Calibration and uncertainty for air temperature measurements

Stephanie Bell, Peng Miao, Jenny Wilkinson, Michael de Podesta
National Physical Laboratory

Metrology for air temperature
9 December 2014
Contents

- Temperature calibration in air at NPL
- Improvement of uncertainties
- Experiments in moving and still air
The needs and traceability

Air temperature measurements with uncertainties less than 0.1 °C to 0.2 °C are needed for various applications.

Uncertainty at:

Primary laboratory

↓

Secondary lab(s)

↓

User

<< ± 0.1 °C

± 0.1 °C to ± 0.2 °C

One or more steps ...

Thermometer calibration uncertainty is significant. Uncertainty accumulates at each step. Top-level uncertainty needs << 0.1 °C
The needs

Thermometer calibration in liquid bath can have small uncertainty (at best a few millikelvin)

- But use in air incurs some extra uncertainty – different thermal medium
- Can the user judge the added uncertainty?

Thermometer performance is affected by medium (air)

- effects of electrical self-heating, stem conduction, others
- typical calibration in liquid bath may not reproduce conditions of use

Calibration in medium of use (in air) allows relevant uncertainties to be included at time of calibration
Temperature calibration in air at NPL
Towards improved calibrations

- Established NPL air temperature calibrations (together with wide scope of humidity work)
  Ranger -40 °C to +100 °C
  *Expanded uncertainty* $U = \pm 0.08 \, ^\circ C$ ($k=2$, coverage probability of 95 %)

- Target improvement $U < 0.05 \, ^\circ C$ in range -20 °C to +50 °C

- Aspects of improvement:
  - upgrading of facilities
  - improvements in uncertainty
  - tests under varying airflows

*Smaller uncertainties require work*
- extra measurements, selectivity, specialisation
NPL air temperature calibration facilities

• 2 to 4 reference PRTs bracketing working air-space
• Fluid-jacketed chambers with good
  ➢ stability
  ➢ uniformity (best over small working space and moderate temperatures)
• Real-time measurements of stability and uniformity, and individually calculated uncertainty
New and improved equipment and sensors
Thermometers obtained for experimental use

- A variety of conventional PRTS, thermocouples and thermistors
- Specialised meteorological open-loom fine-wire PRTs for ground-based use (University of Reading) – fast, low self-heating, low surface area
- Specialised semi-open loom and thin-film PRTs for aircraft-borne atmospheric measurements (FAAM) – for high airspeeds
- Specialised quartz crystal resonator thermometers (ISSP, Bulgaria) – low self-heating
New and improved equipment, and sensors

- Larger TAS Series 3 ITCL/LT climatic chamber range -75 °C to +180 °C.
- Additional Isotech “MicroK” temperature bridge and channel expander
- Testo miniature airflow tunnel and air velocity sensors
- New reference PRTs
- Additional thermometers for study purposes
  - A variety of conventional PRTS, thermocouples and thermistors
  - Some specialised and novel temperature sensors for demonstration purposes
Typical main sources of uncertainty for temperature calibrations in air

- Chamber air temperature non-uniformity
- Chamber air temperature instability
- Reference thermometer
  - calibration uncertainty
  - drift (between calibrations)
  - self-heating
  - stem or lead conduction (heat leak)
- Electrical measurements (resistance bridge or multimeter)
  - calibration, drift, etc …
Approach to improving measurement uncertainties
**Uncertainty approach**

Past uncertainties based on operational criteria feeding into uncertainty

<table>
<thead>
<tr>
<th>Source of Uncertainty</th>
<th>Value</th>
<th>Probability Distribution</th>
<th>Divisor</th>
<th>Standardised °C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chamber uniformity</td>
<td>0.0600</td>
<td>rectangular</td>
<td>1.7321</td>
<td>0.0346</td>
</tr>
<tr>
<td>PRT drift</td>
<td>0.01</td>
<td>rectangular</td>
<td>1.7321</td>
<td>0.0058</td>
</tr>
<tr>
<td>PRT self heating</td>
<td>0.023</td>
<td>rectangular</td>
<td>1.7321</td>
<td>0.0133</td>
</tr>
<tr>
<td>Chamber stability</td>
<td>0.0110</td>
<td>normal</td>
<td>1.0000</td>
<td>0.0110</td>
</tr>
<tr>
<td>PRT calibration</td>
<td>0.015</td>
<td>normal</td>
<td>2.0000</td>
<td>0.0075</td>
</tr>
<tr>
<td>Bridge drift</td>
<td>0.01</td>
<td>rectangular</td>
<td>1.7321</td>
<td>0.0058</td>
</tr>
<tr>
<td>Bridge resistance</td>
<td>0.005</td>
<td>normal</td>
<td>1.0000</td>
<td>0.0050</td>
</tr>
<tr>
<td>Bridge variability</td>
<td>0.005</td>
<td>normal</td>
<td>1.0000</td>
<td>0.0050</td>
</tr>
<tr>
<td>Dew Point stability</td>
<td>0.011</td>
<td>normal</td>
<td>1.0000</td>
<td>0.0030</td>
</tr>
<tr>
<td>PRT non linearity</td>
<td>0.005</td>
<td>rectangular</td>
<td>1.7321</td>
<td>0.0029</td>
</tr>
<tr>
<td>PRT hysteresis</td>
<td>0.005</td>
<td>rectangular</td>
<td>1.7321</td>
<td>0.0029</td>
</tr>
<tr>
<td>Bridge repeatability</td>
<td>0.002</td>
<td>normal</td>
<td>1.0000</td>
<td>0.0020</td>
</tr>
<tr>
<td>Bridge resolution</td>
<td>0.001</td>
<td>rectangular</td>
<td>1.7321</td>
<td>0.0006</td>
</tr>
</tbody>
</table>

**Existing limits set:**

**Sources of error?**

- Chamber uniformity
- PRT drift
- Self heating
- Chamber stability
- Dew point stability

**Limit set °C**

- Max 0.060
- 0.01 to 0.045
- 0.023
- Max 0.011

**Largest components of uncertainty targeted for reduction**

Expanded uncertainty using a coverage factor of \( k = 2 \)

0.0839
Uncertainty improvements (largest ones)

Calibration uncertainty of reference thermometers
- Allowance was up to 0.015 °C
- now $U=0.005$ °C to 0.010 °C ($k=2$, 95 % conf.)

Self-heating of references estimated worst case effect (difference in air)
- Allowance was up to 0.023 °C
- now 0.010 °C

- Estimated long term drift of reference thermometers
  - was 0.010 °C (generalised worst case) –
  - now 0.05 °C to 0.08 °C, from -20 °C to +50 °C depending on temperature, for PRTs with demonstrated stable history
Uncertainty improvements (largest ones)

Short term stability during calibrations
- Generalised allowance of up to 0.011 °C (standard uncertainty) is improved by real-time specific measurements

Chamber uniformity during calibrations (working space)
- Worst-case allowance of up to 0.06 °C (standard uncertainty) is improved by real-time specific measurements (better at moderate \( T \), with some air stirring, or in sub-chamber)
- Some work also on use of stirring
Uncertainty improvement

The improvement strategies summarised:

- Instead of generalisation: specialisation
  - such as by range – lower uncertainties at “easier temperatures”

- Real-time measurements of influence variable
  - not worst-case general estimates

- Selecting best-performing reference PRTs
  - less-good ones → non critical uses

- Uncertainty re-evaluation every time – case by case, not generalised

Reducing uncertainty takes work
Modelling is not enough by itself, the improvements must be achieved.
Other aspects of best practice

**Use of a sub-chamber** – can damp fluctuations due to climatic chamber control cycles

**Immersion** – aim to completely immerse the sensors in the thermal medium (chamber) to avoid heat leaks across different temperature zones.

**Avoidance of lead conduction** - heat can leaks along cables: minimise this by placing the sensor leads mainly inside the chamber if possible.

**Screening from thermal radiation** - chambers that have heating and cooling elements in line of sight. Fluid-jacketed chambers usually have more thermally uniform surfaces.

Plus others …
Flow testing of thermometers
Thermometers in flowing air

- Thermometers and other sensors can be affected by still/flowing air
  - Self-heating, turbulence ...
- Calibration usually does not test these effects

- For PRTs with electrical resistance bridge measurements – effect of self-heating can be measured by applying variations in current (power) supplied to sensor
  - Effect of self-heating can vary from single millikelvins to ~0.1 °C
  - But not all thermometers can be tested this way

- An alternative is to vary airflow to detect self heating
- We studied this using miniature wind tunnel and air velocity sensors, and combinations of thermometers
Varying airflow to study thermometers

Testo mini wind-tunnel
- air velocities up to 10 m/s
- usable at range of temperatures
- air enters via laminar flow element (profile studied)
- fan is last component (suction)

Not quite simple:
- Inside of wind tunnel is at $\Delta P$ from outside (of course!)
- $\Delta P$ causes $\Delta T$ – approximately adiabatically
- Inside and outside of wind tunnel can differ by $\sim 0.3 \, ^\circ C$ (more or less for different flow rates)
  - After each change, tunnel walls need to stabilise at new $T$
- Conclusion: data analysis in terms of difference to subtract effects wherever possible
Varying airflow to study *selected* thermometers

Ignore absolute values (offset – not of interest here)

Several interesting effects:

- Temperature cycling can be seen
- Bare wire sensors track fast fluctuations
- More fluctuations with flow on (effects of turbulence?)
- Flow step up/down not symmetrical
- The step is not the sensor self-heating (it is pressure-heating of flowing air)
- Need to analyse differences
Varying airflow to study thermometers

Analysis in terms of difference:

- At each change in flow, sheathed PRT takes minutes to settle (even for \( \sim 0.5 \, ^\circ\text{C} \) step)
  - We discard that data for difference analysis
- Bare-wire PRT and TC not expected to self-heat

Noise in data increases uncertainty in mean value.
Varying airflow to study thermometers

Difference in temperature reading: any change with varying airflow could indicate self-heating

Change \sim (0.05 \pm 0.03) \degree C

\begin{align*}
U &= 0.007 \degree C \\
U &= 0.011 \degree C \\
U &= 0.022 \degree C \\
U &= 0.030 \degree C
\end{align*}

Uncertainty in mean value increases for noisy data
But subtraction cancels many aspects of uncertainty
Further investigation

- We studied thermometers in airflows of 0 to 10 m/s
- But we saw a number of effects we did not understand
  - due to air temperature changes, or sensor response, or airflow phenomena?
- Tried
  - wind-tunnel inside climatic chamber
  - … with chamber control switched off
  - well-controlled laboratory space
- Finally, close-control dimensional laboratory
  - better than 0.1 °C (actually much better over small working space)
Further investigation

Wind tunnel used in climatic chamber, but cycling conditions not ideal

Figure 12: Influence of airflow on temperature measurement at 0°C
Dimensional lab at NPL - stability, uniformity better than 0.1 °C Could be more suitable test environment (at 20 °C)
Question - could this be partly a "greenhouse effect?"
TC 1: On top of the wind tunnel (white)
TC 4: In wind tunnel: poking through laminar flow element
TC 3: On top of pipe
TC 2: In pipe

Could this be partly a “greenhouse effect?”
No airflow

Perspex wind tunnel
- Inside
- Outside

Outside
- Inside

Black plastic pipe
Still working on it …

The lesson:

Even with
• fast measurements
• fine resolution
• highly controlled conditions
• simplified experiment

experiments with air temperature measurement can be difficult.
Acknowledgements

This work was carried out as part of the EMRP collaborative project *MeteoMet* – Metrology for Meteorology (JRP ENV 07).

It was co-funded by the UK National Measurement System Programme for Engineering and Flow Metrology.

The EMRP is jointly funded by the EMRP participating countries within EURAMET and the European Union.

We gratefully acknowledge

- Prof Giles Harrison of University of Reading UK
- Alan Woolley of FAAM
- Prof Lozan Spassov of ISSP, Bulgaria

for supplying novel air temperature sensors to the project.