1 AND 10 k HIGH PRECISION TRANSPORTABLE SETUP TO CALIBRATE MULTIFUNCTION ELECTRICAL INSTRUMENTS

1 Ω AND 10 kΩ HIGH PRECISION TRANSPORTABLE SETUP TO CALIBRATE MULTIFUNCTION ELECTRICAL INSTRUMENTS

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ABSTRACT

A temperature controlled 1 Ω and 10 kΩ transportable setup was developed at National Institute of Metrological Research (INRIM) for the calibration and adjustment of multifunction electrical instruments as digital multimeters (DMMs) and multifunction calibrators (MFCs). The two standards are made of two 10 Ω and 100 kΩ resistor nets connected in parallel and inserted in a temperature controlled aluminium structure. Novelties of the realization are the oil insertion of the 1 Ω net with the internal side of the connectors lowering the thermo-electromotive forces (EMFs) effects, and the possibility to know instantly the temperatures of the environment, of the internal of the structure and the last calibration values of the 1 Ω and10 kΩ standards. Short- and mid-term stabilities of the setup standards resulted on the order and in some cases better than other metrology-grade 1 Ω and 10 kΩ commercial items. The transport of the setup even turning off its temperature control s did not cause appreciable measurement variations on the two standards. The standards uncertainties meet those requested by DMMs and MFCs manufacturers to calibrate and adjust these instruments. A test to adjust a MFC gave satisfactory results.

Key Words: standard resistor, multifunction calibrator (MFC), digital multimeter (DMM), resistance measurements, measurement stability, power and temperature coefficients, measurement uncertainties.

1. INTRODUCTION

High-accuracy multifunction electrical instruments, such as digital multi-meters (DMMs) and multifunction calibrators (MFCs) operating in the five low frequency electrical quantities, widely used as standards in calibration electrical laboratories, can be calibrated and adjusted by means of a particular process called "artifact calibration". This process requires only few reference standards among which the 1 Ω and 10 kΩ resistance standards and allows to self-assign new values to the internal references of MFCs and DMMs [1–3]. To transport only few calibrated standards, for example from a National Measurement Institute (NMI), to a calibration customer laboratory increases the calibration of its MFCs and DMMs accuracy, reliability and convenience. The calibration of DMMs and MFCs belonging to electrical customer laboratories is an example of the transfer of the condition of traceability from National standards, typical of the measurements of a NMI, to these laboratories [4]. The need to develop, maintain, compare and use high-accuracy 1 Ω and 10 kΩ resistance standards for high level measurements or to involve in artifact calibration had been felt since some decades in NMIs [5–9]. For this reason, at National Institute of Metrological Research (INRIM), a temperature controlled 1 Ω and 10 kΩ high precision setup was developed to calibrate and adjust DMM's and MFC's. This setup could be also involved as local standard to avoid thermal enclosures often necessary for high accuracy primary resistance standards [6] or specially made [10]. In addition, the setup standards could act as traveling standards for international comparisons (ILC's) as in [9] or in [11] and for national ones as in [12]. The present setup involving the two main resistance values for the traceability transfer to DMM's and MFC's is an improvement and upgrading of a first attempt to develop a thermo-regulated standard resistor made at INRIM with encouraging results [13]. Construction details, stability tests also in comparison with metrology-grade 1 Ω and 10 kΩ commercial resistors, determination of the temperature and power coefficients, tests on the transport effect and of a

MFC adjustment, evaluation of the use[1] uncertainties as local laboratory standards and for calibration of electrical instruments for the setup 1 Ω and 10 kΩ standards are given.

2. THE 1 Ω AND 10 kΩ STANDARD NETWORKS

The setup involves two Vishay VHA 512 type resistor nets, having tolerance of ± 0.001 %, temperature coefficient (TCR) lower than 2×10^{-6}/K and long term stability of 5×10^{-6}/year according to the manufacturer specifications. For the 1 Ω standard Resistor, ten 10 Ω resistors were connected in parallel with their leads and a manganin strip. Although manganin has higher resistivity than copper, it was chosen instead of copper for its sensitively lower TCR around 23 °C and high stability [15, 16]. The measurement relative error due to the thermal EMFs due to manganin insertion was evaluated lower than 2×10^{-7}. The 10 kΩ standard was made of a net of ten 100 kΩ resistors connected in parallel. Its parallel connection was made with a manganin strip as for the 1 Ω net. The resistors were soldered with a low EMF tin alloy.

3. THE THERMOSTATIC STRUCTURE

A thermo-regulated aluminium structure (Fig. 1 and 2) was chosen to accommodate the two resistor nets. The 1 Ω net was further placed into a cylindrical space inside this structure filled with mineral oil to enhance the heat conductance. One novelty of the setup was to put in oil the 10 Ω resistors of the net forming the 1 Ω standard directly connected to the internal side (also in oil) of the voltage and current connectors. With this solution, a better temperature uniformity to reduce the thermal EMFs is reached. The 100 kΩ resistors of the net forming the 10 kΩ standard were placed in air into ten holes in an external ring of the structure (Fig. 2). The bottom of the structure is mechanically connected to a Peltier's element

[1] We define use uncertainty the effective uncertainty that a standard or instrument introduces in the time period between two its calibrations when it is used to calibrate other standards or instruments. It normally includes its calibration, drift, environmental conditions and other influence parameters dependence uncertainty components. Similar description was given in [14].

(thermoelectric cooling, TEC) connected to a heat sink outside the aluminium structure. The structure was placed in a metallic case, filled with polystyrene foam.

Fig. 1. View of the aluminium structure connected to a TEC and a heat sink.

Fig. 2 shows the aluminium structure of the 1 Ω and 10 kΩ with all its components.

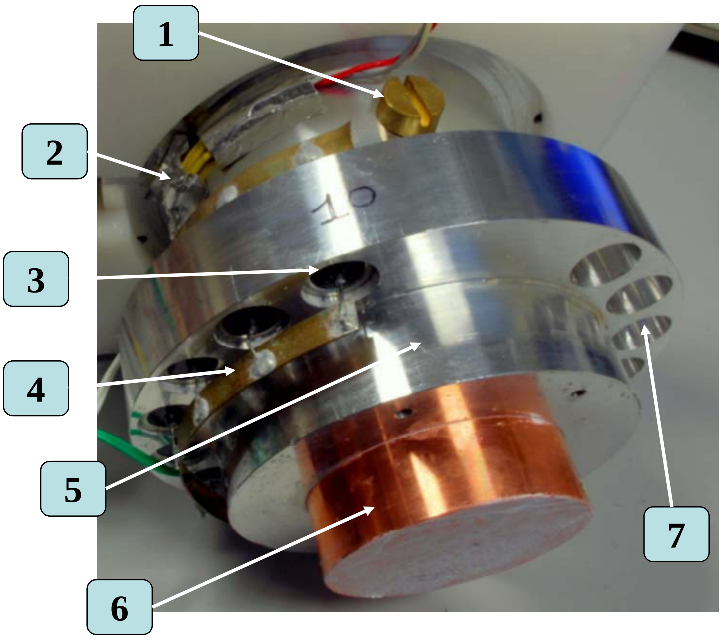

Fig.2. The structure of the 1 Ω and 10 kΩ: 1) cap to insert mineral oil; 2) electronic thermometer; 3) ten 100 kΩ resistors inserted in the holes of the aluminum structure; 4) manganin strip for parallel connection; 5) cylinder containing the ten 10 Ω resistors connected in parallel; 6) copper collector between the cylinder and the TEC where are inserted a thermometer and a PT100 platinum sensor for temperature control (10 kΩ NTC); 7) available empty holes for eventual compensation resistors.

The 10 Ω resistors are placed in a plastic basket closer to each other than the 100 kΩ (#3 in Fig. 2) and directly connected to the voltage and current four binding post connectors fixed to the top cover with thermal conductive resin (Fig. 1).

The TEC is supplied by a Proportional-Integral-Derivative (PID) controller put in another case with an embedded control system and the power supply (Fig. 3).

3.1 Temperature control system

The temperature-control of the structure is based on a commercial low noise PID controller with a negative temperature coefficient temperature sensor (NTC). The system can operate stand-alone or in PC-controlled mode. In stand-alone mode, the controller checks the structure and environment temperatures, the status of the battery and the display.

Fig. 3. Temperature controller system (left) and standards case (right).

Fig. 4 shows a screen shot of the program used to read and set the temperature of setup structure. Another novelty of the setup is that, when the temperature controller operates in PC-controlled mode, the display shows the temperature set point, the temperatures of the environment and of the structure and the last calibration values of the standards. By means of a USB-PC connection it is possible to change the temperature set-point, load the structure and laboratory temperatures and store the standards calibration data on the noise PID controller memory.

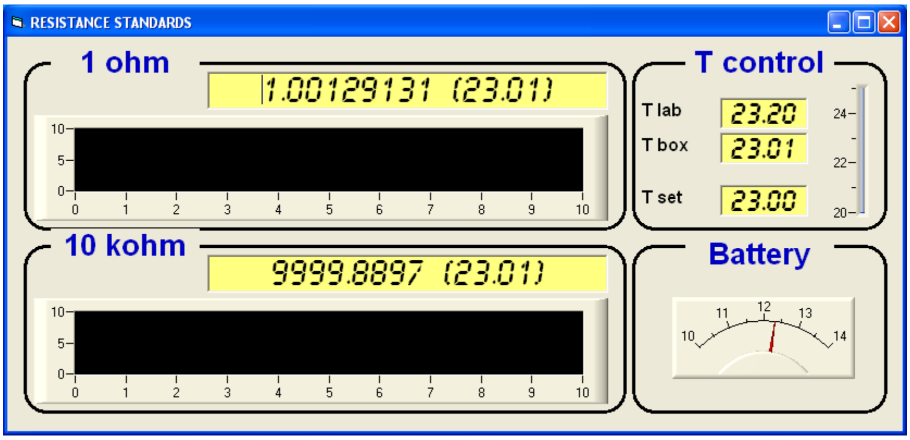

Fig. 4. Main frame of the control program of the setup.

The programs to control the parameters of the standards and the firmware of the embedded system were respectively written in Visual Basic and C.

3.2 Efficiency of the temperature control

Fig. 5 shows the 2 h temperature stability of the structure with the temperature controller set at 23 °C. After a transient due to the temperature set point change, the stability is better than 5 mK. The system needs about 30 min to change the temperature in a range of about 3 degrees around 23 °C to reach the desired stability if placed in a laboratory thermo-regulated at (23 ± 0.5) °C.

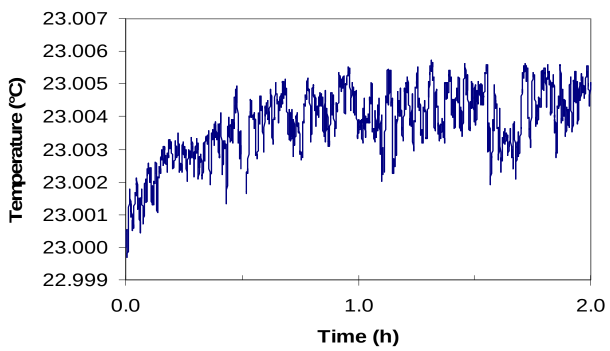

Fig. 5. Temperature stability in the structure. Initial drift is due to a temperature set-point change.

4. EXPERIMENTAL RESULTS

4.1 1 Ω standard

The time drift of the 1 Ω standard is reported in Fig. 6. It shows a very high short-time stability and rejection to temperature change and to thermal instabilities between its potentiometric connections. These measurements were made with a high precision current comparator bridge [17]. The 2h spread (measurements standard deviation) was 4×10^{-8} at the same level of high performance 1 Ω standard resistors in oil baths widely used in NMIs [5, 7, 15, 16]. The temperature dependence of the 1 Ω standard net was evaluated from 22 °C to 24 °C changing the structure temperature set point, resulting about 3×10^{-6}/°C.

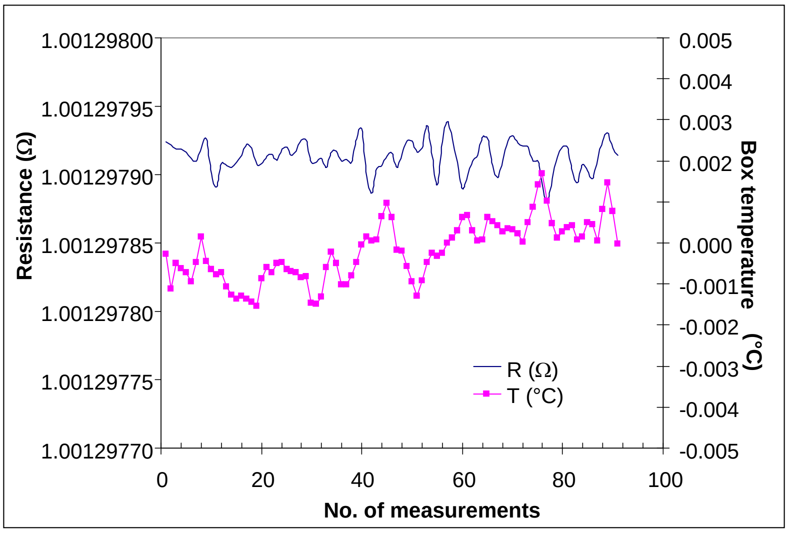

Fig. 6. Measurements on the 1 Ω standard along with the structure temperature drift with the temperature control set at 23 °C.

In addition, the plot in Fig. 7 shows the ultra-high stability of the setup 1 Ω standard in a typical calibration time at a single measurement current. Its measurements spread (evaluated as the measurements standard deviation) at 50 mA, after stabilization, was 1.3×10^{-8} while in the same conditions the spreads of two oil-bath and one air metrology-grade commercial 1 Ω standards were respectively 1.5×10^{-8}, 2.1×10^{-7} and 2.1×10^{-8}. This result allows to the setup 1 Ω to reach a satisfactory stability during its calibration reducing its calibration time. This test further confirms the advantage of the insertion of the 1 Ω standard net in oil internally to the thermo-regulated structure along with their potentiometric connections.

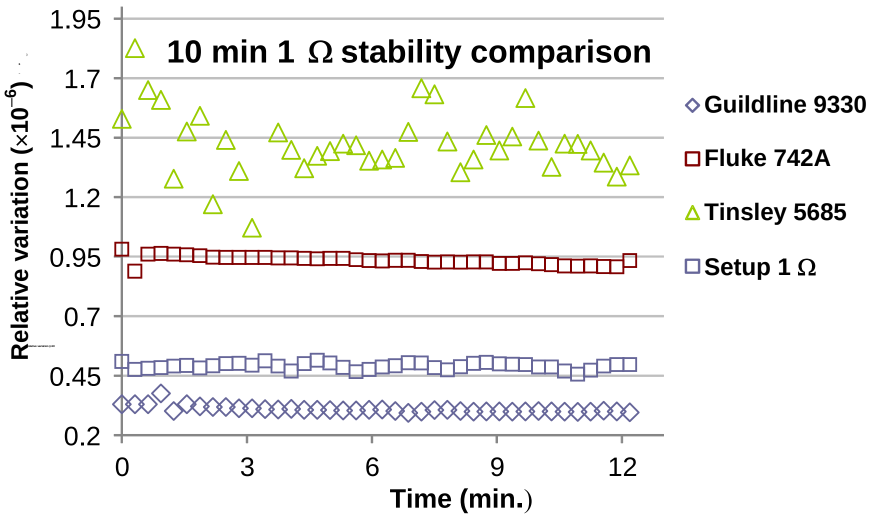

Fig. 7. comparison of the behaviour of the setup 1 Ω standard with three metrology-grade commercial 1 Ω standards during a typical calibration time.

4.2 10 kΩ standard

The 10 kΩ standard shows the 2h similar measurements spread (5×10^{-8}) and temperature dependence of its net from 22 °C to 24 °C of 0.6×10^{-6}/°C although its resistor net is placed in air in an external ring of the aluminium structure (Fig. 2).

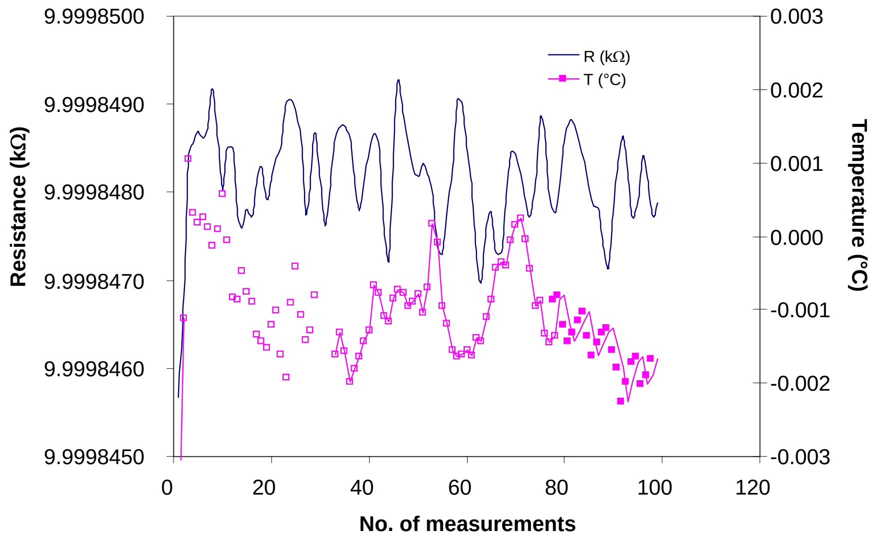

Fig. 8. Measurements on the 10 kΩ standard with the temperature control set at 23 °C.

4.3 Week stability comparison among the setup standards and metrology-grade commercial 1 Ω and 10 kΩ resistance standards

A comparison of the week stability of the setup standards and of the main metrology-grade commercial 1 Ω and 10 kΩ resistance standards was also carried on. This time period could be considered the mid period from a calibration at a NMI to an employment to calibrate DMMs or MFCs in customer laboratories. In Fig. 9 the comparison of 1 Ω standards is shown. The best stability was obtained by the commercial air standard with a maximum relative deviation from the first measure during the week of 2.4×10^{-8} while the commercial oil-bath and the setup standards showed maximum deviations from the first measure respectively of 7.8×10^{-8} and 4.3×10^{-8}. The spreads of the seven-day values were 1.2×10^{-8}, 6.8×10^{-8} and 2.5×10^{-8} respectively for the air, oil and the setup standards.

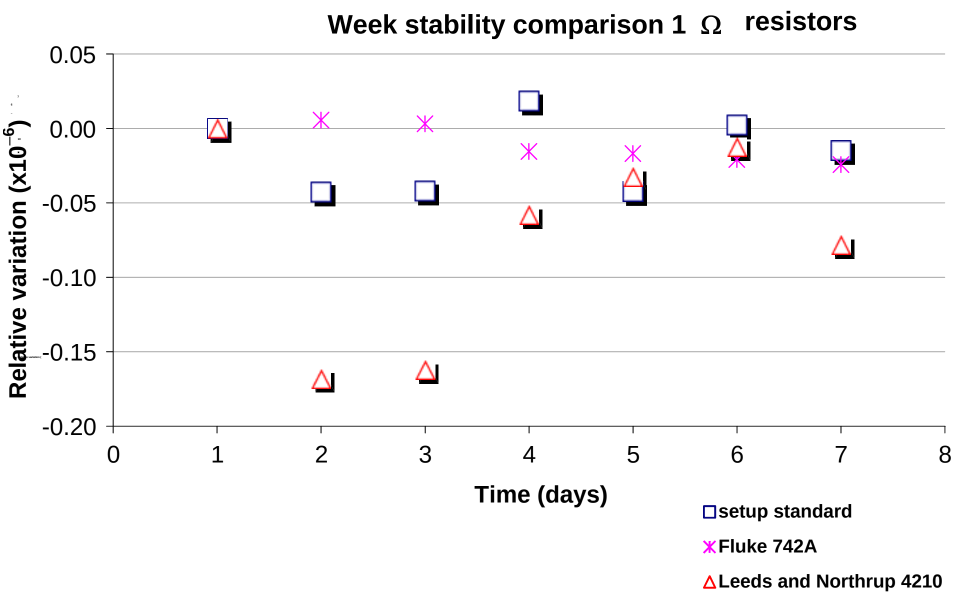

Fig. 9. Week drift of the 1 Ω setup standard in comparison with two metrology-grade 1 Ω standards, one of which in a high stability oil bath.

In Fig. 10 the comparison of the 10 kΩ standards is shown. The best stability was obtained by the setup standard with a maximum value deviation from the first measure during the week of 2.1×10^{-8} while the other two commercial standards showed maximum value deviations from the first measure respectively of 4.3×10^{-8} and 2.9×10^{-8}. The spreads of the seven days values were 0.7×10^{-8}, 1.8×10^{-8} and 0.9×10^{-8} respectively for the setup and the two commercial standards.

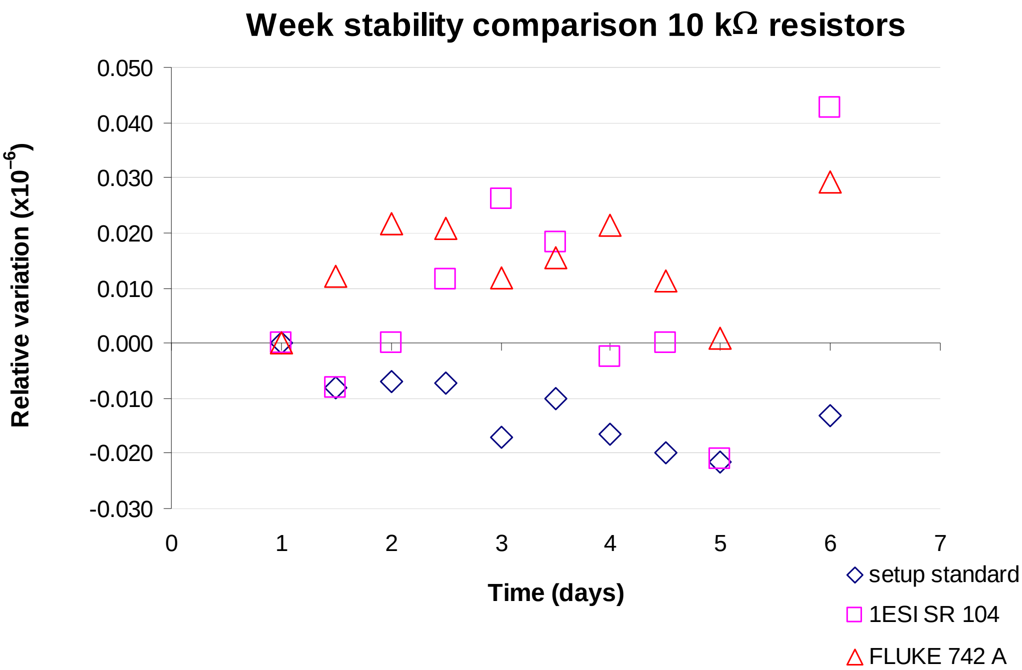

Fig. 10. Week drift of the 10 kΩ setup standard in comparison with two metrology-grade 10 kΩ standards.

4.4 Mid-term stability and power coefficient of the 1 Ω and 10 kΩ standards

Fig. 11 shows the mid-term stability of the two setup standards for about six months since the setup assembly.

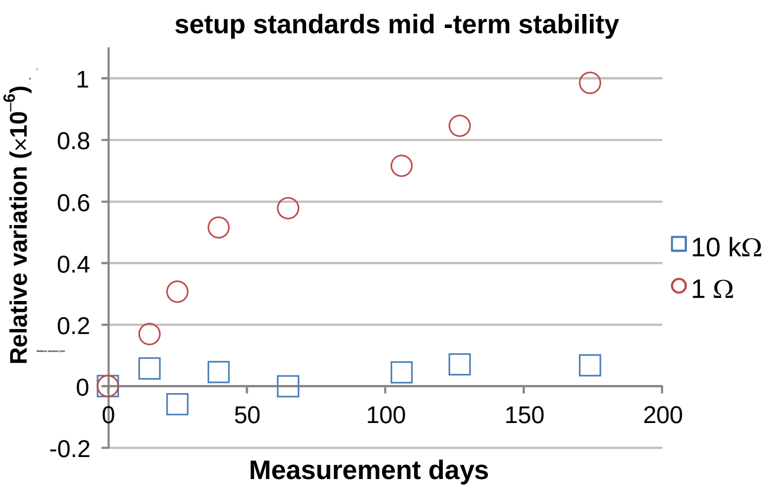

Fig. 11. Mid-term drift of the setup standards measured since the setup assembly.

The 1 Ω showed an increasing .drift of 1.0×10^{-6} while the 10 kΩ standard showed a drift of 6.7×10^{-8}. This lower drift is due to the long storage (several years) of the resistors forming its net before the setup construction so assuring a better stability to this standard. This drift is of the same order of an high accuracy commercial 10 kΩ resistor [18] and better than another 10 kΩ resistor [19]. The 1 Ω will be carefully monitored to verify if its value will reach a better stabilization, but already now its performance is on the order of the standard resistors [19]. The power coefficients of the two standards were evaluated measuring them vs. high stability standard resistors with the same measurement system [17]. The results are reported in Table 1.

Table 1. Power coefficients of the setup standards

standard	power coefficient $\times10^{-6}$/W)
1 Ω	1.7
10 kΩ	2.7

The 1 Ω Power coefficient allows to measure the standard at currents up to 100 mA.

4.5 Temperature coefficients with the temperature control set at 23 °C.

To evaluate the temperature coefficients of the setup standards with the temperature control set at 23°C and in the typical temperature conditions of electrical calibration laboratories that normally is(23 ± 1) °C, the standards were measured, after stabilization, at (22, 23 and 24) °C in a settable temperature laboratory. Their temperature coefficients are reported in Table 2.

Table 2. Temperature coefficients of the setup standards with the temperature control set at 23 °C.

standard	α_{23} ($\times10^{-7}$ K^{-1})	β ($\times10^{-7}$K^{-2})
1 Ω	5.5	1.0
10 kΩ	0.6	1.4

4.6 Transport effect.

The transport effect was evaluated transporting the setup turning off its temperature controller simulating the case in which the setup could belong to an external electrical customer laboratory that periodically send it for calibration of its two standards at a NMI. The setup could be transported by car, van, or plane and maintained for several hours or some days in not controlled temperature conditions till to the arrival to the customer laboratory going beyond the battery capacity of its temperature control. For our test, the setup was transported in a suitable package by car with 2-3h of travel, successively maintained in uncontrolled temperature condition for at least 24h. Then, the measurements were made in a thermo-regulated laboratory 24h after turning on the temperature controller again. Fig. 12 shows the obtained results. The maximun deviations from the initial measurement before transports were 1.4×10^{-7} and 1.7×10^{-7} for the 1 Ω and the 10 kΩ respectively. The spreads of the obtained results were 5.6×10^{-8} and 8.0×10^{-8} for the 1 Ω and the 10 kΩ respectively.

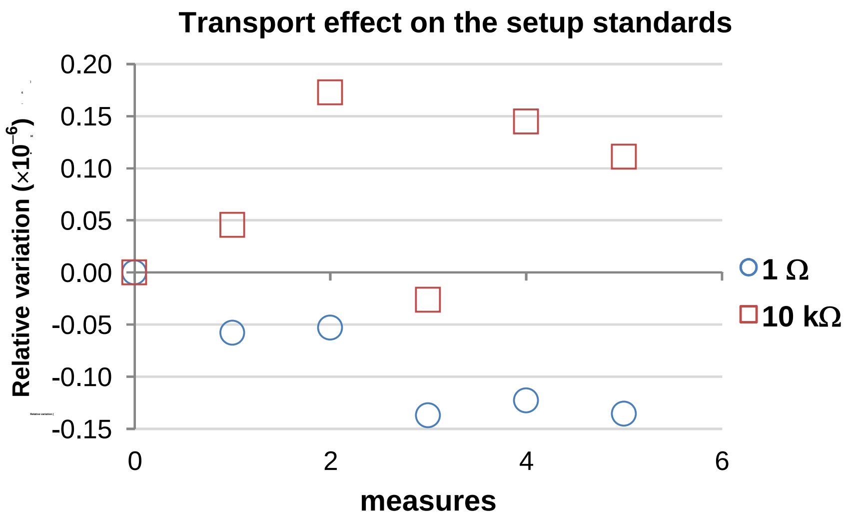

Fig. 12. Relative variation of the setup standards measured after transports turning off the setup temperature control.

Both standards were minimally affected by transport and by turning off the temperature control.

4.7 MFC's calibration and adjustment test.

The "artifact calibration" is a process requiring only a small number of reference standards with which high accuracy DMMs and MFCs can be calibrated and adjusted. At INRIM this operation, for example on a MFC, is performed in three steps [4]. With an initial verification, a set of measurement points in which the MFC operates are compared with the reference system. After this, the adjustment is performed; then a final verification (as performed in the first step) checks the effectiveness of the adjustment. All the measurement deviations between the MFC and the reference system in the two verifications are recorded and inserted in the calibration certificates for customers. To check the suitability of the setup 1 Ω and 10 kΩ standards to adjust DMMs and MFCs, the following test was made. An initial verification of a high performance MFC was performed with the reference system utilized in its last calibration process. In this operation it was observed that the measurement deviations in the 1 Ω and 10 kΩ points were unchanged with respect its last final verification made some months before. Successively, an adjustment process involving the 1 Ω and 10 kΩ setup standards was performed. Then, a final verification as the in the first step to end the process confirmed the same measurement deviations from the reference system of the initial verification in the 1 Ω and 10 kΩ points of the MFC. This result demonstrated that the adjustment with the setup standards didn't introduce any systematic error in the adjustment process.

5. UNCERTANTY EVALUATIONS

5.1 Setup 1 Ω and 10 kΩ calibration and mid-term use uncertainties

The two setup standards are calibrated vs. National resistance standard in the INRIM resistance Calibration laboratory by means of a measurement system involving high precision standard resistors put in a thermo-regulated oil-bath and a high performance current comparator bridge with expanded relative uncertainties of 1.7×10^{-7} for the 1 Ω and 1.2×10^{-7} for the 10 kΩ. With the data obtained in the setup standards characterization, in Tables 3 and 4 their mid-term use relative uncertainty budgets are given. It was assumed to use the setup standards as local standards for 180 days (mid-term period) without recalibration.

Table 3. 1 Ω mid-term use relative uncertainty.

Source	type	1σ ($\times10^{-7}$)
Calibration	B	0.85
Drift	B	2.9
EMFs	B	0.012[2]
Temperature	B	3.2
Power	B	0.02[3]
Total RSS		**4.5**

Table 4. 10 kΩ mid-term use relative uncertainty .

Source	type	1σ ($\times10^{-7}$)
Calibration	B	0.6
Drift	B	0.2
Temperature	B	0.6
Power	B	1.4[3]
Total RSS		**1.7**

For a 95% confidence level the mid-term use relative uncertainties of the setup standards are about 9.0×10^{-7} and 3.4×10^{-7} for the 1 Ω and 10 kΩ respectively.

[2] This component was evaluated taking into account the maximum temperature difference (about 10 mK) between the resistors net and its internal connectors both maintained in oil.

[3] This component was evaluated considering the maximum possible applied power difference between the calibration at INRIM and in the employment in a calibration laboratory of the standard.

5.2 Use uncertainties for MFC's and DMM's calibration

In the evaluation of the use relative uncertainty for DMMs and MFCs calibration it can be considered a one week to one month-drift component as this calibration normally is performed after maximum a month since the calibration of the standards at a NMI, but it is necessary to add a component due to the transport effect. The use relative uncertainties of the two setup standards for DMMs and MFCs calibration are summarized in Table 5 and 6. The evaluation of the use uncertainties is important to establish the overall calibration uncertainty of DMMs and MFCs.

Table 5. 1 Ω use relative uncertainty for DMM's and MFC's calibration.

Source	type	1σ ($\times10^{-7}$)
Calibration	B	0.85
Drift	B	0.5
EMFs	B	0.012
Temperature	B	3.2
Power	B	0.02
Transport	B	0.8
	Total RSS	**3.6**

Table 6. 10 kΩ use relative uncertainty for DMM's and MFC's calibration.

Source	type	1σ ($\times10^{-7}$)
Calibration	B	0.6
Drift	B	0.06
Temperature	B	0.6
Power	B	1.4
Transport	B	1.0
	Total RSS	**1.9**

For a 95% confidence level the use relative uncertainties of the setup standards for DMMs and MFCs calibration are 7.2×10^{-7} and 3.8×10^{-7} respectively for the 1 Ω and for the 10 kΩ.

5.3 Uncertainties summary.

In Table 7 a summary of the relative uncertainties at 2σ confidence level of the setup 1 Ω and 10 kΩ standards is given.

Table 7. Setup standards calibration, mid-term use, and for calibration of electrical instruments 2σ relative uncertainties.

standard	Calibration relative uncertainty	Mid-term use relative uncertainty	DMM-MFC calibration use relative uncertainty
1 Ω	1.7×10^{-7}	9.0×10^{-7}	7.2×10^{-7}
10 kΩ	1.2×10^{-7}	3.4×10^{-7}	3.8×10^{-7}

These uncertainties meet those requested by DMMs and MFCs manufacturers to calibrate and adjust these instruments.

6. CONCLUSIONS

The characterization on the 1 Ω and 10 kΩ setup standards and a test to adjust a MFC gave satisfactory results as well as their use uncertainties, so the setup 1 Ω and 10 kΩ resistance standards can be considered suitable for artifact calibration or Reference standards for maintaining the resistance unit in high level laboratories. The cost of the development of the setup was of the same order of commercial metrology-grade 1 Ω or 10 kΩ standard resistors as this it is a research prototype. Its cost could be significantly lowered if the construction was carried out by an industrial manufacturer. Whit this setup, the acquisition of oil-baths or the actual commercial metrology-grade thermo-stated air resistors could be avoided. Future aims will be the improvement of the temperature control to enhance the TCR of the 1 Ω standard and the prosecution of the observation of its value, the evaluation the setup standards humidity and pressure dependence to evaluate their attitude as travelling standards for high level ILCs.

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