2) &= -R_{L(i,k,1),\mathrm{loop}(i)} + R_{L(i,k,1),\mathrm{loop}(k)} - R_{L(k,j,2),\mathrm{loop}(k)}\\
&\quad + R_{L(k,j,2),\mathrm{loop}(j)} + \delta_{\mathrm{Stab}}(i,j,2)\\
P(i,j,3) &= -R_{L(i,k,2),\mathrm{loop}(i)} + R_{L(i,k,2),\mathrm{loop}(k)} - R_{L(k,j,1),\mathrm{loop}(k)}\\
&\quad + R_{L(k,j,1),\mathrm{loop}(j)} + \delta_{\mathrm{Stab}}(i,j,3)\\
P(i,j,4) &= -R_{L(i,k,2),\mathrm{loop}(i)} + R_{L(i,k,2),\mathrm{loop}(k)} - R_{L(k,j,2),\mathrm{loop}(k)}\\
&\quad + R_{L(k,j,2),\mathrm{loop}(j)} + \delta_{\mathrm{Stab}}(i,j,4)\\
P(i,j,5) &= -R_{L(i,j,1),\mathrm{loop}(i)} + R_{L(i,j,1),\mathrm{loop}(j)} + \delta_{\mathrm{Stab}}(i,j,5)\\
P(i,j,6) &= -R_{L(i,j,2),\mathrm{loop}(i)} + R_{L(i,j,2),\mathrm{loop}(j)} + \delta_{\mathrm{Stab}}(i,j,6)
\end{aligned} \tag{6}$$

and $L(i,j,q)$ is the number of the qth link laboratory between the loops identified by loop(i) and loop(j) ($q \in \{1,2\}$). The index k refers to the loop that is not loop(i) or loop(j). Here, the six possible routes are referred by m. The first four routes pass through another loop (see Fig. 1) and the last two of them go directly to the neighbor loop. The correction δ_{B} is due to possible discrepancies between the results obtained via different routes. Its estimate is zero and the uncertainty is estimated as

$$u(\delta_{\mathrm{B}}) = \frac{1}{2\sqrt{3}}\left[b(i,j,m)_{\max} - b(i,j,m)_{\min}\right] \tag{7}$$

For $m < 5$, all transfer standards contribute to the correction due to the long-term instability of the transfer standards $\delta_{\mathrm{Stab}}(i,j,m)$. As presented in Sect. 2.2, the mean corrections are estimated to zero, and

$$\begin{cases} u(\delta_{\mathrm{stab}}(i,j,m)) = \sqrt{\sum_{k=1}^{3} u^2_{\mathrm{Stab,loop}(k)}} \equiv u_{\mathrm{StabIJK}} & m < 5\\ u(\delta_{\mathrm{stab}}(i,j,m)) = \sqrt{u^2_{\mathrm{Stab,loop}(i)} + u^2_{\mathrm{Stab,loop}(j)}} = u_{\mathrm{Stab}}(i,j,m) & m \geq 5 \end{cases} \tag{8}$$

where $u_{\mathrm{Stab,loop(i)}}$ is the standard uncertainty given in Table 2. When using the function B, the equivalence is weighted by the combined uncertainties of the results of each route. By following well-known principles of uncertainty estimation, we derive an equation for the uncertainty of B:

$$\begin{cases} u^2[B(i,j)] = \left(\sum_{m=1}^{6} \left(u^{-2}[P(i,j,m)] \right) \right)^{-1} + u^2(\delta_B); & \text{loop}(i) \neq \text{loop}(j) \\ u^2[B(i,j)] = u^2_{\text{Stab,loop(i)}}; & \text{loop}(i) = \text{loop}(j) \end{cases}$$

where e.g.:

$$\begin{aligned} u^2[P(i,j,1)] = {} & u^2(R_{L(i,k,1),\text{loop}(i)}) + u^2(R_{L(i,k,1),\text{loop}(k)}) + u^2(R_{L(k,j,1),\text{loop}(k)}) \\ & + u^2(R_{L(k,j,1),\text{loop}(j)}) \\ & + u^2_{\text{StabIJK}} - 2u(R_{L(i,k,1),\text{loop}(i)})u(R_{L(i,k,1),\text{loop}(k)})r_{L(i,k,1)} \\ & - 2u(R_{L(k,j,1),\text{loop}(k)})u(R_{L(k,j,1),\text{loop}(j)})r_{L(k,j,1)} \end{aligned} \tag{9}$$

Here r is the correlation coefficient. The results obtained by the link laboratories in different loops are correlated due to the use of the same reference equipment. The correlation coefficients were estimated on the basis of the uncertainty budgets provided by the link laboratories. From the point of view of the combined uncertainty, the worst case approximation for the coefficient was 0.5. This value was used in calculating the final results.

The uncertainty of the bilateral equivalence is calculated as:

$$u^2(D_{ij}) = u^2(R_{i,\text{loop}(i)}) + u^2(B(i,j)) + u^2(R_{j,\text{loop}(j)}) \tag{10}$$

When applying Eqs. 5–10 to the results of the link laboratories, the following principles are followed:

(1) if the laboratories have participated in the same loop, the results of this loop are used for determining the bilateral equivalence,
(2) when a non-link laboratory is compared with a link laboratory that has not participated in the same loop, the equivalence value is calculated at first for both link laboratory results at two loops. Then, the final equivalence is taken as the mean value of the two equivalence values.

3.4 EURAMET Comparison Reference Values (ERV)

Due to the nature of dew-point temperature scales, the only meaning of a comparison reference value determined by any method is to simplify the interpretation and further use of comparison results. The procedure proposed by Cox [18, 19] was applied to the calculations of the EURAMET Comparison Reference Values (ERV). Because there was no transfer standard measured by all participants or a subset of participants, absolute ERV values were not determined. Only the differences between ERVs and the results of each laboratory were calculated.

The calculations were carried out using the weighted mean of results normalized to the loop of the laboratory under study (x). The normalization was realized using the function B defined by Eq. 6:

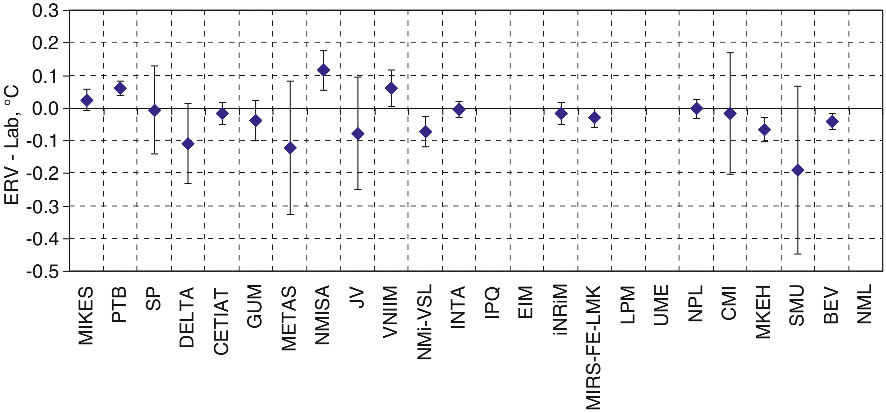

Fig. 2 Difference between the ERV and the result of the laboratories at the nominal frost-point temperature −50 °C. *Error bars* show the expanded uncertainties ($k = 2$) of the difference

$$\begin{aligned}\Delta R_x &= R_{\mathrm{ERV}} - R_x = \frac{\sum_{i=1}^{N} \frac{R_{i'}}{u^2(R_{i'})}}{\sum_{i=1}^{N} u^{-2}(R_{i'})} - R_x \\ &= \frac{\sum_{i=1}^{N} \frac{R_i + B(x,i)}{u^2(R_i)+u^2[B(x,i)]}}{\sum_{i=1}^{N} [u^2(R_i) + u^2[B(x,i)]]^{-1}} - R_x \\ u^2(\Delta R_x) &= \left(\sum_{i=1}^{N} [u^2(R_i) + u^2[B(x,i)]]^{-1}\right)^{-1} + u^2(R_x)\end{aligned} \tag{11}$$

where N is the total number of participants and R_i is the result of the ith laboratory. Because of the normalization, R_{ERV} is not unequivocal but the difference ΔR_x is.

To analyze the quality of the ERV calculation, a chi-squared consistency test [18–20] was carried out and the ERVs were compared with values obtained in terms of the simple mean and median. To avoid a complicated correlation, it was decided to use only the results obtained with the primary standards in the final analysis.

The chi-squared consistency test failed. Therefore, discrepant results were identified with the criterion [18],

$$|R_x - R_{\mathrm{ERV}}| > 2\sqrt{u^2(R_x) - u^2(R_{\mathrm{ERV}})} \tag{12}$$

The analysis was then repeated for the primary laboratory results excluding the discrepant results. All the results passed the second chi-squared consistency test, and ERVs agreed well with the simple mean and median values.

Due to the participation in two loops, the link laboratories form a special case. Their results were combined in the following way:

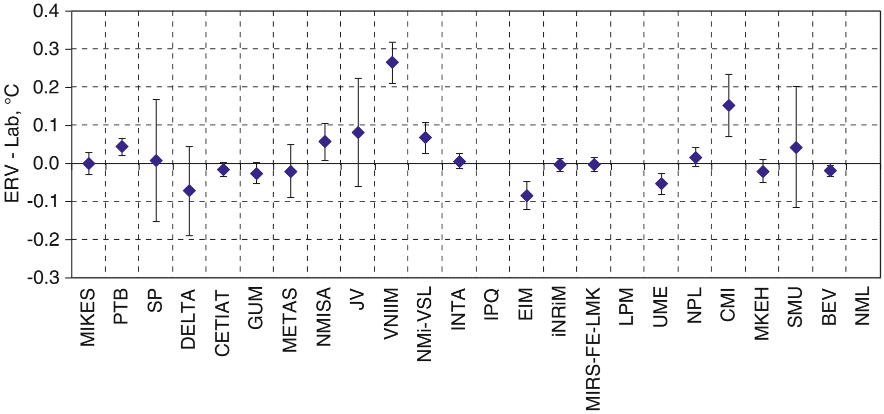

Fig. 3 Difference between the ERV and the result of the laboratories at the nominal frost-point temperature −30 °C. *Error bars* show the expanded uncertainties ($k = 2$) of the difference

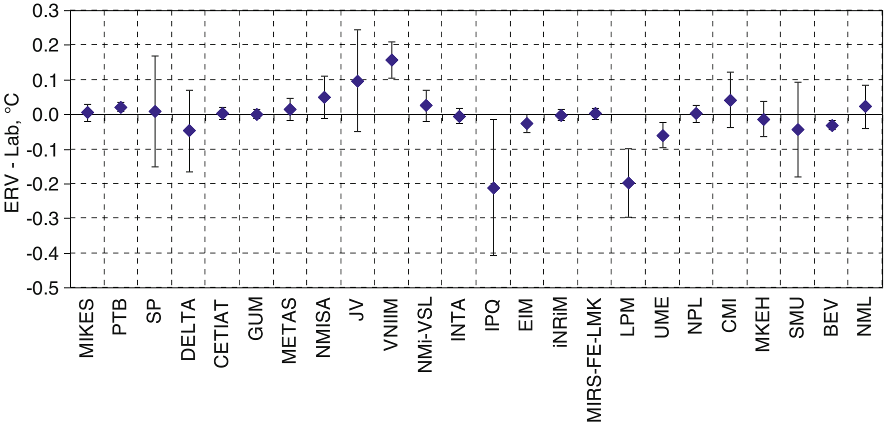

Fig. 4 Difference between the ERV and the result of the laboratories at the nominal frost-point temperature −10 °C. *Error bars* show the expanded uncertainties ($k = 2$) of the difference

$$\Delta R_x = \frac{1}{2}\left[(\Delta R_x)_{\text{LoopA}} + (\Delta R_x)_{\text{LoopB}}\right]$$

$$u^2(\Delta R_x) = \frac{1}{4}\left[u^2(\Delta R_x)_{\text{LoopA}} + u^2(\Delta R_x)_{\text{LoopB}} + u_L^2\right]$$

where

$$u_L^2 = \frac{1}{12}\left[(\Delta R_x)_{\text{LoopA}} - (\Delta R_x)_{\text{LoopB}}\right]^2 \tag{13}$$

Here LoopA and LoopB refer to the loops in which the link laboratory participated.

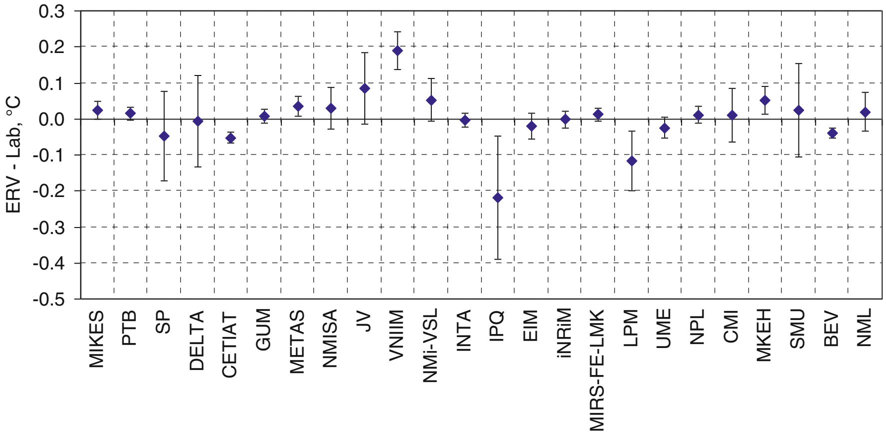

Fig. 5 Difference between the ERV and the result of the laboratories at the nominal frost-point temperature +1 °C. *Error bars* show the expanded uncertainties ($k = 2$) of the difference

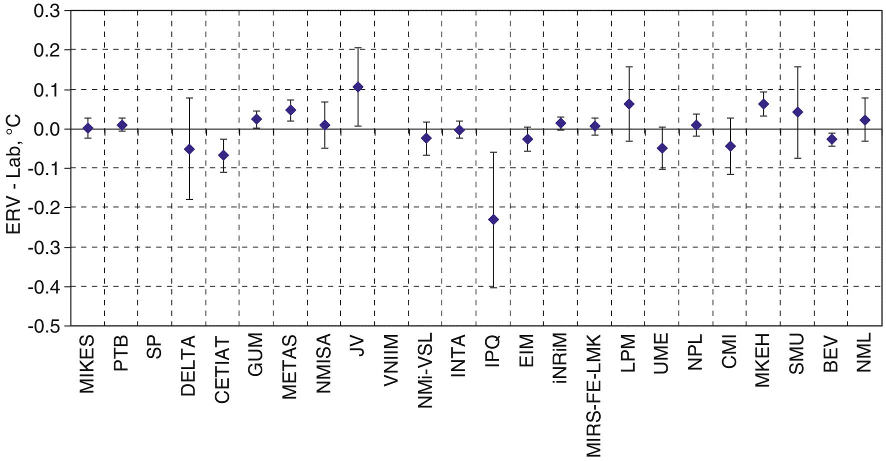

Fig. 6 Difference between the ERV and the result of the laboratories at the nominal frost-point temperature +20 °C. *Error bars* show the expanded uncertainties ($k = 2$) of the difference

4 Results and Discussion

The results of the comparison are summarized in Figs. 2, 3, 4, 5, and 6. The expanded uncertainty of the ERV ($k = 2$) is in the range between 0.005 °C and 0.011 °C except at -50 °C where the maximum uncertainty is 0.018 °C. As shown in Table 4, the minimum expanded uncertainty of the difference ΔR is 0.014 °C. Laboratories SP, EIM, VNIIM, IPQ, UME, LPM, and NML measured only some of the nominal measurement points. Detailed results on the bilateral equivalence between the laboratories can be found in the final report of the comparison [1].

Table 4 Differences between the EURAMET comparison reference values and corresponding results obtained by the participating laboratories (ΔR)

	−50 °C		−30 °C		−10 °C		+1 °C		+20 °C	
Lab.	ΔR	$U(\Delta R)$	ΔR	$U(\Delta R)$	ΔR	$U(\Delta R)$	ΔR	$U(\Delta R)$	ΔR	$U(\Delta R)$
MIKES	0.025	0.032	0.000	0.029	0.005	0.026	0.025	0.025	0.003	0.026
PTB	0.062	0.023	0.044	0.023	0.022	0.014	0.015	0.019	0.011	0.018
SP	−0.006	0.135	0.009	0.161	0.010	0.161	−0.048	0.125		
DELTA	−0.109	0.122	−0.072	0.118	−0.046	0.118	−0.006	0.127	−0.051	0.129
CETIAT	−0.016	0.036	−0.015	0.018	0.004	0.018	−0.052	0.015	−0.068	0.043
GUM	−0.037	0.062	−0.026	0.028	0.001	0.014	0.008	0.021	0.024	0.022
METAS	−0.122	0.205	−0.020	0.070	0.016	0.032	0.034	0.028	0.047	0.028
NMISA	0.116	0.060	0.057	0.050	0.049	0.062	0.031	0.058	0.009	0.059
JV	−0.077	0.172	0.082	0.143	0.098	0.147	0.085	0.099	0.107	0.101
VNIIM	0.062	0.055	0.264	0.054	0.158	0.052	0.190	0.054		
NMi-VSL	−0.071	0.047	0.068	0.041	0.026	0.045	0.053	0.060	−0.025	0.043
INTA	−0.005	0.026	0.007	0.021	−0.004	0.022	−0.004	0.020	−0.002	0.022
IPQ					−0.212	0.197	−0.219	0.172	−0.230	0.172
EIM			−0.084	0.037	−0.025	0.027	−0.020	0.035	−0.026	0.031
iNRiM	−0.017	0.035	−0.003	0.017	−0.002	0.017	−0.002	0.023	0.014	0.018
MIRS-FE-LMK	−0.029	0.029	−0.004	0.019	0.002	0.016	0.012	0.018	0.006	0.022
LPM					−0.197	0.100	−0.117	0.084	0.063	0.094
UME			−0.054	0.029	−0.060	0.037	−0.025	0.030	−0.049	0.053
NPL	−0.002	0.030	0.017	0.025	0.002	0.026	0.011	0.025	0.010	0.028
CMI	−0.016	0.187	0.152	0.082	0.042	0.081	0.010	0.075	−0.043	0.072
MKEH	−0.065	0.037	−0.020	0.030	−0.013	0.052	0.051	0.040	0.064	0.031
SMU	−0.190	0.257	0.043	0.160	−0.043	0.136	0.024	0.130	0.042	0.117
BEV	−0.042	0.025	−0.019	0.015	−0.031	0.014	−0.039	0.015	−0.027	0.017
NML					0.022	0.063	0.020	0.053	0.023	0.054

The expanded uncertainties (U) are given at the approximately 95 % confidence level ($k = 2$)

Table 4 shows that for nine participants, all results deviated from the ERV less than the expanded uncertainties of the deviation ($k = 2$). For 15 participants, the deviation from ERV was at least for one measurement point larger than the expanded uncertainty of the deviation. For three laboratories, the deviation was at all points larger than the expanded uncertainty.

It is worth noting that because of combining results from several measurement sets with two transfer standards, the uncertainties reported in Table 4 are in most cases smaller than the uncertainty stated by the participants for a single calibration result.

Choosing completely new instruments to be used as the transfer standards proved to be a good decision: the quality of the PRTs selected for the instruments was checked in advance, relevant features of the most modern hygrometers were included in the instruments and the instruments were found stable in the long term. However, even with these instruments, several problems appeared during the exercise. More attention should also be paid to the handling of the devices when packing, unpacking, connecting, and disconnecting to the calibration systems. It would be beneficial in future comparisons to arrange a one day training workshop on handling the transfer standards before starting the actual comparison. In particular, this would be useful for those who have less experience with the type of instruments used in the comparison.

5 Conclusion

The comparison method applied in this project was successful. The equivalence between a large number of laboratories was demonstrated at an uncertainty level that is better than achieved in other multilateral comparisons so far [6, 21, 22]. Uncertainty estimations carried out by the participants seem to be realistic in most cases.

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