MINISTRY FOR THE ENVIRONMENT AND SPATIAL PLANNING
SLOVENIAN ENVIRONMENTAL AGENCY

REPUBLIC OF SLOVENIA

Vojkova 1b,
1000 Ljubljana p.p. 2608,
tel.: +386(0)1 478 40 00 fax.: +386(0)1 478 40 52

WMO

WMO CIMO Training Workshop on Metrology for the English-speaking countries of Region V (South-West Pacific)

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Temperature

M.Sc. Drago Groselj
Head of Calibration Laboratory Service

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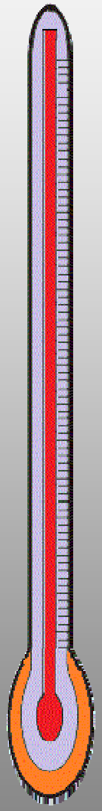
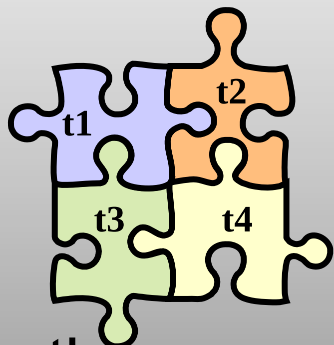


Definitions

- **Temperature** is the level of thermal energy of a body.
- Heat transfer only occurs spontaneously from a high temperature to a low temperature, never the reverse.
- Temperature is intensive and not extensive physical quantity:



t # t1+t2+t3+t4 !

- Not directly measurable
- Thermodynamical temperature: measured by primary thermometers linked with others physical parameters (PV=nRT); → very expensive and quite difficult

International temperature scale ITS

- ✓ History:
  - ➢ Temperature scale is the closest approximation of thermodynamic temperature scale: difference between theoretical and practical scale ITS90 is between 0.1 mK and 0.5 mK
  - ➢ First defined in 1927, last scale in 1990
  - ➢ Expressed in **Kelvin** unit : t(°C)=T(K)-273.15

- ✓ How is the ITS-90 defined in range from 13.8K to1234.9K:
  - ➢ **Fixed points**: Fixed points are physical systems with stable temperature during phase transition and they are reproducible and repeatable.
  - ➢ With a **standard platinum resistance thermometer**.
  - ➢ **Interpolation relationships** with reduced resistance W(T).

Fixed points of ITS-90

- 17 fixed points defines ITS-90
- The most known fixed points are phase changes of pure materials (triple point, freezing point and melting point)
- Meteorological range is between triple point of mercury and freezing point of indium.

No	Temperature		Material	Phase transition
	T_{90} [K]	t_{90} [° C]		
1	3 to 5	-270.15 to -268.154	He	V
2	13.8033	-259.3467	e-H_2	T
3	~17	~-256.15	e-H_2 (or He)	V (or P)
4	~20.3	~-252.85	e-H_2(or He)	V (or P)
5	24.5561	-248.5939	Ne	T
6	54.3584	-218.7916	O_2	T
7	**83.8058**	**-189.3442**	**Ar**	**T**
8	**234.3156**	**-38.8344**	**Hg**	**T**
9	**273.16**	**0.01**	**H_2O**	**T**
10	**302.9146**	**29.7646**	**Ga**	**M**
11	**429.7485**	**156.5985**	**In**	**F**
12	505.078	231.928	Sn	F
13	629.677	419.527	Zn	F
14	933.473	660.323	Al	F
15	1234.93	961.78	Ag	F
16	1337.33	1064.18	Au	F
17	1357.77	1084.62	Cu	F

Interpolating function

✓ Temperatures are determined in terms of the **ratio of resistance** $R(T_{90})$ at temperature T_{90} and the resistance R(273.16K) at the triple point of water:

$$W(T_{90}) = \frac{R(T_{90})}{R(273.16K)}$$

✓ Reference function $W_r(T_{90})$ is defined:

Range from 13.8033 K to 273.16 K	Range from 273.15 K to 1234.94K
$\ln[W_r(T_{90})] = A_0 + \sum_{i=1}^{12} A_i \cdot \left[\frac{\ln\left(\frac{T_{90}}{273.16}\right) + 1.5}{1.5} \right]^i$	$W_r(T_{90}) = C_0 + \sum_{i=1}^{9} C_i \cdot \left[\frac{T_{90} - 754.15}{481} \right]^i$

Numeric values of reference function coefficients (Ai, Ci) and inverse reference function (Bi, Di) are available in literature.

✓ **Deviation function** is a deviation of reference function $W_r(T_{90})$ and ratio $W(T_{90})$ is defined:

$$\Delta W(T_{90}) = W(T_{90}) - W_r(T_{90})$$

Interpolating function

The forms of deviation function **differ** according to different temperature range and used fixed points. In the temperature range from 13.8033 K to 1234.94 K three forms of deviation function are defined:

- from 83.8058 K to 273.16 K:

$$\Delta W(T_{90}) = a \cdot \left[W(T_{90}) - 1\right] + b \cdot \left[W(T_{90}) - 1\right] \cdot \ln\left(W(T_{90})\right)$$

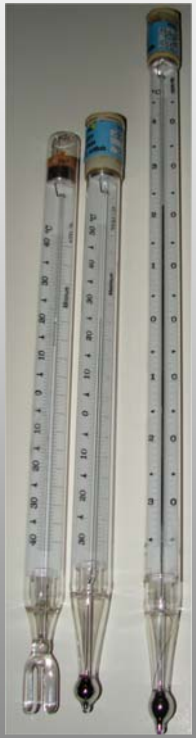
- from 273.15 K to 1234.94 K:

$$\Delta W(T_{90}) = a \cdot \left[W(T_{90}) - 1\right] + b \cdot \left[W(T_{90}) - 1\right]^2 + c \cdot \left[W(T_{90}) - 1\right]^3 + d \cdot \left[W(T_{90}) - W(660.323°C)\right]^2$$

Values of coefficients a, b, c, c_i, d depends on **temperature range** and **fixed point** used in **calibration** and they are results in calibration of standard platinum resistance thermometer.

Types of contact thermometers

Contact thermometers operate on the principle of change of characteristic as a result of change of temperature:



Liquid-in-glass:

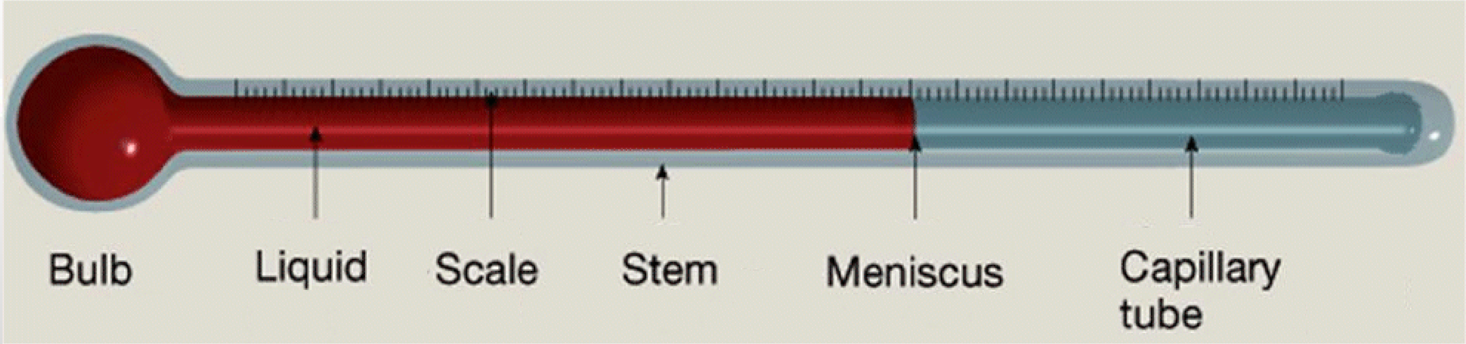
Change of volume depending on the change of temperature.

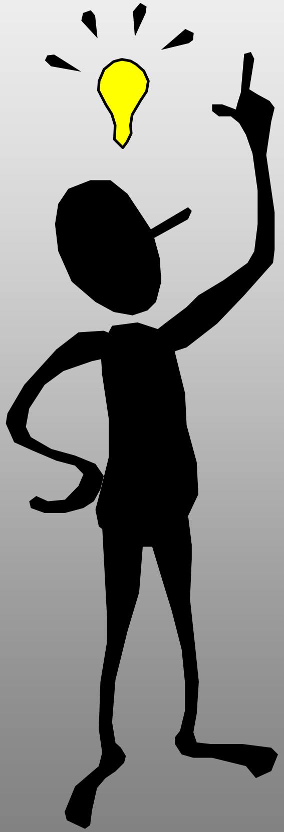
Platinum resistance thermometer, thermistor (change of resistance):

Thermocouple:
Generation of thermoelectric voltage

Thermograph:
Mechanical change

Liquid-in-glass thermometer





- One of the first thermometers
- Different accuracy classes (between mK and 10 K)
- Can be used in the range from –110°C to 600°C
- Simple to use
- As a result of difference in the volume expansion of glass and liquid within it as a change of temperature, the volume of liquid changes.

Liquid-in-glass thermometer

✓ Based on the thermal expansion and contraction of a liquid

Advantage	Disadvantage
no power source required	limited to applications where manual reading is acceptable
repeatable	cannot be digitised or automated
easy to use & cheap	careful handling is required
	mercury vapour is highly toxic

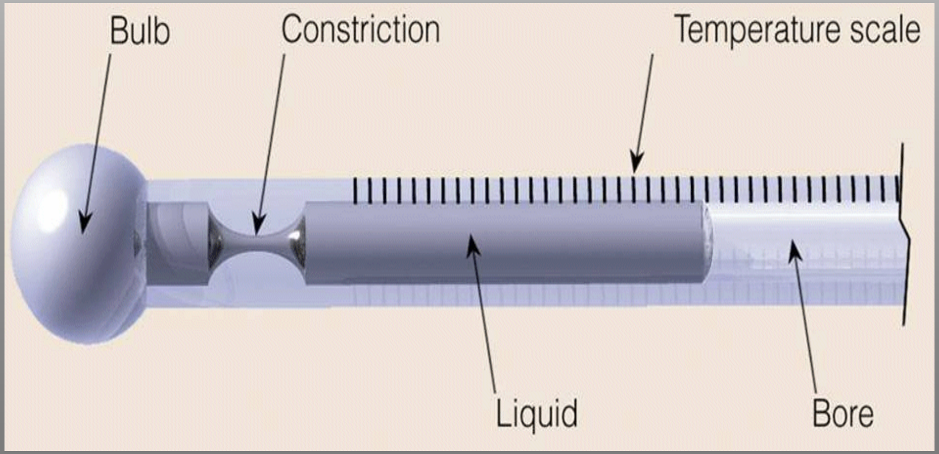
✓ Liquids and range:

Alcohol	-110°C to 100°C
Mercury	-38°C to 650°C
Mercury-thalium	-56°C to 650°C

Maximum thermometer

The maximum thermometer is a mercury thermometer to measure the maximum temperature in a certain period.

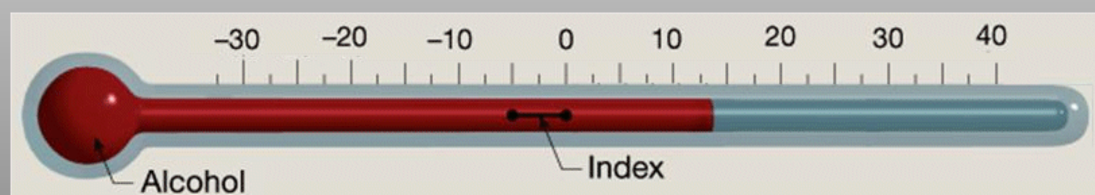
- This thermometer has a **constriction** in the capillary tube where the mercury is constricted between the bulb and the starting point of the scale.
- As air temperature rises, the mercury goes out of the bulb passing through the constriction.
- When air temperature falls, the mercury column breaks at the constriction. Thus mercury in the capillary tube cannot return to the bulb, and remains indicating the maximum temperature.

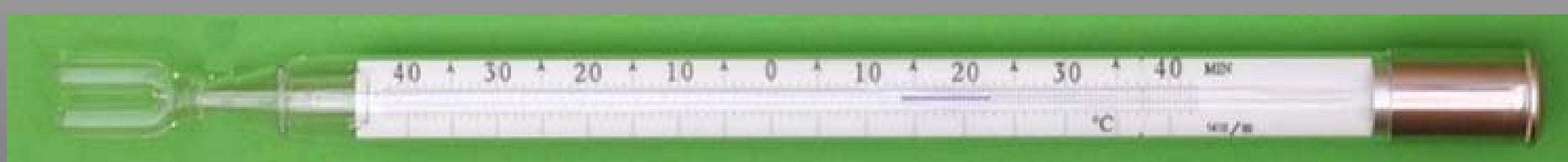


Minimum thermometer

The minimum thermometer is a **spirit thermometer** to measure the minimum temperature in a certain period.

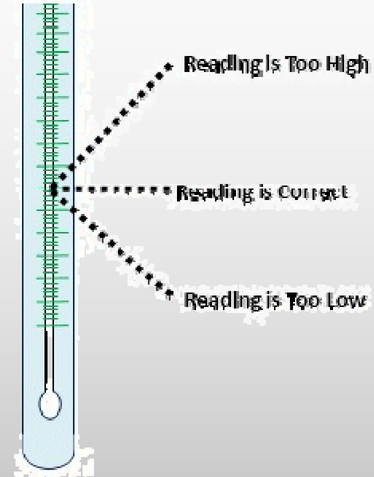
- It has a dumbbell shaped index of colored glass in the spirit column.
- As air temperature falls, the index is dragged by the surface tension of the spirit and moves toward the bulb with the top of the column.
- When temperature rises, the index is left in its position because the spirit flows through it. As a result, the index remains indicating the minimum temperature.



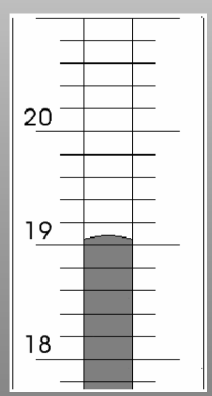


Common errors using Lig thermometers

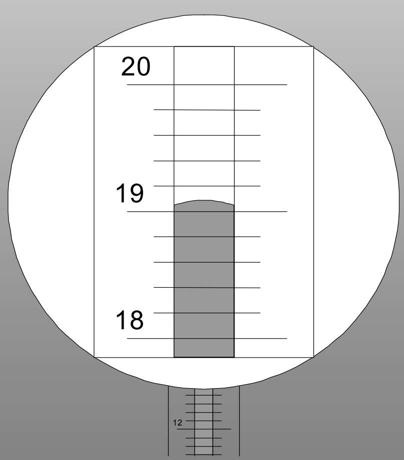
- ✓ **Parallax error** : Parallax errors of many tenths of a division may easily occur in reading a Lig thermometer. To avoid them one must view the thermometer from exactly the same angle as was used for calibration, virtually always perpendicular to the liquid column.



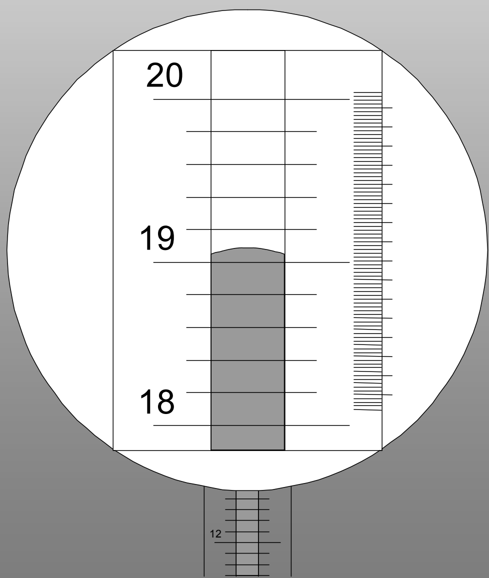
- ✓ **Interpolation error**:



1/3 division



1/5 division



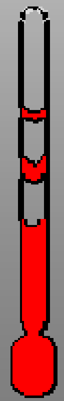
1/8 division

Common errors using Lig thermometers

Range [°C]	Scale division [°C]	Scale division [mm]	Resolution	Expanded uncertainty
		$\Delta < 0.5$	Δ	$0.6 \cdot \Delta$
-30°C÷40°C $_{ord}$	0.2	$0.5 < \Delta < 1$	$0.5 \cdot \Delta$	$0.3 \cdot \Delta$
-40°C÷40°C $_{min}$ -30°C÷50°C $_{max}$	0.5	$1 \leq \Delta < 2$	$0.25 \cdot \Delta$	$0.2 \cdot \Delta$

Δ … scale division [mm]

✓ Breakage in the liquid column



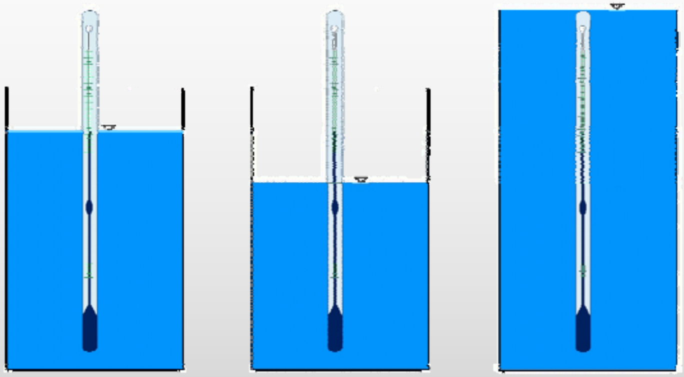
Several ways to reunite the column:

- ➢ Lightly tap the thermometer against the palm of your hand.
- ➢ Apply centrifugal force.
- ➢ Cool the bulb (dry ice, alcohol) so that all the liquid enters the bulb leaving none in the stem. The column may rejoin when it is warmed to room temperature.
- ➢ Heat the thermometer and drive the separated column into expansion chamber. (never fill the expansion chamber more than 2/3 full).

Common errors using Lig thermometers

✓ **Emergent stem**:

During calibration the thermometer must be correctly immersed in the calibration bath to ensure accurate measurements.



Partial immersion correction:

$t_{corr} = t_{inst} + \Delta t$

$\Delta t = K \cdot n \cdot (Tc - Ts)$

K - the combined coefficient of expansion of the thermometric liquid and the glass. (Hg thermometers k=0.00016)

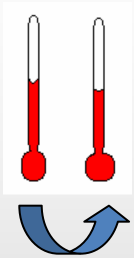
n - the number of scale degrees of the thermometer column between the surface of the liquid being measured and the meniscus of the liquid column.

Tc - the reading of the thermometer

Ts - average temperature of the emergent liquid column.

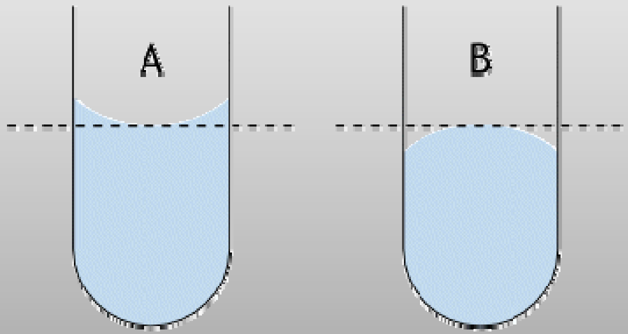
Common errors using Lig thermometers

- ✓ **Changes in the bulb’s volume**



pressure…

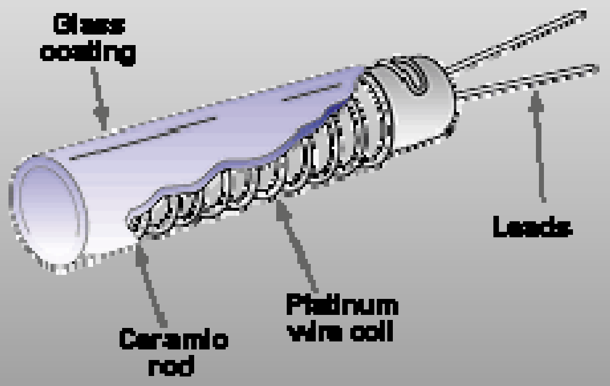
- ✓ **Adhesion to the glass**



- ✓ **Pollution of the liquid**
- ✓ **Glass expansion**

Platinum resistance thermometer

- ➢ Based on the reversible change of the electrical resistance of a metal wire.
- ➢ Advantages of the platinum resistance thermometers:
  - ✓ Chemical stability
  - ✓ Available in a highly pure form
  - ✓ Excellent reproducibility of characteristics
  - ✓ Wide temperature range (–260°C to 1000°C)
  - ✓ Stable over time
  - ✓ Stable over temperature
  - ✓ Shallow slope (i.e. 0.4Ω/°C for a 100Ω PRT)
  - ✓ Relatively easy to measure
  - ✓ Relatively easy to calibrate

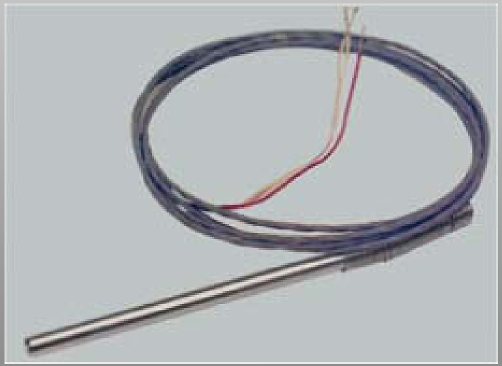


In general two types of resistance thermometers are defined:

- ➢ SPRT – standard platinum resistance thermometer
- ➢ IPRT – industrial platinum resistance thermometer

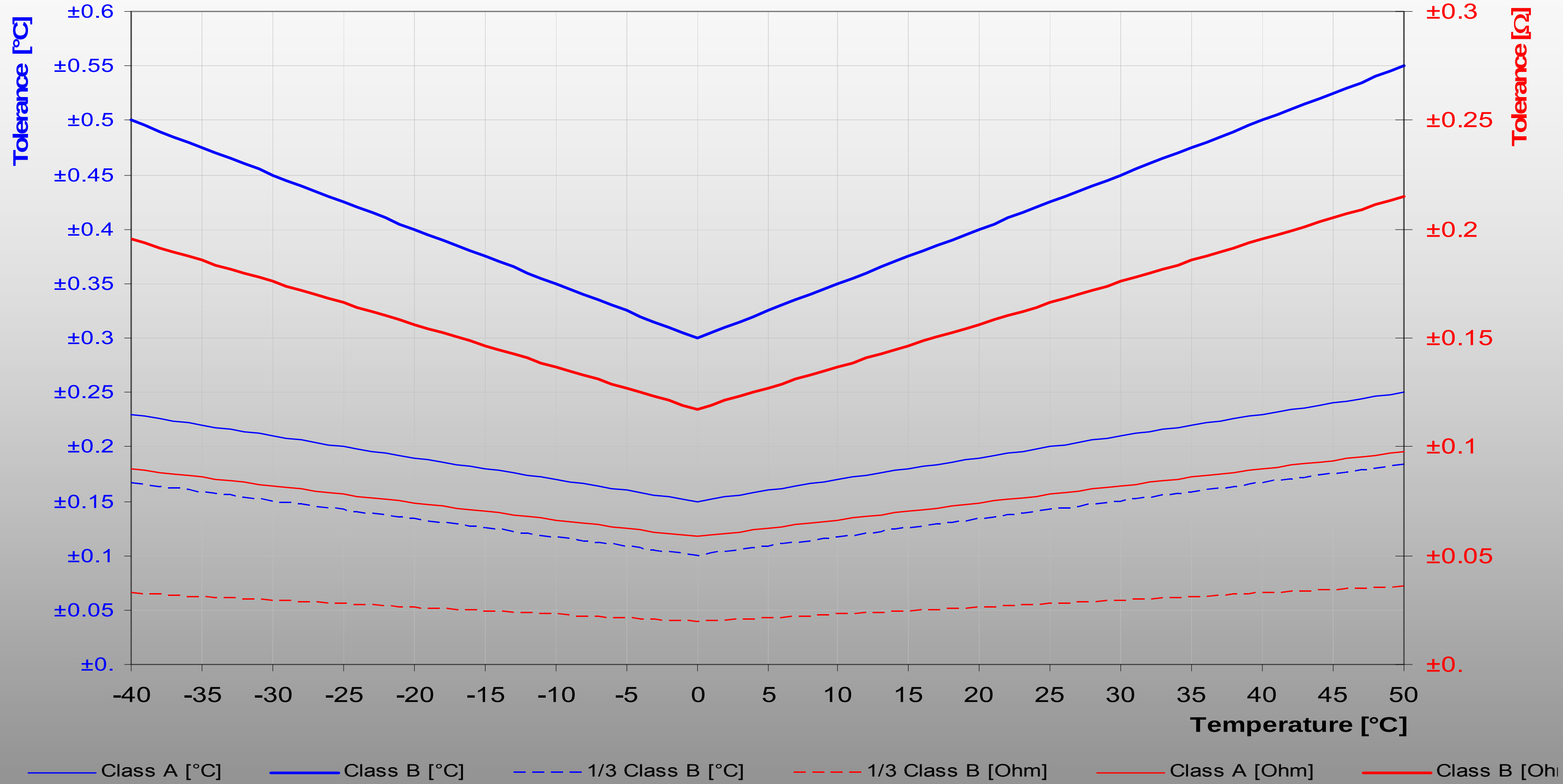
Platinum resistance thermometer

SPRT	IPRT
Capable of very high accuracy (mK)	Capable of moderate to high accuracy (10mK÷100mK)
Capable of wide temperature range	Capable of large temperature range
Extremely stable	Very stable
Relatively expensive to purchase	Relatively inexpensive to purchase
Relatively expensive to calibrate	Relatively inexpensive to calibrate
Extremely delicate	Less delicate



- ✓ Reference functions for IPRT (standard EN 60751):
  - From –200°C to 0°C: $R_t = R_0\left[1 + A\cdot t + B\cdot t^2 + C(t-100)\cdot t^3\right]$
  - From 0°C to 661°C: $R_t = R_0\left[1 + A\cdot t + B\cdot t^2\right]$

Resistance thermometer - standard EN 60751:



Class A: 0.15 +0.002 *|T|
Class B: 0.3 +0.005 *|T|
1/3 Class B: 0.1 +0.00167 *|T|
1/5 Class B: 0.06 +0.001 *|T|
1/10 Class B: 0.03 +0.0005 *|T|

$$R(t) = R(0°C) \cdot (1 + A \cdot t + B \cdot t^2 + C \cdot (t - 100) \cdot t^3)$$

R0 = 100Ω

$A = 3.9083 \cdot 10^{-3}$ [$°C^{-1}$]

$B = -5.775 \cdot 10^{-7}$ [$°C^{-2}$]

$C = -4.183 \cdot 10^{-12}$ [$°C^{-4}$]

Common error sources using Pt thermometers

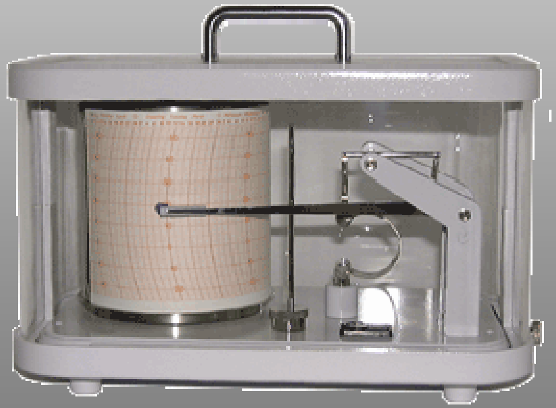
- ***Insulation Resistance:*** Error caused by the inability to measure the actual resistance of element. Current leaks into or out of the circuit through the sheath, between the element leads, or the elements.
- ***Stability:*** Ability to maintain R vs T over time as a result of thermal exposure.
- ***Repeatability:*** Ability to maintain R vs T under the same conditions after experiencing thermal cycling throughout a specified temperature range.
- ***Hysteresis:*** Change in the characteristics of the materials from which the RTD is built due to exposures to varying temperatures.
- ***Immersion depth:*** Error that results from the PRT sheath conducting heat into or out of the process.
- ***Lead Wire:*** Errors that occur because a 4 wire or 3 wire measurement is not used, this is greatly increased by longer connection wires.
  - 2 wire connection adds lead resistance in series with PRT element.
  - 3 wire connection relies on all 3 leads having equal resistance.
- ***Self Heating:*** Error produced by the heating of the PRT element due to the power applied.

Thermograph

- A thermograph is an instrument for recording the temperature of the surrounding air continuously and automatically.
- The sensor used is a bimetallic helix formed from aquaflex or coflex strips.
- Its one end is fixed while the other end is attached to a spindle to which the pen arm is screwed.
- When temperature changes, the curvature of the helix changes and this movement is recorded on a chart.

Thermograph properties:

- temperature range -30°C÷40°C
- very low maintenance
- easy reading and handling
- thermo-mechanic measuring principle
- typical accuracy ±0.3°C



Why calibrate?

Equipment for temperature calibrations

1. Temperature controlled medium:

Liquid baths in temperature range –50°C to 50°C

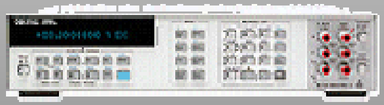



Climatic chambers in temperature range –20°C to 40°C


Equipement for temperature calibrations

2. A reference instrument

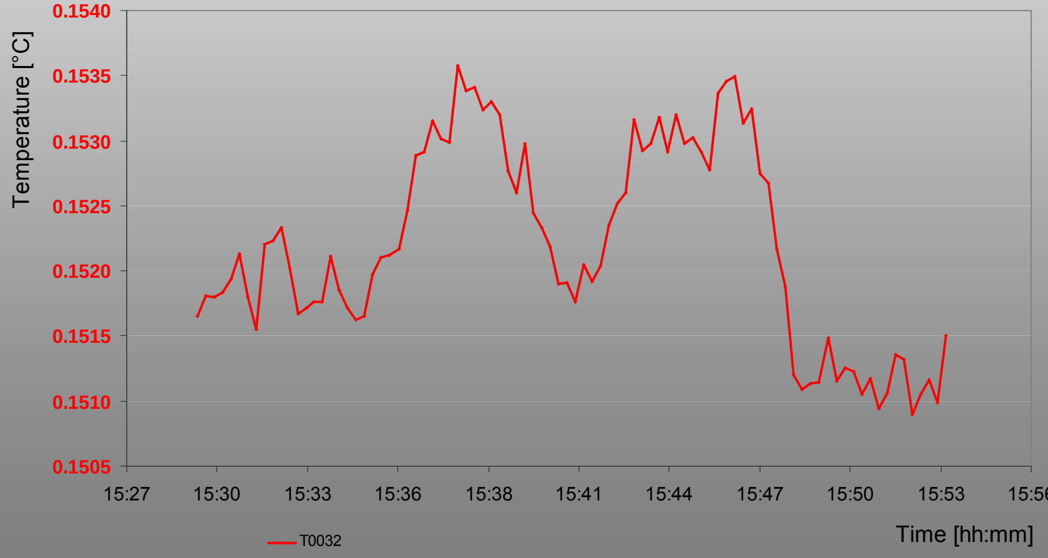
3. Data acqusition unit (for reference and UUT)



Temperature controlled medium

- ✓ Temperature of a calibration bath/chamber cannot be considered as completely stable in time and homogeneous all over its volume.
- ✓ Metrological characterization of calibration bath/chamber consists of two components:

1. **Time stability** or short-term stability of a medium temperature. It strongly depends on type of regulation and flow of medium inside the bath.



$$u_{ts} = \frac{1}{\sqrt{3}} \cdot \left| t_{\max} - t_{\min} \right|$$

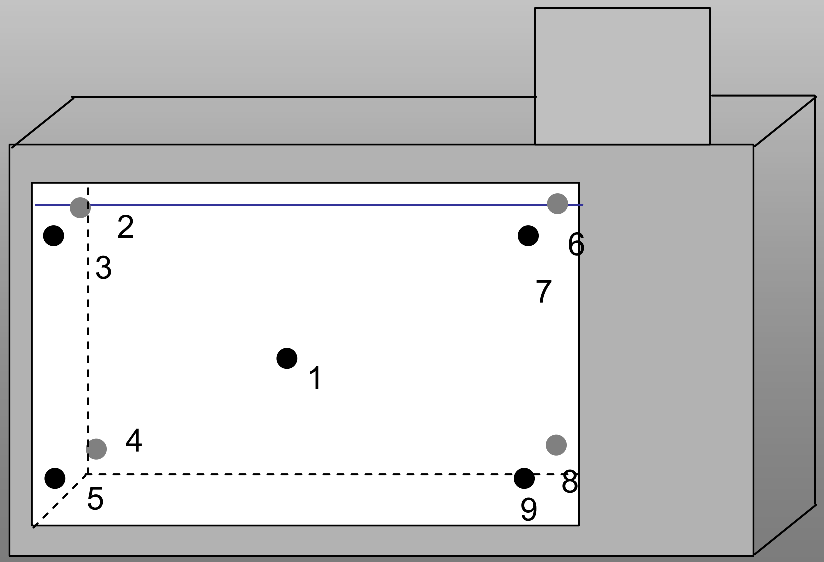
Temperature controlled medium

2. Spatial homogenity: A gradient is observed as a change of a temperature reading of a thermometer according to a change of its position inside a calibration bath.

Basic gradients that can be observed are vertical and horizontal gradient. A lot of calibration baths have either a cylindrical shape or equalizing blocks inside it is sometimes more appropriate to define axial and a radial gradient.

Spatial homogeneity can be measured using:

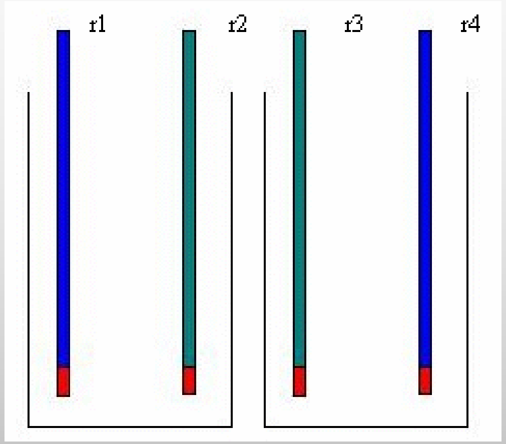
a) same type instruments



$$u_h = \frac{1}{\sqrt{3}} \cdot \left| \bar{t}_i - \bar{t}_j \right|_{max}$$

Temperature controlled medium

b) with two instruments of the same type



$$r_1 = R_1(T)$$
$$r_2 = R_2(T+\varepsilon)$$
$$r_3 = R_2(T)$$
$$r_4 = R_1(T+\varepsilon)$$

and

$$\rho_1 = \frac{r_1}{r_2}$$
$$\rho_2 = \frac{r_3}{r_4}$$

$$\varepsilon = \frac{R(1-\rho_1\rho_2)}{2s}$$

$$U(\varepsilon) = \pm 2\frac{\frac{\Delta\rho}{4}R(T)}{s}$$

with $\Delta\rho$ the range at a level

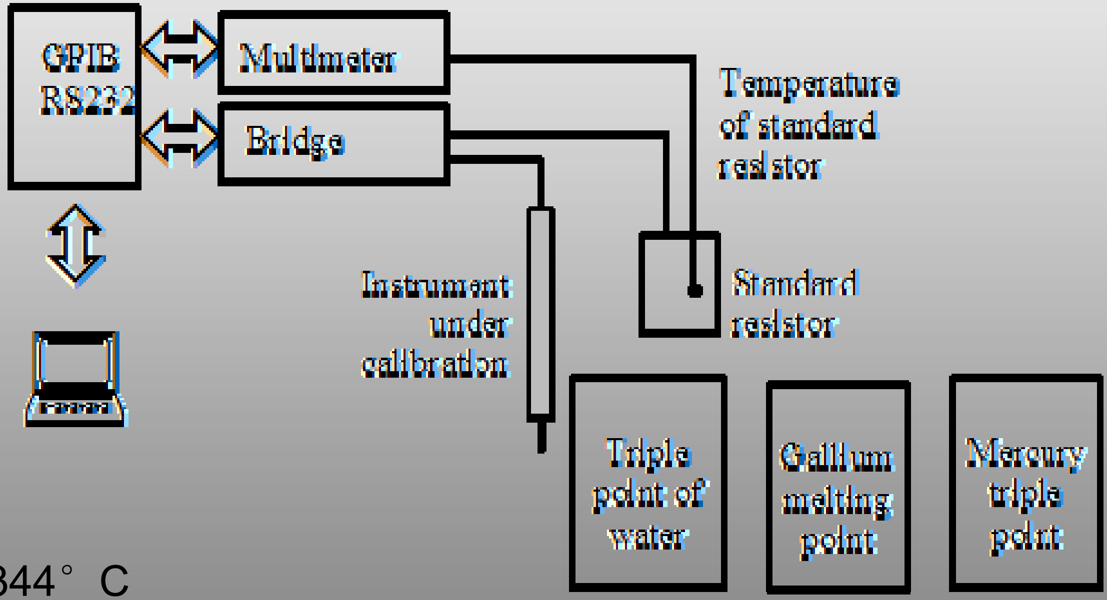
R(T) the average resistance

with s sensitivity

- ✓Time stability and spatial homogenity may represent a major contribution to the total uncertainty of a calibration procedure.
- ✓In order to decrease this uncertainty contributions equalizing blocks can be used in calibration baths.

Methods of calibration

Fixed point method: standard platinum resistance thermometers (SPRTs) at top uncertainty level (mK) are usually calibrated at fixed points, in accordance with ITS-90 definition.

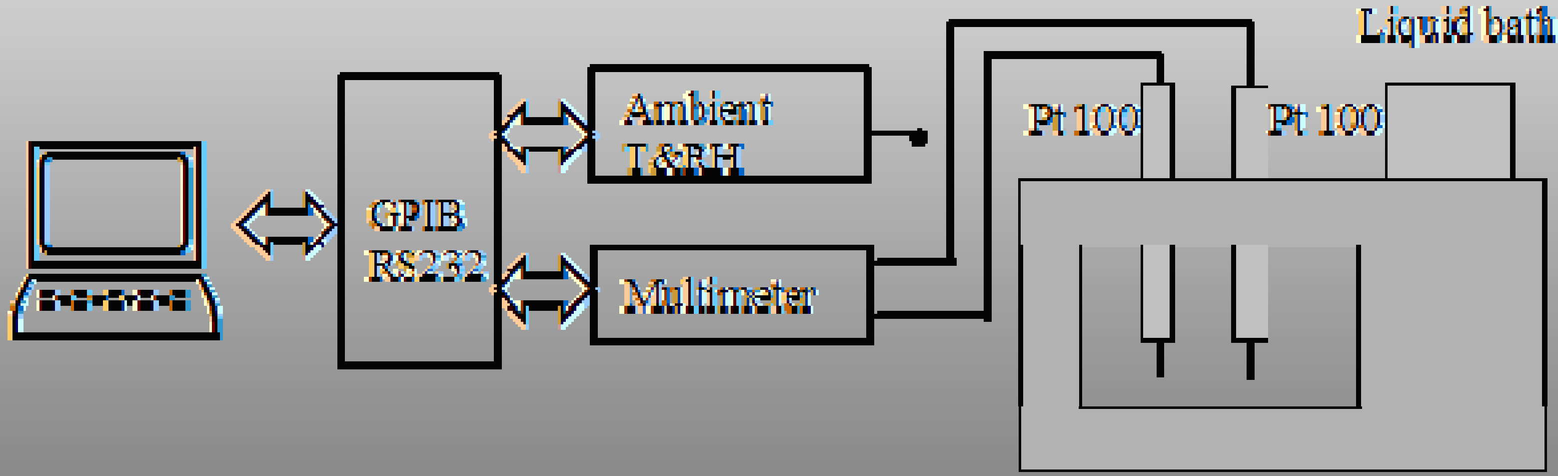


Meteorological range:
Mercury triple point: -38.8344° C
Triple point of water: 0.01°C
Gallium melting point: 29.7646°C
Indium freezing point: 156.5985° C

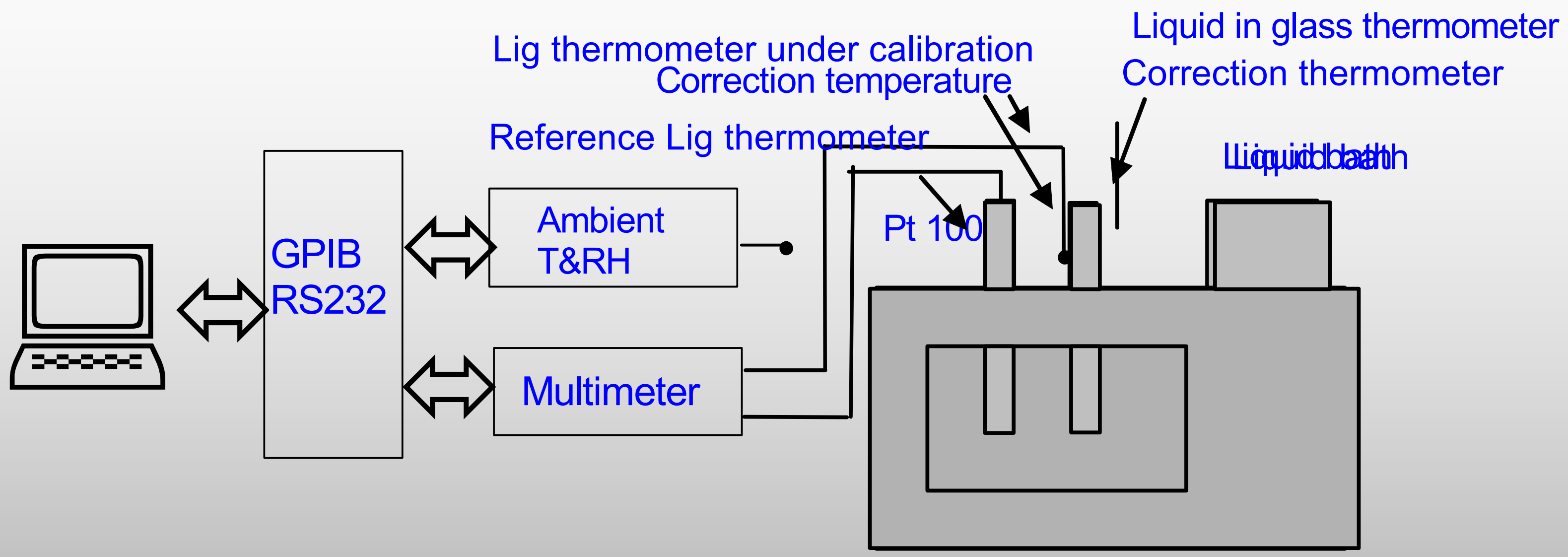
Methods of calibration

Industrial platinum resistance thermometers (IPRT), liquid-in-glass thermometers and thermistors are calibrated **by comparison** with laboratory's reference standard in a temperature controlled medium.

Typical calibration range: -40°C to 50°C (10°C increment)
Number of measurement at each calibration point: 50 - 100



Liquid-in-glass thermometer calibration



Equipment used:

- ✓ Calibrated reference thermometer
- ✓ Liquid medium with known time stability and spatial homogenity

Measurement cycle:

- ➢ 10 readings taken with reference thermometer
- ➢ 10 readings taken with thermometer to be calibrated
- ➢ 10 readings taken with reference thermometer

Liquid-in-glass thermometer calibration

Assumptions:

- Calibration point: 20°C
- Operator able to interpolate to the fifth division and read with naked eye
- Immerged to the read degree
- Check at 0°C with melting ice

$$C = Tr - Tc + \delta T_{R\mathrm{int}erp} + \delta T_{Rcal} + \delta T_{Rdrift} + \delta T_{stem} + \delta T_{bath} + \delta T_{zero} + \delta T_{interp}$$

- ✓ *C*: correction to be determined
- ✓ *Tr*: temperature reading of the reference thermometer
- ✓ *Tc*: temperature reading of the thermometer to be calibrated
- ✓ $\delta T_{Rinterp}$: correction linked to the interpolation of reference thermometer
- ✓ δT_{Rcal}: correction linked to calibration of reference thermometer
- ✓ δT_{Rdrift}: correction linked to drift of reference thermometer bewteen two calib.
- ✓ $\delta T_{stem:}$ correction linked with the emergent stem
- ✓ δT_{bath}: correction linked with the bath instability and uniformity
- ✓ δT_{zero}: correction linked with the check of the zero
- ✓ δT_{interp}: correction linked with the interpolation of UUC

Uncertainty of measured values

- **10 readings of reference thermometer**
  - Average = 20.22°C
  - Reading range = 0.02°C
  - Standard uncertainty = 0.006°C

$$\frac{0.02}{2\sqrt{3}} = 0.006$$

- **10 readings of thermometer to be calibrated**
  - Mean = 20.02°C
  - Reading range = 0.02°C
  - Standard uncertainty =0.006°C

$$\frac{0.02}{2\sqrt{3}} = 0.006$$

Uncertainty contributios of reference instrument

- **$\delta T_{Rinterp}$**: operator is capable of interpolating the readings of reference themometer to the fifth of a division (scale division 0.1°C):

$$\delta T_{Rinterp} = 0; \qquad u(\delta T_{Rinterp}) = \frac{0.1 \cdot \frac{1}{5}}{2 \cdot \sqrt{3}} = 0.006°C$$

- **δT_{Rcalib}**: Correction linked to calibration of reference thermometer. The certificate states correction of -0.1°C with expanded uncertainty 0.15°C:

$$\delta T_{Rinterp} = -0.1°C; \qquad u(\delta T_{Rcal}) = \frac{0.15}{2} = 0.075°C$$

- **δT_{Rdrift}**: Correction linked to reference thermometer drift: Assume no drift, uncertainty contribution equal to interpolation

$$\delta T_{Rdrift} = 0; \qquad u(\delta T_{Rdrift}) = 0.006°C$$

Uncertainties on emergent steam and liquid bath

- **δT_{steam}**: Assume the reference thermometer and thermometer to be calibrated are immersed to the degree read. In practice small part of the column emerges from the bath to be read.

$\delta T_{steam} = 0$ $$u(\delta T_{steam}) = 0.006°C$$

- **δT_{bath}**: Correction linked the time stability and spatial homogenity of calibration bath.

$\delta T_{bath} = 0$ $$u(\delta T_{bath}) = \sqrt{u_{ts}^2 + u_h^2} = 0.010°C$$

Uncertainty linked with instrument to be calibratied

- **δT_{zero}**: Correction linked to the change of zero value of the thermometer to be calibrated before and after calibration. (Uncertainty linked to the interpolaton)

$\delta T_{zero} = 0$ $\quad u(\delta T_{zero}) = 0.006°C$

- **δT_{interp}**: Correction linked to the interpolation of instrument under calibration. Operator is capable of interpolating the readings of reference themometer to the fifth of a division (scale division 0.1°C):

$\delta T_{interp} = 0;$ $\quad u(\delta T_{interp}) = \dfrac{0.1 \cdot \frac{1}{5}}{2 \cdot \sqrt{3}} = 0.006°C$

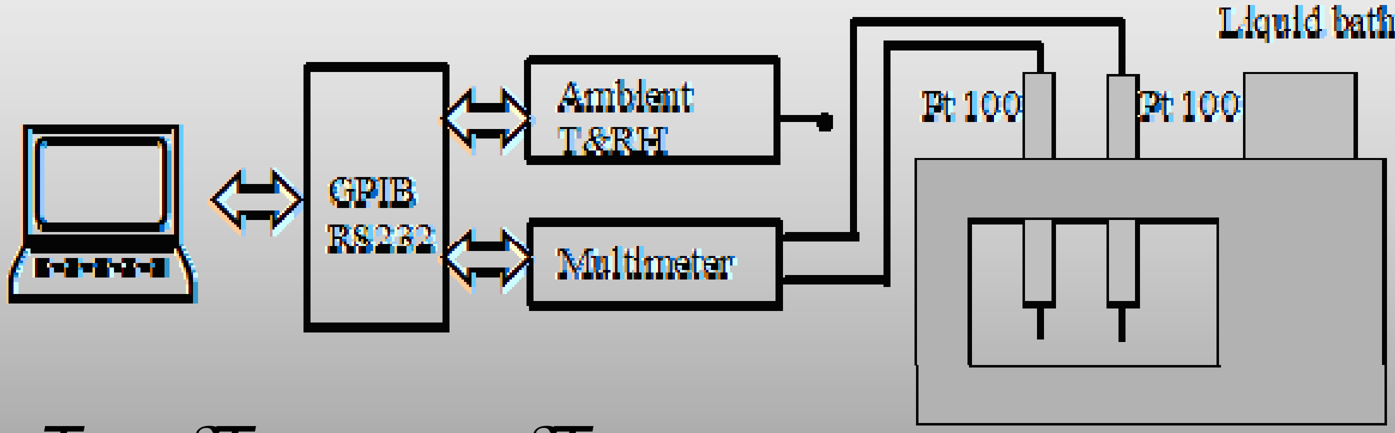
Uncertainty budget of Lig thermometer calibration

Quantity	Symbol	Value/ corr. [°C]	Standard uncert. [°C]	Prob. law	Sensitivity coefficient	Uncertainty contribution [°C]
Reference thermometer reading	δTr	**20.22**	0.006	Rect	1	0.006
Instrument under calibration reading	δTc	**20.02**	0.006	Rect	1	0.006
Reference thermometer interpolation	$\delta T_{Rinterp}$	0	0.006	Rect	1	0.006
Reference thermometer calibration	δT_{Rcal}	-0.1	0.075	Normal	1	0.075
Reference thermometer drift	δT_{Rdrift}	0	0.006	Rect	1	0.006
Reference thermometer emerging steam	δT_{steam}	0	0.006	Rect	1	0.006
Bath stability and homogenity	δT_{bath}	0	0.010	Normal	1	0.010
Change in zero value	δT_{zero}	0	0.006	Rect	1	0.006
Interpolation of instrument under calibration	δT_{interp}	0	0.006	Rect	1	0.006
Correction		**0.10**				**0.078**

Result: 0.10°C±0.16°C (k=2)

Resistance thermometer calibration

- By comparison with our reference standard Pt_{100}
- 7 temperature calibration points in the range from -20°C to 40°C (10°C step)
- Liquid bath without thermal block
- Using multimeters for data acquisition



$$Tc = Tr + \delta T_{acquisition} + \delta T_{bath}$$

- ✓ Tc: temperature of the thermometer to calibrate
- ✓ Tr: temperature of the reference
- ✓ $\delta T_{acquisition}$: correction linked with the data acquisition
- ✓ δT_{bath}: correction linked with the liquid bath

Uncertainty contributions of reference instrument

- Repeatability of measurements during a calibration
  - At least 50 (typically 100) measurements at each calibration point
  - Standard deviation $u_{RAtype} = 0.002°C$

- Correction linked to calibration of reference thermometer. The certificate states correction polinoma cofficients and expanded uncertainty 0.29°C
  - Corrections must be applied
  - Calibration expanded uncertainty: 0.029 °C (k=2)

$$u_{calib} = \frac{0.029}{2} = 0.0145°C$$

- Drift of working standard is based on the maximal difference between 2 calibrations (0.01°C)

$$u_{drift} = \frac{0.01}{\sqrt{3}} = 0.0058°C$$

Uncertainty contributions of reference instrument

- Thermal coupling with the surroundings
  - Tests at different immersion depth
  - Rectangular law

$$u_{coupling} = \frac{0.0055}{\sqrt{3}} = 0.0032°C$$

- Self-heating of reference thermometer
  - Corrections are applied
  - From the measurement of self heating

$$u_{heat} = 0.002°C$$

Uncertainty contributions of calibrated instrument and bath

- Resolution of calibrated instrument
- Repeatability: maximum standard deviation during the calibration
- Self-heating: with 2 electric currents (1mA and √2 mA)

$$R(0mA) = 2 \cdot R(1mA) - R(\sqrt{2}mA)$$

- Uncertainty due to time stability and spatial homogenity of calibration bath.

$$u(T_{bath}) = \sqrt{u_{ts}^{2} + u_{h}^{2}} = 0.010°C$$

Uncertainty contributions of data acqusition unit

- Uncertainty due to calibration of multimeter $u_{dmm} = 0.0013°C$
- Uncertainty due to time stability of multimeter $u_{ts} = 0.0009°C$
- Uncertainty due to ambient temperature influence $u_{ambient} = 0.0002°C$
- Multimeter resolution – least significant bit LSB $u_{resol} = 0.0001°C$
- Multimeter additional noise $u_{resol} = 0.0001°C$
- Uncertainty linked to the connection: The reference probe is four wire connected to multimeter and the uncertainty associated with the connection is taken to be negligible.

Calibration result

- Data supposed to be independent or non-correlated
- Expanded uncertainty:

$$u_c^{\,2} = \sum u_i^2$$

$$U = 2 \cdot u_c$$

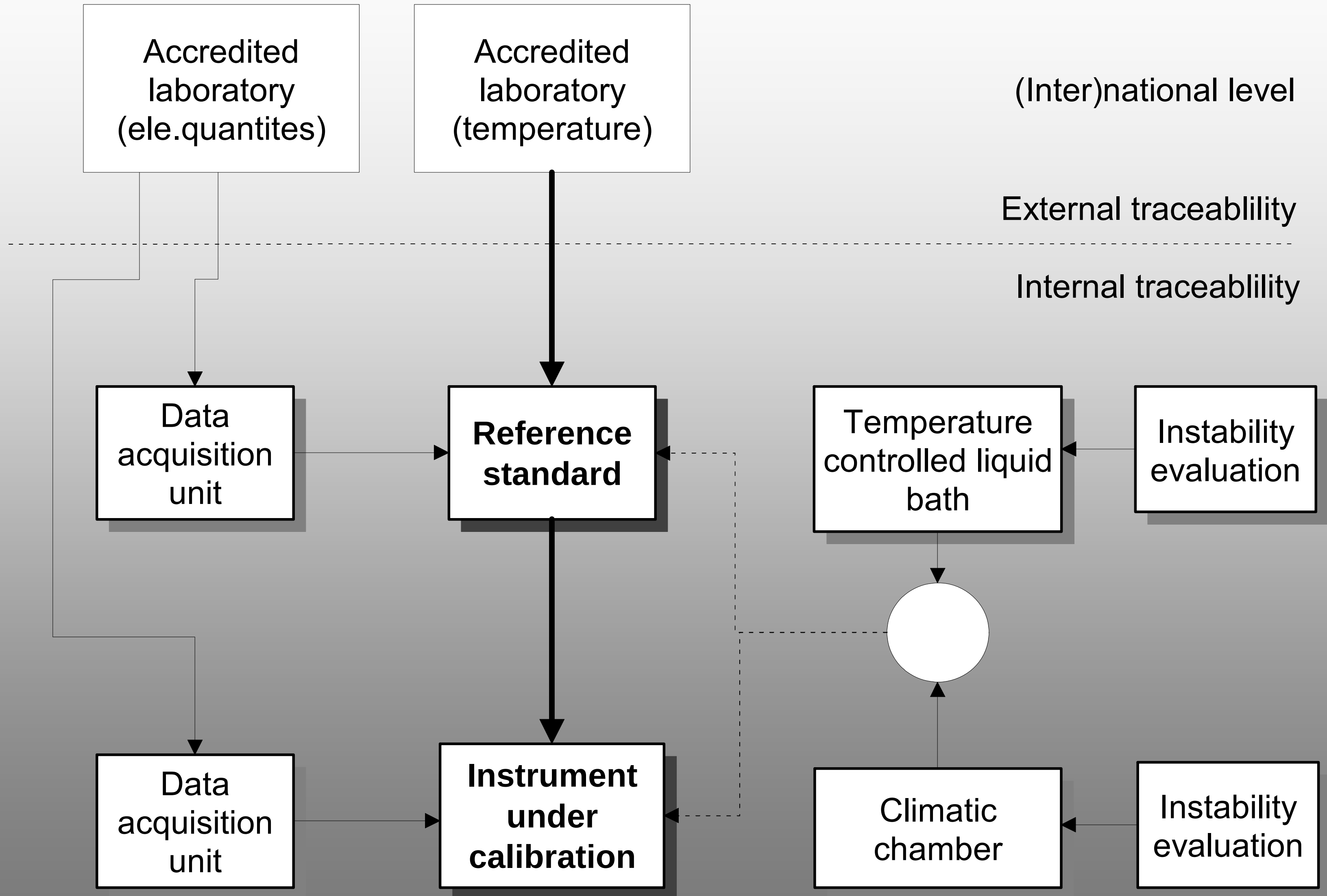
- Example of the result:

T_s	T_x	T_k	U
[°C]	[°C]	[°C]	[°C]
-19.87	-20.04	0.17	0.05
-9.82	-9.82	0.00	0.05
0.15	0.21	-0.06	0.05
10.15	10.08	0.07	0.05
20.18	20.07	0.11	0.05
30.17	30.21	-0.04	0.05
40.07	40.26	-0.19	0.05

Legend

T_S *Value determined by the reference instrument*
T_x *Value determined by the instrument under calibration*
T_k *The correction*
U *The expanded measurement uncertainty of the correction*

Traceability chart



Conclusion

- Neither an easy definition or measurement but a lot of different types of sensors
- Choice according the use
- In meteorology, the more common are:
  - Liquid-in-glass thermometer
  - Resistance thermometer

No adjustment
Accept or reject according the requirements (class A, B…)