ATM

Air Temperature Metrology

EURAMET Project 1459

Task 1.

Comparison of thermometers calibrations in air from -80 °C to +60 °C

Interlaboratory comparison protocol

Version 2.3 (Final), May 2019, amended September 2019

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1 Objective

The main objective of this comparison is to identify unwanted influences on air temperature measurements, and to provide a basis for recommendations to laboratories that offer air temperature calibrations, or in some way use air temperature measurements as important auxiliary information during other calibrations.

It is well known that a host of issues affect the heat transfer between a thermometer and air, such as wind speed, sensor irradiation, air pressure and humidity. A previous EURAMET comparison, P1061, concluded that radiation shielding might alleviate errors due to purely radiative heat loads, but exacerbate errors related to conductive and convective heat transfer (1). However, recent work by de Podesta *et al* (2) suggests a more insidious connection between the heat transfer properties at the sensor interface, by pointing to an interplay between sensor dimension, wind speed and irradiation. Controlled experiments showed that the magnitude of the discrepancy between thermometer reading and actual air temperature can be of concern even in highly controlled laboratories.

This comparison aims to gain further insight into the ways air temperature measurements can be affected by collecting measurements from a number of laboratories employing different techniques to assess air temperature. The data will be used to compute the degree of equivalence (DoE) for the participants using a consensus based reference value, but also to analyse reasons for disparities between laboratories. In addition to the common set of reported results which all participants will be required to supply, some participants will conduct additional measurements that will be taken into account in the analysis.

While the primary aim of the ILC is to conduct research it is still vital that participants do not share results during the measurements. Once all the data have been collected the pilots and the coordinator will analyse the data and prepare a report, and from that point the data will be open to all participants.

2 Equipment

2.1 Circulating instruments

The circulating instruments are PT 100 thermometers. At the start of the ILC six different models are available, each with three units (one for each loop). The models are sourced from different manufacturers and represent diverse applications. The specifics are listed in Table 1, which also includes the geometric dimensions of the sensing element. Most of the sensors can be placed in a TPW cell.

The thermometers are shipped between partners using the service of choice for each laboratory. The participants cover the costs for onward shipping. Although the sensors are robust they should be handled with care, with appropriate protective packaging during shipping between laboratories.

Table 1 List of the circulating thermometers .

Manufacturer/Type	Type Serial numbers/ID	Probe dimensions/ mm		Body dimensions / mm		Fits TPW?
		Length	Diameter	Length	Diameter	
VAISALA/ TMP1	P5150501 P5150502 P5150503	130	6	136	25	Y
Calpower/ NS	NS02 NS04 NS08	130	3	80	6	Y
WIKA/ TR60 Special	WK1 WK2 WK3	44	7.76	62	19.70	N
WIKA/ Model CTP5000-170B	W3450254/CNZF-101 W3450254/CNZF-102 W3450254/CNZF-103	350	6	350	6	Y
PHYSICUS/ PT100/10	702/18 703/18	117	5		10	Y
BEV E+E/PT100	B-1 B-2 B-3	230	6			Y
BEV E+E/PT100 Coated	I-4 I-5 I-6	230	6			Y
MBW	1066 1064 1065					Y

3 Participants and topology

The ILC has three loops with one linking laboratory. JV is the coordinator and linking laboratory. Figure 1 shows an overview of the topology.

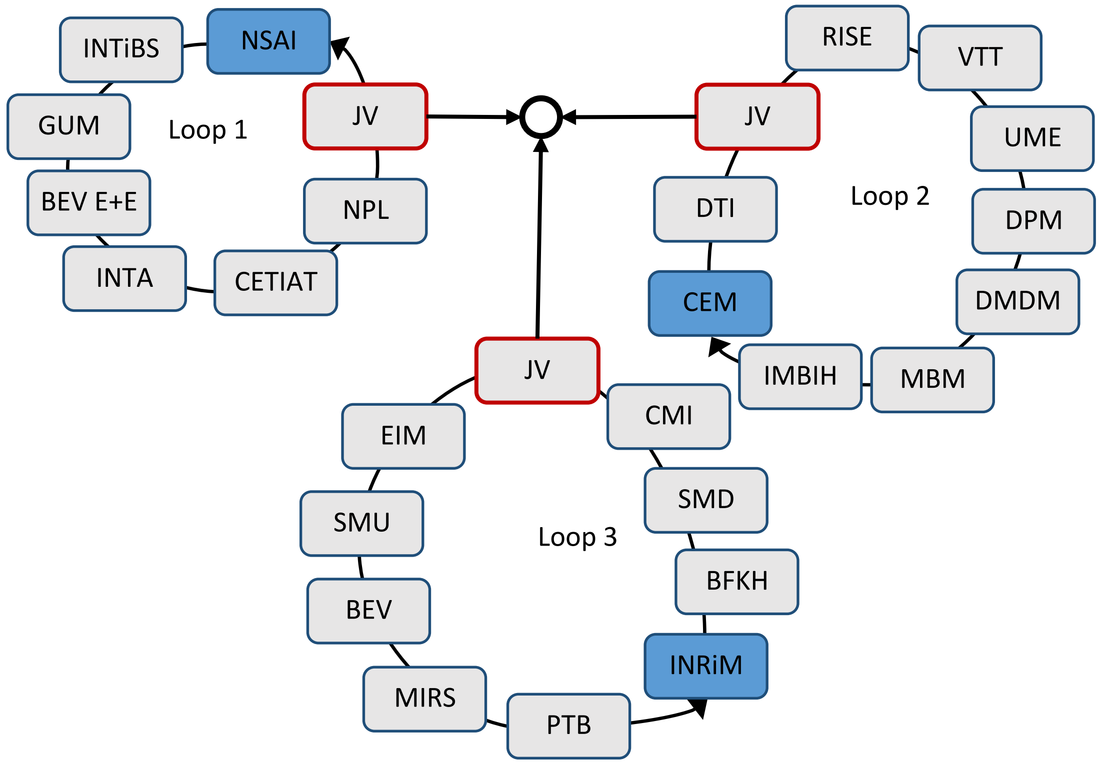

Figure 1 The topology of the comparison. The blue boxes indicate loop pilots. JV provides linkage between the loops. L1 measures down to -80 °C while L2 and L3 measures down to -40 °C. The upper limit in all loops is +60 °C.

3.1 Loop 1

The participants in loop 1 are listed below. The temperature range is -80 °C to 60 °C. JV only measures down to -40 °C, but participates to provide linkage with the other two loops.

NSAI	Pilot
NPL	
LNE CETIAT	
INTA	
GUM	
INTiBS	
BEV E+E	
JV	Link

Loop 1 uses the following thermometers:

Model	*Serial no*
Vaisala TMP1	P5150501
Calpower NS	NS02
Wika TR60 Special	WK1
Wika CTP5000-170B	W3450254/CNZF-101
PHYSICUS PT100/10	702/18
BEV E+E probe	B-1
BEV E+E probe high reflectivity	I-4
MBW probe	1066

3.2 Loop 2

The participants in loop 2 are listed below. The measurement range is -40 °C to 60 °C.

CEM	Pilot
DTI	
RISE	
VTT	
UME	
DMDM	
MBM	
DPM	
IMBiH	
JV	Link

Loop 2 uses the following thermometers:

Model	*Serial no*
Vaisala TMP1	P5150502
Calpower NS	NS04
Wika TR60 Special	WK2
Wika CTP5000-170B	W3450254/CNZF-102
PHYSICUS PT100/10	703/18
BEV E+E probe	B-3
BEV E+E probe high reflectivity	I-5
MBW probe	1064

3.3 Loop 3

The participants in loop 3 are listed below. The measurement range is -40 °C to 60 °C.

INRiM	Pilot
BFKH	
SMD	
PTB	
CMI	
SMU	
MIRS	
BEV	
EIM	
JV	Link

Loop 3 uses the following thermometers:

Model	*Serial no*
Vaisala TMP1	P5150503
Calpower NS	NS08
Wika TR60 Special	WK3
Wika CTP5000-170B	W3450254/CNZF-103
BEV E+E probe	B-5
BEV E+E probe high reflectivity	I-6
MBW probe	1065

4 Schedule

4.1 Overall schedule

The schedule assumes on average 1 week for transportation between laboratories and 4 weeks for measurements. Pilots have another week to complete the measurements to account for measurements in liquid baths.

Protocol final	April 2019
Measurements start	May 2019
Measurements end	Aug 2020
Data analysis	Nov 2020
Draft report	Jan 2021
Final report	Apr 2021

4.2 Detailed schedule in loop 1

	PLANNED START	PLANNED END	REMARKS
NSAI	01 May 2019	05 Jun 2019	
INTIBS	17 Jun 2019	15 Jul 2019	
GUM	10 Sep 2019	08 Oct 2019	
BEV E+E	15 Oct 2019	12 Nov 2019	
INTA	19 Nov 2019	17 Dec 2019	
LNE CETIAT	31 Dec 2019	28 Jan 2020	
NPL	04 Feb 2020	03 Mar 2020	
JV	10 Mar 2020	07 Apr 2020	*Temporary export*
NSAI	21 Apr 2020	26 May 2020	

4.3 Detailed schedule in loop 2

	PLANNED START	PLANNED END	REMARKS
CEM	01 May 2019	05 Jun 2019	
DTI	14 Jul 2019	11 Aug 2019	
JV	18 Aug 2019	15 Sep 2019	*Temporary export*
RISE	22 Sep 2019	20 Oct 2019	
VTT	27 Oct 2019	24 Nov 2019	
UME	01 Dec 2019	29 Dec 2019	*Temporary export*
DPM	12 Jan 2020	09 Feb 2020	*Temporary export*
DMDM	16 Feb 2020	15 Mar 2020	*Temporary export*
MBM	22 Mar 2020	19 Apr 2020	*Temporary export*
IMBIH	03 May 2020	07 Jun 2020	*Temporary export*
CEM	14 Jun 2020	19 Jul 2020	

4.4 Detailed schedule in loop 3

	PLANNED START	PLANNED END	REMARKS
INRIM	01 May 2019	24 Jun 2019	
BFKH	01 Jul 2019	29 Jul 2019	
SMD	05 Aug 2019	02 Sep 2019	
CMI	16 Sep 2019	14 Oct 2019	
JV	21 Oct 2019	18 Nov 2019	*Temporary export*
EIM	25 Nov 2019	23 Dec 2019	
SMU	30 Dec 2019	27 Jan 2020	
BEV	03 Feb 2020	02 Mar 2020	
MIRS	09 Mar 2020	06 Apr 2020	
PTB	20 Apr 2020	18 May 2020	
INRIM	25 May 2020	22 Jun 2020	

4.5 Progress and updates to the schedule

If for any reason a participant is unable to comply with the planned schedule the coordinator will update the schedule for the loop in question, and inform the participants in the loop. The updated schedule will be communicated via email, and included in the ILC report.

5 General instructions

5.1 Handling and financial responsibilities

The circulating probes should be handled with care by all participants. Packaging the sensors for shipping should ensure they are adequately protected. Participants cover the cost of onward shipping (except for non-EU countries, see below).

In case a sensor is broken or lost the participants will share the cost of a replacement. The replacement sensor will be measured at the pilot to be able to link measurements using the broken sensor and the replacement sensor. The coordinator and loop pilots will evaluate if it is also necessary to measure the replacement probe at JV.

For shipment to JV (Norway), DMDM (Serbia), IMBiH (Bosnia-Herzegovina), MBM (Montenegro), DPM (Albania) and UME (Turkey) it is necessary to add customs clearance documents. The participant which forwards the thermometers to one of the 5 relevant countries should include temporary export documents. After measurements the items will be returned. The forwarding participant should then relabel the package and send it on to the next participant in the list.

Additional information for loop 1: some of the sensors may experience issues with the electrical isolation around the leads at low temperatures. In particular, the sensors from BEV E+E have an outer silicone layer which may become brittle at the lowest temperatures. The sensors should be mounted and the cables anchored at room temperature, and then left untouched at the lowest temperatures.

5.2 Participant responsibility

(1) Participants shall realise the measurement temperatures within ±0,5 °C of the nominal temperature.
(2) Participants shall use the provided uncertainty table template. Additional components may be added. Unused components shall be assigned the value 0.
(3) To verify sensor function immediately upon reception using a recording in a TPW cell, and report the value to the loop pilot and coordinator. The WIKA/ TR60 Special sensors cannot be used in TPW cells. An ice bath or similar should be used in this case (in other words, the check is performed at 0 °C).
(4) To carry out measurements according to the schedule. This entails all necessary preparations including verification of the equipment to be used, in ample time before the scheduled arrival of the circulating instruments.
(5) To report the results to the coordinator and the pilot using the templates. The reporting must be complete within 2 weeks after the probes have been sent to the next participant.
(6) To verify the reference equipment and report to the coordinator 2 weeks *before* the scheduled completion for the previous participant.
(7) To cover the cost of *onward* shipping of the circulating instruments.

5.3 Pilot responsibility

In addition to the general participant responsibility, the pilots shall

(1) perform a preliminary analysis of the data in their loop.
(2) collaborate with the coordinator in the data analysis
(3) assist the coordinator in report writing
(4) characterise the response of the thermometers in liquid baths to obtain the response curve for each sensor.
(5) Characterise the self-heating of the sensors at each measurement point in both air and liquid.
(6) To measure the self-heating in TPW cells for all probes which fit inside cells:
    a. Vaisala TMP1
    b. Calpower NS
    c. Wika CTP5000-170B
    d. PHYSICUS PT100/10
    e. Both BEV E+E probes
    f. The MBW probes

5.4 Coordinator responsibility

(1) To oversee the progress of the comparison and, if necessary revise the schedule. Any such revision will be done in agreement with the participants involved.
(2) To inform the participants of delays that will impact their anticipated starting date of measurements.
(3) To analyse the data received in collaboration with the pilots.
(4) To prepare the report of the comparison in collaboration with the pilots.

5.5 Unforeseen issues

In case any unanticipated issues arise which may affect the final results, the pilots and the coordinator will discuss necessary actions to ensure that the objectives of the ILC can be reached.

6 Measurements

6.1 Common measurements

All participants measure the resistance of all 3 circulating thermometers in air at nominal temperatures -40 °C, -20 °C, 0 °C, 20 °C, 40 °C and 60 °C.

In loop 1 additional measurements are carried out at -80 °C and -60 °C.

The measurements shall be carried out in order of increasing temperature.

All participants measure the resistance in a the triple point of water cell or at 0 °C (the ice point or an appropriate liquid bath) when the instruments are received, and just before sending the probes to the next participant.

6.2 Liquid bath measurements

The pilots measure the resistance of the probes in liquid baths in order to obtain the response curve for each sensor. It is assumed that the thermal contact with the liquid is significantly better than in air, and that the response curve obtained in this way describes the intrinsic behaviour of the sensors. The response curve measurements are recorded at -40 °C, -20 °C, 0 °C, 20 °C, 40 °C and 60 °C in loops 2 and 3. In loop 1 two further points are recorded at -60 °C and -80 °C.

6.3 Self heating evaluation

The pilots also reports self-heating measurements in air and liquid baths. Recordings are taken at a minimum of two probe currents, tentatively at 1 mA and 1.4 mA, and the results reported to the coordinator. The actual probe currents should be reported.

The other participants may also measure self-heating at any selected probe current and report the result using the Excel reporting template.

6.4 Auxiliary measurements

Participants with capabilities also measure sensor behaviour with respect to

- relative humidity
- irradiation
- wind speed
- pressure

7 Reporting

Participants report their results to their pilot and JV using the supplied reporting templates.

The reporting consists of five main classes of information:

(1) The reference temperatures realised by each participant, and associated uncertainty (including coverage factor).
(2) The measured resistance in the circulating sensors, the measurement current and reading mode employed, and associated uncertainty (including coverage factor).
(3) The equipment used. This includes details on the reference temperature sensor, sensors for auxiliary measurements, and the climate chamber used. Include as much detail as possible on the air chamber, such as dimensions, sources of heat or light, stability, and uniformity. The reporting template does not give much guidance on the chamber reporting apart from geometry, but participants should include as much detail as possible (using e.g. photos or short reports).
(4) The uncertainty budgets for the reference temperature measurements and the resistance measurements.
(5) Optional measurements depending on the capabilities of the participant: environmental parameters such as wind speed, irradiation, and relative humidity, or systematic investigations of the probe sensitivities.

Excel reporting templates will be distributed by the pilot. Pay close attention to instructions in the template file.

Participants cannot share data during the comparison.

8 Data analysis

The data sets comprise 3 loops, 21 different sensors and a number of different temperatures. To avoid clutter in notation there is no attempt to create unique variable symbols for each case. Instead it should be understood that all computations are repeated for each sensor, each temperature and in each loop.

The first set of results only cover separate loops. The linkage between loops is computed via JVs values, and provides a second set of results.

8.1 Notation

To avoid clutter in the notation there is no distinction between measurements at different points and from different participants. It is implied, however, that all calculations are performed for each reported point separately.

The table below summarises the symbols used in the following.

Symbol	Explanation
u	Standard uncertainty, typically with subscript as identifier.
U	Expanded uncertainty (95% coverage).
$R_C(T)$	Reference resistance curve for a thermometer.
r	Reported resistance values
τ	Reported realised temperatures.
$C_R(N)$	The resistance correction at a temperature N. Computed.
N	Nominal temperature

8.2 Response curve

The 6 measurement points (8 in loop 1) from liquid bath measurements is used to generate a response curve. The response curve is the fitted second-order polynomial

$$R_C(T) = \sum_{n=0}^{2} a_n T^n \qquad (1)$$

The in-use uncertainty of the response curve is given by the uncertainty of the fitting points. The residuals will be inspected for consistency, but they will not be used to compute the in-use uncertainty. The response curve uncertainty is correlated for participants within the same loop, but uncorrelated for participants in different loops.

8.3 Resistance correction

The table of realised temperature τ and associated electrical resistance r is converted to a correction at the nominal temperature N with the aid of the response curve. Firstly, a corrected electrical resistance r_N is computed for each reported (τ, r) duplet:

$$r_N = r + R_C(N) - R_C(\tau) \qquad (2)$$

The corrections used to compare the participants is then the difference between the response curve resistance at N and the corrected reported values:

$$C_R = R_C(N) - r_N = R_C(\tau) - r \qquad (3)$$

The response curve may also be used to convert C_R to a temperature correction using

$$C_T = C_R \left(\frac{\partial R_C}{\partial T}\right)^{-1} \qquad (4)$$

8.4 Calculating uncertainty in temperature

Participants report their uncertainty in resistance of the DUTs and realised temperature separately. When it is necessary to convert between electrical resistance and temperature the sensitivity of the response curves established by the pilots is used. The equations below express uncertainty in temperature.

The uncertainty, u_C, associated with the resistance correction for each reported value is obtained in the usual way. The measurement function is Equation (3), which leads to

$$u_C^2 = u_r^2 + \left.\frac{\partial R_C}{\partial T}\right|_{T=\tau}^2 u_\tau^2 + u_{RC}^2$$

Here u_τ is the uncertainty in the realised temperature, u_r is the uncertainty in the DUT resistance, and u_{RC} is the in-use uncertainty of the response curve polynominal.

8.5 Drift

Drift in the probes is assessed in 3 ways:

(1) All participants measure the probes at the triple point of water upon reception of the probes and prior to sending them to the next participant.
(2) The pilots measure the probes in liquid baths before and after the circulation
(3) The pilots measure the probes in air before and after the circulation.

Drift is a further contribution to the uncertainty of the reference value. The value is determined from the measurements at the pilots. It is modelled as a uniform distribution, $C_\delta \sim U(-\Delta, \Delta)$, where Δ is the difference between the two measurements at the pilot. The mean is 0 and the uncertainty u_δ is:

$$u_\delta = \frac{\Delta}{\sqrt{3}}$$

8.6 Reference value

We compute a consensus value C_r for each sensor and nominal temperature, from the weighted mean of observations. Any correlations between the participants is also taken into account. The computation is performed using

$$C_r = \mathbf{C}\mathbf{V}^{-1}\mathbf{C}^T$$

The covariance matrix $\mathbf{V}$ has variances from each laboratory in the diagonal elements. Correlations between laboratories are quantified by the off-diagonal terms. The correction vector $\mathbf{C}$ is a row vector of the corrections from Equation (3).

8.7 Linking loops

The measurements at JV provide the linkage between loops.

The uncertainty in the reference value at JV is correlated between the loops, apart from the type A contributions. The in-use uncertainty of the response curve is fully correlated for laboratories within the same loop, but completely uncorrelated between loops. When the data are analysed the impact of such correlations will be evaluated, and if needed taken into account.

Data from different sensors may also be pooled if it is appropriate and improves the precision of the reference value. Pooling will also be evaluated in the analysis stage.

9 References

1. **Heinonen, M, et al.** *Comparison of air temperature calibrations.* Espoo : Mikes, 2015. EURAMET project P1061.

2. **de Podesta, Michael, Bell, Stephanie og Underwood, Robin.** Air temperature sensors: dependence of radiative errors on sensor diameter in precision metrology and meteorology. *Metrologia.* 2018, Vol. 55, s. 229.

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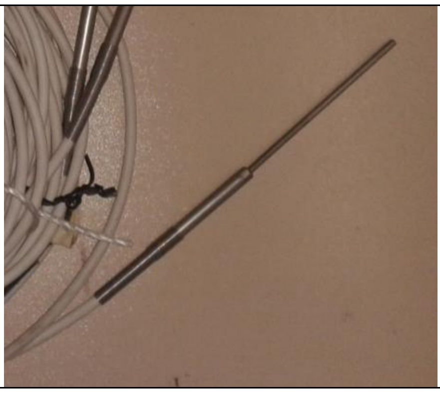
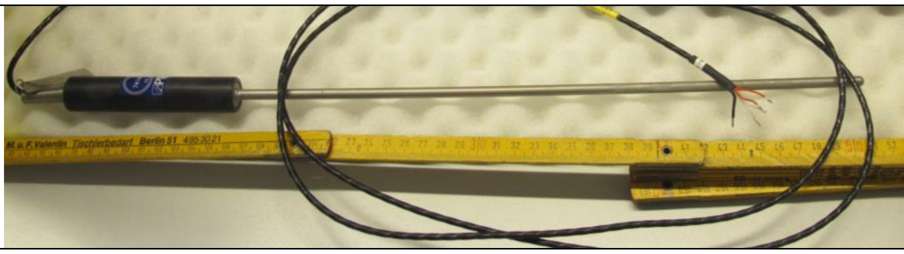
B Photos of the probes

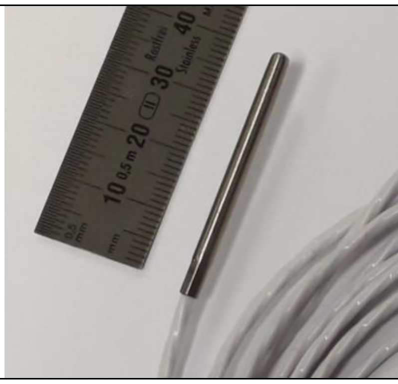


Calpower NS

BEV E+E

PHYSICUS/ PT100/10


Vaisala

WIKA CTP5000

WIKA/ TR60 Special (boxes are removed)

MBW probes

C Changelog

June 2019	Physicus probe removed from loop 3 after measurements at pilot. Added sentence to enforce order (low to high temperature). Corrected labelling for BEV probe.
September 2019	Added new participant, DPM/Albania, to loop 2. • Topology figure updated • Participant table updated (section 3.2) • Schedule updated (section 4.3) • Overall schedule updated (section 4.1) • Participant details added in Appendix A.