Transport Behavior of Commercially Available 100-Ω Standard Resistors

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***Abstract*—Several types of commercial 100-Ω resistors can be used with the cryogenic current comparator to maintain the resistance unit, derived from the quantized Hall effect (QHE), and to disseminate this unit to laboratory resistance standards. Up until now, the transport behavior of these resistors has not been investigated. Such an investigation is of importance for carrying out comparisons that are close to the level of a direct comparison of two QHE apparatuses. A set of five 100-Ω resistors from three different manufacturers has been sent to 11 participating national metrological institutes. All laboratories but one have measured the resistors based on their laboratory's quantized Hall resistance measurements. A constant drift model has been applied, and the results are evaluated in such a way that the transport properties of these resistors are treated independently for the different types of resistor. Under certain conditions, these resistors allow comparisons with uncertainties better than 1 part in 10^8.**

***Index Terms*—Cryogenic electronics, Hall effect, resistance measurement, resistors, transfer standard.**

I. Introduction

An increasing number of national metrological institutes (NMIs) maintain the unit of resistance based on the quantum Hall effect. In the resistance-scaling process linking the quantized Hall resistance to decade value resistors, the smallest uncertainties can be obtained using a cryogenic current comparator (CCC) and a 100-Ω standard resistor. These uncertainties are typically on the order of 1 part in 10^9. The consistency of the realizations at the different NMIs has to be checked by international comparisons. Recently, in order to obtain the smallest possible uncertainties for these comparisons, a transportable quantized Hall effect (QHE) apparatus has been used by the Bureau International de Poids et Mesures (BIPM) [1]–[3]. This way of verifying QHE measurements and scaling is much more complex and expensive than traditional interlaboratory comparison methods.

The classical way to perform comparisons between the different NMIs is to circulate high-precision standard resistors. A prerequisite is that these resistors have a transport behavior that does not dominate the measurement uncertainties. Since the QHE was made the international basis of the unit of resistance in 1990, only one world-wide comparison between the NMIs has been completed [4], using as transfer standards certain 1-Ω and 10-kΩ resistors. No other standard resistors were thought to be stable enough during transport, and in particular, there have been few 100-Ω resistors that have demonstrated appropriate transport behavior. The aim of Euromet project no. 435, coordinated by the Physikalisch Technische Bundesanstalt (PTB) with 11 NMIs participating,[1] is to evaluate the transport behavior of several improved types of 100-Ω resistors. Five commercially available 100-Ω standard resistors from three different manufacturers were included in this study. Their temperature and pressure coefficients were determined and reported in the measurement instructions to allow for corrections. It is well known that

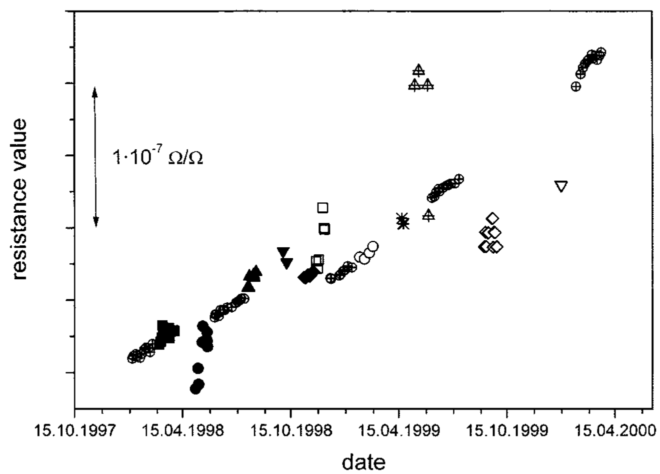

Fig. 1. Measurements of resistor Tinsley Ser. no. 262 767 during EUROMET project 435. The different marks refer to different NMIs.

[1]List of Participants: BNM/LCIE, France; CEM, Spain; CSIR, South Africa; IEN, Italy; JV, Norway; NIST, United States; NPL, United Kingdom; NRC, Canada; OFMET, Switzerland; PTB, Germany (pilot laboratory); SP, Sweden; VTT, Finland.

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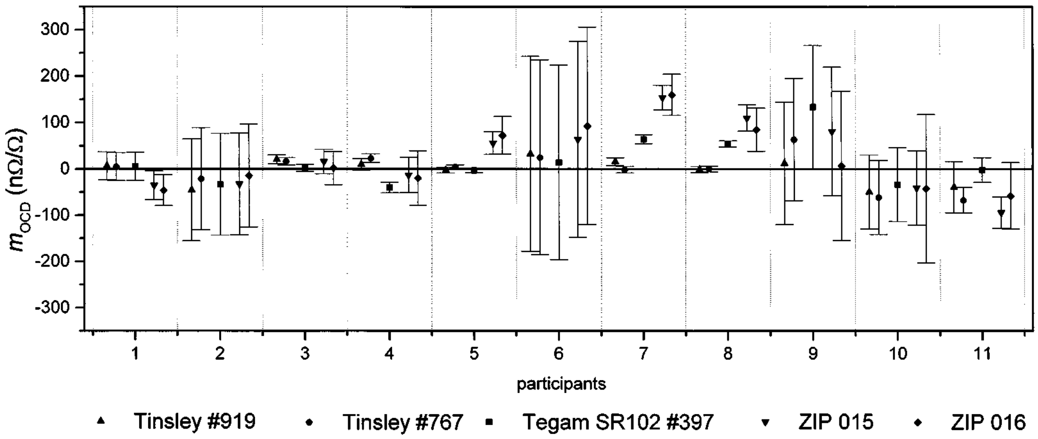

Fig. 2. Difference m_{OCD} as determined by the use of the OCD model by Frenkel between pilot laboratory and the different participants.

the resistance values of standard resistors exhibit a dependence on the transport conditions, i.e., changes of the ambient temperature can result in irreproducible resistance changes [5]–[8]. For this reason, resistors have—in most cases—been hand carried. In this project, the resistors were intentionally shipped to the participating NMIs using commercial carriers. During transport, the ambient temperature was not controlled, but was monitored. At the NMIs, the resistors were calibrated against a resistance standard based on the QHE.

II. Measurements and Results

Because of the large number of participants, the transport of the resistors from PTB to the different NMIs and back was arranged in four loops. In each loop, 2–4 NMIs were included. Seven of the participating laboratories used a cryogenic current comparator, two used a Josephson potentiometer, one used a Hamon network, and one laboratory intended to use a CCC bridge, but due to a system failure, it had to use a conventional measurement system traceable to the BIPM. Sending five resistors in four loops to 11 participants, allowing each participant three weeks of measurements, leads to a large amount of data. The combined measurement results for one resistor are shown in Fig. 1. As can be seen, the resistance value changes with time and this drift has some scatter superimposed on it. This observed scatter is thought to arise from two main sources: the transport behavior of the resistor and the quality of the measurements of the participant. In order to judge the transport behavior, it is necessary to find a way to separate the effects. A recent article by Frenkel [9] gives a method of treating artefact transport data. For the evaluation of comparisons, he describes three models: deviation from fit to pilot (DFP), overall constant drift (OCD), and separately fitted lines (SFL).

The SFL model appears to be best suited to obtaining information about the transport behavior of the resistors. This model assumes a symmetric sequence of measurements, laboratory 1, laboratory 2, and laboratory 1 again. In this case, a linear regression is fitted to each set of results, and from the extrapolation to a common date a difference m and a step h can be calculated. This difference m then is related to the difference in the realization of the physical unit in laboratory 1 and laboratory 2, and h is a measure of irreversible changes in the artefact. To apply this model to the present case, each loop is divided into single quasibilateral comparisons, using only the measurements at PTB before and after the loop and comparing the results with one single participant. Unfortunately, this model was not applicable in the present case for two reasons. First, the sequence of measurements is not symmetrical and the measured drift rates at the pilot laboratory and at the participant laboratory are, in some cases, quite different. This makes the evaluation highly sensitive to the choice of the common date. Second, not all laboratories reported a sufficient number of data to fit a linear regression.

The best overall analysis of results in this study was obtained using the OCD model. This model is justified by the fact that the drift rates determined for the artefacts are in good agreement for a certain number of laboratories. In this model, a linear regression is fitted to the results of the pilot laboratory and the participant's results with the same slope. Since these results do not fit to the same line, an additional parameter m is introduced, yielding two parallel lines with spacing m. This parameter includes both a possible shift of the standard, and a possible difference between the pilot and the participant. This analysis also yields estimates for the uncertainty associated with $m, u(m)$. Other contributions to the combined uncertainty, given by

$$u_{\mathrm{tot}} = \sqrt{u^2(m) + u_{\mathrm{lab}}^2 + u_{\mathrm{pilot}}^2}$$

are the participant's laboratory uncertainty u_{lab} and the pilot laboratory uncertainty u_{pilot}. Fig. 2 shows the differences m with the associated uncertainties $U_{\mathrm{tot}} = k \cdot u_{\mathrm{tot}}$ $(k = 2)$ for all five resistors.

A disadvantage of the OCD model is the inability to separate a transport-induced shift in the resistance of the artefact from a difference in the resistance standard maintained by the relevant laboratory. To overcome this disadvantage, it is assumed that all participating laboratories gave the best estimate for the values of resistance. That means the observed differences m are only due to transportation effects. To reduce the influence of the measurement capabilities, the weighted mean M_W of the differences m of the individual resistors is calculated, using u_{tot}^{-2} as weight

$$M_W = \frac{\sum \frac{1}{u_{\mathrm{tot}}^2} \cdot m}{\sum \frac{1}{u_{\mathrm{tot.}}^2}}$$

TABLE I
WEIGHTED MEAN M_W OF THE DIFFERENCE m WITH ASSOCIATED UNCERTAINTY $U(M_W)$ AND MODIFIED WEIGHTED MEAN M'_W WITH CORRESPONDING UNCERTAINTY $U(M'_W)$ WHERE OUTLIERS ARE DISREGARDED. ALL VALUES ARE IN $n\Omega/\Omega$

resistor	M_W	$U(M_W)$ ($k = 2$)	M'_W	$U(M'_W)$ ($k = 2$)
Tinsley #919	5.1	3.5	-0.7	4.2
Tinsley #767	5.1	2.8	2.2	3.1
TEGAM #397	14.8	3.1	-1.4	4.1
ZIP #015	39.1	11.0	-7.4	17.0
ZIP #016	27.5	16.0	-25.2	22.0

If the resistors were to show no transportation effects, then the weighted mean would be expected to be zero. The results are listed in Table I, and as can be seen, the weighted mean shows a significant positive offset. There was no evidence that the maintained unit of resistance in the pilot laboratory had shifted. Hence, in order to find a possible explanation, a quantity Q is defined as follows:

$$Q = \frac{m}{3 \cdot \sqrt{u_{\text{lab}}^2 + u_{\text{pilot}}^2}}.$$

If $Q > 1$, the difference between each laboratory and the pilot is greater than three combined standard uncertainties, giving an indication that transport affected the stability of the resistor. During transport, the ambient temperature of the resistors has been monitored. This additional information can be used to find some correlation between temperature and shift in value. Indeed, it turns out that in all cases where $Q > 1$, the monitored temperature of the resistors during transport departed from the reference temperature range from 20 °C to 23 °C by more than ±5 °C. Using this information, a modified weighted mean M'_W is calculated for which those results with $Q > 1$ are disregarded. For three of the five resistors ,this modified weighted mean M'_W is practically zero within a combined expanded uncertainty of 5×10^{-9} $(k = 2)$. For the other two resistors, the results are also slightly improved, but the combined expanded uncertainty is larger by a factor of four. This is mainly due to the fact that these resistors show a strong exponential decay after transport and need about two months to reach their established drift rate. This makes a distinct determination of m difficult.

III. CONCLUSION

The transport behavior of new types of 100-Ω standard resistors has been investigated. There is clear evidence that during transport, there are sometimes irreproducible changes in the value of the resistors. These changes are correlated with the difference between the monitored ambient temperature during transport and the normal measuring temperature. The analysis of results submitted by the participating NMIs shows that two of the three types of 100-Ω standard resistors behave as well as the best 1-Ω and 10-kΩ standard resistors. These resistors can be used to compare QHR systems with uncertainties of better than one part in 10^8 $(k = 2)$, even when they are neither hand-carried nor transported in a temperature-controlled enclosure.

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