Euramet EM-S40

DC resistance 1 mΩ, 100 Ω and 100 MΩ

Bilateral Comparison KIM-LIPI / LNE

<u>Final Report</u>

Isabelle BLANC
Laboratoire national de métrologie et d’essais (LNE)
29 avenue Roger Hennequin
F-78190 Trappes (France)

20 novembre 2014

Abstract: This report describes a bilateral comparison of resistance standards organised within the frame of the EU-Indonesia Trade Support Program II (TSP2) / AWP2-2-20-5 between LNE, France and KIM-LIPI, Indonesia. This bilateral comparison registered in the KCDB as EURAMET.EM-S40 was piloted by LNE. LNE participated in CCEM Key Comparison CCEM-K10 and CCEM-K2, thus providing the link between KIM-LIPI results and CCEM-K10 and CCEM-K2. This report includes the measurement results from the participants and information about their calibration methods for measurements of 1 mΩ, 100 Ω and 100 MΩ resistors.

Content

Supplementary Comparison EURAMET EM-S40 Bilateral comparison of DC resistance standards (1 mΩ, 100 Ω and 100 MΩ)

1 INTRODUCTION

The comparison is organised within the EU-Indonesia Trade Support Programme II, Sub-project Number AWP2-2-20-5, "Improvement of traceability of Metrology and Calibration measurements of Puslit KIM".
Two National Metrology Institutes took part in this comparison: LNE (France) and KIM-LIPI (Indonesia).
LNE is acting as the pilot laboratory and in this function is responsible for providing the travelling standard, the evaluation of the measurement results and the final report.

The objective of this comparison is to compare the measurement capabilities of the two National Metrology Institutes for 3 values of resistances : 1 mΩ, 100 Ω and 100 MΩ.

The comparison is linked to the CCEM comparisons CCEM-K10 and CCEM-K2 by the participation of LNE to these two comparisons. It is aimed to validate the competence of the KIM-LIPI to measure accurately DC resistance within their KCDB and/or accreditation uncertainties.

This bilateral comparison was registered in the KCDB as EURAMET.EM-S40 in May 2014.

The comparison is accomplished in accordance with the EURAMET Guidelines on Conducting Comparisons and CCEM Guidelines for Planning, Organising, Conducting and Reporting Key, Supplementary and Pilot Comparisons.

2 DEFINITION OF THE MESURAND

The quantity to be measured is the resistance of the travelling standards in the 4 terminals configuration for the 1 mΩ and the 100 Ω standards and in the 3 terminals configuration for the 100 MΩ standard.

Participants were asked to measure and report additional quantities.

1 mΩ and 100 Ω resistances:

- ***I:*** DC current through the resistor.
- T_{ext}: the temperature (°C) of the environment where the standard is measured.

100 MΩ resistance:

- ***V:*** test voltage.
- T_{ext}: the temperature (°C) of the environment where the standard is measured.
- RH_{ext} : relative humidity of the environment.

3 TRAVELLING STANDARDS

3.1 DESCRIPTION OF THE STANDARDS

The travelling standards were 3 resistors:

- YEW, type 2792 - 1 mΩ - s/n 58FS1075.
- Guildline 9330 - 100 Ω - s/n 51.521.
- Guildline 9330 - 100 MΩ - s/n 61.890.

The devices were chosen with respect to stability and repeatability prior to the start of the comparison. Preliminary measurements were performed to evaluate effect of temperature and power.

3.2 CHARACTERIZATION OF THE STANDARDS

3.2.1 Effect of temperature

The temperature coefficients (CTs) were determined experimentally.

From calibrations performed at 3 temperatures (20°C, 23°C and 26°C), the characteristics parameters R_{to}, α_{to} and β of the equation have been calculated:

$$R_t = R_{t_o}\left[1 + \alpha_{t_o}(t - t_o) + \beta(t - t_o)^2\right]$$

where R_t and R_{t0} represent the values of the resistance at the temperatures t and t_0 (Tab 1).

The value t_0 is fixed at 23,00°C:

Resistance	R_{23}	α_{23} (10^{-6}/°C)	β (10^{-6}/°C^2)
YEW, type 2792 – 1 mΩ - s/n 58FS1075	1,0000278 mΩ	+ 9,81	- 0,57
Guildline 9330 - 100 Ω - s/n 51.521	100,001613 Ω	+ 0,37	- 0,03
Guildline 9330 - 100 MΩ - s/n 61.890	100,0048 MΩ	+ 3,2	- 0,3

Tab 1 – Temperature coefficients

3.2.2 Drift

Measurements were performed prior to the comparison. The drift (µΩ/Ω per year) has been then evaluated (Tab 2).

Resistance	**Drift (µΩ/Ω per year)**
YEW, type 2792 - 1 mΩ - s/n 58FS1075	+ 2,9
Guildline 9330 - 100 Ω - s/n 51.521	- 0,1
Guildline 9330 - 100 MΩ - s/n N 61.890	- 2,2

Tab 2 – Drift of the travelling standards

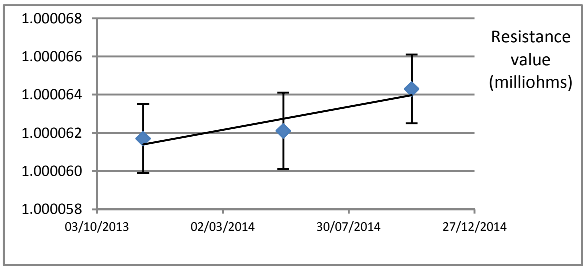

Fig 1 – Drift of 1 mΩ resistance

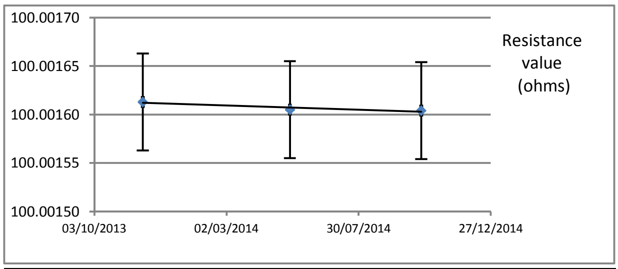

Fig 2 – Drift of 100 Ω resistance

3.2.3 Effect of current

This effect is sensible for 1 mΩ resistance depending on conditions of measurement (air, oil) (Fig 3).

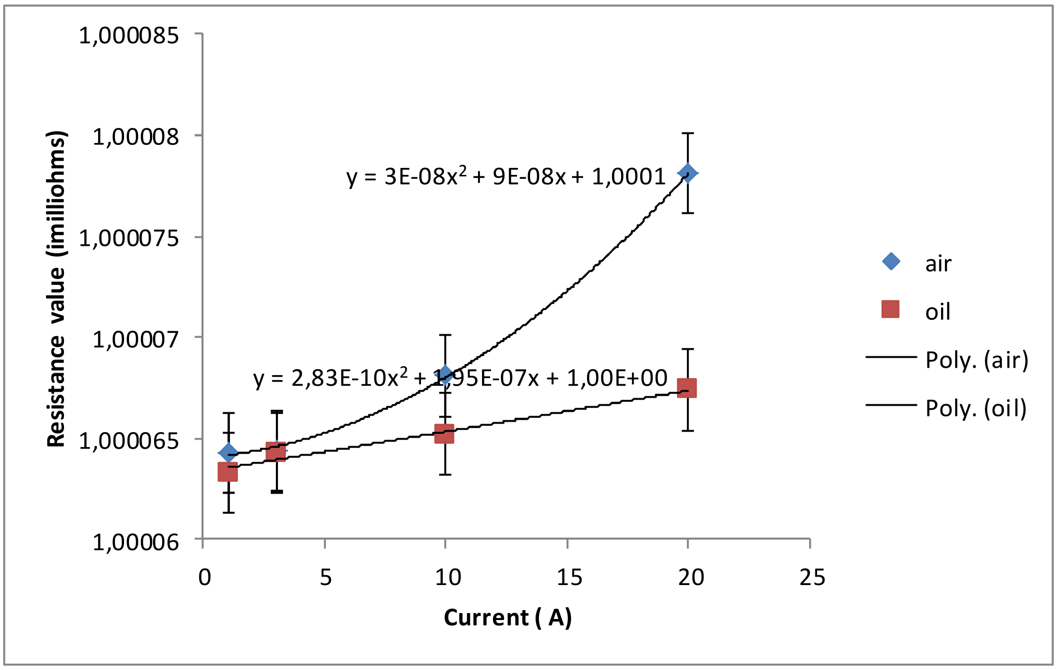

Fig 3 – Effect of current (air, oil bath) for 1 mΩ resistance

3.2.4 Other characteristics

The influence of the current is lower than - 0,2 µΩ/Ω for current increasing from 3 mA to 10 mA for 100 Ω resistance.

4 DESCRIPTION OF THE INTERLABORATORY COMPARISON AND ORGANIZATION

4.1 ORGANIZATION OF THE INTERLABORATORY COMPARISON

The comparison was organized and controlled by the pilot laboratory. The comparison started at LNE, where the three resistors were calibrated and characterized in function of temperature. The standards were sent to KIM-LIPI where they were also calibrated. The standards were then returned to LNE. Finally the standards were re-calibrated by LNE and the results from both laboratories were compared.

4.2 COORDINATOR AND PARTICIPANTS OF THE COMPARISON

Coordinator:	Isabelle Blanc, isabelle.blanc.@lne.fr Laboratoire national de métrologie et d'essais, LNE, France,
Participants:	
Pilot laboratory:	Laboratoire national de métrologie et d'essais, LNE, ZA de Trappes-Élancourt, 29, avenue Roger Hennequin, 78197 TRAPPES Cedex, France Pierre-Jean Janin, pierre-jean.janin@lne.fr
Participant:	KIM-LIPI: Pusat Penelitian Kalibrasi, Instrumentasi, dan Metrologi Lembaga Ilmu Pengetahuan Indonesia (Puslit KIM-LIPI) Kompleks PUSPIPTEK Gedung 420 Tangerang Selatan, Banten Indonesia Lukluk Khairiyati, luluk@kim.lipi.go.id Agah faisal, agahfaisal@yahoo.co.id Muhammad Azzumar, muhammad.azzumar@lipi.go.id

4.3 TIME SCHEDULE

The circulation was scheduled between May 2014 and September 2014.
Preliminary measurements were performed at LNE in November 2013 for the qualification of the standards.

The original measurements were taken from calibrations performed in May 2014. The resistance was sent to KIM-LIPI, Indonesia, on June 5th.
The resistance was carried back to LNE on September 17th and the final measurements were performed at LNE from October 8th to 16th, 2014.

The standards were measured at KIM-LIPI from August 5th and September 9th, 2014.

The preliminary report from KIM-LIPI was received by LNE on September 20th, 2014.

The draft report of the comparison was sent on October 30th 2014 and the final on November 2014.

4.4 INSTRUCTIONS

A copy of the complete measurement instructions sent to the participating laboratory is given in Appendix A.

The measurements were performed under the following conditions.

Resistance 1 mΩ:

- Four terminals ;
- DC current: 1 A, 10 A and 20 A ;
- Temperature of the environment (oil bath) : 23,0°C ± 0,1°C ;
- Measurement performed in oil.

Resistance 100 Ω:

- Four terminals ;
- DC current: 5 mA ;
- Temperature of the environment (oil bath): 23,0°C ± 0,1°C ;
- Measurement performed in oil.

Resistance 100 MΩ:

- Three terminals ;
- Test voltage: 100 V ;
- Temperature of the environment : 23°C ± 2°C ;
- Relative humidity of air: between 30 % and 70 %.

5 METHOD OF MEASUREMENTS

5.1 LNE METHOD

5.1.1 Method

1 mΩ and the 100 Ω resistances:

Measurements were performed by means of a zero flux current comparator MI6010B (Fig 4). The comparator is used alone for ratios between 1 and 10 and coupled with a range extender associated with a current source for ratios lower than 1.

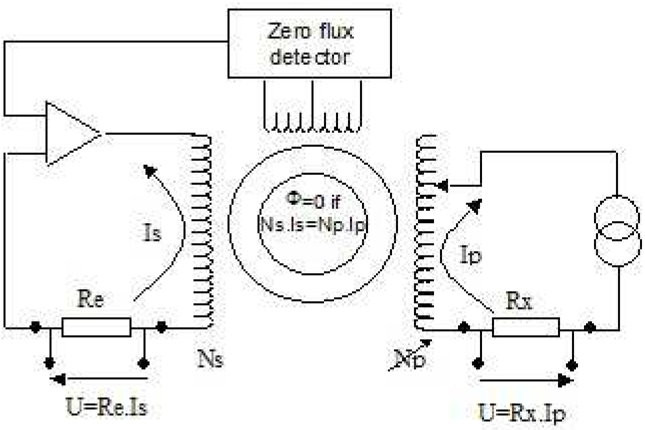

Fig 4: Diagram of the zero flux current comparator MI6010B.

The principle of the comparator is as following: a zero flux is detected when currents I_p and I_s satisfy to the condition $\frac{I_s}{I_p} = \frac{N_p}{N_s}$,

where:

- I_s is the current flowing through the standard resistor R_e ;
- I_p, the current flowing through the resistor R_x to calibrate ;
- N_s, the number of turns of the winding submitted to I_s ;
- N_p, the number of turns of the winding submitted to I_p.

The comparator automatically adjusts N_p so that voltages developed across both resistors are equal. R_e, R_x, I_s and I_p are then linked by the relation $R_e.I_s = R_x.I_p$. The value of R_x is finally given by $R_x = \frac{N_p}{N_s}.R_e = K.R_e$ where K is the ratio of the comparator.

Taking into account the effect of the temperature, this relation can be written as:

$$R_x = K_1.K'_{001}.R_1.\left(1+\alpha_{R_1}.\Delta T_1\right) \quad (1) \quad \text{for the 1 m}\Omega \text{ resistor ;}$$

$$R_x = K_{10}^2.R_1.\left(1+\alpha_{R_1}.\Delta T_1 + \alpha_{R_{10}}.\Delta T_{10}\right) \quad (2) \quad \text{for the 100 }\Omega \text{ resistor.}$$

where:

- K_1 is the exact value of the ratio “1” of the comparator ;
- K'_{10}, the exact value of the ratio “10” of the comparator ;
- K'_{001}, the exact value of the ratio “1/1000” of the comparator ;
- α_{R1}, the temperature coefficient of the 1 Ω standard resistor ;
- α_{R10}, the temperature coefficient of the 10 Ω standard resistor ;
- ΔT_1, the difference between the temperature at which the 1 Ω standard resistor has been calibrated and the temperature at which it was then used to calibrate the 10 Ω resistors ;
- ΔT_{10}, the difference between the temperature at which the 10 Ω standard resistor has been calibrated and the temperature at which it was then used to calibrate the 100 Ω resistor.

The 1 Ω standard resistor (needed for the calibration of the calibration of the 1 mΩ travelling standard and the 10 Ω standard resistor) was directly calibrated against the quantum Hall effect. The 10 Ω standard resistor (needed for the calibration of the 100 Ω travelling standard) was calibrated against the 1 Ω standard resistor using the MI6010B comparator.

<u>100 MΩ resistance:</u>

Measurements were performed by means of a controlled Wheatstone bridge (Fig 5).

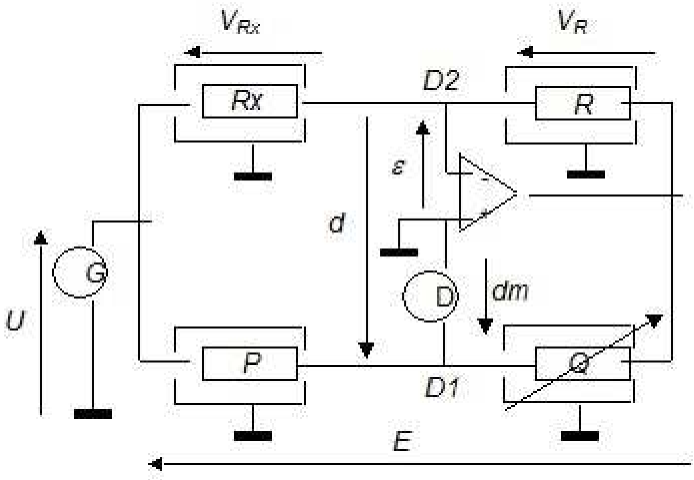

Fig 5: Diagram of the controlled Wheatstone bridge.

Measurement conditions were: U = 100 V, P = 10 MΩ, Q = 100 kΩ and R = 1 MΩ.

When the bridge is balanced ($d = 0$) the value of R_x is given by $R_x = \frac{P}{Q}.R$.

In practice the bridge is considered balanced not when $d = 0$ but when $dm = 0$ where dm is the voltage measured by a null detector. In this case the expression of Rx is $R_x = \frac{R.(1+\delta)}{\frac{Q}{P} - \left(1 + \frac{Q}{p}\right).\frac{dm}{U}}$ (3)

with $\delta = -\frac{R}{g}.\left(\frac{1}{R_{xN}} + \frac{1}{\rho} + \frac{1}{R}\right)$

where:

- g is the open loop gain of the operational amplifier ;
- ρ, its input impedance ;
- R_{xN}, the nominal value of R_x.

5.1.2 Reference standards and source of traceability

<u>1 mΩ and the 100 Ω resistances</u>:

The 1 Ω standard resistor (needed for the calibration of the calibration of the 1 mΩ travelling standard and the 10 Ω standard resistor) was directly calibrated against the quantum Hall effect. The 10 Ω standard resistor (needed for the calibration of the 100 Ω travelling standard) was calibrated against the 1 Ω standard resistor using the MI6010B comparator.

<u>100 MΩ resistance</u>:

The P, Q and R standard resistors used in the controlled Wheatstone bridge were calibrated by means of a MI6000A bridge associated with a 10 kΩ standard resistor directly calibrated against quantum Hall effect.

5.2 KIM-LIPI

5.2.1 Method

1 mΩ resistance

The ILC traveling standard was measured using KIM-LIPI's standard calibration system for low value resistance.
The standard calibration system consists of a DCC Bridge Guildline 6675A, a range extender Guildline 6623, a DC power supply up to 20 A, and a standard resistor of 1 Ω from Leeds & Northrup Company by the model of 4210-B (Fig 6).
The standard resistor was immersed in a oil bath and controlled at the temperature of (23,0 ± 0,1) °C. In order to measure the working current that flows to the UUT during a measurement, a current shunt was put in series to the UUT and the voltage drop across the current shunt was observed by a digital voltmeter.
The measurement was performed by comparing the UUT and the Standard connected to the R_X and R_S arms of the DCC bridge respectively. The current supply to the UUT was fed by the extender at range of X1000. The bridge indicated the ratio between them.

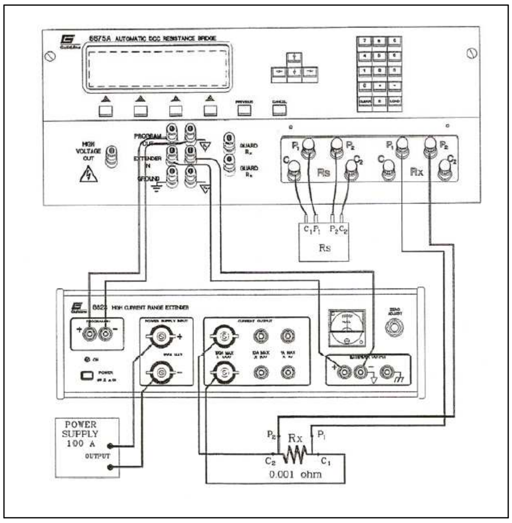

Fig 6: The schematic diagram of standard calibration system in KIM-LIPI (1 mΩ)

100 Ω resistance

The ILC traveling standard was measured using KIM-LIPI's standard calibration system for intermediate value resistance.
The standard calibration system consists of a DCC Bridge Guildline 6675A, and a standard resistor of 100 Ω from Leeds & Northrup Company by the model of 4030-B (Fig 7).

Both standard and UUT resistor were immersed in an oil bath and controlled at the temperature of (23,0 ± 0,1) °C.
The measurement was performed by comparing the UUT and the Standard connected to the RX and RS arms of the DCC bridge respectively. The current supply to the UUT was 5 mA. The bridge indicated the ratio between them.

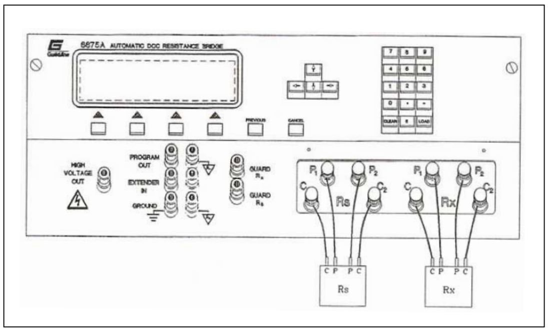

Fig 7: The schematic diagram of standard calibration system in KIM-LIPI (100 Ω)

100 MΩ resistance

The ILC traveling standard was measured using KIM-LIPI's standard calibration system for high value resistance.
The standard calibration system consists of a DCC Bridge Guildline 6675A, and a standard resistor of 10 MΩ from Fluke Company by the model of 742A (Fig 8).
Both standard and UUT resistor were at the room temperature of (23 ± 2) °C.
The measurement was performed by comparing the UUT and the Standard connected to the RX and RS arms of the DCC bridge respectively. The voltage output from DCC bridge were observed prior the measurement and confirmed at 100 V output. The bridge indicated the ratio between them.

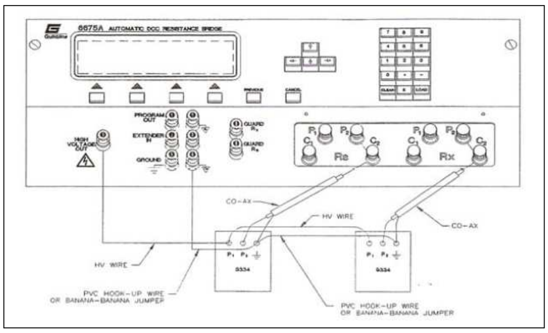

Fig 8: The schematic diagram of standard calibration system in KIM-LIPI (100 MΩ)

5.2.2 Reference standards and source of traceability

The traceability is ensured through a 1 Ω resistance value from which the other values of resistances are derived. This resistance value is obtained from a group of seven 1 Ω resistors maintained by direct comparisons between each other. Traceability of each resistor against QHR system was established on 2007.

6 CHARACTERIZATION OF THE REFERENCE VALUE

6.1 DETERMINATION OF THE COMPARISON REFERENCE VALUE

The comparison reference value, R_{ref}, has been determined as the linear interpolated value between the first and final measurements performed at LNE.

The resistance values were given at (23,0 ± 0,2)°C. The temperature coefficients are only used for the determination of the uncertainty associated to the reference value.

6.2 REFERENCE VALUE OF THE COMPARISON

As a slight drift is observed for the 1 mΩ and the 100 MΩ travelling standards, an interpolated value between the first and the final measurements performed at LNE taking into account the dates of measurement has been chosen as the reference value for the comparison. Expressions of the reference value R_{ref} and its uncertainty $u[R_{ref})]$ are:

$$R_{ref} = \frac{R(t_2) - R(t_1)}{t_2 - t_1}.(t - t_2) + R(t_2)$$

$$u[R_{ref}] = \frac{1}{t_2 - t_1}.\{(t_2 - t)^2.u^2[R(t_1)] + (t - t_1)^2.u^2[R(t_2)]$$
$$+ 2.(t_2 - t).(t - t_1).r[R(t_1), R(t_2)].u[R(t_1)].u[R(t_2)] + (t_2 - t_1)^2.u^2(\Delta T)\}^{1/2}$$

where:

- t_1 is the date of the first measurement at LNE ;
- t_2, the date of the final measurement at LNE ;
- t, the date of measurement at KIM-LIPI ;
- $u[R(t_1),R(t_2)]$, the correlation coefficient between $R(t_1)$ and $R(t_2)$ taken equal to 1 ;
- $u(\Delta T) = R_{ref}.[\alpha.\Delta T + \beta.(\Delta T)^2]$ is an additional uncertainty component linked with the uncertainty of the temperature ΔT, α and β being the temperature coefficients of the resistor.

For the 100 Ω resistor, no significant drift is observed.

The reference value for all measurement is given in Tab 3.

	1 mΩ - 1 A	1 mΩ - 10 A	1 mΩ - 20 A	100 Ω - 5 mA	100 MΩ - 100 V
R_{ref}	1,0000626	1,0000644	1,0000666	100,00161	100,0058
$U[R_{ref}]$ (k = 2)	0,0000023	0,0000023	0,0000023	0,00004	0,0022
unit	mΩ	mΩ	mΩ	Ω	MΩ

Tab 3: Reference value of the comparison

7 MEASUREMENT RESULTS

Only one measurement was performed by LNE on May 2014 for the calibration of 1 mΩ. However as the effect of current was preliminary determined, the measurement results were deduced from the determinations.

Participants were asked to provide estimates of standard uncertainties, the effective degrees of freedom and the combined standard uncertainty. The uncertainty budgets provided by the participants can be found in Appendix B.

The measurement results and their associated expanded uncertainties can be found in Tab 4 to 8. Each table is followed by a graphical illustration of the reported results and the corresponding reference values (Fig 9 to 13).

7.1 RESISTANCE 1 mΩ

	DC resistance value at 1 A				
Lab.	Date	Temperature (°C)	ΔT (°C)	R (mΩ)	U (mΩ)
LNE	13/05/2014	22,98	0,05	1,0000617	0,0000017
KIM-LIPI	05/08/2014	23, 0	0,1	1,0000689	0,000016
LNE	13/10/2014	23,02	0,05	1,0000633	0,0000017

Tab 4: Results for 1 mΩ resistor measured at 1 A

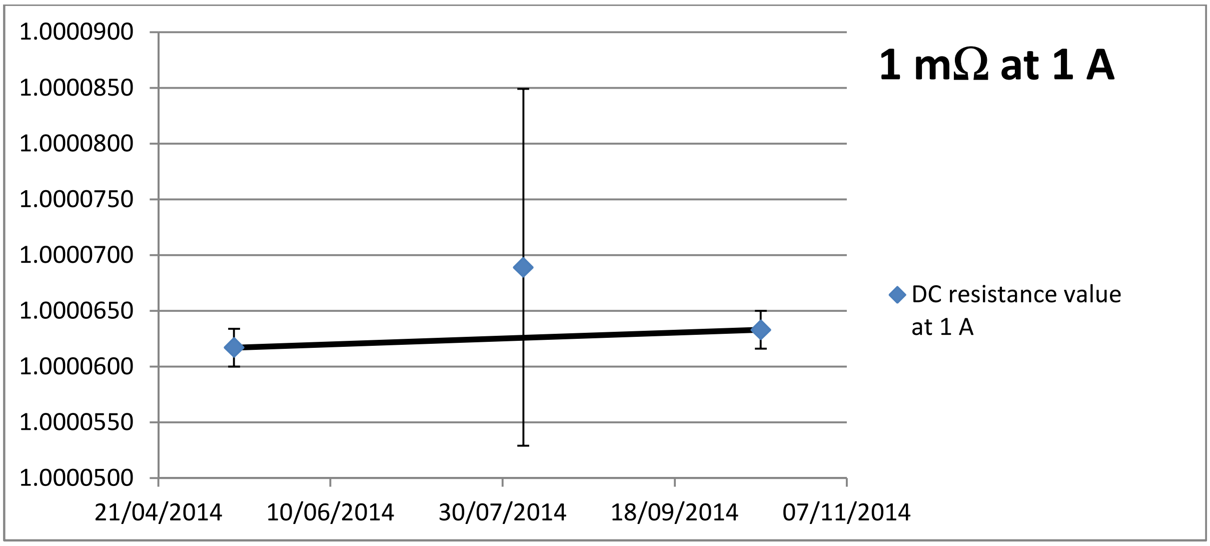

Fig 9: Results for 1 mΩ resistor measured at 1 A

	DC resistance value at 10 A				
Lab.	Date	Temperature (°C)	ΔT (°C)	R (mΩ)	U (mΩ)
LNE	13/05/2014	23,0	0,2	1,0000635	0,0000017
KIM-LIPI	05/08/2014	23, 1	0,1	1,0000638	0,000017
LNE	13/10/2014	23,21	0,2	1,0000652	0,0000017

Tab 5: Results for 1 mΩ resistor measured at 10 A

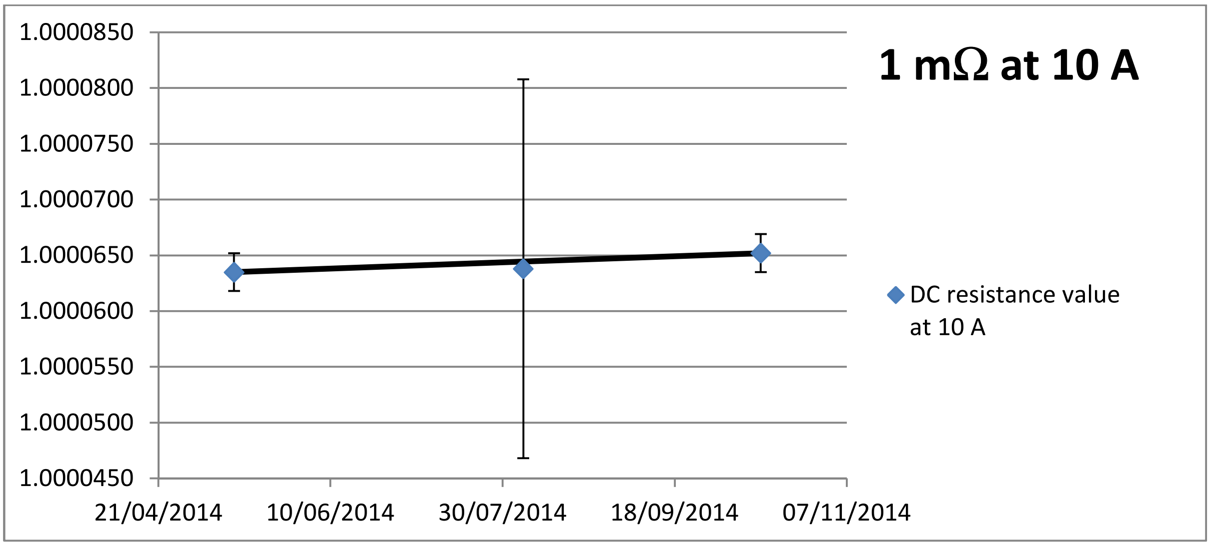

Fig 10: Results for 1 mΩ resistor measured at 10 A

	DC resistance value at 20 A				
Lab.	Date	Temperature (°C)	ΔT (°C)	R (mΩ)	U (mΩ)
LNE	13/05/2014	23,0	0,2	1,0000655	0,0000017
KIM-LIPI	05/08/2014	23, 1	0,1	1,0000660	0,000017
LNE	13/10/2014	23,58	0,2	1,0000674	0,0000017

Tab 6: Results for 1 mΩ resistor measured at 20 A

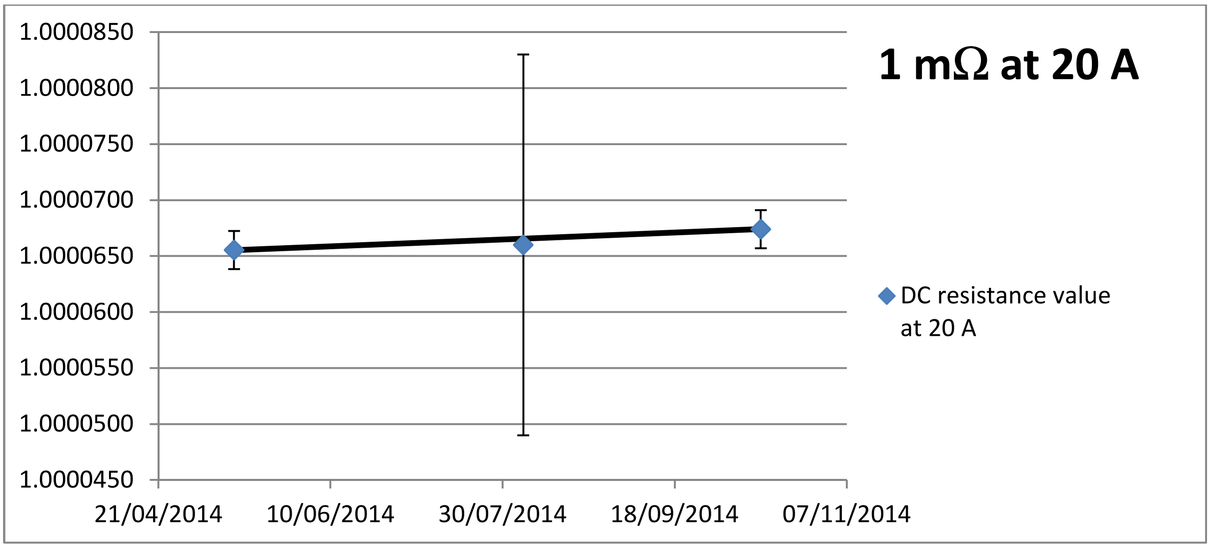

Fig 11: Results for 1 mΩ resistor measured at 20 A

7.2 Resistance 100 Ω

Lab.	Date	Temperature	ΔT (°C)	I(mA)	R (Ω)	U (Ω)
LNE	27/11/2013	22,99	0,05	<10	100,001613	0,000035
LNE	13/05/2014	23,01	0,05	<10	100,001605	0,000035
KIM-LIPI	25/08/2014	23, 0	0,1	5	100,00167	0,00026
LNE	10/10/2014	23,03	0,05	5	100,001604	0,000035

Tab 7: Results for 100 Ω resistor

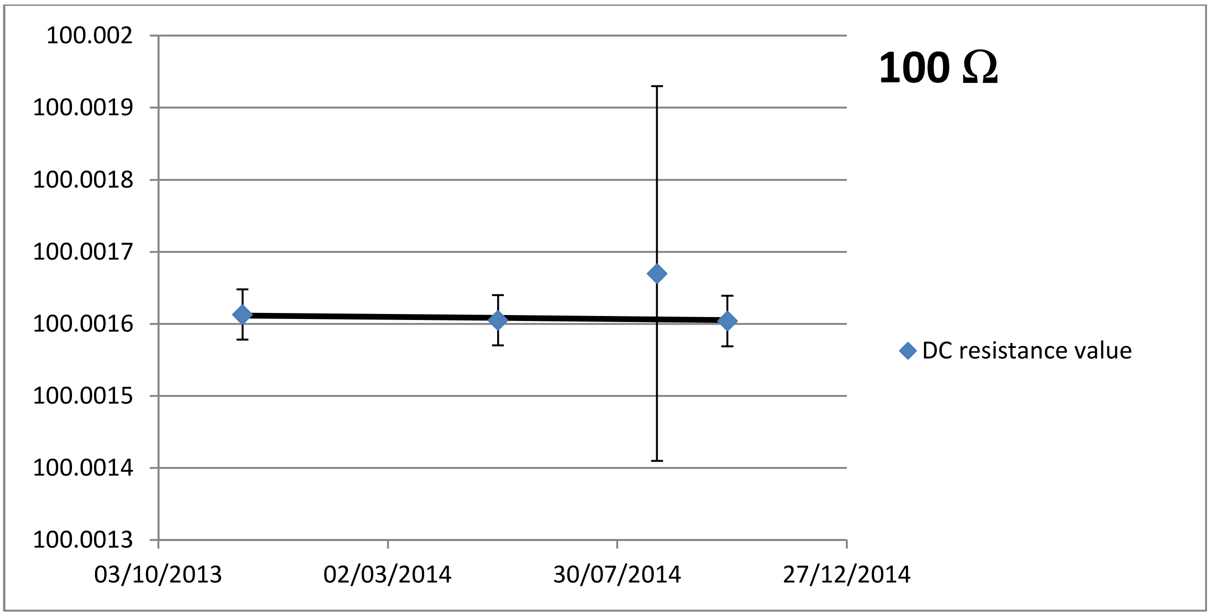

Fig 12: Results for 100 Ω resistor

7.3 RESISTANCE 100 MΩ

Lab.	Date	Temperature	ΔT (°C)	Relative Humidity (%)	Voltage (V)	R (MΩ)	U (MΩ)
LNE	27/11/2013	23,0	0,2	45	100	100,0060	0,0020
KIM-LIPI	09/09/2014	23,1	0,1	51	100	99,9876	0,0034
LNE	16/10/2014	23	0,2	45	100	100,0058	0,0020

Tab 8: Results for 100 MΩ resistor

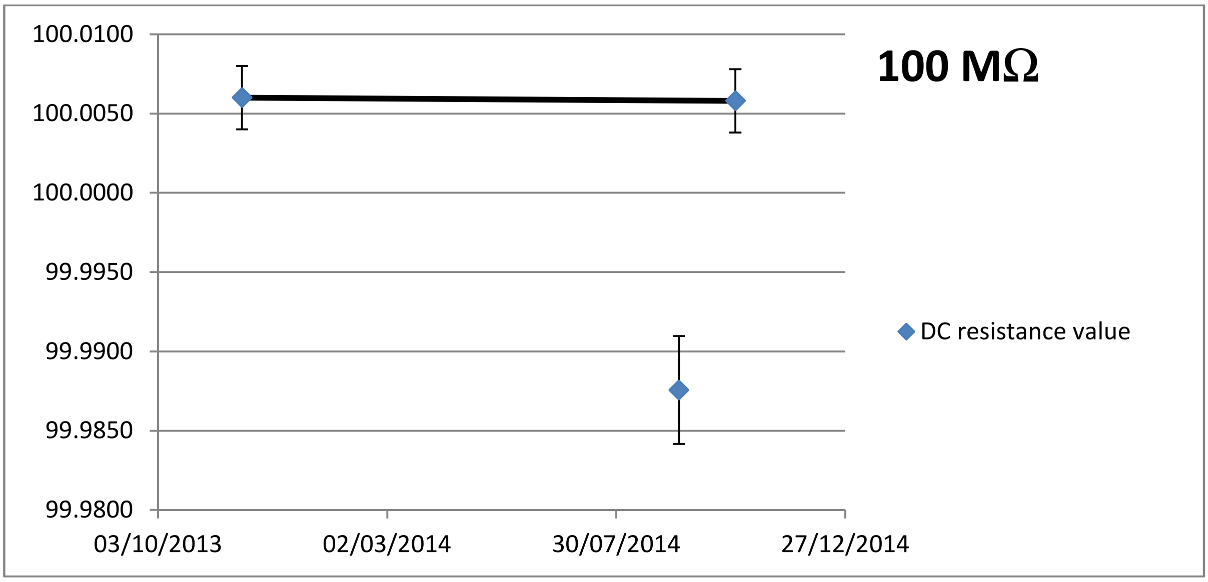

Fig 13: Results for 100 MΩ resistor

8 DISCUSSION OF THE RESULTS

The results presented by KIM-LIPI show a good agreement with the pilot laboratory for 1 mΩ and 100 Ω. Although the measurements used by the participants are quite similar, there is a major variation in the reported uncertainties from each participant.

A contrario, the results for 100 MΩ are not consistent within the associated uncertainties. A difference of 18 kΩ is observed for an uncertainty of 3,4 kΩ.

9 DEGREES OF EQUIVALENCE OF KIM LIPI

9.1 DEGREES OF EQUIVALENCE (DOE) BETWEEN LNE AND KIM-LIPI

The values and the uncertainties reported by both laboratories are used in the calculation of the DoE. The degree of equivalence (DoE) between LNE and KIM-LIPI is summarized as follows:

$$D = R_{KIM-LIPI} - R_{ref}$$

with an expanded uncertainty

$$U[D] = \sqrt{U^2[R_{KIM-LIPI}] + U^2[R_{ref}]}$$

The computed values for the degree of equivalence between LNE and KIM-LIPI are given in table 7 in absolute value and in table 8 in relative value.

	1 mΩ - 1 A	1 mΩ - 10 A	1 mΩ - 20 A	100 Ω - 5 mA	100 MΩ - 100 V
D	0,000006	-0,000001	-0,000001	0,00006	-0,0183
U [*D*]	0,000016	0,000017	0,000017	0,00026	0,0040
unit	mΩ	mΩ	mΩ	Ω	MΩ

Tab 9: Degrees of equivalence between KIM-LIPI and LNE associated to the expanded uncertainties (k = 2) in absolute value.

	1 mΩ - 1 A	1 mΩ - 10 A	1 mΩ - 20 A	100 Ω - 5 mA	100 MΩ - 100 V
D	6	-1	-1	0,6	-183
U [*D*]	16	17	17	2,6	40
unit	μΩ/Ω	μΩ/Ω	μΩ/Ω	μΩ/Ω	μΩ/Ω

Tab 10: Degrees of equivalence between KIM-LIPI and LNE associated to the expanded uncertainties (k = 2) in relative value (μΩ/Ω).

9.2 LINK TO THE CCEM KEY COMPARISON

The results of the comparison can be linked to the CCEM from through the LNE differences from the CCEM-K10 (100 Ω) and CCEM-K2 (100 MΩ) comparison reference values. There's no direct link for results of calibration of 1 mΩ.

Considering the results of the comparison, the link is only established for the 100 Ω resistance.

The reported DoE of LNE with respect to the CCEM-K10 reference value are as follows [1] [2]:

$$d_{LNE} = 13{,}17\ n\Omega/\Omega,\quad U(d_{LNE}) = 19{,}5\ n\Omega/\Omega \quad (k=2)$$

The DoE of KIM-LIPI with respect to the BIPM KCRV is given by the following equation:

$$d_{KIM-LIPI} = D - d_{LNE}$$

The uncertainty is given by:

$$u^2(d_{KIM\text{-}LIPI}) = u^2(D) + u^2(d_{LNE}) + u^2(d_s)$$

where $u(d_s)$ is an additional uncertainty component associated to an eventual drift of the LNE standard in the time interval between the CCEM and the KIM-LIPI comparison. This component has been considered as negligible.

Therefore the $d_{KIM\text{-}LIPI}$ value and the expanded uncertainty (k = 2) are as follows:

$$d_{KIM\text{-}LIPI} = 0{,}6\ \mu\Omega/\Omega,\ U(d_{KIM\text{-}LIPI}) = 2{,}6\ \mu\Omega/\Omega$$

10 CONCLUSION

The degree of equivalence of KIM-LIPI with KCRV for 100 Ω is established and it is consistent with the associated uncertainty.

For 1 mΩ, there's no direct link to CCEM comparisons. The agreement between KIM-LIPI and LNE is good. Nevertheless a large difference is observed between the two laboratories for a current of 1 A, which remains however consistent with the given uncertainties (6,3 µΩ/Ω for 16 µΩ/Ω).

The results for 100 MΩ are not consistent within the associated uncertainties. KIM-LIPI has to identify the causes of this discrepancy.

11 APPENDICES

Appendix A – Instructions
Appendix B – Uncertainty budget

References

[1] *B. Schumacher, Final Report, CCEM-K10 Key Comparison of Resistance Standards at 100 Ω.*

[2] *B. Schumacher, Final Report, EUROMET.EM-K10 Key Comparison of Resistance Standards at 100 Ω.* www.bipm.org

* * * * * * *

Le progrès, une passion à partager

Le 29/01/2013

APPENDIX A - Instructions

BILATERAL COMPARAISON of DC Resistance 1 mΩ

TECHNICAL PROTOCOL

1. INTRODUCTION

The comparison is organised within the EU-Indonesia Trade Support Programme II, Sub-project Number AWP2-2-20-5, "Improvement of traceability of Metrology and Calibration measurements of Puslit KIM".
Two National Metrology Institutes take part in this comparison: LNE (France) and KIM-LIPI (Indonesia).
LNE is acting as the pilot laboratory and in this function is responsible for providing the travelling standard, the evaluation of the measurement results and the final report.
The comparison will be accomplished in accordance with the EURAMET Guidelines on Conducting Comparisons and CCEM Guidelines for Planning, Organising, Conducting and Reporting Key, Supplementary and Pilot Comparisons.

2. TRAVELLING STANDARDS

2.1. The travelling standard is a resistance (YEW, type 2792) having the nominal value of 1 mΩ.

2.2. Specifications

Nominal value of the resistance:	1mΩ
Dimensions of the case:	40 mm x 30 mm x 20 mm
Mass Approx:	3 kg.

3. QUANTITIES TO BE MEASURED

- ***R:*** resistance of the standard (four terminals).
- ***I:*** DC current through the resistor.
- T_{ext}: the temperature (°C) of the environment where the standard is measured.

4. MEASUREMENT INSTRUCTIONS

The measurements should be performed under the following conditions:
- DC current: 1 A, 10 A and 20A.
- Temperature of the environment: 23°C ± 2°C.
- Relative humidity of air: between 30 % and 70 %.

5. REPORTING OF RESULTS

A report should be sent to the pilot laboratory within one month after the measurements are completed. The report should include:
- Description of the measurement method.
- The reference standard.

- The traceability to the SI.
- The results of the quantities to be measured (list of section 3).
- The associated standard uncertainties, the effective degrees of freedom and the expanded uncertainties.

The measurement of the DC current and the temperature of the environment must also be recorded and reported.

6. UNCERTAINTY OF MEASUREMENT

The uncertainty must be calculated following the ISO “Guide to the expression of uncertainty in measurement” (GUM) and the complete uncertainty budget must be reported.

7. TRANSPORTATION

The travelling standard must be transported in the original case and protected from mechanical loads, vibration etc. for transport by plane.

The travel box contains the following items:

- Resistance standard.
- Operating instructions of the travelling standard (this document).

8. CONTACT

Pilot Laboratory:	Laboratoire national de métrologie et d'essais (LNE) ZA de Trappes-Élancourt 29, avenue Roger Hennequin 78197 TRAPPES Cedex France
Contact:	Mrs. BLANC Isabelle Tél.: +33(0)1 30 69 21 08 Fax: +33(0)1 30 16 24 52 Mail: isabelle.blanc.@lne.fr
KIM LIPI:	Pusat Penelitian Kalibrasi, Instrumentasi, dan Metrologi Lembaga Ilmu Pengetahuan Indonesia (Puslit KIM-LIPI) Kompleks PUSPIPTEK Gedung 420 Tangerang Selatan, Banten Indonesia
Contacts:	Mr. Agah Faisal Tel : (+6221) 7560562 Fax : (+6221) 7560064 Email : agahfaisal@yahoo.co.id Mrs. Lukluk Khairiyati Tel : (+6221) 7560562 Fax : (+6221) 7560064 Email : luluk@kim.lipi.go.id

****

Le progrès, une passion à partager

Le 29/01/2013

BILATERAL COMPARAISON of DC Resistance 100 Ω

TECHNICAL PROTOCOL

1. INTRODUCTION

The comparison is organised within the EU-Indonesia Trade Support Programme II, Sub-project Number AWP2-2-20-5, “Improvement of traceability of Metrology and Calibration measurements of Puslit KIM”.
The comparison is linked to the corresponding CCEM comparison CCEM-K10.
Two National Metrology Institutes take part in this comparison: LNE (France) and KIM-LIPI (Indonesia).
LNE is acting as the pilot laboratory and in this function is responsible for providing the travelling standard, the evaluation of the measurement results and the final report.
The comparison will be accomplished in accordance with the EURAMET Guidelines on Conducting Comparisons and CCEM Guidelines for Planning, Organising, Conducting and Reporting Key, Supplementary and Pilot Comparisons.

2. TRAVELLING STANDARDS

2.1. The travelling standard is a resistance (Guildline 9330) having the nominal value of 100 Ω.

2.2. Specifications

Nominal value of the resistance:	100 Ω
Dimensions of the case:	40 mm x 30 mm x 20 mm
Total mass Approx.	5 kg.

3. QUANTITIES TO BE MEASURED

- ***R:*** resistance of the standard (four terminals).
- ***I:*** DC current through the resistor.
- T_{ext}**:** the temperature (°C) of the environment where the standard is measured (oil bath).

4. MEASUREMENT INSTRUCTIONS

The measurements should be performed under the following conditions:

- DC current: 5 mA.
- Temperature of the environment (oil bath): 23°C ± 0.1°C.
- Relative humidity of air: between 30 % and 70 %.

5. REPORTING OF RESULTS

A report should be sent to the pilot laboratory within one month after the measurements are completed. The report should include:

- Description of the measurement method.

- The reference standard.
- The traceability to the SI.
- The results of the quantities to be measured (list of section 3).
- The associated standard uncertainties, the effective degrees of freedom and the expanded uncertainties.

The measurement of the DC current and the temperature of the oil bath must also be recorded and reported.

6. UNCERTAINTY OF MEASUREMENT

The uncertainty must be calculated following the ISO “Guide to the expression of uncertainty in measurement” (GUM) and the complete uncertainty budget must be reported.

7. TRANSPORTATION

The travelling standard must be transported in the original case and protected from mechanical loads, vibration etc. for transport by plane.

The travel box contains the following items:

- Resistance standard.
- Operating instructions of the travelling standard (this document).

8. CONTACT

Pilot Laboratory :

Laboratoire national de métrologie et d’essais (LNE)
ZA de Trappes-Élancourt
29, avenue Roger Hennequin
78197 TRAPPES Cedex
France

Contact :

Mrs. BLANC Isabelle
Tél.: +33(0)1 30 69 21 08
Fax: +33(0)1 30 16 24 52
Mail: isabelle.blanc.@lne.fr

KIM LIPI :

Pusat Penelitian Kalibrasi, Instrumentasi, dan Metrologi
Lembaga Ilmu Pengetahuan Indonesia (Puslit KIM-LIPI)
Kompleks PUSPIPTEK Gedung 420
Tangerang Selatan, Banten Indonesia

Contacts:

Mr. Agah Faisal
Tel : (+6221) 7560562
Fax : (+6221) 7560064
Email : agahfaisal@yahoo.co.id

Mrs. Lukluk Khairiyati
Tel : (+6221) 7560562
Fax : (+6221) 7560064
Email : luluk@kim.lipi.go.id

****

Le progrès, une passion à partager

Le 28/01/2013

BILATERAL COMPARAISON of DC Resistance 100 MΩ

TECHNICAL PROTOCOL

1. INTRODUCTION

The comparison is organised within the EU-Indonesia Trade Support Programme II, Sub-project Number AWP2-2-20-5, "Improvement of traceability of Metrology and Calibration measurements of Puslit KIM".
The comparison is linked to the corresponding CCEM comparison CCEM-K2.
Two National Metrology Institutes take part in this comparison: LNE (France) and KIM-LIPI (Indonesia).
LNE is acting as the pilot laboratory and in this function is responsible for providing the travelling standard, the evaluation of the measurement results and the final report.
The comparison will be accomplished in accordance with the EURAMET Guidelines on Conducting Comparisons and CCEM Guidelines for Planning, Organising, Conducting and Reporting Key, Supplementary and Pilot Comparisons.

2. TRAVELLING STANDARDS

2.1. The travelling standard is a resistance (Guildline 9330) having the nominal value of 100 MΩ.

2.2. Specifications

Nominal value of the resistance:	100 MΩ
Dimensions of the case:	40 mm x 30 mm x 20 mm
Total mass Approx.:	3 kg.

3. QUANTITIES TO BE MEASURED

- ***R:*** resistance of the standard (three terminals).
- ***V:*** test voltage.
- T_{ext}**:** the temperature (°C) of the environment where the standard is measured.
- RH_{ext}: relative humidity of the environment.

4. MEASUREMENT INSTRUCTIONS

The measurements should be performed under the following conditions:

- Test voltage: $V_{test} \leq 100$ V, preferably 100 V.
- Temperature of the environment: 23°C ± 2°C.
- Relative humidity of air: between 30 % and 70 %.

5. REPORTING OF RESULTS

A report should be sent to the pilot laboratory within one month after the measurements are completed. The report should include:

- Description of the measurement method.

- The reference standard.
- The traceability to the SI.
- The results of the quantities to be measured (list of section 3).
- The associated standard uncertainties, the effective degrees of freedom and the expanded uncertainties.

The measurement of the DC current and the temperature of the oil bath must also be recorded and reported.

6. UNCERTAINTY OF MEASUREMENT

The uncertainty must be calculated following the ISO “Guide to the expression of uncertainty in measurement” (GUM) and the complete uncertainty budget must be reported.

7. TRANSPORTATION

The travelling standard must be transported in the original case and protected from mechanical loads, vibration etc. for transport by plane.
The travel box contains the following items:

- Resistance standard.
- Operating instructions of the travelling standard (this document).

8. CONTACT

Pilot Laboratory:

Laboratoire national de métrologie et d’essais (LNE)
ZA de Trappes-Élancourt
29, avenue Roger Hennequin
78197 TRAPPES Cedex
France

Contact:

Mrs. BLANC Isabelle
Tél.: +33(0)1 30 69 21 08
Fax: +33(0)1 30 16 24 52
Mail: isabelle.blanc.@lne.fr

KIM LIPI:

Pusat Penelitian Kalibrasi, Instrumentasi, dan Metrologi
Lembaga Ilmu Pengetahuan Indonesia (Puslit KIM-LIPI)
Kompleks PUSPIPTEK Gedung 420
Tangerang Selatan, Banten Indonesia

Contacts:

Mr. Agah Faisal
Tel : (+6221) 7560562
Fax : (+6221) 7560064
Email : agahfaisal@yahoo.co.id

Mrs. Lukluk Khairiyati
Tel : (+6221) 7560562
Fax : (+6221) 7560064
Email : luluk@kim.lipi.go.id

****

APPENDIX B - UNCERTAINTY BUDGET

LNE uncertainty budget

1 mΩ and 100 Ω resistances

For measurements performed with the MI6010B comparator (1 mΩ and 100 Ω) the uncertainty budget is as follows. From equations (1) and (2) it can be deduced:

$$u(R_x)=\sqrt{10^{-6}.u^2(K_1)+u^2(K'_{0,001})+10^{-6}.u^2(R_1)+(0,001.\Delta T_1)^2.u^2(\alpha_{R_1})+(0,001.\alpha_{R_1})^2.u^2(\Delta T_1)}$$

for the 1 mΩ resistor and

$$u(R_x)=\sqrt{\begin{aligned}&400.u^2(K_{10})+10^4.u^2(R_1)+(100.\Delta T_1)^2.u^2(\alpha_{R_1})+(100.\alpha_{R_1})^2.u^2(\Delta T_1)\\&+(100.\Delta T_{10})^2.u^2(\alpha_{R_{10}})+(100.\alpha_{R_{10}})^2.u^2(\Delta T_{10})\end{aligned}}$$

for the 100 Ω resistor.

Following uncertainty components have been identified:

- *A*1: component linked to the stability (including noise) and the resolution of the bridge alone. It is estimated to $A1 = 1.10^{-8}.K$ for $K \geq 1$.
- *A*2: component linked to the stability (including noise) and the resolution of the bridge associated with the range extender needed for ratios lower than 1. It is estimated to $A2 = 5.10^{-7}.K$ for k = 0,001.
- *B*1: calibration uncertainty of the 1 Ω standard resistor against the quantum Hall effect. It is equal to $B1 = 5.10^{-8}.R$ (k = 1).
- *B*2: uncertainty of the evaluation of the ratio *K* = 1 of the bridge estimated to $B2 = 1,3.10^{-8}.K$.
- *B*3: uncertainty of the evaluation of the ratio *K* = 10 of the bridge estimated to $B3 = 6,9.10^{-8}.K$.
- *B4* : uncertainty of the evaluation of the ratio *K* = 0.001 of the bridge estimated to $B4 = 5,7.10^{-7}.K$.
- *B5*: uncertainty component linked to the drift of the 1 Ω standard resistor estimated to $B5 = 2,9.10^{-8}.R$.
- *B6*: uncertainty component linked to the difference between the temperature at which the 1 Ω standard resistor has been calibrated and the temperature at which it served as reference for subsequent calibrations. It has been estimated to *B6* = 0,008 °C.
- *B7*: uncertainty component linked to the difference between the temperature at which the 10 Ω standard resistor has been calibrated and the temperature at which it served as reference for the calibration of the 100 Ω travelling standard. It has been estimated to *B7* = 0,003 °C.
- *B8*: uncertainty component linked with the influence of the current generated by the current source associated with the range extender on the ratio *K* = 0.001 of the bridge. It has been estimated to $B8 = 2,6.10^{-7}.K$.

Taking into account all these components, the two equations above lead to:

$$\mathrm{u}(\mathrm{R}_x)=\sqrt{10^{-6}.\mathrm{B2}^2+(\mathrm{A2}^2+\mathrm{B4}^2+\mathrm{B8}^2)+10^{-6}.(\mathrm{B1}^2+\mathrm{B5}^2)+(0,001.\alpha_{\mathrm{R}_1})^2.\mathrm{B6}^2}$$

for the 1 mΩ resistor and

$$\mathrm{u}(\mathrm{R}_x)=\sqrt{400.(\mathrm{A1}^2+\mathrm{B3}^2)+10^4.(\mathrm{B1}^2+\mathrm{B5}^2)+(100.\alpha_{\mathrm{R}_1})^2.\mathrm{B6}^2+(100.\alpha_{\mathrm{R}_{10}})^2.\mathrm{B7}^2}$$

for the 100 Ω resistor.

Detailed values of the uncertainty budget for the 1 mΩ and the 100 Ω resistors are given in tables B1 and B2.

Quantity	Standard uncertainty		Probability distribution /method of evaluation (A,B)	Sensitivity coefficient		Uncertainty contribution (nΩ)	Degree of freedom
X_i	$u(x_i)$			c_i		$u(R_i)$	υ_i
stability including noise and resolution of the brige associated with the range extender needed for ratios lower than 1	0,5	10^{-9}	type A	1	Ω	0,50	5
calibration uncertainty of the 1 Ω standard resistor against the quantum Hall effect	50	nΩ	norm/type B	0,001		0,05	inf
evaluation of the ratio K = 1 of the bridge	13	10^{-9}	norm/type B	0,001	Ω	0,01	inf
evaluation of the ratio K = 0,001 of the bridge	0,57	10^{-9}	norm/type B	1	Ω	0,57	inf
drift of the 1 Ω standard resistor	29	nΩ	rect/type B	0,001		0,03	inf
uncertainty component linked to the difference between the temperature at which the 1 Ω standard resistor has been calibrated and the temperature at which it served as reference for subsequent calibration	0,008	°C	U/type B	4,00E-01	νΩ/°C	0,00	inf
influence of the current generated by the current source associated with the range extender on the ratio K = 0,001 of the bridge	0,26	10^{-9}	rect/type B	1	Ω	0,26	inf
	Combined standard uncertainty					0,8	
	Effective degrees of freedom					inf	
	Expanded uncertainty (k=2)					1,7	nΩ
						1,7	μΩ/Ω

Table B1: Uncertainty budget for the 1 mΩ resistor.

Quantity	Standard uncertainty		Probability distribution /method of evaluation (A,B)	Sensitivity coefficient		Uncertainty contribution (μΩ)	Degree of freedom
X_i	$u(x_i)$			c_i		$u(R_i)$	υ_i
stability including noise and resolution of the brige	0,10	10^{-6}	type A	20	Ω	2,0	5
calibration uncertainty of the 1 Ω standard resistor against the quantum Hall effect	0,05	μΩ	norm/type B	100		5,0	inf
evaluation of the ratio K = 10 of the bridge	0,69	10^{-6}	norm/type B	20	Ω	13,8	inf
drift of the 1 Ω standard resistor	0,03	μΩ	rect/type B	100		2,9	inf
uncertainty component linked to the difference between the temperature at which the 1 Ω standard resistor has been calibrated and the temperature at which it served as reference for subsequent calibration	0,008	°C	U/type B	40	μΩ/°C	0,32	inf
uncertainty component linked to the difference between the temperature at which the 10 Ω standard resistor has been calibrated and the temperature at which it served as reference for the calibration of the 100 Ω travelling standard	0,003	°C	U/type B	160	μΩ/°C	0,48	inf
	Combined standard uncertainty					15,1	
	Effective degrees of freedom					inf	
	Expanded uncertainty (k=2)					32	μΩ
						0,32	μΩ/Ω

Table B2: Uncertainty budget for the 100 Ω resistor.

100 MΩ resistance

For measurements performed with the controlled Wheatstone bridge (100 MΩ) the uncertainty budget is as follows. From equation (3) it can be deduced:

$$u(R_X) = \sqrt{\left(\frac{P.R}{Q}\right)^2.u^2(\delta)+\left(\frac{R}{Q}\right)^2.u^2(P)+\left(\frac{P}{Q}\right)^2.u^2(R)+\left(\frac{P.R}{Q^2}\right)^2.u^2(Q) + \left(\frac{Rx.(P+Q)}{Q.U-(P+Q).dm}\right)^2.u^2(dm)}$$

Detailed values of the uncertainty budget for the 100 MΩ resistor are given in table B3.

Quantity	Standard uncertainty		Probability distribution /method of evaluation (A,B)	Sensitivity coefficient		Uncertainty contribution (Ω)	Degree of freedom
X_i	$u(x_i)$			c_i		$u(R_i)$	υ_i
calibration uncertainty of P standard resistor in the Wheatstone bridge	25	Ω	norm/type B	10		250	inf
calibration uncertainty of R standard resistor in the Wheatstone bridge	1	Ω	norm/type B	100		100	inf
calibration uncertainty of Q standard resistor in the Wheatstone bridge	0,25	Ω	norm/type B	1000		250	inf
drift of P standard restistor	8	Ω	rect/type B	10		80	inf
drift of Q standard restistor	0,8	Ω	rect/type B	100		80	inf
drift of R standard restistor	0,08	Ω	rect/type B	1000		80	inf
influence of temperature on standard resistor P in the Wheatstone bridge	11	Ω	U/type B	10		110	inf
influence of temperature on standard resistor R in the Wheatstone bridge	0,06	Ω	U/type B	100		6	inf
influence of temperature on standard resistor Q in the Wheatstone bridge	0,006	Ω	U/type B	1000		6	inf
effect of the input impedance and the open loop gain of the amplifier	51	Ω	rect/type B	1		51	inf
noise and sensitivity of the bridge	1,5	µV	rect/type B	100	$\Omega.\mu V^{-1}$	150	inf
leakage resistance	0,0005	Ω	rect/type B	100		0,05	inf
	Combined standard uncertainty					438	
	Effective degrees of freedom					inf	
	Expanded uncertainty (k=2)					875	µΩ
						8,8	µΩ/Ω

Table B3: Uncertainty budget for the 100 MΩ resistor.

For the need of this comparison, this uncertainty will be enlarged to 20 µΩ/Ω (k = 2).

KIM-LIPI uncertainty budget

1 mΩ resistance

Model equation.

The mathematical model for evaluating the measurement result is determined by following equation:

$$R_X = \frac{\frac{\Gamma}{1000}\cdot(1+\delta B_A)\cdot(1+\delta B_T)\cdot(1+\delta B_R)\cdot R_S\cdot(1+\delta R_{SD})\cdot(1+\delta R_{ST})\cdot(1+\delta R_{SI})}{(1+\delta R_{XT})\cdot(1+\delta R_{XI})\cdot(1+\delta R_{XR})}$$

Where:

R_X	:	The unknown value of the 1 mΩ traveling standard (UUT)
Γ	:	The indicated mean ratio of the UUT over the 1 Ω standard resistor
δB_A	:	The correction due to the accuracy of the DCC bridge
δB_T	:	The correction due to the temperature instability effect to the bridge during a measurement
δB_R	:	The correction due to the resolution of the bridge ratio indication
R_S	:	The known value of the 1 Ω standard resistor
δR_{SD}	:	The correction due to the drift of the 1 Ω standard resistor
δR_{ST}	:	The correction due to the temperature instability effect to the 1 Ω standard resistor
δR_{SI}	:	The correction due to the current dependency effect to the 1 Ω standard resistor
δR_{XT}	:	The correction due to the temperature instability effect to the UUT
δR_{XI}	:	The correction due to the current dependency effect to the UUT
δR_{XR}	:	The correction due to the rounding the reported value of the UUT

To estimate the mean ratio value, the measurement was taken 10 times.

UNCERTAINTY BUDGET (1 mΩ)

at 1 A

Quantity	**Estimate**		**Standard uncertainty**		**Probability distribution /method of evaluation (A,B)**	**Sensitivity coefficient**		**Uncertainty contribution**	**Degree of freedom**
X_i	x_i		$u(x_i)$			c_i		$u(R_i)$	υ_i
The mean of ratio indication	0,001000076	Ω/Ω	1,5E-10	Ω/Ω	type A	0,999992830	Ω	1,5E-10	9
The accuracy of the bridge	0		6,9E-07	Ω/Ω	rect/ type B	0,001000069	Ω	6,9E-10	1E+20
The temperature instability effect to the bridge	0		1,2E-08	Ω/Ω	rect/ type B	0,001000069	Ω	1,2E-11	1E+20
The resolution of the bridge ratio indication	0		2,9E-08	Ω/Ω	rect/ type B	0,001000069	Ω	2,9E-11	1E+20
The trueness 1 Ω standard resistor	0,99999283	Ω	4,0E-07	Ω	norm/ type B	0,001000076	Ω/Ω	4,0E-10	1E+20
The drift of the 1 Ω standard resistor	0		1,0E-08	Ω/Ω	norm/ type B	0,001000069	Ω	1,0E-11	1E+20
Temperature instability effect to the 1 Ω standard resistor	0		1,0E-07	Ω/Ω	rect/ type B	0,001000069	Ω	1,0E-10	1E+20
The current dependency effect to the 1 Ω standard resistor	0		3,5E-11	Ω/Ω	rect/ type B	0,001000069	Ω	3,5E-14	1E+20
The temperature instability effect to the UUT	0		8,3E-06	Ω/Ω	rect/ type B	0,001000069	Ω	8,3E-09	1E+20
The current dependency effect to the UUT	0		1,4E-07	Ω/Ω	rect/ type B	0,001000069	Ω	1,4E-10	1E+20
Rounding the reported value of UUT	0		2,9E-08	Ω/Ω	rect/ type B	0,001000069	Ω	2,9E-11	1E+20
R_X	0,0010000689	Ω							
	1,000069	**mΩ**	Combined standard uncertainty:					8,3E-09	
			Effective degrees of freedom:					86382048	
			Coverage factor at 95 % confidence level					2,0	
			Expanded uncertainty (95% coverage factor):					0,0000000163	Ω
								0,000016	**mΩ**
								16	**μΩ /Ω**

UNCERTAINTY BUDGET (1 mΩ)

at 10 A

Quantity	**Estimate**		**Standard uncertainty**		**Probability distribution /method of evaluation (A,B)**	**Sensitivity coefficient**		**Uncertainty contribution**	**Degree of freedom**
X_i	x_i		$u(x_i)$			c_i		$u(R_i)$	υ_i
The mean of ratio indication	0,001000071	Ω/Ω	4,1E-11	Ω/Ω	type A	0,999992830	Ω	4,1E-11	9
The accuracy of the bridge	0		6,9E-07	Ω/Ω	rect/ type B	0,001000064	Ω	6,9E-10	1E+20
The temperature instability effect to the bridge	0		1,2E-08	Ω/Ω	rect/ type B	0,001000064	Ω	1,2E-11	1E+20
The resolution of the bridge ratio indication	0		2,9E-08	Ω/Ω	rect/ type B	0,001000064	Ω	2,9E-11	1E+20
The trueness 1 Ω standard resistor	0,99999283	Ω	4,0E-07	Ω	norm/ type B	0,001000071	Ω/Ω	4,0E-10	1E+20
The drift of the 1 Ω standard resistor	0		1,0E-08	Ω/Ω	norm/ type B	0,001000064	Ω	1,0E-11	1E+20
Temperature instability effect to the 1 Ω standard resistor	0		1,0E-07	Ω/Ω	rect/ type B	0,001000064	Ω	1,0E-10	1E+20
The current dependency effect to the 1 Ω standard resistor	0		3,5E-11	Ω/Ω	rect/ type B	0,001000064	Ω	3,5E-14	1E+20
The temperature instability effect to the UUT	0		8,3E-06	Ω/Ω	rect/ type B	0,001000064	Ω	8,3E-09	1E+20
The current dependency effect to the UUT	0		1,4E-07	Ω/Ω	rect/ type B	0,001000064	Ω	1,4E-10	1E+20
Rounding the reported value of UUT	0		2,9E-08	Ω/Ω	rect/ type B	0,001000064	Ω	2,9E-11	1E+20
	0,0010000638	Ω							
	1,000064	**mΩ**	Combined standard uncertainty:					8,3E-09	
			Effective degrees of freedom:					15594880031	
			Coverage factor at 95 % confidence level					2,0	
			Expanded uncertainty (95% coverage factor):					0,0000000166	Ω
								0,000017	**mΩ**
								17	**µΩ /Ω**

UNCERTAINTY BUDGET (1 mΩ)

at 20 A

Quantity	**Estimate**		**Standard uncertainty**		**Probability distribution /method of evaluation (A,B)**	**Sensitivity coefficient**		**Uncertainty contribution**	**Degree of freedom**
X_i	x_i		$u(x_i)$			c_i		$u(R_i)$	υ_i
The mean of ratio indication	0,001000073	Ω/Ω	1,1E-11	Ω/Ω	type A	0,999992830	Ω	1,1E-11	9
The accuracy of the bridge	0		6,9E-07	Ω/Ω	rect/ type B	0,001000066	Ω	6,9E-10	1E+20
The temperature instability effect to the bridge	0		1,2E-08	Ω/Ω	rect/ type B	0,001000066	Ω	1,2E-11	1E+20
The resolution of the bridge ratio indication	0		2,9E-08	Ω/Ω	rect/ type B	0,001000066	Ω	2,9E-11	1E+20
The trueness 1 Ω standard resistor	0,99999283	Ω	4,0E-07	Ω	norm/ type B	0,001000073	Ω/Ω	4,0E-10	1E+20
The drift of the 1 Ω standard resistor	0		1,0E-08	Ω/Ω	norm/ type B	0,001000066	Ω	1,0E-11	1E+20
Temperature instability effect to the 1 Ω standard resistor	0		1,0E-07	Ω/Ω	rect/ type B	0,001000066	Ω	1,0E-10	1E+20
The current dependency effect to the 1 Ω standard resistor	0		3,5E-11	Ω/Ω	rect/ type B	0,001000066	Ω	3,5E-14	1E+20
The temperature instability effect to the UUT	0		8,3E-06	Ω/Ω	rect/ type B	0,001000066	Ω	8,3E-09	1E+20
The current dependency effect to the UUT	0		1,4E-07	Ω/Ω	rect/ type B	0,001000066	Ω	1,4E-10	1E+20
Rounding the reported value of UUT	0		2,9E-08	Ω/Ω	rect/ type B	0,001000066	Ω	2,9E-11	1E+20
	0,0010000660	Ω							
	1,000066	**mΩ**	Combined standard uncertainty:					8,3E-09	
			Effective degrees of freedom:					3090233620538	
			Coverage factor at 95 % confidence level					2,0	
			Expanded uncertainty (95% coverage factor):					0,0000000166	Ω
								0,000017	**mΩ**
								17	**µΩ /Ω**

100 Ω resistance

Model equation.

The mathematical model for evaluating the measurement result is determined by following equation:

$$R_X = \frac{\Gamma \cdot (1+\delta B_A) \cdot (1+\delta B_T) \cdot (1+\delta B_R) \cdot R_S \cdot (1+\delta R_{SD}) \cdot (1+\delta R_{ST})}{(1+\delta R_{XT}) \cdot (1+\delta R_{XR})}$$

Where:

R_X	:	The unknown value of the 100 Ω traveling standard (UUT)
Γ	:	The indicated mean ratio of the UUT over the 100 Ω standard resistor
δB_A	:	The correction due to the accuracy of the DCC bridge
δB_T	:	The correction due to the temperature instability effect to the bridge during a measurement
δB_R	:	The correction due to the resolution of the bridge ratio indication
R_S	:	The known value of the 100 Ω standard resistor
δR_{SD}	:	The correction due to the drift of the 100 Ω standard resistor
δR_{ST}	:	The correction due to the temperature instability effect to the 100 Ω standard resistor
δR_{XT}	:	The correction due to the temperature instability effect to the UUT
δR_{XR}	:	The correction due to the rounding the reported value of the UUT

To estimate the mean ratio value, the measurement was taken 10 times.

UNCERTAINTY BUDGET (100 Ω)

at 5 mA

Quantity	**Estimate**		**Standard uncertainty**		**Probability distribution /method of evaluation (A,B)**	**Sensitivity coefficient**		**Uncertainty contribution**	**Degree of freedom**
X_i	x_i		$u(x_i)$			c_i		$u(R_i)$	υ_i
The mean of ratio indication	1,000031055	Ω/Ω	1,7E-09	Ω/Ω	type A	99,99856054	Ω	1,7E-07	9
The accuracy of the bridge	0		5,8E-08	Ω/Ω	rect/ type B	100,0016660	Ω	5,8E-06	1E+20
The temperature instability effect to the bridge	0		1,2E-08	Ω/Ω	rect/ type B	100,0016660	Ω	1,2E-06	1E+20
The resolution of the bridge ratio indication	0		2,9E-09	Ω/Ω	rect/ type B	100,0016660	Ω	2,9E-07	1E+20
The trueness 100 Ω standard resistor	99,99856054	Ω	1,3E-04	Ω	norm/ type B	1,000031055	Ω/Ω	1,3E-04	1E+20
The drift of the 100 Ω standard resistor	0		1,0E-08	Ω/Ω	norm/ type B	100,0016660	Ω	1,0E-06	1E+20
Temperature instability effect to the 100 Ω standard resistor	0		1,0E-07	Ω/Ω	rect/ type B	100,0016660	Ω	1,0E-05	1E+20
The temperature instability effect to the UUT	0		1,2E-07	Ω/Ω	rect/ type B	100,0016660	Ω	1,2E-05	1E+20
Rounding the reported value of UUT	0		2,9E-08	Ω/Ω	rect/ type B	100,0016660	Ω	2,9E-06	1E+20
	100,00167	**Ω**	Combined standard uncertainty:					1,3E-04	
			Effective degrees of freedom:					3380921284969	
			Coverage factor at 95 % confidence level					2,0	
			Expanded uncertainty (95% coverage factor):					**0,00026**	**Ω**
								2,6	**µΩ /Ω**

100 MΩ resistance

Model equation.

The mathematical model for evaluating the measurement result is determined by following equation:

$$R_X = \frac{\Gamma \cdot (1+\delta B_A)\cdot(1+\delta B_T)\cdot(1+\delta B_R)\cdot R_S \cdot (1+\delta R_{SD})\cdot(1+\delta R_{ST})}{(1+\delta R_{XT})\cdot(1+\delta R_{XR})}$$

Where:

R_X	:	The unknown value of the 100 MΩ traveling standard (UUT)
Γ	:	The indicated mean ratio of the UUT over the 10 MΩ standard resistor
δB_A	:	The correction due to the accuracy of the DCC bridge
δB_T	:	The correction due to the temperature instability effect to the bridge during a measurement
δB_R	:	The correction due to the resolution of the bridge ratio indication
R_S	:	The known value of the 10 MΩ standard resistor
δR_{SD}	:	The correction due to the drift of the 10 MΩ standard resistor
δR_{ST}	:	The correction due to the temperature instability effect to the 10 MΩ standard resistor
δR_{XT}	:	The correction due to the temperature instability effect to the UUT
δR_{XR}	:	The correction due to the rounding the reported value of the UUT

To estimate the mean ratio value, the measurement was taken 5 times.

UNCERTAINTY BUDGET (100 MΩ)

at 100 V

Quantity	**Estimate**		**Standard uncertainty**		**Probability distribution /method of evaluation (A,B)**	**Sensitivity coefficient**		**Uncertainty contribution**	**Degree of freedom**
X_i	x_i		$u(x_i)$			c_i		$u(R_i)$	υ_i
The mean of ratio indication	9,999018949	Ω/Ω	1,2E-04	Ω/Ω	type A	9,999737716	MΩ	1,2E-03	4
The accuracy of the bridge	0		1,4E-06	Ω/Ω	rect/ type B	99,98756691	MΩ	1,4E-04	1E+20
The temperature instability effect to the bridge	0		1,2E-08	Ω/Ω	rect/ type B	99,98756691	MΩ	1,2E-06	1E+20
The resolution of the bridge ratio indication	0		2,9E-06	Ω/Ω	rect/ type B	99,98756691	MΩ	2,9E-04	1E+20
The trueness 100 Ω standard resistor	9,999737716	MΩ	6,3E-05	Ω	norm/ type B	9,999018949	Ω/Ω	6,3E-04	1E+20
The drift of the 100 Ω standard resistor	0		3,7E-06	Ω/Ω	norm/ type B	99,98756691	MΩ	3,7E-04	1E+20
Temperature instability effect to the 100 Ω standard resistor	0		4,9E-09	Ω/Ω	rect/ type B	99,98756691	MΩ	4,9E-07	1E+20
The temperature instability effect to the UUT	0		5,8E-06	Ω/Ω	rect/ type B	99,98756691	MΩ	5,8E-04	1E+20
Rounding the reported value of UUT	0		2,9E-07	Ω/Ω	rect/ type B	99,98756691	MΩ	2,9E-05	1E+20
	99,98757	**MΩ**	Combined standard uncertainty:					1,5E-03	
			Effective degrees of freedom:					12	
			Coverage factor at 95 % confidence level					2,2	
			Expanded uncertainty (95% coverage factor):					**0,0034**	**MΩ**