Final Report - AFRIMETS.EM-S1

Supplementary comparison of Resistance Standards at 1 Ω, 10 Ω, 100 Ω, 1 kΩ and 10 kΩ

Authors

Michael Khoza,[1] Hala M. Abdel Mageed[2]

[1]National Metrology Institute of South Africa (NMISA), South Africa

[2]National institute of Standards (NIS), Egypt

mkhoza@nmisa.org, halaabdelmegeed@yahoo.com

Contents

1 Introduction

The AFRIMETS TC-EM meeting of 17th June 2014 held in Addis Ababa, Ethiopia, approved a supplementary comparison [1] [2] [3] on resistance standards at 1 Ω, 10 Ω, 100 Ω, 1 kΩ and 10 kΩ. The National Metrology Institute of South Africa (NMISA) piloted the comparison and seven AFRIMETS national metrology designated institutes participated. The comparison commenced November 2015 and completed June 2018. This report describes the behaviour of the comparison standards, participants corrected results and calculated comparison reference values associated with uncertainties of measurements at 95% confidence level, normalized errors and degrees of equivalence.

2 Organisation of the comparison

2.1 Participants

The pilot laboratory is the National Metrology Institute of South Africa (NMISA). The list of participants in the comparison are shown in Table 1.

Table 1: List of participants

Country	Institute	Acronym	Contact person	e-mail	Shipping address
South Africa	National Metrology Institute of South Africa (pilot laboratory)	NMISA	Michael Khoza	mkhoza@nmisa.org	Building 5, CSIR Scientia campus, Meiring Naude Road, Pretoria, 0001, South Africa
Tunisia	Designated National Institute DEFNAT	DEF-NAT	Abdelkarim MALLAT Zouaoui Jihén	metrologie@defense.tn	Direction Générale des Transmissions et de l'Informatique, Base Militaire Bab Saadoun EL Omrane 1005 Tunis TUNISIE
Egypt	National Institute of Standards	NIS	Rasha Sayed Attiya Mohammed	Rasha_sama79@hotmail.com	National Institute of Standards (NIS) Tersa Street, El Haram, Giza P.O. Box: 136 Giza Code 12211 Giza – EGYPT
Kenya	Kenya Bureau of Standards	KEBS	Paul Matendechere Gibson Aguko	matendecherep@kebs.org gibsonaguko@yahoo.com	Popo Road, Off Mombasa Road, Nairobi, Kenya

Morocco	**Laboratoire Public d'Essais et d'Etudes / Laboratoire National de Métrologie**	**LPEE/ LNM**	**Abdellah ZITI**	**ziti@LPEE.MA**	**Km 7, Route d' El Jadida-Oasis, Casablanca, Morocco**
Uganda	**Uganda National Bureau of Standards**	**UNBS**	**Patrick Kizito Musaazi**	**patrickmusazi@yahoo.co.uk** **Patrick.kizito@unbs.go.ug**	**Plot M217 Nakawa Industrial Area, Kampala, Uganda**
Ethiopia	**National Metrology Institute (NMI) of Ethiopia**	**NMIE**	**Nesredin Nezir**	**nesredin03@gmail. com**	**Bole sub city, Woreda 06, Megenagna to Bole Ring Road, next to A.M.C.E.**

2.2 Measurement schedule

The travelling standards were circulated to the participating laboratories in a loop configuration in the order listed in Table 2.

Table 2: Comparison schedule

Loop	National Metrology Institute	Measurement date
A	NMISA	01 November 2015
	LPEE/LNM	08 January 2016
	DEF-NAT	16 March 2016
	NMISA	20 April 2016
B	NMISA	20 April 2016
	KEBS	12 July 2016
	NMISA	10 January 2017
C	NMISA	10 January 2017
	NIS	18 June 2017
	NMISA	18 September 2017
D	NMISA	18 September 2017
	UNBS	16 January 2018
	NMIE	20 March 2018
	NMISA	21 June 2018

2.3 Reported incidents

No incidents involving the travelling standards were reported. However, the travelling standards were adversely affected by the adverse environmental conditions and transportation. The effects were determined, evaluated and the results were compensated.

3 Travelling standards and required measurements

3.1 Description of travelling standards

The travelling standards are described in Table 3.

Table 3: Description of the travelling standards

Model	Serial no.	Nominal value	Test current	Temperature coefficient (α) (23 °C)	Temperature coefficient (β) (23 °C)	Pressure coefficient (γ) (870 hPa)	Current coefficient (R_c)
Fluke 742A-1	4935018	1 Ω	100 mA	- 0.08 E-6/K	- 0.044 E-6/K^2	-0.17E-9/hPa	-0.0131 ppm / 10 mA
Fluke 742A-10	4920006	10 Ω	10 mA	- 0.02 E-6/K	- 0.036 E-6/K^2	-0.178E-9/hPa	0.0027 ppm / 1 mA
Fluke 742A-100	5485007	100 Ω	1 mA	- 0.009 E-6/K	- 0.044 E-6/K^2	-0.185E-9/hPa	0.0013 ppm / 0,1 mA
Fluke 742A-1k	7733002	1 kΩ	1 mA	0.05 E-6/K	- 0.022 E-6/K^2	0.185E-9/hPa	0.0012 ppm / 0.1 mA
Fluke 742A-10k	5065038	10 kΩ	0.1 mA	0.04 E-6/K	- 0.020 E-6/K^2	0.148E-9/hPa	-0.0647 ppm / 10 µA

Note:

1) Temperature coefficients α and β are obtained from the technical specification of the travelling standards.
2) Pressure coefficients γ for 1 Ω, 100 Ω and 10 kΩ are obtained from the BIPM calibration data of similar models and the data is used to interpolate pressure coefficients γ for 10 Ω and 1 kΩ.
3) The pilot laboratory performed measurements at various test currents and the resistance change per change in test current was determined.

3.2 Measurement instructions

The required measurements as per protocol are described in Table 4.

Table 4: Measurement instructions

Nominal value	Test current	Environmental Conditions		
1 Ω	100 mA	(23 ± 2) °C	(50% ± 10%) RH	Laboratory Atmospheric Pressure
10 Ω	10 mA			
100 Ω	1 mA			
1 kΩ	1 mA			
10 kΩ	0.1 mA			

3.3 Participants measurement methods

The participants provided a brief overview of their measurement methods, setups used and source of traceability. These are summarised below.

NMISA

The 4-terminal resistance of the comparison standards were measured using Measurement International Limited 6010C an automated resistance measurement system. The reference resistance standards were calibrated by BIPM, France. The latest calibration was performed February 2015. Traceability is transferred from reference standards to other standards in a ratio build-up method. The measurements are performed at ambient temperature of 23,08 °C, relative humidity of 47,6 % RH and atmospheric pressure of 870 hPa.

LPEE/LNM

Substitution method using the function "Ohm-meter" of a 8 ½ digit multimeter. The reference standard resistor and the travelling standard resistor have the same nominal value. All the reference resistance standards were calibrated by LNE, France. The latest calibration was performed in August 2015. The measurements are performed at ambient temperature of 23,5 °C, relative humidity of 48 % RH and atmospheric pressure of 1013 hPa.

DEFNAT

The value of the unknown resistor R_x is obtained by comparison to a standard resistor R_s via Resistance Bridge GUILDLINE 9975. The equation used to determine R_x is as follow:

$R_x = R_s * K_e = R_{s0} * [1 + (\alpha * \Delta T) + (\beta * \Delta T_2)] * (k_x + c)$

Where:

R_x : the value of the unknown (Artifact) resistance at T_x.

R_s : the value of the standard resistance at T_e.

R_{s0} : the value of the standard resistance at T_0.

K_x : the Ratio displayed on the DCC-RES bridge

C : the correction of the Ratio K_x

α and β : Temperature coefficient of the standard resistance.

ΔT : $(T_e - T_0)$

The reference resistance standards are calibrated annually by LNE, France. The latest calibration was performed December 2015. Traceability is transferred from reference standards to the Resistors under test (Artifacts) using a resistance Bridge GUILDLINE 9975. The measurements are performed at ambient temperature of 23,94 °C, relative humidity of 50 % RH and atmospheric pressure of 996 hPa.

KEBS

The substitution method used, and digital multimeter/ null detector used as transfer standard between reference standard resistor and travelling standard. The 1 Ω and 10 kΩ reference standards are calibrated by National Institute of Turkey (UME), latest calibration performed March 2016. Traceability is transferred from reference standards using transfer standard and a measuring system through a build-up method. The measurements are performed at ambient temperature of 23,78 °C, relative humidity of 48,7 % RH and atmospheric pressure of 836 hPa.

NIS

The 4-terminal resistance of the comparison standards were measured using Measurement International Limited 6010C an automated resistance measurement system. The reference resistance standards were calibrated by BIPM, France. The latest calibration was performed November 2016. Traceability is transferred from reference standards to other standards in a ratio build-up method. The measurements are performed at ambient temperature of 23,1 °C, relative humidity of 48,2 % RH and atmospheric pressure of 1 008,5 hPa.

UNBS

The comparison standards were measured directly using digital multimeter. The multimeter was traceable calibrated at NMISA, and latest calibration performed May 2013. The measurements are performed at ambient temperature of 23,12 °C, relative humidity of 58,5 % RH and atmospheric pressure of 881 hPa.

NMIE

The reference resistance standards 1 Ω, 1 kΩ and 10 kΩ were traceable calibrated by NMISA, South Africa. The latest calibration was performed June 2015. Traceability is transferred from reference standards to other standards in a 1:10 and 1:100 ratio using a 8 ½ DMM and a calibrator by connected the resistor in series using voltage drop method. The measurements are performed at ambient temperature of 23,0 °C, relative humidity of 50,0 % RH and atmospheric pressure of 769 hPa.

3.4 Deviation from the protocol

Some participants measured the travelling standards at test currents and environmental conditions other than mentioned in the comparison protocol however the results have been corrected.

3.5 Drift of the travelling standards

NMISA repeated the measurements according to the schedule order shown in Table 2 from November 2015 to June 2018. The linear fit Equation (1) is used to calculate the drifts of the travelling standards.

$$(y - y_0) = m(x - x_0) \qquad (1)$$

Where:

x is a selected NMISA measurement date.
x_o is the average of the NMISA measurement dates.
y is the resistance value given by the linear fit on a selected date.
y_o is the average of the NMISA measurements.
m is the drift of the resistance value per day.

The behaviour of the travelling standards is given in Table 5.

Table 5: Behaviour of travelling standards

Nominal values (Ω)	x_o	y_o (Ω)	m (Ω/day)
1	25/1/2017	1.0000503	5.294 E-09
10		10.000506	5.959 E-08
100		100.00726	9.224 E-07
1000		1000.0068	1.322 E-06
10000		10000.137	5.569 E-06

The behaviour of the travelling standards according to NMISA measurements over the comparison period are illustrated in Figure 1 to 5.

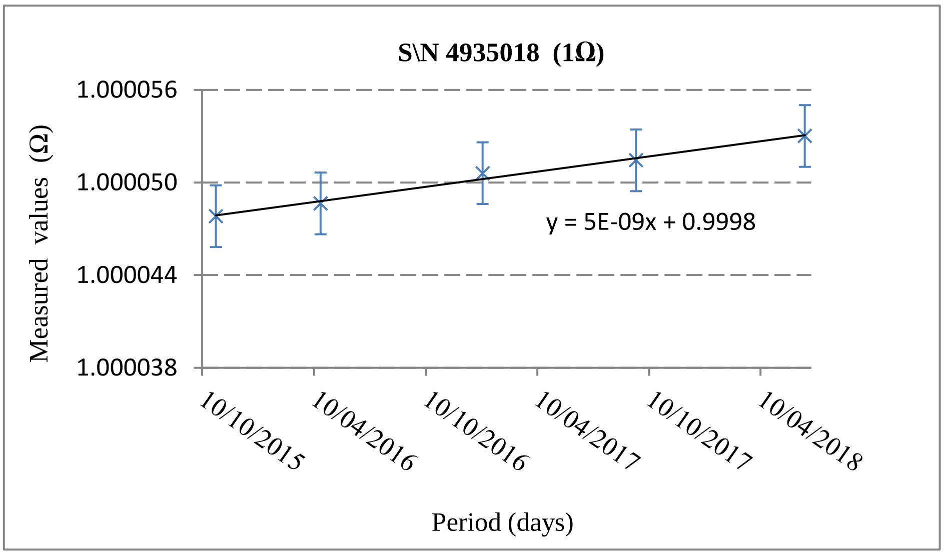

Figure 1: Behaviour of 1 Ω travelling standard: S/N 4935018

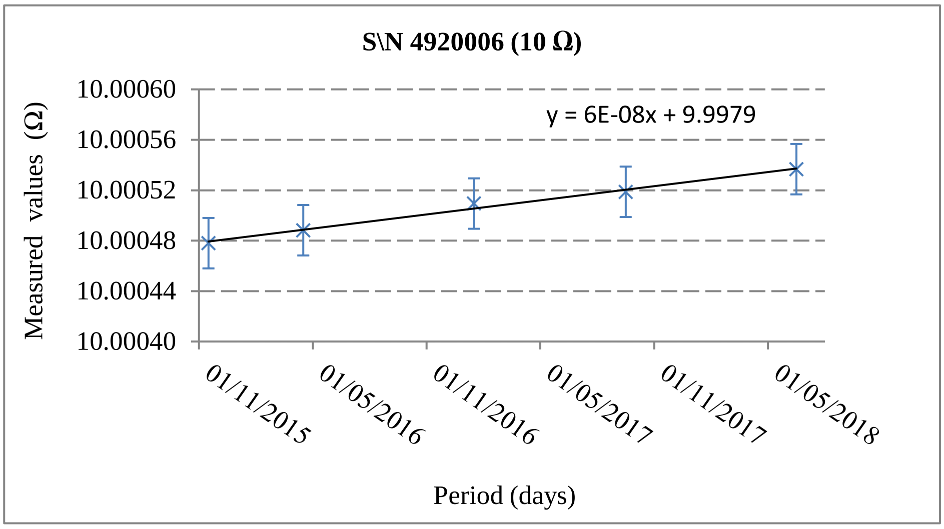

Figure 2: Behaviour of 10 Ω travelling standard: S/N 4920006

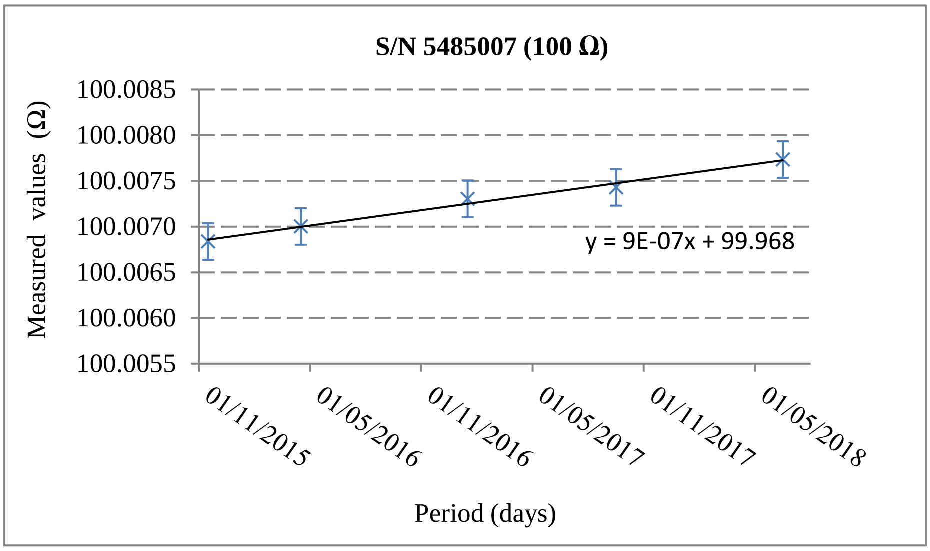

Figure 3: Behaviour of 100 Ω travelling standard: S/N 5485007

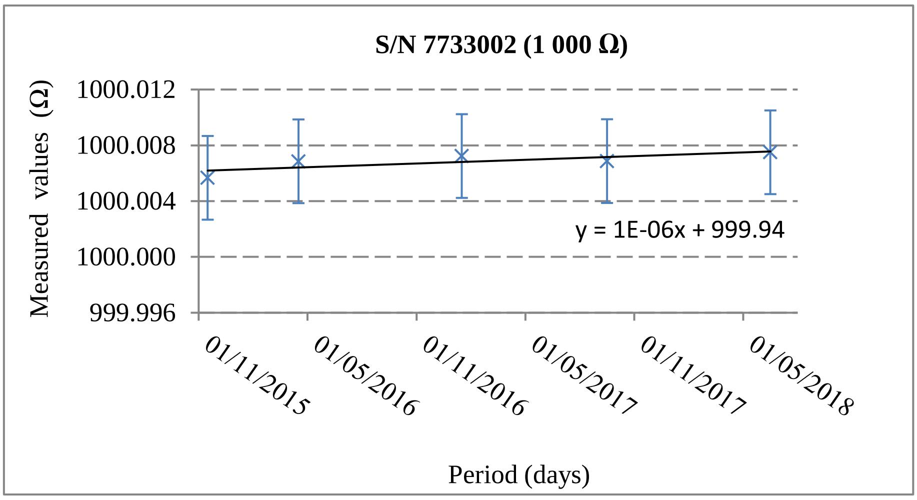

Figure 4: Behaviour of 1 000 Ω travelling standard: S/N 7733002

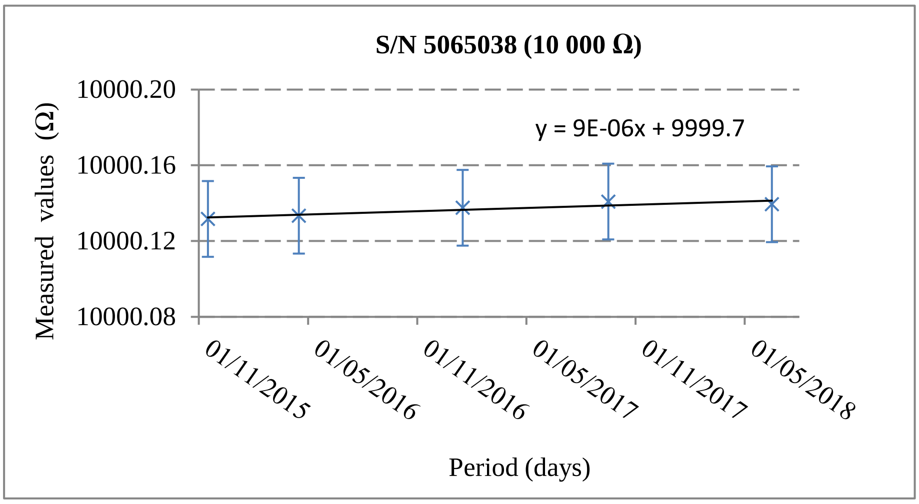

Figure 5: Behaviour of 10 000 Ω travelling standard: S/N 5065038

4 Discussion of the comparison results

4.1 Drift, current, temperature and atmospheric pressure corrections

The participants reported values are drifted corrected to initial NMISA measurement dated 01/November/2015 using Equation (2).

$$R_x = R_r - (m * D_y) \qquad (2)$$

Where:

R_x is the corrected reported resistance value of the participant.

R_r is the reported resistance value by participant.

m is the estimated resistance drift per day of the travelling standard since initial NMISA measurement.

D_y is the period lapsed in days since initial NMISA measurement, 01/November/2015

The participants reported values were current corrected using Equation (3).

$$R_x = R_r + R_c * (C_x - C_r) \qquad (3)$$

Where:

R_x is the resistance at required test current C_x

C_x is the test current as per technical protocol at resistance R_x

R_r is the participant reported resistance value at test current C_r

C_r is the test current at which the participant performed R_r measurement

R_c is current coefficient of R_x listed in Table 3

The participants reported values were corrected to reference temperature which the pilot performed the measurements using Equation (4) [4].

$$R = R(T) \times [1 - \alpha_{23}(T - T_0) - \beta(T - T_0)^2] \qquad (4)$$

Where:

R is the required resistance at the reference temperature T_0 = 23 °C

$R(T)$ is the participant reported resistance at temperature T

T is the temperature at which participant measured the resistance $R(T)$

α and β are temperature coefficients of $R(T)$ listed in Table 3.

The participants reported values were corrected to reference atmospheric pressure which pilot performed the measurements using Equation (5) [4].

$$R_x = R_r(1 - \gamma(P_x - P_r)) \qquad (5)$$

Where:

R_x is the required resistance at reference atmospheric pressure P_r = 870 hPa

R_r is the participated reported resistance at atmospheric pressure P_x

P_x is the atmospheric pressure at which participant measured the resistance R_r

γ is pressure coefficient of R_r listed in Table 3.

4.2 NMISA Measurements over the comparison period

The NMISA corrected measurements associated with their uncertainties at 95% confidence level over the comparison period are listed in Table 6.

Table 6: NMISA corrected measurements associated with their uncertainties for the travelling standards

Travelling Standard	1st Measurements (1/11/2015)		2nd Measurements (20/4/2016)		3rd Measurements (10/1/2017)		4th Measurements (18/9/2017)		5th Measurements (21/6/2018)	
	Value (Ω)	U_{exp} μΩ/Ω	Value (Ω)	U_{exp} μΩ/Ω	Value (Ω)	U_{exp} μΩ/Ω	Value (Ω)	U_{exp} μΩ/Ω	Value (Ω)	U_{exp} μΩ/Ω
1 Ω	1.0000478	2.0	1.0000477	2.0	1.0000483	2.0	1.0000478	2.0	1.0000480	2.0
10 Ω	10.000478	2.0	10.000478	2.0	10.000483	2.0	10.000479	2.0	10.000480	2.0
100 Ω	100.00684	2.0	100.00684	2.0	100.00690	2.0	100.00680	2.0	100.00685	2.0
1000 Ω	1000.0057	3.0	1000.0066	3.0	1000.0067	3.0	1000.0061	3.0	1000.0062	3.0
10000 Ω	10000.132	2.0	10000.132	2.0	10000.135	2.0	10000.138	2.0	10000.134	2.0

4.3 Participants Measurements

Participants corrected measurements associated with their uncertainties at 95% confidence level are listed in Table 7.

Table 7: Participants corrected measurements associated with their uncertainties

Travelling Standard	LPEE/LNM		DEFNAT		KEBS		NIS		UNBS		NMIE	
	Value (Ω)	U_{exp} μΩ/Ω	Value (Ω)	U_{exp} μΩ/Ω	Value (Ω)	U_{exp} μΩ/Ω	Value (Ω)	U_{exp} μΩ/Ω	Value (Ω)	U_{exp} μΩ/Ω	Value (Ω)	U_{exp} μΩ/Ω
1 Ω	1.0000466	4.0	1.0000481	3.0	1.0000366	5.2	1.0000467	0.6	0.9999917	50.2	1.0000506	13.0
10 Ω	10.000456	4.0	10.000482	3.8	9.999945	8.4	10.000470	0.3	9.999943	50.0	10.000362	13.9
100 Ω	100.00674	3.0	100.00687	3.7	100.00701	8.4	100.00682	0.4	100.00635	50.0	100.00657	13.1
1000 Ω	1000.0059	3.0	1000.0038	3.2	1000.0257	6.2	1000.006	0.7	1000.0073	50.0	1000.0062	11.2
10000 Ω	10000.13	2.0	10000.137	1.4	10000.117	4.2	10000.134	0.3	10000.496	50.1	9999.793	10.0

4.4 Stability check of the travelling standards

The stability check has been performed using the five NMISA corrected measurements (over the comparison period). To prove that the travelling standards are stable, their drift values over time (*m*) should fulfil the following stability criterion in accordance with ISO 13528:2015 [5] using the Equation 6.

$$m \leq 0.9\sqrt{U_{X_{min}}^2 + U_{X_{NMISA}}^2} \qquad (6)$$

Where

$U_{x_{min}}$ is the minimum uncertainty reported by the participating NMIs.

$U_{X_{NMISA}}$ is the uncertainty reported by NMISA.

In this case, the comparison reference value (CRV) will be the arithmetic mean of the five NMISA measurements, $\bar{X}$ and their uncertainty will be the reference uncertainty, $U_{\bar{X}}$

The results of the stability check are presented in Table 8.

Table 8: Results of Stability Criterion

Travelling Standards	m (Ω/day)	$0.9\sqrt{U_{X_{min}}^2 + U_{X_{NMISA}}^2}$ (Ω)	Status
1 Ω	**5.294 E-09**	**1.88 E-06**	**Fulfil**
10 Ω	**5.959 E-08**	**1.82 E-05**	**Fulfil**
100 Ω	**9.224 E-07**	**1.84 E-04**	**Fulfil**
1 000 Ω	**1.322 E-06**	**2.77 E-03**	**Fulfil**
10 000 Ω	**5.569 E-06**	**1.82 E-02**	**Fulfil**

4.5 Comparison reference values

Accordingly, the comparison reference value R_{CRV} is determined by arithmetic mean of the NMISA measurements ($\bar{X}$), using Equation (7) and the uncertainty of the reference value U_{RCV} is the uncertainty of $\bar{X}$ [6] [7].

$$\bar{X} = \frac{\sum_{i=1}^{N} X_i}{N} \qquad (7)$$

Where:

$\bar{X}$ is the (R_{CRV}) arithmetic mean of (NMISA) measurements

X_i is the measurements performed by NMISA

N is the number of measurements performed by NMISA

The R_{CRV} values and their associated uncertainties (k = 2) are as shown in Table 9.

Table 9: Comparison Reference values (R_{CRV})

Travelling Standards	Comparison Reference Value (Ω)	Uncertainty (k=2)
1 Ω	**1.0000479**	**2.0 μΩ/Ω**
10 Ω	**10.000480**	**2.0 μΩ/Ω**
100 Ω	**100.00685**	**2.0 μΩ/Ω**
1000 Ω	**1 000.0063**	**3.0 μΩ/Ω**
10000 Ω	**10 000.134**	**2.0 μΩ/Ω**

4.6 Normalised error (E_n)

The normalised errors of the corrected reported values have been calculated using Equation (8),

$$E_N = \frac{R_x - R_{CRV}}{\sqrt{(U_{CRV})^2 + (U_{Rx})^2}} \qquad (8)$$

where:
E_n is the normalised error.
R_X is the corrected value reported by participant.
R_{CRV} is the comparison reference value.
U_{RX} is the uncertainty reported by participant.
U_{CRV} is the uncertainty of the reference value.

4.7 Deviation from R_{CRV}

The deviation from R_{CRV}, D_i (in relative, μΩ/Ω) is determined the using the Equation (9) [6] [7].

$$D_i = R_X - R_{\mathrm{CRV}} \qquad (9)$$

Where R_X is the corrected reported value by participant and R_{CRV} is the comparison reference value.

4.8 Participants reported results

Table 10 to 14 presents the corrected measurement results associated with their uncertainties, R_{CRV}, U_{CRV}, E_n values and the deviation from R_{CRV} for the travelling standards from 1 Ω to 10 kΩ respectively. Graphical representations of the comparison results in the ranges from 1 Ω to 10 kΩ are shown in Figure 6 to 10.

Table 10: Results for 1 Ω travelling standard: S/N 4935018

Participating NMIs	Corrected values (Ω)	Uncertainty (µΩ/Ω)	R_{CRV} (Ω)	U_{CRV} (µΩ/Ω)	En	D_i (µΩ/Ω)
NMISA	1.0000478	2.0			-0.04	-0.10
LPEE/LNM	1.0000466	4.0			-0.29	-1.30
DEFNAT	1.0000481	3.0			0.06	0.20
NMISA	1.0000477	2.0			-0.07	-0.20
KEBS	1.0000366	5.2			-2.03	-11.30
NMISA	1.0000483	2.0	1.0000479	2	0.14	0.40
NIS	1.0000467	0.6			-0.57	-1.20
NMISA	1.0000478	2.0			-0.04	-0.10
UNBS	0.9999917	50.2			-1.12	-56.20
NMIE	1.0000506	13.0			0.21	2.70
NMISA	1.0000480	2.0			0.04	0.10

Table 11: Results for 10 Ω travelling standard: S/N 4920006

Participating NMIs	Corrected values (Ω)	Uncertainty (µΩ/Ω)	R_{CRV} (Ω)	U_{CRV} (µΩ/Ω)	En	D_i (µΩ/Ω)
NMISA	10.000478	2.0			-0.07	-0.20
LPEE/LNM	10.000456	4.0			-0.54	-2.40
DEFNAT	10.000482	3.8			0.05	0.20
NMISA	10.000478	2.0			-0.07	-0.20
KEBS	9.999945	8.4			-6.20	-53.50
NMISA	10.000483	2.0	10.000480	2	0.11	0.30
NIS	10.000470	0.3			-0.49	-1.00
NMISA	10.000479	2.0			-0.04	-0.10
UNBS	9.999943	50.0			-1.07	-53.70
NMIE	10.000362	13.9			-0.84	-11.80
NMISA	10.000480	2.0			0.00	0.00

Table 12: Results for 100 Ω travelling standard: S/N 5485007

Participating NMIs	Corrected values (Ω)	Uncertainty (µΩ/Ω)	R_{CRV} (Ω)	U_{CRV} (µΩ/Ω)	En	D_i (µΩ/Ω)
NMISA	100.00684	2.0	100.00685	2	-0.04	-0.10
LPEE/LNM	100.00674	3.0			-0.31	-1.10
DEFNAT	100.00687	3.7			0.05	0.20
NMISA	100.00684	2.0			-0.04	-0.10
KEBS	100.00701	8.4			0.19	1.60
NMISA	100.00690	2.0			0.18	0.50
NIS	100.00682	0.4			-0.15	-0.30
NMISA	100.00680	2.0			-0.18	-0.50
UNBS	100.00635	50.0			-0.10	-5.00
NMIE	100.00657	13.1			-0.21	-2.80
NMISA	100.00685	2.0			0.00	0.00

Table 13: Results for 1000 Ω travelling standard: S/N 7733002

Participating NMIs	Corrected values (Ω)	Uncertainty (µΩ/Ω)	R_{CRV} (Ω)	U_{CRV} (µΩ/Ω)	En	D_i (µΩ/Ω)
NMISA	1000.0057	3.0	1000.0063	3	-0.14	-0.60
LPEE/LNM	1000.0059	3.0			-0.09	-0.40
DEFNAT	1000.0038	3.2			-0.57	-2.50
NMISA	1000.0066	3.0			0.07	0.30
KEBS	1000.0257	6.2			2.82	19.40
NMISA	1000.0067	3.0			0.09	0.40
NIS	1000.0060	0.7			-0.10	-0.30
NMISA	1000.0061	3.0			-0.05	-0.20
UNBS	1000.0073	50.0			0.02	1.00
NMIE	1000.0062	11.2			-0.01	-0.10
NMISA	1000.0062	3.0			-0.02	-0.10

Table 14: Results for 10 kΩ travelling standard: S/N 5065038

Participating NMIs	Corrected values (Ω)	Uncertainty (μΩ/Ω)	R_{CRV} (Ω)	U_{CRV} (μΩ/Ω)	En	D_i (μΩ/Ω)
NMISA	10000.132	2.0	10000.134	2	-0.07	-0.20
LPEE/LNM	10000.130	2.0			-0.14	-0.40
DEFNAT	10000.137	1.4			0.12	0.30
NMISA	10000.132	2.0			-0.07	-0.20
KEBS	10000.117	4.2			-0.37	-1.70
NMISA	10000.135	2.0			0.04	0.10
NIS	10000.134	0.3			0.00	0.00
NMISA	10000.138	2.0			0.14	0.40
UNBS	10000.496	50.1			0.72	36.20
NMIE	9999.793	10.0			-3.34	-34.10
NMISA	10000.134	2.0			0.00	0.00

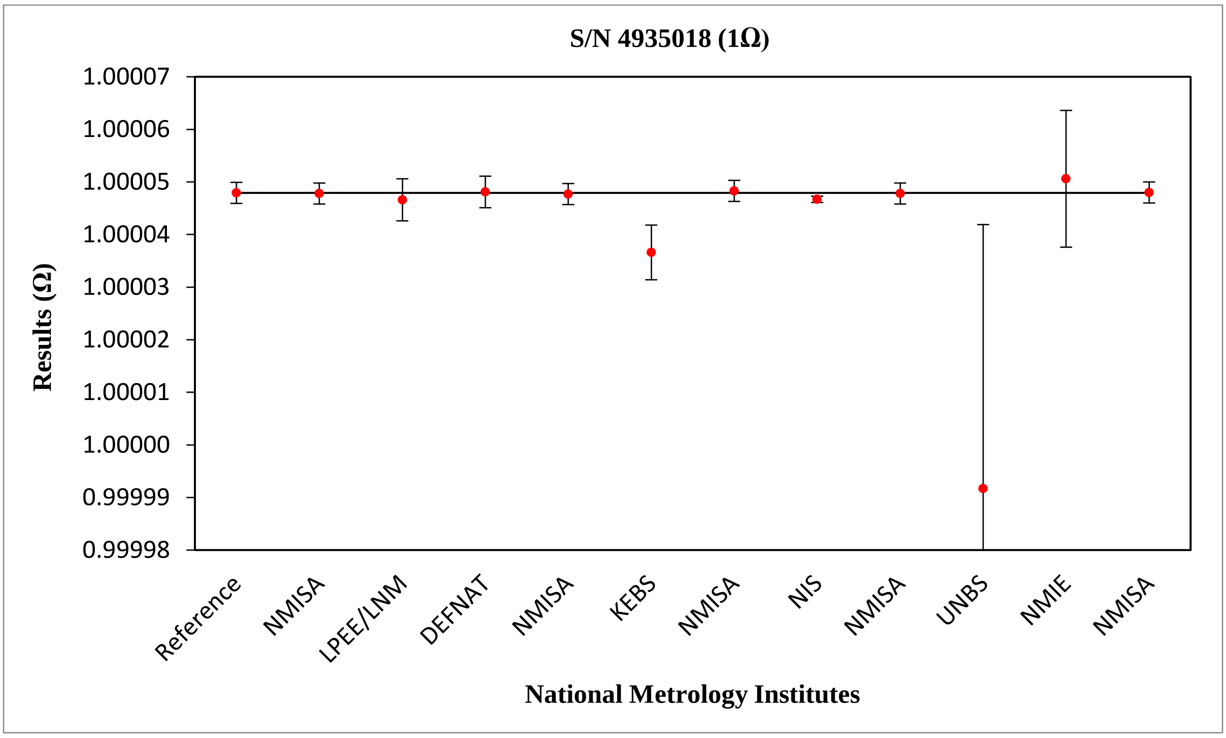

Figure 6: Results for 1 Ω travelling standard: S/N 4935018

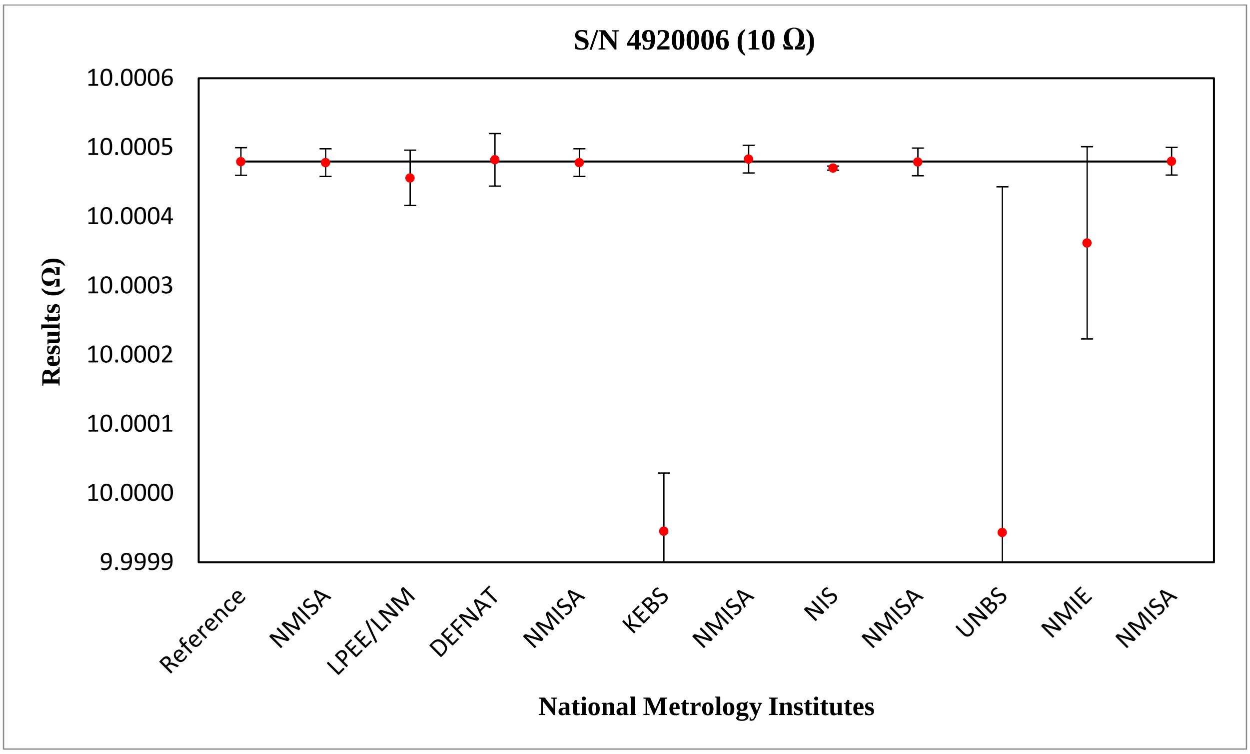

Figure 7: Results for 10 Ω travelling standard: S/N 4920006

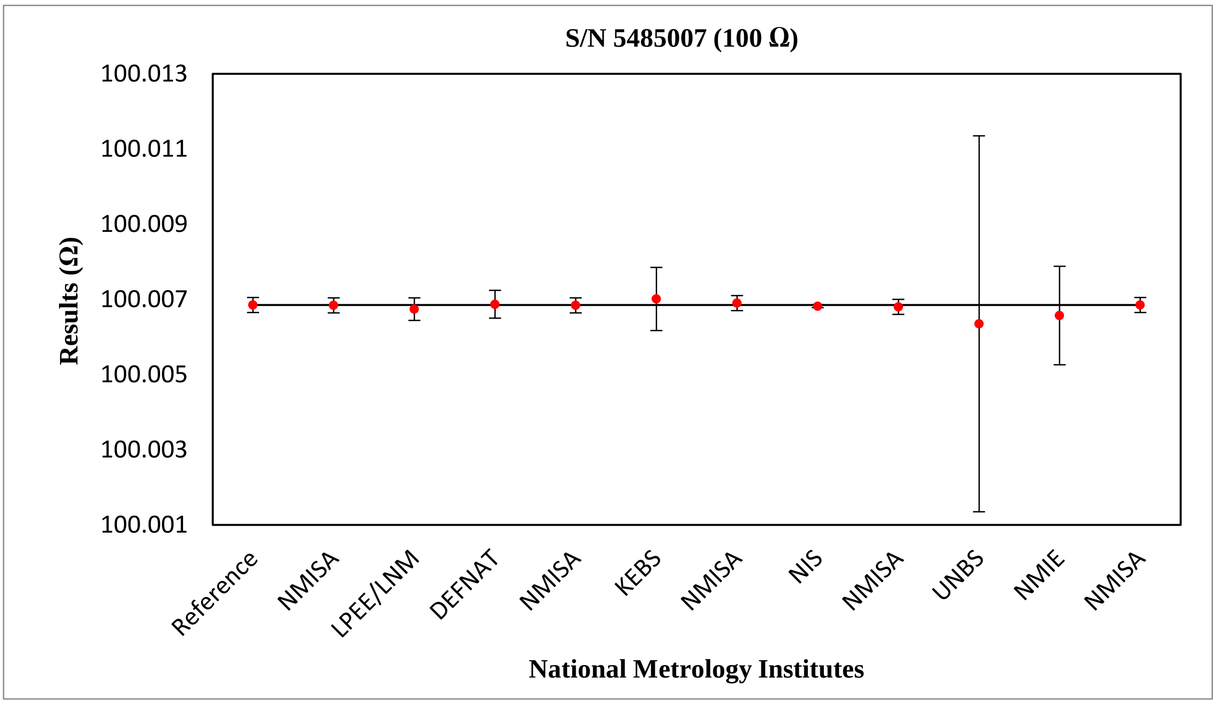

Figure 8: Results for 100 Ω travelling standard: S/N 5485007

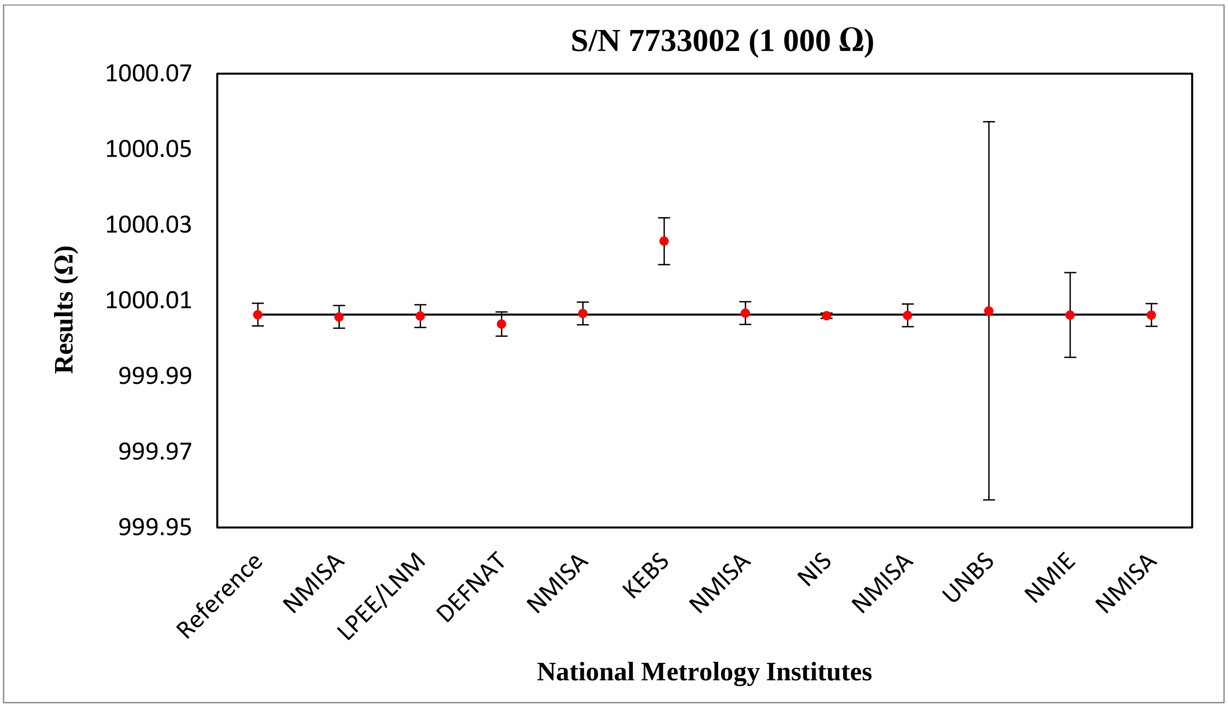

Figure 9: Results for 1 000 Ω travelling standard: S/N 7733002

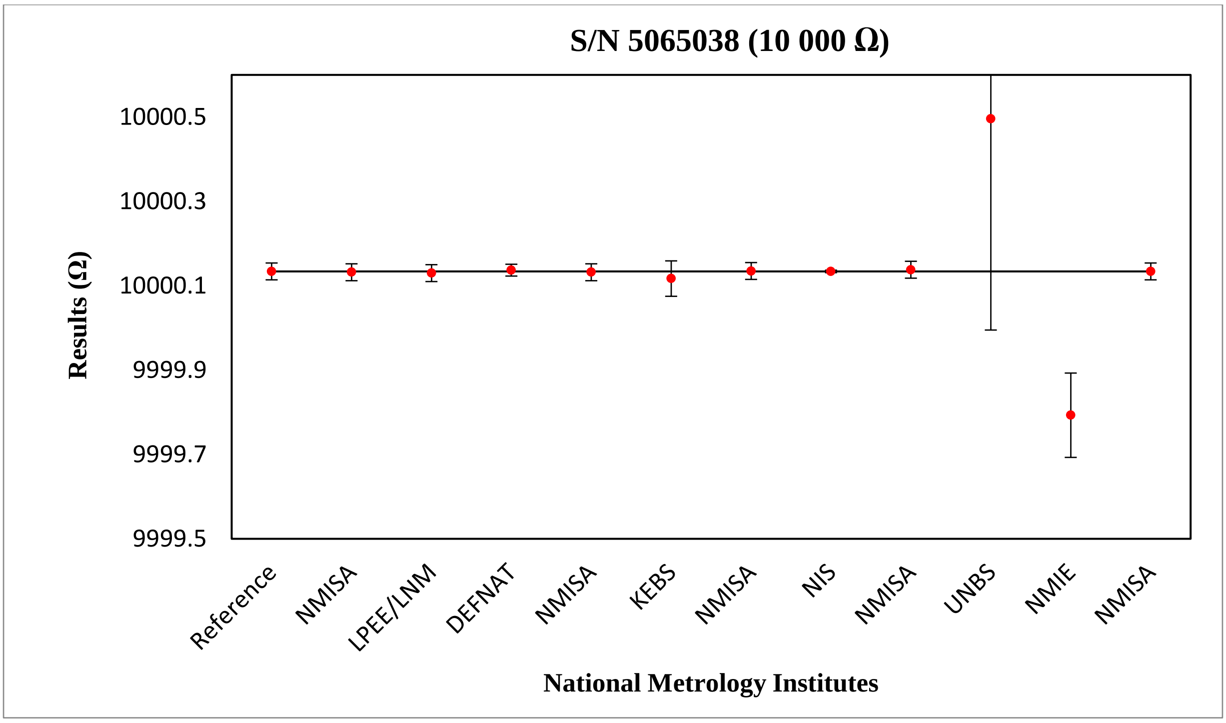

Figure 10: Results for 10 000 Ω travelling standard: S/N 5065038.

5 Summary and conclusions

NMISA has provided the 1 Ω, 10 Ω, 100 Ω, 1 kΩ and 10 kΩ travelling resistance standards and piloted the comparison. The comparison commenced November 2015 and completed June 2018. Stability criterion according to ISO 13528:2015 has been performed to assess the travelling standards behaviour during the period of comparison. It is proved that the insignificant drift of the travelling standards did not affect their stability. Different methods used by participants were tested and results proved equivalent between participants. The National metrology institutes are encouraged to implement root cause analysis and corrective actions on values not in good agreement with other participants.

6 References

[1] Technical Protocol, AFRIMETS Supplementary Comparison, AFRIMETS.EM-S1,
1 Ω, 10 Ω, 100 Ω, 1 kΩ and 10 kΩ resistance standards.
[2] CCEM Guidelines for Planning, Organizing, Conducting and Reporting Key, Supplementary and Pilot Comparisons, version 2.1, 2017.
http://www.bipm.org/utils/common/pdf/ccem_guidelines.pdf.
[3] Measurement comparisons in the CIPM MRA, CIPM MRA-D-05 Version 1.6.
[4] Characteristics of precision 1Ω standard resistors influencing transport behaviour and the uncertainty of key comparisons. G R Jones, B J Pritchard and R E Elmquist Metrologia 46 (2009) 503–511
[5] ISO - ISO 13528:2015 - Statistical methods for use in proficiency testing by interlaboratory comparison
[6] CCQM Guidance note: Estimation of a consensus KCRV and associated Degrees of Equivalence, version 10, 2013.
[7] Update to proposal for KCRV & degree of equivalence for GTRF key comparisons,
J. Randa, NIST, February 2005

7 Appendix A: Technical protocol

RMO Supplementary Comparison AFRIMETS.EM-S1
Comparison of Resistance Standards at 1 Ω, 10 Ω,
100 Ω, 1 kΩ and 10 kΩ

Technical Protocol

Coordinator:
Mr Michael Khoza
mkhoza@nmisa.org

Pilot laboratory:
National Metrology Institute of South Africa
Private Bag X34
Lynnwood Ridge
Pretoria
0040
South Africa

TABLE OF CONTENTS

7 Comparison report

8 References

9 Annexes

1 Introduction

The Mutual Recognition Arrangement states that it is the responsibility of a Regional Metrology Organisation to carry out supplementary comparisons and other actions designed to support mutual confidence in the validity of calibration and measurement certificates issued by participating institutes. As part of this process, AFRIMETS initiated a comparison of resistance standards at 1 Ω, 10 Ω, 100 Ω, 1 kΩ and 10 kΩ (AFRIMETS.EM-S1).

The protocol was documented following the CCEM guidelines for planning, organizing, conducting and reporting Key and Supplementary comparisons. [1]

2 Travelling standards

2.1 Description of standards

1 Ω standard, Fluke 742A-1, SN 4935018, (α = - 0,080 E-6, β = - 0,044 E-6)
10 Ω standard, Fluke 742A-10, SN 4920006, (α = - 0,020 E-6, β = - 0,036 E-6)
100 Ω standard, Fluke 742A-100, SN 5485007, (α = - 0,009 E-6, β = - 0,044 E-6)
1 kΩ standard, Fluke 742A-1k, SN 7733002, (α = 0,050 E-6, β = - 0,022 E-6)
10 kΩ standard, Fluke 742A-10k, SN 5065038, (α = 0,040 E-6, β = - 0,020 E-6)

The resistors are housed in shielded enclosures.

2.2 Quantities to be measured

Four terminal resistance of the 1 Ω standard under the following conditions:
Test current: 100 mA
Ambient temperature: 23 °C ± 2 °C
Relative humidity 50 %rh ± 10 %rh
Atmospheric pressure: Participant laboratory atmospheric pressure

Four terminal resistance of the 10 Ω standard under the following conditions:
Test current: 10 mA
Ambient temperature: 23 °C ± 2 °C
Relative humidity 50 %rh ± 10 %rh
Atmospheric pressure: Participant laboratory atmospheric pressure

Four terminal resistance of the 100 Ω standard under the following conditions:
Test current: 1 mA
Ambient temperature: 23 °C ± 2 °C
Relative humidity 50 %rh ± 10 %rh
Atmospheric pressure: Participant laboratory atmospheric pressure

Four terminal resistance of the 1 kΩ standard under the following conditions:
Test current: 1 mA
Ambient temperature: 23 °C ± 2 °C
Relative humidity 50 %rh ± 10 %rh
Atmospheric pressure: Participant laboratory atmospheric pressure

Four terminal resistance of the 10 kΩ standard under the following conditions:
Test current: 100 µA
Ambient temperature: 23 °C ± 2 °C
Relative humidity 50 %rh ± 10 %rh
Atmospheric pressure: Participant laboratory atmospheric pressure

2.3 Method of computation of reference value

The comparison reference values (CRV) of the travelling standards will be computed using the arithmetic mean of the NMISA results.

Drift of standards during the comparison period will be established using measurement results of NMISA and the participants reported results will be corrected to the initial date of NMISA measurements.

3. Organisation

3.1 Coordinator

The pilot laboratory for the comparison is the National Metrology Institute of South Africa (NMISA), South Africa

Coordinator and contact person for technical questions:
Mr Michael Khoza
Tel: +27 12 841 2408
Mobile: +27 73 290 3540
e-mail: mkhoza@nmisa.org

3.2 Participants

No	Country	Institute	Acronym
1	South Africa	National Metrology Institute of South Africa	NMISA
2	Morocco	Laboratoire Public d'Essais et d'Etudes / Laboratoire National de Métrologie	LPEE/LNM
3	Tunisia	Designated National Institute DEFNAT/ANM	DEFNAT/ ANM
4	Kenya	Kenya Bureau of Standards	KEBS
5	Egypt	National Institute for Standards	NIS
6	Uganda	Uganda National Bureau of Standards	UNBS
7	Ethiopia	National Metrology Institute of Ethiopia	NMIE

3.3 Time schedule

A period of four weeks is allowed for the measurements in each laboratory, including time for transportation. See A2.

NMIs who confirmed participation will be bound by the limited period allocated in the time schedule. In case a participant is not ready to perform measurements during a scheduled time period, the laboratory is required to contact the coordinator in the pilot laboratory. Arrangements will then be made that the laboratory performs measurement at the end of the comparison

In case of unforeseen delays, the pilot laboratory shall inform affected participants and if required revise the measurements schedule

3.4 Transportation

Each participant is responsible for transporting the travelling standards to next scheduled laboratory at own cost. Laboratories should resolve any possible custom problems that can delay circulation of the travelling standards. In an ATA Carnet is used, please familiarize yourself with its proper use.

A courier service provider used should be informed that a warning note should be attached to the transport case to avoid exposure to mechanical shock, the carry case not be exposed to extreme temperature conditions, and should under normal circumstances only be opened by laboratory personnel.

Before dispatching the package, please inform the next scheduled laboratory and provide transport details like tracking number etc.

Countries will be grouped in such a way that those that recognize use of an ATA perform comparison measurements in a loop format. Example: (pilot, participant 1, participant 2, participant 3, pilot) and those that do not recognize use of an ATA Carnet perform comparison measurements in a star format. Example: (pilot, participant 4, pilot, participant 5, pilot, participant 6, pilot).

For allowed measurement period and transport period see A2.

3.5 Unpacking, handling, packing

The carry case contains the following items:

One 1 Ω standard resistor, Fluke 742A-1, SN 4935018
One 10 Ω standard resistor, Fluke 742A-10, SN 4920006
One 100 Ω standard resistor, Fluke 742A-100, SN 5485007
One 1 kΩ standard resistor, Fluke 742A-1k, SN 7733002
One 10 kΩ standard resistor, Fluke 742A-10k, SN 5065038
Copy of comparison technical protocol

On receipt of shipment, unpack carefully and inspect for damage and completeness according to packaging list. Any damage to standards or missing standards should be reported to the coordinator immediately.

For countries using the ATA Carnet, make sure that you keep the ATA Carnet safely because loss of the ATA Carnet will result in serious clearance problems with custom officials. Before sending the standards to next scheduled participant, check contents of carry case against packaging list.

For countries using the ATA Carnet, make sure you hand the ATA Carnet together with carry case to your courier. Do not put ATA Carnet inside the carry case in order to ensure easy access by customs officials.

3.6 Failure of the travelling standards

In case that one or more of the travelling standards is damaged during the comparison, the pilot laboratory must be informed immediately.

3.7 Financial aspects and insurance

Each participating laboratory is responsible for cost related to measurements, damage that may occur within its country and transportation to next scheduled laboratory. Other comparison cost will be covered by the pilot laboratory.

4. Measurement instructions

4.1 Tests before measurements

The standards should be allowed to stabilise in a controlled laboratory for a minimum of 24 hours before measurements.

4.2 Measurement performance

Measurand: Four terminal, DC resistance of the travelling standards

Test current: 1 Ω: 100 mA
10 Ω: 10 mA
100 Ω: 1 mA
1 kΩ: 1 mA
10 kΩ: 100 µA

Temperature: 23 °C ± 2 °C

Relative humidity: 50 %rh ± 15 %rh

4.3 Method of measurement

Participants will perform measurements according to methods used in their laboratories. Note: The method used and traceability must be described in measurement report.

5. Uncertainty of measurement

A detailed uncertainty budget in accordance with the ISO Guide to the Expression of Uncertainty in Measurement shall be reported for each resistance value.

To have a comparable uncertainty evaluation, main uncertainty contributors are listed below, and depending on the method used, this list may be vary from one participant to another.
Reference standard (calibration, drift, temperature, power coefficient)
Measuring system (stability, gain, offset effects)
Standard Deviation or Experimental Standard Deviation of the Mean in case the reported mean was calculated from more than one set of measurement results. An uncertainty budget template is given in annex A3

6. Laboratory reports

Each participant is required to submit a signed report by mail within 6 weeks after completing the measurements. A copy can be sent by e-mail. In case of a difference between the electronic and a signed hard copy version of the report, the signed hard copy of the report will be considered a correct and valid version. Reports from participating laboratories should contain at least the following information:

Description of measurement setup/ connection
Traceability chain (Note: Traceability must be from an NMI that is a signatory of the Metre convention. Otherwise comparison results cannot be used to support CMC claims)
Brief description of measurement procedure
Measurement results: Mean resistance value, including uncertainty for each standard, and corresponding mean date of measurement
Test current for each measurement
Temperature and relative humidity including limits of variation
Complete uncertainty budget in accordance with the principles of the ISO Guide to the Expression of Uncertainty in Measurement, including degrees of freedom for every component and calculation of coverage factor. Such an analysis is an important part of the final report which will be published in the BIPM Key Comparison Database in support of your Measurement Capabilities.

7. Comparison report

The pilot laboratory will prepare a Draft A report within three months after completion of circulation of the travelling standards. The report will be sent to all participants for comments. Comments from participants will be incorporated in a draft B report.

8. References

[1] CCEM Guidelines for Planning, Organizing, Conducting and Reporting Key, Supplementary and Pilot Comparisons, Annex 2, The BIPM Key Comparison Database, March 2007.

[2] ISO/IEC Guide 98-3:2008, Uncertainty of measurement-Par 3: Guide to the expression of uncertainty in measurement (GUM: 1995), 2008.

9. Annexes

A1 Detailed list of participants

Institute	Contact person	e-mail	Shipping address
NMISA	Michael Khoza	mkhoza@nmisa.org Tel: +27 12 841 4343 Mobile: +27 82 802 2408	Building 5, CSIR Scientia campus, Meiring Naude Road, Pretoria, 0001, South Africa
LPEE/LNM	Abdellah ZITI	ziti@LPEE.MA Tel: +212 5 22 48 87 29	Km 7, Route d' El Jadida- Oasis, Casablanca, Morocco
DEFNAT/ANM	Abdelkarim MALLAT	metrologie@defense.tn Tel: +216 71 560 488 extension 14241	Direction Générale des Transmissions et de l'Informatique, Base militaire Bab Sâadoun-1005-El Omrane- Tunis
KEBS	Paul Matendechere	matendecherep@kebs.org Tel: +254(0)206948274 Mobile: +254 722 979 632	Popo Road, Off Mombasa Road, Nairobi, Kenya

NIS	Rasha Sayed Attiya Mohammed	Rasha_sama79@hotmail.com Tel: Mobile:	Tersa Street, El-Haram, Giza, 12211, Egypt
UNBS	Patrick Kizito Musaazi	patrickmusazi@yahoo.co.uk Patrick.kizito@unbs.go.ug Tel: +256 712 570 472 Mobile: +256 704 899 154	Plot M217 Nakawa Industrial Area, Kampala, Uganda
NMIE	Nesredin Nezir	nesredin03@gmail.com	Bole sub city, Woreda 06, Megenagna to Bole Ring Road, next to A.M.C.E.

A2 Schedule of the measurements

Institute	Country	Start date	Period for measurements and transport
Pilot (NMISA)	South Africa	November 2015	4 weeks
LPEE/LNM	Morocco	November 2015	4 weeks
DEFNAT/ANM	Tunisia	January 2016	4 weeks
Pilot (NMISA)	South Africa	February 2016	4 weeks
Pilot (NMISA)	South Africa	April 2016	4 weeks
KEBS	Kenya	May 2016	4 weeks
Pilot (NMISA)	South Africa	June 2016	4 weeks
NIS	Egypt	May 2017	4 weeks
Pilot (NMISA)	South Africa	June 2017	4 weeks
NMIE	Ethiopia	March 2018	4 weeks
Pilot (NMISA)	South Africa	June 2018	4 weeks

A3 Typical scheme for an uncertainty budget [2]

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution/ method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution $u(R_i)$	Degrees of freedom ν_i
		Combined standard uncertainty				
		Effective degrees of freedom				
		Expanded uncertainty (95 % coverage factor)				

A4 Layout of measurement report

Nominal resistance
Measurement setup
Traceability chain
Measurement procedure
Detailed measurement results
Standard serial number:

Date	Measured Atmospheric Pressure	Measured Temperature	Measured Relative Humidity	Test current	Measurement result

Detailed uncertainty budget
Standard serial number:

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution/ method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution $u(R_i)$	Degrees of freedom ν_i
		Combined standard uncertainty				
		Effective degrees of freedom				
		Expanded uncertainty (95 % coverage factor)				

Summary of results
Mean temperature and uncertainty
Mean relative humidity and uncertainty
Test current
Mean date of measurement
Mean resistance value and expanded uncertainty

A5 Confirmation note of receipt

Please send copy to shipment sender and coordinator

Name of receiving Institute	
Date of receipt	
Condition of carry case	
Condition of standards	
Total number of standards	
Nominal values	
Serial numbers	
ATA Carnet for countries using ATA Carnet for custom clearance	

A6 Confirmation note of dispatch

Please send copy to next scheduled laboratory and coordinator

Name of dispatching institute	
Name of receiving institute	
Date of dispatch	
Tracking number	
Condition of carry case	
Condition of standards	
Total number of standards	
Nominal values	
Serial numbers	
ATA Carnet for countries using ATA Carnet for custom clearance	

8 Appendix B: NMISA uncertainty Budgets

UNCERTAINTY BUDGET MATRIX (UBM)		
	Certificate No	AFRIMETS.EM-S1
	Procedure No	DCLF\R-0008
Description: Standard resistor	**Type & Serial Number** 742A / 4935018	**Range:** 1 Ω
		Metrologist M Khoza

Symbol	Input Quantity (Source of Uncertainty) (X_i)	Estimated Input Quantity (x_i)	Estimated Uncertainty	Unit	Probability Distribution (N, R, T, U)	k= ▼	Divisor factor	Standard Uncertainty $U(Xi)$	Sensitivity Coefficient Ci	Unit	Standard Uncertainty Contribution $Ui(y)$	Reliability %	Degrees of Freedom v	Remarks
▼ Standards and Reference Equipment (Uncorrelated) ▼											μΩ/Ω			
Std	Rstd calibration		2.000E-01	μΩ/Ω	Normal k = 2		2.00	1.000E-01	1.0		1.000E-01	100	infinite	UoM of the reference standard
	Rstd drift		8.760E-02	μΩ/Ω	Rectangular √3		1.73	5.058E-02	1.0		5.058E-02	100	infinite	Estimated using previous Calibration data standard
	6010C Bridge accuracy		5.000E-02	μΩ/Ω	Normal k = 2		2.00	2.500E-02	1.0		2.500E-02	100	infinite	Obtained from 6010C specification
	6010C Bridge resolution		1.000E-03	μΩ/Ω	Rectangular √12		3.46	2.887E-04	1.0		2.887E-04	100	infinite	Obtained from 6010C specification
	6010C linearity		1.000E-02	μΩ/Ω	Normal k = 2		2.00	5.000E-03	1.0		5.000E-03	100	infinite	Obtained from 6010C specification
	6010C Ratio error		1.400E-02	μΩ/Ω	Normal k = 1		1.00	1.400E-02	1.0		1.400E-02	100	infinite	Obtained from NMISA experimental data
Data	Type "B" Evaluation Range of the results (Rectangular)											100		
	Type "A" Evaluation Exp Std Dev of the Mean (ESDM)		6.291E-01	μΩ/Ω	Normal K = 1		1.00	6.291E-01	1.0		6.291E-01		4	No of Readings 5
▼ Unit Under Test / Calibration (Correlated) ▼														

NOTE! *ONLY CHANGE BLUE CELLS - All OTHER CELLS (WHITE) ARE PROTECTED*

About UBM	TOTAL COMBINED UNCERTAINTY			μΩ/Ω			
Best Measurement Capability (Excluding UUT contribution)		Combined Uncertainty (Normal)	▼ Level of Confidence ▼ **95,45 % K = 2**	1.158E-01	V_{eff}	infinite	Checked and Approved By:
		Expanded Uncertainty		**2.32E-01**	**k =**	**2.00**	
Uncertainty of Measurement (Including UUT contribution)		Combined Uncertainty (Normal)	▼ Level of Confidence ▼ **95,45 % K = 2**	6.397E-01	V_{eff}	4.27554	
		Expanded Uncertainty		**1.84E+00**	**k =**	**2.87**	

UNCERTAINTY BUDGET MATRIX (UBM)											Certificate No		AFRIMETS.EM-S1	
											Procedure No		DCLF\R-0008	
Description:	Standard resistor		**Type & Serial Number**		742A / 4920006			**Range:**	10 Ω				**Metrologist**	
													M Khoza	
Symbol	**Input Quantity (Source of Uncertainty) (X_i)**	**Estimated Input Quantity (x_i)**	**Estimated Uncertainty**	**Unit**	**Probability Distribution (N, R, T, U)**	**k= ▼**	**Divisor factor**	**Standard Uncertainty U(Xi)**	**Sensitivity Coefficient Ci**	**Unit**	**Standard Uncertainty Contribution Ui (y)**	**Reliability %**	**Degrees of Freedom ν**	**Remarks**
▼ Standards and Reference Equipment (Uncorrelated) ▼											**μΩ/Ω**			
Std	Rstd calibration		2.000E-01	μΩ/Ω	Normal k = 2		2.00	1.000E-01	1.0		1.000E-01	100	infinite	UoM of the reference standard
	Rstd drift		8.760E-02	μΩ/Ω	Rectangular √3		1.73	5.058E-02	1.0		5.058E-02	100	infinite	Estimated using previous Calibration data standard
	6010C Bridge accuracy		5.000E-02	μΩ/Ω	Normal k = 2		2.00	2.500E-02	1.0		2.500E-02	100	infinite	Obtained from 6010C specification
	6010C Bridge resolution		1.000E-03	μΩ/Ω	Rectangular √12		3.46	2.887E-04	1.0		2.887E-04	100	infinite	Obtained from 6010C specification
	6010C linearity		1.000E-02	μΩ/Ω	Normal k = 2		2.00	5.000E-03	1.0		5.000E-03	100	infinite	Obtained from 6010C specification
	6010C Ratio error		1.400E-02	μΩ/Ω	Normal k = 1		1.00	1.400E-02	1.0		1.400E-02	100	infinite	Obtained from NMISA experimental data
Data	Type "B" Evaluation Range of the results (Rectangular)											100		
	Type "A" Evaluation Exp Std Dev of the Mean (ESDM)		6.185E-01	μΩ/Ω	Normal K = 1		1.00	6.185E-01	1.000E+00		6.185E-01		4	No of Readings 5
▼ Unit Under Test / Calibration (Correlated) ▼							NOTE!	***ONLY CHANGE BLUE CELLS - All OTHER CELLS (WHITE) ARE PROTECTED***						
About UBM	**TOTAL COMBINED UNCERTAINTY**										**μΩ/Ω**			
Best Measurement Capability (<u>Excluding</u> UUT contribution)				Combined Uncertainty (Normal)				▼ Level of Confidence ▼ 95,45 % K = 2			1.158E-01	**V_{eff}**	infinite	Checked and Approved By:
				Expanded Uncertainty							**2.32E-01**	**k =**	**2.00**	
Uncertainty of Measurement (Including UUT contribution)				Combined Uncertainty (Normal)				▼ Level of Confidence ▼ 95,45 % K = 2			6.292E-01	**V_{eff}**	4.28523	
				Expanded Uncertainty							**1.81E+00**	**k =**	**2.87**	

UNCERTAINTY BUDGET MATRIX (UBM)	Certificate No	AFRIMETS.EM-S1
	Procedure No	DCLF\R-0008

Description: Standard resistor

Type & Serial Number 742A / 5485007

Range: 100 Ω

Metrologist M Khoza

Symbol	Input Quantity (Source of Uncertainty) (X_i)	Estimated Input Quantity (x_i)	Estimated Uncertainty	Unit	Probability Distribution (N, R, T, U)	k= ▼	Divisor factor	Standard Uncertainty $U(Xi)$	Sensitivity Coefficient Ci	Unit	Standard Uncertainty Contribution $Ui\ (y)$	Reliability %	Degrees of Freedom v	Remarks
	▼ Standards and Reference Equipment (Uncorrelated) ▼										µΩ/Ω			
Std	Rstd calibration		2.000E-01	µΩ/Ω	Normal k = 2		2.00	1.000E-01	1.0		1.000E-01	100	infinite	UoM of the reference standard
	Rstd drift		1.440E-01	µΩ/Ω	Rectangular √3		1.73	8.314E-02	1.0		8.314E-02	100	infinite	Estimated using previous Calibration data standard
	6010C Bridge accuracy		5.000E-02	µΩ/Ω	Normal k = 2		2.00	2.500E-02	1.0		2.500E-02	100	infinite	Obtained from 6010C specification
	6010C Bridge resolution		1.000E-03	µΩ/Ω	Rectangular √12		3.46	2.887E-04	1.0		2.887E-04	100	infinite	Obtained from 6010C specification
	6010C linearity		1.000E-02	µΩ/Ω	Normal k = 2		2.00	5.000E-03	1.0		5.000E-03	100	infinite	Obtained from 6010C specification
	6010C Ratio error		1.400E-02	µΩ/Ω	Normal k = 1		1.00	1.400E-02	1.0		1.400E-02	100	infinite	Obtained from NMISA experimental data
Data	Type "B" Evaluation Range of the results (Rectangular)											100		
	Type "A" Evaluation Exp Std Dev of the Mean (ESDM)		6.368E-01	µΩ/Ω	Normal K = 1		1.00	6.368E-01	1.000E+00		6.368E-01		4	No of Readings 5

▼ Unit Under Test / Calibration (Correlated) ▼

NOTE! ***ONLY CHANGE BLUE CELLS - All OTHER CELLS (WHITE) ARE PROTECTED***

About UBM	**TOTAL COMBINED UNCERTAINTY**			**µΩ/Ω**		
Best Measurement Capability (Excluding UUT contribution)	Combined Uncertainty (Normal)	▼ Level of Confidence ▼		1.333E-01	V_{eff} infinite	Checked and Approved By:
	Expanded Uncertainty	**95,45 %**	**K = 2**	**2.67E-01**	**k = 2.00**	
Uncertainty of Measurement (Including UUT contribution)	Combined Uncertainty (Normal)	▼ Level of Confidence ▼		6.506E-01	V_{eff} 4.358	
	Expanded Uncertainty	**95,45 %**	**K = 2**	**1.87E+00**	**k = 2.87**	

UNCERTAINTY BUDGET MATRIX (UBM)												Certificate No	AFRIMETS.EM-S1	
												Procedure No	DCLF\R-0008	
Description:	Standard resistor		**Type & Serial Number**		742A / 7733002			**Range:**	1000 Ω			**Metrologist**	M Khoza	
Symbol	**Input Quantity (Source of Uncertainty) (X_i)**	**Estimated Input Quantity (x_i)**	**Estimated Uncertainty**	**Unit**	**Probability Distribution (N, R, T, U)**	**k= ▼**	**Divisor factor**	**Standard Uncertainty $U(Xi)$**	**Sensitivity Coefficient Ci**	**Unit**	**Standard Uncertainty Contribution $Ui(y)$**	**Reliability %**	**Degrees of Freedom v**	**Remarks**
▼ Standards and Reference Equipment (Uncorrelated) ▼											**µΩ/Ω**			
Std	Rstd calibration		3.000E-01	µΩ/Ω	Normal k = 2		2.00	1.500E-01	1.0		1.500E-01	100	infinite	UoM of the reference standard
	Rstd drift		3.240E-01	µΩ/Ω	Rectangular √3		1.73	1.871E-01	1.0		1.871E-01	100	infinite	Estimated using previous Calibration data standard
	6010C Bridge accuracy		5.000E-02	µΩ/Ω	Normal k = 2		2.00	2.500E-02	1.0		2.500E-02	100	infinite	Obtained from 6010C specification
	6010C Bridge resolution		1.000E-03	µΩ/Ω	Rectangular √12		3.46	2.887E-04	1.0		2.887E-04	100	infinite	Obtained from 6010C specification
	6010C linearity		1.000E-02	µΩ/Ω	Normal k = 2		2.00	5.000E-03	1.0		5.000E-03	100	infinite	Obtained from 6010C specification
	6010C Ratio error		1.400E-02	µΩ/Ω	Normal k = 1		1.00	1.400E-02	1.0		1.400E-02	100	infinite	Obtained from NMISA experimental data
Data	Type "B" Evaluation Range of the results (Rectangular)											100		
	Type "A" Evaluation Exp Std Dev of the Mean (ESDM)		7.542E-01	µΩ/Ω	Normal K = 1		1.00	7.542E-01	1.000E+00		7.542E-01		4	No of Readings 5
▼ Unit Under Test / Calibration (Correlated) ▼														NOTE! ***ONLY CHANGE BLUE CELLS - All OTHER CELLS (WHITE) ARE PROTECTED***
About UBM	**TOTAL COMBINED UNCERTAINTY**										**µΩ/Ω**			
Best Measurement Capability (Excluding UUT contribution)			Combined Uncertainty (Normal)			▼ Level of Confidence ▼					2.415E-01	Veff	infinite	Checked and Approved By:
			Expanded Uncertainty			**95,45 %**		**K = 2**			**4.84E-01**	**k =**	**2.00**	
Uncertainty of Measurement (Including UUT contribution)			Combined Uncertainty (Normal)			▼ Level of Confidence ▼					7.919E-01	Veff	4.86256	
			Expanded Uncertainty			**95,45 %**		**K = 2**			**2.27E+00**	**k =**	**2.87**	

UNCERTAINTY BUDGET MATRIX (UBM)

Certificate No	AFRIMETS.EM-S1
Procedure No	DCLF\R-0008

Description:	Standard resistor	**Type & Serial Number**	742A / 5065038	**Range:**	10000 Ω	**Metrologist**	M Khoza

Symbol	Input Quantity (Source of Uncertainty) (X_i)	Estimated Input Quantity (x_i)	Estimated Uncertainty	Unit	Probability Distribution (N, R, T, U)	k= ▼	Divisor factor	Standard Uncertainty $U(Xi)$	Sensitivity Coefficient Ci	Unit	Standard Uncertainty Contribution $Ui (y)$	Reliability %	Degrees of Freedom v	Remarks
	▼ Standards and Reference Equipment (Uncorrelated) ▼										µΩ/Ω			
Std	Rstd calibration		4.000E-01	µΩ/Ω	Normal k = 2		2.00	2.000E-01	1.0		2.000E-01	100	infinite	UoM of the reference standard
	Rstd drift		1.734E-01	µΩ/Ω	Rectangular √3		1.73	1.001E-01	1.0		1.001E-01	100	infinite	Estimated using previous Calibration data standard
	6010C Bridge accuracy		5.000E-02	µΩ/Ω	Normal k = 2		2.00	2.500E-02	1.0		2.500E-02	100	infinite	Obtained from 6010C specification
	6010C Bridge resolution		1.000E-03	µΩ/Ω	Rectangular √12		3.46	2.887E-04	1.0		2.887E-04	100	infinite	Obtained from 6010C specification
	6010C linearity		1.000E-02	µΩ/Ω	Normal k = 2		2.00	5.000E-03	1.0		5.000E-03	100	infinite	Obtained from 6010C specification
	6010C Ratio error		1.400E-02	µΩ/Ω	Normal k = 1		1.00	1.400E-02	1.0		1.400E-02	100	infinite	Obtained from NMISA experimental data
Data	Type "B" Evaluation Range of the results (Rectangular)											100		
	Type "A" Evaluation Exp Std Dev of the Mean (ESDM)		5.491E-01	µΩ/Ω	Normal K = 1		1.00	5.491E-01	1.000E+00		5.491E-01		4	No of Readings 5
	▼ Unit Under Test / Calibration (Correlated) ▼													

NOTE! ***ONLY CHANGE BLUE CELLS** - All OTHER CELLS (WHITE) ARE PROTECTED*

About UBM	**TOTAL COMBINED UNCERTAINTY**			µΩ/Ω	
Best Measurement Capability (Excluding UUT contribution)	Combined Uncertainty (Normal)	▼ Level of Confidence ▼ **95,45 % K = 2**	2.255E-01	V_{eff} infinite	Checked and Approved By:
	Expanded Uncertainty		**4.52E-01**	**k = 2.00**	
Uncertainty of Measurement (Including UUT contribution)	Combined Uncertainty (Normal)	▼ Level of Confidence ▼ **95,45 % K = 2**	5.936E-01	V_{eff} 5.46355	
	Expanded Uncertainty		**1.57E+00**	**k = 2.65**	

9 Appendix C: LPEE/LNM Results

Summary of results:

Date	Nominal value of traveling standard	Measued Temperature and uncertainty	Measued Relative Humidity and uncertainty	Test current	Measurement result	Expanded uncertainty (95% coverage factor)
08/01/2016	1 Ω	(23,6 ± 0,3)°C	(48 ± 2)%	100 mA	1,000047 Ω	4 µΩ
08/01/2016	10 Ω	(23,8 ± 0,3)°C	(48 ± 2)%	10 mA	10,00046 Ω	0,04 mΩ
08/01/2016	100 Ω	(23,7 ± 0,3)°C	(48 ± 2)%	1 mA	100,0068 Ω	0,3 mΩ
08/01/2016	1 kΩ	(22,9 ± 0,3)°C	(49 ± 2)%	1 mA	1,000006 kΩ	3 mΩ
08/01/2016	10 kΩ	(23,5 ± 0,3)°C	(49 ± 2)%	100 µA	10,00013 kΩ	0,02 Ω

For the informations below, the following notations are used :
Re : Standard resistance value from the last calibration certificate.
Rx : Unknown resistance value (Artificat to be calibrated).
L1 : Reading value on multimeter when unknown resistance is connected.
L2 : Reading value on multimeter when standard resistance is connected.
e : error of the multimeter.
N.B : Re and Rx have the same nominal value.

Detailed measurement results and Detailed uncertainty budget for 1 Ω :

Configuration of the multimeter "F8505A"	
RANGE	2 Ω
FAST	OFF
4-WIRE	ON
DIGIT	7
FILT	ON (Low pass Filter)
CURRENT	100 mA (LoI OFF)

Re		Coefficient temperature value of Re in °C^{-1}
1.00002841	Ω	-4.00E-08

$$L2 = \mathrm{Re} + \varepsilon$$

$$L1 = Rx + \varepsilon$$

$$Rx = L1 - L2 + \mathrm{Re}$$

$$Rx = L1 - L2 + \mathrm{Re} + \alpha_{\mathrm{Re}}.\mathrm{Re}(T_{Etal} - T_0)$$

L1 (Ω)	Stability on L1	L2 (Ω)	Stability on L2	Rx (Ω)
1.000041	stable	1.000022	stable	1.000047

Rx nominal value	1	Ω
Rx measured value (calculated)	1.000047	Ω
Expanded Uncertainty (k=2)	0.000004	Ω

Uncertainty Budget

Rx 1 Ω

Quantity		Standard uncertainty (1σ)	Sensitivity coefficient	Uncertainty contribution (1σ)
B1	Calibration of Re	1.50E-07 Ω	1	1.50E-07 Ω
B2	Drift of Re	1.53E-06 Ω	1	1.53E-06 Ω
B3	Calibration temperature of Re	0.14 °C	-4.00E-08 $\Omega.°C^{-1}$	-5.66E-09 Ω
B4	Stability of the L2 Reading	2.89E-07 Ω	1	2.89E-07 Ω
B5	Temperature coeff of Re	0E+00		0.00E+00 Ω
B6	Power coeff of Re	0E+00		0.00E+00 Ω
B7	Stability of the L1 Reading	2.89E-07 Ω	1	2.89E-07 Ω
B8	Resolution of L1	2.89E-07 Ω	1	2.89E-07 Ω
B9	Linearity error of the multimeter	0E+00		0.00E+00 Ω
B10	Resolution of L2	2.89E-07 Ω	1	2.89E-07 Ω
B11	Temperature effect on Re	0.71 °C	-4.00E-08 $\Omega.°C^{-1}$	-2.83E-08 Ω
B12	Leakage resistance of Re	0E+00		0.00E+00 Ω
B13	Leakage resistance of Rx	0E+00		0.00E+00 Ω
B14	Contact resistance of Re	0E+00		0.00E+00 Ω
B15	Contact resistance of Rx	0E+00		0.00E+00 Ω
B16	Fem parasites	0E+00		0.00E+00 Ω
B17	Variation of temperature during measurement	0E+00		0.00E+00 Ω
Combined standard uncertainty				**1.6E-06 Ω**
Expanded uncertainty calculated (95% coverage factor)				**3.3E-06 Ω**
Expanded uncertainty proposed (95% coverage factor)				**4.0E-06 Ω**

Detailed measurement results and Detailed uncertainty budget for 10 Ω :

Configuration of the multimeter "F8505A"	
RANGE	20 Ω
FAST	OFF
4-WIRE	ON
DIGIT	7
FILT	ON (Low pass Filter)
CURRENT	10 mA (LoI OFF)

Re		Coefficient temperature value of Re in °C^{-1}
10.0001029	Ω	-1.00E-07

$$L2 = \mathrm{Re} + \varepsilon$$

$$L1 = Rx + \varepsilon$$

$$Rx = L1 - L2 + \mathrm{Re}$$

$$Rx = L1 - L2 + \mathrm{Re} + \alpha_{\mathrm{Re}} . \mathrm{Re} (T_{Etal} - T_0)$$

L1 (Ω)	Stability on L1	L2 (Ω)	Stability on L2	Rx (Ω)
10.00045	+ 0,01 mΩ	10.00009	- 0,01 mΩ	10.00046

Rx nominal value	10	Ω
Rx measured value (calculated)	10.00046	Ω
Expanded Uncertainty (k=2)	0.00004	Ω

Uncertainty Budget

Rx 10 Ω

Quantity		Standard uncertainty (1σ)	Sensitivity coefficient	Uncertainty contribution (1σ)
B1	Calibration of Re	1.50E-06 Ω	1	1.50E-06 Ω
B2	Drift of Re	8.95E-06 Ω	1	8.95E-06 Ω
B3	Calibration temperature of Re	0.14 °C	-0.000001 Ω.°C^{-1}	-1.41E-07 Ω
B4	Stability of the L2 Reading	2.89E-06 Ω	1	2.89E-06 Ω
B5	Temperature coeff of Re	0E+00		0.00E+00 Ω
B6	Power coeff of Re	0E+00		0.00E+00 Ω
B7	Stability of the L1 Reading	2.89E-06 Ω	1	2.89E-06 Ω
B8	Resolution of L1	2.89E-06 Ω	1	2.89E-06 Ω
B9	Linearity error of the multimeter	0E+00		0.00E+00 Ω
B10	Resolution of L2	2.89E-06 Ω	1	2.89E-06 Ω
B11	Temperature effect on Re	0.71 °C	-0.000001 Ω.°C^{-1}	-7.07E-07 Ω
B12	Leakage resistance of Re	0E+00		0.00E+00 Ω
B13	Leakage resistance of Rx	0E+00		0.00E+00 Ω
B14	Contact resistance of Re	0E+00		0.00E+00 Ω
B15	Contact resistance of Rx	0E+00		0.00E+00 Ω
B16	Fem parasites	0E+00		0.00E+00 Ω
B17	Variation of temperature during measurement	0E+00		0.00E+00 Ω
Combined standard uncertainty				**1.1E-05 Ω**
Expanded uncertainty calculated (95% coverage factor)				**2.2E-05 Ω**
Expanded uncertainty proposed (95% coverage factor)				**4.0E-05 Ω**

Detailed measurement results and Detailed uncertainty budget for 100 Ω :

Configuration of the multimeter "F8505A"	
RANGE	200 Ω
FAST	OFF
4-WIRE	ON
DIGIT	7
FILT	ON (Low pass Filter)
CURRENT	1 mA (LoI ON)

Re		Coefficient temperature value of Re in °C⁻¹
100.000944	Ω	4.00E-08

$$L2 = \mathrm{Re} + \varepsilon$$

$$L1 = Rx + \varepsilon$$

$$Rx = L1 - L2 + \mathrm{Re}$$

$$Rx = L1 - L2 + \mathrm{Re} + \alpha_{\mathrm{Re}} . \mathrm{Re} . (T_{Etal} - T_0)$$

L1 (Ω)	Stability on L1	L2 (Ω)	Stability on L2	Rx (Ω)
100.0068	stable	100.0009	stable	100.0068

Rx nominal value	100	Ω
Rx measured value (calculated)	100.0068	Ω
Expanded Uncertainty (k=2)	0.0003	Ω

Uncertainty Budget

Rx 100 Ω

	Quantity	Standard uncertainty (1σ)	Sensitivity coefficient	Uncertainty contribution (1σ)
B1	Calibration of Re	2.00E-05 Ω	1	2.00E-05 Ω
B2	Drift of Re	3.46E-05 Ω	1	3.46E-05 Ω
B3	Calibration temperature of Re	0.14 °C	0.000004 $\Omega.°C^{-1}$	5.66E-07 Ω
B4	Stability of the L2 Reading	2.89E-05 Ω	1	2.89E-05 Ω
B5	Temperature coeff of Re	0E+00		0.00E+00 Ω
B6	Power coeff of Re	0E+00		0.00E+00 Ω
B7	Stability of the L1 Reading	2.89E-05 Ω	1	2.89E-05 Ω
B8	Resolution of L1	2.89E-05 Ω	1	2.89E-05 Ω
B9	Linearity error of the multimeter	0E+00		0.00E+00 Ω
B10	Resolution of L2	2.89E-05 Ω	1	2.89E-05 Ω
B11	Temperature effect on Re	0.71 °C	0.000004 $\Omega.°C^{-1}$	2.83E-06 Ω
B12	Leakage resistance of Re	0E+00		0.00E+00 Ω
B13	Leakage resistance of Rx	0E+00		0.00E+00 Ω
B14	Contact resistance of Re	0E+00		0.00E+00 Ω
B15	Contact resistance of Rx	0E+00		0.00E+00 Ω
B16	Fem parasites	0E+00		0.00E+00 Ω
B17	Variation of temperature during measurement	0E+00		0.00E+00 Ω
Combined standard uncertainty				**7.0E-05 Ω**
Expanded uncertainty calculated (95% coverage factor)				**1.4E-04 Ω**
Expanded uncertainty proposed (95% coverage factor)				**3.0E-04 Ω**

Detailed measurement results and Detailed uncertainty budget for 1 kΩ :

Configuration of the multimeter "F8505A"	
RANGE	2 kΩ
FAST	OFF
4-WIRE	ON
DIGIT	7
FILT	ON (Low pass Filter)
CURRENT	1 mA (LoI OFF)

Re		Coefficient temperature value of Re in °C⁻¹
1.00000518	kΩ	2.00E-08

$$L2 = \mathrm{Re} + \varepsilon$$

$$L1 = Rx + \varepsilon$$

$$Rx = L1 - L2 + \mathrm{Re}$$

$$Rx = L1 - L2 + \mathrm{Re} + \alpha_{\mathrm{Re}} . \mathrm{Re} (T_{Etal} - T_0)$$

L1 (kΩ)	Stability on L1	L2 (kΩ)	Stability on L2	Rx (kΩ)
1.000005	stable	1.000004	stable	1.000006

Rx nominal value	1	kΩ
Rx measured value (calculated)	1.000006	kΩ
Expanded Uncertainty (k=2)	0.000003	kΩ

Uncertainty Budget

Rx 1000 Ω

Quantity		Standard uncertainty (1σ)		Sensitivity coefficient		Uncertainty contribution (1σ)	
B1	Calibration of Re	2.00E-04	Ω	1		2.00E-04	Ω
B2	Drift of Re	2.60E-04	Ω	1		2.60E-04	Ω
B3	Calibration temperature of Re	0.14	°C	0.00002	$\Omega.°C^{-1}$	2.83E-06	Ω
B4	Stability of the L2 Reading	2.89E-04	Ω	1		2.89E-04	Ω
B5	Temperature coeff of Re	0E+00				0.00E+00	Ω
B6	Power coeff of Re	0E+00				0.00E+00	Ω
B7	Stability of the L1 Reading	2.89E-04	Ω	1		2.89E-04	Ω
B8	Resolution of L1	2.89E-04	Ω	1		2.89E-04	Ω
B9	Linearity error of the multimeter	0E+00				0.00E+00	Ω
B10	Resolution of L2	2.89E-04	Ω	1		2.89E-04	Ω
B11	Temperature effect on Re	0.71	°C	0.00002	$\Omega.°C^{-1}$	1.41E-05	Ω
B12	Leakage resistance of Re	0E+00				0.00E+00	Ω
B13	Leakage resistance of Rx	0E+00				0.00E+00	Ω
B14	Contact resistance of Re	0E+00				0.00E+00	Ω
B15	Contact resistance of Rx	0E+00				0.00E+00	Ω
B16	Fem parasites	0E+00				0.00E+00	Ω
B17	Variation of temperature during measurement	0E+00				0.00E+00	Ω
Combined standard uncertainty						**6.6E-04**	**Ω**
Expanded uncertainty calculated (95% coverage factor)						**1.3E-03**	**Ω**
Expanded uncertainty proposed (95% coverage factor)						**3.0E-03**	**Ω**

Detailed measurement results and Detailed uncertainty budget for 10 kΩ :

Configuration of the multimeter "F8505A"	
RANGE	20 kΩ
FAST	OFF
4-WIRE	ON
DIGIT	7
FILT	ON (Low pass Filter)
CURRENT	100 µA (LoI OFF)

Re		**Coefficient temperature value of Re in °C^{-1}**
10.0001065	kΩ	**-3.00E-08**

$$L2 = \mathrm{Re} + \varepsilon$$

$$L1 = Rx + \varepsilon$$

$$Rx = L1 - L2 + \mathrm{Re}$$

$$Rx = L1 - L2 + \mathrm{Re} + \alpha_{\mathrm{Re}} . \mathrm{Re} . (T_{Etal} - T_0)$$

L1 (kΩ)	Stability on L1	L2 (kΩ)	Stability on L2	Rx (kΩ)
10.000130	± 2 mΩ	10.000103	± 2 mΩ	10.00013

Rx nominal value	10	kΩ
Rx measured value (calculated)	10.00013	kΩ
Expanded Uncertainty (k=2)	0.00002	kΩ

Uncertainty Budget

Rx 10000 Ω

Quantity		Standard uncertainty (1σ)	Sensitivity coefficient	Uncertainty contribution (1σ)
B1	Calibration of Re	2.00E-03 Ω	1	2.00E-03 Ω
B2	Drift of Re	3.20E-03 Ω	1	3.20E-03 Ω
B3	Calibration temperature of Re	0.14 °C	-0.0003 $\Omega.°C^{-1}$	-4.24E-05 Ω
B4	Stability of the L2 Reading	1.15E-03 Ω	1	1.15E-03 Ω
B5	Temperature coeff of Re	0E+00		0.00E+00 Ω
B6	Power coeff of Re	0E+00		0.00E+00 Ω
B7	Stability of the L1 Reading	1.15E-03 Ω	1	1.15E-03 Ω
B8	Resolution of L1	2.89E-04 Ω	1	2.89E-04 Ω
B9	Linearity error of the multimeter	0E+00		0.00E+00 Ω
B10	Resolution of L2	2.89E-04 Ω	1	2.89E-04 Ω
B11	Temperature effect on Re	0.71 °C	-0.0003 $\Omega.°C^{-1}$	-2.12E-04 Ω
B12	Leakage resistance of Re	0E+00		0.00E+00 Ω
B13	Leakage resistance of Rx	0E+00		0.00E+00 Ω
B14	Contact resistance of Re	0E+00		0.00E+00 Ω
B15	Contact resistance of Rx	0E+00		0.00E+00 Ω
B16	Fem parasites	0E+00		0.00E+00 Ω
B17	Variation of temperature during measurement	0E+00		0.00E+00 Ω
Combined standard uncertainty				**4.1E-03 Ω**
Expanded uncertainty calculated (95% coverage factor)				**8.3E-03 Ω**
Expanded uncertainty proposed (95% coverage factor)				**2.0E-02 Ω**

Comments :

B5 : The temperature coefficient of Re was determined with very low uncertainty, thus B5 is negligible compared to B11.
B6 : The loss power through Re is lower than 10 mW, thus there is no significant effect on the measurement.
B9 : Due to low errors between the readings L1 and L2, and due to manufacturer's specifications of the multimeter, B9 is negligible.
B11 : We have considered that the measurements were done with conditions 23°C ± 1°C
B12 to B15 : Re and Rx have 4-wire terminals and was connected to the multimeter with 4-wire configuration.
The Ground terminal of the resistance was connected to the Guard terminal of the multimeter.
These quantities have a negligible effect on the measurements.
B16 : The fem parasites are the same either with Re or Rx. Thus, because of the substitution method principle, B16 is considered negligible.
B17 : This effect is already considered in the B4 and B7 quantities.

10 Appendix D: DEF-NAT results

Measurement report

Measurement results:

The resistance RX of the unknown resistor is obtained from the relationship:

Rx= Rs*Ke = Rs0*[1 + (α*ΔT) + (β*ΔT2)] * (kx+c)
Where:
Rx : the value of the unknown (Artifact) resistance at Tx.
Rs : the value of the standard resistance at Te.
Rs0 : the value of the standard resistance at T0.
Kx : the Ratio displayed on the DCC-RES bridge
C : the correction of the Ratio Kx
α and β : Temperature coefficient of the standard resistance.
ΔT : (Te - T0)

Resistor Fluke 742A-1 :

Artifact serial number: 4935018

Date	Measured Temperature Tx	Measured Relative Humidity	Test current	Measurement result
11/03/2016	23,8°C	Between 30 and 50%	30 mA	1,000049 Ω
14/03/2016	23,9°C			1,000050 Ω
15/03/2016	23,9°C			1,000050 Ω
16/03/2016	24°C			1,000049 Ω
17/03/2016	24°C			1,000050 Ω
18/03/2016	24°C			1,000049 Ω
22/03/2016	23.8°C			1,000049 Ω

Detailed uncertainty budget
$Ue \quad (R_x) = k * U_c(R_x)$; k = 2
and $Uc \quad (R_x) = \sqrt{A^2 + B^2}$

Where:
Ue : the expanded uncertainty
Uc : the combined uncertainty
K : the coverage factor
A : uncertainty type A evaluation
Arep = $\frac{STD.DEV}{\sqrt{N}}$
Where:
Arep is the uncertainty of repeated measurement
N : number of repeated measurement

B : uncertainty type B evaluation

$$B = \sqrt{B_s^2 + B_r^2 + B_{ds}^2 + B_{dr}^2 + B_{dx}^2 + B_T^2 + B_{res}^2}$$

Where:

Bs is the uncertainty of the standard resistance LN4210 (1Ω)

$B_s = \frac{Ue}{2}$ in 1σ;

"Ue" is the expanded uncertainty of the standard Resistance

Br = is the uncertainty of the Ratio (1,0) of the bridge Guildline 9975

$B_r = \frac{Ue}{2}$; in 1σ

"Ue" is the expanded calibration uncertainty of the ratio (1,0)

Bds= is the uncertainty due to the drift of the standard resistance

$B_{ds} = \frac{drift of the standard resistance}{2\sqrt{3}}$ in 1σ;

Bdr = is the uncertainty of the bridge Guildline 9975 ratio (1,0)

$B_{dr} = \frac{drift of the ratio since its last calibration}{2\sqrt{3}}$; in 1σ

Bdx = is the short time drift of the unknown resistance (the artifact)

$B_{dx} = \frac{maximum drift between concecutif measurements of the artifact at 23°C}{2\sqrt{3}}$; in 1σ

BT = is the uncertainty of the temperature variation of the standard Resistance

$B_T = \alpha_e \times \Delta T + \beta_e \times \Delta T^2$;

ΔT is the difference of temperature between standard calibration and in process calibration (Te - T0)

Bres = is the uncertainty due to the resolution of the Bridge Guildline 9975

$B_{res} = \frac{measurement resolution}{2\sqrt{3}}$; in 1σ

Uncertainty budget

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution/ method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution $u(R_i)$ (Ω)
A_{rep}	$4,3.10^{-7}$	$1,6.10^{-7}$	A	1	$1,6.10^{-7}$
B_s	$1,5.10^{-6}$	$7,6.10^{-7}$	B	1	$7,6.10^{-7}$
B_r	$4,5.10^{-7}$	$2,3.10^{-7}$	B	1 Ω	$2,3.10^{-7}$
B_{ds}	$1,52.10^{-6}$	$4,38.10^{-7}$	B	1	$4,38.10^{-7}$
B_{dr}	$2,3.10^{-7}$	$6,6.10^{-8}$	B	1 Ω	$6,6.10^{-8}$
B_{dx}	$1,03.10^{-6}$	$3,0.10^{-7}$	B	1	$3,0.10^{-7}$
B_{res}	1.10^{-7}	$2,9.10^{-8}$	B	1	$2,9.10^{-8}$
B_T	$1,1.10^{-6}$	$1,1.10^{-6}$	B	1 Ω	$1,1.10^{-6}$
		Combined standard uncertainty			$1,5.10^{-6}$

[redacted]	Expanded uncertainty (95 % coverage factor)	3.10^{-6}

Summary of results
Mean temperature and uncertainty (23,9±0,3)°C
Mean relative humidity and uncertainty between 30 and 50%
Test current 30 mA
Mean date of measurement 16/03/2016
Mean resistance value and expanded uncertainty :1,000049 Ω ± 3.10-6 Ω

Resistor Fluke 742A-10:

Artifact serial number: 4920006

Date	Measured Temperature	Measured Relative Humidity	Test current	Measurement result
11/03/2016	23,8°C	Between 30 and 50%	10 mA	10,00050 Ω
14/03/2016	23,9°C	Between 30 and 50%	10 mA	10,00050 Ω
15/03/2016	23,9°C	Between 30 and 50%	10 mA	10,00049 Ω
16/03/2016	24,1°C	Between 30 and 50%	10 mA	10,00049 Ω
17/03/2016	23,9°C	Between 30 and 50%	10 mA	10,00049 Ω
18/03/2016	23,9°C	Between 30 and 50%	10 mA	10,00049 Ω
22/03/2016	23.9°C	Between 30 and 50%	10 mA	10,00048 Ω

Detailed uncertainty budget
$Ue\ \ (R_x) = k * U_c(R_x)$; k = 2
and $Uc\ \ (R_x) = \sqrt{A^2 + B^2}$

Where:
Ue : the expanded uncertainty
Uc : the combined uncertainty
K : the coverage factor
A : uncertainty type A evaluation

Arep = $\frac{STD.DEV}{\sqrt{N}}$
Where:
Arep is the uncertainty of repeated measurement
N : number of repeated measurement

B : uncertainty type B evaluation

$$B = \sqrt{B_s^2 + B_r^2 + B_{ds}^2 + B_{dr}^2 + B_{dx}^2 + B_T^2 + B_{res}^2}$$

Where:
Bs is the uncertainty of the standard resistance L&N 4030B - 100Ω
$B_s = \frac{Ue}{2}$ in 1σ;
"Ue" is the expanded uncertainty of the standard Resistance

Br = is the uncertainty of the Ratio (0,1) of the bridge Guildline 9975

$B_r = \frac{Ue}{2}$; in 1σ

"Ue" is the expanded calibration uncertainty of the ratio (0,1)

Bds= is the uncertainty due to the drift of the standard resistance

$B_{ds} = \frac{drift of the standard resistance}{2\sqrt{3}}$ in 1σ;

Bdr = is the uncertainty of the bridge Guildline 9975 ratio (0,1)

$B_{dr} = \frac{drift of the ratio since its last calibration}{2\sqrt{3}}$; in 1σ

Bdx = is the short time drift of the unknown resistance (the artifact)

$B_{dx} = \frac{maximum drift between concecutif measurements of the artifact at 23°C}{2\sqrt{3}}$; in 1σ

BT = is the uncertainty of the temperature variation of the standard Resistance

$B_T = \alpha_e \times \Delta T + \beta_e \times \Delta T^2$;

ΔT is the difference of temperature between standard calibration and in process calibration (Te - T0)

Bres = is the uncertainty due to the resolution of the Bridge Guildline 9975

$$B_{res} = \frac{measurement resolution}{2\sqrt{3}}$$

Uncertainty budget

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution/ method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution $u(R_i)(\Omega)$
A_{rep}	$8,1.10^{-6}$	$3,1.10^{-6}$	A	1	$3,1.10^{-6}$
B_s	$2,2.10^{-5}$	$1,1.10^{-5}$	B	1	$1,1.10^{-5}$
B_r	$9,3.10^{-7}$	$4,7.10^{-7}$	B	10 Ω	$4,7.10^{-6}$
B_{ds}	$1,6.10^{-4}$	$4,5.10^{-6}$	B	1	$4,5.10^{-6}$
B_{dr}	$1,1.10^{-7}$	$3,2.10^{-7}$	B	10 Ω	$3,2.10^{-6}$
B_{dx}	$1,7.10^{-5}$	$4,9.10^{-6}$	B	1	$4,9.10^{-6}$
B_{res}	1.10^{-5}	$2,9.10^{-6}$	B	1	$2,9.10^{-6}$
B_T	$1,2.10^{-6}$	$1,2.10^{-6}$	B	10 Ω	$1,2.10^{-5}$
		Combined standard uncertainty			$1,9.10^{-5}$
		Expanded uncertainty (95 % coverage factor)			$3,8.10^{-5}$

Summary of results

Mean temperature and uncertainty (23,9±0,3)°C

Mean relative humidity and uncertainty between 30 and 50%

Test current 10 mA

Mean date of measurement 16/03/2016

Mean resistance value and expanded uncertainty :10,00049 Ω ± 3,8.10-5Ω

Resistance Fluke 742A-100:

Artifact serial number: 5485007

Date	Measured Temperature	Measured Relative Humidity	Test current	Measurement result
11/03/2016	23,9°C	Between 30 and 50%	1 mA	100,0071 Ω
14/03/2016	24,0°C	Between 30 and 50%	1 mA	100,0071 Ω
15/03/2016	23,9°C	Between 30 and 50%	1 mA	100,0071 Ω
16/03/2016	24,0°C	Between 30 and 50%	1 mA	100,0071 Ω
17/03/2016	23,9°C	Between 30 and 50%	1 mA	100,0071 Ω
18/03/2016	24,0°C	Between 30 and 50%	1 mA	100,0069 Ω
22/03/2016	23.8°C	Between 30 and 50%	1 mA	100,0069 Ω

6. Detailed uncertainty budget

$Ue \quad (R_x) = k * U_c(R_x)$; k = 2

and $Uc \quad (R_x) = \sqrt{A^2 + B^2}$

Where:

Ue : the expanded uncertainty

Uc : the combined uncertainty

K : the coverage factor

A : uncertainty type A evaluation

Arep = $\frac{STD.DEV}{\sqrt{N}}$

Where:

Arep is the uncertainty of repeated measurement

N : number of repeated measurement

B : uncertainty type B evaluation

$$B = \sqrt{B_s^2 + B_r^2 + B_{ds}^2 + B_{dr}^2 + B_{dx}^2 + B_T^2 + B_{res}^2}$$

Where:

Bs is the uncertainty of the standard resistance L&N 4030B - 100Ω

$B_s = \frac{Ue}{2}$ in 1σ;

"Ue" is the expanded uncertainty of the standard Resistance

Br = is the uncertainty of the Ratio(1,0) of the bridge Guildline 9975

$B_r = \frac{Ue}{2}$; in 1σ

"Ue" is the expanded calibration uncertainty of the ratio (1,0)

Bds= is the uncertainty due to the drift of the standard resistance

$B_{ds} = \frac{drift of the standard resistance}{2\sqrt{3}}$ in 1σ;

Bdr = is the uncertainty of the bridge Guildline 9975 ratio (1,0)

$B_{dr} = \frac{drift of the ratio since its last calibration}{2\sqrt{3}}$; in 1σ

Bdx = is the short time drift of the unknown resistance (the artifact)

$B_{dx} = \frac{maximumdriftbetweenconcecutifmeasurementsoftheartifactat23°C}{2\sqrt{3}}$; in 1σ

BT = is the uncertainty of the temperature variation of the standard Resistance

$B_T = \alpha_e \times \Delta T + \beta_e \times \Delta T^2$;

ΔT is the difference of temperature between standard calibration and in process calibration (Te - T0)

Bres = is the uncertainty due to the resolution of the Bridge Guildline 9975

$$B_{res} = \frac{measurementresolution}{2\sqrt{3}}$$

Uncertainty budget

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution/ method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution $u(R_i)$(Ω)
A_{rep}	$9,4.10^{-5}$	$3,6.10^{-5}$	A	1	$3,6.10^{-5}$
B_s	$2,2.10^{-4}$	$1,1.10^{-4}$	B	1	$1,1.10^{-4}$
B_r	$4,5.10^{-7}$	$2,3.10^{-7}$	B	100 Ω	$2,3.10^{-5}$
B_{ds}	$1,6.10^{-4}$	$4,5.10^{-5}$	B	1	$4,5.10^{-5}$
B_{dr}	$2,3.10^{-7}$	$6,6.10^{-8}$	B	100 Ω	$6,6.10^{-6}$
B_{dx}	$1,9.10^{-4}$	$5,4.10^{-5}$	B	1	$5,4.10^{-5}$
B_{res}	1.10^{-5}	$2,9.10^{-6}$	B	1	$2,9.10^{-6}$
B_T	$1,2.10^{-6}$	$1,2.10^{-6}$	B	100 Ω	$1,2.10^{-4}$
		Combined standard uncertainty			$1,8.10^{-4}$
		Expanded uncertainty (95 % coverage factor)			$3,7.10^{-4}$

Summary of results

Mean temperature and uncertainty (23,9±0,3)°C

Mean relative humidity and uncertainty between 30 and 50%

Test current 1 mA

Mean date of measurement 16/03/2016

Mean resistance value and expanded uncertainty :100,0070 Ω ± 3,7.10-4Ω

Resistance Fluke 742A-1k:

Artifact serial number: 7733002

Date	Measured Temperature	Measured Relative Humidity	Test current	Measurement result
11/03/2016	23,9°C	Between 30 and 50%	1 mA	1,000005 kΩ
14/03/2016	24,2°C	Between 30 and 50%	1 mA	1,000004 kΩ
15/03/2016	23,8°C	Between 30 and 50%	1 mA	1,000004 kΩ
16/03/2016	23,8 °C	Between 30 and 50%	1 mA	1,000005 kΩ
17/03/2016	24,1°C	Between 30 and 50%	1 mA	1,000004 kΩ
18/03/2016	24,1°C	Between 30 and 50%	1 mA	1,000004 kΩ
22/03/2016	24.1°C	Between 30 and 50%	1 mA	1,000004 kΩ

Detailed uncertainty budget
$Ue \quad (R_x) = k * U_c(R_x)$; k = 2
and $Uc \quad (R_x) = \sqrt{A^2 + B^2}$

Where:
Ue : the expanded uncertainty
Uc : the combined uncertainty
K : the coverage factor
A : uncertainty type A evaluation
Arep = $\frac{STD.DEV}{\sqrt{N}}$
Where:
Arep is the uncertainty of repeated measurement
N : number of repeated measurement
B : uncertainty type B evaluation

$$B = \sqrt{B_s^2 + B_r^2 + B_{ds}^2 + B_{dr}^2 + B_{dx}^2 + B_T^2 + B_{res}^2}$$

Where:
Bs is the uncertainty of the standard resistance SR1010 – 10 kΩ S¥N:917006 (10 parallel steps)
$B_s = \frac{Ue}{2}$ in 1σ;
"Ue" is the expanded uncertainty of the standard Resistance
Br = is the uncertainty of the Ratio(1,0) of the bridge Guildline 9975
$B_r = \frac{Ue}{2}$; in 1σ
"Ue" is the expanded calibration uncertainty of the ratio (1,0)
Bds= is the uncertainty due to the drift of the standard resistance
$B_{ds} = \frac{drift of the standard resistance}{2\sqrt{3}}$ in 1σ;
Bdr = is the uncertainty of the bridge Guildline 9975 ratio (1,0)

$B_{dr} = \frac{drift of the ratio since its last calibration}{2\sqrt{3}}$; in 1σ

Bdx = is the short time drift of the unknown resistance (the artifact)

$B_{dx} = \frac{maximumdriftbetweenconcecutifmeasurementsoftheartifactat23°C}{2\sqrt{3}}$; in 1σ

BT = is the uncertainty of the temperature variation of the standard Resistance

$B_T = \alpha_e \times \Delta T + \beta_e \times \Delta T^2$;
ΔT is the difference of temperature between standard calibration and in process calibration (Te - T0)
Bres = is the uncertainty due to the resolution of the Bridge Guildline 9975

$$B_{res} = \frac{measurementresolution}{2\sqrt{3}}$$

Bsp = is the uncertainty of the serial parallel coupling between the steps of our transfert resistance SR1010 (1kΩ/step)
$B_{sp} = cst/\left(2 \times \sqrt{3}\right)$; cst = $(R \times 1.10^{-6} + 1\mu\Omega)$
The equation of "cst" is taked from the manufacturer data sheet of the transfert resistance.

Uncertainty budget

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution/ method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution $u(R_i)$(Ω)
A_{rep}	$1{,}6.10^{-7}$	$6{,}1.10^{-8}$	A	1	$6{,}1.10^{-8}$
B_s	$1{,}0.10^{-6}$	$5{,}0.10^{-7}$	B	1	$5{,}0.10^{-7}$
B_r	$4{,}5.10^{-7}$	$2{,}3.10^{-7}$	B	1 kΩ	$2{,}3.10^{-7}$
B_{ds}	$5{,}0.10^{-6}$	$1{,}4.10^{-6}$	B	1	$1{,}4.10^{-6}$
B_{dr}	$2{,}3.10^{-7}$	$6{,}6.10^{-8}$	B	1 kΩ	$6{,}6.10^{-8}$
B_{dx}	$2{,}6.10^{-7}$	$7{,}4.10^{-8}$	B	1	$7{,}4.10^{-8}$
B_{res}	2.10^{-4}	$5{,}8.10^{-8}$	B	1	$5{,}8.10^{-8}$
B_T	$-1{,}1.10^{-7}$	$-1{,}1.10^{-7}$	B	1 kΩ	$-1{,}1.10^{-7}$
B_{sp}	1.10^{-3}	$2{,}9.10^{-7}$	B	1	$2{,}9.10^{-7}$
		Combined standard uncertainty			$1{,}6.10^{-6}$
		Expanded uncertainty (95 % coverage factor)			$3{,}2.10^{-6}$

Summary of results
Mean temperature and uncertainty (24±0,3)°C
Mean relative humidity and uncertainty between 30 and 50%
Test current 1 mA
Mean date of measurement 16/03/2016
Mean resistance value and expanded uncertainty:1,000004 kΩ ± 3,2.10-6 kΩ

Resistance Fluke 742A-10k:

Artifact serial number: 5065038

Date	Measured Temperature	Measured Relative Humidity	Test current	Measurement result
11/03/2016	24,0°C	Between 30 and 50%	0.1 mA	10,000118 kΩ
14/03/2016	23,8°C	Between 30 and 50%	0.1 mA	10,000119 kΩ
15/03/2016	24,1°C	Between 30 and 50%	0.1 mA	10,000119 kΩ
16/03/2016	24,0 °C	Between 30 and 50%	0.1 mA	10,000119 kΩ
17/03/2016	24,1°C	Between 30 and 50%	0.1 mA	10,000115 kΩ
18/03/2016	23,9°C	Between 30 and 50%	0.1 mA	10,000119 kΩ
22/03/2016	23.9°C	Between 30 and 50%	0.1 mA	10,000117 kΩ

Detailed uncertainty budget

$Ue \quad (R_x) = k * U_c(R_x)$; k = 2

and $Uc \quad (R_x) = \sqrt{A^2 + B^2}$

Where:

Ue : the expanded uncertainty

Uc : the combined uncertainty

K : the coverage factor

A : uncertainty type A evaluation

Arep = $\frac{STD.DEV}{\sqrt{N}}$

Where:

Arep is the uncertainty of repeated measurement

N : number of repeated measurement

B : uncertainty type B evaluation

$$B = \sqrt{B_s^2 + B_r^2 + B_{ds}^2 + B_{dr}^2 + B_{dx}^2 + B_T^2 + B_{res}^2}$$

Where:

Bs is the uncertainty of the standard resistance SR104 – 10 kΩ

$B_s = \frac{Ue}{2}$ in 1σ;

"Ue" is the expanded uncertainty of the standard Resistance

Br = is the uncertainty of the Ratio(1,0) of the bridge Guildline 9975

$B_r = \frac{Ue}{2}$; in 1σ

"Ue" is the expanded calibration uncertainty of the ratio (1,0)

Bds= is the uncertainty due to the drift of the standard resistance

$B_{ds} = \frac{drift of the standard resistance}{2\sqrt{3}}$ in 1σ;

Bdr = is the uncertainty of the bridge Guildline 9975 ratio (1,0)

$B_{dr} = \frac{drift of the ratio since its last calibration}{2\sqrt{3}}$; in 1σ

Bdx = is the short time drift of the unknown resistance (the artifact)

$$B_{dx} = \frac{maximumdriftbetweenconcecutifmeasurementsoftheartifactat23°C}{2\sqrt{3}}$$; in 1σ

BT = is the uncertainty of the temperature variation of the standard Resistance

$B_T = \alpha_e \times \Delta T + \beta_e \times \Delta T^2$;

ΔT is the difference of temperature between standard calibration and in process calibration (Te - T0)

Bres = is the uncertainty due to the resolution of the Bridge Guildline 9975

$$B_{res} = \frac{measurementresolution}{2\sqrt{3}}$$

Uncertainty budget

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution/ method of evaluation (A, B)	Sensitivity coefficient c_i	Uncertainty contribution $u(R_i)$(Ω)
A_{rep}	$1,6.10^{-6}$	$6,1.10^{-7}$	A	1	$6,1.10^{-7}$
B_s	$4,0.10^{-6}$	$2,0.10^{-6}$	B	1	$2,0.10^{-6}$
B_r	$4,5.10^{-7}$	$2,3.10^{-7}$	B	10 kΩ	$2,3.10^{-6}$
B_{ds}	$6,8.10^{-6}$	$2,0.10^{-6}$	B	1	$2,0.10^{-6}$
B_{dr}	$2,3.10^{-7}$	$6,6.10^{-8}$	B	10 kΩ	$6,6.10^{-7}$
B_{dx}	$4,1.10^{-6}$	$1,2.10^{-6}$	B	1	$1,2.10^{-6}$
B_{res}	2.10^{-6}	$5,8.10^{-6}$	B	1	$5,8.10^{-6}$
B_T	$9,6.10^{-9}$	$9,6.10^{-9}$	B	10 kΩ	$9,6.10^{-8}$
		Combined standard uncertainty			$7,0.10^{-6}$
		Expanded uncertainty (95 % coverage factor)			$1,4.10^{-5}$

Summary of results

Summary of results

Mean temperature and uncertainty (24±0,3)°C

Mean relative humidity and uncertainty between 30 and 50%

Test current 0,1 mA

Mean date of measurement 16/03/2016

Mean resistance value and expanded uncertainty:10,00012 kΩ ± 1,4.10-5 kΩ

Approved

Lt-Col Abdelkarim Mallat

March 2016

11 Appendix E: KEBS Results

Measurement Results

Date	Nominal Value (R)	Reference standard (R_{iS})	UUT, Fluke 742A (R_{iX})
4th July 2016	10 kΩ	10.0001935	10.0002116
		10.0002211	10.0001554
		10.0002110	10.0002132
		10.0002233	10.0002270
		10.0002128	10.0002160
		10.0002258	10.0002292
		10.0002125	10.0002142
		10.0002263	10.0002320
		10.0002118	10.0001962
		10.0002165	10.0002172
Mean Reading		10.0002155 kΩ	10.0002112 kΩ
6th July 2016	1 kΩ	1.0000364	1.0000236
		1.0000376	1.0000246
		1.0000376	1.0000238
		1.0000381	1.0000250
		1.0000380	1.0000246
		1.0000386	1.0000254
		1.0000410	1.0000290
		1.0000412	1.0000286
		1.0000412	1.0000286
		1.0000410	1.0000288
Mean Reading		1.0000391 kΩ	1.0000212 kΩ
7th July 2016	100 Ω	99.9997	100.0048
		99.9978	100.0028
		99.9994	100.0044
		99.9978	100.0032
		99.9992	100.0048
		99.9974	100.0028
		99.9997	100.0046
		99.9980	100.0030
		99.9998	100.0050
		99.9980	100.0036
Mean Reading		99.9987 Ω	100.0039 Ω
11th July 2016	10 Ω	9.9962	9.9965
		9.9976	9.9983
		9.9961	9.9966
		9.9979	9.9984
		9.9962	9.9966
		9.9980	9.9984
		9.9960	9.9965
		9.9980	9.9983
		9.9960	9.9966

		9.9980	9.9984
Mean reading		9.9970 Ω	9.9975 Ω
12th July 2016	1 Ω	0.99996	1.00001
		0.99994	1.00000
		0.99995	1.00002
		0.99996	1.00000
		0.99996	1.00001
		0.99995	1.00000
		0.99994	1.00001
		0.99995	1.00000
		0.99996	1.00002
		0.99995	1.00001
Mean Reading		0.99996 Ω	1.00001 Ω

The standard uncertainty associated with each measurement is given by the following steps:

Standard deviation, $S(R_i)=\sqrt{\frac{1}{n}\sum_{i=1}^{i=10}\left(R_i-\bar{R}\right)^2}$ --- (iv)

Experimental standard deviation of the mean, ESDM, standard uncertainty), $S\left(\bar{R}\right)=\frac{1}{\sqrt{n}}S(R_i)$ --(v)

10 kΩ (Using SR1010 transfer standard in parallel configuration- 1 kΩ/step)

$R_S = 10.000121$ kΩ (certified value from UME-Turkey) $\Rightarrow \Delta R_S = +0{,}000121$kΩ

$\Delta R_{742A} = \bar{R}_{iX} - \bar{R}_{iS} + \Delta R_S$ = $(10.000212 - 10.0002155) + 0.000121$ = 0.0001175 kΩ

$\therefore R_{742A} = (10.000000 + 0.0001175) = 10.0001175$kΩ

From equation (v),

$S\left(10\bar{k}\Omega\right) = 0.000007$ kΩ

Relative standard uncertainty, u_1 = $0.7 \bullet 10^{-6}$ = 0.7 μΩ/Ω.

Drift of the standard, u_2 = $(10.000121 - 10.000116)$ kΩ = 0.000005 kΩ = 0.5 μΩ/Ω

Standard uncertainty from calibration certificate, u_3 = $\frac{0.5}{2}$ μΩ/Ω = 0.3 μΩ/Ω

Temperature coefficient = 3 ppm/0C = 3 μΩ $\Omega^{-1}\,{}^0C^{-1}$

Uncertainty due to temperature (1^0C), u_4 = $\frac{3}{\sqrt{3}} = 1.8$ μΩ $\Omega^{-1}\,{}^0C^{-1}$

Combined standard uncertainty, u = $\sqrt{\left(u_1^2+u_2^2+u_3^2+u_4^2\right)^2}$

$$= \sqrt{\left(0.7^2+0.5^2+0.3^2+1.8^2\right)}\ \mu\Omega/\Omega$$

$$= 2,1\ \mu\Omega/\Omega$$

Expanded uncertainty (k =2), U = 4,2 μΩ/Ω

1 kΩ (Using SR1010 transfer standard in series/parallel configuration- 1 kΩ/step)

SR1010 (1 kΩ/step) for 10 kΩ =10.0002042 kΩ → 1 kΩ =1.00002042 kΩ, hence ΔR_S =+0.00002042 kΩ

$$\Delta R_{742A} = \bar{R}_{iX} - \bar{R}_{iS} + \Delta R_S = (1.0000212 - 1.0000391) + 0.00002042 = 0.00000252 \text{ k}\Omega$$

$$\therefore R_{742A} = (1.000000 + 0.00000252) = 1.00000252 \text{k}\Omega$$

From equation (v),

$$S\left(\overline{1k\Omega}\right) = 0.0000007 \text{ k}\Omega$$

Relative standard uncertainty, u_1 = $0.7 \bullet 10^{-6}$ = 0.7 μΩ/Ω.

Drift of the standard, u_2 = 0.5 μΩ/Ω

Transfer accuracy (1 ppm), u_3 = $\frac{1}{\sqrt{3}}$ μΩ/Ω = 0.6 μΩ/Ω

Temperature coefficient = 5 ppm/0C = 5 μΩ $\Omega^{-1}\,{}^0C^{-1}$

Uncertainty due to temperature (1^0C), u_4 = $\frac{5}{\sqrt{3}} = 2.9$ μΩ $\Omega^{-1}\,{}^0C^{-1}$

Combined standard uncertainty, u = $\sqrt{\left(u_1^2+u_2^2+u_3^2+u_4^2\right)^2}$

$$= \sqrt{\left(0.7^2+0.5^2+0.6^2+2.9^2\right)}\ \mu\Omega/\Omega$$

$$= 3,1\ \mu\Omega/\Omega$$

Expanded uncertainty (k =2), U = 6,2 μΩ/Ω

100 Ω (Using SR1010 transfer standard in parallel configuration- 1 kΩ/step)

SR1010 (1 kΩ/step) for 1 kΩ =1.00002042 kΩ → 100 Ω =100.002042 Ω, hence ΔR_S =+0.002042 Ω

$\Delta R_S = 0.002042$ Ω

$\Delta R_{742A} = \bar{R}_{iX} - \bar{R}_{iS} + \Delta R_S = (100.0039 - 99.9987) + 0.002042 = 0.0072$ Ω

$\therefore R_{742A} = (100.0000 + 0.0072) = 100.0072\,\Omega$

From equation (v),

$S\left(\overline{100}\Omega\right) = 0.0002864\,\Omega$

Relative standard uncertainty, $u_1 = 2.9 \bullet 10^{-6} = 2.9$ µΩ/Ω.

Drift of the standard, $u_2 = 0.5$ µΩ/Ω

Transfer accuracy (1 ppm), $u_3 = \frac{1}{\sqrt{3}}$ µΩ/Ω = 0.6 µΩ/Ω

Temperature coefficient = 5 ppm/0C = 5 µΩ $\Omega^{-1}\,{}^0C^{-1}$

Uncertainty due to temperature (1^0C), $u_4 = \frac{5}{\sqrt{3}} = 2.9$ µΩ $\Omega^{-1}\,{}^0C^{-1}$

Combined standard uncertainty, u = $\sqrt{\left(u_1^2 + u_2^2 + u_3^2 + u_4^2\right)^2}$

$= \sqrt{\left(2.9^2 + 0.5^2 + 0.6^2 + 2.9^2\right)}$ µΩ/Ω

= 4,2 µΩ/Ω

Expanded uncertainty (k =2), U = 8,4 µΩ/Ω

10 Ω (SR1010 transfer standard 10 Ω/step calibrated against 1 kΩ/step-parallel configuration)

SR1010 (10 Ω/step) for 100 Ω value = 99.9988 Ω → ΔR_S = −0.0012 Ω

Hence for 10 Ω, ΔR_S = −0.00012 Ω

$\Delta R_{742A} = \bar{R}_{iX} - \bar{R}_{iS} + \Delta R_S = (9.9975 - 9.9970) + (-0.00012) = -0.00004$ Ω

$\therefore R_{742A} = (10.0000 - 0.00004) = 9.99996\,\Omega$

From equation (v),

$$S\left(\bar{10\Omega}\right) = 0.00003004\,\Omega$$

Relative standard uncertainty, u_1 = $3.0 \bullet 10^{-6}$ = 3.0 μΩ/Ω.

Drift of the standard, u_2 = 0.5 μΩ/Ω

Transfer accuracy (1 ppm), u_3 = $\frac{1}{\sqrt{3}}$ μΩ/Ω = 0.6 μΩ/Ω

Temperature coefficient = 5 ppm/0C = 5 μΩ $\Omega^{-1}\,{}^{0}C^{-1}$

Uncertainty due to temperature (1^0C), u_4 = $\frac{5}{\sqrt{3}} = 2.9$ μΩ $\Omega^{-1}\,{}^{0}C^{-1}$

Combined standard uncertainty, u = $\sqrt{\left(u_1^2 + u_2^2 + u_3^2 + u_4^2\right)^2}$

= $\sqrt{\left(3.0^2 + 0.5^2 + 0.6^2 + 2.9^2\right)}$ μΩ/Ω

= 4,2 μΩ/Ω

Expanded uncertainty (k =2), U = 8,4 μΩ/Ω

1 Ω (SR1010 transfer standard 10 Ω/step calibrated against 1 kΩ/step-parallel configuration)

$R_S = 0.9999883$ Ω (certified value from UME-Turkey) $\Rightarrow \Delta R_S = -0{,}00000117\,\Omega$

$\Delta R_{742A} = \bar{R}_{iX} - \bar{R}_{iS} + \Delta R_S$ = $(1.00001 - 0{,}99996) + (-0.00000117)$ = 0.000003883 Ω

$\therefore R_{742A} = (1.000000 + 0.000004883) = 1.00003883\,\Omega$

From equation (v),

$$S\left(\bar{1\Omega}\right) = 0.0000025\,\Omega$$

Relative standard uncertainty, u_1 = $2.5 \bullet 10^{-6}$ = 2.5 μΩ/Ω.

Drift of the standard, u_2 = $0.9999883 - 0.9999880$ Ω = 0.0000003 Ω = 0.3 μΩ/Ω

Standard uncertainty from calibration certificate, u_3 = $\frac{0.3}{2}$ μΩ/Ω = 0.2 μΩ/Ω

Temperature coefficient = 1 ppm/0C = 3 μΩ Ω-1 0C-1

Uncertainty due to temperature (1^0C), u_4 = $\frac{1}{\sqrt{3}} = 0.6$ μΩ $Ω^{-1}$ $^0C^{-1}$

Combined standard uncertainty, u = $\sqrt{\left(u_1^2 + u_2^2 + u_3^2 + u_4^2\right)^2}$

$= \sqrt{\left(2.5^2 + 0.3^2 + 0.2^2 + 0.6^2\right)}$ μΩ/Ω

= 2,6 μΩ/Ω

Expanded uncertainty (k =2), U = 5,2 μΩ/Ω

Summary of the Measurement Results

Nominal Value	Measured Value	Expanded Relative Uncertainty, U (k = 2)
1 Ω	1,000038 Ω	$5{,}2 \cdot 10^{-6}$
10 Ω	9,999960 Ω	$8{,}4 \cdot 10^{-6}$
100Ω	100,00724 Ω	$8{,}4 \cdot 10^{-6}$
1 kΩ	1,000026 kΩ	$6{,}2 \cdot 10^{-6}$
10 kΩ	10,000118 kΩ	$4{,}2 \cdot 10^{-6}$

12 Appendix F: NIS results

Measurement Report

1. Detailed Measurement Results of the 1 Ω Standard:

Table 1 shows the measurement results of the 1 Ω standard

Date	Measured Atmospheric Pressure (hpa)	Measured Temperature (°C)	Measured Relative Humidity (%)	Test Current (mA)	Measurement Result (Ω)
11/06/2017	1007.12	23.1	48.2	50	1.000049994
12/06/2017	1010.08	22.9	46.8	50	1.000050007
13/06/2017	1008.37	22.4	48.0	50	1.000049978
14/06/2017	1007.23	22.4	53.4	50	1.000049922
15/06/2017	1008.46	23.2	50.9	50	1.000049978
18/06/2017	1006.23	23.0	46.2	50	1.000049936
19/06/2017	1006.44	23.0	48.0	50	1.000049925
20/06/2017	1010.02	23.7	42.5	50	1.000050010
21/06/2017	1009.39	23.2	49.8	50	1.000049910
22/06/2017	1011.26	23.4	48.4	50	1.000049882

Detailed Uncertainty Budget of the 1 Ω Standard:

The uncertainty sources are listed in Table 2

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution /method of evaluation (A, B)	Sensitivity Coefficient c_i	Uncertainty Contribution $u(R_i)$	Degree of Freedom ν_i
Repeatability	1.0×10^{-8} Ω	1.0×10^{-8} Ω	Normal/A	1	1.0×10^{-8} Ω	24
Calibration of R_s	3.4×10^{-8} Ω	1.7×10^{-8} Ω	Normal/B	1	1.7×10^{-8} Ω	∞
Drift of R_s	6.2×10^{-10} Ω	3.6×10^{-10} Ω	Rectangular/B	1	3.6×10^{-10} Ω	∞
Expected Value Error	2.6×10^{-8} Ω	1.5×10^{-8} Ω	Rectangular/B	1	1.5×10^{-8} Ω	∞
Temp. Coefficient of R_s	4.7×10^{-7} Ω	2.7×10^{-7} Ω	Rectangular/B	1	2.7×10^{-7} Ω	∞
Power Coefficient of R_s	5.0×10^{-8} Ω	2.9×10^{-8} Ω	Rectangular/B	1	2.9×10^{-8} Ω	∞
Pressure Coefficient of R_s	13.7×10^{-9} Ω	7.9×10^{-9} Ω	Rectangular/B	1	7.9×10^{-9} Ω	∞
Bridge Calibration	5.0×10^{-8} Ω	2.5×10^{-8} Ω	Normal/B	1	2.5×10^{-8} Ω	∞
Bridge Resolution	5.0×10^{-10} Ω	2.9×10^{-10} Ω	Rectangular/B	1	2.9×10^{-10} Ω	∞
Bridge offset	15.9×10^{-9} Ω	9.2×10^{-9} Ω	Rectangular/B	1	9.2×10^{-9} Ω	∞
Stability of R_x During The Period of Measurement	8.3×10^{-8} Ω	4.8×10^{-8} Ω	Rectangular/B	1	4.8×10^{-8} Ω	∞
Temp. Coefficient of R_x	8.0×10^{-8} Ω	4.6×10^{-8} Ω	Rectangular/B	1	4.6×10^{-8} Ω	∞
		Combined standard uncertainty:			2.8×10^{-7} Ω	
		Effective degrees of freedom:			∞	
		Expanded uncertainty (95% coverage factor):			5.6×10^{-7} Ω = 0.56 μΩ/Ω	

2. Detailed Measurement Results of the 10 Ω Standard:

Table 3 shows the measurement results of the 10 Ω standard

Date	Measured Atmospheric Pressure (hpa)	Measured Temperature (°C)	Measured Relative Humidity (%)	Test Current (mA)	Measurement Result (Ω)
11/06/2017	1007.12	23.1	48.2	5	10.00050553
12/06/2017	1010.08	22.9	46.8	5	10.00050448
13/06/2017	1008.37	22.4	48.0	5	10.00050496
14/06/2017	1007.23	22.4	53.4	5	10.00050507
15/06/2017	1008.46	23.2	50.9	5	10.00050409
18/06/2017	1006.23	23.0	46.2	5	10.00050485
19/06/2017	1006.44	23.0	48.0	5	10.00050374
20/06/2017	1010.02	23.7	42.5	5	10.00050414
21/06/2017	1009.39	23.2	49.8	5	10.00050325
22/06/2017	1011.26	23.4	48.4	5	10.00050324

Detailed Uncertainty Budget of the 10 Ω Standard:

The uncertainty sources are listed in Table 4

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution /method of evaluation (A, B)	Sensitivity Coefficient c_i	Uncertainty Contribution $u(R_i)$	Degree of Freedom ν_i
Repeatability	$1.1 \times 10^{-7}\ \Omega$	$1.1 \times 10^{-7}\ \Omega$	Normal/A	1	$1.1 \times 10^{-7}\ \Omega$	24
Calibration of R_s	$3.4 \times 10^{-8}\ \Omega$	$1.7 \times 10^{-8}\ \Omega$	Normal/B	1	$1.7 \times 10^{-8}\ \Omega$	∞
Drift of R_s	$6.2 \times 10^{-10}\ \Omega$	$3.6 \times 10^{-10}\ \Omega$	Rectangular/B	1	$3.6 \times 10^{-10}\ \Omega$	∞
Expected Value Error	$2.6 \times 10^{-8}\ \Omega$	$1.5 \times 10^{-8}\ \Omega$	Rectangular/B	1	$1.5 \times 10^{-8}\ \Omega$	∞
Temp. Coefficient of R_s	$4.7 \times 10^{-7}\ \Omega$	$2.7 \times 10^{-7}\ \Omega$	Rectangular/B	1	$2.7 \times 10^{-7}\ \Omega$	∞
Power Coefficient of R_s	$5.0 \times 10^{-8}\ \Omega$	$2.9 \times 10^{-8}\ \Omega$	Rectangular/B	1	$2.9 \times 10^{-8}\ \Omega$	∞
Pressure Coefficient of R_s	$13.7 \times 10^{-9}\ \Omega$	$7.9 \times 10^{-9}\ \Omega$	Rectangular/B	1	$7.9 \times 10^{-9}\ \Omega$	∞
Bridge Calibration	$4.0 \times 10^{-7}\ \Omega$	$2.0 \times 10^{-7}\ \Omega$	Normal/B	1	$2.0 \times 10^{-7}\ \Omega$	∞
Bridge Resolution	$5.0 \times 10^{-9}\ \Omega$	$2.9 \times 10^{-9}\ \Omega$	Rectangular/B	1	$2.9 \times 10^{-9}\ \Omega$	∞
Bridge offset	$10.0 \times 10^{-9}\ \Omega$	$5.8 \times 10^{-9}\ \Omega$	Rectangular/B	1	$5.8 \times 10^{-9}\ \Omega$	∞
Stability of R_x During The Period of Measurement	$24.0 \times 10^{-7}\ \Omega$	$14 \times 10^{-7}\ \Omega$	Rectangular/B	1	$14 \times 10^{-7}\ \Omega$	∞
Temp. Coefficient of R_x	$2.1 \times 10^{-7}\ \Omega$	$1.2 \times 10^{-7}\ \Omega$	Rectangular/B	1	$1.2 \times 10^{-7}\ \Omega$	∞
		Combined standard uncertainty:			$1.43 \times 10^{-4}\ \Omega$	
		Effective degrees of freedom:			∞	
		Expanded uncertainty (95% coverage factor):			$2.9 \times 10^{-6}\ \Omega = 0.29\ \mu\Omega/\Omega$	

3. Detailed Measurement Results of the 100 Ω Standard:

Table 5 shows the measurement results of the 100 Ω standard

Date	Measured Atmospheric Pressure (hpa)	Measured Temperature (°C)	Measured Relative Humidity (%)	Test Current (mA)	Measurement Result (Ω)
11/06/2017	1007.12	23.1	48.2	0.5	100.0073688
12/06/2017	1010.08	22.9	46.8	0.5	100.0073752
13/06/2017	1008.37	22.4	48.0	0.5	100.0073712
14/06/2017	1007.23	22.4	53.4	0.5	100.0073720
15/06/2017	1008.46	23.2	50.9	0.5	100.0073632
18/06/2017	1006.23	23.0	46.2	0.5	100.0073666
19/06/2017	1006.44	23.0	48.0	0.5	100.0073691
20/06/2017	1010.02	23.7	42.5	0.5	100.0073748
21/06/2017	1009.39	23.2	49.8	0.5	100.0073728
22/06/2017	1011.26	23.4	48.4	0.5	100.0073732

Detailed Uncertainty Budget of the 100 Ω Standard:

The uncertainty sources are listed in Table 6

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution /method of evaluation (A, B)	Sensitivity Coefficient c_i	Uncertainty Contribution $u(R_i)$	Degree of Freedom ν_i
Repeatability	1.1×10^{-6} Ω	1.1×10^{-6} Ω	Normal/A	1	1.1×10^{-6} Ω	24
Calibration of R_s	3.6×10^{-6} Ω	1.8×10^{-6} Ω	Normal/B	1	1.8×10^{-6} Ω	∞
Drift of R_s	2.9×10^{-5} Ω	1.7×10^{-5} Ω	Rectangular/B	1	1.7×10^{-5} Ω	∞
Temp. Coefficient of R_s	14.0×10^{-8} Ω	8.1×10^{-8} Ω	Rectangular/B	1	8.1×10^{-8} Ω	∞
Power Coefficient of R_s	2.4×10^{-9} Ω	1.4×10^{-9} Ω	Rectangular/B	1	1.4×10^{-9} Ω	∞
Pressure Coefficient of R_s	1.9×10^{-7} Ω	1.1×10^{-7} Ω	Rectangular/B	1	1.1×10^{-7} Ω	∞
Bridge Calibration	5.0×10^{-6} Ω	2.5×10^{-6} Ω	Normal/B	1	2.5×10^{-6} Ω	∞
Bridge Resolution	5.0×10^{-8} Ω	2.9×10^{-8} Ω	Rectangular/B	1	2.9×10^{-8} Ω	∞
Bridge offset	2.3×10^{-6} Ω	1.3×10^{-6} Ω	Rectangular/B	1	1.3×10^{-6} Ω	∞
Stability of R_x During The Period of Measurement	2.4×10^{-6} Ω	1.4×10^{-6} Ω	Rectangular/B	1	1.4×10^{-6} Ω	∞
Temp. Coefficient of R_x	9.0×10^{-7} Ω	5.2×10^{-7} Ω	Rectangular/B	1	5.2×10^{-7} Ω	∞
		Combined standard uncertainty:			1.7×10^{-5} Ω	
		Effective degrees of freedom:			∞	
		Expanded uncertainty (95% coverage factor):			3.5×10^{-5} Ω = 0.35 μΩ/Ω	

4. Detailed Measurement Results of the 1 kΩ Standard:

Table 7 shows the measurement results of the 1 kΩ standard

Date	Measured Atmospheric Pressure (hpa)	Measured Temperature (°C)	Measured Relative Humidity (%)	Test Current (mA)	Measurement Result (Ω)
11/06/2017	1007.12	23.1	48.2	1	1000.006793
12/06/2017	1010.08	22.9	46.8	1	1000.006795
13/06/2017	1008.37	22.4	48.0	1	1000.006787
14/06/2017	1007.23	22.4	53.4	1	1000.006581
15/06/2017	1008.46	23.2	50.9	1	1000.006616
18/06/2017	1006.23	23.0	46.2	1	1000.006769
19/06/2017	1006.44	23.0	48.0	1	1000.006561
20/06/2017	1010.02	23.7	42.5	1	1000.006691
21/06/2017	1009.39	23.2	49.8	1	1000.006624
22/06/2017	1011.26	23.4	48.4	1	1000.006717

Detailed Uncertainty Budget of the 1 kΩ Standard:

The uncertainty sources are listed in Table 8

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution /method of evaluation (A, B)	Sensitivity Coefficient c_i	Uncertainty Contribution $u(R_i)$	Degree of Freedom ν_i
Repeatability	2.0×10^{-5} Ω	2.0×10^{-5} Ω	Normal/A	1	2.0×10^{-5} Ω	24
Calibration of R_s	3.4×10^{-4} Ω	1.7×10^{-4} Ω	Normal/B	1	1.7×10^{-4} Ω	∞
Drift of R_s	3.5×10^{-4} Ω	2.0×10^{-4} Ω	Rectangular/B	1	2.0×10^{-4} Ω	∞
Expected Value Error	4.0×10^{-4} Ω	2.3×10^{-4} Ω	Rectangular/B	1	2.3×10^{-4} Ω	∞
Temp. Coefficient of R_s	5.0×10^{-5} Ω	2.9×10^{-5} Ω	Rectangular/B	1	2.9×10^{-5} Ω	∞
Power Coefficient of R_s	10.0×10^{-7} Ω	5.8×10^{-7} Ω	Rectangular/B	1	5.8×10^{-7} Ω	∞
Pressure Coefficient of R_s	15.4×10^{-6} Ω	8.9×10^{-6} Ω	Rectangular/B	1	8.9×10^{-6} Ω	∞
Bridge Calibration	3.5×10^{-5} Ω	2.0×10^{-5} Ω	Normal/B	1	2.0×10^{-5} Ω	∞
Bridge Resolution	5.0×10^{-7} Ω	2.9×10^{-7} Ω	Rectangular/B	1	2.9×10^{-7} Ω	∞
Bridge offset	12.0×10^{-6} Ω	6.9×10^{-6} Ω	Rectangular/B	1	6.9×10^{-6} Ω	∞
Stability of R_x During The Period of Measurement	10.7×10^{-5} Ω	6.2×10^{-5} Ω	Rectangular/B	1	6.2×10^{-5} Ω	∞
Temp. Coefficient of R_x	5.0×10^{-5} Ω	2.9×10^{-5} Ω	Rectangular/B	1	2.9×10^{-5} Ω	∞
		Combined standard uncertainty:			3.6×10^{-4} Ω	
		Effective degrees of freedom:			∞	
		Expanded uncertainty (95% coverage factor):			7.2×10^{-4} Ω = 0.72 μΩ/Ω	

5. Detailed Measurement Results of the 10 kΩ Standard:

Table 9 shows the measurement results of the 10 kΩ standard

Date	Measured Atmospheric Pressure (hpa)	Measured Temperature (°C)	Measured Relative Humidity (%)	Test Current (μA)	Measurement Result (Ω)
11/06/2017	1007.12	23.1	48.2	100	10000.13828
12/06/2017	1010.08	22.9	46.8	100	10000.13745
13/06/2017	1008.37	22.4	48.0	100	10000.13849
14/06/2017	1007.23	22.4	53.4	100	10000.13837
15/06/2017	1008.46	23.2	50.9	100	10000.13892
18/06/2017	1006.23	23.0	46.2	100	10000.13708
19/06/2017	1006.44	23.0	48.0	100	10000.13878
20/06/2017	1010.02	23.7	42.5	100	10000.13688
21/06/2017	1009.39	23.2	49.8	100	10000.13731
22/06/2017	1011.26	23.4	48.4	100	10000.13662

Detailed Uncertainty Budget of the 10 kΩ Standard:

The uncertainty sources are listed in Table 10

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution /method of evaluation (A, B)	Sensitivity Coefficient c_i	Uncertainty Contribution $u(R_i)$	Degree of Freedom ν_i
Repeatability	3.0×10^{-4} Ω	3.0×10^{-4} Ω	Normal/A	1	3.0×10^{-4} Ω	24
Calibration of R_s	3.4×10^{-4} Ω	1.7×10^{-4} Ω	Normal/B	1	1.7×10^{-4} Ω	∞
Drift of R_s	3.5×10^{-4} Ω	2.0×10^{-4} Ω	Rectangular/B	1	2.0×10^{-4} Ω	∞
Expected Value Error	4.0×10^{-4} Ω	2.3×10^{-4} Ω	Rectangular/B	1	2.3×10^{-4} Ω	∞
Temp. Coefficient of R_s	5.0×10^{-5} Ω	2.9×10^{-5} Ω	Rectangular/B	1	2.9×10^{-5} Ω	∞
Power Coefficient of R_s	10.0×10^{-7} Ω	5.8×10^{-7} Ω	Rectangular/B	1	5.8×10^{-7} Ω	∞
Pressure Coefficient of R_s	15.4×10^{-6} Ω	8.9×10^{-6} Ω	Rectangular/B	1	8.9×10^{-6} Ω	∞
Bridge Calibration	2.0×10^{-3} Ω	1.0×10^{-3} Ω	Normal/B	1	1.0×10^{-3} Ω	∞
Bridge Resolution	5.0×10^{-6} Ω	2.9×10^{-6} Ω	Rectangular/B	1	2.9×10^{-6} Ω	∞
Bridge offset	1.9×10^{-4} Ω	1.1×10^{-4} Ω	Rectangular/B	1	1.1×10^{-4} Ω	∞
Stability of R_x During The Period of Measurement	12×10^{-4} Ω	$6{,}9 \times 10^{-4}$ Ω	Rectangular/B	1	6.9×10^{-4} Ω	∞
Temp. Coefficient of R_x	4.0×10^{-4} Ω	2.3×10^{-4} Ω	Rectangular/B	1	2.3×10^{-4} Ω	∞
		Combined standard uncertainty:			1.3×10^{-3} Ω	
		Effective degrees of freedom:			∞	
		Expanded uncertainty (95% coverage factor):			2.7×10^{-3} Ω = 0.27 μΩ/Ω	

Summary of Results:
Mean Date of Measurement: 18th of June, 2017
Mean Resistance Value and Expanded Uncertainty at the mean date:

Nominal Resistance Value	Mean Resistance Value	Expanded Uncertainty, ±
1 Ω	1.000049936 Ω	0.56 μΩ/Ω
10 Ω	10.00050485 Ω	0.29 μΩ/Ω
100 Ω	100.0073666 Ω	0.35 μΩ/Ω
1 kΩ	1000.006769 Ω	0.72 μΩ/Ω
10 kΩ	10000.13708 Ω	0.27 μΩ/Ω

13 Appendix G: UNBS results

1. Nominal Resistance : 1Ω
   Serial number : 4935018
   Model : 742A-1

Date	*Measured Atmospheric Pressure*	*Measured Temperature*	*Measured Relative Humidity*	*Test current*	*Measurement result*	
	(mbar)	*(^{0}C)*	*(%)*	*(mA)*	*Certificate value (Ω)*	*Mean UUT reading (Ω)*
2018-01-16	881.5	23.2	58.5	100	0.999999	0.999996

UNCERTAINTY COMPUTATION							
Sources of uncertainty	Value (Ω)	Diviser	Probability distribution	Sensitivity Coeff	Uncertainty Contribution	Reliability percentage	Degree of freedom
uncertainty of the Standard	5.00E-05	2	Normal(K=2)	1	2.50000E-05	95	200
standard uncertainty of the mean	2.17E-06	1	Normal(K=1)	1	2.17096E-06	10	9
Resolution of UUT	5.00E-07	√3	Rectangular	1	2.88675E-07	95	200
uncertainty due Stability	1.00E-06	√3	Rectangular	1	5.77350E-07	95	200
Combined Uncertainty					2.51024E-05		203.0399
Expanded Uncertainty(2*U, k=2)					5.021E-05		2

2. Nominal Resistance : 10Ω
   Serial number : 4920006
   Model : 742A-10

Date	*Measured Atmospheric Pressure*	*Measured Temperature*	*Measured Relative Humidity*	*Test current*	*Measurement result*	
	(mbar)	*(^{0}C)*	*(%)*	*(mA)*	*Certificate value (Ω)*	*Mean UUT reading (Ω)*
2018-01-11	880.0	23.4	58.5	10mA	9.999992	9.999991

UNCERTAINTY COMPUTATION							
Sources of uncertainty	Value (Ω)	Diviser	Probability distribution	Sensitivity Coeff	Uncertainty Contribution	Reliability percentage	Degree of freedom
uncertainty of the Standard	5.00E-04	2	Normal(K=2)	1	2.50000E-04	95	200
standard uncertainty of the mean	2.69E-06	1	Normal(K=1)	1	2.69485E-06	10	9
Resolution of UUT	5.00E-07	√3	Rectangular	1	2.88675E-07	95	200
uncertainty due Stability	1.00E-05	√3	Rectangular	1	5.77350E-06	95	200
Combined Uncertainty					2.50081E-04		200.26031
Expanded Uncertainty(2*U, k=2)					5.00E-04		2

3. Nominal Resistance : 100Ω
   Serial number : 5485007
   Model : 742A-100

Date	***Measured Atmospheric Pressure***	***Measured Temperature***	***Measured Relative Humidity***	***Test current***	***Measurement result***	
	(mbar)	***(^{0}C)***	***(%)***	***(mA)***	***Certificate value (Ω)***	***Mean UUT reading (Ω)***
2018-01-11	881.2	23.3	57.5	1mA	100.00015	100.00709

UNCERTAINTY COMPUTATION							
Sources of uncertainty	Value (Ω)	Diviser	Probability distribution	Sensitivity Coeff	Uncertainty Contribution	Reliability percentage	Degree of freedom
uncertainty of the Standard	5.00E-03	2	Normal(K=2)	1	2.50000E-03	95	200
standard uncertainty of the mean	3.01E-05	1	Normal(K=1)	1	3.0148E-05	10	9
Resolution of UUT	5.00E-06	√3	Rectangular	1	2.8868E-06	95	200
uncertainty due Stability	1.00E-04	√3	Rectangular	1	5.77350E-05	95	200
Combined Uncertainty					0.00250085		200.271976
Expanded Uncertainty(2*U, k=2)					5.00E-03		2

4. Nominal Resistance : 1kΩ
Serial number : 7733002
Model : 742A-1k

Date	*Measured Atmospheric Pressure*	*Measured Temperature*	*Measured Relative Humidity*	*Test current*	*Measurement result*	
	(mbar)	*(^{0}C)*	*(%)*	*(mA)*	*Certificate value (kΩ)*	*Mean UUT reading (kΩ)*
2018-01-12	881.0	22.4	60.0	1mA	0.9999990	1.0000084

UNCERTAINTY COMPUTATION							
Sources of uncertainty	Value (kΩ)	Diviser	Probability distribution	Sensitivity Coeff	Uncertainty Contribution	Reliability percentage	Degree of freedom
uncertainty of the Standard	5.00E-05	2	Normal(K=2)	1	2.50000E-05	95	200
standard uncertainty of the mean	1.44E-07	1	Normal(K=1)	1	1.4391E-07	10	9
Resolution of UUT	5.00E-08	√3	Rectangular	1	2.8868E-08	95	200
uncertainty due Stability	1.00E-07	√3	Rectangular	1	5.77350E-08	95	200
Combined Uncertainty					2.50005E-05		200.0159
Expanded Uncertainty(2*U, k=2)					5.0001E-05		2

5. Nominal Resistance : 10kΩ
Serial number : 5065038
Model : 742A-10k

Date	*Measured Atmospheric Pressure*	*Measured Temperature*	*Measured Relative Humidity*	*Test current*	*Measurement result*	
	(mbar)	*(^{0}C)*	*(%)*	*(mA)*	*Certificate value (kΩ)*	*Mean UUT reading (kΩ)*
2018-01-15	881.3	23.3	57.5	1µA	9.99996	10.00050

UNCERTAINTY COMPUTATION							
Sources of uncertainty	Value (kΩ)	Diviser	Probability distribution	Sensitivity Coeff	Uncertainty Contribution	Reliability percentage	Degree of freedom
uncertainty of the Standard	5.00E-04	2	Normal(K=2)	1	2.49999E-04	95	200
standard uncertainty of the mean	1.26E-05	1	Normal(K=1)	1	1.25831E-05	10	9
Resolution of UUT	5.00E-06	√3	Rectangular	1	2.88675E-06	95	200
uncertainty due Stability	1.00E-05	√3	Rectangular	1	5.77350E-06	95	200
Combined Uncertainty					2.50399E-04		201.25329
Expanded Uncertainty(2*U, k=2)					5.01E-04		2

14 Appendix H: NMIE Results

Summary of Measurement results

Nominal Value	Nominal Test current	Measured Value	Uncertainty
[Ω]		[Ω]	(±)
1	100 mA	1.0000552	$13.0 \bullet 10^{-6} \bullet R$
10	10 mA	10.0004136	$13.9 \bullet 10^{-6} \bullet R$
100	1 mA	100.007375	$13.1 \bullet 10^{-6} \bullet R$
[KΩ]		[KΩ]	(±)
1	1 mA	1.0000073	$11.2 \bullet 10^{-6} \bullet R$
10	100 µA	9.999798	$10.0 \bullet 10^{-6} \bullet R$

Uncertainty budget of 1 Ω of reference resistor

Quantity	Estimation	Value	Unit	Probablity Distribution	sensitivity Coefficient	Uncertainity Contribution	Degree of freedom
***R*s**	1.0000242	0.30	μΩ/Ω	Normal	1.00003099	0.15	∞
***V*s**	100.0003	5.80	μV/V	Rectangular	-0.010000519	3.35	4
***V*x**	100.0034	5.80	μV/V	Rectangular	0.010000209	3.35	4
δV_{DMMx}	0.0000	3.90	μV/V	Rectangular	0.010000209	2.25	∞
δV_{DMMs}	0.0000	0.00	μV/V	Rectangular	-0.010000519	0.00	∞
δR_D	0.00000000	5.00	μΩ/Ω	Rectangular	1.00003099	2.89	∞
δR_{TS}	0.00000000	2.00	μΩ/Ω	Rectangular	1.00003099	1.15	∞
$R_{resolution}$	0.0000000	0.50	μΩ/Ω	Rectangular	1.00003099	0.29	∞
$R_{instability}$	0.0000000	0.00	μΩ/Ω	Rectangular		0.00	∞
$R_{connection}$	0.0000000	1.00	μΩ/Ω	Rectangular		0.58	∞
R_x	1.0000552					6.13	∞
				EXPANDED UNCRTAINTY		12.26	∞

Calibration Result: 1.0000552 Ω ± 0.00001226 Ω

1.0000552 Ω ± 12.26 X $10^{-6}R$

Uncertainty budget of 10 Ω of reference resistor

Quantity	Estimation	Value	Unit	Probablity Distribution	sensitivity Coefficient	Uncertainity Contribution	Degree of freedom
***R*s**	1.0000242	0.30	μΩ/Ω	Normal	10.00017209	0.15	∞
***V*s**	10.0005	5.80	μV/V	Rectangular	-0.99999541	3.35	4
***V*x**	100.0063	5.80	μV/V	Rectangular	0.09999782	3.35	4
δVDMMx	0.0000	5.80	μV/V	Rectangular	0.09999782	3.35	∞
δVDMMs	0.0000	3.80	μV/V	Rectangular	-0.99999541	2.19	∞
δR_D	0.00000000	5.00	μΩ/Ω	Rectangular	10.00017209	2.89	∞
δR_{TS}	0.00000000	2.00	μΩ/Ω	Rectangular	10.00017209	1.15	∞
$R_{resolution}$	0.0000000	0.50	μΩ/Ω	Rectangular	10.00017209	0.29	∞
$R_{instability}$	0.0000000	0.00	μΩ/Ω	Rectangular		0.00	∞
$R_{connection}$	0.0000000	1.00	μΩ/Ω	Rectangular		0.58	∞
R_x	10.00041410					6.97	∞
				EXPANDED UNCRTAINTY		13.94	∞

Calibration Result 10.00041410 Ω ± 0.00001394 Ω

10.00041410 Ω ± 13.94 X 10^{-6}*R*

Uncertainty budget of 100 Ω of reference resistor

Quantity	Estimation	Value	Unit	Probablity Distribution	sensitivity Coefficient	Uncertainity Contribution	Degree of freedom
Rs	999.997	0.80	µΩ/Ω	Normal	0.100007675	0.40	∞
Vs	1.0000	3.80	µV/V	Rectangular	-100.007287	2.19	4
Vx	0.1000	5.80	µV/V	Rectangular	999.99612	3.35	4
δVDMMx	0.0000	5.90	µV/V	Rectangular	999.99612	3.41	∞
δVDMMs	0.0000	3.90	µV/V	Rectangular	-100.007287	2.25	∞
δRD	0.00000000	5.00	µΩ/Ω	Rectangular	0.100007675	2.89	∞
δR_{TS}	0.00000000	2.00	µΩ/Ω	Rectangular	0.100007675	1.15	∞
$R_{resolution}$	0.0000000	0.50	µΩ/Ω	Rectangular	0.100007675	0.29	∞
$R_{instability}$	0.0000000	0.00	µΩ/Ω	Rectangular		0.00	∞
$R_{connection}$	0.0000000	0.00	µΩ/Ω	Rectangular		0.00	∞
R_x	100.0073750					6.53	∞
				EXPANDED UNCRTAINTY		13.06	∞

Calibration Result	100.0073750 Ω ± 0.00001306 Ω
	100.0073750 Ω ± 13.06 X $10^{-6}R$

Uncertainty budget of 1 kΩ of reference resistor

Quantity	Estimation	Value	Unit	Probablity Distribution	sensitivity Coefficient	Uncertainity Contribution	Degree of freedom
***R*s**	0.999997	0.80	μΩ/Ω	Normal	1.00000932	0.40	∞
***V*s**	1.0000	3.80	μV/V	Rectangular	-1.00000578	2.19	4
***V*x**	1.0000	5.80	μV/V	Rectangular	0.99999646	3.35	4
δVDMMx	0.0000	3.90	μV/V	Rectangular	0.99999646	2.25	∞
δVDMMs	0.0000	0.00	μV/V	Rectangular	-1.00000578	0.00	∞
δRD	0.00000000	5.00	μΩ/Ω	Rectangular	1.00000932	2.89	∞
δR_{TS}	0.00000000	2.00	μΩ/Ω	Rectangular	1.00000932	1.15	∞
$R_{resolution}$	0.0000000	0.50	μΩ/Ω	Rectangular	1.00000932	0.29	∞
$R_{instability}$	0.0000000	0.00	μΩ/Ω	Rectangular		0.00	∞
$R_{connection}$	0.0000000	1.00	μΩ/Ω	Rectangular		0.58	∞
R_x	1.00000632					5.60	∞
				EXPANDED UNCRTAINTY		11.20	∞

Calibration Result

1.00000632 kΩ ± 0.00001120 kΩ

1.00000632 kΩ ± 11.2 X 10^{-6}R

Uncertainty budget of 10 kΩ of reference resistor

Quantity	Estimation	Value	Unit	Probablity Distribution	sensitivity Coefficient	Uncertainity Contribution	Degree of freedom
Rs	10.000002	0.30	µΩ/Ω	Normal	0.999979601	0.15	∞
Vs	1.0001	3.80	µV/V	Rectangular	-9.999212658	2.19	4
Vx	1.0000	3.80	µV/V	Rectangular	9.999416634	2.19	4
δVDMMx	0.0000	3.90	µV/V	Rectangular	9.999416634	2.25	∞
δVDMMs	0.0000	0.00	µV/V	Rectangular	-9.999212658	0.00	∞
δR_D	0.00000000	5.00	µΩ/Ω	Rectangular	0.999979601	2.89	∞
δR_{TS}	0.00000000	2.00	µΩ/Ω	Rectangular	0.999979601	1.15	∞
$R_{resolution}$	0.0000000	0.50	µΩ/Ω	Rectangular	0.999979601	0.29	∞
$R_{instability}$	0.0000000	0.00	µΩ/Ω	Rectangular		0.00	∞
$R_{connection}$	0.0000000	1.00	µΩ/Ω	Rectangular		0.58	∞
R_x	9.99979801					4.98	∞
				EXPANDED UNCRTAINTY		9.96	∞

Calibration Result

9.99979801 KΩ ± 0.00000996 kΩ

9.99979801 KΩ ± 9.96 X $10^{-6}R$