Revised Report on
APMP.EM-S6
APMP Bilateral Supplementary Comparison of Resistance between the National Institute of Metrology Thailand and the National Measurement Institute, Australia
December 2003 to April 2004

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1. Introduction

A bilateral supplementary comparison of resistance, APMP.EM-S6, was conducted between the National Institute of Metrology Thailand (NIMT) and the CSIRO National Measurement Laboratory of Australia which became part of the National Measurement Institute, Australia (NMIA) on the 1st July 2004.

The measurements for the comparison were made between December 2003 and April 2004. In 2008, it was discovered that it was necessary to correct the NMIA values given in the report. In the process of revising the report, errors in Table 4 were noted and corrected.

NMIA was the pilot laboratory for the intercomparison. Dr Henry Chen was the contact person at NMIA and Ms Ajchara Charoensook was the contact person at NIMT. Dr Brian Ricketts of NMIA was responsible for preparing the protocol and the original report of the comparison. The revised comparison report was prepared by Dr Leigh Johnson of NMIA.

The comparison started in December 2003. The comparison covered seven values of resistance, 0.1 Ω, 1 Ω, 100 Ω, 10 kΩ, 100 kΩ, 1 MΩ, and 100 MΩ.

The resistors were supplied by NIMT.

The resistors were measured on three separate occasions by NIMT and on two separate occasions by NMIA. Table 1 gives the sequence of measurements and the date of completion of each set of measurements.

	Date of completion of measurements
First measurements at NIMT	26 December 2003
First measurements at NMIA	3 February 2004
Second measurements at NIMT	9 March 2004
Second measurements at NMIA	19 March 2004
Third measurements at NIMT	29 April 2004

Table 1. Schedule of measurements.

2. Travelling Artefacts

As stated above, the resistors used for this comparison were be supplied by NIMT. Table 2 gives details of the resistors. The temperature coefficients for the 0.1 Ω and 100 MΩ resistors were measured by NMIA. The temperature coefficients for the other 5 resistors were taken from the manufacturer's data.

Nominal value (Ω)	Manufacturer	Model	Serial no.	First order temperature coefficient (μΩ/Ω)/K	Second order temperature coefficient (μΩ/Ω)/K^2
0.1	YEW	2792	26FS3097	2.55	-0.6
1	Fluke	742A	7792005	-0.063	-0.013
100	Fluke	742A	7798002	-0.029	-0.023
10 k	Fluke	742A	TS48981	-0.08	-0.02
100 k	Fluke	742A	8363002	0.134	0.004
1 M	Fluke	742A	8363001	0.014	-0.013
100 M	IET	SRC	H1-9950106	-16.1	0.585

Table 2. Details of the resistors used in the comparison.

3. Transport of Artefacts

3.1 Customs arrangements

The resistors were transported using an ATA carnet prepared by NIMT. No significant delays occurred during Customs clearances.

3.2 Transport case

The resistors were sent to NMIA for the first NMIA measurement in a wooden crate. Although the crate was strong, upon arrival at NMIA it was noticed that the lid had been attached with large nails. The use of large nails as a means of attaching the lid would have exposed the resistors to a degree of mechanical disturbance that would not be appropriate for comparison artefacts. The box was modified at NMIA so that the lid was attached by screws. Apart from avoiding mechanical disturbance during despatch it was hoped that any Customs or security inspection would not result in the use of nails for reattachment of the lid.

When the resistors arrived at NMIA the second time they were again in a wooden crate. This crate was different to the one used for the first NIMT-NMIA-NIMT return trip but again the lid had been nailed down. The crate was in poor condition and after the NMIA measurements the resistors were returned to NIMT in a closely-packed cardboard carton. A shock monitor was attached to the crate on the first return trip to NIMT.

4. Reported results

4.1 General comments

It is not expected that the relative humidity in the laboratory at the time of measurement will have a significant effect on the resistance values or on their uncertainties unless extreme values of relative humidity were recorded. As noted below, the relative humidity at NIMT had a range of 35 % to 65 %. It is not considered that this range of relative humidity would have a significant effect on the resistance values or the uncertainties reported in this comparison.

Temperature and humidity conditions in the laboratories were:

Laboratory	Temperature °C	Relative humidity %
NIMT	23 ± 2	50 ±15
NMIA	20 ± 0.2	50 ±5

Table 3. Temperature and Humidity Conditions

In both laboratories the 0.1 Ω resistor was measured while it was in an oil bath at 23 °C. The uncertainty in the oil bath temperature at NMIA was ±0.01 °C.

At NIMT the resistors, other than the 0.1 Ω resistor, were measured while in the laboratory environment given in the above table. At NMIA the resistors, again other than the 0.1 Ω resistor, were measured while they were in an air bath with a temperature of 23.0 °C ± 0.1 °C.

The currents used to measure the resistors in the two laboratories are listed in the result summary sheets below. In all cases the currents were sufficiently small to not cause a significant change in resistance due to dissipation within the resistors.

4.2 Methods Used

At NIMT the 0.1 Ω, 1 Ω, 100 Ω and 10 kΩ resistors were measured on a Measurement International (MI) 6010B bridge and the 100 kΩ, 1 MΩ and 100 MΩ resistors were measured on an MI 6000B bridge. At NMIA the 0.1 Ω resistor was measured on a Guildline 9920 bridge, the 1 Ω, 100 Ω and 10 kΩ resistors were measured on an MI 6010B bridge and the 100 kΩ, 1 MΩ and 100 MΩ resistors were measured by substitution on a Wheatstone bridge with the decade ratios being defined by transfer standards. The resistors of nominal values 0.1 Ω, 1 Ω, 100 Ω and 10 kΩ were measured as four-terminal resistors while the 100 kΩ, 1 MΩ and 100 MΩ resistors were measured as two-terminal resistors.

4.3 Traceability

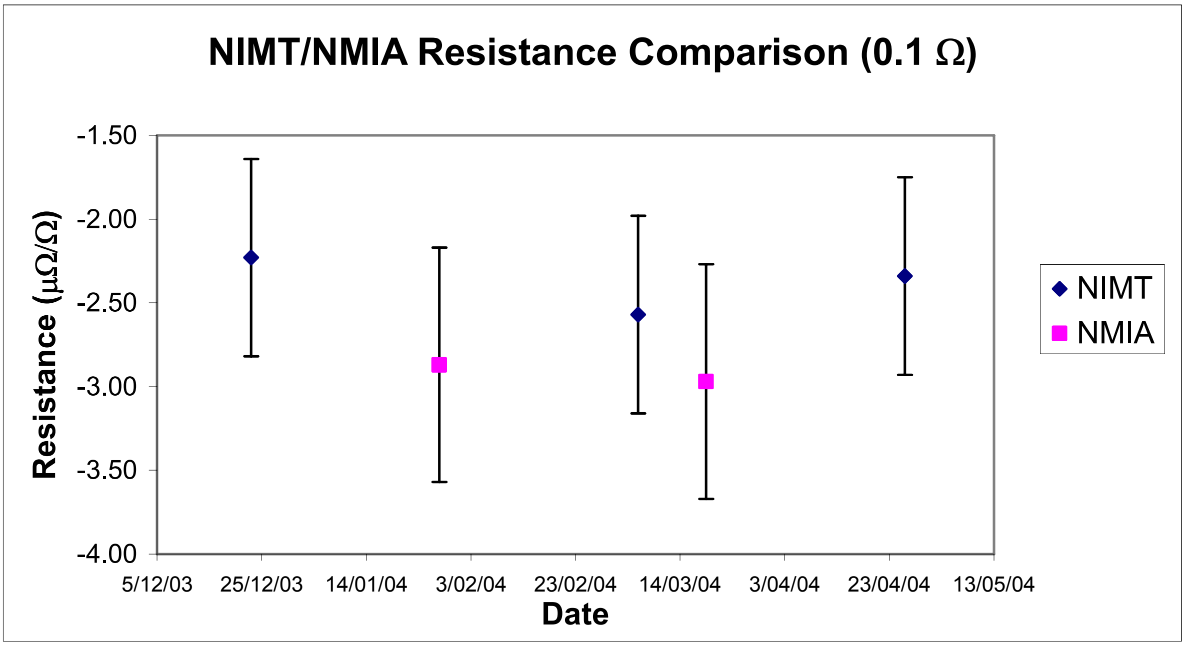
The NIMT measurements are traceable to Physikalisch-Technische Bundesanstalt through calibration certificate reference no. PTB2.12-4004253/02-67, 2002-09-23. The original NMIA measurements were traceable to the NMIA primary standard of resistance. The revised measurements are expressed in terms of NMIA's realisation of the SI Ω derived from the institute's Thompson-Lampard calculable capacitor.

4.4 Result Summary Sheets

Comparison results are summarised on the following pages.

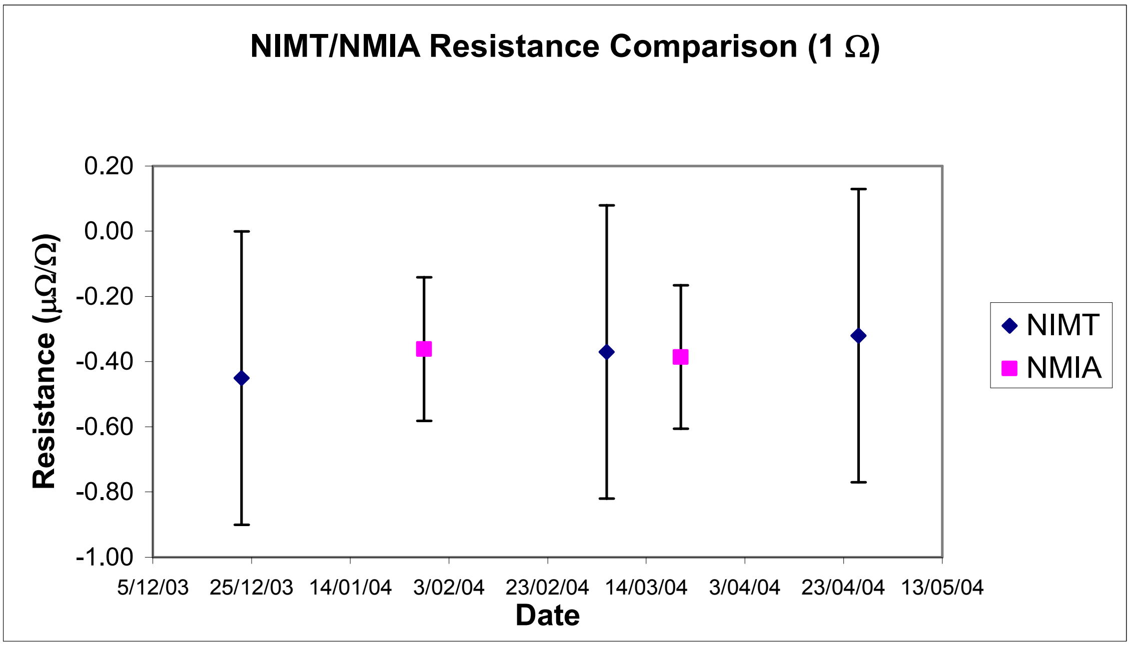
0.1 Ω S/No: 26FS3097

Date	Lab	R(Ω)	NIMT	NMIA	±U(μΩ/Ω)	±U(μΩ/Ω)	k	I(mA)	T(°C)
23/12/03	NIMT	0.099999777	-2.23		0.59		2	100	
28/01/04	NMIA	0.099999713		-2.87		0.7	2.2	300	23.00
6/03/04	NIMT	0.099999743	-2.57		0.59		2	100	
19/03/04	NMIA	0.099999703		-2.97		0.7	2.2	300	23.00
26/04/04	NIMT	0.099999766	-2.34		0.59		2	100	
		Weighted Mean:	-2.38	-2.92					



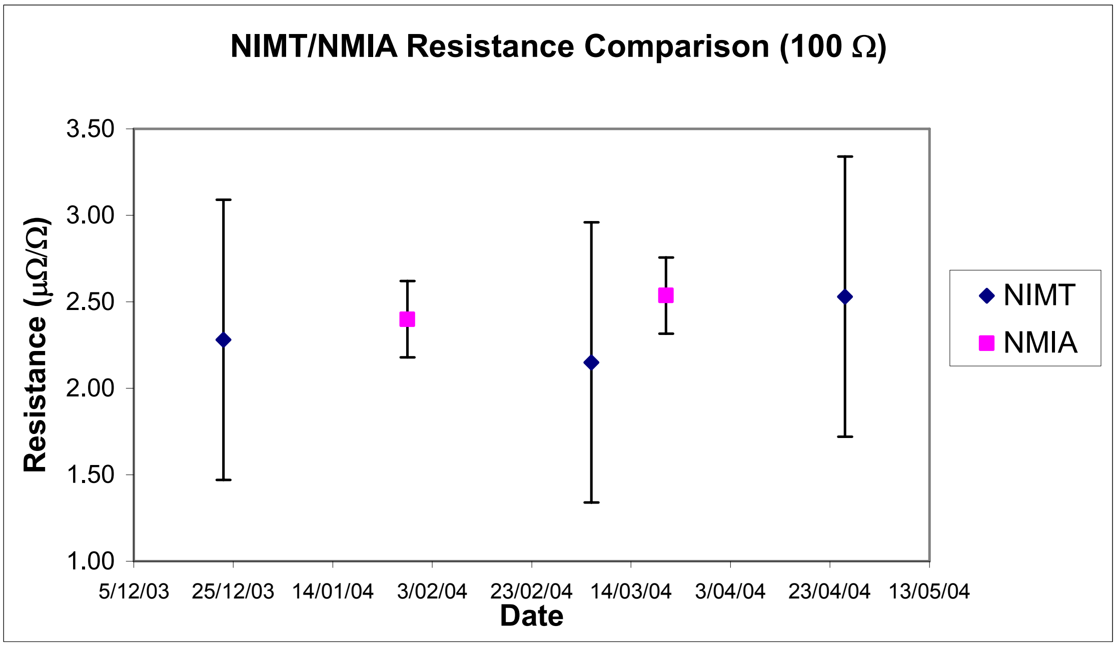
1 Ω S/No: 7792005

Date	Lab	R(Ω)	NIMT	NMIA	±U(μΩ/Ω)	±U(μΩ/Ω)	k	I(mA)	T(°C)
23/12/03	NIMT	0.99999955	-0.45		0.45		2	100	
29/1/04	NMIA	0.99999964		-0.36		0.22	2.1	100	23.00
6/3/04	NIMT	0.99999963	-0.37		0.45		2	100	
21/3/04	NMIA	0.99999961		-0.39		0.22	2.1	100	23.00
26/4/04	NIMT	0.99999968	-0.32		0.45		2	100	
		Weighted Mean:	-0.38	-0.37					



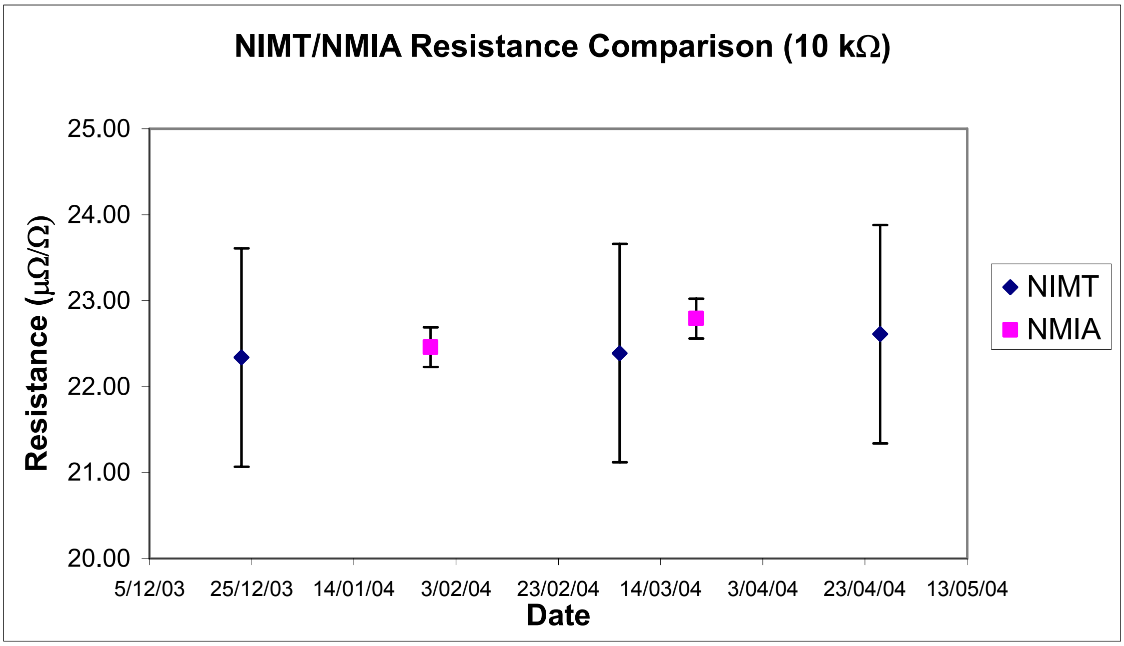
100 Ω S/No: 7798002

Date	Lab	R(Ω)	NIMT	NMIA	±U(μΩ/Ω)	±U(μΩ/Ω)	k	I(mA)	T(°C)
23/12/03	NIMT	100.000228	2.28		0.81		2	2	
29/1/04	NMIA	100.000240		2.40		0.22	2.1	10	23.00
6/3/04	NIMT	100.000215	2.15		0.81		2	2	
21/3/04	NMIA	100.000254		2.54		0.22	2.1	10	23.00
26/4/04	NIMT	100.000253	2.53		0.81		2	2	
		Weighted Mean:	2.32	2.47					



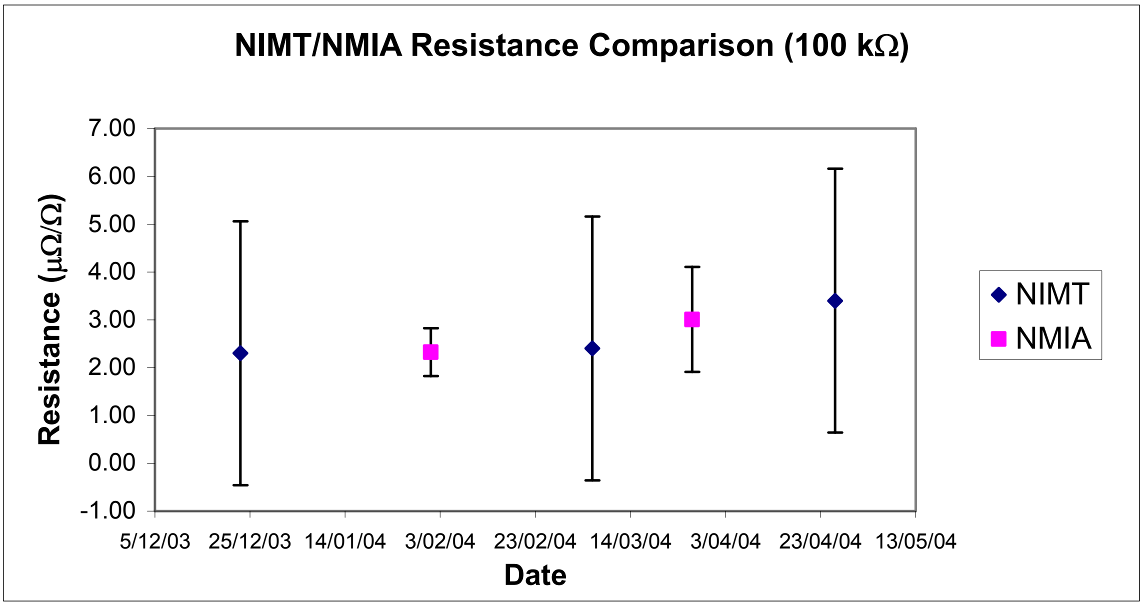
10 kΩ S/No: TS48981

Date	Lab	R(Ω)	NIMT	NMIA	±U(μΩ/Ω)	±U(μΩ/Ω)	k	I(mA)	T(°C)
23/12/03	NIMT	10000.2234	22.34		1.27		2	0.3	
29/1/04	NMIA	10000.2246		22.46		0.23	2.1	1	23.00
6/3/04	NIMT	10000.2239	22.39		1.27		2	0.3	
21/3/04	NMIA	10000.2279		22.79		0.23	2.1	1	23.00
26/4/04	NIMT	10000.2261	22.61		1.27		2	0.3	
		Weighted Mean:	22.45	22.63					



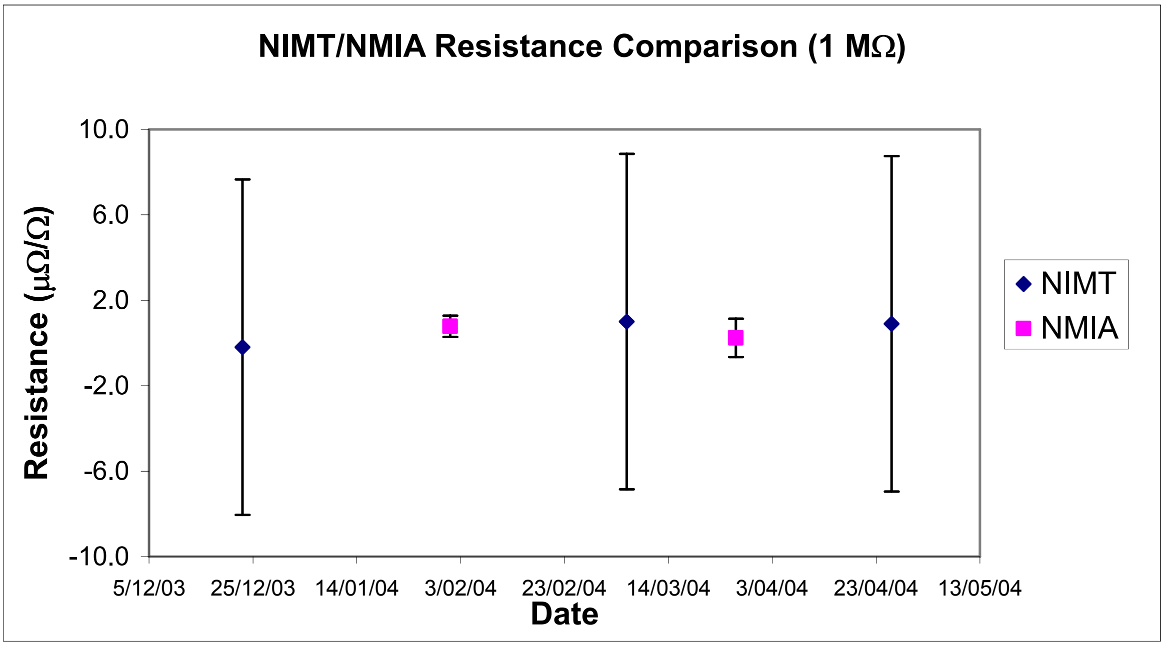
100 kΩ S/No: 8363002

Date	Lab	R(kΩ)	NIMT	NMIA	±U(μΩ/Ω)	±U(μΩ/Ω)	k	I(mA)	T(°C)
23/12/03	NIMT	100.00023	2.30		2.76		2	0.1	
1/2/04	NMIA	100.00023		2.32		0.5	2.1	0.18	23.00
6/3/04	NIMT	100.00024	2.40		2.76		2	0.1	
27/3/04	NMIA	100.00030		3.01		1.1	2.7	0.18	23.00
26/4/04	NIMT	100.00034	3.40		2.76		2	0.1	
		Weighted Mean:	2.70	2.66					



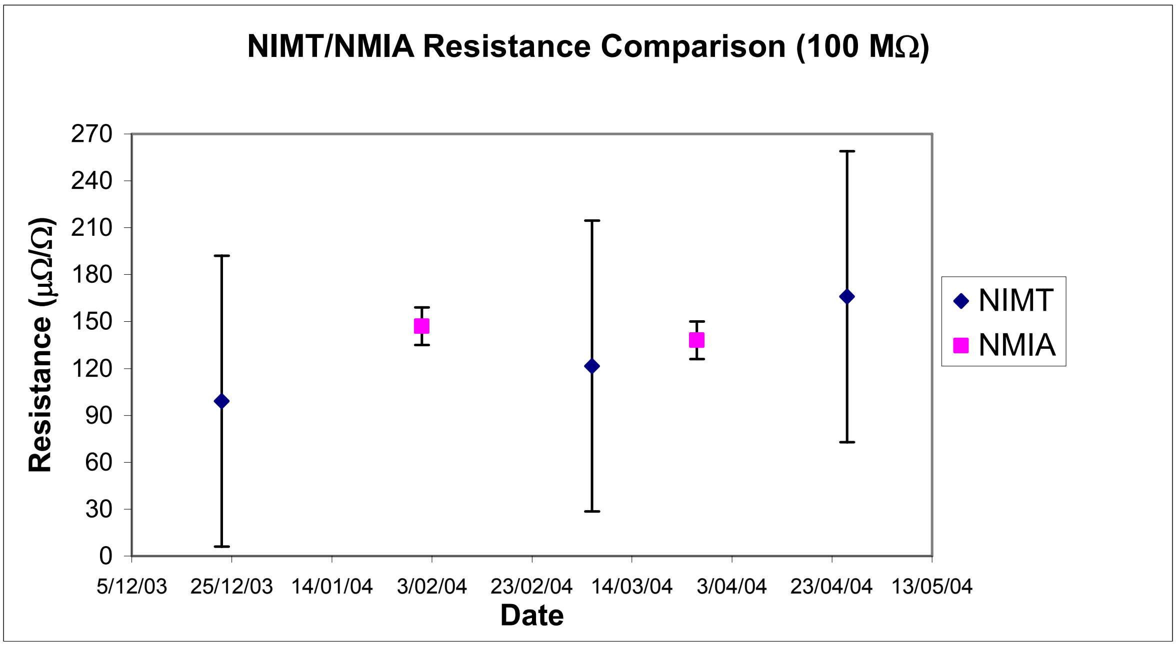
1 MΩ S/No: 8363001

Date	Lab	R(MΩ)	NIMT	NMIA	±U(μΩ/Ω)	±U(μΩ/Ω)	k	I(μA)	T(°C)
23/12/03	NIMT	0.9999998	-0.2		7.85		2	10	
1/2/04	NMIA	1.0000008		0.8		0.5	2.0	80	23.00
6/3/04	NIMT	1.0000010	1.0		7.85		2	10	
27/3/04	NMIA	1.0000002		0.2		0.9	2.5	80	23.00
26/4/04	NIMT	1.0000009	0.9		7.85		2	10	
		Weighted Mean:	0.57	0.65					



100 MΩ S/No: H1-9950106

Date	Lab	R(MΩ)	NIMT	NMIA	±U(μΩ/Ω)	±U(μΩ/Ω)	k	I(μA)	T(°C)
23/12/03	NIMT	100.00992	99.2		93		2	1	
1/2/04	NMIA	100.0147		147		12	2.1	0.9	23.00
6/3/04	NIMT	100.01215	121.5		93		2	1	
27/3/04	NMIA	100.0138		138		12	2.1	0.9	23.00
26/4/04	NIMT	100.01659	165.9		93		2	1	
		Weighted Mean:	129	143					



4.5 Summary of results and calculation of En

It was considered that the time span, from December 2003 to April 2004, over which the measurements were made, was too short to allow the determination of a drift rate for any of the resistors. Consequently all the results reported by NMIA for a particular resistor were treated as belonging to a single population, and a weighted mean value calculated for the set of measurements. The results reported by NMIT were treated in the same way. Note that where the uncertainty associated with each measurement in the set is the same, the weighted mean reduces to a simple mean.

E_n is the absolute value of the difference between the values obtained at the two laboratories divided by the root sum square of the expanded uncertainties of the two values. This factor is a measure of how well the values obtained by the two laboratories agree within the uncertainties of the two measurements. Comparisons having E_n values of less than 1 can be regarded as satisfactory.

Table 4 on the following page shows details of the calculation of E_n.

Resistance Value		0.1 Ω	1 Ω	100 Ω	10 kΩ	100 kΩ	1 MΩ	100 MΩ
NIMT	R_1	-2.23	-0.45	2.28	22.34	2.30	-0.20	99.2
	R_2	-2.57	-0.37	2.15	22.39	2.40	1.00	121.5
	R_3	-2.34	-0.32	2.53	22.61	3.40	0.90	165.9
	u_i	0.31	0.25	0.41	0.65	1.38	3.93	46.7
	ν_i	154	2.E+05	2.E+06	1.E+07	6.E+04	4.E+06	1.E+09
	R_{NIMT}	-2.38	-0.38	2.32	22.45	2.70	0.57	128.9
	u_{NIMT}	0.18	0.14	0.24	0.38	0.80	2.27	27.0
	ν_{NIMT}	462	6.E+05	5.E+06	3.E+07	2.E+05	1.E+07	3.E+09
	k_{NIMT}	1.97	1.96	1.96	1.96	1.96	1.96	1.96
	U_{NIMT}	0.35	0.28	0.47	0.74	1.56	4.44	52.8
NMIA	R_1	-2.97	-0.36	2.40	22.46	2.32	0.78	147.0
	u_1	0.29	0.11	0.11	0.11	0.22	0.23	5.7
	ν_1	11	40	40	41	19	39	18
	R_2	-2.87	-0.39	2.54	22.79	3.01	0.24	138.0
	u_2	0.29	0.11	0.11	0.11	0.41	0.37	5.7
	ν_2	11	40	41	41	4	6	18
	w_1	0.50	0.50	0.50	0.50	0.77	0.73	0.50
	w_2	0.50	0.50	0.50	0.50	0.23	0.27	0.50
	R_{NMIA}	-2.92	-0.37	2.47	22.63	2.48	0.63	142.5
	u_{NMIA}	0.21	0.08	0.08	0.08	0.19	0.19	4.0
	ν_{NMIA}	22	80	81	81	23	39	36
	k_{NMIA}	2.07	1.99	1.99	1.99	2.07	2.02	2.0
	U_{NMIA}	0.43	0.15	0.15	0.16	0.40	0.39	8.2
$R_{NIMT} - R_{NMIA}$		0.54	-0.01	-0.15	-0.18	0.22	-0.06	-13.6
$(U^2_{NIMT} + U^2_{NMIA})^{1/2}$		0.55	0.32	0.49	0.75	1.61	4.46	53.48
E_n		0.99	0.02	0.30	0.24	0.14	0.01	0.25

Table 4. Summary of differences in the resistance values and their associated uncertainties. All non-dimensionless quantities are given in μΩ/Ω .

4.6 Comparison of NIMT reported uncertainties with the uncertainties given in the NIMT Calibration and Measurement Capabilities (CMCs).

Table 5 shows the uncertainties reported by NIMT for this comparison and the uncertainties claimed in the NIMT CMCs as listed on Appendix C of the BIPM Key Comparison Database (KCDB) as at 23/7/04.

Resistance (Ω)	NIMT expanded uncertainty in this comparison (μΩ/Ω)	NIMT uncertainty given in CMCs on the KCDB on 23/7/04
0.1	0.59	2.3
1	0.45	1.5
100	0.81	2.2
10 k	1.27	2.4
100 k	2.76	2.5
1 M	7.85	18
100 M	93	120

Table 5 Comparison of the expanded uncertainties reported by NIMT for this comparison and the uncertainties given in the NIMT CMCs.

It can be seen from Table 5 that the uncertainties given in the NIMT CMCs are greater than the corresponding uncertainties reported in this comparison (except for 100 kΩ for which the uncertainties are very nearly equal). This supports the NIMT CMC claims as they now appear on the KCDB.

5. Report Summary

The conditions set down in the protocol for the comparison were generally followed. There was concern about the exposure of the resistor to mechanical disturbance in view of the use of nails to attach the lid of the crates used to transport the resistors. In fact, apart from the difference in the two NMIA measurements of the 10 kΩ resistor, there was no evidence of changes in value of the resistors due to mechanical disturbance. However the exposure of the resistors to mechanical disturbance caused by use of nails to attach the lid to the transport crate was a matter of concern. This highlights the need for future comparisons to have sufficient funding to allow the purchase of a metal transport case with suitable means of sealing and locking so that Customs and security inspections do not result in inappropriate means of re-sealing the transport case.

This comparison has shown that the resistance measurements made at NIMT and NMIA for resistance values 0.1 Ω, 1 Ω, 100 Ω, 10 kΩ, 100 kΩ, 1 MΩ and 100 MΩ agree within the stated uncertainties. The value of the quantity E_n was less than 1 for all of the seven values used in this comparison.

The results of this comparison support NIMT's CMC claims (as at 23/7/04) for the seven resistance values that were the subject of this comparison. The changes made to this report in 2008 as a result of corrections to the NMIA values do not affect this conclusion.

Appendix 1 Uncertainty Statements: NIMT

NIMT Mathematical Model : (0,1 ohm, 1 ohm, 100 ohm, 10 kohm)

$$Rx = (Rs + \Delta Rscal + \delta Rsd + \delta Rst) \bullet (k + \Delta kcal + \delta li + \delta acc + \delta re + \delta sc + \delta ext) - \delta Rxt$$

Rx =The value of unknown resistor
Rs = The value of the standard resistor
$\Delta Rscal$ = The error of the reference standard resistor
$\Delta kcal$ = The error of the ratio Rx/Rs
δRsd = Secular drift of the standard resistor
δRst = Temperature related resistance variation of the standard resistor
k = The indicated ratio on Automatic Resistance Bridge
δli = Linearity of Automatic Resistance Bridge
δacc = Accuracy of Automatic Resistance Bridge
δre = Dial resolution of Automatic Resistance Bridge
δRxt = Temperature related resistance variation of the unknown resistor
δsc = Error contribution and thermal EMFs of scanner

NIMT Mathematical Model : (100 kohm, 1 Mohm, 100 Mohm)

$$Rx = (Rsnom + \Delta Rscal + \delta Rsd + \delta Rst) \bullet (r + \Delta rcal + \delta r_{ac} + \delta r_{li} + \delta r_{rs} + \delta r_{st} + \delta r_{s}) - \delta Rxt$$

Rx = The value of the unknown resistor
r = Ratio of reference standard and unknown resistor
δr_{ac} = Accuracy of high resistance ratio bridge
δr_{li} = Linearity of high resistance ratio bridge
δr_{rs} = Resolution of the DVM used in null mode
δr_{st} = Stability of DVM
δr_{s} = Short term noise stability of the source
R_{snom} = The value of the reference standard resistor
ΔR_{scal} = The error of the reference standard resistor
δR_{sd} = The secular drift of the reference standard resistor
δR_{st} = The temperature related resistance variation of the standard resistor

NIMT Uncertainty Budget For Standard Resistor 0,1 Ω @ 100 mA

Quantity XI	Estimate xi	Standard Uncertainty u(xi)		Probability distribution	Effective degrees of freedom(gi)	Sensitivity coefficient ci	Uncertainty Contribution ui(y)	
		Relative	Absolute				Relative	Absolute
K	0.100000501	**1.50E-07**	-	Normal	9	1	1.50E-07	-
Rs	**0.999992652**	3.50E-09	-	Normal	∞	1	3.50E-09	-
δRsd	0	8.00E-08	-	Rectangular	∞	1	8.00E-08	-
δli	0	3.00E-08	-	Rectangular	∞	1	3.00E-08	-
δacc	0	1.50E-07	-	Rectangular	∞	1	1.50E-07	-
δre	0	6.00E-10	-	Rectangular	∞	1	6.00E-10	-
δext	10	1.20E-07	-	Rectangular	∞	1	1.20E-07	-
δsc	0	1.40E-07	-	Rectangular	∞	1	1.40E-07	-
δRst	0	2.00E-08	-	Rectangular	∞	1	2.00E-08	-
δRxt	0	**8.00E-08**	-	Rectangular	∞		8.00E-08	-
Rx	**0.099999766**				∞		**3.05E-07**	-

Expanded Uncertainty :

$$U = k \cdot u(Rx) = 2 \cdot 3{,}05 \cdot 10^{-7}$$
$$= 6.10E-07$$

NIMT Uncertainty Budget For Standard Resistor 1 Ω @ 100 mA

Quantity	Estimate	Standard Uncertainty u(xi)		Probability distribution	Effective degrees of freedom(γi)	Sensitivity coefficient	Uncertainty Contribution ui(y)	
XI	xi	Relative	Absolute			ci	Relative	Absolute
K	1.000007023	**2.00E-08**	-	Normal	9	1	2.00E-08	-
Rs	**0.999992652**	3.50E-09	-	Normal	∞	1	3.50E-09	-
δRsd	0	8.00E-08	-	Rectangular	∞	1	8.00E-08	-
δli	0	3.00E-08	-	Rectangular	∞	1	3.00E-08	-
δacc	0	1.50E-07	-	Rectangular	∞	1	1.50E-07	-
δre	0	6.00E-10	-	Rectangular	∞	1	6.00E-10	-
δsc	0	1.40E-07	-	Rectangular	∞	1	1.40E-07	-
δRst	0	2.00E-08	-	Rectangular	∞	1	2.00E-08	-
δRxt	0	**1.02E-07**	-	Rectangular	∞		1.02E-07	-
Rx	**0.999999675**				∞		**2.46E-07**	-

Expanded Uncertainty :

$$U = k \cdot u(Rx) = 2 \cdot 2{,}46 \cdot 10^{-7}$$

$$= 4.92E\text{-}07$$

NIMT Uncertainty Budget For Standard Resistor 100 Ω   2 mA

Quantity XI	Estimate xi	Standard Uncertainty u(xi)		Probability distribution	Effective degrees of freedom(γi)	Sensitivity coefficient ci	Uncertainty Contribution ui(y)	
		Relative	Absolute				Relative	Absolute
K	0.999999753	**2.00E-08**	-	Normal	9	1	2.00E-08	-
Rs	100.000278	3.30E-07	-	Normal	∞	1	3.30E-07	-
δRsd	0	1.00E-07	-	Rectangular	∞	1	1.00E-07	-
δli	0	3.00E-08	-	Rectangular	∞	1	3.00E-08	-
δacc	0	1.50E-07	-	Rectangular	∞	1	1.50E-07	-
δre	0	6.00E-10	-	Rectangular	∞	1	6.00E-10	-
δsc	0	1.40E-07	-	Rectangular	∞	1	1.40E-07	-
δRst	0	2.00E-08	-	Rectangular	∞	1	2.00E-08	-
δRxt	0	**8.70E-08**	-	Rectangular	∞		8.70E-08	-
Rx	**100.0002533**				∞		**4.13E-07**	-

Expanded Uncertainty :

$$\mathbf{U = k \cdot u(Rx) = 2 \cdot 4{,}13 \cdot 10^{-7}}$$

$$\mathbf{= 8.25E\text{-}07}$$

NIMT Uncertainty Budget For Standard Resistor 10 kΩ @0.3 mA

Quantity XI	Estimate xi	Standard Uncertainty u(xi)		Probability distribution	Effective degrees of freedom(γi)	Sensitivity coefficient ci	Uncertainty Contribution ui(y)	
		Relative	Absolute				Relative	Absolute
K	0.999991009	**2.00E-08**	-	Normal	9	1	2.00E-08	-
Rs	**10000.316**	2.50E-09	-	Normal	∞	1	2.50E-09	-
δRsd	0	6.00E-07	-	Rectangular	∞	1	6.00E-07	-
δli	0	3.00E-08	-	Rectangular	∞	1	3.00E-08	-
δacc	0	1.50E-07	-	Rectangular	∞	1	1.50E-07	-
δre	0	6.00E-10	-	Rectangular	∞	1	6.00E-10	-
δsc	0	1.40E-07	-	Rectangular	∞	1	1.40E-07	-
δRst	0	2.00E-08	-	Rectangular	∞	1	2.00E-08	-
δRxt	0	**1.40E-07**	-	Rectangular	∞		1.40E-07	-
Rx	**10000.22609**				∞		6.51E-07	-

Expanded Uncertainty :

$$U = k \cdot u(Rx) = 2 \cdot 6{,}51 \cdot 10^{-7}$$

$$= 1.30E-06$$

NIMT Uncertainty Budget For Standard Resistor 100 kΩ @ 10 V

Quantity XI	Estimate xi	Standard Uncertainty u(xi)		Probability distribution	Effective degrees of freedom(γi)	Sensitivity coefficient ci	Uncertainty Contribution ui(y)	
		Relative	Absolute				Relative	Absolute
r	9.999718	**1.50E-07**	-	Normal	9	1	1.50E-07	-
Rs	**10000.31626**	2.50E-09	-	Normal	∞	1	2.50E-09	-
δRsd	0	6.00E-07	-	Rectangular	∞	1	6.00E-07	-
δr_{ac}	0	6.00E-08	-	Rectangular	∞	1	6.00E-08	-
δr_{li}	0	6.00E-09	-	Rectangular	∞	1	6.00E-09	-
δr_{rs}	0	3.00E-08	-	Rectangular	∞	1	3.00E-08	-
δr_{rst}	0	2.70E-07	-	Rectangular	∞	1	2.70E-07	-
δr_{s}	0	6.00E-08					6.00E-08	
δRst	0	2.00E-08	-	Rectangular	∞	1	2.00E-08	-
δRxt	0	**1.20E-06**	-	Rectangular	∞		1.20E-06	-
Rx	**100000.3425**				∞		1.38E-06	-

Expanded Uncertainty :

$$U = k \bullet u(Rx) = 2 \bullet 1{,}38 \bullet 10^{-6}$$

$$= 2.76E\text{-}06$$

NIMT Uncertainty Budget For Standard Resistor 1 MΩ @ 10 V

Quantity XI	Estimate xi	Standard Uncertainty u(xi)		Probability distribution	Effective degrees of freedom(γi)	Sensitivity coefficient ci	Uncertainty Contribution ui(y)	
		Relative	Absolute				Relative	Absolute
r	9.999999	**1.50E-07**	-	Normal	9	1	1.50E-07	-
Rs	**100000.1**	6.80E-07	-	Normal	∞	1	6.80E-07	-
δRsd	0	3.46E-06	-	Rectangular	∞	1	3.46E-06	-
δr_{ac}	0	6.00E-08	-	Rectangular	∞	1	6.00E-08	-
δr_{li}	0	6.00E-09	-	Rectangular	∞	1	6.00E-09	-
δr_{rs}	0	3.00E-08	-	Rectangular	∞	1	3.00E-08	-
δr_{rst}	0	2.70E-07	-	Rectangular	∞	1	2.70E-07	-
δr_{s}	0	6.00E-08					6.00E-08	
δRst	0	1.20E-06	-	Rectangular	∞	1	1.20E-06	-
δRxt	0	**1.20E-06**	-	Rectangular	∞		1.20E-06	-
Rx	1000000.9				∞		3.93E-06	-

Expanded Uncertainty :

$$U = k \cdot u(Rx) = 2 \cdot 3{,}93 \cdot 10^{-6}$$

$$= 7.85E\text{-}06$$

NIMT Uncertainty Budget For Standard Resistor 100 MΩ @ 100 V

Quantity XI	Estimate xi	Standard Uncertainty u(xi)		Probability distribution	Effective degrees of freedom(γi)	Sensitivity coefficient ci	Uncertainty Contribution ui(y)	
		Relative	Absolute				Relative	Absolute
r	10.00153548	**1.50E-07**	-	Normal	9	1	1.50E-07	-
Rs	**10000123.5**	6.00E-06	-	Normal	∞	1	6.00E-06	-
δRsd	0	5.20E-06	-	Rectangular	∞	1	5.20E-06	-
δr_{ac}	0	2.90E-07	-	Rectangular	∞	1	2.90E-07	-
δr_{li}	0	6.00E-09	-	Rectangular	∞	1	6.00E-09	-
δr_{rs}	0	3.00E-08	-	Rectangular	∞	1	3.00E-08	-
δr_{rst}	0	2.70E-07	-	Rectangular	∞	1	2.70E-07	-
δr_{s}	0	6.00E-08					6.00E-08	
δRst	0	1.73E-06	-	Rectangular	∞	1	1.73E-06	-
δRxt	0	**1.70E-05**	-	Rectangular	∞		1.70E-05	-
Rx	**100016590**				∞		1.88E-05	-

Expanded Uncertainty :

$$U = k \cdot u(Rx) = 2 \cdot 18{,}8 \cdot 10^{-6}$$

$$= 3.77E\text{-}05$$

Appendix 2 NMIA Uncertainty Statements

Component (U_c)	Deg. of freedom	S/N 26FS3097
		0.1
1. NML STD value at last cal	10	0.05
2. NML STD value extrapolation	4	0.05
3a. +/- 0.01degC temp of STD	5	0.00
3b. +/- 0.1degC temp of STD	5	
4a. +/- 0.1degC temp of TEST	5	
4b. +/- 0.01degC temp of TEST	5	0.13
5. Relative humidity (+/- 5%)	5	
6. Current setting (+/- 3%)	5	
7. Comparator ratio	5	0.23
8. Resolution of comparator reading	5	0.03
9. Setting of 9920 dials	5	0.03
10. Rounding of resistance value	1000	0.03
11. Rounding of uncertainty	1000	0.03
12. Realisation of SI ohm	88	0.066
RSS of (1-12 & Type A)		0.2887
Effective degrees of freedom		11.21
Coverage factor		2.20
Expanded uncertainty		0.64
Reported uncertainty		0.7
Value 1 (Correction)		-2.7
Value 2 (Correction)		-2.8
Value 3 (Correction)		-2.7
Value 4 (Correction)		-2.8
Mean Value		-2.75
Mean Value in terms of realisation of SI ohm		-2.97
Normalised Resistance Value		0.9999970
Experimental S.D. of Mean (i.e. Type A)		0.0289
Degrees of Freedom of Type A		3

Appendix 2 Fig 1. Typical NMIA Uncertainty budget for 0.1 Ω. Values in μΩ/Ω.

Component (U_c)	Deg. of freedom	S/N 7792005 1 Ω	S/N 7798002 100 Ω	S/N TS48981 10 kΩ
1. NML STD value at last cal	10	0.05	0.05	0.05
2. NML STD value extrapolation	4	0.05	0.05	0.05
3a. +/- 0.01degC temp of STD	5	0.00		
3b. +/- 0.1degC temp of STD	5		0.01	0.02
4a. +/- 0.01degC temp of TEST	5			
4b. +/- 0.1 degC temp of TEST	5	0.006	0.003	0.008
5. +/- 5% relative humidity	5			
6. +/- 3% current setting	5			
7. Bridge correction uncert	5	0.05	0.05	0.05
8. Rounding of resistance value	1000			
9. Realisation of SI ohm	88	0.066	0.066	0.066
RSS of 1-9 & Type A		0.1091	0.1095	0.1112
Effective degrees of freedom		38.75	39.28	41.45
Coverage factor		2.03	2.03	2.02
Expanded uncertainty		0.22	0.22	0.22
Reported uncertainty		0.22	0.22	0.22
Value 1 (Correction)		-0.16	2.77	23.02
Value 2 (Correction)		-0.16	2.75	23.01
Value 3 (Correction)		-0.17	2.76	23.03
Value 4 (Correction)		-0.16	2.76	23.00
Mean Value		-0.16	2.76	23.02
Mean Value in terms of realisation of SI ohm		-0.38	2.54	22.80
Normalised Resistance Value		0.99999962	1.00000254	1.00002280
Standard error of mean (Type A)		0.0025	0.0041	0.0065
Degrees of Freedom of Type A		3	3	3

Appendix 2. Fig 2. Typical NMIA Uncertainty Budget for 1 Ω, 100 Ω, and 10 kΩ. Values in μΩ/Ω.

Component	Degrees of freedom	S/S 8363002 100 kΩ	S/N 8363001 1 MΩ	S/N 9950106 100 MΩ
1. NML STD value at last cal	10	0.05	0.05	0.05
2. NML STD value extrapolation	3	0.05	0.05	0.05
3. Wheatstone bridge (including build-up)	18	0.10	0.13	5.2
4. +/-0.1degC temp of STD	5	0.02	0.02	0.02
5a. +/-0.01degC temp of TEST	5			
5b. +/-0.1 degC temp of TEST	5	0.01	0.00	1.61
6. +/-5% relative humidity	5			
7. Nonlinearity of null detector	5	0.10	0.10	0.1
8. Bridge self heating	5	0.02	0.05	0.05
9. Insulation leakage	4	0.01	0.03	1.0
10. Rounding of resistance value	1000	0.03	0.03	0.29
11. Rounding of uncertainty value	1000	0.03	0.03	0.0
12. 2-T to 4-T Correction	4			
13. Reallisation of SI ohm	88	0.066	0.066	0.066
RSS of 1-13 & Type A		0.4075	0.3676	5.5978
Effective degrees of freedom		4.59	6.21	23.19
Coverage factor		2.65	2.44	2.07
Expanded uncertainty		1.08	0.90	11.60
Reported uncertainty		**1.1**	**0.9**	**12**
Value 1 (Correction)		2.55	0.48	140.43
Value 2 (Correction)		2.65	0.53	136.75
Value 3 (Correction)		3.89	1.16	137.83
Value 4 (Correction)		3.84	-0.33	138.41
Mean Value		3.23	0.46	138.36
Mean Value in terms of realisation of SI ohm		3.01	0.24	138.14
Lead Correction (2-T to 4-T)		0.00	0.00	0.00
Reported Resistance Value (Correction)		**3.0**	**0.2**	**138.1**
Normalised Final Resistance Value		1.0000030	1.0000002	1.0001381
Standard error of mean (Type A)		0.3659	0.3054	0.7725
Degrees of Freedom of Type A		3	3	3

Appendix 2. Fig. 3 Typical NMIA Uncertainty for 100 kΩ, 1 MΩ and 100 MΩ. Values in μΩ/Ω.

Appendix 3 List of Laboratory Reports Containing Measurements used in this Comparison

NIMT: Certificate No EL-0119/04

NMIA: Reports RN46805A to RN46811A and RN47130A to RN47136A