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Stability evaluation of 1 Ω and 10 kΩ standard resistors using a step-down method

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ABSTRACT

The traceability chain of electrical resistance in Brazil relies upon standard resistors of 1 Ω and 10 kΩ maintained by the Electrical Standardization Metrology Laboratory (Lampe) at the National Institute of Metrology, Quality and Technology (INMETRO), the country's national metrology institute. These standard resistors are periodically calibrated at the Bureau International des Poids et Mesures (BIPM) in France to ensure traceability to the International System of Units (SI). Transport can influence the properties of the resistors and change their values. Lampe checks resistors' changes before and after calibration at the BIPM. The highest differences tend to occur with the 1 Ω resistors. However, drift rate evaluation becomes arduous when the check results show slight changes in the values – of about 0.10 $\mu\Omega\ \Omega^{-1}$ – due to the uncertainty components involved. In this work, the step-down is a procedure to measure the 1 Ω resistors through a 10 kΩ resistor. The comparison of results between Lampe and INMETRO's Quantum Electrical Metrology Laboratory (Lameq) shows a relative difference of less than 0.07 $\mu\Omega\ \Omega^{-1}$. The results agreement allowed Lampe to confidently use the step-down method to evaluate 1 Ω resistors' drift.

Section: RESEARCH PAPER

Keywords: Traceability; quantum Hall system; step-down; stability; transport; standard resistor

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1. INTRODUCTION

Brazil's National Institute of Metrology, Quality and Technology (INMETRO), through its Electrical Standardization Metrology Laboratory (Lampe), provides research centres, laboratories, industries, electric power companies, and universities with calibration services of standard resistors in direct current (DC) in the 1 Ω to 10 kΩ range using current comparison. Such calibrations are traceable to the International System of Units (SI) as the Lampe periodically calibrates its own 1 Ω and 10 kΩ standard resistors at the Bureau International des Poids et Mesures (BIPM) in France.

Temperature [1], [2], humidity [1], pressure [2], short-term drift [3], leakage currents [4], [5], insulation resistance of the resistor terminals and connection cables [5], and low-frequency resistance noise due to resistor material and resistance range [6] are well-known factors that affect the calibration of standard resistors. Nevertheless, the transport of resistors should be included in this list since its influence may alter the resistor values. Yu et al. [7] attribute these alterations to the mechanical stress that the coils of the Thomas-type resistors experience due to temperature fluctuations along the journey. Warnecke et al. [8] have already demonstrated that resistors made from Manganin alloy, such as the Thomas type, present significant hysteresis conditional to such temperature changes.

Still regarding transport behaviour, Jones [9] studied environmental conditions that could affect six 1 Ω Thomas-type resistors. Thomas-type resistors values may exhibit hysteresis with temperature changes, and the drift rate changes for some months after the temperature change event. In two out of six Thomas-type resistors, significant changes in resistance values were measured – about $-0.065\ \mu\Omega\ \Omega^{-1}$, after cycling from 20 °C to 25 °C.

Lampe calibrates two Thomas-type resistors of 1 Ω and one ESI (Electro Scientific Industries)-type resistor of 10 kΩ at the BIPM. Lampe checks the resistor's changes before and after calibration at the BIPM. The highest differences tend to occur with the Thomas-type resistors. In 2015, due to budget constraints, Lampe sent the standard resistors to the BIPM using airplane luggage (rather than transporting them as carry-on luggage, as usual) and included a temperature data logger accompanying the resistors during the trip. It recorded a temperature oscillation between 8 °C and 30 °C – which is much more pronounced than the fluctuation between 20 °C and 25 °C typically observed in the aircraft cabin. The value of one of the Thomas-type resistors changed at about $-0.4\ \mu\Omega\ \Omega^{-1}$, and Lampe suspended calibrations with this standard until the resistor value became stable again.

The interval for checking the resistors after the trip to the BIPM is six months or more. Typically, Lampe uses a set of five 1 Ω Thomas-type resistors to check the two calibrated 1 Ω Thomas-type resistors and a set of five 10 kΩ that includes ESI, Leeds and Northrup (L&N), and Fluke type resistors to check the calibrated 10 kΩ ESI resistor. Environmental conditions are well controlled, and the method to check the 10 kΩ resistors using the 1:1 ratio is satisfactory. However, in checking Thomas-type resistors, drift rate evaluation becomes arduous when the results show slight changes in the values due to the uncertainty components involved. Evaluating the hysteresis influence on Thomas-type resistor values is affected by the difference between the temperature coefficients of the resistors, the uncertainty of the bridge used in the measurements, and the six-month drift of the Thomas-type resistors. The monthly calibration routine of the Lampe hinders a more frequent follow-up of this drift.

As an alternative to this issue, the quantum Hall system (QHS) of the INMETRO, operated by the Quantum Electrical Metrology Laboratory (Lameq), was employed. Although not officially providing calibration services at the time the measurements discussed in this paper were performed, the INMETRO had already sent the request for the insertion of new, QHS-based services in its Calibration and Measurement (CMC) capabilities listed in Appendix C of Mutual Recognition Organization of the International Committee for Weights and Measures (CIPM) – named CIPM MRA [10], since its QHS obtained good results in the BIPM.EM-K13.a&b bilateral comparison with the BIPM in 2022 [11]. Such satisfactory results enabled Lampe to use the QHS to validate the step-down method presented in this paper for evaluating Thomas-type resistors between calibrations.

The main objective of this study is to validate the use of a step-down method to evaluate the drift of 1-Ω Thomas-type standard resistors from a 10 kΩ primary standard resistor and the MIL 6010D commercial bridge. Through the QHS, it was possible to validate the step-down method.

2. MATERIALS AND METHODS

In this work, the step-down is a procedure to measure a 1 Ω resistor through a 10 kΩ resistor. The three resistors calibrated in the BIPM are coded as TH1 (1 Ω), TH2 (1 Ω), and R1 (10 kΩ). In this work, resistors TH1 and TH2 were measured with resistor R1.

Resistor R1 is the most stable among all resistors in Lampe and has a steady drift rate (of around +0.08 μΩ per year). Transport influenced this resistor less than resistors TH1 and TH2.

The main parameters that influence the step-down are the temperature stability in the oil bath and air bath, leakage resistance of the resistors and their connection cables, uncertainty and stability of the bridge, temperature coefficients of the resistors involved, and the power dissipated by the resistor during measurements. The bridge used is a commercial bridge by Measurements International (MIL) model 6010D.

Due to a fault in its oil bath, Lameq could not perform QHS measurements on resistors TH1 and TH2. Nevertheless, Lameq has standard resistors in the range of 1 Ω to 10 kΩ with small first-order temperature coefficients (less than $0.5 \times 10^{-6}\ \Omega\ \mathrm{K}^{-1}$) that were fit to this work. These resistors are preferably measured in an oil bath but can be measured in an air bath.

To obtain better reliability of the results, we adopted the following procedures:

1) step-down of three 1 Ω resistors from the 10 kΩ resistor, replacing Lampe resistors with Lameq resistors where necessary;
2) QHS measurement of Lameq and Lampe resistors when possible;
3) comparison of the results from Lampe with those from Lameq.

During the step-down, the oil and air baths involved were maintained at a controlled temperature of (23.000±0.004) °C and (23.00±0.06) °C, respectively.

The procedure previously adopted for stability evaluation consisted of triangulations of 1:1 ratio measurements in the 1-Ω range with all available Thomas-type resistors (7 resistors in total, including the traveling standards, resulting in a set of 21 measurements). Similarly, triangulations of 1:1 ratio measurements were performed in the 10-kΩ range with all six resistors available at the Lampe, resulting in a 15-measurement set. Still, this procedure did not allow conclusive evaluations on the stability of Thomas-type traveling standards due to their large temperature coefficients (coefficient α_{23} ranging from $4.1 \times 10^{-6}\ \Omega\ \mathrm{K}^{-1}$ to $7.1 \times 10^{-6}\ \Omega\ \mathrm{K}^{-1}$) and because even non-traveling patterns are subject to hysteresis due to temperature variation. For the same reasons, estimating the resistor values was difficult; thus, this procedure limited itself to the "before versus after" evaluation of the standards based solely on ratio measurements.

The step-down has two significant advantages over the previous triangulation procedure – although the measurement uncertainties are equivalent:

1) it allows working with resistor values, not just the measurement ratios, enabling the stability evaluation at any time;
2) it allows the assessment of intermediate ranges with a smaller number of measurement sets (e.g., in this work, we verified the 10 Ω, 100 Ω, and 1 kΩ ranges from 31 measurement sets in total).

3. STEP-DOWN PROCEDURE DESCRIPTION AND RESULTS

Lampe reduced, when possible, the main parameters that influence the measurements. The cables that connect the resistors had conductor-to-conductor insulation resistance values greater than 1 TΩ for resistors connected in an air bath and values greater than 100 GΩ for resistors connected in an oil bath [12], [13]. On the 6010D bridge, this range of values can cause an error of up to $0.01\ \mu\Omega\ \Omega^{-1}$ for 10 kΩ resistors measured in the air bath and $0.1\ \mu\Omega\ \Omega^{-1}$ for 10 kΩ resistors measured in the oil bath. For values smaller than 1 kΩ, the errors caused in the oil bath can reach up to $0.01\ \mu\Omega\ \Omega^{-1}$. Thus, to prevent these errors from influencing the step-down, 10 kΩ resistors were used only in the air bath. Furthermore, measurements were performed over one week to minimize the

Table 1. Temperature coefficients of the standard resistors used in the step-down.

Resistor code / (laboratory)	Manufacturer	Model	Nominal value	α_{23} in μΩ K⁻¹	β in μΩ K⁻²
TH1 (Lampe)	L&N	4210	1 Ω	4.7	−0.5
TH2 (Lampe)	L&N	4210	1 Ω	4.272	−0.508
PT16 (Lameq)	Tinsley	5685A	1 Ω	−0.2103	−0.0161
6A (Lampe)	L&N	4025-B	10 Ω	1.0	−0.5
PT17 (Lameq)	Tinsley	5685A	10 Ω	0.379	−0.0246
7A (Lampe)	L&N	4030-B	100 Ω	6.0	−0.5
7D (Lameq)	L&N	SR-102/DC	100 Ω	−0.079	−0.019
7E (Lameq)	L&N	5685A	100 Ω	0.4	−0.07
8B (Lampe)	L&N	4035-B	1 kΩ	8.0	−0.5
PT18 (Lameq)	Tinsley	5685B	1 kΩ	0.4986	−0.0023
R1 (Lampe)	ESI	SR-104	10 kΩ	−0.11	−0.024
R3 (Lampe)	ESI	SR-104	10 kΩ	−0.07	−0.0255
9F (Lampe)	Fluke	742A-10k	10 kΩ	0.02	0.003

influence of the stability of the 6010D bridge, air bath, oil bath, and environmental conditions.

The ideal scenario is to use stable resistors in pairs, with temperature coefficients α_{23} and β smaller than $0.5 \times 10^{-6}\ \Omega\ \mathrm{K}^{-1}$ and $0.5 \times 10^{-6}\ \Omega\ \mathrm{K}^{-2}$ (in absolute values). However, this was not the case since not all available resistors met these conditions. Table 1 shows α_{23} and β values for the resistors used (part of the set mentioned above).

In Table 1, it is possible to observe varied α_{23} values. Thus, finding a current that generated the lowest heat in the resistor and did not create instability in the 6010D bridge was required. Besides, at each range change, it was necessary to check the stability of the 6010D bridge through a triangulation between three resistors.

During the calibration performed with the 6010D bridge in the 10:1 configuration (Rx:Rs), the power Ps dissipated in the Rs resistor is 10 times greater than in the Rx resistor (Rx and Rs are the bridge terminals where the resistors are connected). The applied current in Rx was configured so that the dissipated power in Rs was less than 2.5 mW. Resistor 8B, whose α_{23} is $8.0 \times 10^{-6}\ \Omega\ \mathrm{K}^{-1}$, showed a temperature increase of 0.006 K when dissipating 2.5 mW, while the others had a maximum increase in temperature of 0.003 K.

The temperature measured by the platinum thermometer in the resistor reflects a sample of the average temperature dissipated by the resistor core. Although this temperature value is enough for calibrating client resistors in Lampe, in the step-down, this temperature can significantly influence and generate systematic errors during the change of steps. An error of 0.003 K in the temperature measurement of the 8B can cause a relative error of $0.024\ \mu\Omega\ \Omega^{-1}$. To reduce this error, the maximum current applied to the 1 kΩ resistors 8B and PT18 was 1 mA and the power dissipated was about 1 mW.

Figure 1 shows the simplified diagram of the configuration used to carry out the measurements during the step-down. The indicated current value next to the arrow corresponds to the current value applied to the pointed resistor. The double line with a single arrow illustrates that two measurements are performed in each cycle. The double horizontal line with a double arrow indicates the measurement result corresponds to the mean in the forward and reverse directions.

Although the 1 Ω resistors are measured from the 10 kΩ resistor, the ratio measurements start from the 1 Ω resistors to reduce the thermal effects during the step-down. Each 6010D program records the measured ratio between the resistors. From these records, it is possible to determine the values of all resistors as a function of R1's value.

The sequence begins by performing a triangulation between three 1 Ω resistors that dissipate 2.5 mW of power. Afterward, the measurement of the 10 Ω resistor is carried out, maintaining the same current previously applied in Rs, whereas, in Rx, a power Px ten times lower is obtained. Then, the power dissipated in the 10 Ω resistor is increased to 2.5 mW, the resistor is pre-heated, and the triangulation between the 10 Ω and 1 Ω resistors is completed. This procedure is followed until reaching the 1 kΩ resistors. In the 1 kΩ resistors, a power of 1 mW is applied, and in the 10 kΩ, 0.1 mW. The step-down is finished with the triangulation in 10 kΩ of R1, R3, and 9F using a power of 2.5 mW. Table 2 shows the sequence used to perform these measurements, and Table 3 shows the average temperature values measured in the resistors during the measurements. Resistors R1, R3, 9F and 7D were kept in the air bath at an average temperature of 23.00 °C.

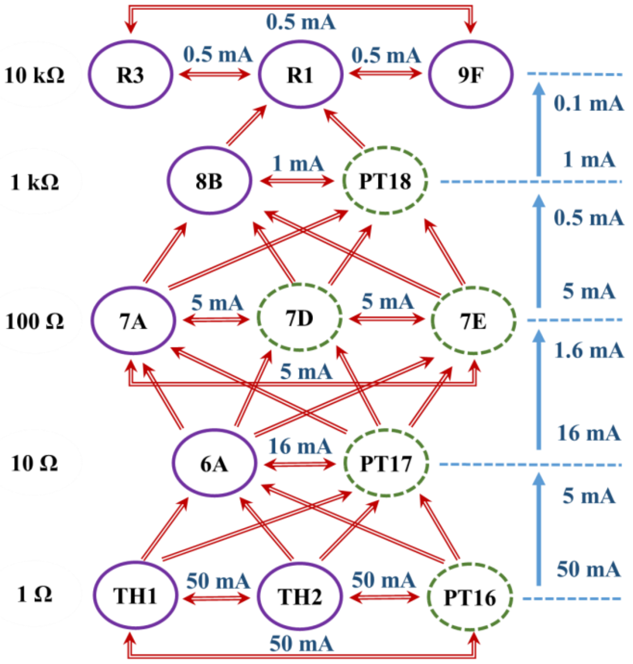

Figure 1. Simplified diagram of the configuration used to measure the resistors during the step-down. Solid purple line circles represent Lampe's resistors. Dashed green line circles indicate Lameq's resistors.

Table 2. Sequence and configuration of measurements performed on the 6010D bridge.

Step	*R*s	*R*x	Applied current [*I*s:*I*x] in mA	[*P*s:*P*x] in mW	Resistors	6010D program
1 Ω triangulation	1 Ω	1 Ω	50:50	2.5:2.5	TH1, TH2, PT16	M1 to M12
Step 10:1	1 Ω	10 Ω	50:5	2.5:0.25	(6A, PT17)	M13 to M20
Step 1:1	10 Ω	10 Ω	16:16	2.5:2.5	6A, PT17	M21, M22
Step 10:1	10 Ω	100 Ω	16:1.6	2.5:0.25	(6A, PT17)-(7A, 7D, 7E)	M23 to M28
Step 1:1	100 Ω	100 Ω	5:5	2.5:2.5	7A, 7D, 7E	M29 to M34
Step 10:1	100 Ω	1 kΩ	5:0.5	2.5:0.25	(7A, 7D, 7E)-(PT18, 8B)	M35 to M40
Step 1:1	1 kΩ	1 kΩ	1:1	1:1	8B, PT18	M41, M42
Step 10:1	1 kΩ	10 kΩ	1:0.1	1:0.1	(8B, PT18)-(R1, R3, 9F)	M43 to M48
10 kΩ triangulation	10 kΩ	10 kΩ	0.5:0.5	2.5:2.5	R1, R3, 9F	M49 to M54

After the measurements, the values of all resistors were calculated from the predicted value of R1 on the measurement date, using the ratio values previously recorded by the 6010D programs. The values obtained from the measurements are shown in tables 4 and 5; *U* is relative expanded uncertainty, *k* is the coverage factor, and ν_{eff} denotes the effective degrees of freedom. The tables also have simplified results of the triangulations in each step, presented as "*Dif*" (relative difference). Through *Dif*, it is possible to evaluate the bridge stability and the temperature corrections of the resistors in the calibrations.

The term "Mean" adopted in Table 4 and Table 5 refers to the average between the results obtained through the resistors used as a standard. The correlation during measurements is high, and the difference between the results is much smaller than their uncertainty. Thus, to simplify the calculations, the uncertainty of the mean was considered the highest-valued term among the two used in calculating the mean.

The results of these triangulations show *Dif* between $-0.045\ \mu\Omega\ \Omega^{-1}$ and $+0.034\ \mu\Omega\ \Omega^{-1}$. The bridge uncertainty is $0.04\ \mu\Omega\ \Omega^{-1}$. *Dif* values exceeding the bridge uncertainty occurred due to the bath stability and the temperature coefficient of the resistors.

4. MEASUREMENT RESULTS WITH THE QUANTUM HALL SYSTEM

The measurements carried out by Lameq in the air bath obtained satisfactory results and allowed intermediate comparisons to the results by Lampe. Hence, it was possible to re-evaluate the values of resistors TH1 and TH2 with greater reliability. Table 6 shows the results of measurements performed on Lameq.

Table 3. Resistors mean temperature in oil bath.

Resistor code/ (laboratory)	Dissipated power		
	≤ 0.25 mW	1 mW	2.5 mW
TH1 (Lampe)	-	-	23.0060 °C
TH2 (Lampe)	-	-	23.0045 °C
PT16(Lameq)	-	-	23.0055 °C
6A (Lampe)	23.0015 °C	-	23.0050 °C
PT17(Lameq)	23.0045 °C	-	23.0045 °C
7A (Lampe)	23.0055 °C	-	23.0090 °C
7E(Lameq)	23.0025 °C	-	23.0025 °C
8B (Lampe)	23.0045 °C	23.0070 °C	-
PT18(Lameq)	23.0035 °C	23.0035 °C	-

5. COMPARISON OF RESULTS BETWEEN LAMPE AND LAMEQ

The differences between the results obtained by Lampe and Lameq and the absolute values of normalized error ($|E_{\mathrm{n}}|$) are shown in Table 7. The values obtained by Lampe were based on the predicted value of R1. The interval time between resistor measurements of Lampe and Lameq was about 45 days. It was necessary to consider the monthly drift rate of the resistors (Table 8) to evaluate the *Dif*. Still, when the monthly drift values are very close to the uncertainty of the 6010D bridge, which is $0.04\ \mu\Omega\ \Omega^{-1}$, it is necessary to verify the results of the triangulation of the resistors during the step-down.

Table 7 shows that the $|E_{\mathrm{n}}|$ between the measurements carried out between Lampe and Lameq are satisfactory, that is, $|E_{\mathrm{n}}| < 1$, and agree with Lampe's CMC. If the predicted value of R1 is corrected with the value measured in Lameq and the monthly drift of R1, all resistors $|Dif|$ drops to a value less than $0.07\ \mu\Omega\ \Omega^{-1}$ as shown in Figure 2.

The comparison of values between Lampe and Lameq shows that it is possible to evaluate the trend of resistors TH1 and TH2 from the step-down of the R1 resistor.

6. CONCLUSION

Evaluating the stability of standard resistors after transport is relevant because they may undergo alterations due to the temperature variations they experience during the journey. Such alterations can limit their use immediately after travel. One may use triangulations of 1:1 ratio measurements for this evaluation, but such a procedure may not be effective when the standard resistors have large temperature coefficients. Besides, the non-traveling standards used in the triangulation are also prone to alterations, making it difficult to estimate the drift of the standards.

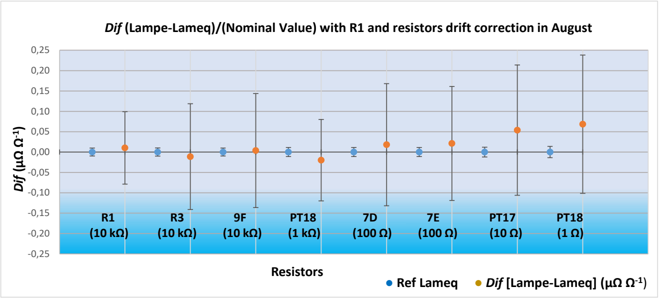

Figure 2. *Dif* (Lampe – Lameq) with R1 and resistors drift correction

Table 4. Values obtained through the step-down between the 10 kΩ and 100 Ω resistors.

Rx	**Rs**	**Measured value (Ω)**	***U* in μΩ Ω^{-1}**	***k***	ν_{eff}	**Date (mm/dd/yy)**
R1	Predicted	10000.01595	0.088	2.21	13.2	08/10/22
R3	R1	10000.02086	0.13	2.03	74.1	08/10/22
9F	R1	10000.06359	0.14	2.03	77.2	08/10/22
9F	R3	10000.06356	0.16	2.01	195	08/10/22
		***Dif*[9F(R3)-9F]**	**−0.003 μΩ Ω^{-1}**			
8B	R1	1000.024687	0.12	2.07	38.5	08/07/22
PT18	R1	999.997651	0.10	2.13	20.5	08/07/22
PT18	8B	999.997659	0.12	2.05	47.1	08/07/22
		***Dif*[8B(PT18)-8B]**	**0.008 μΩ Ω^{-1}**			
7A	Mean(8B;PT18)	100.001964 6	0.13	2.05	49.6	08/07/22
7D	Mean((8B;PT18)	100.0002099	0.15	2.02	111.2	08/07/22
7E	Mean(8B;PT18)	99.9999177	0.14	2.04	69.3	08/07/22
7D	7A	100.0002121	0.16	2.02	110.9	08/07/22
7E	7A	99.9999185	0.14	2.04	71.4	08/07/22
7E	7D	99.9999211	0.16	2.02	129.2	08/07/22
		***Dif*[7D(7A)-7D]**	**0.022 μΩ Ω^{-1}**			
		***Dif*[7E(7A)-7E]**	**0.008 μΩ Ω^{-1}**			
		***Dif*[7E(7D)-7E]**	**0.034 μΩ Ω^{-1}**			

Table 5. Values obtained through the step-down between the 100 Ω and 1 Ω resistors.

Rx	**Rs**	**Measured value (Ω)**	***U* in μΩ Ω^{-1}**	***k***	ν_{eff}	**Date (mm/dd/yy)**
6A	Mean(7A;7D;7E)	9.99997239	0.16	2.02	129.8	08/07/22
PT17	Mean(7A;7D;7E)	10.00000647	0.16	2.02	129.5	08/07/22
PT17	6A	10.00000619	0.16	2.02	147.1	08/07/22
		***Dif*[6A*(*PT17)-6A]**	**−0.028 μΩ Ω^{-1}**			
TH1	Mean(6A;PT17)	0.999992173	0.17	2.02	154.9	08/07/22
TH2	Mean(6A;PT17)	0.999993152	0.17	2.02	153.0	08/07/22
PT16	Mean(6A;PT17)	1.000001890	0.17	2.02	147.7	08/07/22
TH2	TH1	0.999993135	0.17	2.01	173.9	08/07/22
PT16	TH1	1.000001846	0.18	2.01	187.8	08/07/22
PT16	TH2	1.000001845	0.18	2.01	182.9	08/07/22
		***Dif*[TH2(TH1)-TH2]**	**−0.017 μΩ Ω^{-1}**			
		***Dif*[PT16(TH1)-PT16]**	**−0.044 μΩ Ω^{-1}**			
		***Dif*[PT16(TH2)-PT16]**	**−0.045 μΩ Ω^{-1}**			

Table 6. Results of Lameq measurements.

Rx	**Rs**	**Measured value (Ω)**	***U* in μΩ Ω^{-1}**	***k***	ν_{eff}	**Date (mm/dd/yy)**
R1	7D	10000.015358	0.0098	2.01	323.8	09/05/22
R3	7D	10000.02051	0.010	2.01	193.8	09/08/22
9F	7D	10000.06319	0.0098	2.00	∞	09/13/22
PT18	7D	999.9976347	0.011	2.00	∞	09/06/22
7D	QHS2	100.0002052	0.011	2.52	6.6	08/28/22
7E	7D	99.9999107	0.011	2.32	9.3	09/15/22
PT17	7D	10.00000549	0.012	2.17	16.5	09/24/22
PT16	PT17	1.000001785	0.014	2.06	41.4	09/30/22

Table 7. Summary of Lampe and Lameq results.

Resistor	**Lampe**		**Lameq**		***Dif* in μΩ Ω^{-1}**	$\lvert E_n \rvert$
	Measured value (Ω)	***U* in μΩ Ω^{-1}**	**Measured value (Ω)**	***U* in μΩ Ω^{-1}**		
R1	10000.015950	0.088	10000.015358	0.0098	−0.0592	0.67
R3	10000.02086	0.13	10000.02051	0.010	−0.035	0.27
9F	10000.06359	0.14	10000.06319	0.0098	−0.040	0.29
PT18	999.9976510	0.10	999.9976347	0.011	−0.016	0.16
7D	100.0002099	0.15	100.0002052	0.011	−0.047	0.31
7E	99.9999177	0.14	99.9999107	0.011	−0.070	0.50
PT17	10.0000647	0.16	10.00000549	0.012	−0.098	0.61
PT16	1.000001890	0.17	1.000001785	0.014	−0.104	0.61

Table 8. Monthly drift of resistors measured at Lameq.

Resistor	Monthly drift in $\mu\Omega\ \Omega^{-1}$
R1	0.007
R3	0.010
9F	0.016
PT18	0.012
7D	0.038
7E	0.006
PT17	0.007
PT16	0.011

The step-down procedure described in this paper is more advantageous than the triangulation because it allows evaluation based on the resistor values rather than the ratios, especially for 1-Ω Thomas-type resistors. Furthermore, the step-down lets one employ fewer measurement sets and evaluate intermediate values in the 1-Ω to 10-kΩ range.

This paper discussed the main parameters influencing the step-down procedure and ways to minimize such influence. The comparison presented in this paper permitted Lampe to identify the alterations that occurred during the transport of two 1-Ω Thomas-type resistors and one 10 kΩ resistor to/from the BIPM and to re-evaluate the points used in the calibration history to predict the 10 kΩ resistor value.

Despite the difficulties Lameq encountered in calibrating the oil resistors in the air bath, the results were positive. They increased the reliability of the step-down procedure to verify the Lampe resistors calibrated at the BIPM.

This study highlights the importance of validating measurement methods to ensure the reliability of results and the traceability of measurements to the SI. The authors encourage the readers to validate their methods whenever possible. While we have used the QHS for such validation, it may not be available in all cases, so readers can determine their own means of doing so.

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