Guide for temperature calibration of reference sensors for MEMS and automated testing equipment

Activity A4.3.3 of Work Package 4

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metrology for the factory of the future
Digital Calibration Confidence Data quality

EMPIR EURAMET
The EMPIR initiative is co-funded by the European Union's Horizon 2020 research and innovation programme and the EMPIR Participating States

1. Work package	2. Activity number	3. Reporting date
WP4	4.3.3	31/12/2020

4. Title of activity:
Guide for temperature calibration of reference sensors for MEMS and automated testing equipment

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8. Supplementary notes

Summary

1 Introduction

Traceability for practical MEMS calibration services is currently lacking at the level of both NMIs and accredited calibration services. This is a consequence of the lack of adequate technical set-ups and procedures as well as normative standards.

The current challenge for in situ MEMS calibration is the establishment of a robust traceability route to SI units whilst maintaining the overall efficiency of automated testing equipment (ATE).

This best-practice guide addresses a possible solution to bring the measurement traceability to MEMS and, more generally, to digital temperature sensors tested in ATE. It also proposes a traceable calibration framework able to provide robust measurement traceability to MEMS sensors tested/calibrated in ATE systems.

MEMS and IC temperature sensors with digital output differ from model to model. Even two models manufactured by the same manufacturer can differ by size, form factor, case geometry, pinout or further parameters. This mean that is not possible to calibrate/test these devices with the same “tool”; on the contrary, a set of custom tools for each model need to be designed.

This best-practice guide describes a new temperature calibration facility setup at INRIM to address the above issue. It is based on the calibration by comparison method in steady-state conditions and exploits a calibration tool which acts as a temperature equalizer block and comparison medium to compare the MEMS readings against one or more platinum resistance thermometers (PRTs) traceable to ITS-90 used as the reference.

The document aim is to provide a guidance to metrology-laboratory technicians in performing calibrations of MEMS or semiconductor IC temperature sensors with digital output, providing an overall description of the tasks with details about the selected MEMS temperature calibration procedure. The concepts described in this guide may need to be further adapted if different sensors or calibration equipment are used.

The guide can be better understood in combination with the report A1.4.4 [1] and the calibration training webinar material [2].

2 Traceability chain

This document is addressed to ATE which are developed by SPEA, however its scope and methods are general in order to be addressed to ATEs which rely on the same working principle built by other manufacturers.

An ATE for thermal testing is a system which embed a number of “on-board” sensors to measure the reference conditions and to control the thermal stimulus which is generated for testing of devices and sensors. Such on-board sensors are generally MEMS or IC sensors with a digital output.

The ATE measurement and control sensors were named “ATE reference sensors”, while the units under test were named “ATE UUTs”.

The calibration service offered by laboratory accredited under the ISO EN 17025 is generally limited to the calibration of such “ATE reference sensors.” The overall goal of this project is to further extend this concept and to provide measurements traceability to the ATE UUTs - by developing and validating suitable measurement procedures - and ultimately to the end-users of the above MEMS or IC sensors.

The measurements traceability chain developed for MEMS sensors for ATEs thermal testing and calibration is depicted in Figure 1.

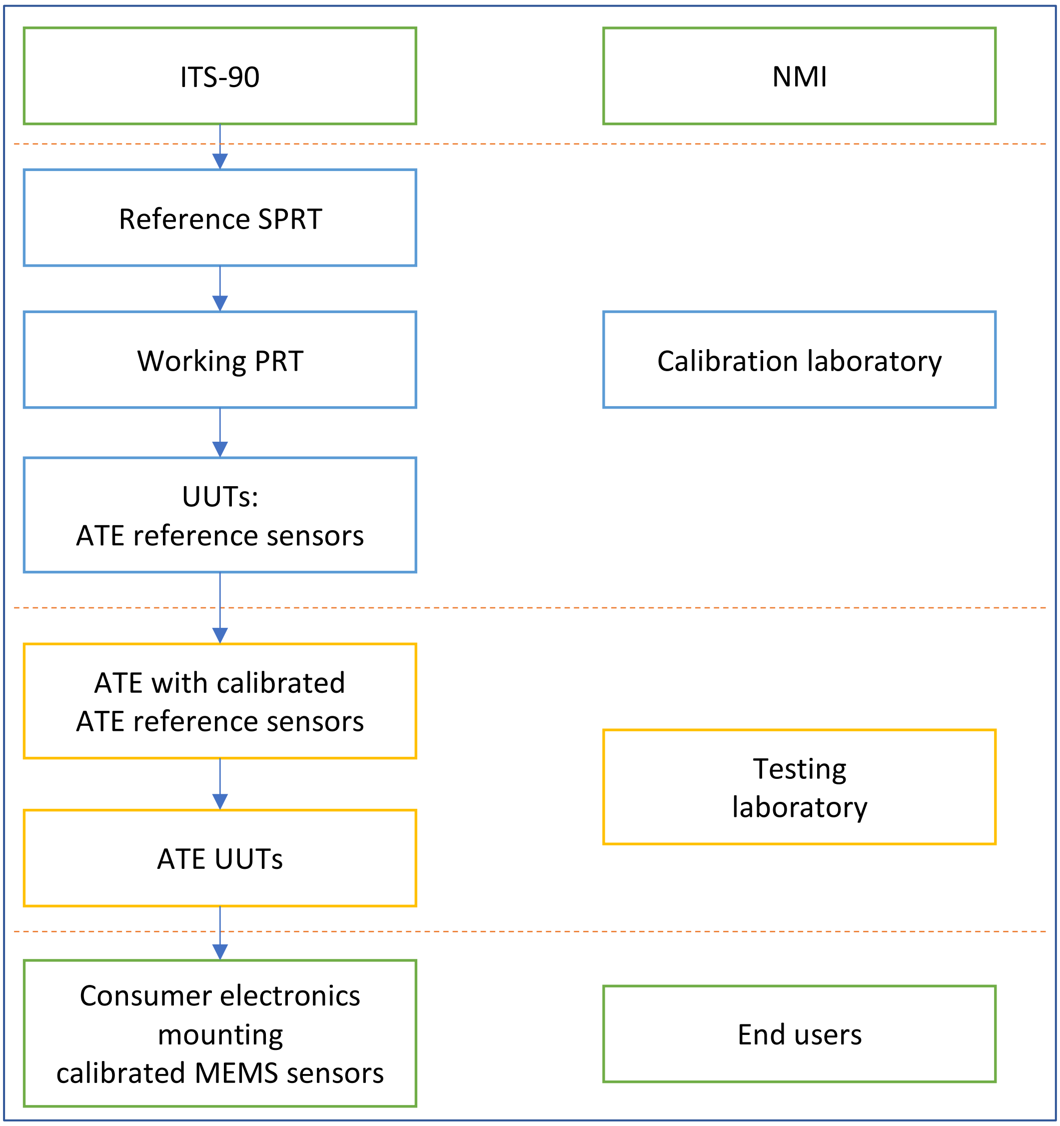


Figure 1. Metrological traceability implemented in ATEs for thermal testing and calibration.

Figure 1 shows how the proposed method will insure that a sensor mounted into an electronic device - available to a generic user -can perform traceable measurements.

This guide will discuss all the steps necessary for assuring that the metrological traceability provided by a calibration service of a NMI can be successfully implemented to calibrated the ATE reference sensors which actually are the UUTs of a calibration laboratory.

Please note that the subsequent steps which concern how a testing laboratory will assures the metrological traceability to the UUTs tested/calibrated by an ATE are not discussed in this guide.

3 Description of the facility developed at INRIM for ATE reference sensors calibration.

The reference system setup arranged at INRIM for the calibration of the ATE reference sensors consists of the following components:

A. One or more reference thermometers (PRT)
B. A digital multimeter (DMM), a resistance bridge or a digital acquisition system (DAQ)
C. A comparison medium
D. A calibration tool to host the specific UUT model under calibration (and used as a liquid-tight capsule and thermal equalizer).

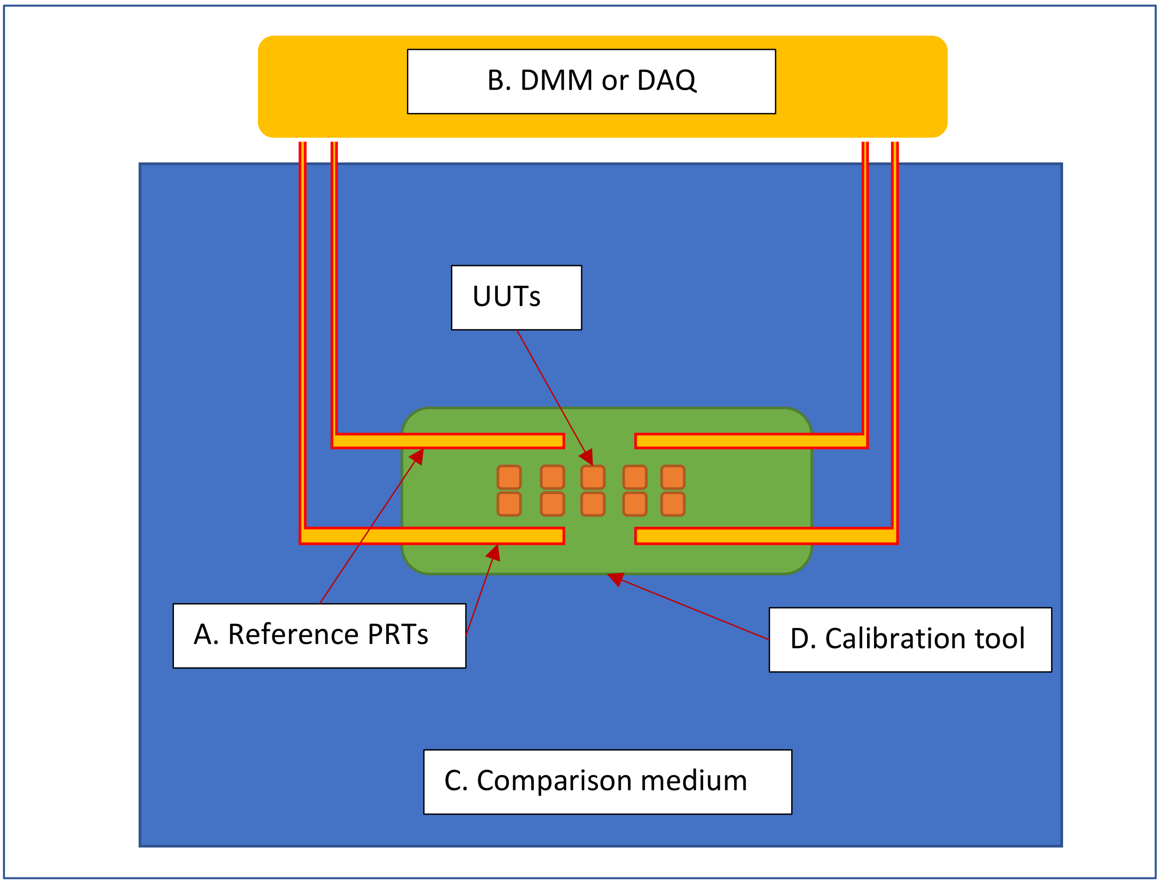


Figure 2. Setup of the calibration facility.

The reference thermometers (PRTs) are used to determine the calibration reference temperature when the comparison medium reached the thermal equilibrium.
During the calibration, additional PRTs can be used to estimate the temperature homogeneity either during a calibration run or prior the calibration. For that purpose, the calibration tool was designed to accommodate several PRTs for such a temperature characterization.

Either a digital multimeter (DMM), a resistance bridge or a digital acquisition system (DAQ) are used as the readout and data logging system of the PRTs.

The comparison medium is intended in its preferred solution as a thermostatic bath but even a thermostatic chamber can play the same role. This component is used to generate a stable temperature condition for the UUTs and the reference PRTs during a calibration run.

For each UUT model to be tested in a ATE , a suitable ATE thermal conditioning system have to be developed in order to generate the temperature stimulus during the tests. This is the so-called “thermal chuck”. As a result, for each ATE thermal chuck design, a custom calibration tool need to be designed and manufactured.

In the course of the project, INRIM and SPEA developed two different hardware setups as the “calibration tool.” They can host several ATE reference sensors inside a liquid-tight “sensor capsule” which can be either immersed in a thermostatic bath or put in thermostatic chamber during a calibration run.

Figure 3 shows the sensor capsule concept which was used for laboratory calibration of ATE reference sensors, while Figures from 4 to 6 provide more details about the design and construction of both calibration tool #1 and #2.

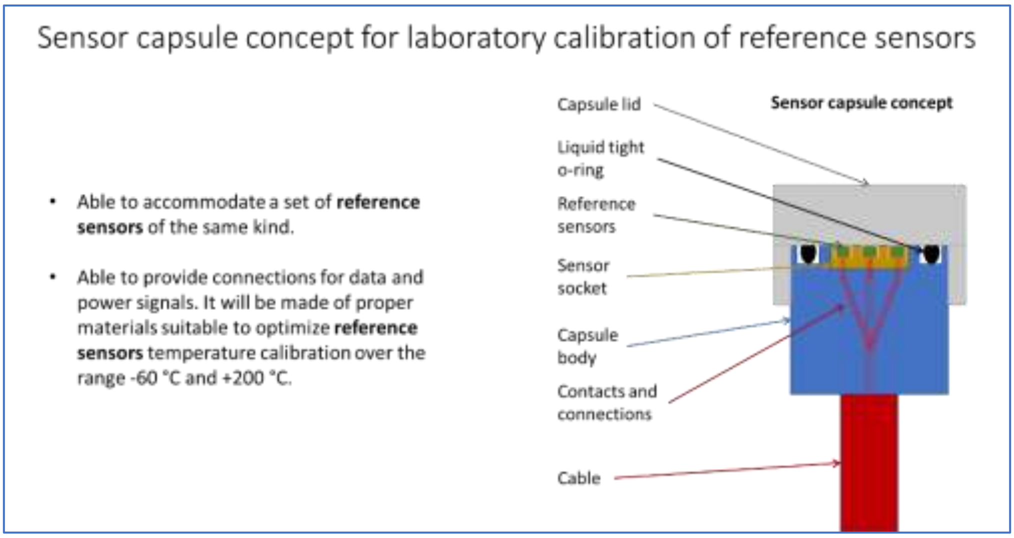


Figure 3. Sensor capsule concept.

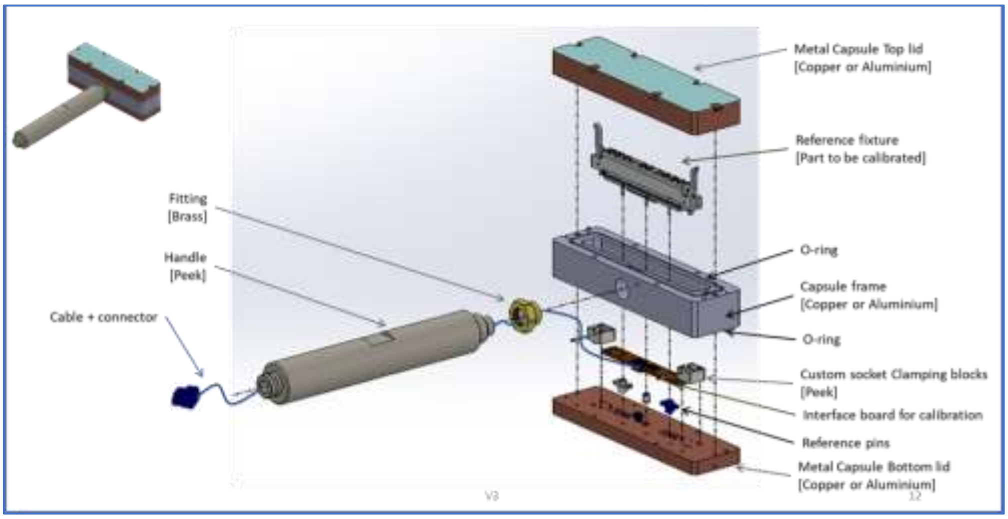


Figure 4. The calibration tool #1 hosts a single strip of ATE reference sensors for calibration.

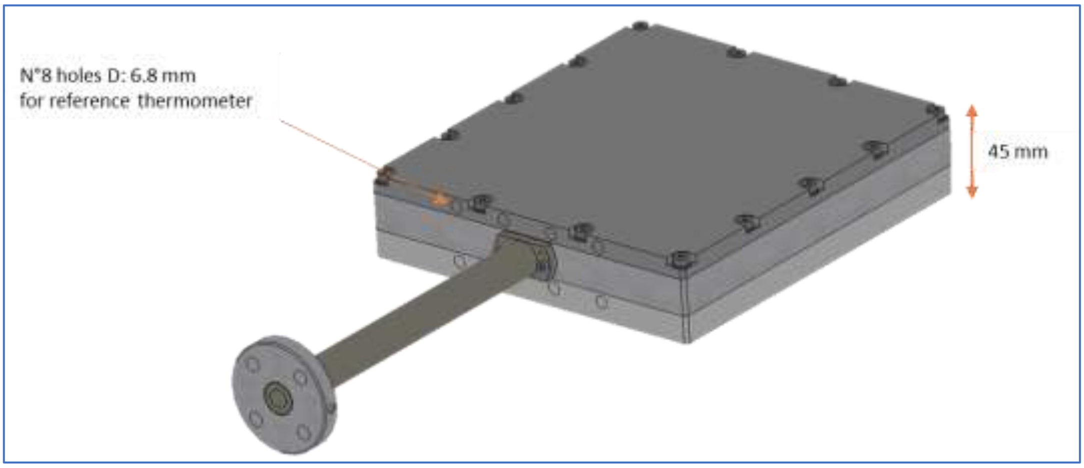


Figure 5. The calibration tool #2 hosts an array of ATE reference sensors for calibration.

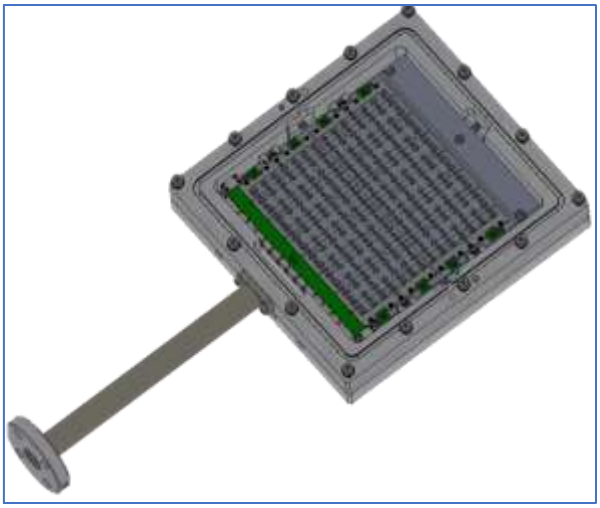


Figure 6. Calibration tool #2 for ATE reference sensors calibration – inner view

The calibration setup also include an interface board which connect the UUTs to be calibrated with a computer. The interface board is sensor-specific; it is developed for each calibration tool and affords the power signals and a data bus. A software programme running on a PC acquires the sensor data. Figure 7 shoes the connection scheme.

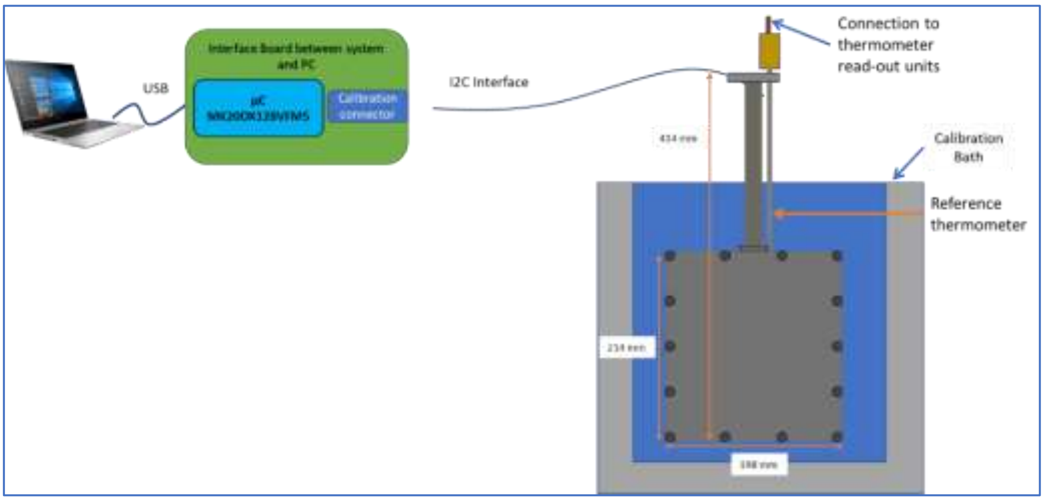


Figure 7. Calibration tool #2. Connection scheme.

Pictures of the calibration tool hardware construction are shown in Figures 8 and 9, while the whole calibration setup is showed in Figure 10.

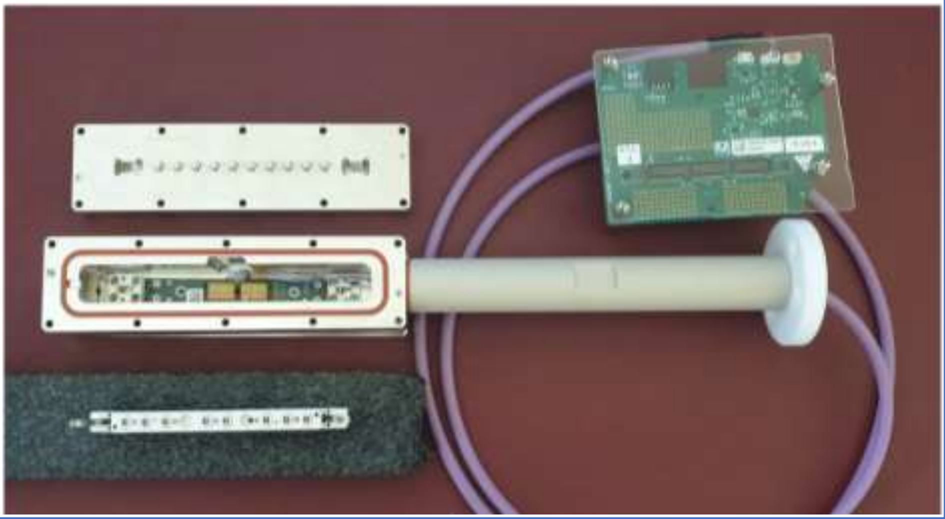
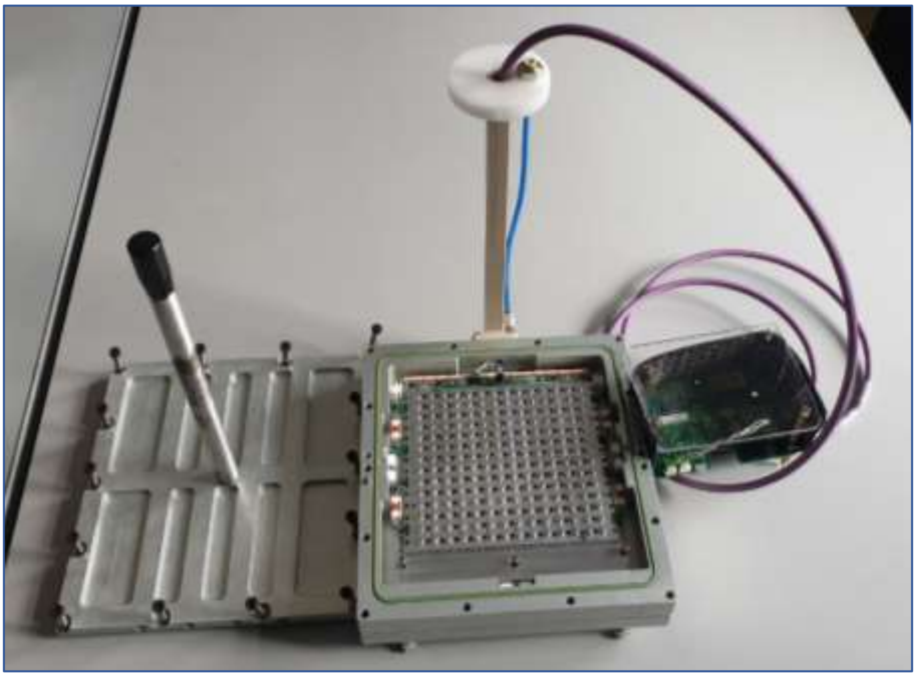


Figure 8. Calibration tool #1 hardware construction.



Picture 9. Calibration tool #2 hardware construction

Both calibration tools entails a gas channel where a dry gas is made to flow (at approximately 0.15 L/min) to avoid any risk of water condensation when the calibration temperatures are lower than the ambient dew-point temperature.

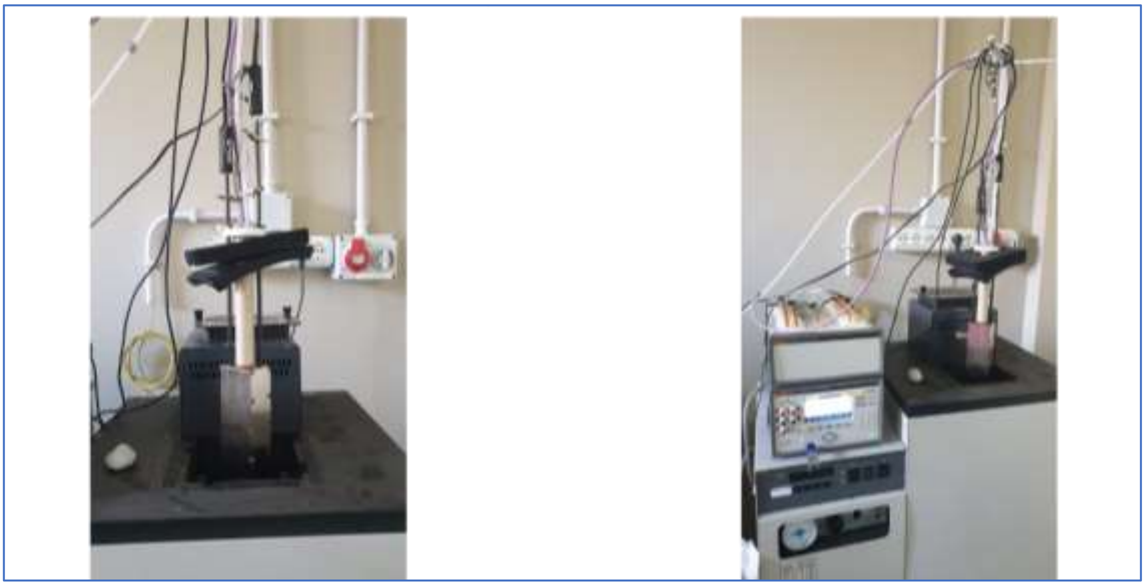


Figure 10. Calibration setup for the calibration tool #1.

4 Uncertainty evaluation.

The model equation describes the calibration in terms of the difference (error) between the mean temperature measured by the UUT and the reference temperature.

$$E = T_{UUT} - T_{REF} \quad (1)$$

The corresponding variance $u_E{}^2$according to the uncertainty propagation law [3] is estimated as:

$$u_E{}^2 = \left(\frac{\partial E}{\partial T_{UUT}} \quad u_{T_{UUT}}\right)^2 - \left(\frac{\partial E}{\partial T_{REF}} \quad u_{T_{REF}}\right)^2 \quad (2)$$

T_{UUT} and T_{REF} are defined as follow:

$$T_{UUT} = \overline{T_{UUT}} + \delta_{UUT_{RES}} + \delta_{UUT_{REP}} \ (3)$$

Where the following are the meaning of each contribution:

$\overline{T_{UUT}}$ = is the mean temperature of at least 10 minute and/or 20 readings of the UUT. Often with negligible uncertainty.
$\delta_{UUT_{RES}}$ = is a zero mean value term with uncertainty which takes into account the resolution of the UUT.
$\delta_{UUT_{REP}}$ = is a zero mean value term with uncertainty which takes into account the repeatability (stability on short term) of the UUT.

$$T_{REF} = \overline{T_{REF}} + \delta_{REF_{REP}} + \delta_{REF_{CAL}} + \delta_{REF_{DRIFT}} + \delta_{REF_{FIT}} + \delta_{DAQ_{RES}} + \delta_{DAQ_{ACC}} + \delta_{DAQ_{STABILITY}} + \delta_{CAL\_TOOL_{HOMOG}} \quad (4)$$

With:

$\overline{T_{REF}}$ = is the mean temperature of at least 10 minute and/or 20 readings of the reference temperature. Often with negligible uncertainty.
$\delta_{REF_{REP}}$ = is a zero mean value term but uncertainty which takes into account the repeatability (stability on short term) of the reference temperature.
$\delta_{REF_{CAL}}$ = is a term with uncertainty which takes into account the calibration correction of the reference PRT.
$\delta_{REF_{DRIFT}}$ = is a zero mean value term with uncertainty which takes into account the annual stability (stability on long term) of the reference PRT.
$\delta_{REF_{FIT}}$ = is a zero mean value term with uncertainty which takes into account of the interpolation process done to get the correction function of the reference PRT.
$\delta_{DAQ_{RES}}$ = is a zero mean value term with uncertainty which takes into account the resolution of the DAQ used as read-out instrument for the reference PRT.
$\delta_{DAQ_{STABILITY}}$ = is a zero mean value term with uncertainty which takes into account the annual stability (stability on long term) of the DAQ.
$\delta_{CAL\_TOOL_{HOMOG}}$ = is a zero mean value term with uncertainty which takes into account the temperature homogeneity inside the calibration tool.

Replacing equations (3) and (4) in (2) it is possible to calculate the variance ${u_E}^2$ where its positive squared root corresponds to the standard uncertainty of the output quantity. The calibration expanded uncertainty is calculated as:

$$U_E = 2 \cdot u_E$$

considering for the quantity E a normal probability distribution function and a confidence level of approximately 95 %.

The method proposed above can be implemented in an electronic spreadsheet as in the Figure 11.

Code	Contributions	Units	Value	Moltiplicative factor	Pdf	Divisor	St. Dev	(St.Dev)^2	
							ºC	ºC^2	
UNCERTAINTIES OF THE REFERENCE CALIBRATION SYSTEM									
1aa	PRT REF calibration	°C	0.020	1	Normal	2	0.010	1.00E-04	
1ab	PRT REF drift	°C	0.050	1	Rectangular	3.46	0.014	2.08E-04	
1ac	PRT REF fitting	°C	0.025	1	Normal	1	0.025	6.25E-04	
1ad	PRT REF repeatability	°C	0.004	1	Normal	1	0.004	1.27E-05	
1ba	DAQ Accuracy	°C	0.010	1	Normal	2.00	0.005	2.50E-05	
1bb	DAQ stability	°C	0.010	1	Rectangular	3.46	0.003	8.33E-06	
1bc	DAQ resolution	°C	0.001	1	Rectangular	3.46	0.000	8.33E-08	
1bd	Calibration tool Temp. Homogeneity	°C	0.002	1	Rectangular	1.73	0.001	1.00E-06	
Combined standard uncertainty of the reference calibration system		ºC				u_C	**0.03**	<------------	=+SQRT(SUM.SQ(contributions code from 1aa to 1bd))
Expanded uncertainty $U(k=2)$		ºC				U_{95}	**0.06**		
UNCERTAINTIES OF THE UUT									
2aa	UUT repeatability	°C	0.008	1	Normal	1	0.008	6.30E-05	
2ab	UUT resolution	°C	0.001	1	Rectangular	3.46	0.000	8.33E-08	
Combined calibration standard uncertainty		ºC				u_C	**0.03**	<------------	=+SQRT(SUM.SQ(contributions code from 1aa to 1bd and 2aa and 2ab))
Expanded uncertainty $U(k=2)$		ºC				U_{95}	**0.06**		

Figure 11. Example of calibration uncertainty budget.

The table in Figure 11 reports an example of uncertainty budget for a single calibration point. The values highlighted in yellow are the estimates that varied at each calibration point.

5 Calibration process.

The following scheme reports the key steps of the calibration by comparison process.

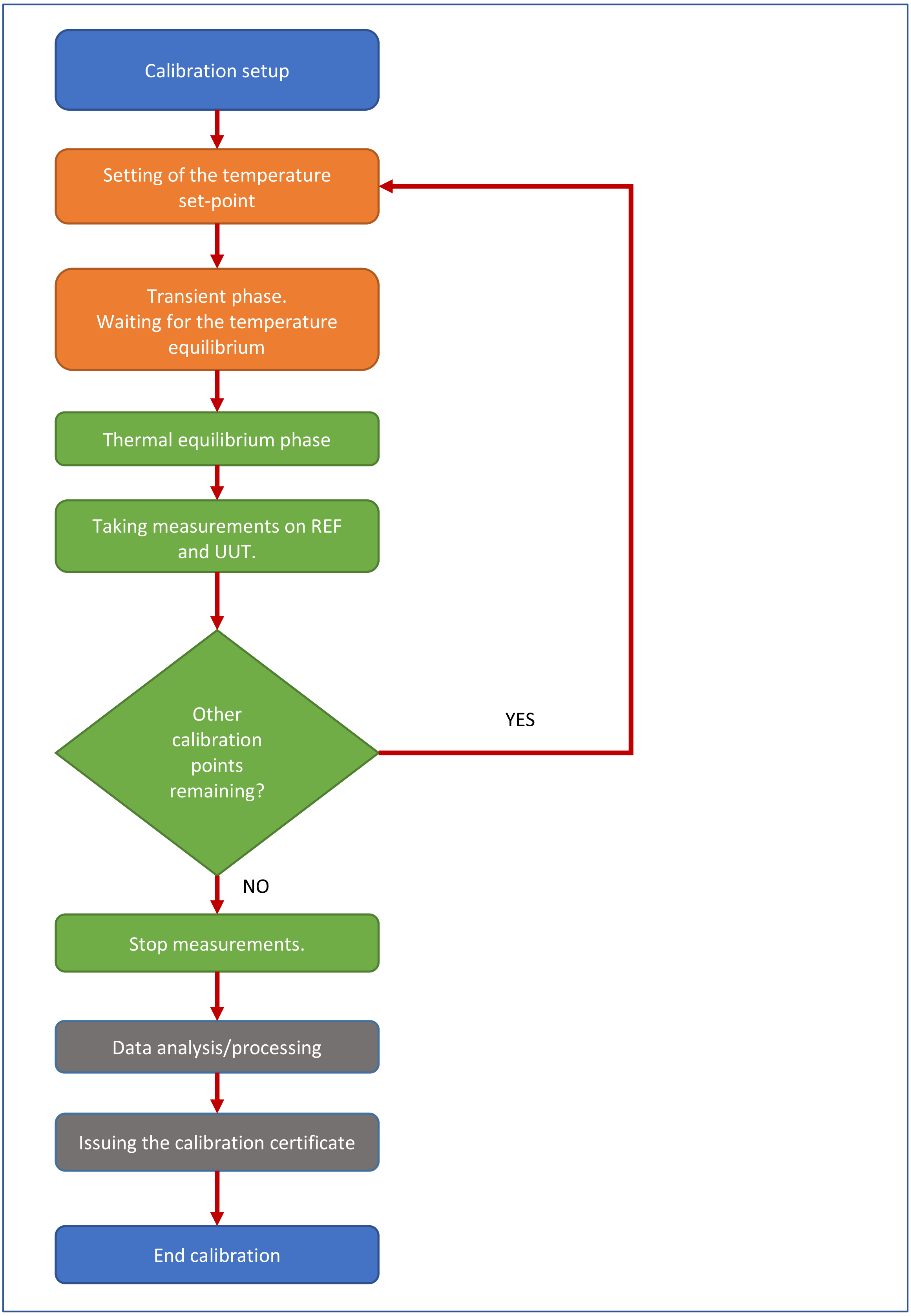


Figure 12. Schematic of a temperature static calibration process by comparison.

The calibration by comparison method relies on the fact that both the reference temperature and the UUT temperature show short-term stability and both instruments (REF and UUT) are subjected to the same temperature conditions. During the thermal equilibrium phase the temperature may oscillate periodically or fluctuate randomly around a mean value within an upper and a lower stability limit as shown on Figure 15.

The transient interval is the time between the change of the set point and the following equilibrium phase as the Figures 13 shows. A transient can be characterised by a slope depending mainly to the comparison medium (Figure 14).

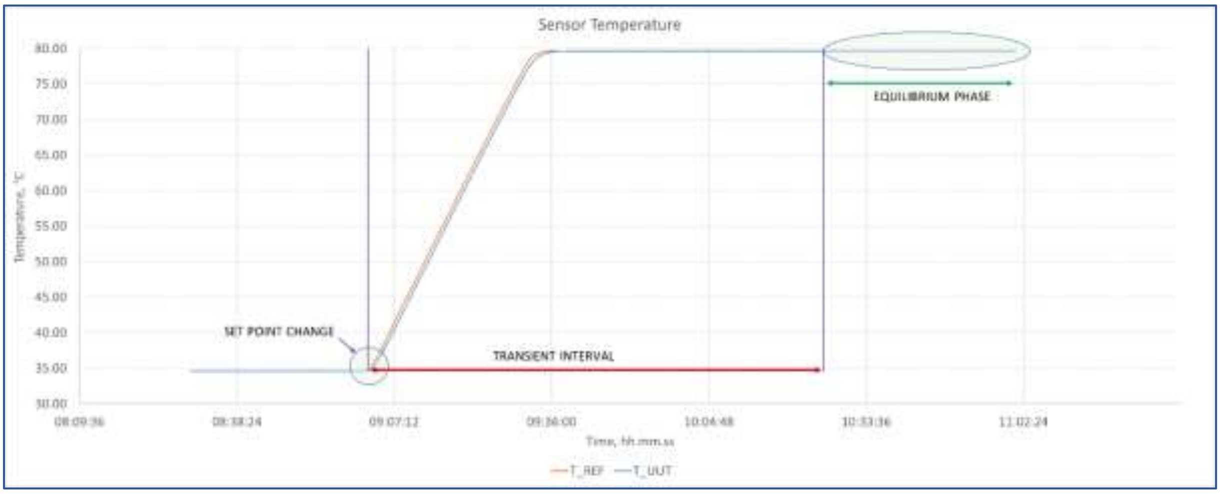


Figure 13. Transient interval

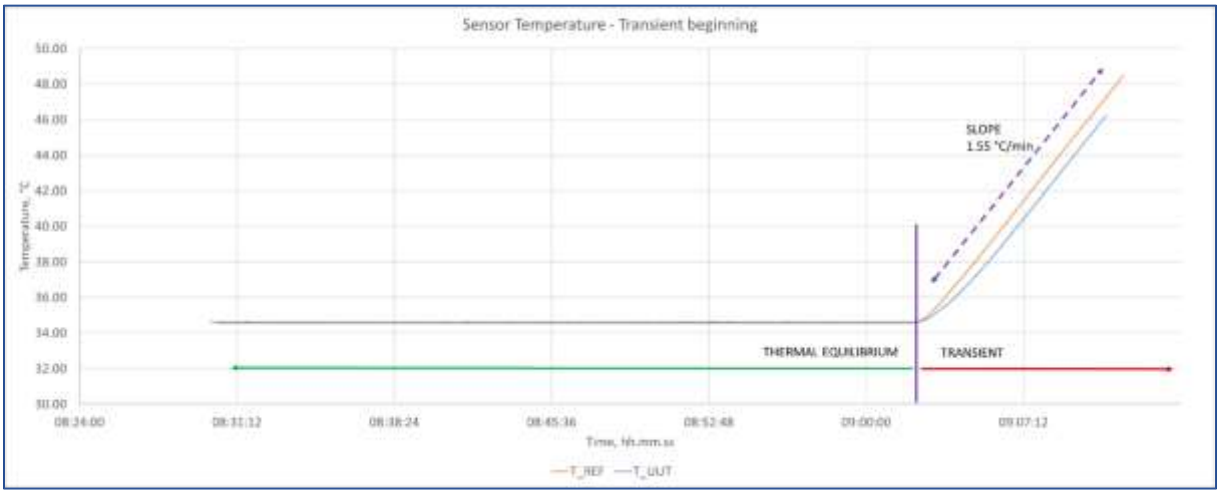


Figure 14. Slope of the temperature change.

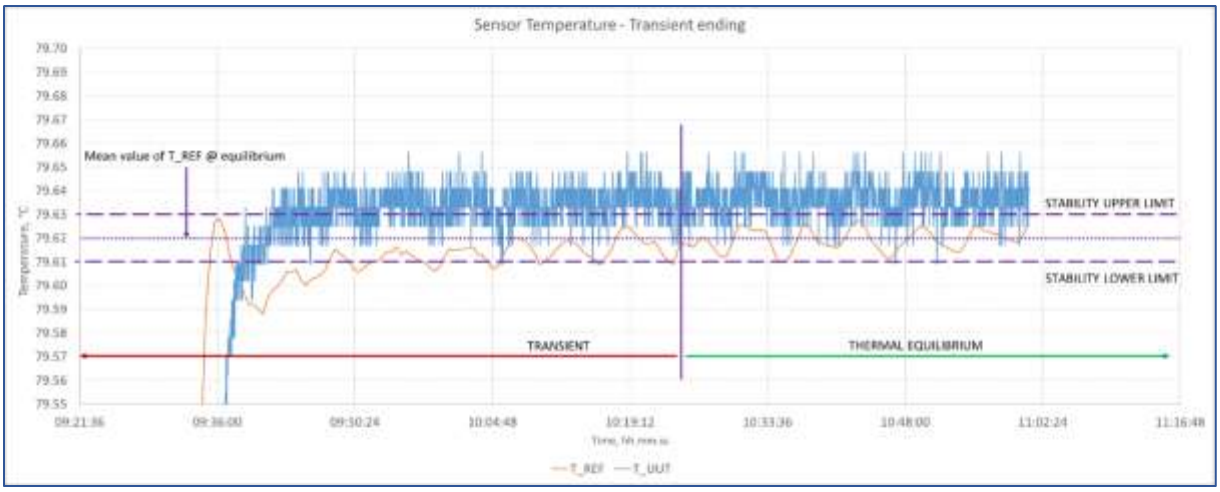


Figure 15. Transient ending and beginning of the equilibrium phase.

The measurements for the comparison between the mean value of the reference temperature and the UUT temperature is performed along the equilibrium phase as in the example shown in the Figure 16.

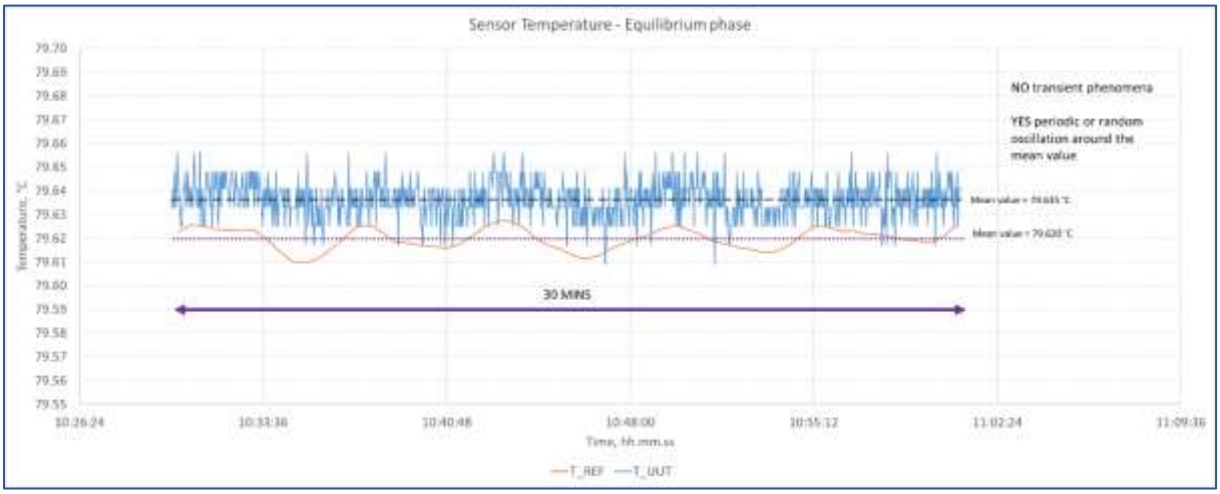


Figure 16. Temperature equilibrium phase.

The data analysis and processing of all thermal equilibrium phases of the measurement schedule are reported as the calibration results in the calibration certificate.
The following section will describe how to process data of a generic calibration point and the associated uncertainty in order to prepare the calibration certificate.

6 Results of the elaboration method implementation.

In this example, it is considered the experimental setup discussed in the Figure 2. The calibration tool entails the use of a reference PRT and three more PRT for determining the temperature homogeneity of the calibration tool. There are 64 UUT sensors accommodated in the calibration tool, but the example focus on one sensor.

The sampling time of the reference PRT is 30 s while it is approximately 2 s for the UUT, so the measurements data-set have different size, as depicted in Figure 18 where three data-set segments were put in sequence.

TIME STAMP	PRT HOMOG_2	PRT HOMOG_3	PRT HOMOG_4	PRT REF		TIME STAMP	UUT	
hh.mm.ss	°C	°C	°C	°C		hh.mm.ss	°C	
10:30:16	79.62	79.62	79.62	79.62		10:30:00	79.63	
10:30:46	79.63	79.63	79.62	79.62		10:30:02	79.63	
10:31:16	79.63	79.62	79.62	79.63		10:30:04	79.64	
10:31:46	79.62	79.62	79.62	79.62		10:30:06	79.63	
10:32:16	79.62	79.62	79.62	79.62		10:30:08	79.65	
10:32:46	79.62	79.62	79.62	79.62		10:30:10	79.64	
10:33:16	79.62	79.62	79.62	79.62		10:30:12	79.63	
10:33:46	79.62	79.62	79.62	79.62		10:30:14	79.66	
10:34:16	79.61	79.61	79.61	79.61		10:30:16	79.65	
10:34:46	79.61	79.61	79.61	79.61		10:30:18	79.64	
10:35:16	79.61	79.61	79.61	79.61		10:30:20	79.63	
10:35:46	79.61	79.61	79.61	79.61		10:30:22	79.63	
10:36:16	79.62	79.62	79.61	79.61		10:30:24	79.63	
10:36:46	79.62	79.62	79.62	79.62		10:30:26	79.63	
10:37:16	79.62	79.62	79.62	79.62		10:30:28	79.64	
10:37:46	79.63	79.62	79.62	79.62		10:30:30	79.64	
10:38:16	79.62	79.62	79.62	79.62		10:30:32	79.65	
10:38:46	79.62	79.62	79.62	79.62		10:30:34	79.64	
10:39:16	79.62	79.62	79.62	79.62		10:30:36	79.63	
10:39:46	79.62	79.62	79.62	79.62		10:30:38	79.65	
10:40:16	79.62	79.62	79.61	79.62		10:30:40	79.64	
10:40:46	79.62	79.61	79.61	79.62		10:30:42	79.63	
10:41:16	79.62	79.62	79.61	79.62		10:30:44	79.64	
10:41:46	79.62	79.62	79.62	79.62		10:30:46	79.64	
10:42:16	79.62	79.62	79.62	79.62		10:30:48	79.63	
10:42:46	79.63	79.63	79.63	79.62		10:30:50	79.63	
10:43:16	79.63	79.63	79.62	79.63		10:30:52	79.65	
10:43:46	79.62	79.62	79.62	79.62		10:30:54	79.66	
10:44:16	79.62	79.62	79.62	79.62		10:30:56	79.64	
10:44:46	79.62	79.62	79.62	79.62		10:30:58	79.64	
10:45:16	79.62	79.61	79.61	79.62		10:31:00	79.63	
10:45:46	79.61	79.61	79.61	79.61		10:31:02	79.63	
10:50:16	79.62	79.62	79.62	79.62		10:31:20	79.64	
10:50:46	79.62	79.62	79.62	79.62		10:31:22	79.65	
10:51:16	79.62	79.62	79.62	79.62		10:31:24	79.65	
10:51:46	79.62	79.62	79.61	79.62		10:31:26	79.64	
10:52:16	79.62	79.62	79.61	79.62		10:31:28	79.64	
10:52:46	79.62	79.61	79.61	79.62		10:31:30	79.63	
10:53:16	79.61	79.61	79.61	79.61		10:31:32	79.64	
10:53:46	79.61	79.61	79.61	79.61		10:31:34	79.65	
10:54:16	79.62	79.62	79.62	79.62		10:31:36	79.63	
10:54:46	79.62	79.62	79.62	79.62		10:31:38	79.63	
10:55:16	79.63	79.63	79.62	79.62		10:31:40	79.64	
10:55:46	79.62	79.62	79.62	79.62		10:31:42	79.65	
10:56:16	79.62	79.62	79.62	79.62		10:31:44	79.64	
10:56:46	79.62	79.62	79.62	79.62		10:31:46	79.65	
10:57:16	79.62	79.62	79.62	79.62		10:31:48	79.65	
10:57:46	79.62	79.62	79.62	79.62		10:31:50	79.63	
10:58:16	79.62	79.62	79.62	79.62		10:31:52	79.63	
10:58:46	79.62	79.62	79.62	79.62		10:31:54	79.65	
10:59:16	79.62	79.62	79.61	79.62		10:31:56	79.63	
10:59:46	79.62	79.62	79.62	79.62		10:31:58	79.65	
11:00:16	79.62	79.62	79.62	79.62		10:32:00	79.64	
11:00:46	79.63	79.63	79.62	79.62		10:32:02	79.65	
						11:00:29	79.65	
						11:00:31	79.64	
						11:00:33	79.65	
						11:00:35	79.63	
						11:00:37	79.65	
						11:00:39	79.63	
						11:00:41	79.63	
						11:00:43	79.64	
						11:00:45	79.63	
						11:00:47	79.64	
						11:00:49	79.65	
						11:00:51	79.63	
						11:00:53	79.64	
						11:00:55	79.64	
						11:00:57	79.64	
						11:00:59	79.64	
	PRT HOMOG_2	PRT HOMOG_3	PRT HOMOG_4	PRT REF			UUT	
	°C	°C	°C	°C			°C	
Mean	79.62	79.62	79.62	79.62	°C	Mean	79.64	°C
St. Dev.	0.003	0.004	0.003	0.003	°C	St. Dev.	0.008	°C

Figure 18. Example of data calibration elaboration. Data-set of REF and UUT.

The data-set reported in Figure 18 is plotted on a graph "temperature vs time" in the Figure 19. It refers to the equilibrium phase at the calibration point with nominal temperature equal to 80 °C. The data processing was performed over the last 10 minutes of acquisition, this include approx. 20 readings of the reference PRT and 330 readings of the UUT (highlighted with a green background in Figure 18).

The mean value and the standard deviation over 10 min were then estimated. The standard deviation of the PRT REF and the UUT corresponds to the respective repeatability contribution to the uncertainty. The mean value of the Reference temperature and the temperature of UUT in the thermal equilibrium phase will be reported in the calibration certificate for this calibration point.

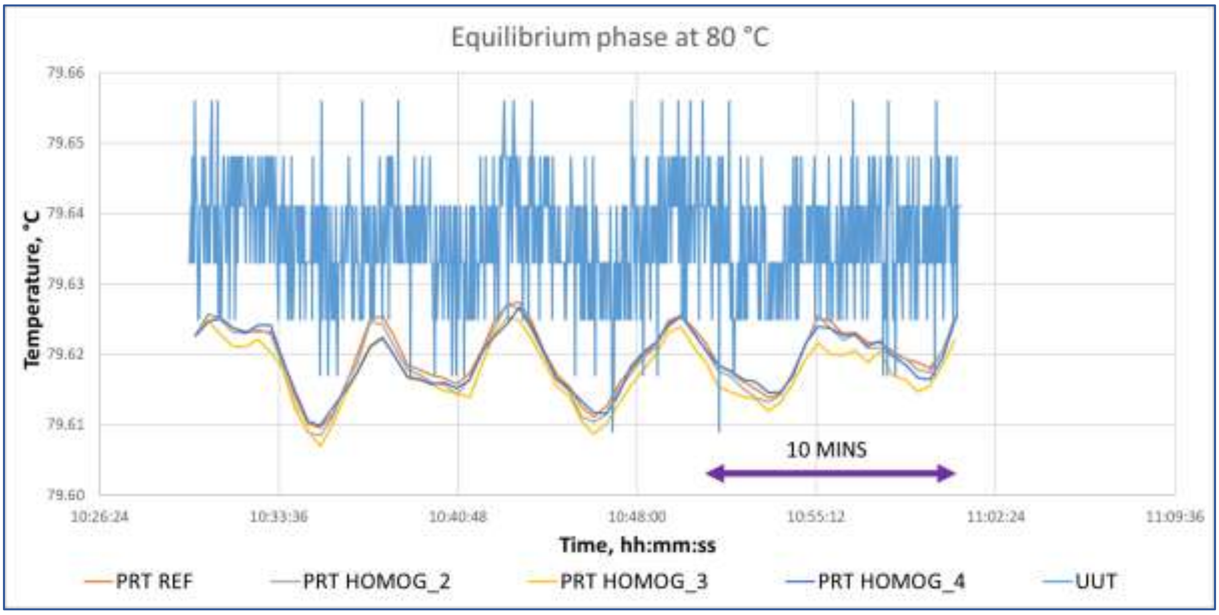


Figure 19. Example of data calibration processing. Equilibrium phase.

In Figure 20 are described the Excel functions about how the temperature homogeneity of the calibration tool is estimated.

	A	B	C	D	E	F	G	H	I	J
915								11:00:29	79.65	
916								11:00:31	79.64	
917								11:00:33	79.65	
918								11:00:35	79.63	
919								11:00:37	79.65	
920								11:00:39	79.63	
921								11:00:41	79.63	
922								11:00:43	79.64	
923								11:00:45	79.63	
924								11:00:47	79.64	
925								11:00:49	79.65	
926								11:00:51	79.63	
927								11:00:53	79.64	
928								11:00:55	79.64	
929								11:00:57	79.64	
930								11:00:59	79.64	
931										
932			**PRT HOMOG_2**	**PRT HOMOG_3**	**PRT HOMOG_4**	**PRT REF**			**UUT**	
933			**°C**	**°C**	**°C**	**°C**			**°C**	
934		**Mean**	**79.62**	**79.62**	**79.62**	**79.62**	**°C**	**Mean**	**79.64**	**°C**
935		**St. Dev.**	**0.003**	**0.004**	**0.003**	**0.003**	**°C**	**St. Dev.**	**0.008**	**°C**
936										
937		**Reference Temp.**		**79.62**	**°C**					
938		Corresponds to mean value of the REF PRT								
939		Excel formula		=+F932						
940										
941		**Ref. PRT Repeatability**		**0.003**	**°C**					
942		Calculated as the maximum value of the standard deviations								
943		Excel formula		=+F933						
944										
945		**Temp. Homogeneity**		**0.002**	**°C**					
946		Calculated as the maximum absolute difference between the maximum temp. or								
947		minimum temp. of the PRT_HOMOG with respect to the reference temperature								
948										
949										
950		Excel formula		=+MAX(ABS(MAX(C66:E66)-D69);ABS(MIN(C66:E66)-D69))						

Figure 20. Example of data calibration elaboration. Determining calibration parameters.

After estimating the mean values of the reference PRT and the UUT, the uncertainty associated to their difference have to be estimated as discussed in section 4.

Code	Contributions	Units	Value	Moltiplicative factor	Pdf	Divisor	St. Dev °C	(St.Dev)^2 °C²
UNCERTAINTIES OF THE REFERENCE CALIBRATION SYSTEM								
1aa	PRT REF calibration	°C	0.020	1	Normal	2	0.010	1.00E-04
1ab	PRT REF drift	°C	0.050	1	Rectangular	3.46	0.014	2.08E-04
1ac	PRT REF fitting	°C	0.025	1	Normal	1	0.025	6.25E-04
1ad	PRT REF repeatability	°C	0.003	1	Normal	1	0.003	1.00E-05
1ba	DAQ Accuracy	°C	0.010	1	Normal	2.00	0.005	2.50E-05
1bb	DAQ stability	°C	0.010	1	Rectangular	3.46	0.003	8.33E-06
1bc	DAQ resolution	°C	0.001	1	Rectangular	3.46	0.000	8.33E-08
1bd	Calibration tool Temp. Homogeneity	°C	0.002	1	Rectangular	1.73	0.001	1.00E-06
Combined standard uncertainty of the reference calibration system		°C				u_C	**0.03**	
Expanded uncertainty $U(k=2)$		°C				U_{95}	**0.06**	
UNCERTAINTIES OF THE UUT								
2aa	UUT repeatability	°C	0.008	1	Normal	1	0.008	6.30E-05
2ab	UUT resolution	°C	0.001	1	Rectangular	3.46	0.000	8.33E-08
Combined calibration standard uncertainty		°C				u_C	**0.03**	
Expanded uncertainty $U(k=2)$		°C				U_{95}	**0.06**	

Figure 21. Example of data calibration elaboration. Uncertainty budget.

The Figure 21 reports the uncertainty budget of the present example. The values highlighted in yellow correspond to the estimates of Figure 20.

The final result associated to the calibration point reported in the present example is reported in the third row of Table 1.

Table 1. Example of processed data to be reported in the calibration certificate.

#	Nominal Temp.	T_REF	T_UUT	T_UUT-T_REF	*U*
	°C	°C	°C	°C	°C
1	5	4.58	4.66	0.08	0.07
2	35	34.56	34.61	0.05	0.06
3	80	79.62	79.64	0.02	0.06

7 References.

[1] Report on in-situ calibration method for MEMS temperature sensor with traceability to SI units, including an architecture for a reference fixture of RTD sensor networks. (Deliverable D3).
EMPIR Project 17IND12 Met4Fof
[2] Video training course: Calibration of a reference fixture to provide a measurement traceability to improved ATEs for temperature MEMS testing.
EMPIR Project 17IND12 Met4Fof
[3] Evaluation of measurement data – Guide to the expression of uncertainty in measurement JCGM 100:2008.