

Measurement comparison between a commercial high resistance bridge and validated systems at ultra-high resistance values

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Abstract – At the National Institute of Metrological Research (INRIM) a comparison between the measurements of a commercial high resistance bridge and two validated high resistance methods from 100 G Ω to 1 P Ω has been performed. The systems showed satisfactory agreement except at 1 P Ω . The commercial bridge recently has been improved by means of a new software revised by the manufacturer according to the INRIM requests. This software allows the automatic calibration of the DC Voltage sources of the bridge, with a high precision DMM, taking into account these calibration results in the subsequent resistors calibrations. With the previous software version, bridge measurements at INRIM were limited at 10 T Ω . Also the bridge uncertainty specifications were updated, now being more reliable with respect to their first issue.

I. INTRODUCTION

At National Institute of Metrological Research (INRIM) high DC Resistance measurements from 1 G Ω to 100 T Ω are made with two measurement methods [1]. With these methods INRIM participated with satisfactory results at the comparisons [2,3]. One method, DMM-Cal method (DC) is based on a DC Voltage calibrator and a digital multimeter (DMM). It usually operates at INRIM from 1 G Ω to 1 T Ω . The second one, INRIM bridge (IB), is based on a modified Wheatstone bridge with two DC Voltage Calibrators in the active arms operating at INRIM from 100 G Ω to 100 T Ω [1]. In addition, in past years INRIM acquired an automated high resistance commercial bridge (CB) operating in the range from 100 k Ω to 10 P Ω whose operation mode is similar to the INRIM bridge and to the system in [4]. The instrument is equipped with a software that processes the data and provides an output file with the

ratio of the resistors under comparison, the resistance value of the resistor under calibration and the measurements uncertainty. The aim and relevance of this work has been the metrological validation of this commercial bridge in the configuration with which it was supplied to INRIM by the manufacturer and in the verification of the improvements on the instrument made by the manufacturer itself in agreement with INRIM. This validation has been performed comparing the commercial bridge results with those of the other two validated methods. In [5] a first evaluation of the bridge performance was made but the compatibility check was limited at 10 T Ω because at 100 T Ω the commercial bridge did not carry the measurements when the deviation from the nominal value of the resistor under calibration was remarkable. It was stated also that the sources calibration was not useful as it allowed only the verification of their deviation with respect to the values read by a calibrated DMM. The bridge software did not take into account these calibration results. Other open problems were found on the instrument manual available at that time [6] as:

In the specifications, the drift of the voltage sources and of the detector most likely were not considered. Thus, these specifications resulted too small and not referred to a definite time-period (e.g. 1-year); The suggested measurement settle times were too short to complete the undesired parasitic effects affecting high and ultra-high resistance measurements.

II. RECENT IMPROVEMENTS

After INRIM suggestions the bridge manufacturer made available a new software that takes into account the results of the calibration of the sources. Once evaluated the voltage deviation of the sources from standard values by the calibration with the DMM,

these deviations are then taken into account to correct the voltage values in the successive calibrations made by the bridge. This improvement is in agreement with a similar choice at NIST [7]. In the current issue of the operator manual [8] the suggested settle times have been correctly increased despite not available for resistors above 100 TΩ. Also the specifications were updated despite not reported in [8] but available on the manufacturer website. Unfortunately, it is not declared how these new specifications were evaluated and they are still not referred to a definite time period. In the bridge supplied by the manufacturer to INRIM, the internal detector Keithley mod. 6514 was placed close to the internal computer disturbing its measurements. Opening the bridge, the detector first was moved far from the internal computer, then this computer was definitely removed taking the control of the bridge by an external computer. To further improve the bridge performance, it was placed in a metal shielded chamber connected to ground potential. All the cables shields, resistors, as well the low terminals of the sources and of the detector have been connected to the same ground point to avoid ground loops. These solutions allowed to obtain more stable measurements.

III. MEASUREMENT SETUPS

In table 1 are reported the resistors that have been involved in the compatibility tests while in Table 2 are reported models of the DC Voltage calibrators, of the detector and of the DMM used in the DC and IB methods.

Table 1. High value resistors involved in the compatibility tests.

Value	Model	Serial no.
10 GΩ	Guildline 9336	63866
100 GΩ	Guildline 9336	65928
1 TΩ	Guildline 9337	64486
10 TΩ	MI 9331G	1101167
100 TΩ	MI9331G	1101170
1 PΩ	Guildline 9337	72587

Table 2. Digital calibrators, detector and DMM involved in the compatibility tests.

Method	Model	Serial no.
DMM	DMM J. Fluke 8508A	867448828
Cal	Cal. J. Fluke 5440B	3405011
	Cal. J. Fluke 5440B	4360204
INRIM	Cal. J. Fluke 5440B	4615007
bridge	Det. Keithley 6514	0641940

IV. MEASUREMENT PROCEDURE

The compatibility test started with the calibration of the 10 GΩ resistor with the DC method at 100 V, 250 V, 500 V and 1000 V to evaluate its voltage coefficient. With this method a DC Voltage calibrator supplies a voltage to the series of the standard and unknown resistors while the DMM measures both the total voltage and the voltage on the standard resistor. An auxiliary divider provides a guard voltage. For this guard voltage, a Kelvin-Varley voltage resistive divider is utilized. The values of the 10 GΩ at 50 V and 100 V have been evaluated through a data interpolation. These two values have been utilized for the calibration of the 100 GΩ resistor at 500 V and 1000 V with the two bridges in 1:10 ratio. The DC method has been also involved in the calibration of the 100 GΩ and 1 TΩ resistors for a further check.

V. MAIN UNCERTAINTY COMPONENTS OF THREE METHODS

Main uncertainty components of the DC method are:

- DC Voltage calibrator stability;
- Calibration uncertainty of the standard resistor;
- Drift of the standard resistor;
- Temperature effect on the standard resistor;
- Temperature effect on the unknown resistor;
- DMM calibration and accuracy;
- Bias current and emf residual effects;
- DMM load effect;
- Leakage effects;
- Stabilization of the resistor under calibration;
- Measurement repeatability (noise).

Main uncertainty components of the INRIM bridge are:

- DC Voltage calibrators calibration and accuracy;
- Calibration uncertainty of the standard resistor;
- Drift of the standard resistor;
- Temperature and voltage effects on the standard resistor;
- Offset and emfs residual effects
- Detector resolution;
- Detector Voltage burden;
- Balance interpolation error;
- Leakage effects;
- Stabilization of the resistor under calibration;
- Measurement noise.

Main uncertainty components of the commercial bridge are:

- Calibration uncertainty of the standard resistor;
- Drift of the standard resistor;
- Temperature and voltage effects on the standard

resistor;
 Offset and emfs residual effects;
 10:1 bridge ratio accuracy;
 Leakage effects;
 Stabilization of the resistor under calibration;
 Measurement noise.

A. Examples of uncertainty budgets

In Tables 3-5 the uncertainty budgets of the three methods for the calibration of a 1 TΩ resistor are reported. As the one-year specifications of the instruments were taken into account for the DC and IB methods, these uncertainty budgets could be valid within a year. Normally the instruments drift is negligible and included in the accuracy specifications. In the uncertainty budget with the INRIM bridge the drift of the detector was not taken into account because it acts as null detector and not as picoammeter taking advantage of its linearity around the balance condition.

Table 3. Uncertainty budget for the calibration of a 1 TΩ resistor at 1000 V with the DC method.

Source	Type	$1\sigma (\times 10^{-6})$
$R_s \text{ cal}$	B	2.0
$R_s \text{ drift}$	B	0.6
$R_s \text{ temp}$	B	0.06
$R_x \text{ temp}$	B	0.6
Load	B	45
DMM _{cal Lo volt}	B	14
DMM _{cal Hi volt}	B	2.0
DMM _{acc. Lo volt}	B	8.9
DMM _{acc. Hi volt}	B	3.6
Leakages	B	8.7
$R_x \text{ noise}$	A	2.2
Stabilization	B	28
¹ Cal _{corr. Hi-Lo volt}	B	17
¹ Acc _{corr. Hi-Lo volt}	B	6.2
¹ Noise _{corr. Hi-Lo volt}	A	0.4
RSS		58

Table 4. Uncertainty budget for the calibration of a 1 TΩ resistor at 1000 V with the NRIM bridge.

Source	Type	$1\sigma (\times 10^{-6})$
$R_s \text{ cal}$	B	47
$R_s \text{ drift}$	B	2.9
$R_s \text{ temp}$	B	0.3

¹ This component is due to the use of the same DMM for the measurement of the Lo and Hi voltages.

$R_x \text{ temp}$	B	0.3
Detector resol.	B	14
Interp.	B	2.9
$R_s \text{ volt}$	B	11
Connections	B	5.8
Leakages	B	5.8
$R_x \text{ noise}$	A	5.4
$V_{\text{Hi-acc}}$	B	1.7
$V_{\text{Hi-cal}}$	B	3.7
$V_{\text{Lo-acc}}$	B	1.7
$V_{\text{Lo-cal}}$	B	4.0
Voltage burden	B	0.02
RSS		51.9

Table 5. Uncertainty budget for the calibration of a 1 TΩ resistor at 1000 V with the commercial bridge.

Source	Type	$1\sigma (\times 10^{-6})$
$R_s \text{ cal}$	B	25
$R_s \text{ drift}$	B	2.9
$R_s \text{ temp}$	B	1.4
$R_x \text{ temp}$	B	2.9
$R_s \text{ volt}$	B	11
Connections	B	5.8
Leakages	B	5.8
$R_x \text{ noise}$	A	6.7
Balance	B	17.3
Sensitivity	B	13.9
Meas. Stab.	B	20.2
Bridge spec.	B	6.5
RSS		42.7

VI. MEASUREMENT RESULTS

The measurements have been made in two separate shielded laboratories. The measurements with the INRIM bridge and with the DC method have been made placing the resistors in a commercial high stability air-bath at $(23 \pm 0.01)^\circ\text{C}$ while the measurements with the commercial bridge have been made placing the resistors in an INRIM-built air-bath at $(23 \pm 01)^\circ\text{C}$. In Table 6 the results from 100 GΩ to 1PΩ are reported along with their expanded uncertainties and the normalized error between the methods. Results are reported in form of relative differences between couples of methods. The normalized errors between the measurements of the two bridges have been evaluated taking into account a partial correlation due to the use of the same standard resistor.

Table 6: Synthesis of the measurement results and of their compatibility.

Res.	Volt.	Δ_{IB-DC}	Δ_{IB-CB}	Δ_{DC-CB}	U_{IB}	U_{DC}	U_{CB}	E_{nIB-DC}	E_{nIB-CB}	E_{nDC-CB}
	(V)	$\times 10^{-6}$	$(\times 10^{-6})$	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$	$\times 10^{-6}$			
100 G Ω	500	-15.2	-3	12	91	96	40	-0.1	-0.03	0.1
	1000	8.1	12	-20	78	67	40	0.1	-0.1	-0.3
1 T Ω	500	90	5	-86	104	160	90	0.5	0.0	-0.5
	1000	-38	43	80	104	120	85	-0.2	0.3	0.6
1 T Ω 1:100	500		87		96		90		0.7	
	1000		40		100		85		0.3	
10 T Ω	500		-8		310		280		0.0	
	1000		192		320		260		-0.5	
100 T Ω	500		351		570		680		0.4	
	1000		93		500		650		0.1	
1 P Ω	500		-29106		8200		14000		-1.8	
	1000		-26026		7800		14000		-1.6	

A. Results in graphical form

In Fig. 1-6 the measurement results from 100 G Ω to 1 P Ω are reported. The uncertainty bars correspond to the expanded uncertainties. In Fig. 6 also a compatibility test in ratio 1:100, concerning the calibration of the 1 T Ω resistor, is shown.

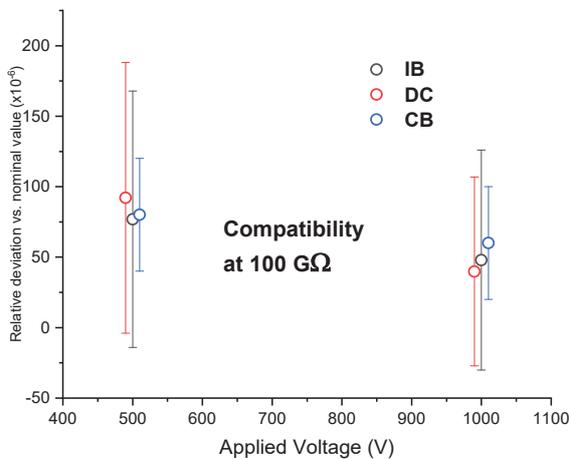


Fig. 1. Compatibility test at 100 G Ω .

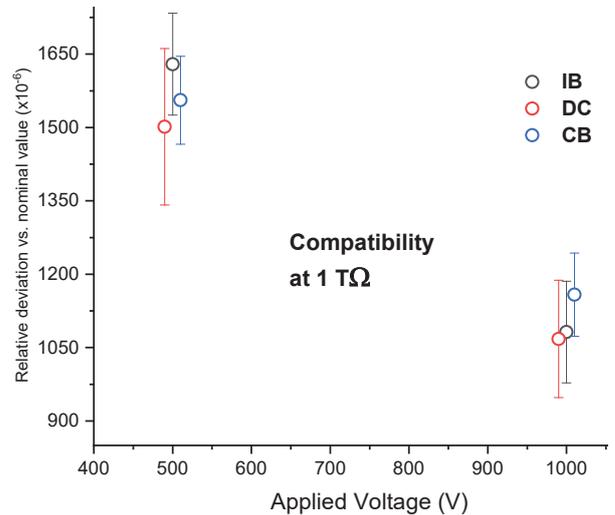


Fig. 2. Compatibility test at 1 T Ω .

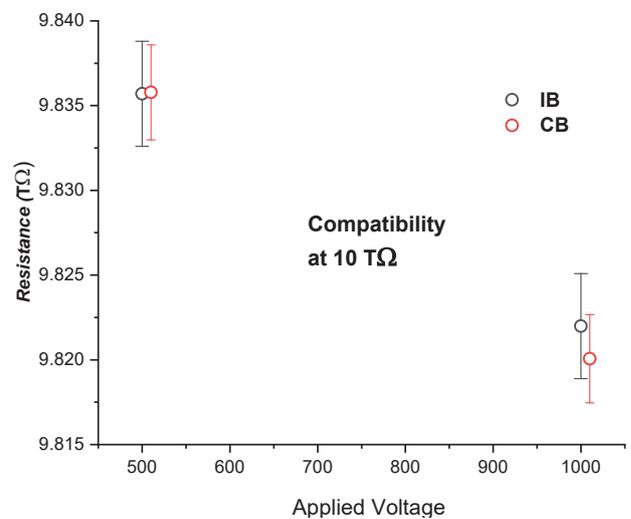


Fig. 3. Compatibility test at 10 T Ω .

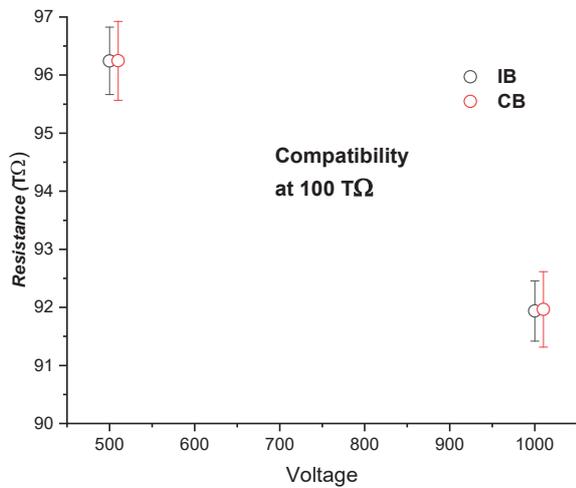


Fig. 4. Compatibility test at 100 TΩ.

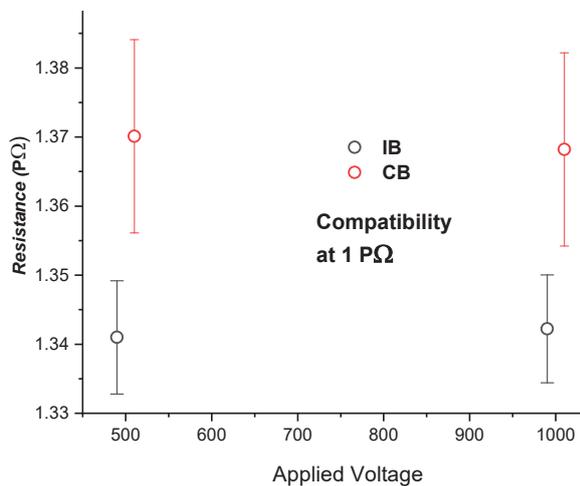


Fig. 5. Compatibility test at 1 PΩ.

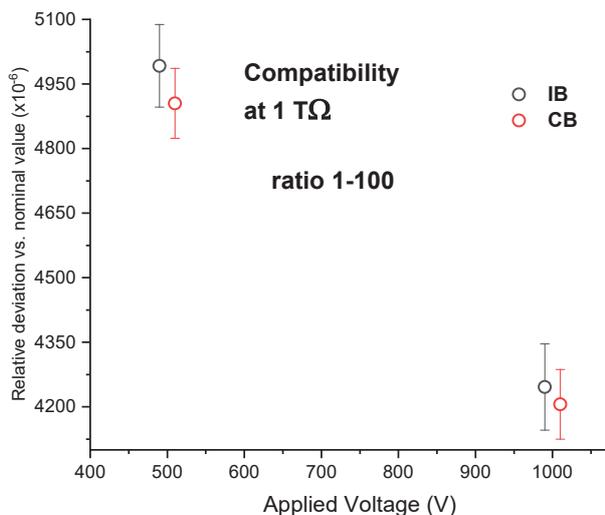


Fig. 6. Compatibility test at 1 TΩ in 1:100 ratio.

V. DISCUSSION

The outcome of the compatibility test is not totally satisfactory as, for both bridges, hard measurement noises and instabilities have been detected in particular at 1 PΩ where the compatibility has not yet been achieved. The noises for the commercial bridge have been presumably due to ground configuration as it had to be moved temporarily to another laboratory not equally correctly shielded. The measurement cables (RG58) provided with the bridge do not seem enough suitable for ultra-high resistance measurements. Other two points have to be further investigated: the first consists in the finding of correct resistors settle times with which to set the measurements with the commercial bridge. This task seems critical in particular when two different typologies of resistors are under comparison as in the case of our 100 TΩ and 1 PΩ. The 100 TΩ is a mono-block resistor while the 1 PΩ is a resistance network based resistor so they have presumably different settle times. Limitations of the dual source technique at PΩ level are anyway mentioned also in [9]. The other point to be investigated concerns the great measurement deviation at 1 TΩ between the measurements in ratios 1:10 and 1:100 respectively obtained by both bridges. Although the compatibility between the two bridges has been obtained, it is necessary to understand if this difference of the 1 TΩ value is due to a drift or damage to the resistor itself or to systematic errors of both bridges.

CONCLUSION

From the results it can be observed an improvement with respect to the results obtained in [5] when measurements at 100 TΩ level were not allowed with the commercial bridge. Investigations on the suitable settle times for the ratio measurements with the commercial bridge and for different resistors typologies will be made. Further contacts with the manufacturer will prosecute to improve the commercial bridge performance. The operating mode of the INRIM bridge will be also reviewed and adapted to measurements at PΩ level.

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