THE INFLUENCE OF THE RESISTOR TEMPERATURE COEFFICIENT TO THE UNCERTAINTY OF THE TEMPERATURE MEASUREMENT

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ABSTRACT

In this paper the influence of the resistor temperature coefficient to the uncertainty of the temperature measurement is presented. At the level of highest accuracy of the temperature measurements the standard platinum resistance thermometers (SPRT) in combination with an automatic resistance bridge and a standard resistor is used. The electrical resistance is like any other quantity more or less dependent on the temperature. This dependence is usually specified using the temperature coefficient, which gives the relative change of resistance, when the temperature changes for one °C.

A temperature coefficient is also temperature dependent, so the relation between an electrical resistance and a temperature is given using the polynomial equations. These equations have an inflection point at a certain temperature, where the derivative of the resistance change on temperature (temperature coefficient) is equal to zero. The knowledge of the temperature of the inflection point is very important, because the use of the standard resistor at this temperature greatly reduces the influence of temperature on the electrical resistance, even if the thermal conditions are not optimal, and thus enabling low uncertainty and accurate measurements of the temperature using a SPRT.

In the scope of this paper, measurements of the temperature coefficient are performed on series of a standard resistors in a wide temperature range and the temperature of the inflection point was determined for each standard resistor. All the measurements were performed by placing the resistors in an oil bath, where temperatures in the range from 19 °C to 37 °C could be precisely set. Electrical resistance of each resistor was measured using the precise automatic resistance bridge, which had its reference resistor placed in a separate thermal enclosure at constant temperature. Thus the resistor temperature coefficient of each standard resistor has been measured. It is influence to the uncertainty of the temperature measurement has been evaluated and uncertainty model presented.

INTRODUCTION

The electrical resistance of an electrical conductor is the opposition to the passage of an electric current through that conductor. Electrical resistance is like any other quantity more or less dependent on temperature. This dependence is specified using the temperature coefficient, which gives the relative change of resistance, when the temperature changes for one °C. Temperature coefficient is also temperature dependent, so the relation between the electrical resistance and temperature is given using the polynomial equations. These equations have an inflection point at a certain temperature, where the derivative of the resistance change on temperature (temperature coefficient) is equal to zero.

Standard platinum resistance thermometers (SPRTs) are one of the most accurate types of thermometers. According to the International Temperature Scale of 1990 (ITS-90) [1], t_{90} is in the range from –259.3467 °C to 961.78 °C defined by means of SPRTs, calibrated at specified sets of defining fixed points and using specified interpolation procedures. In order to use an SPRT to measure temperature accurately, we must first be able to measure the resistance accurately and only afterwards transform the measured resistance into temperature. A simplified description of resistance measurement can be reduced to applying a known measurement current I over the measured resistance R and measuring the voltage U. Usually, at the highest level of accuracy, resistance bridges are used in combination with the reference resistors. Resistance bridges used in thermometry are high accuracy measurement instruments that work on the physical limits of resistance measurement. Detailed analysis of the resistance measurement reveals several uncertainty sources [2,3], where in normal operating conditions the dominating source is the bridge nonlinearity. Bridge nonlinearity is a well-researched phenomenon with and special procedures and devices for its evaluation were developed, [4]. On the other hand, there are several other uncertainty sources, which may in certain condition represent a much higher and especially more unpredictable uncertainty contribution, especially if the measurement conditions are not perfect, [5]. Evaluation of these additional uncertainty sources, such as resistance value and temperature coefficient, is therefore essential even for the top level measurement laboratories with near-perfect laboratory conditions, [6].

NOMENCLATURE

R	[Ω]	resistance
t_{90}	[°C]	temperature in accordance with ITS-90
Special characters		
ppm	[-]	part per million
β	[1/°C]	the temperature coefficient of the resistor
Subscripts		
bath		temperature of the oil or air bath used to maintain the resistor during use
cal		the temperature of the bath used to maintain the resistor when it was calibrated
S		standard resistor

REFERENCE RESISTORS

Resistance measurements in platinum thermometry are usually made using automatic low-frequency resistance bridges, [3]. There are two basic types in common use: AC bridges using a sinusoidal sensing current in the frequency range 10 Hz to 90 Hz, and the so-called DC bridges, which use a low-frequency square-wave (AC) sensing current in the range 0.01 Hz to 1 Hz. The bridges used for SPRT resistance measurements typically have a resolution of six to nine digits and a specified uncertainty in resistance ratio of between 2×10^{-8} and 5×10^{-6}, corresponding to equivalent uncertainties in temperature measurements ranging from about 5µK to 2 mK, depending on the operating conditions. The bridges all employ a 4-terminal, or 4-terminal-coaxial, or guarded 4-terminal definition of resistance to reduce the effect of lead resistances and stray impedances. The major sources of uncertainty associated with the resistance measurements include the reference resistor value and its stability, and self-heating of the SPRT due to the sensing current. There are additional minor effects associated with the connecting cables and the resistance bridge itself. In this paper we are going to concentrate on temperature coefficient of used reference resistors. These reference resistors are placed in temperature stable environments (oil baths or special air temperature baths) with very stable and homogenous temperature.

Simple model for the temperature dependence of the resistance is described in equation 1:

$$R_S(t_{bath}) = R_S(t_{cal}) \cdot [1 + \beta \cdot (t_{bath} - t_{cal})] \qquad (1)$$

where t_{bath}, is the temperature of the oil or air bath used to maintain the resistor during use, t_{cal} is the temperature of the bath used to maintain the resistor when it was calibrated, and β is the temperature coefficient of the resistor. The temperature coefficient is normally expressed as the fractional change per degree; i.e.:

$$\beta = \frac{1}{R_S} \cdot \frac{dR_S}{dt} \qquad (2)$$

with typical values for good-quality resistors within the range $\pm5\times10^{-6}$/°C.

Until the discovery of the quantum Hall effect (QHE) in 1980,[7], most NMIs maintained national standards of resistance using 1 Ω wirewound reference resistors. Both 1 Ω and 10 kΩ resistors are used as traveling standards to compare resistance standards between laboratories. Finally, NMIs which do not possess QHR standards mostly use banks of 1 Ω standards as national standards, [8].

Starting in 1930, Thomas, at the National Bureau of Standards, designed [9] developed, refined and evaluated [10,11] a new type of 1 Ω standard resistor that was produced commercially by Leeds and Northrup (L and N) and is still very widely used in metrology laboratories. In Thomas' final design, the resistance coil is made up of a bifilar winding of 28 turns of 2.05 mm diameter manganin wire of nominal composition of 83% Cu, 12% Mn, 5% Ni and traces of Fe. To improve the stability of the resistance with time, the coils were annealed at 550 °C. The ends of the coil were connected via manganin terminal plates to four nickel-plated Cu terminals, two current terminals and two voltage terminals, making the resistor a four-terminal device. The resistance is defined as the potential difference across the voltage terminals divided by the current through the current terminals. Thomas chose the proportions of his alloy to achieve a low thermal emf with respect to Cu (2–3 µV/K) and a small temperature coefficient near room temperature.

The design of used Tinsley AC/DC Standard Resistors is based on work carried out over several years with co-operation of the National Physical Laboratory in Teddington, UK and Tinsley. The design originated with F. J. Wilkins of the N.P.L. and has evolved as the result of many tests on stability and temperature coefficient using both AC and DC [12].

The used Tinsley resistors are made from a specially selected alloy having a low temperature coefficient mounted in a strain free manner on formers made from material of low dielectric loss but of high mechanical stability. All the connections are welded. Prolonged heat treatment of the elements ensures long term stability and low temperature coefficient of resistance, [12].

The elements are hermetically sealed in stainless steel containers which are filled with dry oil (Castrol Whitemor WOM14), Figure 1. Provision is made for inserting a thermometer but the resistors are intended to be used in an oil bath which is temperature controlled. Tests have shown that resistors of this type are stable to within 1 ppm over a period of ten years [12]. These resistors are widely used in thermometry community

Figure 1 Tinsley wirewound reference resistor

Discrete reference resistors are usually used on circuit boards of modern ADC bridges. They are made in so called metal film technology. On non-conducting support thin film of conductor is put. Afterwards, it is additionally manufactured with use of lasers to achieve required value of resistance. They are much smaller than wirewound reference resistors. Usually they are used in precision test and measuring systems and design of calibration reference standards.

In our paper, we have used Vishay ultra-high precision foil wraparound surface mount chip resistor (VSMP), [13], Figure 2. VSMP Series provide high rated power and excellent load life stability along with extremely low temperature coefficient of resistance. One of the most important parameters influencing stability is the temperature coefficient of resistance (TCR). Although the TCR of foil resistors is considered extremely low, this characteristic has been further refined over the years. TheVSMP Series utilizes ultra-high precision Bulk Metal®Z-Foil. The Z-Foil technology provides a significant reduction of the resistive element’s sensitivity to ambient temperature variations (TCR) and to self-heating when power is applied (power coefficient of resistance, or PCR). Along with the inherently low PCR and TCR, Z-Foil technology also provides improved load life stability, low noise and tight tolerances. The VSMP resistor has a full wraparound termination which provides stability during multiple thermal cycling..

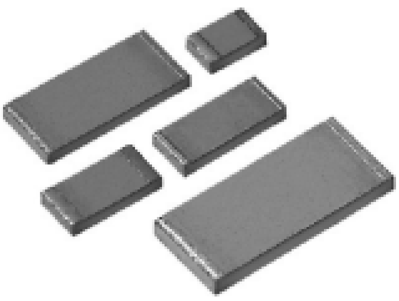


Figure 2 Vishay discrete element reference resistor

MEASUREMENT SYSTEM AND RESULTS

The measurement system consists of automatic DC resistance bridge MI6010B together with resistance scanner 4220A, seven wirewound Tinsley 5685A resistors (2x 1 Ω, 1 x 10 Ω, 2x 25 Ω, 1 x 100 Ω, 1x 300 Ω), one discrete reference resistor Vishay VSMP 2500 Ω, [14]. All these resistors were placed in the thermal controlled oil bath Kambič OB 70. During the measurement of TCR we have changed temperature within the bath from 19 °C to 37 °C. Additionally, as a reference resistor with which all other resistors were compared using automatic DC bridge, Tinsley 5685A 100 Ω resistor was placed in independent thermal controlled air bath at the temperature of 36 °C. The temperature of the bath was measured with platinum resistance thermometer in combination with digital multimeter HP 34401A. The elements of the measurement system can be seen on the Figure 3.

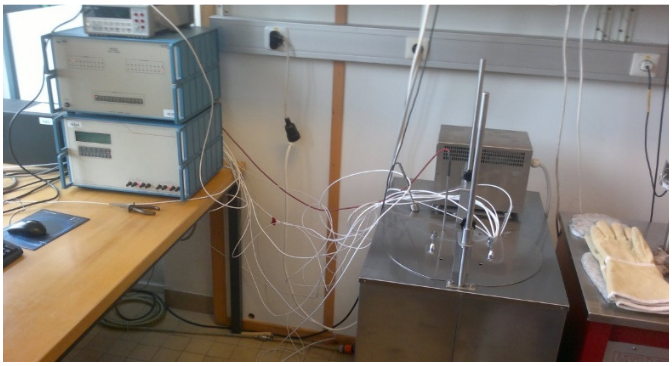
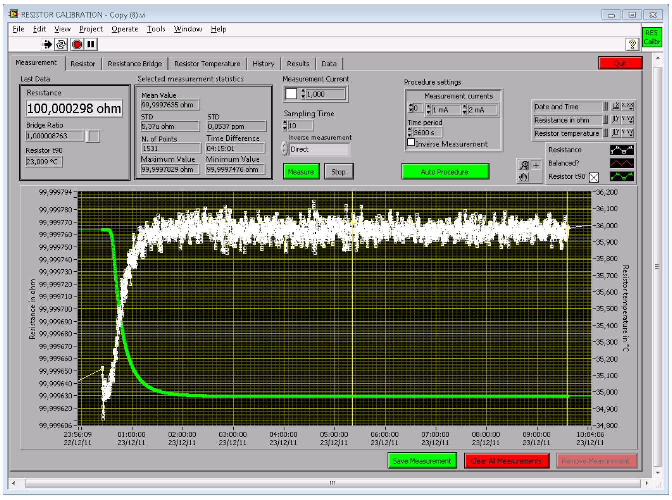


Figure 3 Measurement system

For easier data acquisition, analysis, presentation and archiving of acquired data, we have used custom made software developed in LabVIEW, [15]. The computer and all measuring instruments were connected via GPIB. The reference resistors oil bath was connected with the computer via RS 232. The front panel of the used software can be seen on the Figure 4. All the measurements were automated.



RESISTOR CALIBRATION - Copy (8).vi

Last Data
Resistance: 100,000298 ohm
Bridge Ratio: 1,000008763
Resistor t90: 23,009 °C

Selected measurement statistics
Mean Value: 99,9997635 ohm
STD: 5,37u ohm
STD: 0,0537 ppm
N. of Points: 1531
Time Difference: 04:15:01
Maximum Value: 99,9997829 ohm
Minimum Value: 99,9997476 ohm

Measurement Current: 1,000
Sampling Time: 10
Inverse measurement: Direct

Procedure settings
Measurement currents: 0, 1 mA, 2 mA
Time period: 3600 s
☐ Inverse Measurement

Figure 4 The front panel of the custom made LabVIEW software

In the Table 1 list of the reference resistors together with used measurement current for which the temperature coefficient of resistance was determined. It has to be noted that R_s measurement current changed depending on the resistor connected on the DC bridge.

Table 1 List of used reference resistors together with the measurement current

Label	Serial number	Man.	Nominal resistance (Ω)	Measurement current (mA)
R_1	280316	Tinsley	1	10
R_2	274733	Tinsley	1	10
R_3	280202	Tinsley	10	2
R_4	274957	Tinsley	25	1
R_5	275171	Tinsley	25	1

R_6	6419/03	Tinsley	100	1
R_7	6419/07	Tinsley	300	0.5
R_8	2500/01	Vishay	2500	0.1
R_s	274931	Tinsley	100	/

During the measurement process, first the bath temperature was set at certain temperature within temperature range of interest. After the temperature of the oil bath and resistance of the reference resistor is stable, measurement at this temperature is performed. Due to the fact that according to the manufacturer data all the reference resistors had inflection point of their TCR at 23 °C (0 ppm/°C), the first measurement was performed at that temperature, [14]. After 23 °C, we have performed measurements at other temperature points. Cumulative change of the reference resistors values from first value measured at 23 °C, expressed as ppm of change, can be seen on Figure 5. One can see that for Vishay reference resistor (R8), the dominating factor is not TCR, but hysteresis. We have started at 23 °C, then changed temperature to 19 °C went back to 23 °C and then to 37 °C and back. The step in change of cumulative change for Vishay reference resistor (R8), is visible on the Figure 5. This is due to hysteresis.

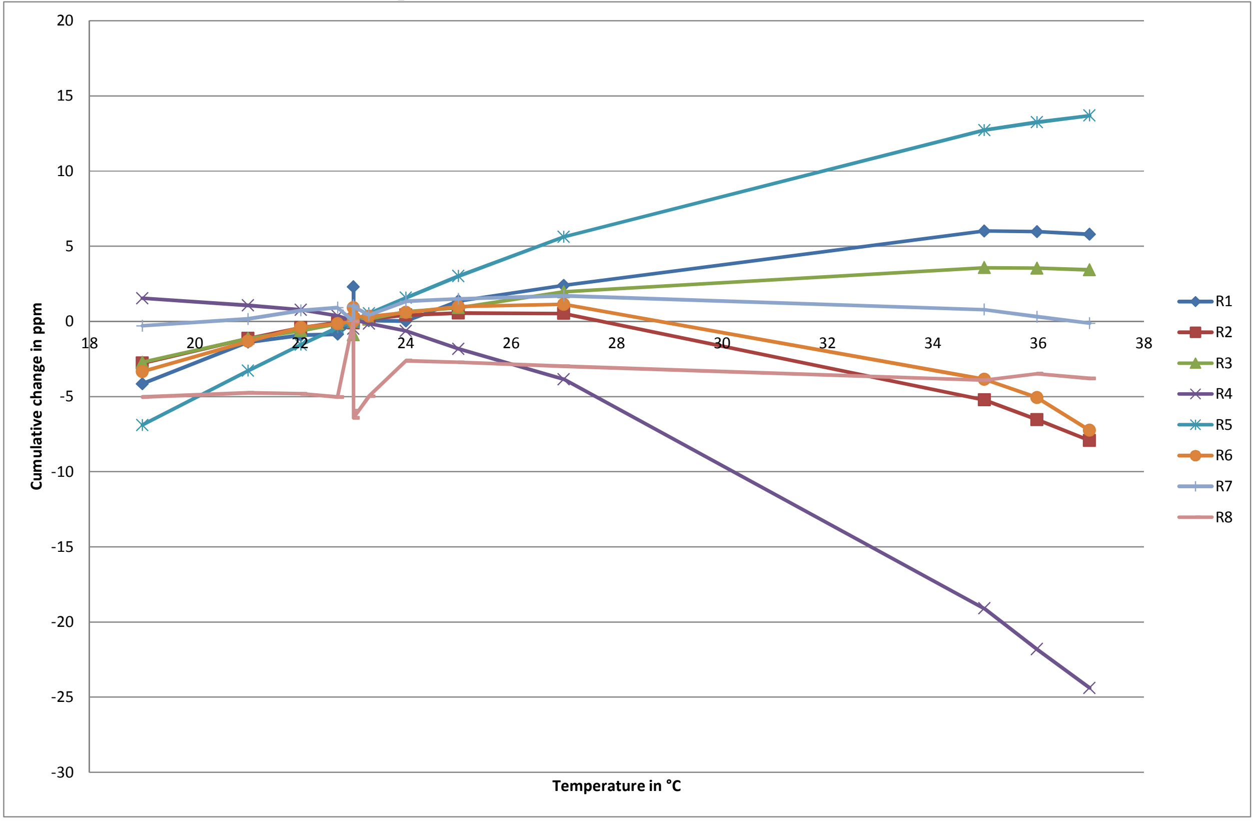


Figure 5 Cumulative change of resistance from first measurement at 23 °C expressed in ppm

In the next step, quadratic equations using least square regression method has been determined for each reference resistor, as presented in equation 3 for reference resistor R1:

$$\frac{\Delta R_1}{R_1} = -0.0280t^2 + 2.1025t - 33.566 \qquad (3)$$

Equation 3 was derived over temperature and TCR equation was determined, as presented in equation 4:

$$T_{C_{R_1}} = -\,0.0560t + 2.1025 \qquad (4)$$

The equation 4 enables us to calculate TCR for each temperature point in the range of measurement. In the Table 2 the TCR for each reference resistor is presented at different temperature. For the calculation of the TCR we have used equation 4. In order to calculate the temperature of the inflection point, in the equation 4 TCR=0 ppm and t is calculated. The temperature of inflection point for each resistor is presented in Table 3.

CONCLUSION

The measurement has shown that all of the reference resistors have the temperature coefficient of resistance within manufacturer specification. The problem is that the temperature of the inflection point, where TCR is 0 ppm is not as suggested by manufacturer. The knowledge of the temperature of the inflection point is very important, because the use of the standard resistor at this temperature greatly reduces the influence of temperature on electrical resistance, even if the thermal conditions are not optimal. Furthermore, usage of the reference resistor at temperatures near to the temperature of the inflection point greatly reduces loading effect due to self-heating of reference resistor. As a consequence, each laboratory should perform determination of particular TCR of reference resistor in order to be able to determine uncertainty source arising from temperature change of the oil or air bath

Table 2 TCR at different temperatures for all reference resistors

Temperature (°C)	R1 (ppm)	R2 (ppm)	R3 (ppm)	R4 (ppm)	R5 (ppm)	R6 (ppm)	R7 (ppm)	R8 (ppm)
18	1.0945	0.4843	0.7952	0.0692	1.3581	1.1164	1.9914	0.5481
19	1.0385	0.4389	0.7502	-0.082	1.2025	0.9754	1.9070	0.5013
20	0.9825	0.3935	0.7052	-0.234	1.0469	0.8344	1.8226	0.4545
21	0.9265	0.3481	0.6602	-0.386	0.8913	0.6934	1.7382	0.4077
22	0.8705	0.3027	0.6152	-0.538	0.7357	0.5524	1.6538	0.3609
23	0.8145	0.2573	0.5702	-0.689	0.5801	0.4114	1.5694	0.3141
24	0.7585	0.2119	0.5252	-0.841	0.4245	0.2704	1.4850	0.2673
25	0.7025	0.1665	0.4802	-0.993	0.2689	0.1294	1.4006	0.2205
26	0.6465	0.1211	0.4352	-1.145	0.1133	-0.011	1.3162	0.1737
27	0.5905	0.0757	0.3902	-1.2970	-0.0423	-0.152	1.2318	0.1269
28	0.5345	0.0303	0.3452	-1.4488	-0.1979	-0.293	1.1474	0.0801
29	0.4785	-0.0151	0.3002	-1.6006	-0.3535	-0.434	1.0630	0.0333
30	0.4225	-0.0605	0.2552	-1.7524	-0.5091	-0.575	0.9786	-0.0135
31	0.3665	-0.1059	0.2102	-1.9042	-0.6647	-0.716	0.8942	-0.0603
32	0.3105	-0.1513	0.1652	-2.0560	-0.8203	-0.857	0.8098	-0.1071
33	0.2545	-0.1967	0.1202	-2.2078	-0.9759	-0.998	0.7254	-0.1539
34	0.1985	-0.2421	0.0752	-2.3596	-1.1315	-1.139	0.6410	-0.2007
35	0.1425	-0.2875	0.0302	-2.5114	-1.2871	-1.280	0.5566	-0.2475
36	0.0865	-0.3329	-0.0148	-2.6632	-1.4427	-1.421	0.4722	-0.2943
37	0.0305	-0.3783	-0.0598	-2.8150	-1.5983	-1.562	0.3878	-0.3411

Table 3 The temperature of inflection point where TCR = 0 ppm

Reference resistor	R1	R2	R3	R4	R5	R6	R7	R8
Temperature (°C)	37.5450	28.6674	35.6710	18.4559	26.7282	25.9177	41.5948	29.7180

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