Traceability transfer in high accuracy contact temperature measurements for length interferometry

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Abstract: Some relevant components of uncertainty in interferometric measurements are associated with temperature measurements of material standards. This paper proposes a traceability transfer chain through a high accuracy contact temperature measurement system towards other temperature measurements systems. Those are traced to the best national metrological references in appropriate configurations for gauge-block length calibrations, allowing in that way investigations of effects and uncertainty components linked to temperature measurement of those blocks as further reductions in these uncertainties. As an application example a study of temperature gradients on gauge blocks is shown.

1. Introduction

Dimensional precise definitions for the length of any materialized artifact undergo exact measures its temperature at the instant of its dimensional measurement, and the uncertainty components of this magnitude is directly proportional to the sizes measured. Contact measurement systems have been specially developed in the Interferometry Laboratory of Optical Metrology Division of the Brazilian National Metrology Institute - INMETRO – as seen in references [1] and [2], aiming to significant reductions in uncertainty propagation over the entire traceability chain. This should cover all the chain since the primary standards and national references until the temperature sensor systems and readers used in synchronous temperature measurements obtained in high accuracy interferometric measurements. This method is commonly used in commercial length calibration services for gauge blocks of best classes, which are the transfer standards "par excellence" of industry for length unit. The reduction of uncertainty components in this type of measurement is linked to a detailed definition of various auxiliary quantities, and of those components with higher relative weight associated with temperature measurements.
2. Traceability Chain in Temperature & Length

To perform the realization of temperature scale standards internationally known as fixed points are used, in which the reference temperatures of phase transitions are kept stable for long times.

Whereas the dimensional measurements are performed around the reference temperature of 20 °C the standards most suitable for checking the measurement system are the triple point of water cells (reference temperature = 0.01 °C) and the melting Gallium cells (reference temperature = 29.7646 °C). Thermal Metrology Division (Diter) of INMETRO maintains cells of these types as references in international comparisons and for periodic checking of the measurement systems used in regular calibration services. The temperature reading systems used in interferometric measurements, whose measurement values affect the final result in length, should be periodically sent for calibration. However, the offered temperature calibration service is carried out through comparisons with systems directly traced to the fixed points. In those systems the sensors involved are not held in physical contact with a solid medium as in the usual operation of gauge block measurements. Instead they are measured after thermal equilibrium in a water, oil or air bath, including a possible extra insulation to prevent undesirable leakages inside the sensor body immersed in the heat transfer media. These methodological differences produce higher final uncertainties, requiring application of long time thermal exchange, thus reaching minimum conditions of thermal equilibrium for a given uncertainty after those times. Some temperature uncertainty contributions in block measurements were discriminated by Decker and Pekelsky [3].

3. High Accuracy System of Temperature Measurements

Aiming to minimize undesirable effects and to achieve best adequacy in reasonable time a contact measurement system was designed, which consists of a temperature bridge read by a locally developed automated software and the a standard resistor thermostatically stabilized with nominal value 25 Ω, and a long metal sheath 25 Ω SPRT of high quality and stability. The SPRT is kept in direct physical contact with the sensor to be compared, both being carefully positioned within a good thermal insulated Dewar. This contact is accomplished through a simple related material structure comprising a copper block with a hole for long sensors and a second block with similar dimensions to the artifact to be measured by the intended sensors. The whole system should be checked periodically against the two fixed points cited, and from these checks are produced high accuracy estimates both of their direct corrections as the coefficients of variation of the reference sensor resistance, therefore closing the traceability chain in an appropriate form for this system. The assembly is simple and fully reproducible by any metrology lab with the access to high accuracy temperature references such as the fixed points. Some images of the system can be seen in Figure 1. This system also allows the verification of other high accuracy sensors. Such sensors can, from this type of scan, be used in studies and tests of tiny effects than their direct temperature measurements. These effects are linked to both temporal / spatial evolution of artifact temperatures as also to their material propagation (for interesting case studies on these small variation scales, realized by specific type sensors, see refs. [1], [2] and [4]).
Figure 1. Temperature Measurement Systems

In Figure 2 we have the schematic view of the traceability chain, which spreads from checks against national temperature standards, having reduced uncertainty propagation, from the comparison system developed and its contact block measurement systems, until the final application steps. These steps are related to measurement of effects associated with waiting time for thermal equilibrium and gradients generated dynamically inside gauge blocks to be calibrated by interferometric measurement systems.

Figure 3. Traceability Chain

3.1. Uncertainty Propagation

From Table 1 we have presented a budget showing contributions from various elements of temperature measurement comparison system. From these values the greatest contributions for uncertainty propagation in all steps refers themselves to inner gradients linked to the verification process (without
considering external factors such as aging of electronic components, sensors jitter / drift, large temperature differences towards the reference temperature, degradation of fixed points, etc.).

| Components                        | Uncertainty Budget | c_i | u_i, c_i (mK) |
|-----------------------------------|--------------------|-----|---------------|
| Triple Point of Water             | 8.50E-02           | 1   | 8.50E-02      |
| Melting Point of Gallium          | 1.25E-01           | 1   | 1.25E-01      |
| **Uncertainties of Standards**    |                    |     |               |
| Bridge Temperature                | 3.10E-01           | 1   | 3.10E-01      |
| Gradient                          | 2.50E-01           | 1   | 2.50E-01      |
| Drift                             | 2.50E-01           | 1   | 2.50E-01      |
| **Measurement System Uncertainties** |                    |     |               |
| Resolution                        | 2.89E-02           | 1   | 2.89E-02      |
| Stability (4 hours)               | 1.30E-01           | 1   | 1.30E-01      |
| **Combined Uncertainty**          | 0.51 mK            |     |               |

4. System Operation Proposed Methodology

Studies realized at Interferometry Lab of INMETRO show marked differences in intrinsic response time of both compared sensors (due, for example, to their physical size) that may produce anomalous results in obtained corrections if instantaneous measuring speeds are not considered (see [1] and [2]). In Figure 3 there are presented some cycles of temperature variation whose amplitude differences were due to stepped variations and of different response times in both systems. To minimize these inaccuracies for every temperature change executed inside the Dewar (this step is essential to estimate variation coefficients of the respective sensors) it should be waited a required minimum time until the difference between both systems achieves reduced values and it is stable for long enough (shown in graph lower baselines). This condition is monitored by automating readings of both sensors. Such is the case of applications of a four-channel sensor digitizer used in gradient tests or a compound temperature bridge + scanner connected to six reduced size PT100 used in a commercial interferometer Mitutoyo GBI temperature reading system, both devices are operating in Interferometry Lab.
Figure 3. Evolution of the temperature difference between two sensors with different sizes and response times

5. Case Study: Gradient Measures in Gauge-Blocks
In Figure 4 two operating instances of a temperature measurement system with two PT100 connected to a gauge block of 100 mm are shown. In smaller ellipse we found reduced cyclical variations in temperature associated with night fluctuations in control room. Differences between values read from two sensors are due to their distinct deviations. In daytime, a heating caused by inner thermal sources after interferometer was switched on not only caused a progressive increase in the absolute temperature of the block as also of reading differences between both sensors, indicating the presence of dynamic gradient effects to be considered.
6. Conclusions
The proposed system was internally characterized and adequately compared to similar systems and
fixed points in Thermometry Metrology Division (Diter) of INMETRO, for its validation. Given the
requirements for high accuracy temperature measurements in interferometric systems, Diter staff can
still easily reproduce an identical system, intending future mutual periodic comparisons and, therefore,
a good warranty of long-term quality for these best defined results. Some isolated uncertainty
components of the system must still be evaluated, as well as certain effects and additional
contributions, such as electrical noise, characterization of immersion depth in fixed-point cells
thermometric wells, and setting limits on waiting times for thermal stabilization. Calculation routines
for computing effects associated with possible dynamic variations in compared systems were
developed, settling it in a measurement form very similar to that used in gauge blocks measurements.

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Figure 4. Temperature evolution at two instances for a 100 mm gauge block