Special Interest Group Meeting on Thermal Issues
ETH, Zurich, Switzerland, March 2022
www.euspen.eu

Performing absolute temperature measurements for length metrology applications using a digital multimeter

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Abstract
To perform traceable temperature measurements for length metrology applications we stabilized a digital multimeter using two reference resistors. For the monitoring of several temperature sensors we added a cross switch box and a computer that controls the measurement process. To prove the concept, we investigated the repeatability of standard platinum resistance thermometer (SPRT) measurements at the gallium melting point, the self-heating of a SPRT and the calibration of SPRTs in a metal block calibrator with respect to a calibrated SPRT in the temperature range between 18 °C and 22 °C. The repeatability of the SPRT measurements remained below 0.1 mK and the self-heating for a measurement current of 1 mA was estimated to 0.3 mK. In the evaluation of the calibration data of the SPRTs the maximum of the fit residuals remains below 0.2 mK using a quadratic least-squares-fit. The measurement uncertainty of the temperature measurement system is currently limited by the calibration of the nonlinearity of the multimeter.

Keywords Digital multimeter, temperature measurement, Standard Platinum Resistance Thermometer, self-heating, calibration

1. Introduction

Temperature is one of the most important influence factors in length metrology applications. Not only that the length of measurement objects needs to be corrected to 20 °C but also measurement instruments are sensitive to temperature changes. Therefore, usually a larger number of temperature sensors is required for the correction of the thermal influences and the surveillance of the environment. The first aspect becomes particularly important when optical interferometers are used as displacement / position sensor. Except for the most advanced applications a measurement uncertainty of ten Millikelvin (mK) is sufficient.

Most often platinum resistance thermometers or thermistors are used for this purpose. In some applications thermocouples are advantageous due to their small dimensions. In addition, they do not suffer from self-heating effects. But if absolute temperature measurements are required then an additional absolute temperature sensor at the reference junction is required.

To reach a total expanded measurement uncertainty of ten mK the temperature measurement system needs to achieve a reproducibility well below this value, because the system needs to be calibrated, the self-heating has to be determined and if a block calibrator or a calibration bath are used, the temporal and spatial temperature distribution have to be characterized in addition.

Usually, AC and DC bridges are employed to perform highly accurate temperature measurements. But due to the large number of required sensors these bridges are too slow. In addition, they are rather expensive which usually does not allow to operate a greater number of them.

We therefore developed a thermocouple measurement system that reached a long-term stability of about 0.1 mK using a digital multimeter together with home-built cross switchboxes [1]. The chosen digital multimeter provides an accurate voltage and resistance measurement capability. Unfortunately, the related long-term specification for the resistance measurement is not sufficient to achieve an uncertainty below 10 mK. But this problem can be eliminated if reference resistors are measured regularly. This approach is not new [2] but it seemed not to be widely in use yet. In this contribution we will present an implementation of this method and provide experimental data that proves the concept. In addition, we discuss the main sources of measurement uncertainty of the measurement system.

2. Temperature measurement system

Fig. 1 shows the schematic layout of the measurement system. It consists of a multimeter, a switch box, temperature sensors and a computer.

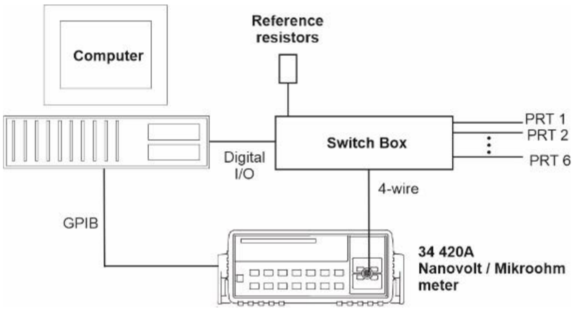

Figure 1: Components of the temperature measurement system.

2.1. *Multimeter*

Several vendors offer multimeter that are capable to perform resistance measurements with a relative uncertainty of at about 10^{-5} or below over a day. According to

$$\Delta T = \frac{\Delta R}{\alpha R} \tag{2}$$

the relative resistance uncertainty ΔR/R leads to an uncertainty of the temperature Δ*T* of about 2.5 mK or below if a platinum resistance thermometer (PRT, $\alpha \approx 3.93 \times 10^{-3}$/K) is used. We chose a Keysight 34 420 multimeter for the following reasons:

(a) Compared to the Keysight 3458A it showed a better repeatability and it has a 10 Ω range that extends to 12 Ω in practise, which suits the 10 Ω standard platinum thermometer that we use at room temperature also, well. In addition, the Keysight 34 420 allows to use different currents for the resistance measurements.

(b) The high performance Fluke and Keithley multimeters have 20 Ω and 200 Ω ranges. Again, the extended 10 Ω, 100 Ω range suits the 10 Ω, 25 Ω and 100 Ω PRTs that we intend to use much better.

During the measurements presented here the four wire mode was used and the integrated correction features of the multimeter were turned off. Except for the determination of the self-heating, the measurement current was always 1 mA. The 24 hour accuracy is specified with 20 μΩ /Ω*R_{max} + 15 μΩ / Ω*R (Low Power Mode) in the 10 Ω and 100 Ω range. In addition, the multimeter was calibrated at PTB with an uncertainty of 10 μΩ / Ω*R.

2.2. Relay s*witch box*

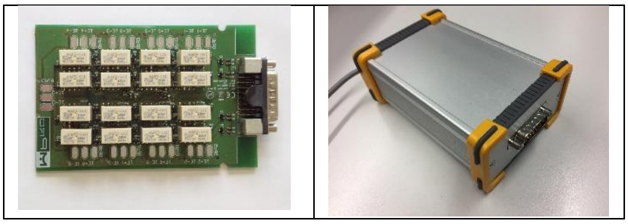

Figure 2: a) switch box circuit board b) switchbox.

The home-built switch box shown in **Error! Reference source not found.**2 consists of two circuit boards. The first is equipped 16 relays, which are pairwise connected to form a cross switch. This allows to connect 8 resistors to a single multimeter in both polarities. A second circuit board with 8 relays is used to link the sense current in a 4-wire connection style. The corresponding schematic is shown in Figure 3. Two of the eight channels are used for the reference resistors while the others are linked with PRTs. The capability of reading the sensors in both polarities allows to compensate for parasitic thermoelectric voltages and static offsets, while the two reference resistors compensate for drift influences.

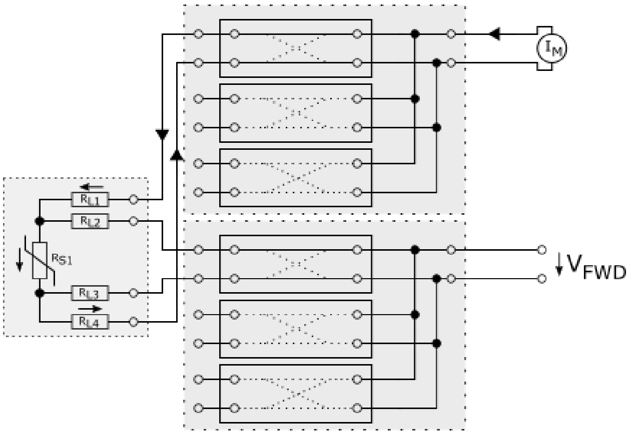

Figure 3: Schematic of two switchboxes for 4-wire sensor readout.

2.3 *Reference resistors*

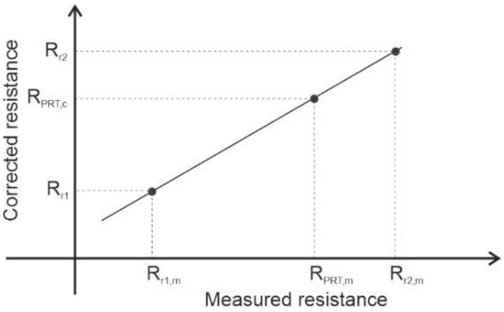

Figure 4: Illustration of the correction applied to the measured resistance values of the PRTs.

We use two reference resistors. They are chosen such that the value of the smaller one is close to the lower level and that the value of the larger one is close to the higher level of the expected resistance values of the PRTs. Because the long-term stability and the temperature dependence will limit the performance these resistors have to be selected carefully. We use a Tinsely reference resistor (type 5685, stability 2 ppm/year, temperature coefficient: 2 ppm/K) that matches the lower value of the expected resistance range and a serial combination of this resistor and a small resistor for the upper value. In our experiments the temperature measurement range is restricted to 0.01 °C (triple point of water) and 29.76 °C (melting point of gallium) the value of the small resistor needs to be about ten percent of the other resistor (3 Ω for the 25 Ω SPRT and 1 Ω for the 10 Ω SPRTs). Therefore, its specification can be reduced considerably.

After all selected PRTs have been measured, the two reference resistors are measured. Then the correction illustrated in figure 4 is applied to the measured value of the PRTs. Let R_{r1}, R_{r2} be the correct values of reference resistors and $R_{1r,m}$, $R_{2r,m}$ and $R_{PRT,m}$ be the measured values of the reference resistors and the PRT under consideration. If the measurement deviations of the multimeter are constant over the time required to measure all the resistances, which is usually below 100 s, and if the nonlinearity of the multimeter is negligible then the corrected resistance value $R_{PRT,c}$ of the PRT

$$R_{PRT,c} = R_{r1} + \frac{R_{PRT,m} - R_{r1,m}}{R_{r2,m} - R_{r1,m}} (R_{r2} - R_{r1}) \qquad (1)$$

is exact. Note that in a ratio measurement mode offered by many multimeters only the constant term is corrected for.

2.4 Temperature sensors

Figure 5 shows a photo of the standard platinum resistors (SPRT) used in this investigation. A Rosemount model 162CE 25 Ω SPRT, which is calibrated by the PTB temperature department regularly, serves as reference. Two old quartz 10 Ω SPRT produced at the Thermometer Geraberg were used in the basic investigations and were calibrated using the aforementioned Rosemount SPRT and a metal block calibrator.

Figure 5: Photo of the chosen 10 Ω and 25 Ω SPRTs.

2.5 Computer control

The computer controls the whole measurement process. It switches between the reference resistors and the different temperature sensors and changes the direction of the measurement current. Then it starts the data acquisition, collects the data, calculates the temperatures according to the ITS 90 [3] and saves the acquisition times, raw resistance data, the corrected resistance values calculated according Eq. 1 and the resulting temperature values calculated using additional calibration data. The acquisition time is used to select the relevant values in other applications. The data is accessed over the internet.

Here a Raspberry Pi 3b [4] is used, see figure 6. It offers sufficient digital I/O lines to control the relays of the switchboxes.

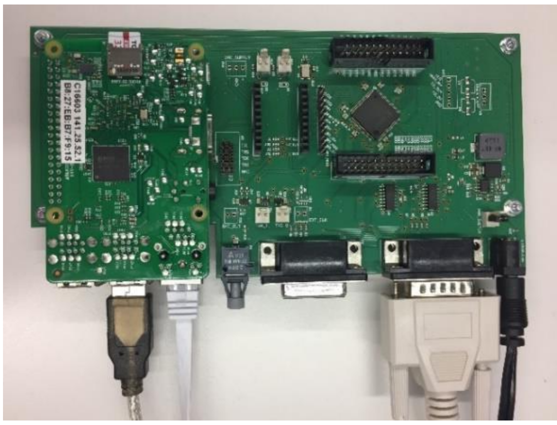

Figure 6: Raspberry Pi controller and switchbox interface.

We also implemented the programme on a PC running under Windows using an additional digital I/O card.

A USB to GPIB converter links the multimeter with the Raspberry Pi. A C-program iterates through the 8 channels and reads the corresponding resistance from the multimeter.

3. Experimental results

The temperature measurement system was placed in a temperature-controlled measurement room that is specified with +/- 0.1 °C. The reference resistors were put in a polystyrene box to reduce the influence temperature fluctuations of the air.

3.1 Repeatability test

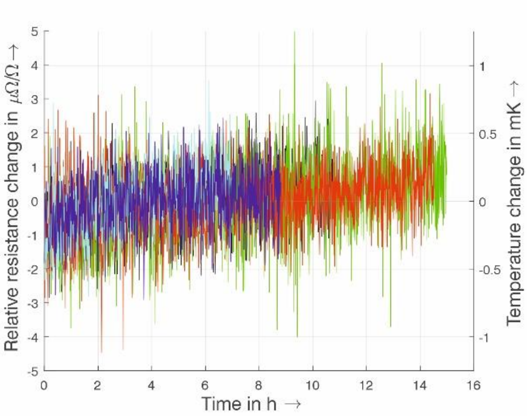

Figure 6: Variation of the relative resistance of a 10 Ω PRT of the five measurements at the Gallium melting point.

To verify that the use of the reference resistors leads to the desired improvement of the measurement stability a 10 Ω PRT was investigated in a gallium cell. The measurements were repeated five times. The variation of the relative resistance (R_{rel} =(R-R_m)/R_m, where R_m equals the mean of R) data is shown in figure 6. The right y-axis illustrates the related temperature variation calculated according to Eq. 2. The linear drift of approx. 0.7 mK/12 h is caused by the gallium cell. The peak-to-peak noise is slightly greater than 1 mK. The averages of the 5 measurements vary by 2.8 μΩ, which results in a standard uncertainty contribution smaller than 0.07 mK. We like to note that the gallium cell was calibrated with an (2σ) uncertainty of 0.5 mK. The uncertainty is limited by the used cell itself. Therefore, the repeatability contribution, which includes the variations caused by the temperature measurement system, would not limit the measurement uncertainty when it would be calibrated at the water triple point and the gallium melting point.

3.2 Determination of the self-heating contribution

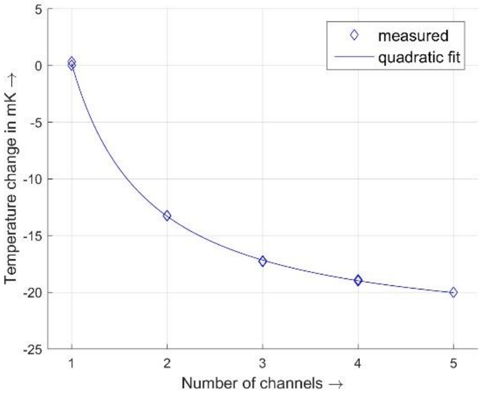

Figure 7: Self-heating of a Rosemount 25 Ω SPRT in the gallium cell.

Due to the measurement current heat is dissipated in resistive temperature sensors like PRTs or thermistors. The resulting temperature increase of SPRTs in fixpoint cells due to self-heating is usually in the range from 0.2 mK to 3 mK for a current of 1 mA [5]. It is approximately linear to the dissipated electrical power [5]. In addition, it depends on the sensor design, the surrounding medium and the measured temperature [5]. When industrial PT 100 sensors are used in air the self-heating can reach more than 100 mK [6]. The measurement of the reference resistors will also be affected by self-heating effects, however, due to the much smaller temperature coefficient the influence is negligible. By applying the correction according to Eq. (1) temperature related deviations caused by the multimeter will be reduced considerably as well. However, because the self-heating may lead to a significant uncertainty contribution the temperature measurement system needs to able to determine its size. While temperature measurement bridges allow to use many different currents only some multimeters can perform measurements with two different currents. These two currents are a factor of 10 apart. Another way to vary the heat dissipated in the sensor is to change the cycle time for example by changing the number of channels that are measured during one cycle. To be able to use just one channel, the reference resistors are not measured in this investigation and therefore the correction using Eq. 1 is omitted. The results obtained in this way using a 25 Ω SPRT at the gallium point and a measurement current of 10 mA are shown in figure 7. Here a value represents an average of data taken in approximately 20 minutes. To detect drift influences the number of measured channels was increased from one to five and then decreased again from five to one. In order to quantify the self-heating contribution, the measured relationship is approximated by the function

$$\Delta T = c_o + \frac{c_1}{n} + \frac{c_2}{n^2} \tag{3}$$

Here ΔT and n denote the temperature increase due to self-heating and the number of channels measured. Eq. 3 needs to be interpolated to the case of zero current, which is equivalent to the case that n is increased to infinity. So, the offset c_o equals the maximum self-heating contribution. The fit leads to a value of 29.8 mK for c_o for a current of 10 mA. Note that the influence shows a quadratic dependence on the measurement current. Therefore, the influence will become 0.3 mK when the measurement current is reduced to 1 mA so that the related uncertainty contribution remains sufficiently small.

3.3 Calibration of SPRTs in a metal block calibrator

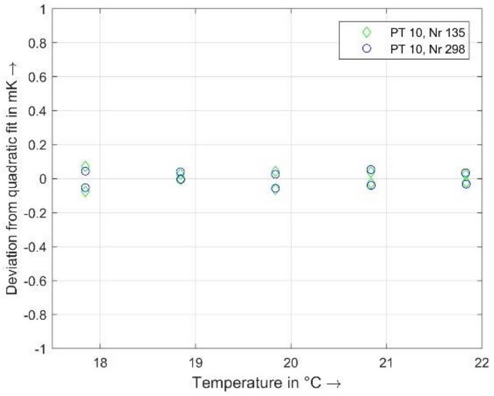

Figure 8: Fit residuals of 2nd order least-squares fit using the resistance values as independent variable.

In this experiment two 10 Ω and one 25 Ω SPRT are located inside a metal block calibrator [7]. We used here an additional 10 Ω and 11 Ω reference resistor for the correction of the 10 Ω SPRTs according to Eq. 1. To improve the thermal contact between the SPRTs and the metal block distilled water was used. Subsequently, the metal block was heated up from 4 °C to 30 °C and cooled down back to 4 °C. Because this version of the block calibrator has no computer interface the temperature had to be adjusted manually. Therefore, only the temperatures 4 °C, 10 °C, 14 °C, 18 °C, 19 °C, 20 °C, 21 °C, 22 °C and 30 °C were chosen. At each step data is collected for more than ten hours. The whole calibration cycle lasted two weeks. The data in the stable range of the plateau is averaged and used to calibrate the 10 Ω PRTs. The 25 Ω SPRT has been calibrated by the temperature calibration facility of the PTB at the H_2O triple point and the Gallium melting point with an expanded uncertainty of 1 mK. Because we focus on the use of temperature sensors for length metrology applications only, the limited temperature range from 18 °C to 22 °C is considered here in detail. For the later use a quadratic fit of the measured resistance values of the 10 Ω SPRTs to the related temperature values of 25 Ω reference SPRT is performed. The residuals of these fits are shown in figure 8. All points are all well below 0.2 mK.

4. Summary

The data of the repeatability study in section 3.1 and the data of the calibration of the 10 Ω SPRTs demonstrate that stabilization of the digital multimeter using two reference resistors works so well that repeatability and drift contribution remain much smaller than the systematic uncertainty contributions originating from the calibration of the used gallium cell and the reference SPRT.

In addition, we showed in section 3.2 that the self-heating influence can be determined experimentally by varying the number of channels that are measured in one acquisition cycle. The maximum contribution, that occurs in the gallium cell when only one channel is constantly measured is about 0.3 mK using a 25 Ω SPRT and a measurement current of 1 mA. But the self-heating contribution depends on the temperature and the surrounding of the sensor. Therefore, it needs to be determined when the setup or the measurement mode is changed because the heat flux from the temperature sensor into the environment may be different. Consequently, it has to be performed not only during the calibration of the sensors but also with the sensors installed at the location of the final application. However, it seems that the uncertainty contribution of the self-heating for contact thermometers can be reduced to values in the order of 0.1 mK.

The contribution of the multimeter nonlinearity has not been investigated in detail so far. Therefore, the value of 10 $\mu\Omega$ / Ω from the calibration of the multimeter has to be used in the uncertainty estimation, which leads to an uncertainty contribution of 2.5 mK. Here improvement might be possible through a direct calibration of the nonlinear deviation using resistance networks or a comparison measurement using a more accurate temperature measurement bridge. The determination of the nonlinearity will be pursued in the near future.

In addition, a new calibration bath will be used to replace the metal block calibrator. It offers a computer interface so that a calibration as described in section 3.3 can be performed in an automated manner. In addition, the temperature stability and inhomogeneity are much better. It also will allow to use a H_2O triple point so that temperature sensors can also be calibrated at the two relevant temperature fix points.

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[1] Certain equipment is identified here to provide an accurate description of the experiments performed here. This is neither an endorsement nor may it be the best equipment available of the intended purpose.