EURAMET TC Project
Final Report

Project Title

Pilot study: Calibration of very high value resistors (>100 GΩ)

Coordinator, Institute, Country

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EURAMET Registration No.

1687

Subject Field

Electricity and Magnetism

KCDB Identifier

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Date

2025-12-31

FINAL REPORT

Project n°	EURAMET 1687
Participants	LNE (FR), INRiM (IT)
Type of comparison	Pilot study
Range of comparison	High Value Resistors in the range 1 TΩ - 1 PΩ
Starting date	01.09.2024
Completion date	31.12.2025

Context and aim

Ultra-high resistance values (10^{12} Ω ≤ R ≤ 10^{15} Ω) are generally used to calibrate teraohmmeters for checking the insulation of electrical installations or equipment. Depending on the applied voltage, low currents (< 1 nA) flow through these high value resistors. Applications asking traceable calibrations of such low currents relates to the fundamental metrology but also ionization chambers used in the healthcare sector, in electrometers, etc. The calibration of such high value resistors is important both to metrological institutes and to concrete societal applications.

This pilot study n° EURAMET.EM 1687 offered the framework of a bilateral collaboration between LNE (FR) and INRiM (IT) national metrology institutions. The purpose of the study was multiple:

- Calibrate of several ultra-high value resistors (UHVR) with different methods;
- Identify the issues related to UHVR measurements under low voltages (≤ 10 V);
- Investigate the feasibility of the INRiM approach for UHVR under voltages lower than 10 V.

Work description

Calibrations of ultra-high value resistors was performed as indicated in the table:

1 PΩ network resistor	± 1 V[1]; ± 10 V[1]; ± 500 V[2,3]; ± 750 V[3]; ± 1000 V[2,3]
100 TΩ network resistor	± 1 V[1]; ± 10 V[1,2]; ± 50 V[2]; ± 100 V[2]; ± 250 V[3]; ± 500 V[2,3]; ± 750 V[3]; ± 1000 V[2,3]
100 TΩ bulk resistor	± 10 V[1]; ± 250 V[3]; ± 500 V[2,3]; ± 750 V[3]; ± 1000 V[2,3]
10 TΩ bulk resistor	± 5 V[2]; ± 10 V[1,2]; ± 50 V[2]; ± 100 V[2]; ± 250 V[2,3]; ± 500 V[3]; ± 750 V[3]; ± 1000 V[3]
1 TΩ network resistor	± 1 V[1,2]; ± 10 V[1,2]; ± 100 V[2]

with:

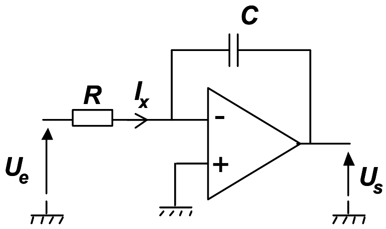
[1] refers to the LNE low current amplifier (LCA) method;

[2] refers to the LNE charging capacitor (CCI) method;

[3] refers to the INRiM modified Wheastone bridge/Dual Source bridge (DSB) method.

The low-current amplifier (LCA) method was tested by LNE to obtain the absolute values of the UHVR under 1 V, respectively under 10 V. This method is based on a commercial low-current amplifier of variable gain from 10^{11} V/A to 10^{13} V/A. The amplifier is used as a trans resistance/current detector with limited bandwidth to reduce noise. Measurements employ polarity reversals and data selection after transient periods; spurious spikes being removed in post-processing phase.

The CCI method, the LNE traceable calibration method [1] for UHVR and low currents, was used under voltages varying from 10 V up to 1000 V. It relies on the principle of the integration of the constant current, I_x, flowing through a stable air capacitor, C as illustrated in the following scheme.



$$I_\mathrm{x} = -\,C \cdot \frac{\mathrm{d}U_\mathrm{s}}{\mathrm{d}t}$$

$$R = \frac{U_\mathrm{e} + e_\mathrm{i}}{I_\mathrm{x}}$$

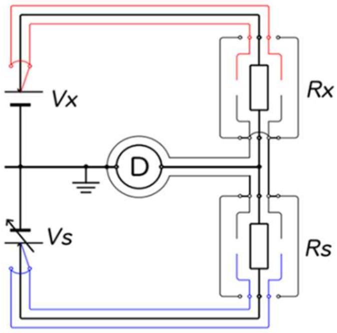
with :

U_e - input voltage generated by a reference source;

e_i - input residual voltage of the integration bridge.

Measurements are collected over repeated charge/discharge cycles until stability is reached; cycle averages are used as the reported resistance value.
Traceability is established through calibration of the voltage source, capacitors, voltmeter, and timing/frequency chain to French national standards (Josephson voltage standards, quantum Hall resistance, and Global Navigation Satellite System referenced frequency).

In this pilot study, INRiM used the commercial bridge Model 6600A MI, which apply the modify Wheatstone bridge/Dual Source bridge (DSB) method. The DSB is an adapted Wheatstone bridge in which two arms are programmable voltage sources as illustrated in the following scheme.



$$I_\mathrm{D} = I_\mathrm{s} + I_\mathrm{x} = \frac{V_\mathrm{s}}{R_\mathrm{s}} + \frac{V_\mathrm{x}}{R_\mathrm{x}}$$

$$r = \frac{R_\mathrm{x}}{R_\mathrm{s}} = \left|-\frac{V_\mathrm{x}}{V_s}\right|$$

A bias source applies V_x across the unknown resistor R_x, while a second source applies V_s (opposite
polarity) across a reference resistor R_s. The bridge is adjusted in iterative steps until the null detector indicates equilibrium, yielding the resistance ratio, $r = R_x/R_s$ equal to the voltage ratio, V_x/V_s. Practical operation requires careful settling time, polarity reversals and attention to error sources such as voltage source instability, residual balance currents, detector burden, offsets/thermal EMFs, electronic noise, and leakage.
Existing commercial DSB are designed for multiple resistance ratios like 1:1, 10:1, 100:1, 1000:1. Let's consider one example of 100:1 ratio:

$$r = \frac{100}{1} = \frac{1\ \mathrm{P\Omega}}{10\ \mathrm{T\Omega}} = \frac{1000\ \mathrm{V}}{10\ \mathrm{V}} = \frac{500\ \mathrm{V}}{5\ \mathrm{V}}$$

As it can be noticed, if the 10 TΩ resistor is the standard one used to find out the value of the 1 PΩ resistor, it is necessary to know the value of the standard resistor under 10 V or 5 V.

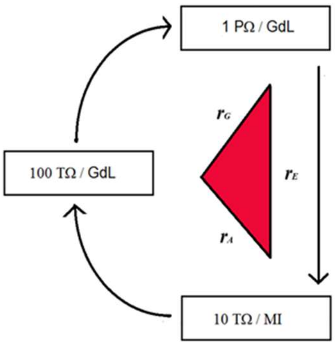
Determining the UHVR at low voltages with low uncertainties is a very challenging task since different types of noises have a high impact. INRiM approach to overcome this limitation is to find the resistance values at low voltages by extrapolation, using a combination of the INRiM Calibration Curves Computing (CCC) software and the triangulation rule as an internal consistency and risk-assessment tool.

INRiM's CCC software fits calibration data (typically obtained at higher voltages) with statistical models (ordinary, weighted, or total least squares) to predict resistance values below the calibration interval.
The triangulation-based validation strategy: three intermediate calibration values, built from independent ratios, must satisfy a strict triangle closure and a metrological compatibility condition; their corrected weighted mean is treated as the most reliable calibration value.

For a triangle of resistors, corresponding to three resistors ratios r_A, r_E, r_G, the closure rule requires the product of two ratios to match the third ratio as closely as possible. A stricter metrological compatibility condition compares the deviation from closure with the combined uncertainty and a chosen coverage factor k (often k = 2, but possibly k = 1 for very low voltage-coefficient resistors). If the criteria are met, the corrected weighted mean of the three intermediate values is proposed as the most reliable calibration value.
Let's consider the example of the measurements performed by applying the triangle method between 10 TΩ - 100 TΩ - 1PΩ (figure below). One might start with the value of the ultra-high value resistors obtained from the Calibration Certificate (usually at voltages ≥ 250 V) and with the value generated by the predicted model (using CCC software) at low voltages (< 250 V).

Comparisons		Ratio	Average resistance ratio, $\bar{r}$	standard deviation of the mean (sdvm), u_r
A	100 TΩ : 10 TΩ	10 : 1	$\bar{r}_A$	u_{rA}
E	1 PΩ : 10 TΩ	100 : 1	$\bar{r}_E$	u_{rE}
G	1 PΩ : 100 TΩ	10 : 1	$\bar{r}_G$	u_{rG}

The criteria to validate the triangle method and the predicted model are based on the restrictive rules to be satisfied in terms of ratios and their type A uncertainties, given below.



$$\bar{r}_A \cdot \bar{r}_G \cong \bar{r}_E$$

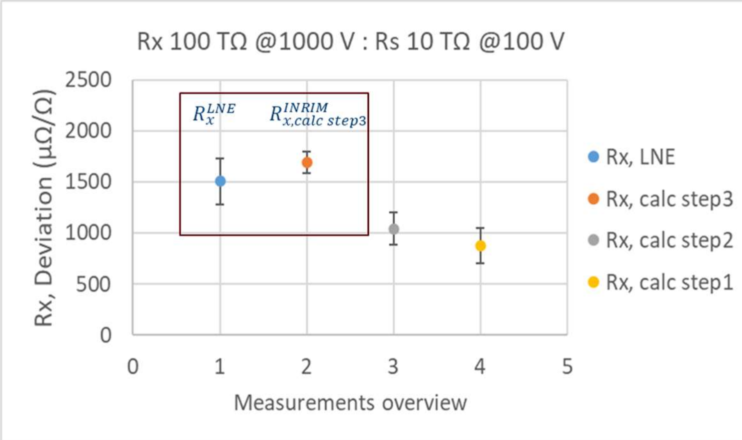
$$\left|1 - \frac{\bar{r}_A \cdot \bar{r}_G}{\bar{r}_E}\right| \leq k\sqrt{u_{rA}^2 + u_{rE}^2 + u_{rG}^2}$$

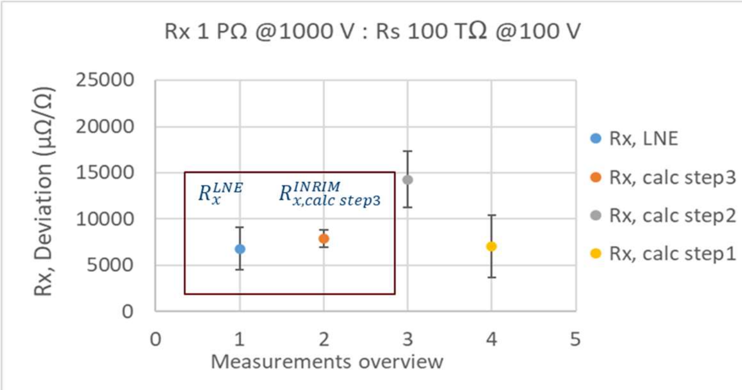
where k is the cover factor adjustable depending on the type of resistor manufacturing (k =1 for very low voltage coefficient resistors, elsewhere k =2).

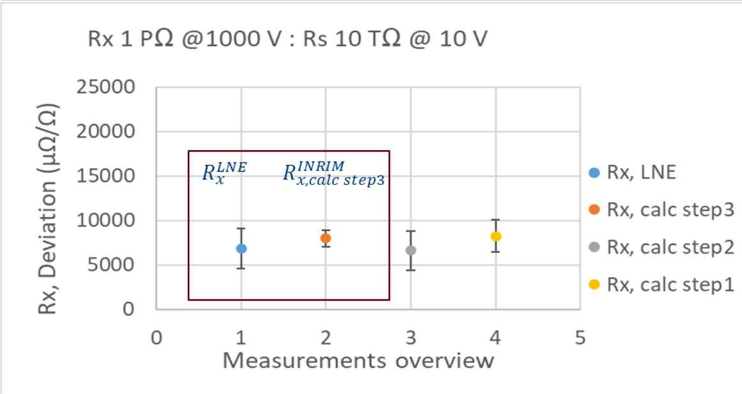
Results

All the 5 UHVR were calibrated and measured under voltages varying from 1 V up to 1000 V.

Good results are obtained for the studied 10 TΩ - 100 TΩ - 1PΩ triangle. The compatibility criteria are satisfied at 500 V and 1000 V for the network-type 100 TΩ resistor, supporting the use of regression-based low-voltage predictions for the 10 TΩ resistor in this case.







The DSB method offers accurate results after a 3 steps iterative procedure that was established through intensive characterization by INRiM [2]. The previous graphs illustrate the compatibility among the results obtained through traceable calibration, R_x^{LNE}, respectively through INRiM DSB+ CCC+ triangulation method, $R_{x,calc\ step3}^{INRiM}$.

Two types of resistors were available and were measured during this pilot study: network-type, respectively bulk-type. The obtained results emphasize that bulk resistors require longer stabilization to reach a stable value at a given voltage, and that noise/drift contributions dominate at the highest resistance levels, calling for deeper quantification and modeling.

It is worthy to be noted that we had the possibility (chance) to calibrate the network-type resistor SN° 69040 from Guildline that was one of the traveling standard during the EURAMET.EM-S32 comparison. The recently obtained results allowed us to compare the 3 presented methods and to cross-validate them. These results generated a co-authored paper, accepted for an oral presentation at the **CPEM 2026** conference. It is about:

I.Mihai, E. Patois, P. P. Capra, F. Galliana, F. Piquemal and D. Istrate,

"***Ultra-high electrical resistance calibration at 100*** TΩ ***addressing the open problems identified in the low voltage measurements***."

Conclusions and perspectives

The study indicates that the existing calibration methods apply properly for UHVR with the reduced uncertainties (the declared CMCs on the BIPM's KCDB) for voltages ≥ 10 V.

On the contrary, deeper investigations and improvements are necessary to reach repeatable and traceable calibrations of UHVR for voltages < 10 V with reduced uncertainties.

For the bulk-type resistors, the additional effects (e.g., stabilization time, voltage coefficient, noise, drift, or leakage) needs to be fully captured and managed.

The DSB method can be used to efficiently link resistors over a wide range (from 1 TΩ to 1 PΩ), with a recognition of the detector sensitivity and of the low-frequency noise that might limit low-voltage operations. Caution is mandatory when using the DSB to the choice of the resistors forming the ratios. It is recommended to prefer large ratios (e.g. 100:1) instead of multiple smaller ratios. Except the required voltage to supply (higher, the better), this support also to minimize the propagated uncertainty.

Different resistor technologies (bulk vs network) may behave differently (stabilization, voltage coefficients, noise), so risk assessment and method choice should be technology-aware.

The use of the regression/extrapolation should be done cautiously. To consolidate the results, it is necessary to validate the predicted low-voltage values of the resistors by the triangulation criteria and by comparing them with independent absolute measurements when possible.

This collaboration demonstrates a structured way to compare and cross-validate three methods for
ultra-high value resistance calibration. Moreover, it allows to LNE and INRiM :

- exchanging experiences on a challenging topic,
- studying different technologies of realizing UHVR and their appropriate parameters (time constant, low frequency noise behavior),
- exploring several calibration methods to identify complementarities and differences among them;
- generating new ideas to push the limits of UHVR calibration up to 10 PΩ.

The one month presence of Iulian Mihai from INRiM in the LNE premises under the International Technical Cooperation agreement n° 2024-001 partially funded by the LNE and the regular meetings contributed to the fruitful collaboration and to the publication of the common paper at the CPEM 2026.

References

[1] B. Jeckelmann et al., "Supplementary Comparison EURAMET.EM-S32 Comparison of Resistance Standards at 1 TΩ and 100 TΩ", *Metrologia*, vol. 50, no. 1A:20131980
[2] I. Mihai and F. Galliana, "An approach for reliable calibrations of ultra-high value resistors with the dual source bridge Mapan Journal of Metrology Society of India Vol.40 (2) 547-555 June 2025, https://doi.org/10.1007/s12647-025-00819-9