Final report

APMP.EM-S12
Comparison of Standards for the Calibration of Voltage, Current and Resistance Meters

24 November 2017

Louis Marais[1], Steven Yang[2], Brenda Lam[2], LIU Yue[3], Thomas John[4], P.S. Negi[4], Hiroaki Sakuma[5], Eiji Watabe[5], Chua Sze Wey[6], Chalit Kumtawee[7] and Yaowaret Pimsut[7]

[1]National Measurement Institute, 36 Bradfield Rd, West Lindfield, NSW 2070, Australia
[2]Standards and Calibration Laboratory, 36/F, Immigration Tower, 7 Gloucester Road, Wan Chai, Hong Kong
[3]National Institute of Metrology, Room 210, Building 2, No.18 Bei San Huan Dong Lu, Chaoyang District, Beijing, China
[4]National Physical Laboratory, Dr. K. S. Krishnan Road, New Delhi-110012, India
[5]Japan Electric Meters Inspection Corporation, 15-7, 4-chome, Shibaura, Minato-ku, Tokyo, 108-0023, Japan
[6]National Metrology Centre, 1 Science Park Drive, Singapore 118221, Republic of Singapore
[7]National Institute of Metrology (Thailand), 3/4-5 Moo 3, Klong 5, Klongluang, Pathumthani 12120, Thailand

Contents

Contents (continued)

1. Introduction

The 14th Meeting of the APMP Technical Committee on Electricity and Magnetism, held on 5 December 2011 in Kobe, Japan, decided to hold a comparison of standards for the calibration of voltage, current and resistance meters at the lowest attainable level of uncertainty. This comparison complements the APMP.EM-S8 comparison using a 6.5 digit multimeter and the following comparisons of primary standards that provide traceability for the calibration of voltage, current and resistance meters: APMP.EM-K2: DC high resistance at 10 MΩ, 1 GΩ (in progress); APMP.EM.BIPM-K11.3: DC voltage, 10 V and 1.018 V (completed); APMP.EM-K6.a: AC/DC transfer at 3 V (completed); APMP.EM-K9: AC/DC transfer at 500 V, 1000 V (completed). The National Measurement Institute, Australia (NMIA) has been appointed as the pilot laboratory.

2. Participants and organisation of the comparison

2.1 Participants

Country	Laboratory	Details
Australia	NMIA	Louis Marais National Measurement Institute, 36 Bradfield Rd, Lindfield, NSW 2070, Australia Tel: +61 2 8467 3543 Fax: +61 2 8467 3655 Email: louis.marais@measurement.gov.au
China	NIM	LIU Yue National Institute of Metrology Room 210, Building 2, No.18 Bei San Huan Dong Lu, Chaoyang District, Beijing, China Tel: 86-10-64524524 Fax: 86-10-64524524 Email: Liuyue@nim.ac.cn
Hong Kong	SCL	Steven Yang and Brenda Lam Standards and Calibration Laboratory, 36/F, Immigration Tower, 7 Gloucester Road, Wan Chai, Hong Kong Tel: (852) 2829 4855 (852) 2829 4832 Fax: (852) 2829 4865 Email: steven.yang@itc.gov.hk hslam@ict.gov.hk
India	NPLI	Thomas John and P.S. Negi National Physical Laboratory, Dr. K. S. Krishnan Road, New Delhi-110012, India Tel: 91-11-4560 8233 91-11-4560 9344 Fax: 91-11-4560 9310 Email: tjohn@nplindia.org psnegi@nplindia.org
Japan	JEMIC	Hiroaki Sakuma and Eiji Watabe Japan Electric Meters Inspection Corporation, 15-7, 4-chome, Shibaura, Minato-ku, Tokyo, 108-0023, JAPAN Tel: +81-3-3451-3485 Fax: +81-3-3451-1497 Email: h-sakuma@jemic.go.jp e-watabe@jemic.go.jp
Singapore	NMC	Chua Sze Wey National Metrology Centre, 1 Science Park Drive, Singapore 118221, Republic of Singapore Tel: +65 6279 1909 Fax: +65 6279 1993 Email: chua_sze_wey@nmc.a-star.edu.sg

Country	Laboratory	Details
Thailand	NIMT	Chalit Kumtawee and Yaowaret Pimsut National Institute of Metrology (Thailand), 3/4-5 Moo 3, Klong 5, Klongluang, Pathumthani 12120, Thailand Tel: +66 2577 5100 ext. 1234 Fax: +66 2577 5093 Email: chalit@nimt.or.th yaowaret@nimt.or.th

2.2 Support group

Initially the Measurement Standards Laboratory (MSL) of New Zealand agreed to support the comparison, but they had to withdraw their participation and support early in 2017. Subsequently the Standards and Calibration Laboratory (SCL) of Hong Kong agreed to support the comparison.

2.3 Organisation of the comparison

Circulation of the travelling standard started in February 2015 and the comparison concluded in October 2016. Between each of the comparison rounds the travelling standard was returned to the NMIA for measurement.

Comparison schedule

Dates	Laboratory
27 February 2015 to 24 March 2015	NMIA
6 April 2015 to 8 June 2015	NPLI
6 July 2015 to 4 August 2015	NMC*
17 August 2015 to 14 September 2015	JEMIC
21 September 2015 to 14 October 2015	NMIA
3 November 2015 to 2 December 2015	NIM
15 December 2015 to 26 January 2016	NMIA
10 February 2016 to 7 March 2016	NIMT
17 March 2016 to 8 April 2016	SCL
14 April 2016 to 3 June 2016	MSL**
15 June 2016 to 15 July 2016	NMIA
22 July 2016 to 19 August 2016	NMC*
15 September 2016 to 27 October 2016	NMIA

* NMC reported equipment failure and repeated the measurements at the end of the comparison.
** MSL withdrew from the comparison early in 2017.

2.4 Unexpected events

Severe customs and transport delays were experienced during the comparison. This caused the extension of the comparison from the originally planned 10 months to 20 months. This meant that the drift of the travelling standard became significant and had to be corrected for. The measurements at the NMIA were used to calculate these corrections.

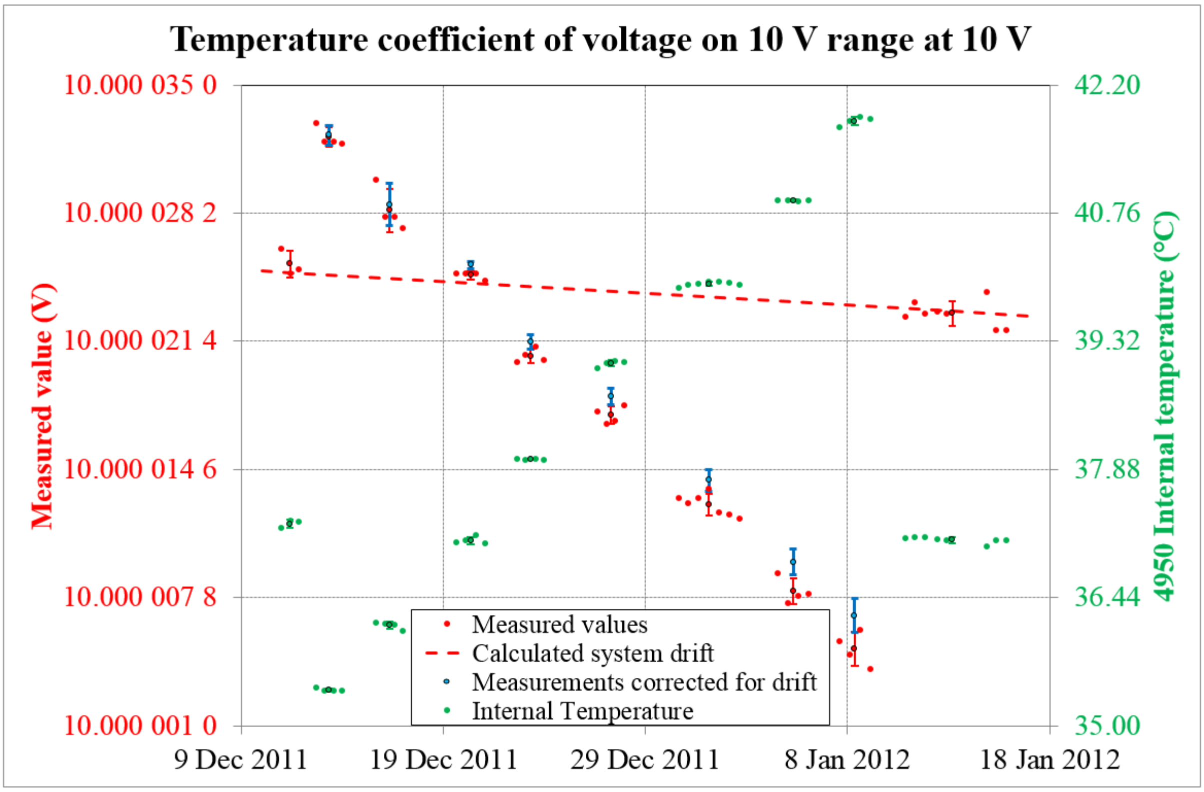
After measurements at NMC, the pilot was informed that one of the reference instruments used in their measurements failed but they only became aware of this after dispatching the instrument. It was agreed that they could repeat their measurements at the end of the comparison. Only their second set of results is reported here.

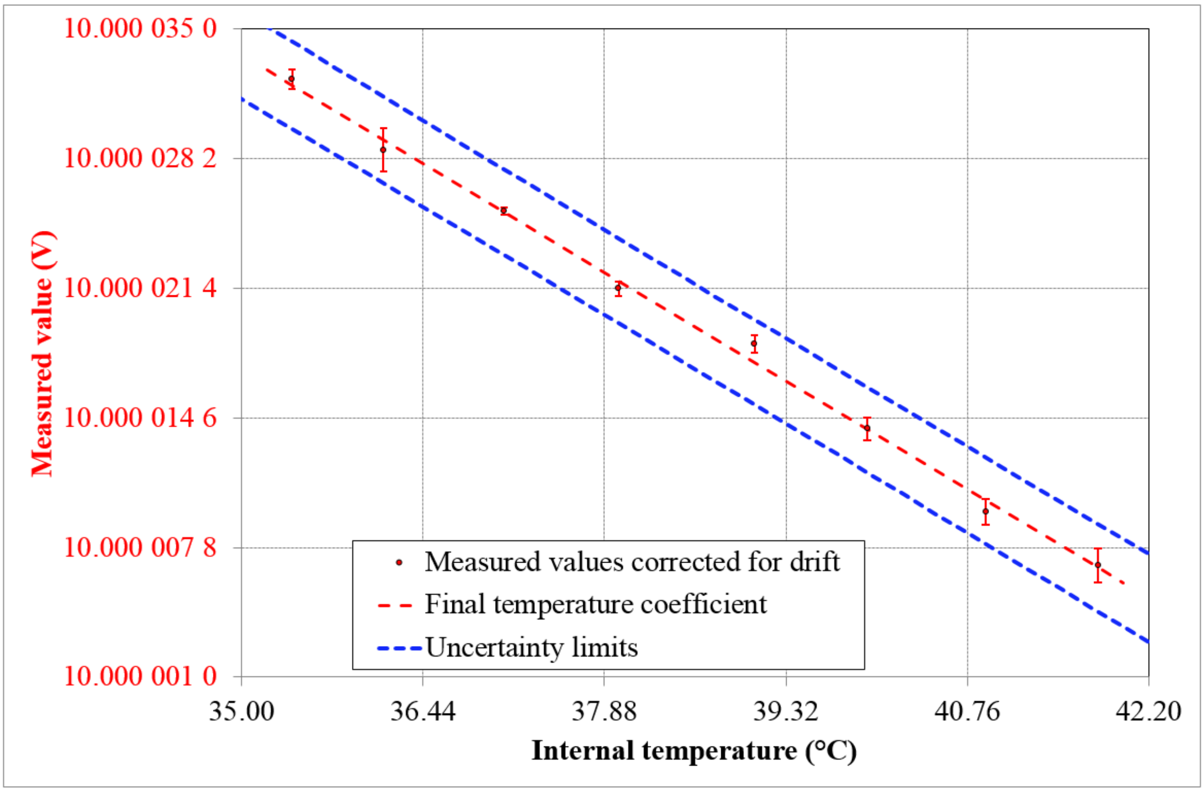
3. Preparation for the comparison

The travelling standard was carefully assessed at the NMIA before the start of the comparison. An experiment was performed at the NMIA from October 2014 to February 2015 to determine the temperature coefficients of the travelling standard. The internal temperatures of the travelling standard as reported by the participants were used to standardise the measurements by correcting all results to an internal temperature of 40 °C. The uncertainties of these corrections are the quadratic sum of the standard error of the fit, the maximum deviation from a linear response, and a factor to account for the offset from the mean temperature. The uncertainty of this correction was added to the uncertainty reported by the participants.

The travelling standard was also evaluated for its response to variations in humidity. It turned out that the humidity variations have very little effect on the travelling standard at the time scale used for the evaluation, and since the humidity variations during the comparison was not significant, no corrections were calculated for humidity.

The results obtained for the temperature coefficient at 10 V direct voltage is shown here. The results are first corrected for drift (determined from measurements at the start, middle and end of the experiment) and a straight line is then fitted to determine the temperature coefficient.





Refer to appendix III for the temperature coefficients.

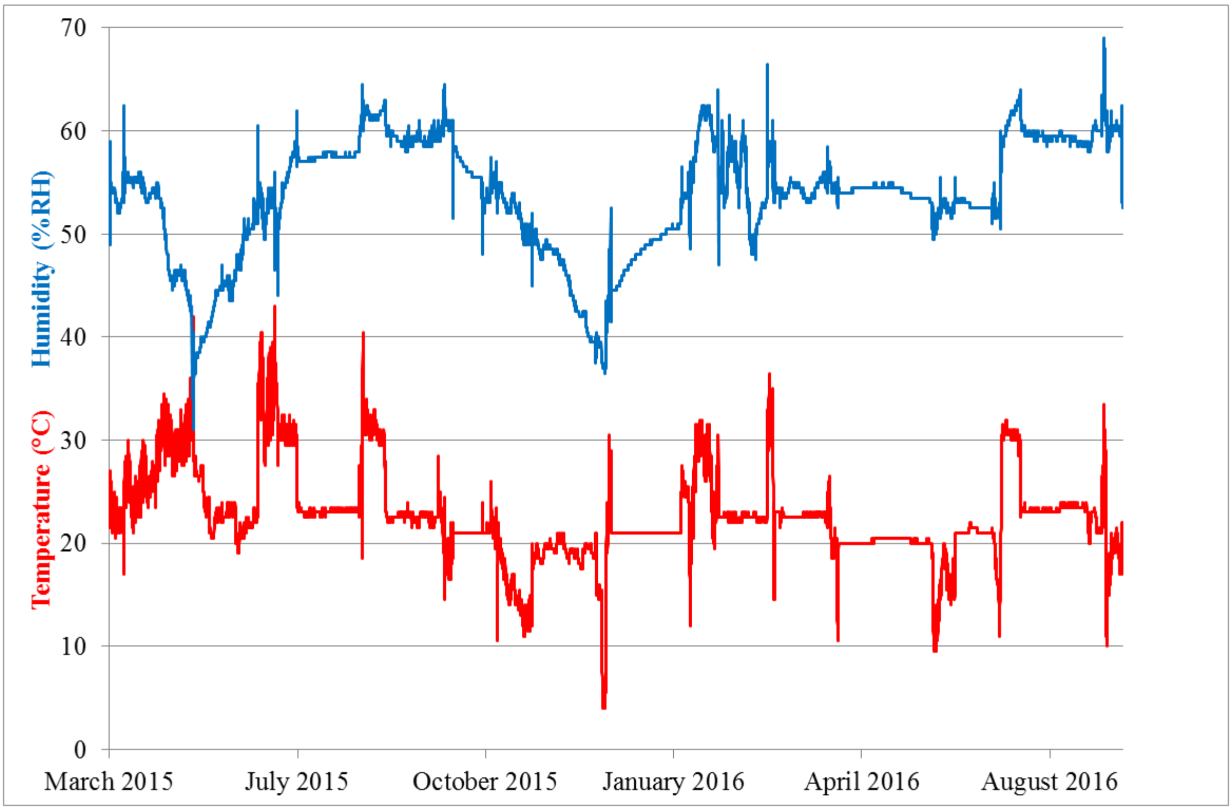
4. Travelling standard and measurement instructions

The travelling standard was a Wavetek model 4950 Multifunction Transfer Standard (MTS), serial number 33528. The travelling standard was shipped in a ruggedized transit case with dimensions 75 cm × 58 cm × 29 cm, and the package weighed approximately 27 kg. A temperature monitor and a temperature and humidity logger accompanied the travelling standard.

4.1 Quantities to be measured

Function	Measurement points
Direct voltage	+ 0.1 V, + 1 V, + 10 V, + 19 V, + 100 V, + 1000 V
Direct current	+ 0.001 A, + 1 A
Alternating voltage	V at 10 Hz, 55 Hz, 1.005 kHz, 20 kHz, 50 kHz and 1 MHz 0.1 V at 10 Hz, 55 Hz, 1.005 kHz, 20 kHz, 50 kHz and 1 MHz 1 V at 10 Hz, 55 Hz, 1.005 kHz, 20 kHz, 50 kHz and 1 MHz 10 V at 10 Hz, 55 Hz, 1.005 kHz, 20 kHz, 50 kHz and 1 MHz 19 V at 1.005 kHz 100 V at 10 Hz, 55 Hz, 1.005 kHz, 20 kHz and 50 kHz 700 V at 55 Hz, 1.005 kHz, 20 kHz and 50 kHz
Alternating current	0.001 A at 55 Hz, 1.005 kHz and 5 kHz 1 A at 55 Hz, 1.005 kHz and 5 kHz
Resistance	10 Ω, 100 Ω, 1 kΩ, 10 kΩ, 100 kΩ, 1 MΩ, 10 MΩ, 100 MΩ

4.2 Temperature and humidity during the comparison

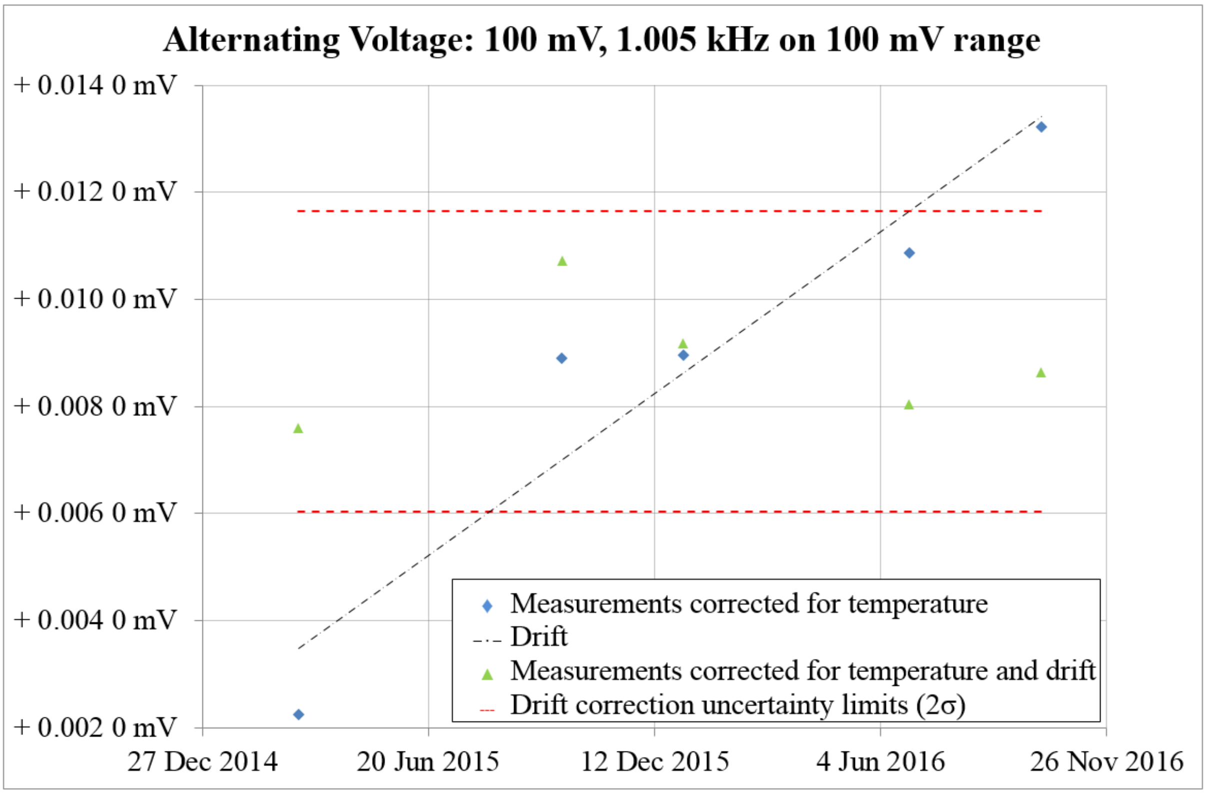


The environmental data show that the travelling standard was not subjected to significant temperature or humidity strain during the comparison.

4.3 Drift of the travelling standard

The drift of the standard was determined from the measurements at the NMIA, and was used to correct the measurements reported by the participants. The uncertainty of this correction was added to the uncertainty reported by the participants.

The drift proved to be significant for several measurement points, and for uniformity was applied across all measurements. The drift values were determined after correcting the NMIA measurements for temperature. Least squares regression was used to determine the drift correction and the uncertainty was taken as the standard error of the fit. This uncertainty was added to participant results. The results of drift determination are shown below for the measurements at 100 mV and 1.005 kHz on the 100 mV range.



Refer to appendix IV for the drift corrections and their uncertainties.

4.4 Measurement instructions

Detailed measurements instructions were provided in the comparison protocol – see Protocol (appendix V). In addition a set of video tutorials were produced and shipped on a DVD with the travelling standard. These videos were also published on a YouTube channel [1].

5. Evaluation of the measurement results

Some of the participants did not have the capability to perform measurements of all the quantities to be measured. SCL did not perform alternating voltage measurements at 10 Hz. They also did not perform the alternating voltage measurements of 10 mV at 1 MHz, and 100 mV at 1 MHz. JEMIC did not perform any alternating voltage or alternating current measurements.

The measurement results were carefully evaluated at the NMIA after completion of all participant measurements. The results were checked by the support group before the Draft A report was circulated for comments. The travelling standard exhibited poor stability for the measurements at 1 A direct current, 0.01 V at 1 MHz and 0.1 V at 1 MHz alternating voltage, and these were excluded from the comparison with the agreement of the participants. At 1 A all the measurement results fall within the specification of the travelling standard. This indicates that although the instrument performed satisfactorily for some applications, it may not be suitable for a comparison at this level of accuracy. At 10 mV and 100 mV at 1 MHz the uncertainties contributed by the corrections for the temperature coefficient and the drift of the travelling standard during the comparison dominated to the extent that no meaningful comparison of the results could be made.

The protocol states that the comparison reference values (CRVs) will be calculated as the weighted average of results from laboratories with independent realisations of the relevant primary standards. This was not an issue for the direct voltage measurements, but for alternating voltage, resistance and direct and alternating current measurements this was an issue, as the CRVs would in some cases be based on the measurements of a single participant. It was agreed by all participants to change the methodology of calculating the CRVs. The measurements from all participants were used after removal of outliers. Outlier detection was performed using the median of absolute deviations (MAD) approach [2, 3]. The CRV was then computed as the weighted mean of the remaining results.

Participants were asked to measure the frequency of the sources used for alternating voltage and current measurements, because the travelling standard has a known frequency dependency. It was not necessary to correct for this dependency, as the reported participant measurements showed that all the measurements were done sufficiently close to the nominal frequencies.

The values reported for the NMIA are the weighted average of all the measurement performed at the NMIA during the comparison.

5.1 Anomalous results

Results that were identified as possibly anomalous were reported to participants before distribution of the Draft A report. Several numerical errors were identified by participants, and these were corrected.

A small number of measurements remained apparently anomalous but these anomalies were not due to numerical errors. The institutes were asked if they could explain these anomalies. For the measurements of 1 V at 1 MHz and 10 V at 1 MHz, NIMT reported that their measurements were performed with the travelling standard set to an incorrect mode. No other explanations were received.

5.2 Degree of equivalence

The results of the comparison are reported as the degree of equivalence between a participant's result and the CRV.

The degree of equivalence of each laboratory with the CRV, D_i, has been calculated as:

$$D_i = \delta_i - \delta_R \quad (1)$$

where δ_i is the laboratory value, and δ_R is the CRV.

The expanded uncertainty of the degree of equivalence for a participant's result, U, has been calculated as:

$$U^2 = U_i^2 - U_R^2 \quad (2)$$

$$U^2 = U_i^2 + U_R^2 \quad (3)$$

where U_i is the expanded uncertainty of the measured value of each laboratory and U_R is the expanded uncertainty of the CRV. Equation 2 is used where the laboratory contributes to the CRV (due to the correlation with the CRV) and equation 3 is used where the laboratory does not contribute to the CRV.

The results are shown in tabular format in appendix I and graphically in appendix II. The dashed red lines in the graphs indicate the uncertainty limits of the CRV.

6. Summary and conclusions

The comparison measurements were started in February 2015 and completed in October 2016. The comparison reference values were calculated from all participant results that survived outlier detection. Most of the results show good agreement with the comparison reference values.

7. References

[1] https://www.youtube.com/channel/UCDe-vgs0rJlOkllkLrOt6Mw, last accessed 17 August 2017.

[2] Randa, J., “Proposal for KCRV and Degree of Equivalence for GTRF Key Comparisons,” GT-RF/2000-12, August 2000.

[3] Randa, J., “Update to proposal for KCRV & degree of equivalence for GTRF key comparisons,” GT-RF/2005-04, February 2005.

Appendix I: Degrees of Equivalence

Direct Voltage

100 mV

Laboratory	Value	Uncertainty
NPLI	+ 0.000 10 mV	± 0.001 51 mV
JEMIC	+ 0.000 15 mV	± 0.000 35 mV
NIM	– 0.000 25 mV	± 0.000 36 mV
NMIA	– 0.000 02 mV	± 0.000 28 mV
NIMT	+ 0.000 53 mV	± 0.000 52 mV
SCL	– 0.000 03 mV	± 0.000 25 mV
NMC	– 0.000 18 mV	± 0.000 49 mV

1 V

Laboratory	Value	Uncertainty
NPLI	– 0.000 000 7 V	± 0.000 002 1 V
JEMIC	+ 0.000 000 7 V	± 0.000 002 0 V
NIM	+ 0.000 000 1 V	± 0.000 001 2 V
NMIA	– 0.000 000 4 V	± 0.000 001 5 V
NIMT	– 0.000 000 1 V	± 0.000 001 9 V
SCL	+ 0.000 000 4 V	± 0.000 001 3 V
NMC	– 0.000 000 1 V	± 0.000 001 1 V

10 V

Laboratory	Value	Uncertainty
NPLI	+ 0.000 004 V	± 0.000 021 V
JEMIC	+ 0.000 002 V	± 0.000 018 V
NIM	– 0.000 006 V	± 0.000 013 V
NMIA	– 0.000 006 V	± 0.000 016 V
NIMT	– 0.000 001 V	± 0.000 016 V
SCL	– 0.000 001 V	± 0.000 012 V
NMC	+ 0.000 008 V	± 0.000 012 V

19 V

Laboratory	Value	Uncertainty
NPLI	+ 0.000 007 V	± 0.000 036 V
JEMIC	+ 0.000 002 V	± 0.000 044 V
NIM	– 0.000 012 V	± 0.000 022 V
NMIA	– 0.000 002 V	± 0.000 029 V
NIMT	+ 0.000 001 V	± 0.000 028 V
SCL	+ 0.000 012 V	± 0.000 027 V
NMC	+ 0.000 030 V	± 0.000 031 V

100 V

Laboratory	Value	Uncertainty
NPLI	+ 0.002 91 V	± 0.000 26 V
JEMIC	– 0.000 03 V	± 0.000 22 V
NIM	– 0.000 01 V	± 0.000 13 V
NMIA	– 0.000 02 V	± 0.000 19 V
NIMT	– 0.000 11 V	± 0.000 21 V
SCL	+ 0.000 06 V	± 0.000 14 V
NMC	+ 0.000 03 V	± 0.000 12 V

1000 V

Laboratory	Value	Uncertainty
NPLI	+ 0.012 9 V	± 0.007 1 V
JEMIC	– 0.000 3 V	± 0.003 0 V
NIM	– 0.001 4 V	± 0.001 6 V
NMIA	+ 0.000 4 V	± 0.001 9 V
NIMT	– 0.000 3 V	± 0.002 1 V
SCL	– 0.000 2 V	± 0.002 2 V
NMC	+ 0.001 2 V	± 0.001 4 V

Direct Current

1 mA

Laboratory	Value	Uncertainty
NPLI	– 0.000 000 9 mA	± 0.000 009 0 mA
JEMIC	+ 0.000 002 5 mA	± 0.000 006 0 mA
NIM	– 0.000 001 2 mA	± 0.000 006 9 mA
NMIA	+ 0.000 001 3 mA	± 0.000 005 6 mA
NIMT	+ 0.000 001 1 mA	± 0.000 009 6 mA
SCL	– 0.000 001 4 mA	± 0.000 003 9 mA
NMC	– 0.000 000 1 mA	± 0.000 005 2 mA

Alternating Voltage

10 mV

Laboratory	10 Hz		55 Hz	
	Value	Uncertainty	Value	Uncertainty
NPLI	+ 0.008 5 mV	± 0.003 9 mV	+ 0.002 1 mV	± 0.003 4 mV
NIM	+ 0.000 1 mV	± 0.001 7 mV	0.000 0 mV	± 0.001 6 mV
NMIA	+ 0.000 1 mV	± 0.000 5 mV	– 0.000 2 mV	± 0.000 9 mV
NIMT	– 0.007 8 mV	± 0.001 4 mV	– 0.007 9 mV	± 0.001 0 mV
SCL	–	–	0.000 0 mV	± 0.000 3 mV
NMC	– 0.000 4 mV	± 0.001 6 mV	0.000 0 mV	± 0.000 5 mV

Laboratory	1.005 kHz		20 kHz	
	Value	**Uncertainty**	**Value**	**Uncertainty**
NPLI	+ 0.003 1 mV	± 0.002 7 mV	+ 0.020 2 mV	± 0.003 8 mV
NIM	+ 0.000 2 mV	± 0.001 1 mV	+ 0.000 1 mV	± 0.001 5 mV
NMIA	– 0.000 1 mV	± 0.000 7 mV	– 0.000 2 mV	± 0.000 7 mV
NIMT	– 0.007 7 mV	± 0.001 0 mV	– 0.008 2 mV	± 0.001 0 mV
SCL	0.000 0 mV	± 0.000 2 mV	+ 0.000 2 mV	± 0.000 6 mV
NMC	– 0.000 1 mV	± 0.000 7 mV	– 0.000 1 mV	± 0.000 6 mV

Laboratory	50 kHz	
	Value	**Uncertainty**
NPLI	+ 0.008 4 mV	± 0.009 2 mV
NIM	+ 0.000 5 mV	± 0.001 7 mV
NMIA	+ 0.000 2 mV	± 0.000 7 mV
NIMT	– 0.008 2 mV	± 0.001 1 mV
SCL	– 0.000 5 mV	± 0.001 6 mV
NMC	– 0.000 1 mV	± 0.000 6 mV

100 mV

Laboratory	10 Hz		55 Hz	
	Value	**Uncertainty**	**Value**	**Uncertainty**
NPLI	+ 0.008 5 mV	± 0.007 7 mV	+ 0.000 7 mV	± 0.007 4 mV
NIM	+ 0.001 1 mV	± 0.005 2 mV	+ 0.000 5 mV	± 0.004 2 mV
NMIA	+ 0.001 2 mV	± 0.003 4 mV	+ 0.000 4 mV	± 0.002 8 mV
NIMT	+ 0.000 1 mV	± 0.003 9 mV	– 0.000 3 mV	± 0.003 1 mV
SCL	–	–	– 0.000 8 mV	± 0.003 5 mV
NMC	– 0.002 0 mV	± 0.003 5 mV	– 0.002 8 mV	± 0.003 8 mV

Laboratory	1.005 kHz		20 kHz	
	Value	**Uncertainty**	**Value**	**Uncertainty**
NPLI	– 0.002 0 mV	± 0.007 5 mV	+ 0.023 6 mV	± 0.008 3 mV
NIM	+ 0.001 6 mV	± 0.004 2 mV	0.000 0 mV	± 0.004 2 mV
NMIA	+ 0.001 2 mV	± 0.003 0 mV	+ 0.000 2 mV	± 0.002 8 mV
NIMT	+ 0.000 6 mV	± 0.003 3 mV	– 0.000 2 mV	± 0.003 2 mV
SCL	0.000 0 mV	± 0.003 7 mV	– 0.001 3 mV	± 0.004 9 mV
NMC	– 0.002 4 mV	± 0.003 1 mV	– 0.004 1 mV	± 0.004 3 mV

Laboratory	50 kHz	
	Value	Uncertainty
NPLI	+ 0.006 2 mV	± 0.012 6 mV
NIM	+ 0.002 2 mV	± 0.005 8 mV
NMIA	+ 0.001 4 mV	± 0.003 7 mV
NIMT	+ 0.001 1 mV	± 0.004 4 mV
SCL	– 0.002 7 mV	± 0.006 4 mV
NMC	– 0.003 3 mV	± 0.004 0 mV

1 V

Laboratory	10 Hz		55 Hz	
	Value	Uncertainty	Value	Uncertainty
NPLI	+ 0.000 093 V	± 0.000 052 V	+ 0.000 046 V	± 0.000 045 V
NIM	– 0.000 023 V	± 0.000 026 V	– 0.000 011 V	± 0.000 019 V
NMIA	– 0.000 002 V	± 0.000 018 V	– 0.000 001 V	± 0.000 005 V
NIMT	+ 0.000 001 V	± 0.000 013 V	– 0.000 002 V	± 0.000 011 V
SCL	–	–	+ 0.000 028 V	± 0.000 041 V
NMC	+ 0.000 006 V	± 0.000 010 V	+ 0.000 005 V	± 0.000 007 V

Laboratory	1.005 kHz		20 kHz	
	Value	Uncertainty	Value	Uncertainty
NPLI	+ 0.000 017 V	± 0.000 048 V	+ 0.000 261 V	± 0.000 050 V
NIM	– 0.000 009 V	± 0.000 014 V	– 0.000 015 V	± 0.000 021 V
NMIA	– 0.000 002 V	± 0.000 005 V	– 0.000 001 V	± 0.000 005 V
NIMT	– 0.000 008 V	± 0.000 011 V	– 0.000 007 V	± 0.000 010 V
SCL	+ 0.000 020 V	± 0.000 016 V	+ 0.000 019 V	± 0.000 017 V
NMC	+ 0.000 009 V	± 0.000 011 V	+ 0.000 006 V	± 0.000 010 V

Laboratory	50 kHz		1 MHz	
	Value	Uncertainty	Value	Uncertainty
NPLI	+ 0.000 072 V	± 0.000 105 V	+ 0.006 37 V	± 0.000 63 V
NIM	– 0.000 016 V	± 0.000 042 V	– 0.000 18 V	± 0.000 43 V
NMIA	– 0.000 002 V	± 0.000 009 V	+ 0.000 14 V	± 0.000 12 V
NIMT	– 0.000 009 V	± 0.000 012 V	+ 0.007 07 V	± 0.000 33 V
SCL	+ 0.000 016 V	± 0.000 017 V	– 0.000 15 V	± 0.000 12 V
NMC	+ 0.000 004 V	± 0.000 010 V	+ 0.000 02 V	± 0.000 11 V

10 V

Laboratory	10 Hz		55 Hz	
	Value	Uncertainty	Value	Uncertainty
NPLI	+ 0.001 39 V	± 0.000 55 V	– 0.000 19 V	± 0.000 45 V
NIM	– 0.000 16 V	± 0.000 25 V	– 0.000 08 V	± 0.000 17 V
NMIA	+ 0.000 02 V	± 0.000 17 V	+ 0.000 01 V	± 0.000 07 V
NIMT	+ 0.000 04 V	± 0.000 14 V	– 0.000 03 V	± 0.000 12 V
SCL	–	–	+ 0.000 10 V	± 0.000 13 V
NMC	0.000 00 V	± 0.000 10 V	– 0.000 02 V	± 0.000 08 V

Laboratory	1.005 kHz		20 kHz	
	Value	Uncertainty	Value	Uncertainty
NPLI	+ 0.000 15 V	± 0.000 35 V	+ 0.000 09 V	± 0.000 48 V
NIM	– 0.000 06 V	± 0.000 11 V	– 0.000 08 V	± 0.000 16 V
NMIA	+ 0.000 05 V	± 0.000 07 V	+ 0.000 04 V	± 0.000 07 V
NIMT	– 0.000 02 V	± 0.000 12 V	– 0.000 02 V	± 0.000 12 V
SCL	+ 0.000 07 V	± 0.000 12 V	+ 0.000 06 V	± 0.000 12 V
NMC	– 0.000 06 V	± 0.000 08 V	– 0.000 07 V	± 0.000 10 V

Laboratory	50 kHz		1 MHz	
	Value	Uncertainty	Value	Uncertainty
NPLI	– 0.000 01 V	± 0.001 05 V	+ 0.066 9 V	± 0.006 2 V
NIM	– 0.000 05 V	± 0.000 31 V	+ 0.000 4 V	± 0.002 7 V
NMIA	+ 0.000 05 V	± 0.000 10 V	+ 0.001 7 V	± 0.001 2 V
NIMT	0.000 00 V	± 0.000 14 V	+ 0.065 7 V	± 0.003 8 V
SCL	+ 0.000 04 V	± 0.000 11 V	– 0.002 2 V	± 0.001 4 V
NMC	– 0.000 07 V	± 0.000 09 V	+ 0.000 1 V	± 0.001 1 V

19V, 1.005 kHz

Laboratory	Value	Uncertainty
NPLI	+ 0.000 25 V	± 0.000 87 V
NIM	– 0.000 44 V	± 0.000 60 V
NMIA	+ 0.000 18 V	± 0.000 11 V
NIMT	– 0.000 15 V	± 0.000 22 V
SCL	+ 0.000 03 V	± 0.000 21 V
NMC	– 0.000 18 V	± 0.000 16 V

100 V

Laboratory	10 Hz		55 Hz	
	Value	Uncertainty	Value	Uncertainty
NPLI	+ 0.014 4 V	± 0.005 7 V	+ 0.000 2 V	± 0.004 1 V
NIM	– 0.006 3 V	± 0.021 0 V	0.000 0 V	± 0.003 2 V
NMIA	+ 0.000 7 V	± 0.001 7 V	0.000 0 V	± 0.000 9 V
NIMT	+ 0.000 4 V	± 0.001 6 V	– 0.000 3 V	± 0.001 5 V
SCL	–	–	+ 0.000 2 V	± 0.001 5 V
NMC	– 0.001 0 V	± 0.001 5 V	– 0.001 3 V	± 0.002 0 V

Laboratory	1.005 kHz		20 kHz	
	Value	Uncertainty	Value	Uncertainty
NPLI	+ 0.000 3 V	± 0.003 6 V	+ 0.002 7 V	± 0.005 5 V
NIM	+ 0.000 1 V	± 0.003 1 V	+ 0.000 1 V	± 0.003 2 V
NMIA	+ 0.000 5 V	± 0.000 9 V	+ 0.000 5 V	± 0.000 9 V
NIMT	– 0.000 3 V	± 0.001 5 V	– 0.000 2 V	± 0.001 6 V
SCL	+ 0.000 1 V	± 0.001 3 V	+ 0.000 3 V	± 0.001 4 V
NMC	– 0.001 0 V	± 0.001 6 V	– 0.001 0 V	± 0.001 4 V

Laboratory	50 kHz	
	Value	Uncertainty
NPLI	– 0.000 6 V	± 0.010 4 V
NIM	0.000 0 V	± 0.006 6 V
NMIA	+ 0.000 7 V	± 0.001 2 V
NIMT	+ 0.000 1 V	± 0.002 1 V
SCL	+ 0.000 3 V	± 0.001 4 V
NMC	– 0.001 0 V	± 0.001 3 V

700 V

Laboratory	55 Hz		1.005 kHz	
	Value	Uncertainty	Value	Uncertainty
NPLI	+ 0.015 V	± 0.041 V	+ 0.024 V	± 0.035 V
NIM	0.000 V	± 0.028 V	0.000 V	± 0.025 V
NMIA	– 0.001 V	± 0.008 V	0.000 V	± 0.007 V
NIMT	+ 0.001 V	± 0.024 V	0.000 V	± 0.019 V
SCL	+ 0.006 V	± 0.013 V	+ 0.004 V	± 0.011 V
NMC	– 0.004 V	± 0.012 V	– 0.005 V	± 0.015 V

Laboratory	20 kHz		50 kHz	
	Value	Uncertainty	Value	Uncertainty
NPLI	+ 0.006 V	± 0.042 V	– 0.153 V	± 0.057 V
NIM	+ 0.004 V	± 0.028 V	+ 0.006 V	± 0.046 V
NMIA	– 0.002 V	± 0.008 V	– 0.004 V	± 0.016 V
NIMT	0.000 V	± 0.019 V	+ 0.003 V	± 0.029 V
SCL	+ 0.003 V	± 0.019 V	+ 0.003 V	± 0.028 V
NMC	+ 0.001 V	± 0.017 V	+ 0.001 V	± 0.020 V

Alternating Current

1 mA

Laboratory	55 Hz		1.005 kHz	
	Value	Uncertainty	Value	Uncertainty
NPLI	– 0.000 046 mA	± 0.000 092 mA	– 0.000 048 mA	± 0.000 094 mA
NIM	+ 0.000 031 mA	± 0.000 063 mA	+ 0.000 045 mA	± 0.000 069 mA
NMIA	+ 0.000 019 mA	± 0.000 049 mA	+ 0.000 006 mA	± 0.000 056 mA
NIMT	– 0.000 028 mA	± 0.000 107 mA	– 0.000 034 mA	± 0.000 112 mA
SCL	– 0.000 021 mA	± 0.000 049 mA	– 0.000 028 mA	± 0.000 059 mA
NMC	+ 0.000 005 mA	± 0.000 055 mA	+ 0.000 023 mA	± 0.000 064 mA

Laboratory	5 kHz	
	Value	Uncertainty
NPLI	– 0.000 785 mA	± 0.000 129 mA
NIM	+ 0.000 130 mA	± 0.000 074 mA
NMIA	– 0.000 017 mA	± 0.000 062 mA
NIMT	– 0.000 078 mA	± 0.000 114 mA
SCL	– 0.000 053 mA	± 0.000 064 mA
NMC	– 0.000 003 mA	± 0.000 068 mA

1 A

Laboratory	55 Hz		1.005 kHz	
	Value	Uncertainty	Value	Uncertainty
NPLI	– 0.000 104 A	± 0.000 077 A	– 0.000 135 A	± 0.000 072 A
NIM	+ 0.000 020 A	± 0.000 051 A	+ 0.000 014 A	± 0.000 041 A
NMIA	– 0.000 002 A	± 0.000 020 A	– 0.000 003 A	± 0.000 026 A
NIMT	+ 0.000 007 A	± 0.000 077 A	0.000 000 A	± 0.000 076 A
SCL	+ 0.000 002 A	± 0.000 051 A	– 0.000 016 A	± 0.000 046 A
NMC	+ 0.000 001 A	± 0.000 034 A	+ 0.000 005 A	± 0.000 039 A

Laboratory	5 kHz	
	Value	Uncertainty
NPLI	– 0.000 775 A	± 0.000 093 A
NIM	– 0.000 019 A	± 0.000 060 A
NMIA	+ 0.000 016 A	± 0.000 047 A
NIMT	0.000 000 A	± 0.000 086 A
SCL	– 0.000 097 A	± 0.000 163 A
NMC	– 0.000 002 A	± 0.000 053 A

Resistance

10 Ω

Laboratory	Value	Uncertainty
NPLI	+ 0.000 153 Ω	± 0.000 061 Ω
JEMIC	0.000 000 Ω	± 0.000 020 Ω
NIM	– 0.000 004 Ω	± 0.000 020 Ω
NMIA	+ 0.000 003 Ω	± 0.000 017 Ω
NIMT	– 0.000 009 Ω	± 0.000 031 Ω
SCL	– 0.000 004 Ω	± 0.000 023 Ω
NMC	+ 0.000 007 Ω	± 0.000 019 Ω

100 Ω

Laboratory	Value	Uncertainty
NPLI	+ 0.000 27 Ω	± 0.000 42 Ω
JEMIC	– 0.000 02 Ω	± 0.000 09 Ω
NIM	0.000 00 Ω	± 0.000 11 Ω
NMIA	+ 0.000 01 Ω	± 0.000 04 Ω
NIMT	– 0.000 07 Ω	± 0.000 29 Ω
SCL	+ 0.000 01 Ω	± 0.000 40 Ω
NMC	+ 0.000 01 Ω	± 0.000 14 Ω

1 kΩ

Laboratory	Value	Uncertainty
NPLI	+ 0.000 003 9 kΩ	± 0.000 004 4 kΩ
JEMIC	– 0.000 000 5 kΩ	± 0.000 001 4 kΩ
NIM	+ 0.000 000 1 kΩ	± 0.000 001 5 kΩ
NMIA	– 0.000 000 1 kΩ	± 0.000 000 8 kΩ
NIMT	– 0.000 000 3 kΩ	± 0.000 002 3 kΩ
SCL	+ 0.000 000 2 kΩ	± 0.000 000 8 kΩ
NMC	+ 0.000 000 5 kΩ	± 0.000 001 6 kΩ

10 kΩ

Laboratory	Value	Uncertainty
NPLI	+ 0.000 028 kΩ	± 0.000 048 kΩ
JEMIC	0.000 000 kΩ	± 0.000 009 kΩ
NIM	+ 0.000 002 kΩ	± 0.000 018 kΩ
NMIA	– 0.000 002 kΩ	± 0.000 005 kΩ
NIMT	– 0.000 003 kΩ	± 0.000 033 kΩ
SCL	+ 0.000 002 kΩ	± 0.000 006 kΩ
NMC	+ 0.000 009 kΩ	± 0.000 014 kΩ

100 kΩ

Laboratory	Value	Uncertainty
NPLI	+ 0.000 07 kΩ	± 0.000 58 kΩ
JEMIC	– 0.000 01 kΩ	± 0.000 38 kΩ
NIM	– 0.000 06 kΩ	± 0.000 17 kΩ
NMIA	– 0.000 03 kΩ	± 0.000 07 kΩ
NIMT	+ 0.000 08 kΩ	± 0.000 38 kΩ
SCL	– 0.000 04 kΩ	± 0.000 20 kΩ
NMC	+ 0.000 13 kΩ	± 0.000 14 kΩ

1 MΩ

Laboratory	Value	Uncertainty
NPLI	+ 0.000 009 9 MΩ	± 0.000 009 7 MΩ
JEMIC	0.000 000 0 MΩ	± 0.000 003 8 MΩ
NIM	– 0.000 000 7 MΩ	± 0.000 005 1 MΩ
NMIA	+ 0.000 000 3 MΩ	± 0.000 001 1 MΩ
NIMT	+ 0.000 001 8 MΩ	± 0.000 005 5 MΩ
SCL	– 0.000 000 4 MΩ	± 0.000 001 0 MΩ
NMC	+ 0.000 000 8 MΩ	± 0.000 005 2 MΩ

10 MΩ

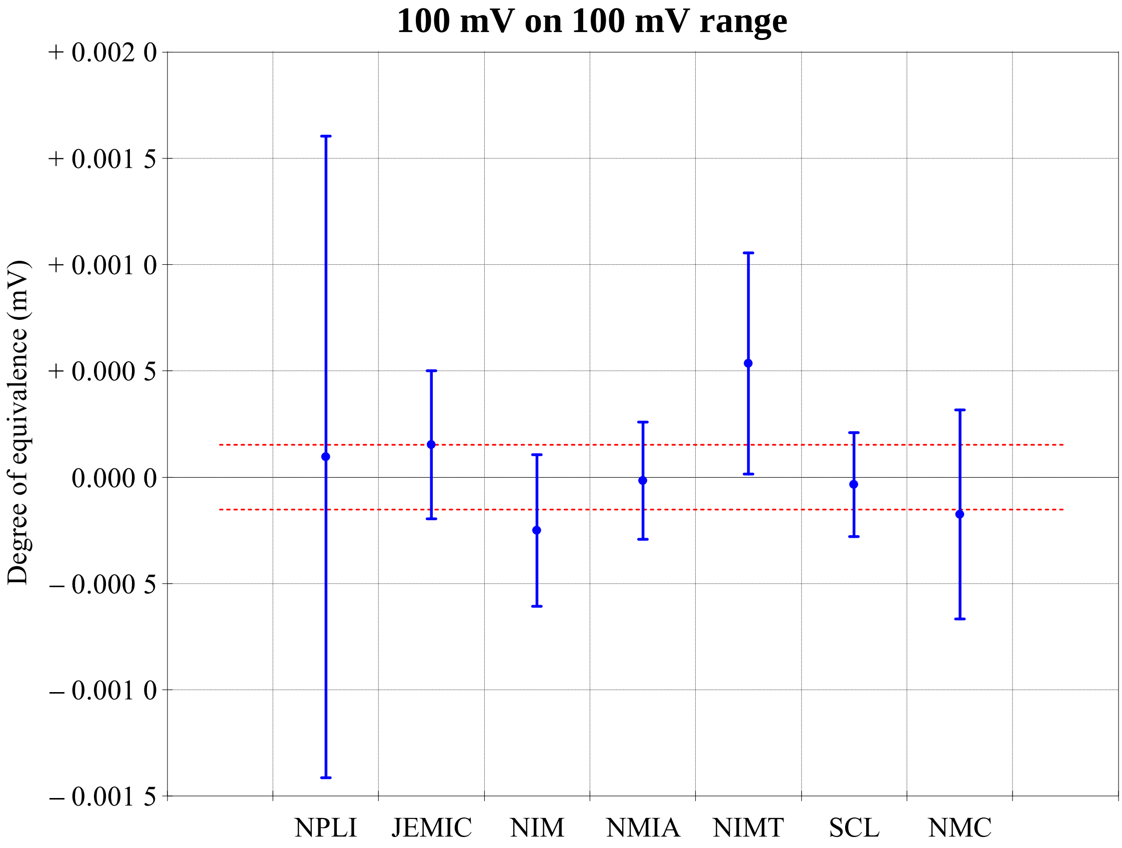
Laboratory	Value	Uncertainty
NPLI	+ 0.000 06 MΩ	± 0.000 15 MΩ
JEMIC	– 0.000 07 MΩ	± 0.000 26 MΩ
NIM	0.000 00 MΩ	± 0.000 06 MΩ
NMIA	0.000 00 MΩ	± 0.000 03 MΩ
NIMT	– 0.000 07 MΩ	± 0.000 10 MΩ
SCL	+ 0.000 02 MΩ	± 0.000 04 MΩ
NMC	0.000 00 MΩ	± 0.000 08 MΩ

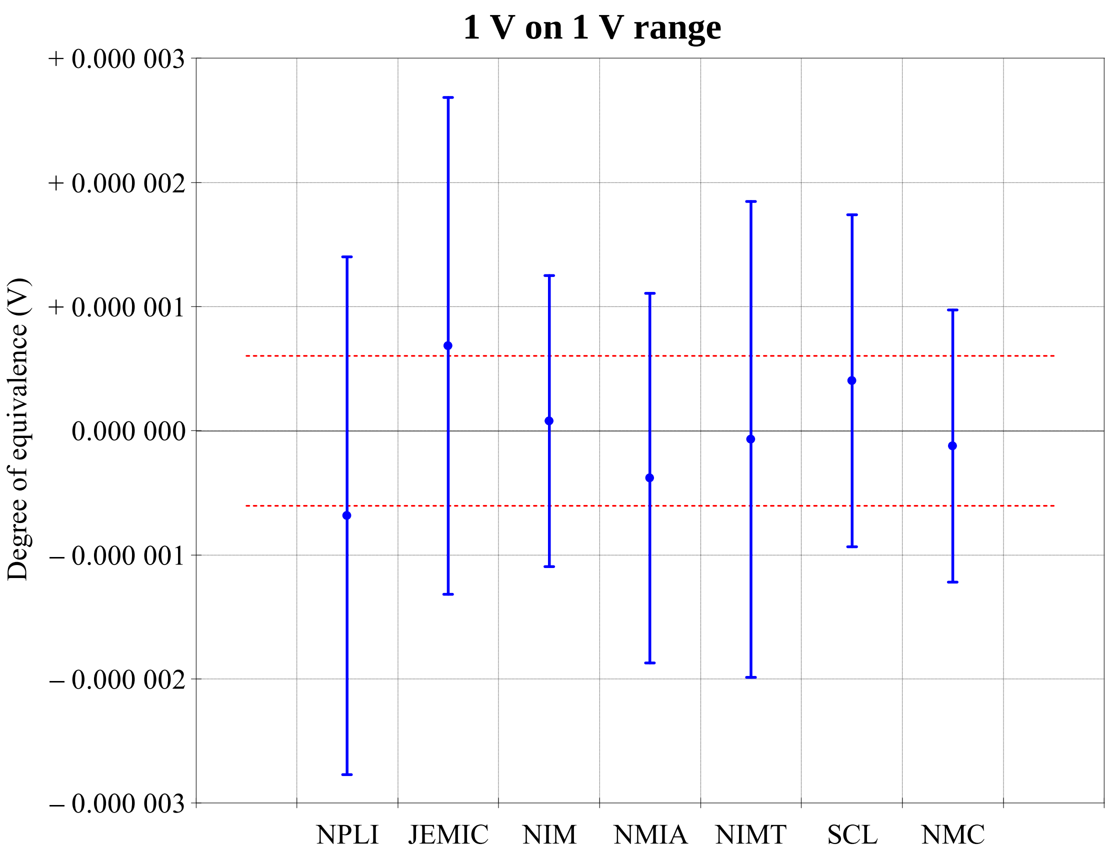
100 MΩ

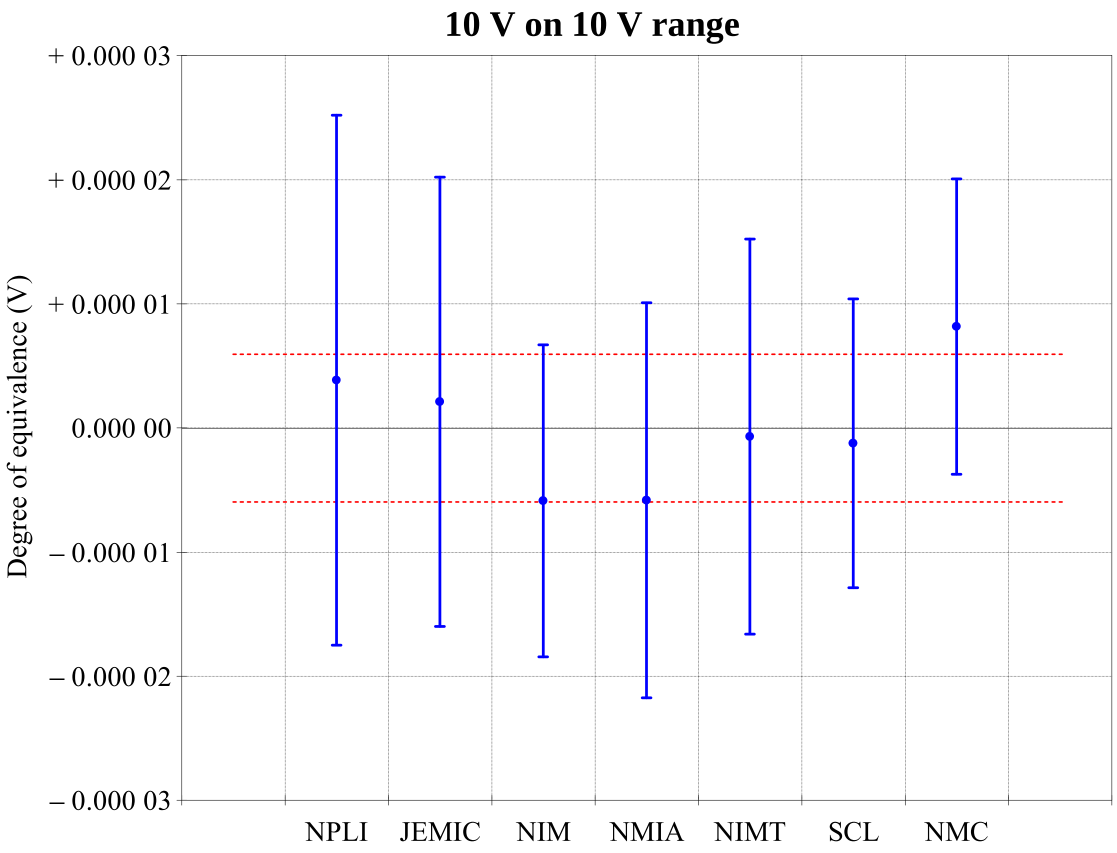
Laboratory	Value	Uncertainty
NPLI	+ 0.023 2 MΩ	± 0.021 0 MΩ
JEMIC	– 0.000 1 MΩ	± 0.002 9 MΩ
NIM	+ 0.000 3 MΩ	± 0.001 9 MΩ
NMIA	+ 0.000 2 MΩ	± 0.001 3 MΩ
NIMT	0.000 0 MΩ	± 0.005 9 MΩ
SCL	– 0.000 6 MΩ	± 0.001 5 MΩ
NMC	+ 0.000 4 MΩ	± 0.002 0 MΩ

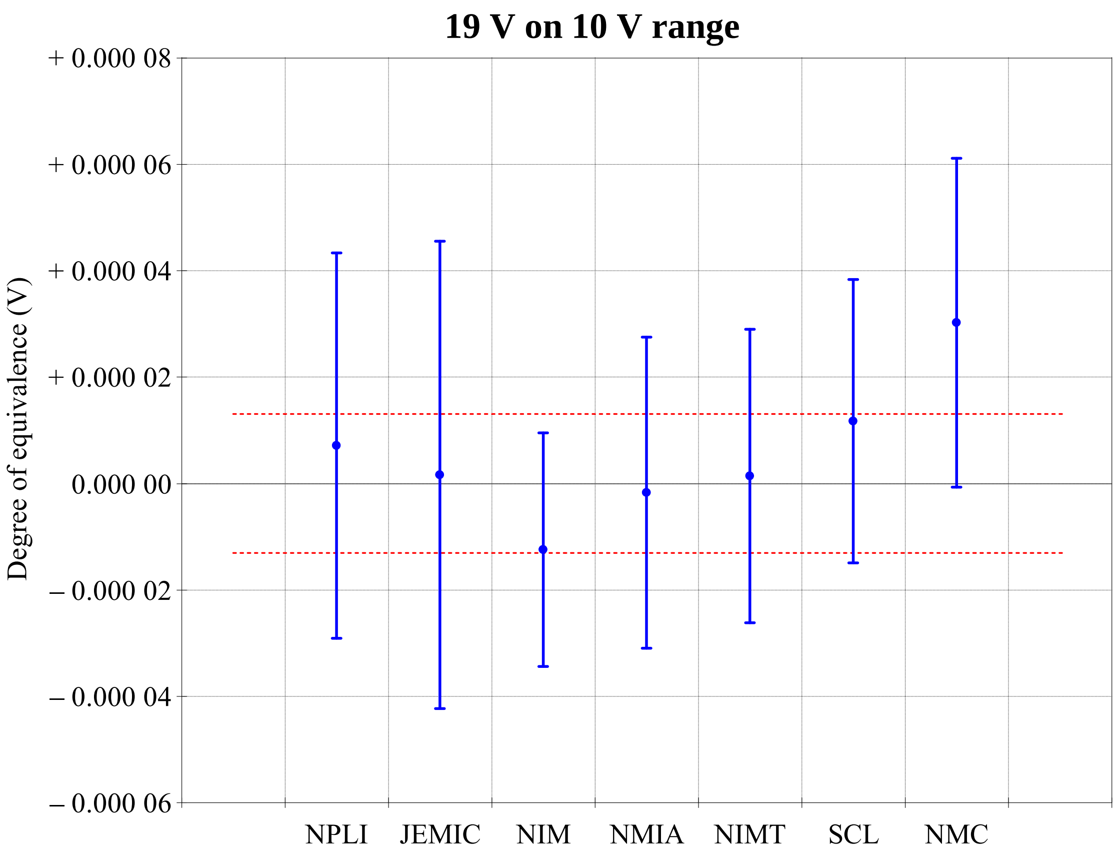
Appendix II: Graphs

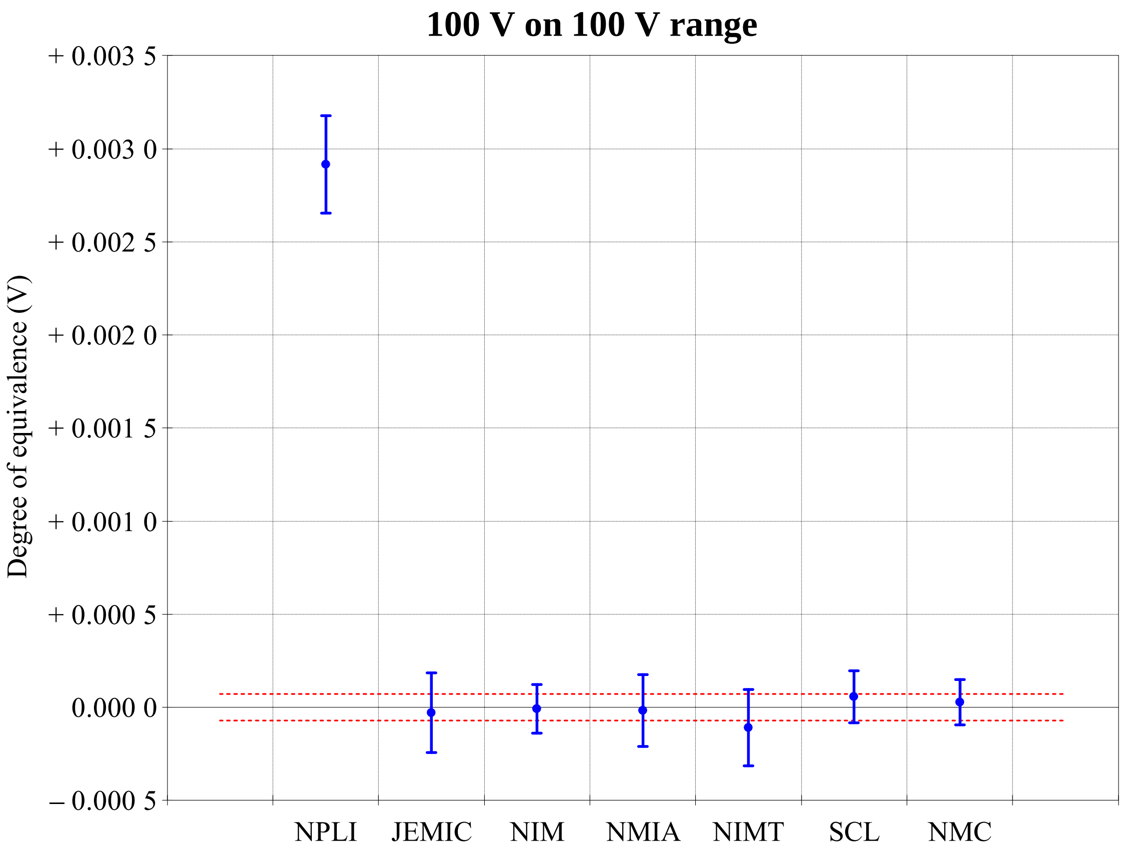
Direct Voltage

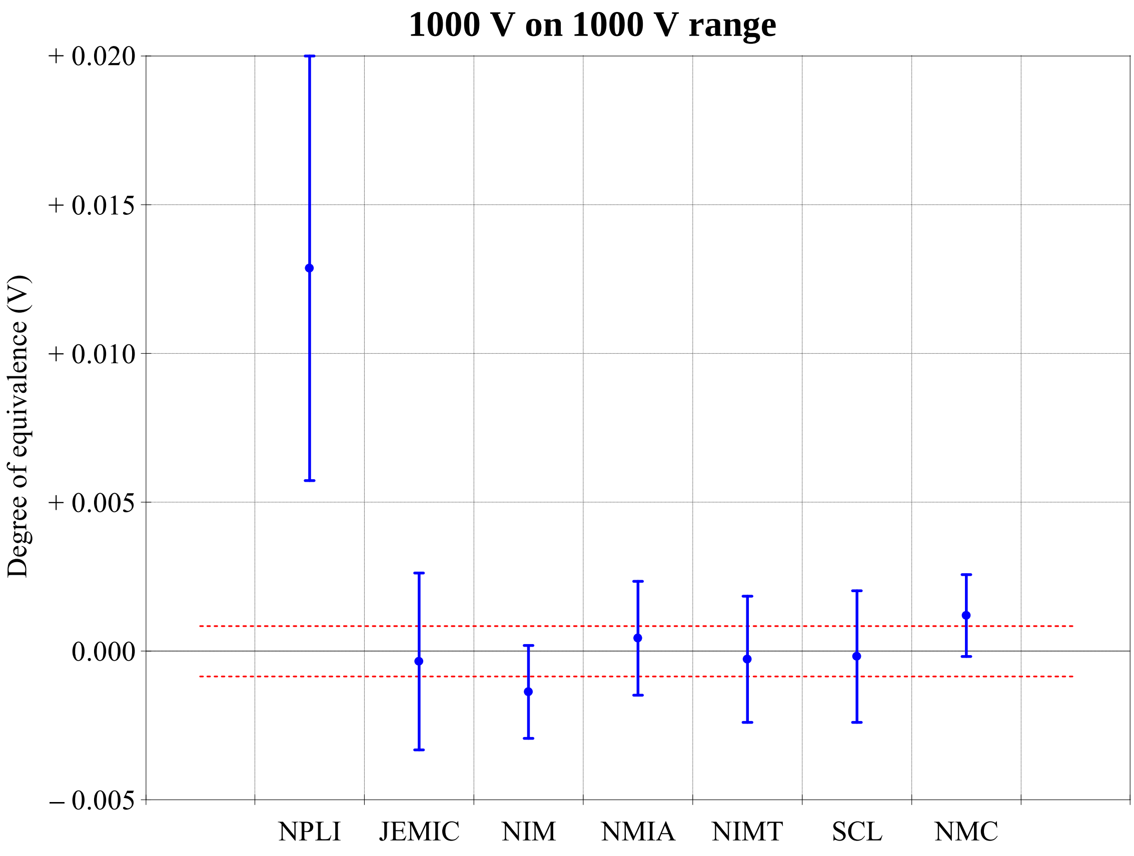




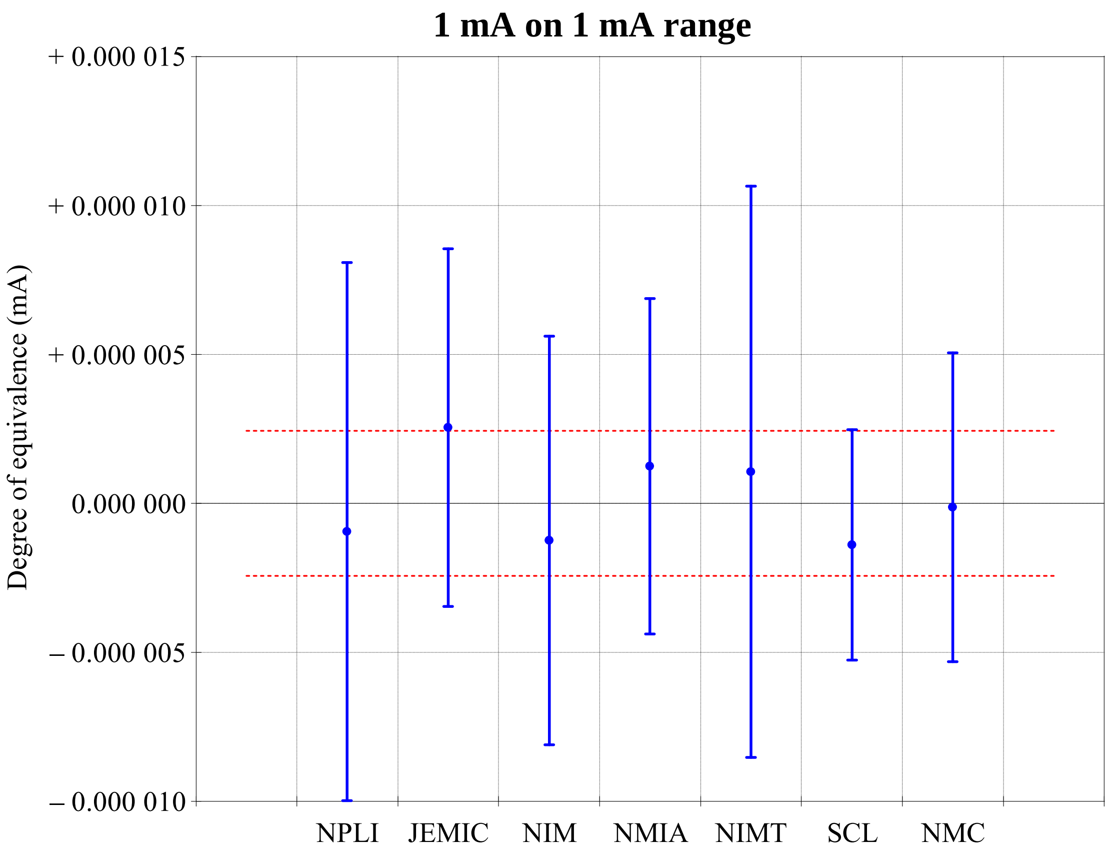

10 V on 10 V range
+ 0.000 03
+ 0.000 02
+ 0.000 01
0.000 00
– 0.000 01
– 0.000 02
– 0.000 03
Degree of equivalence (V)
NPLI
JEMIC
NIM
NMIA
NIMT
SCL
NMC


19 V on 10 V range
+ 0.000 08
+ 0.000 06
+ 0.000 04
+ 0.000 02
0.000 00
– 0.000 02
– 0.000 04
– 0.000 06
Degree of equivalence (V)
NPLI
JEMIC
NIM
NMIA
NIMT
SCL
NMC

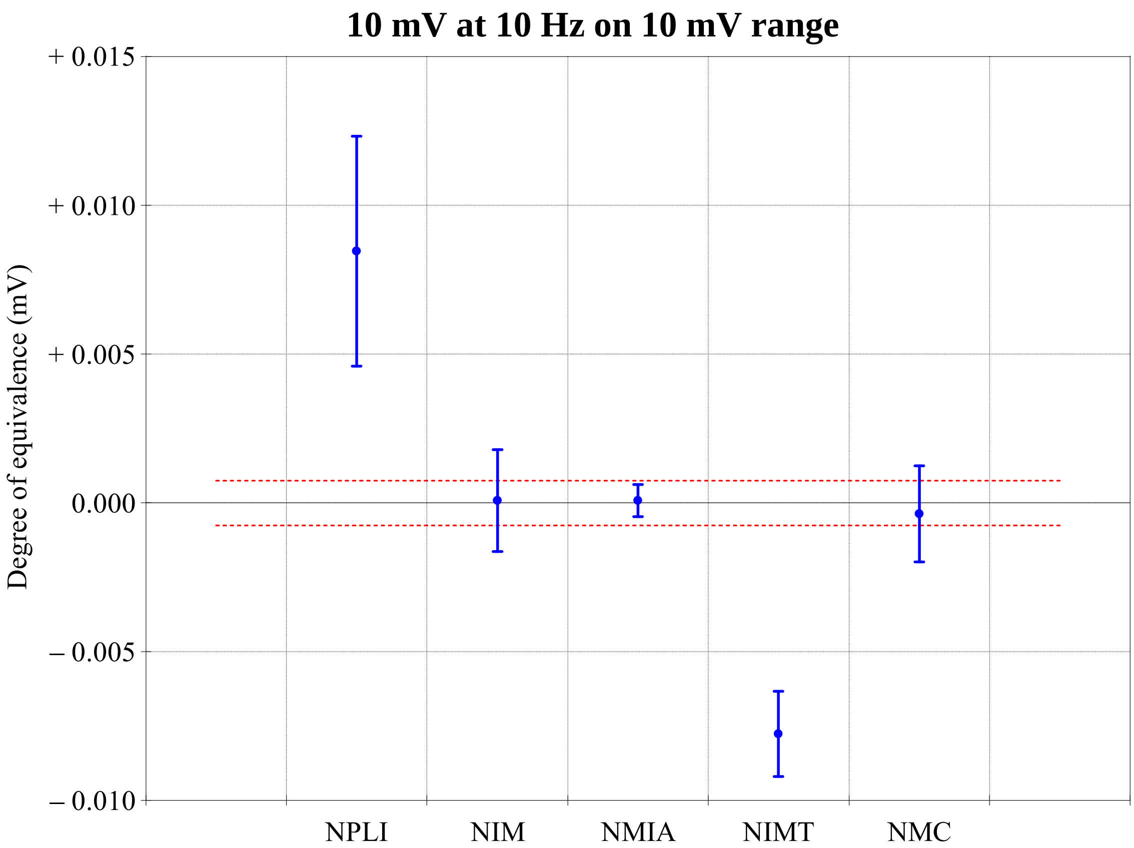

100 V on 100 V range
Degree of equivalence (V)
+ 0.003 5
+ 0.003 0
+ 0.002 5
+ 0.002 0
+ 0.001 5
+ 0.001 0
+ 0.000 5
0.000 0
– 0.000 5
NPLI
JEMIC
NIM
NMIA
NIMT
SCL
NMC

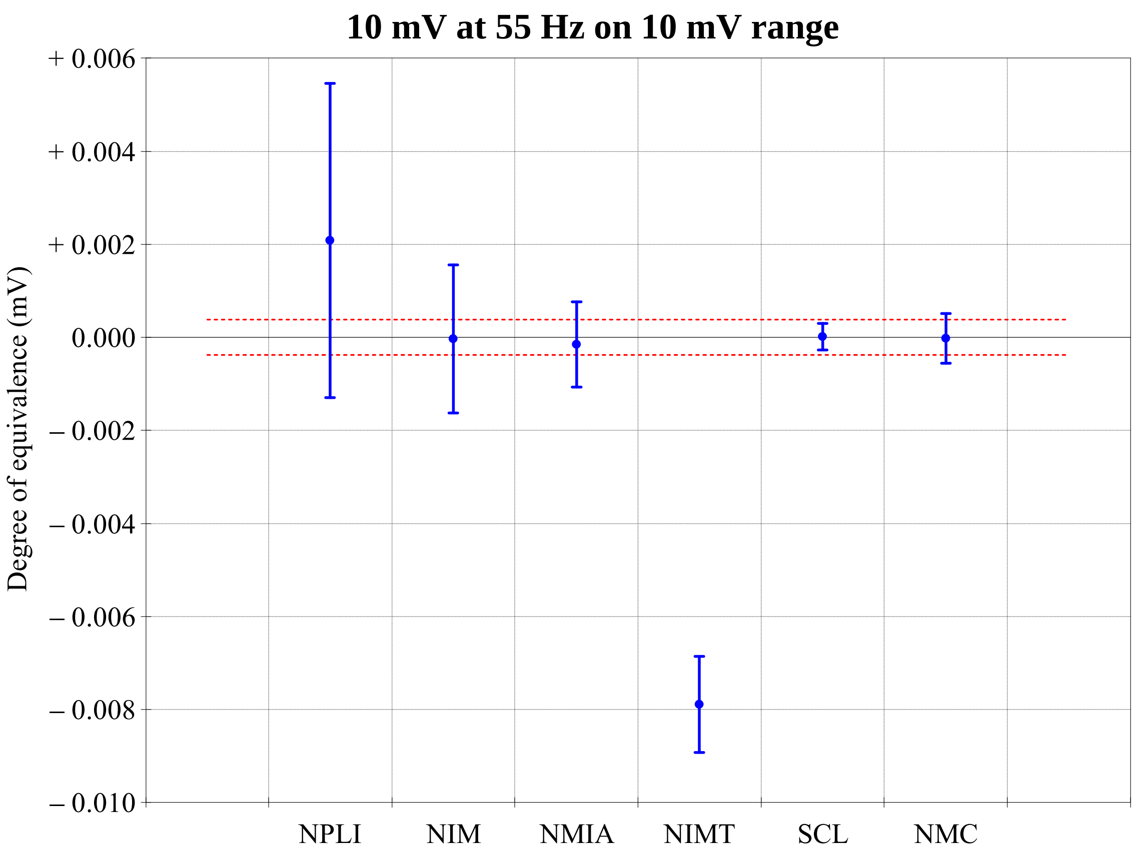

1000 V on 1000 V range
Degree of equivalence (V)
+ 0.020
+ 0.015
+ 0.010
+ 0.005
0.000
– 0.005
NPLI
JEMIC
NIM
NMIA
NIMT
SCL
NMC

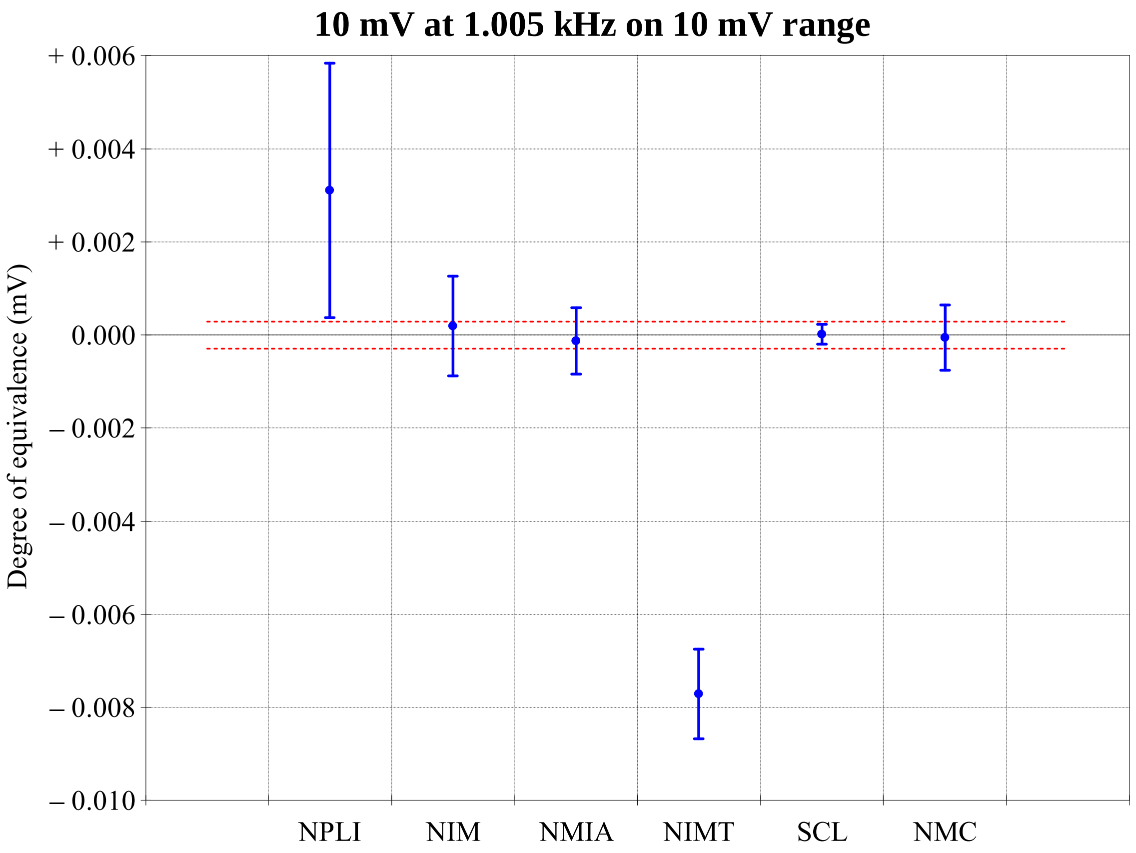
Direct Current

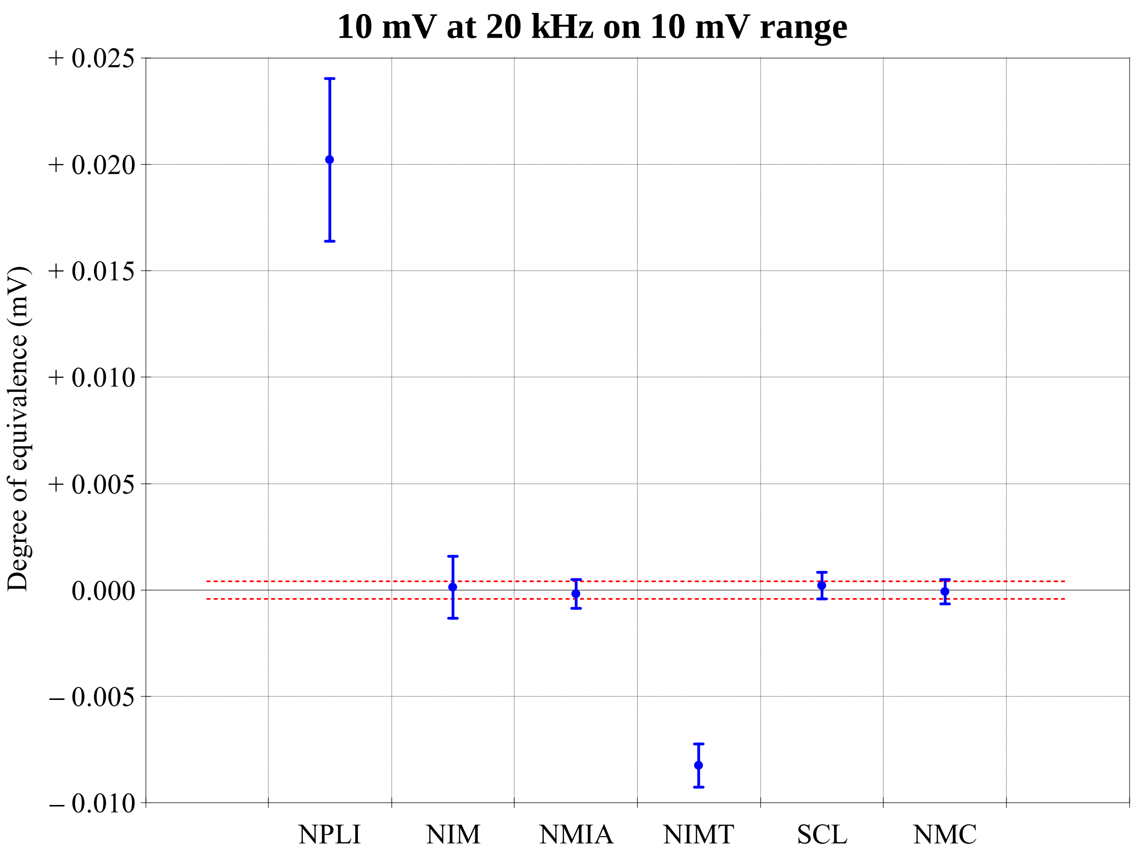


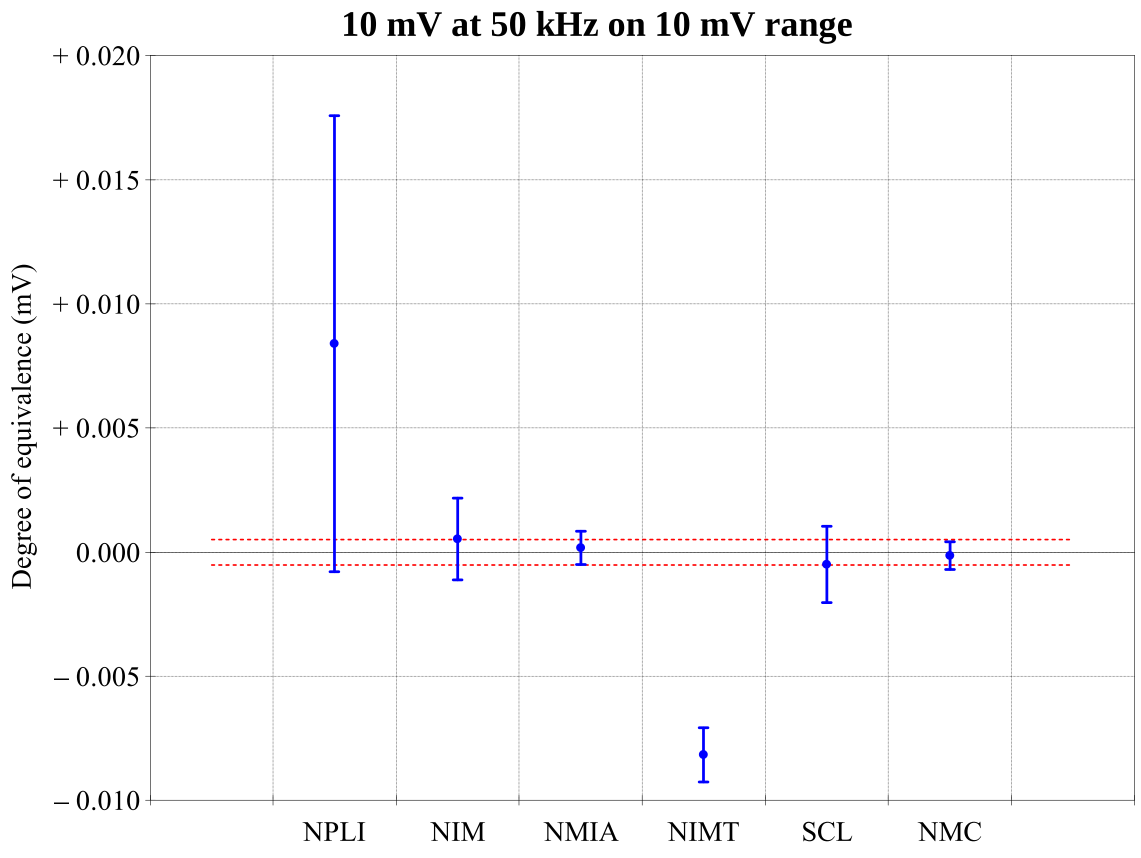
Alternating Voltage

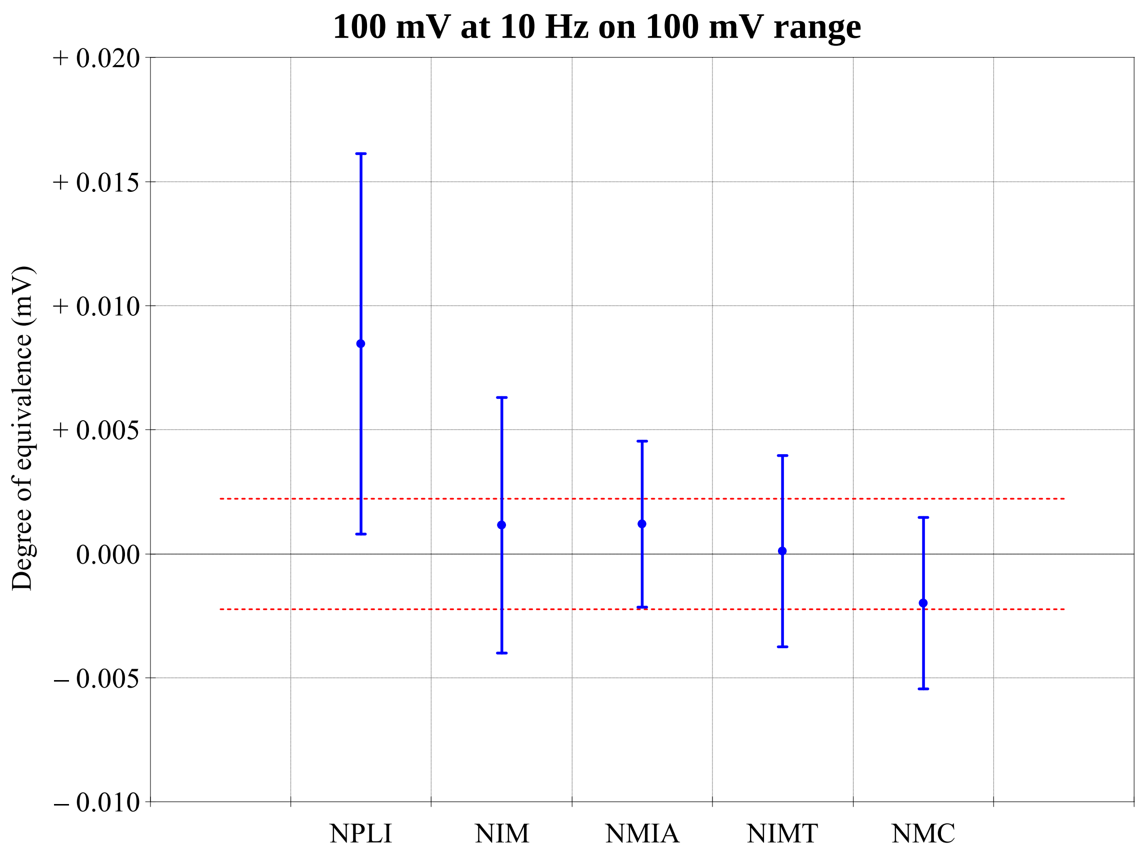


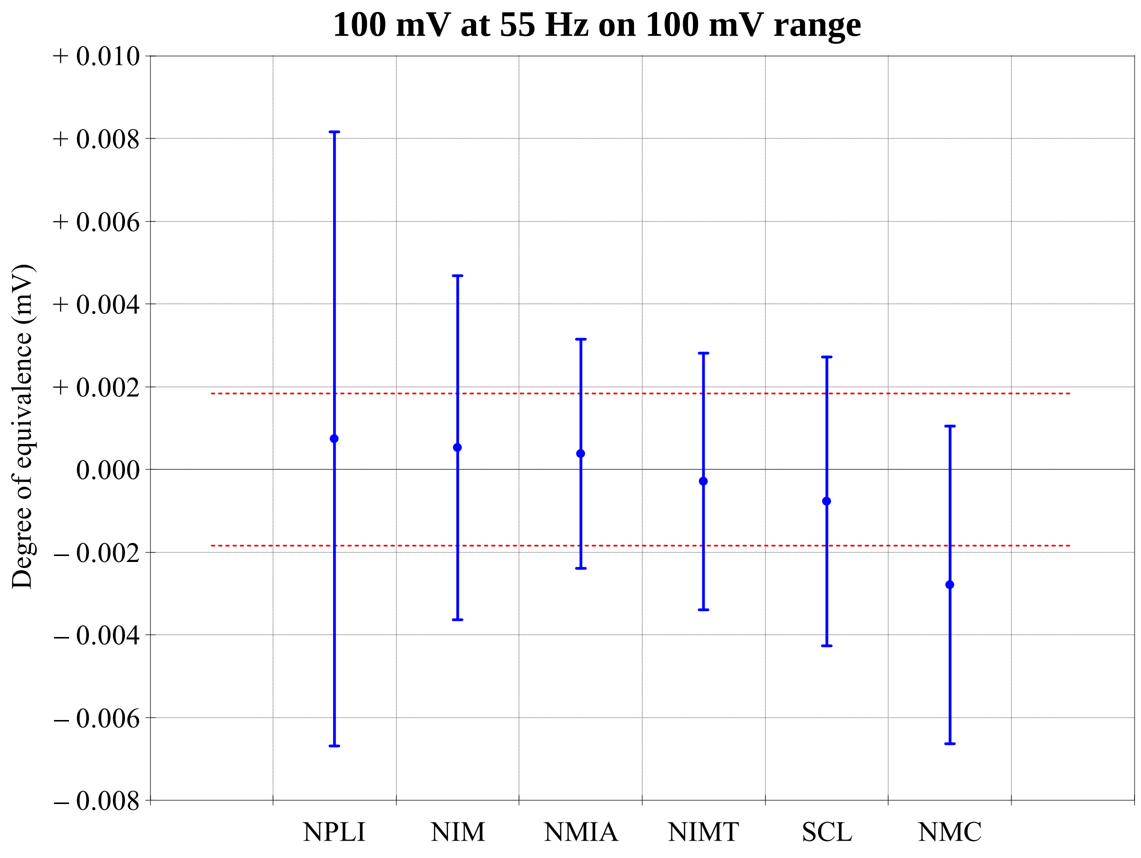


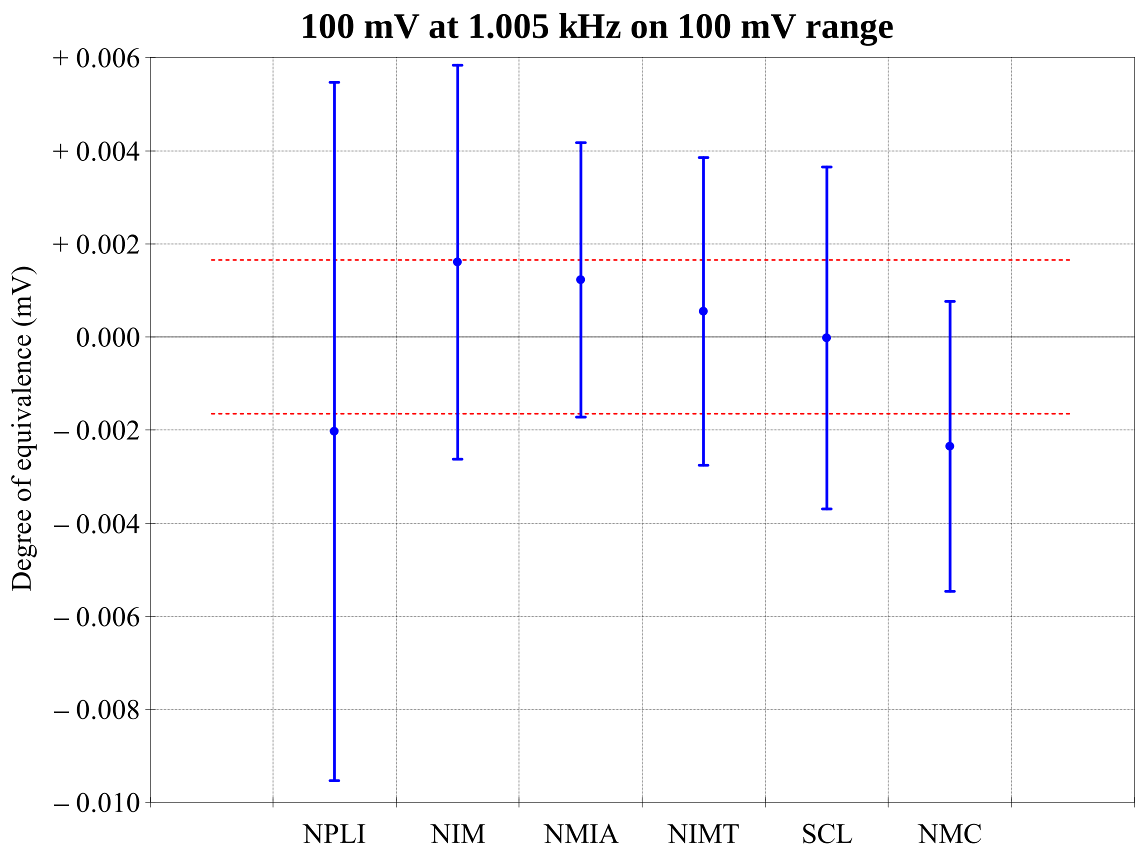

10 mV at 1.005 kHz on 10 mV range
Degree of equivalence (mV)
+ 0.006
+ 0.004
+ 0.002
0.000
– 0.002
– 0.004
– 0.006
– 0.008
– 0.010
NPLI
NIM
NMIA
NIMT
SCL
NMC


10 mV at 20 kHz on 10 mV range
Degree of equivalence (mV)
+ 0.025
+ 0.020
+ 0.015
+ 0.010
+ 0.005
0.000
– 0.005
– 0.010
NPLI
NIM
NMIA
NIMT
SCL
NMC

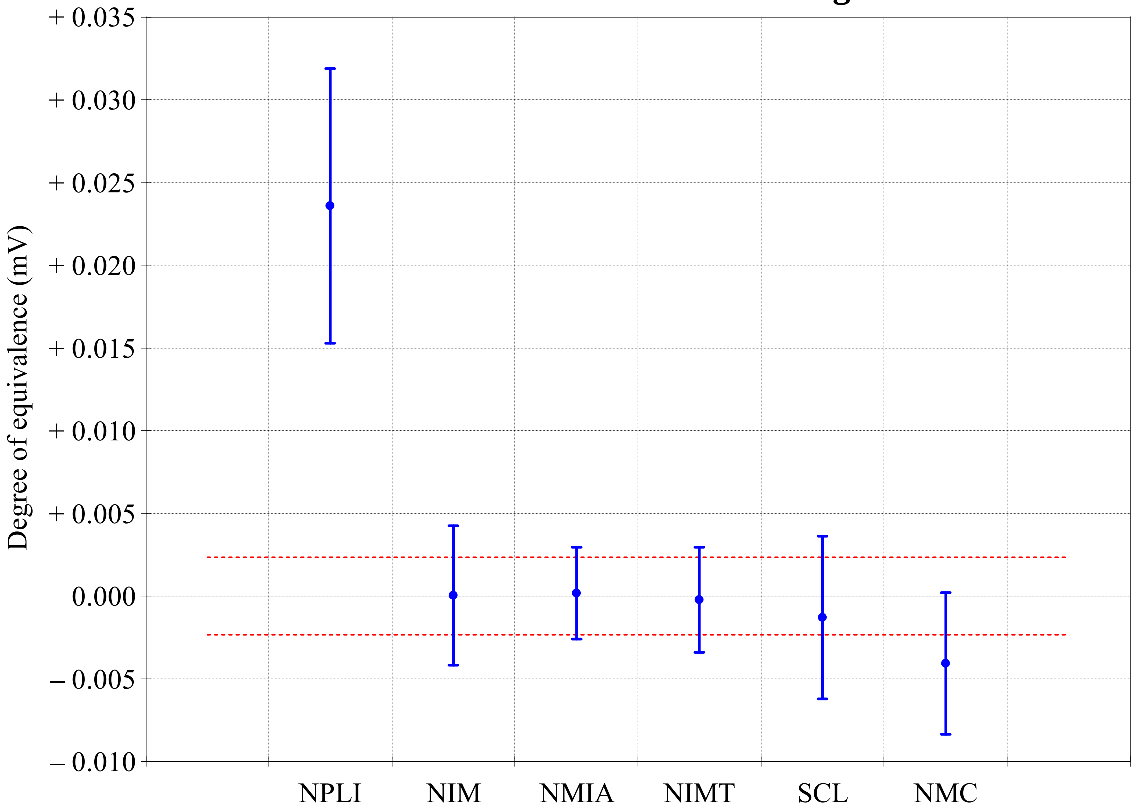

10 mV at 50 kHz on 10 mV range
Degree of equivalence (mV)
+ 0.020
+ 0.015
+ 0.010
+ 0.005
0.000
– 0.005
– 0.010
NPLI
NIM
NMIA
NIMT
SCL
NMC


100 mV at 10 Hz on 100 mV range
Degree of equivalence (mV)
+ 0.020
+ 0.015
+ 0.010
+ 0.005
0.000
– 0.005
– 0.010
NPLI
NIM
NMIA
NIMT
NMC

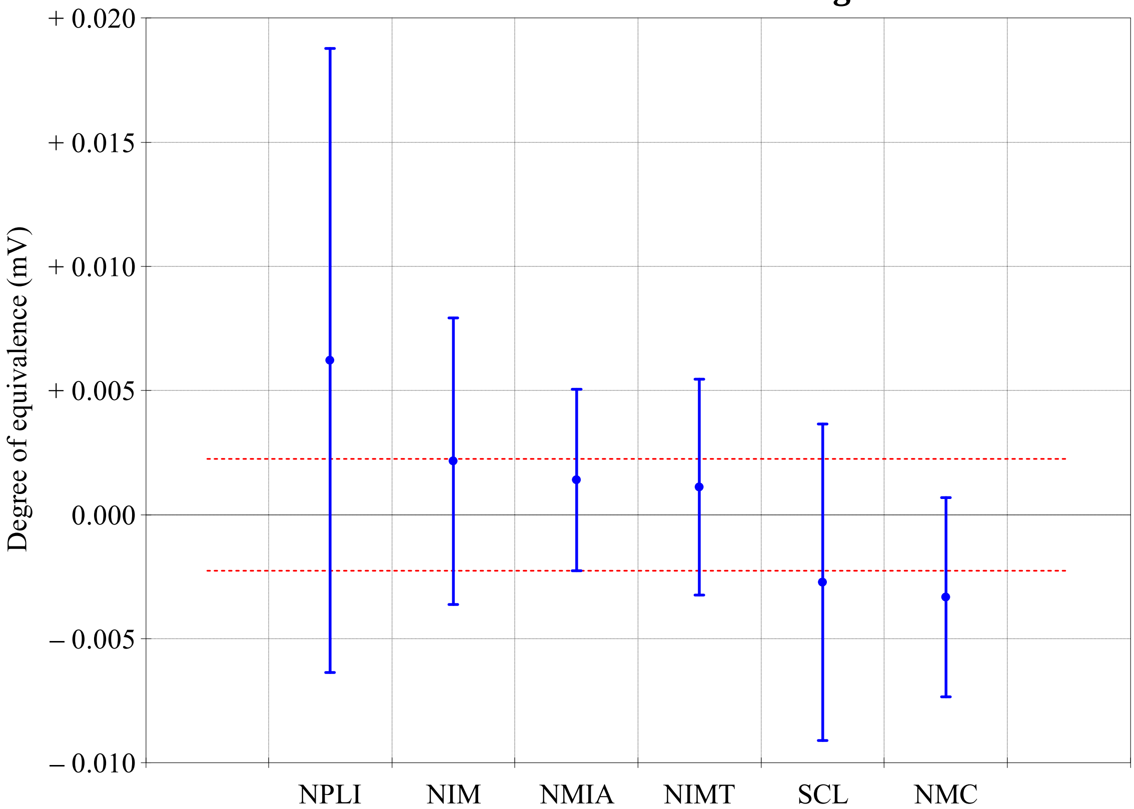

100 mV at 55 Hz on 100 mV range
+ 0.010
+ 0.008
+ 0.006
+ 0.004
+ 0.002
0.000
– 0.002
– 0.004
– 0.006
– 0.008
Degree of equivalence (mV)
NPLI
NIM
NMIA
NIMT
SCL
NMC

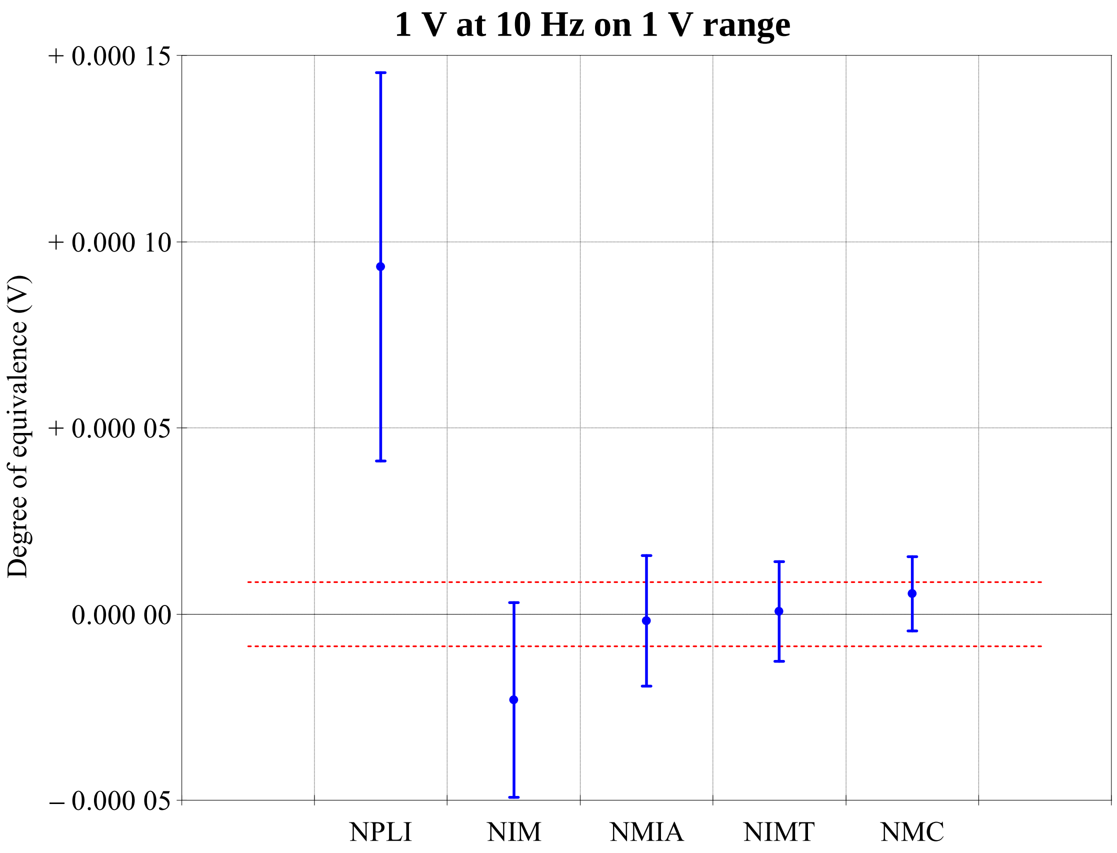

100 mV at 1.005 kHz on 100 mV range
+ 0.006
+ 0.004
+ 0.002
0.000
– 0.002
– 0.004
– 0.006
– 0.008
– 0.010
Degree of equivalence (mV)
NPLI
NIM
NMIA
NIMT
SCL
NMC

100 mV at 20 kHz on 100 mV range

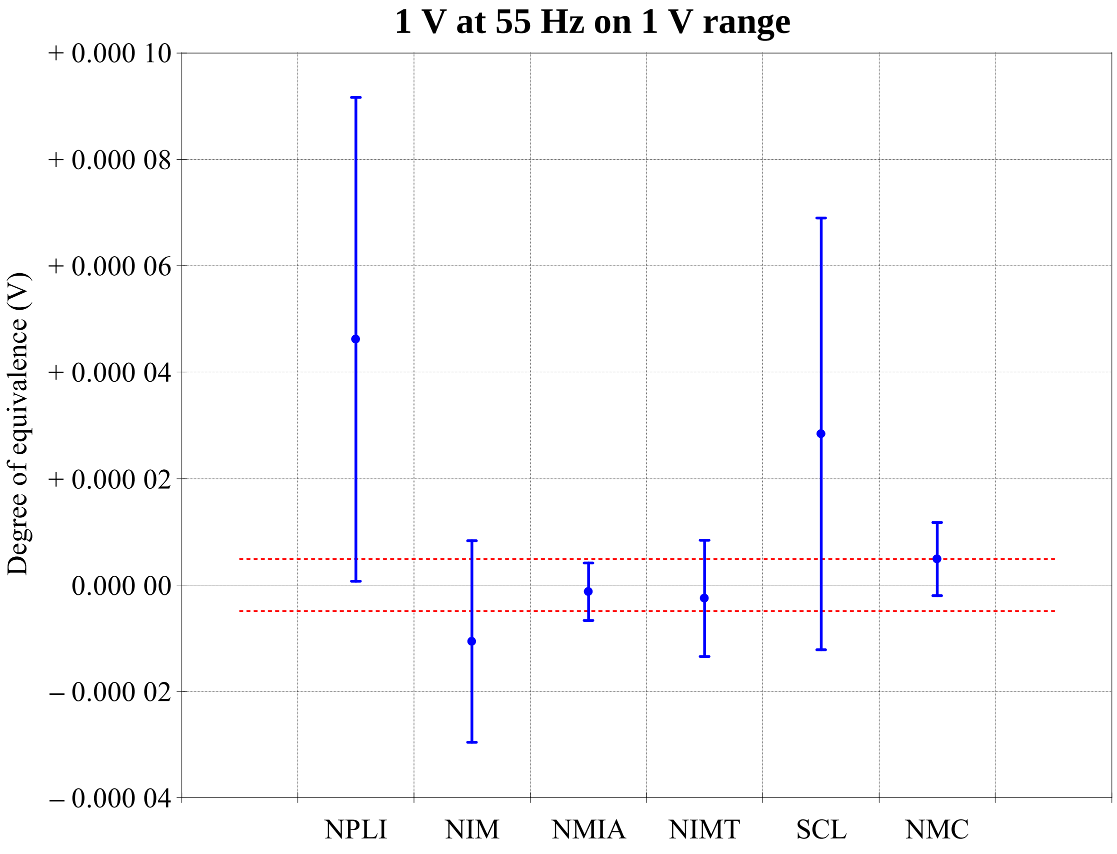


100 mV at 50 kHz on 100 mV range

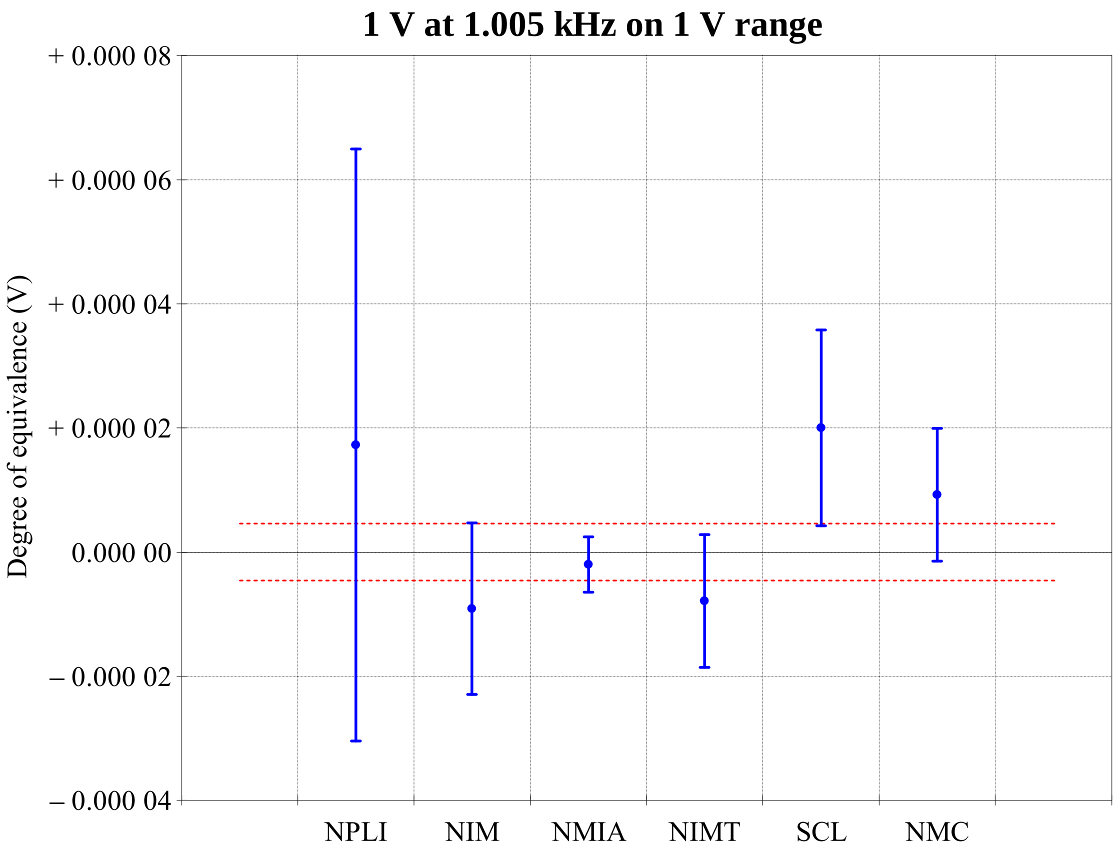


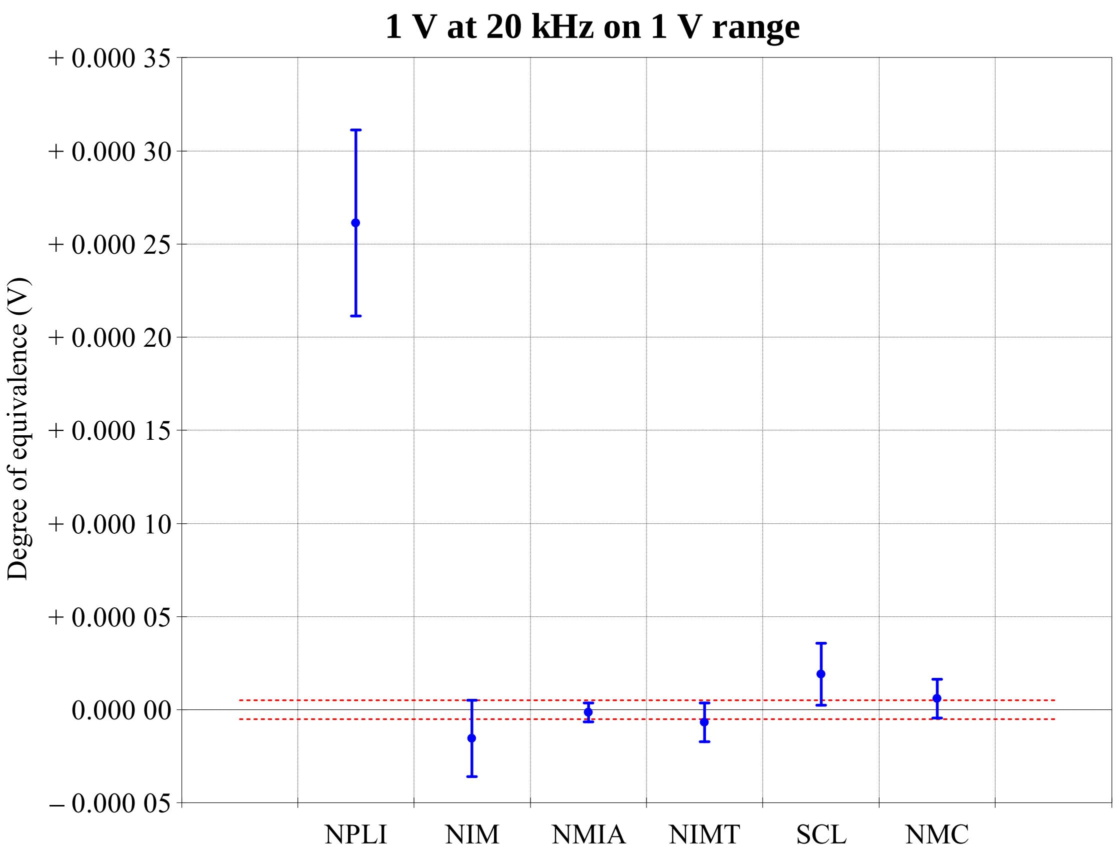


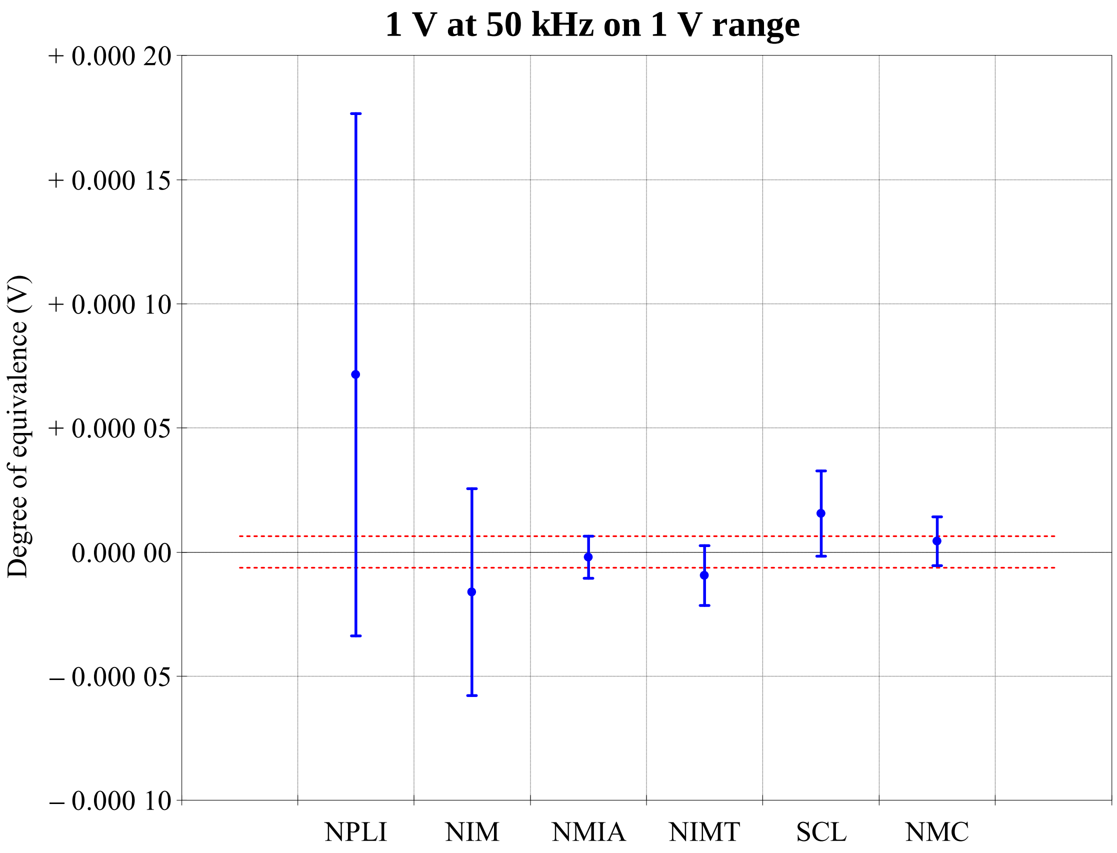
1 V at 10 Hz on 1 V range
+ 0.000 15
+ 0.000 10
+ 0.000 05
0.000 00
– 0.000 05
Degree of equivalence (V)
NPLI
NIM
NMIA
NIMT
NMC

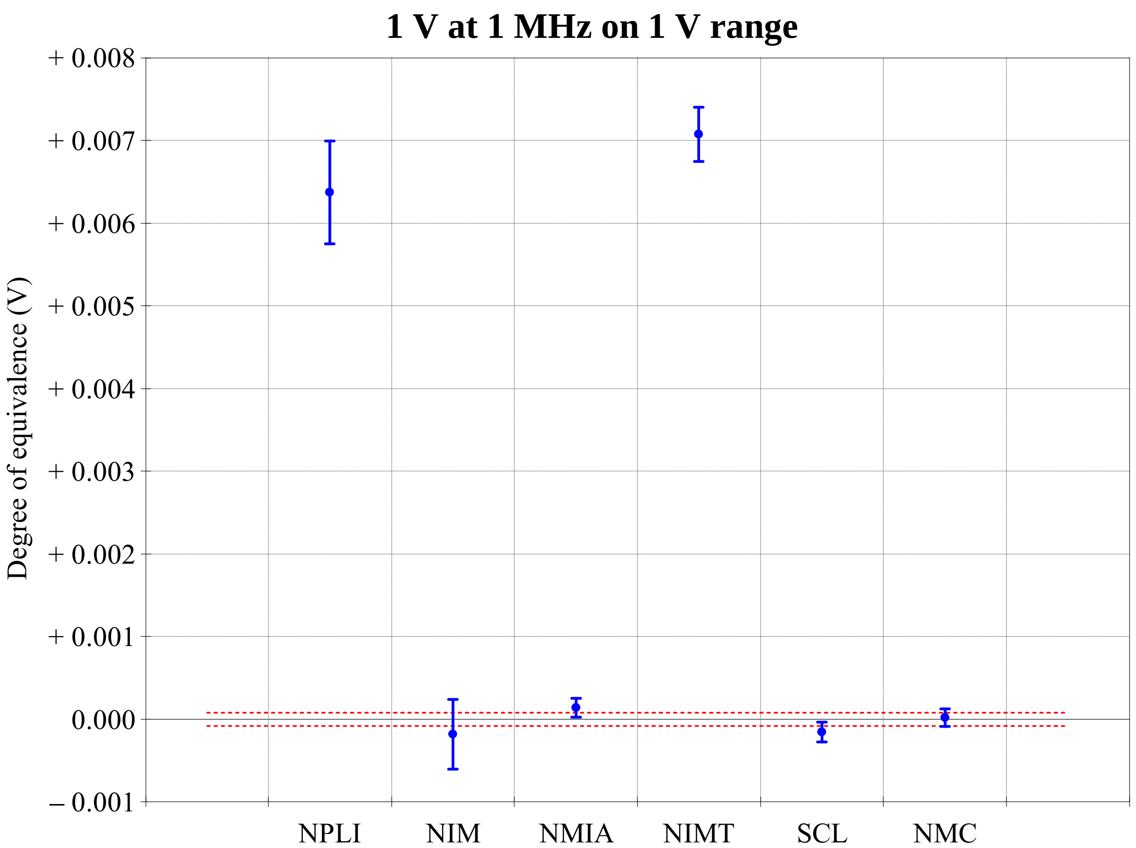


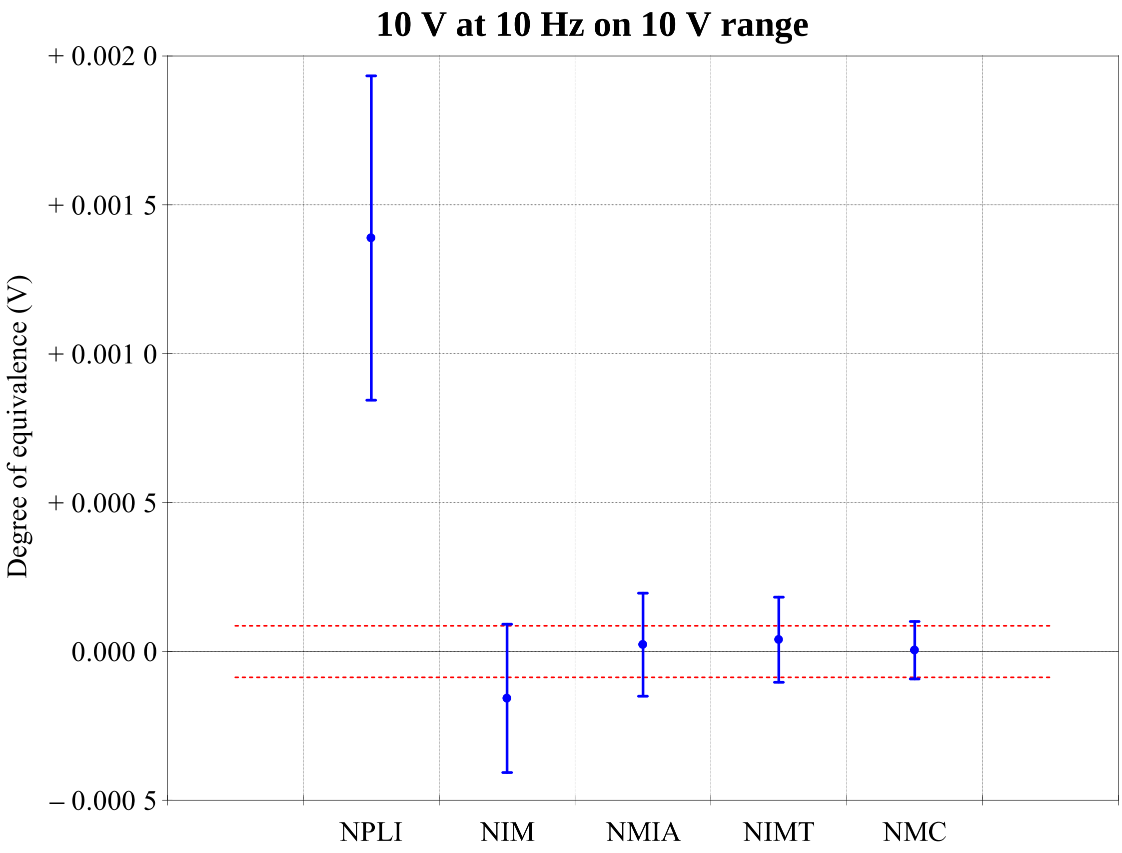
1 V at 55 Hz on 1 V range
+ 0.000 10
+ 0.000 08
+ 0.000 06
+ 0.000 04
+ 0.000 02
0.000 00
– 0.000 02
– 0.000 04
Degree of equivalence (V)
NPLI
NIM
NMIA
NIMT
SCL
NMC

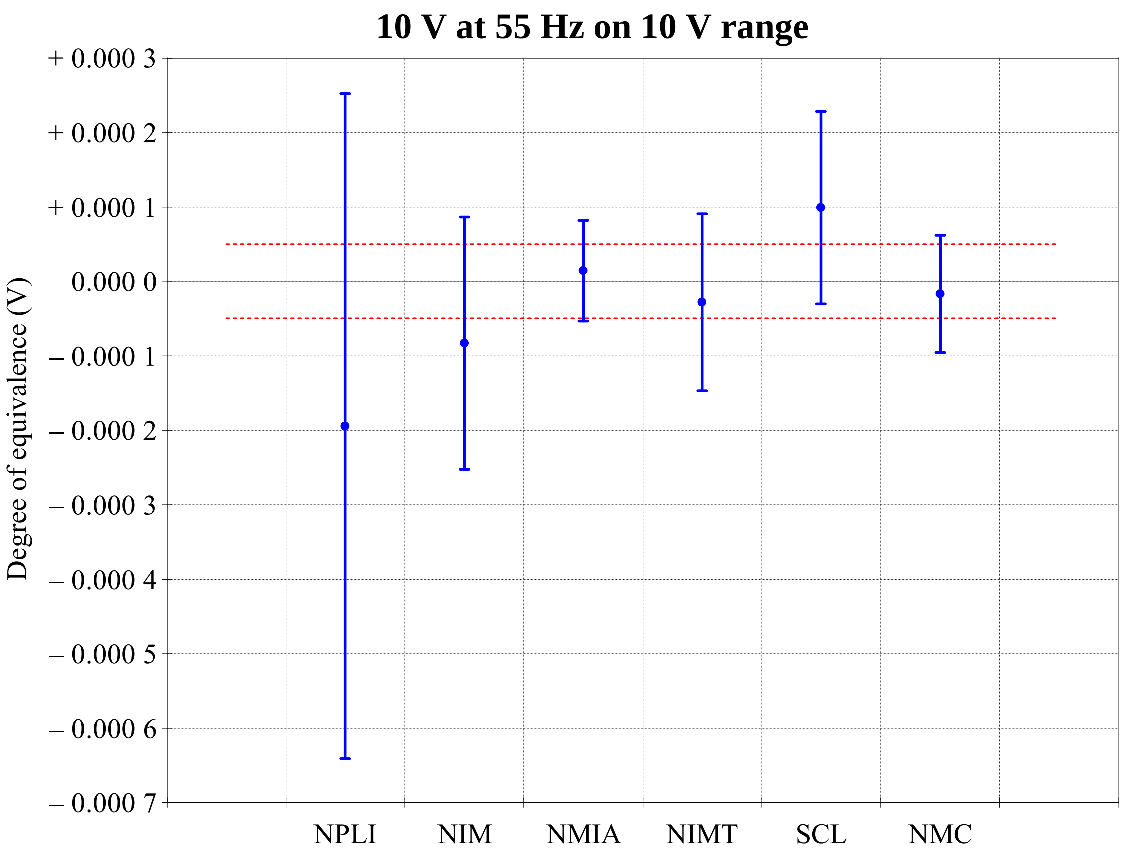

1 V at 1.005 kHz on 1 V range
Degree of equivalence (V)
+ 0.000 08
+ 0.000 06
+ 0.000 04
+ 0.000 02
0.000 00
– 0.000 02
– 0.000 04
NPLI
NIM
NMIA
NIMT
SCL
NMC

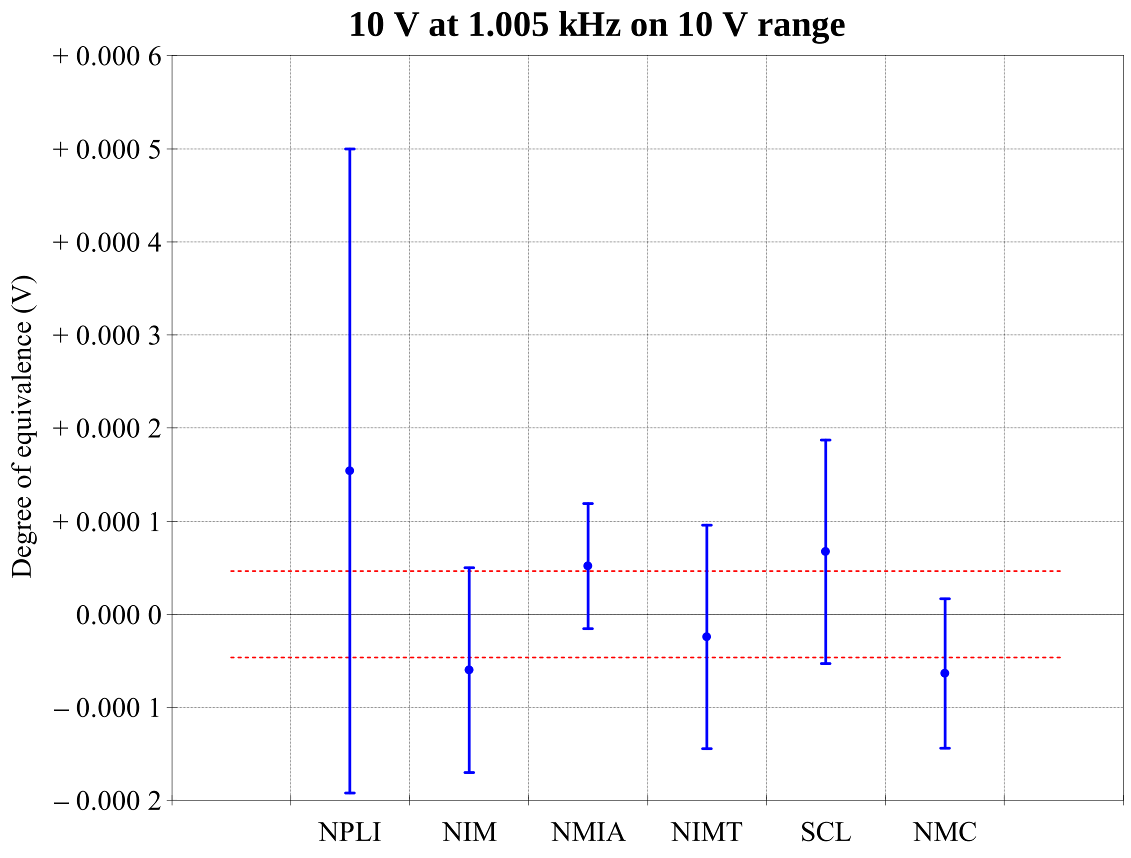

1 V at 20 kHz on 1 V range
Degree of equivalence (V)
+ 0.000 35
+ 0.000 30
+ 0.000 25
+ 0.000 20
+ 0.000 15
+ 0.000 10
+ 0.000 05
0.000 00
– 0.000 05
NPLI
NIM
NMIA
NIMT
SCL
NMC

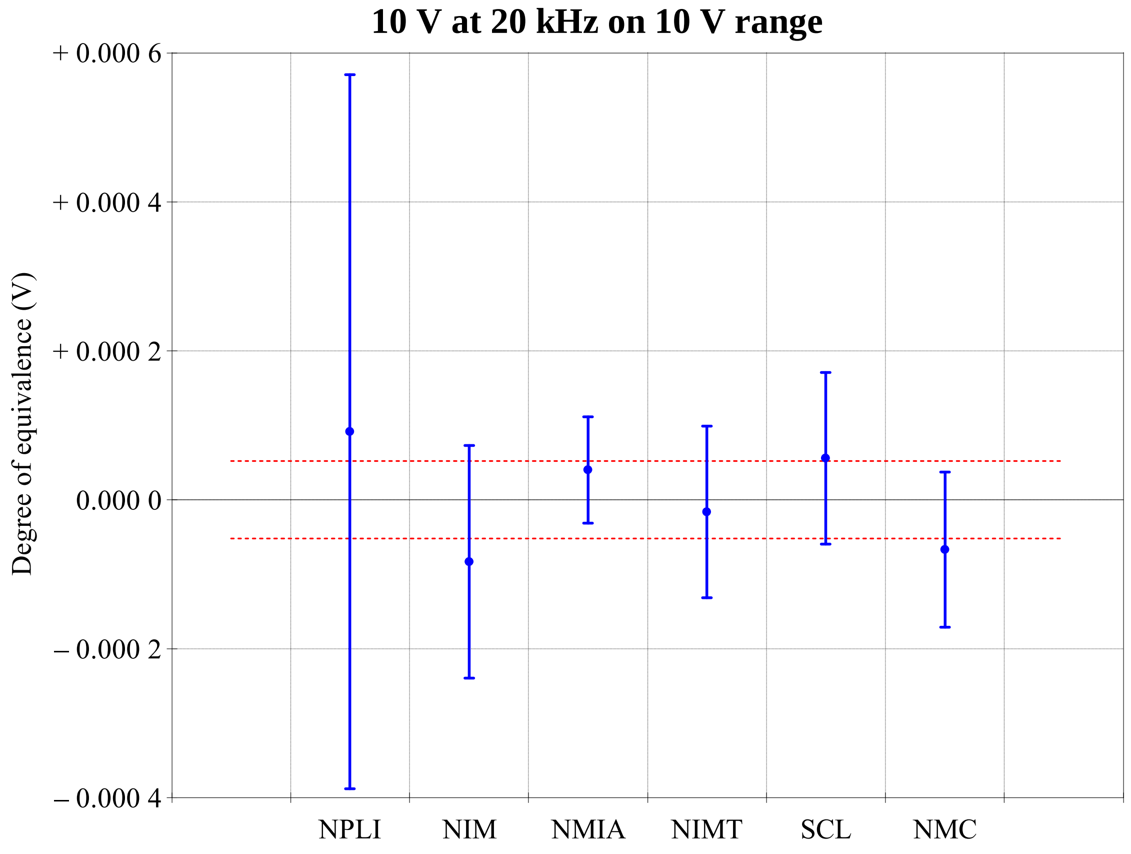

1 V at 50 kHz on 1 V range
Degree of equivalence (V)
+ 0.000 20
+ 0.000 15
+ 0.000 10
+ 0.000 05
0.000 00
– 0.000 05
– 0.000 10
NPLI
NIM
NMIA
NIMT
SCL
NMC

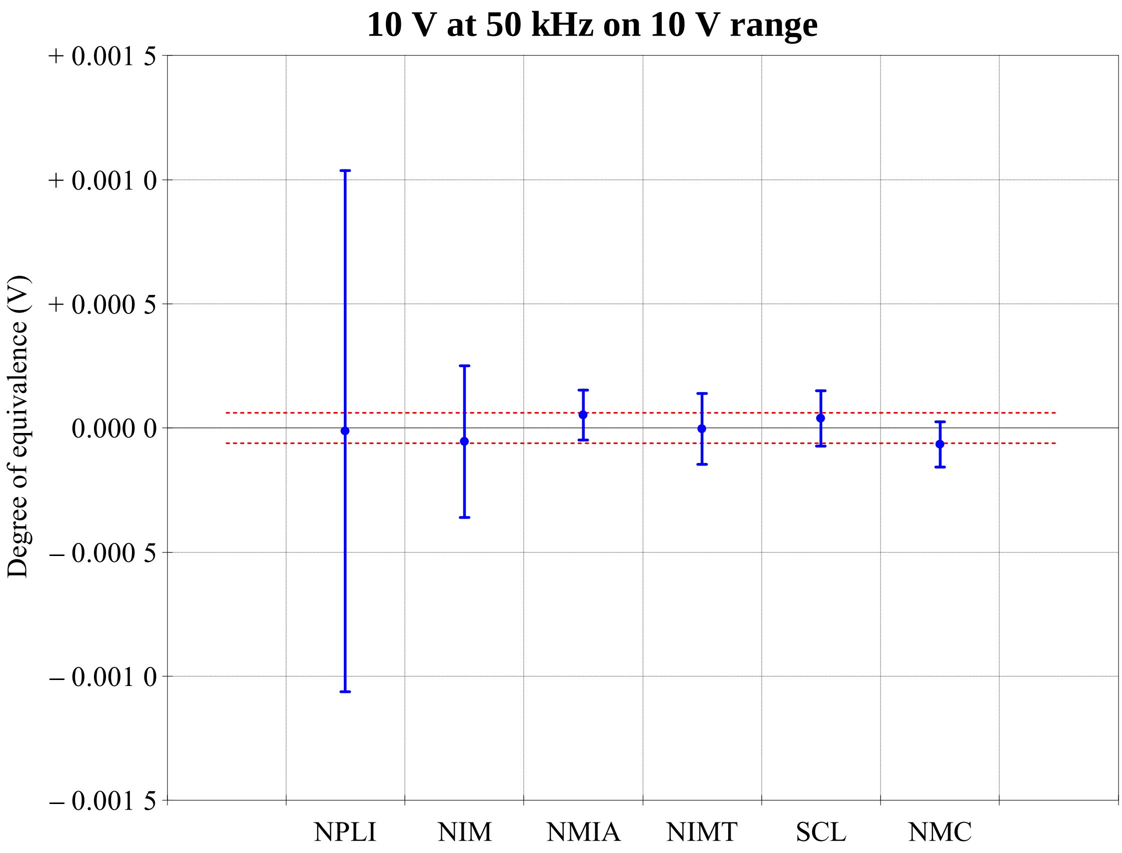

1 V at 1 MHz on 1 V range
Degree of equivalence (V)
+ 0.008
+ 0.007
+ 0.006
+ 0.005
+ 0.004
+ 0.003
+ 0.002
+ 0.001
0.000
– 0.001
NPLI
NIM
NMIA
NIMT
SCL
NMC

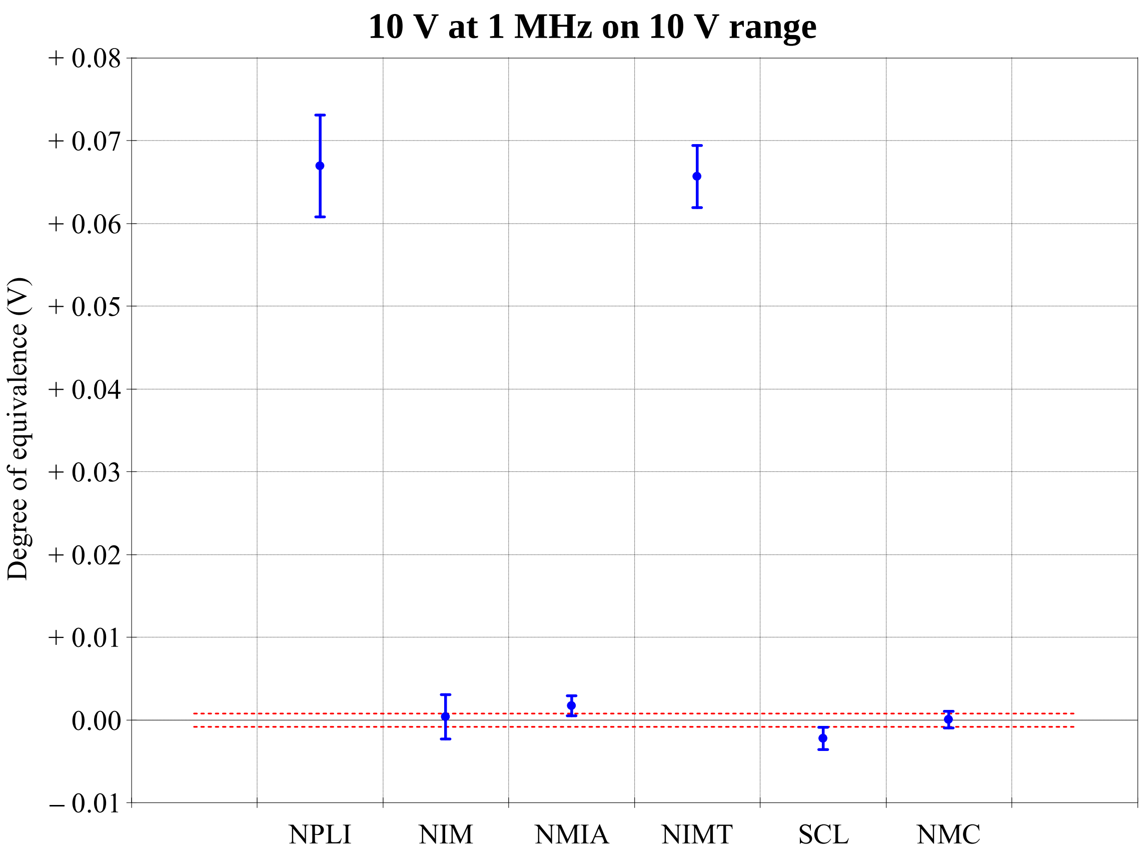

10 V at 10 Hz on 10 V range
Degree of equivalence (V)
+ 0.002 0
+ 0.001 5
+ 0.001 0
+ 0.000 5
0.000 0
– 0.000 5
NPLI
NIM
NMIA
NIMT
NMC


10 V at 55 Hz on 10 V range
Degree of equivalence (V)
+ 0.000 3
+ 0.000 2
+ 0.000 1
0.000 0
– 0.000 1
– 0.000 2
– 0.000 3
– 0.000 4
– 0.000 5
– 0.000 6
– 0.000 7
NPLI
NIM
NMIA
NIMT
SCL
NMC

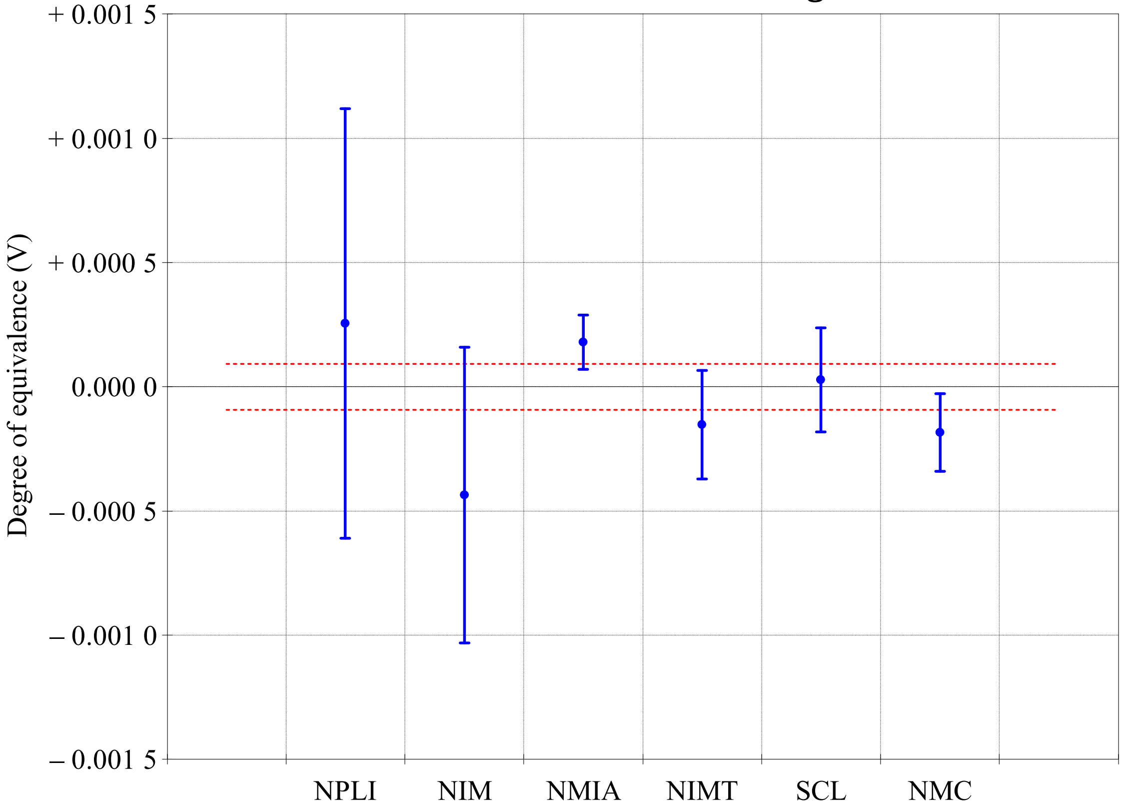

10 V at 1.005 kHz on 10 V range
Degree of equivalence (V)
+ 0.000 6
+ 0.000 5
+ 0.000 4
+ 0.000 3
+ 0.000 2
+ 0.000 1
0.000 0
– 0.000 1
– 0.000 2
NPLI
NIM
NMIA
NIMT
SCL
NMC


10 V at 20 kHz on 10 V range
Degree of equivalence (V)
+ 0.000 6
+ 0.000 4
+ 0.000 2
0.000 0
– 0.000 2
– 0.000 4
NPLI
NIM
NMIA
NIMT
SCL
NMC

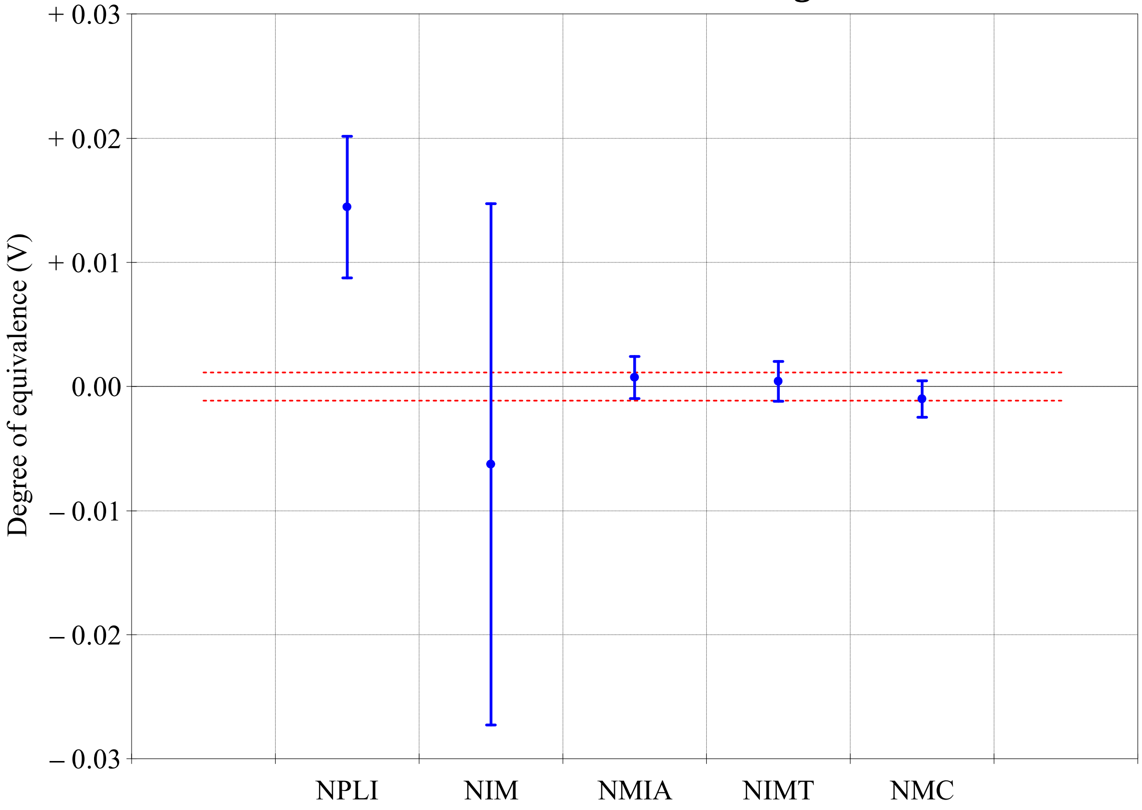

10 V at 50 kHz on 10 V range
Degree of equivalence (V)
+ 0.001 5
+ 0.001 0
+ 0.000 5
0.000 0
– 0.000 5
– 0.001 0
– 0.001 5
NPLI
NIM
NMIA
NIMT
SCL
NMC

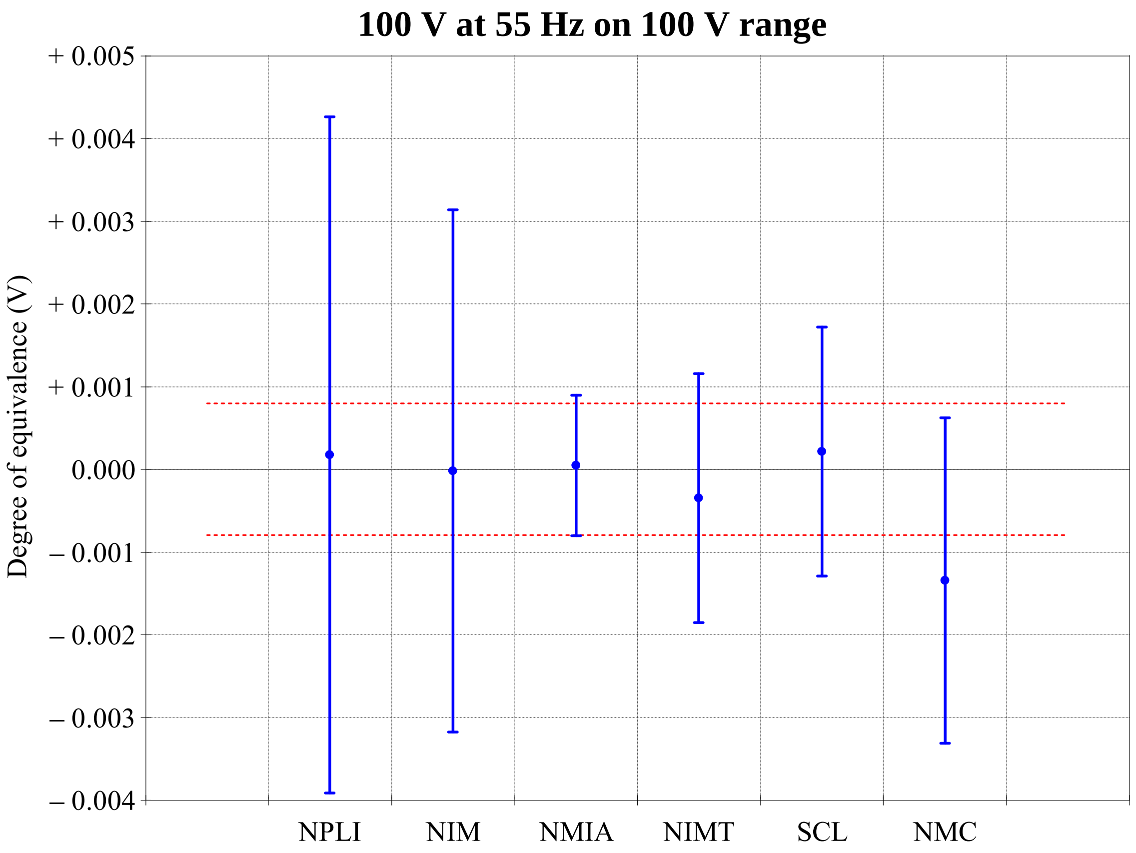

10 V at 1 MHz on 10 V range
Degree of equivalence (V)
+ 0.08
+ 0.07
+ 0.06
+ 0.05
+ 0.04
+ 0.03
+ 0.02
+ 0.01
0.00
– 0.01
NPLI
NIM
NMIA
NIMT
SCL
NMC

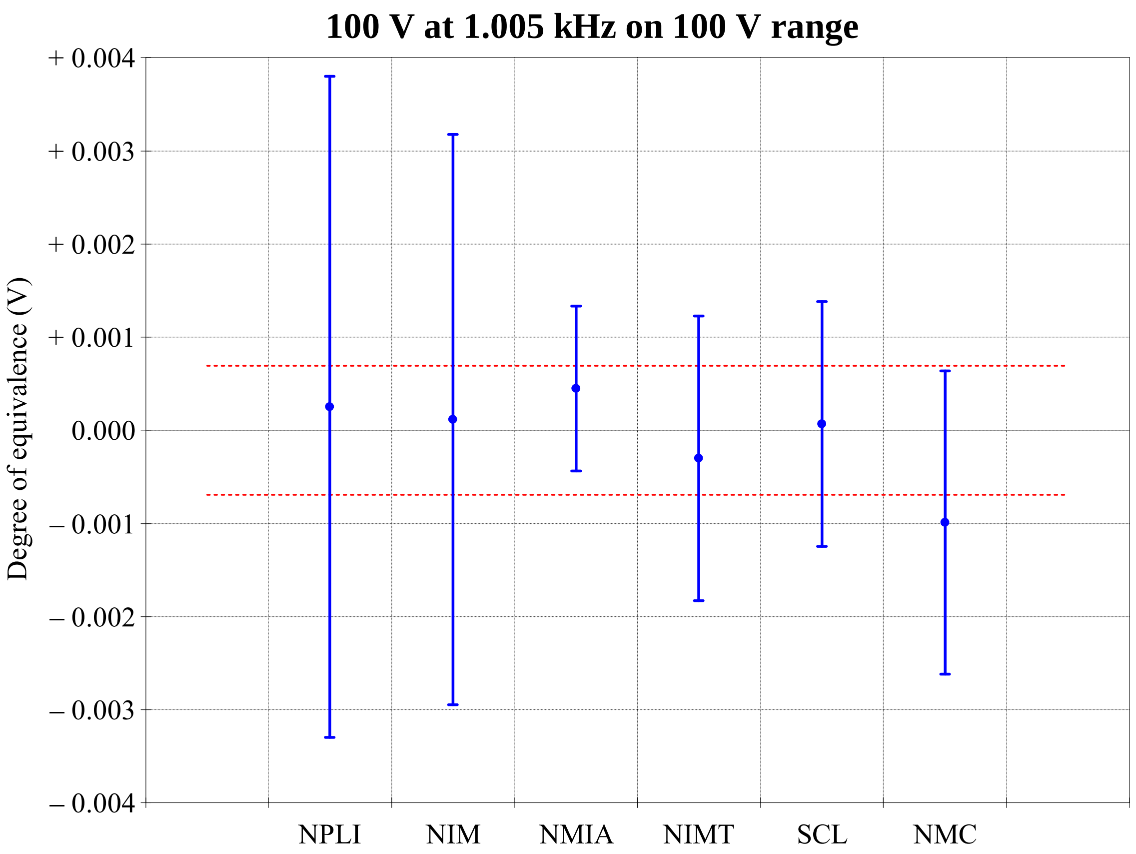
19 V at 1.005 kHz on 10 V range



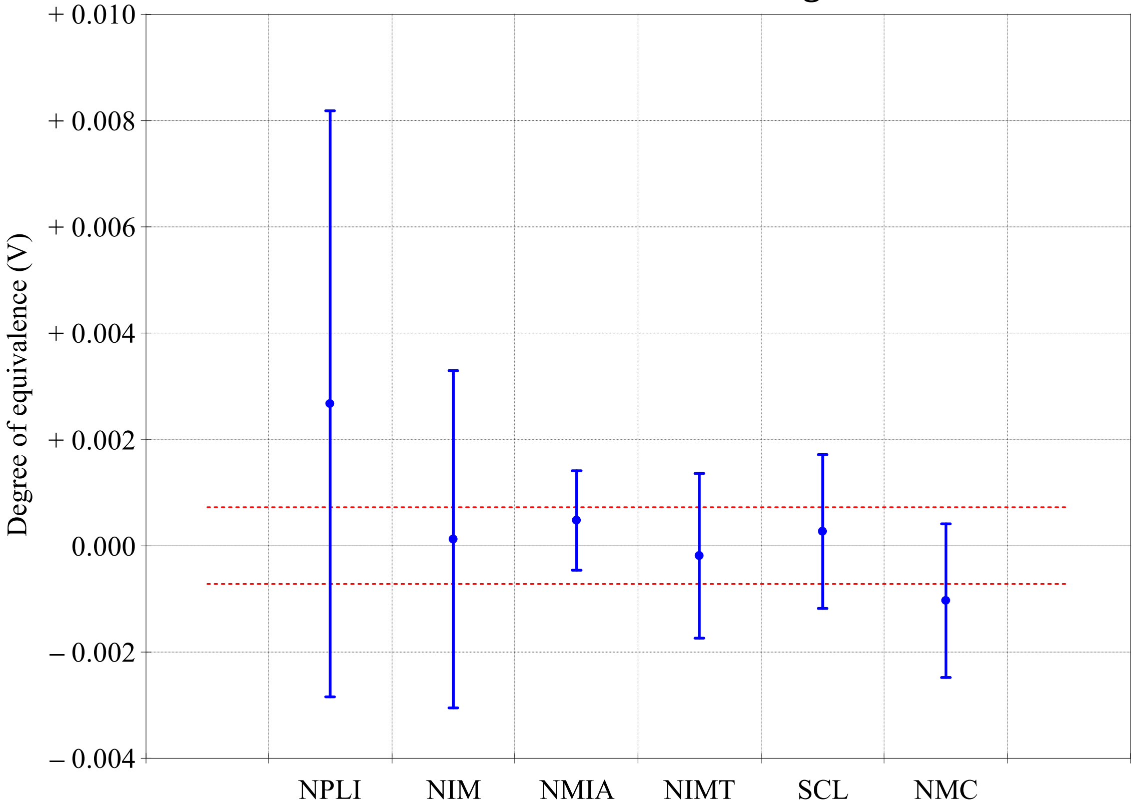
100 V at 10 Hz on 100 V range



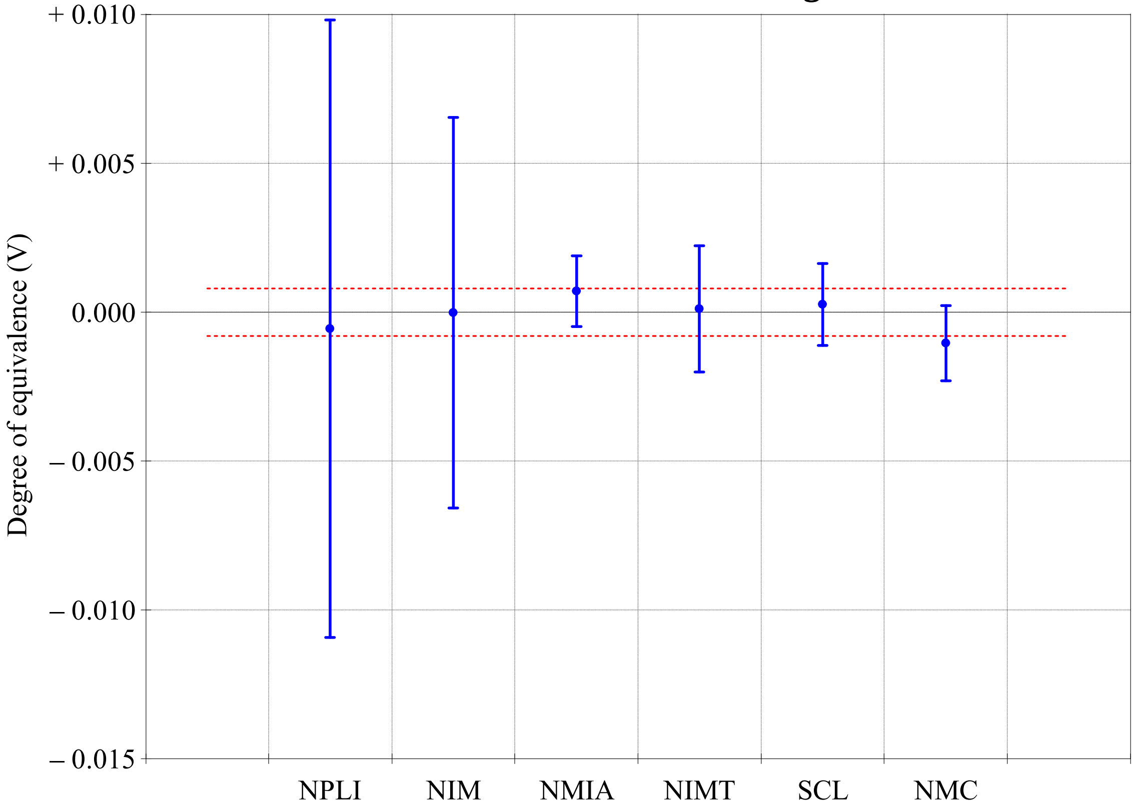

100 V at 55 Hz on 100 V range
Degree of equivalence (V)
+ 0.005
+ 0.004
+ 0.003
+ 0.002
+ 0.001
0.000
– 0.001
– 0.002
– 0.003
– 0.004
NPLI
NIM
NMIA
NIMT
SCL
NMC

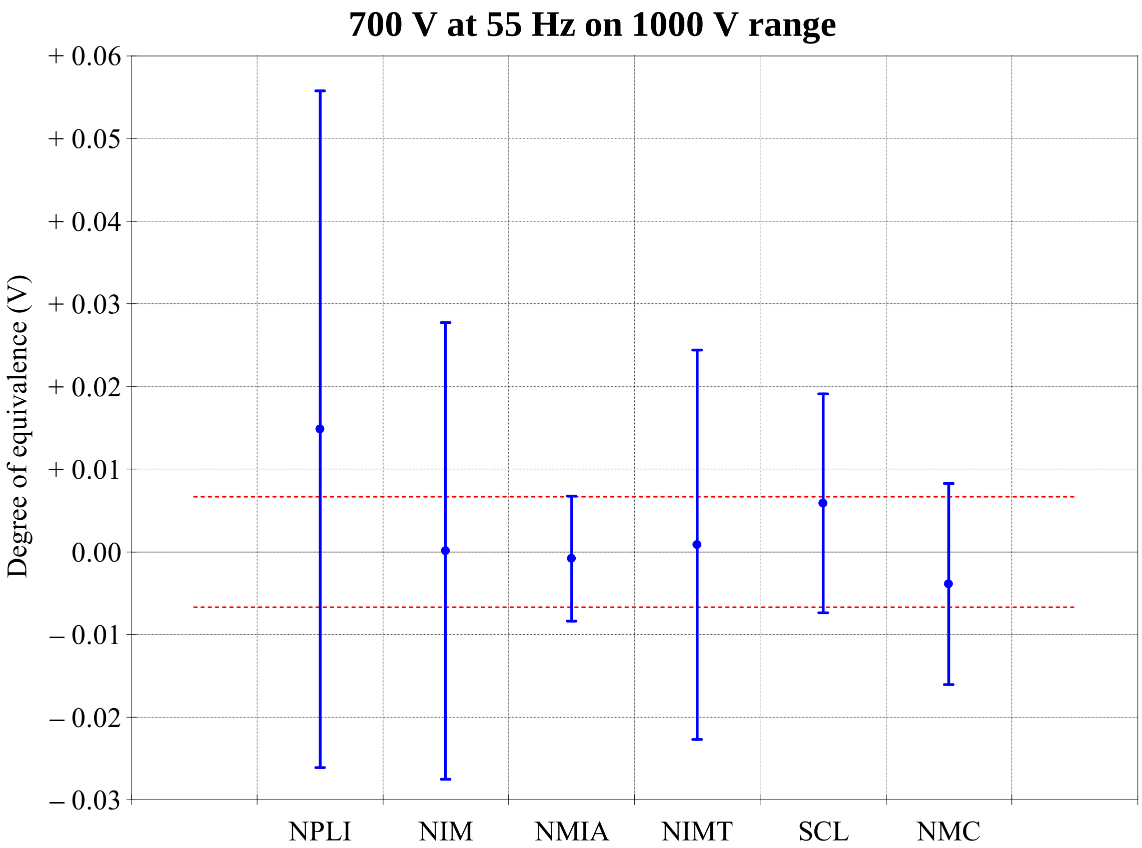

100 V at 1.005 kHz on 100 V range
Degree of equivalence (V)
+ 0.004
+ 0.003
+ 0.002
+ 0.001
0.000
– 0.001
– 0.002
– 0.003
– 0.004
NPLI
NIM
NMIA
NIMT
SCL
NMC

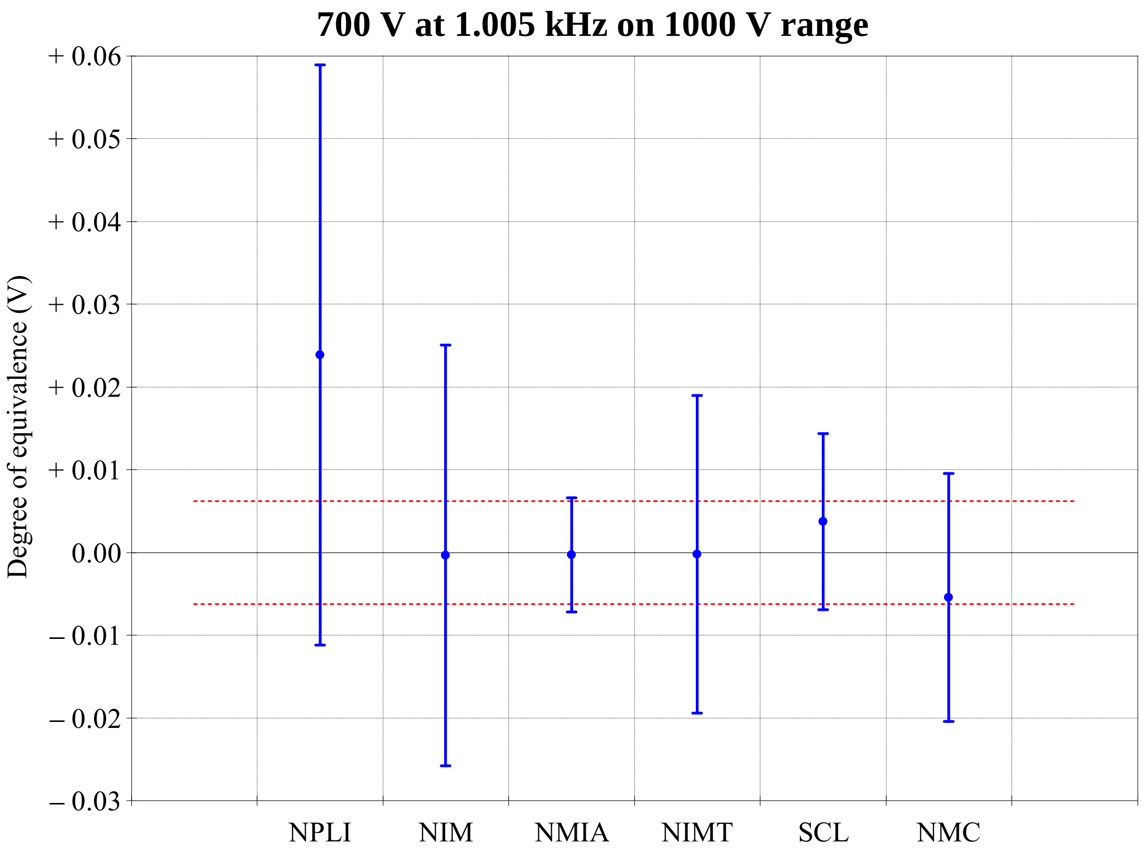
100 V at 20 kHz on 100 V range



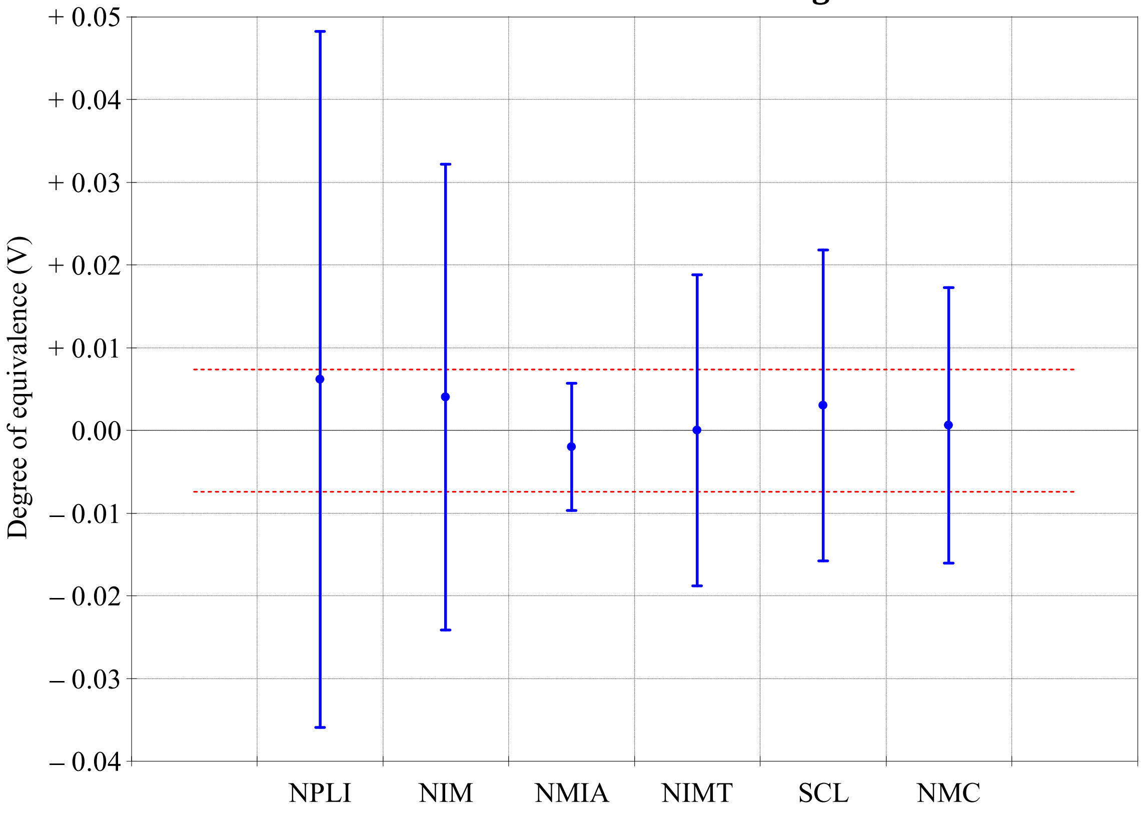
100 V at 50 kHz on 100 V range



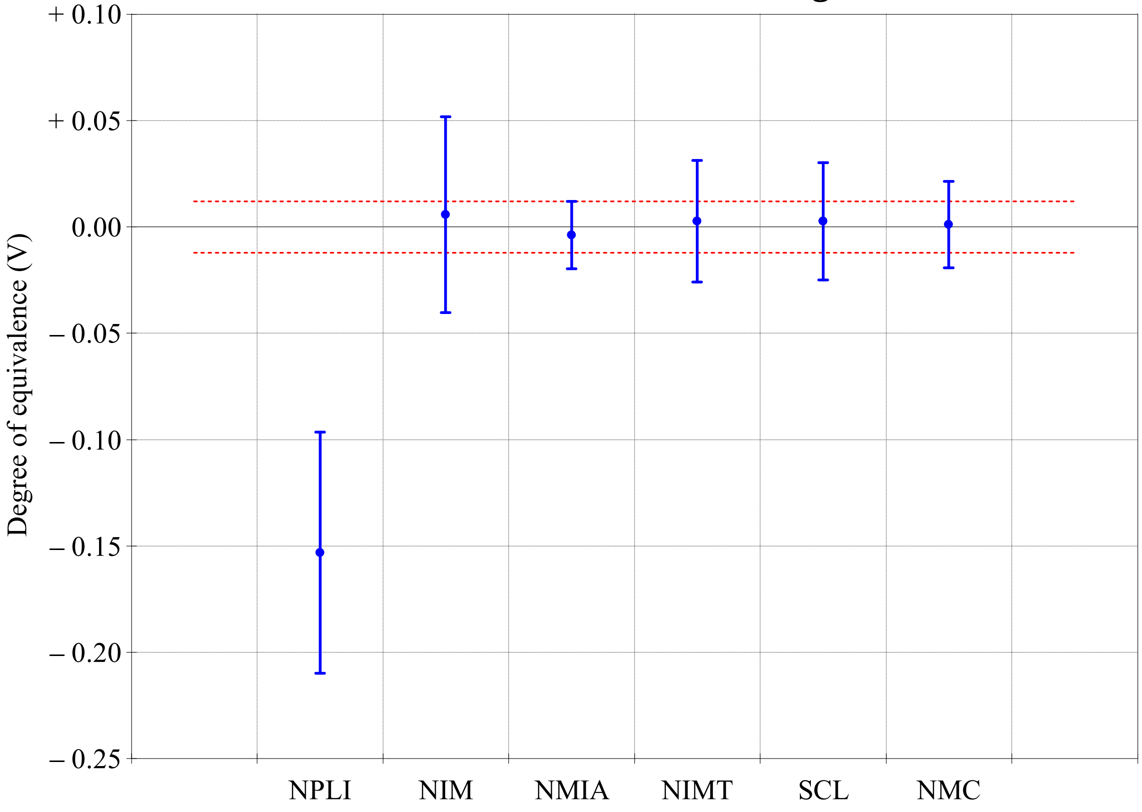

700 V at 55 Hz on 1000 V range
+ 0.06
+ 0.05
+ 0.04
+ 0.03
+ 0.02
+ 0.01
0.00
– 0.01
– 0.02
– 0.03
Degree of equivalence (V)
NPLI
NIM
NMIA
NIMT
SCL
NMC


700 V at 1.005 kHz on 1000 V range
+ 0.06
+ 0.05
+ 0.04
+ 0.03
+ 0.02
+ 0.01
0.00
– 0.01
– 0.02
– 0.03
Degree of equivalence (V)
NPLI
NIM
NMIA
NIMT
SCL
NMC

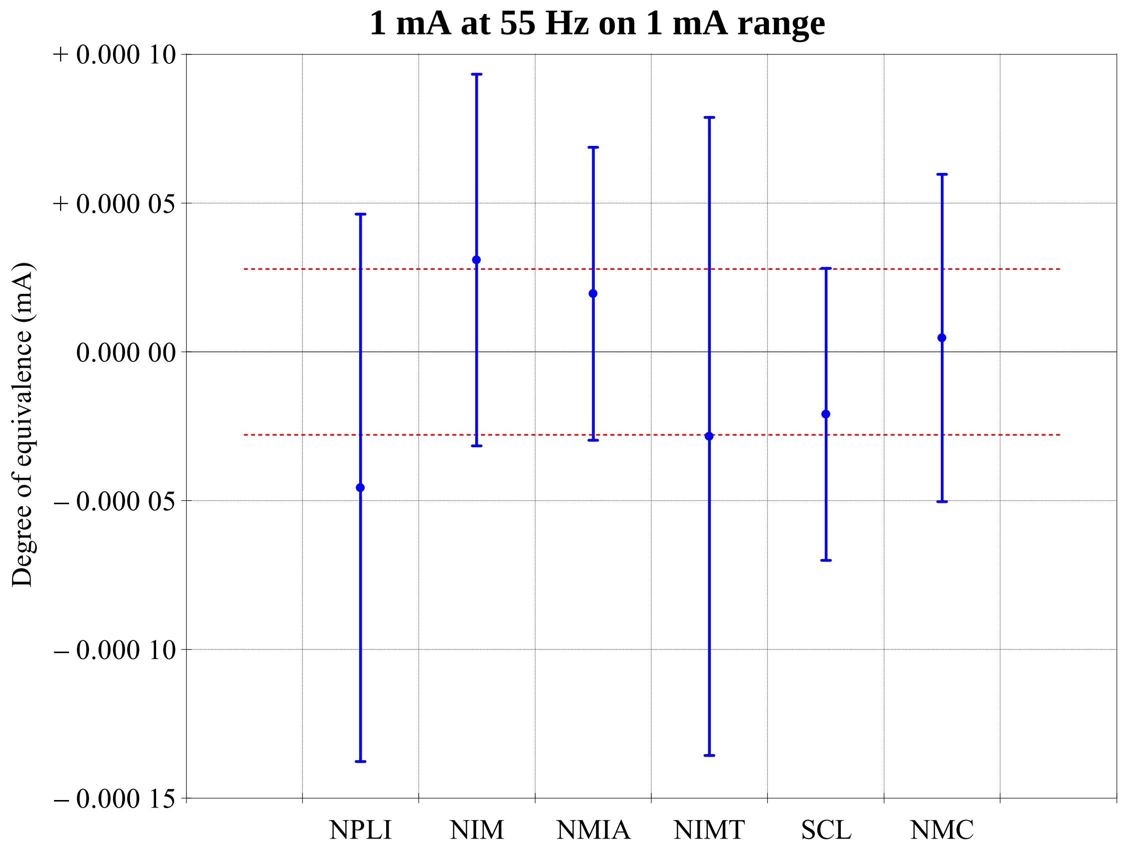
700 V at 20 kHz on 1000 V range

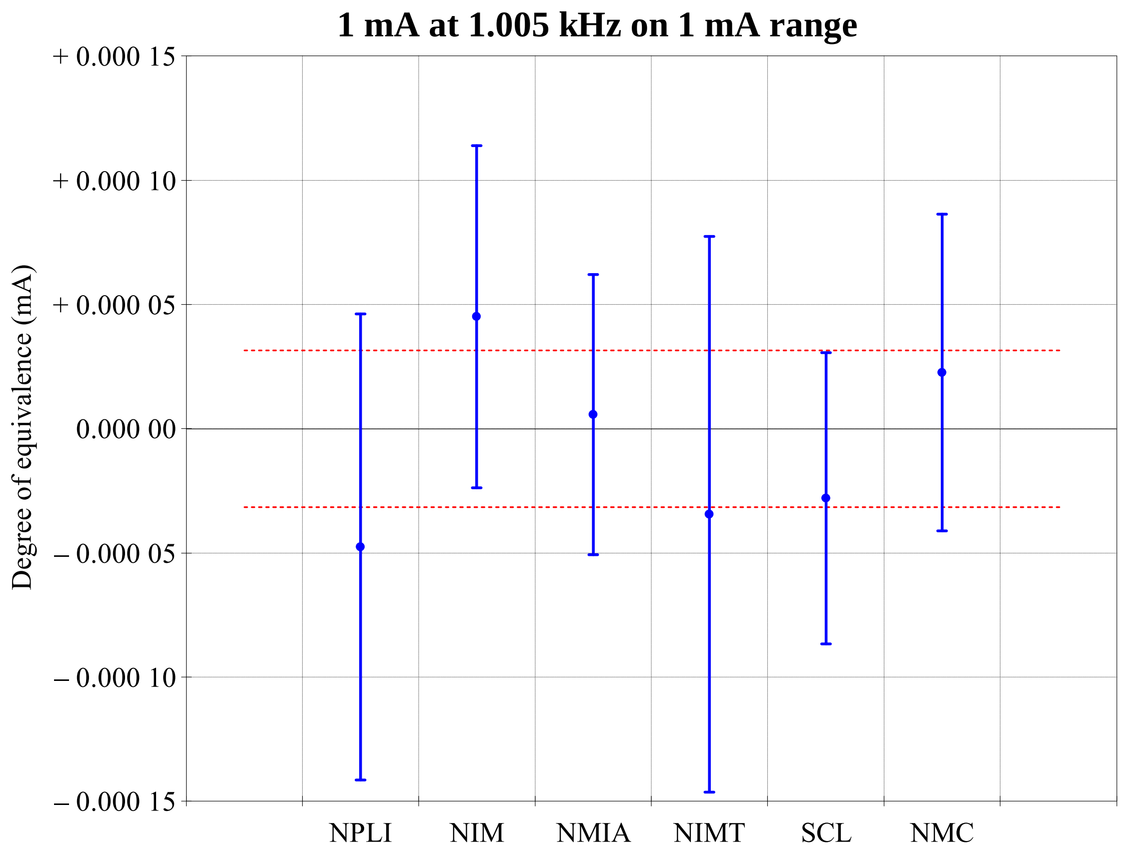


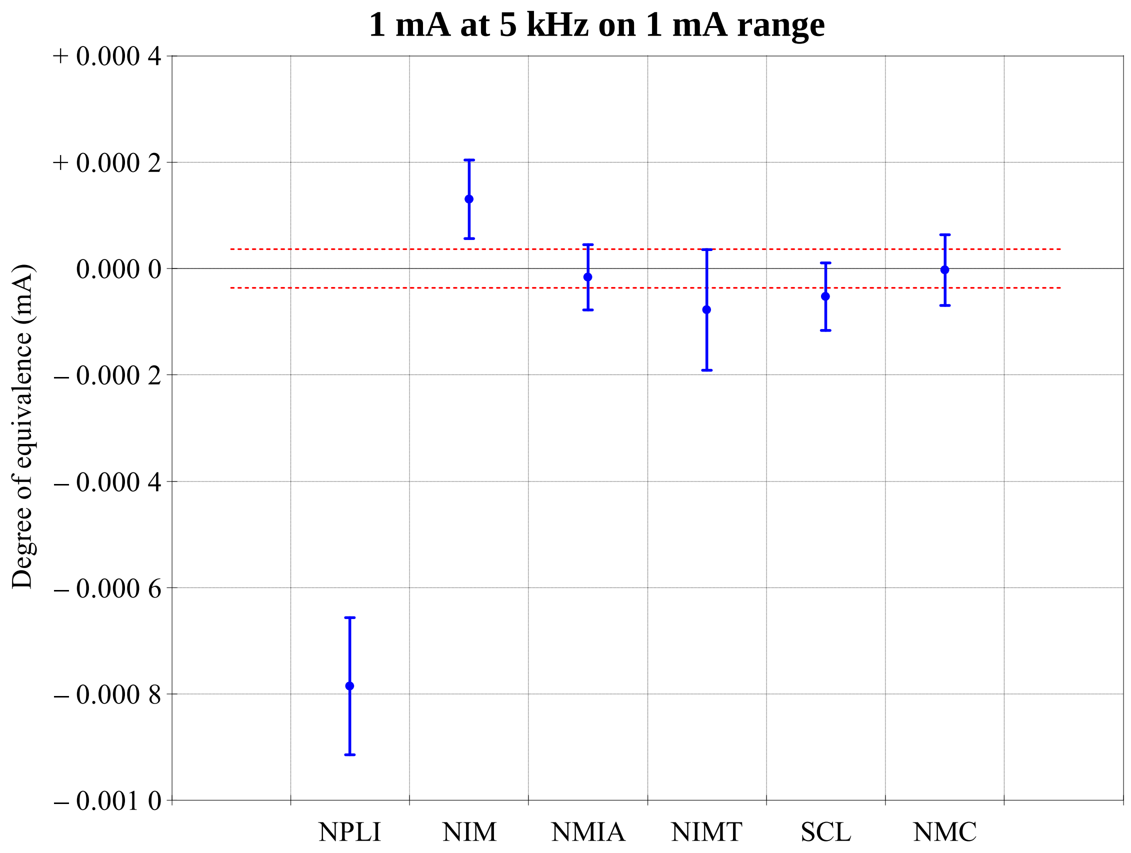
700 V at 50 kHz on 1000 V range

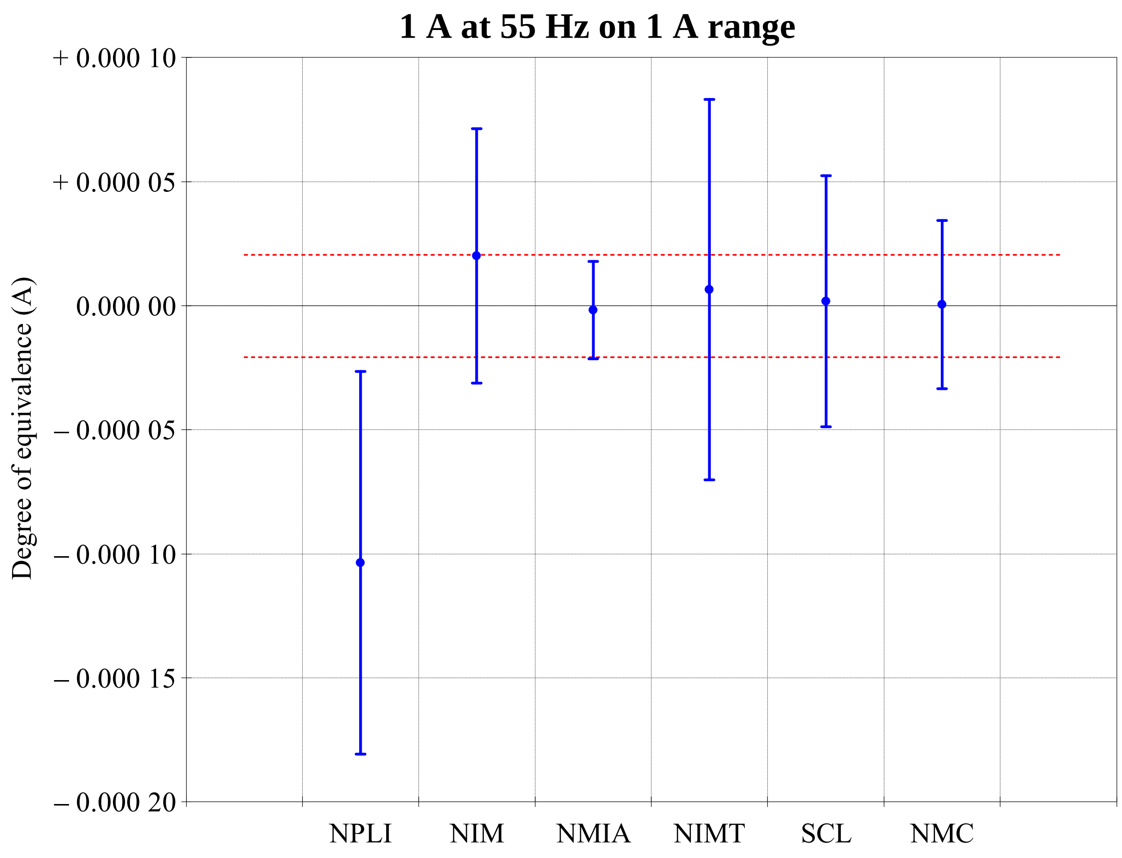


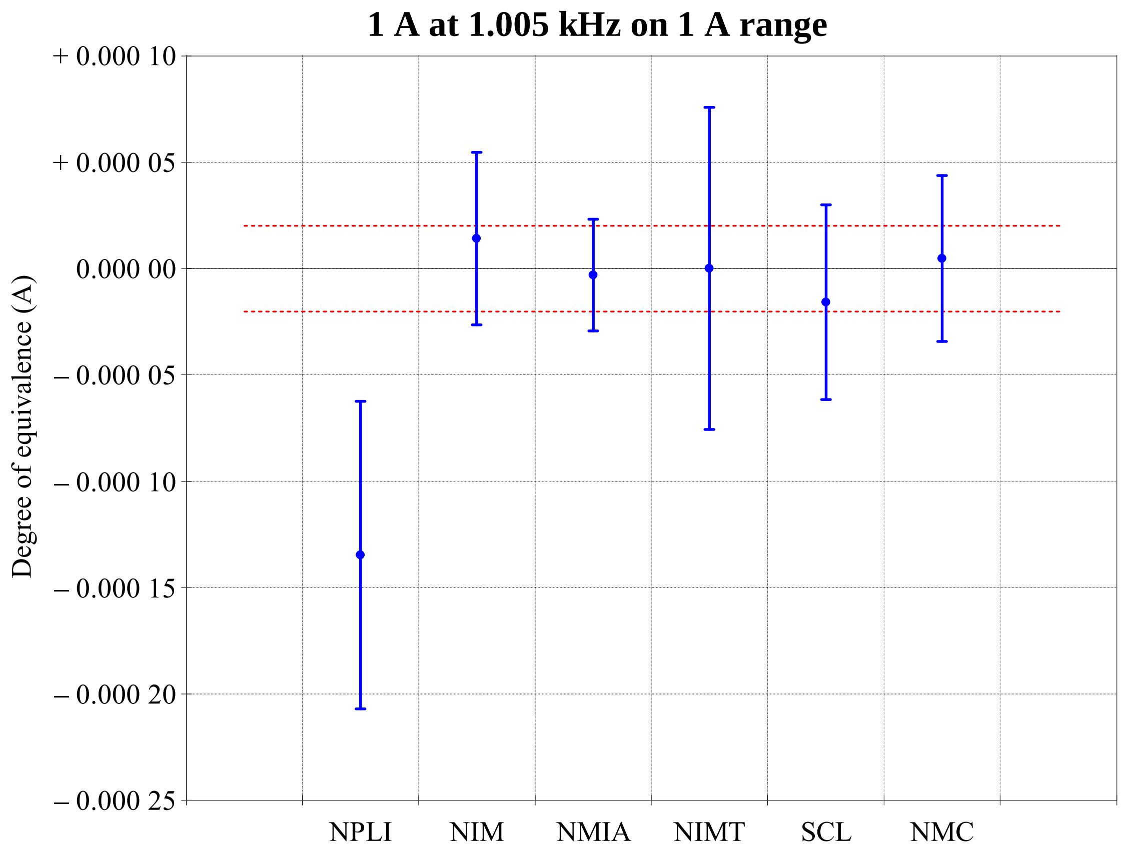
Alternating Current

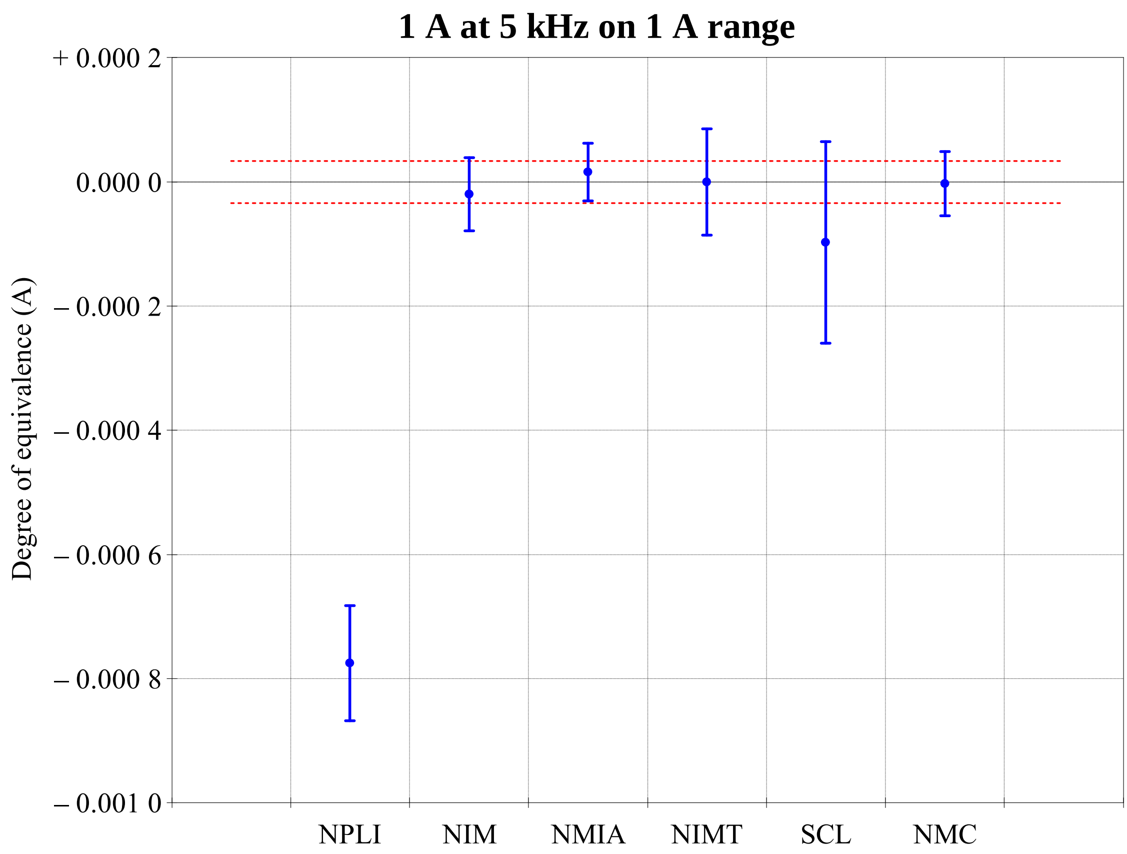




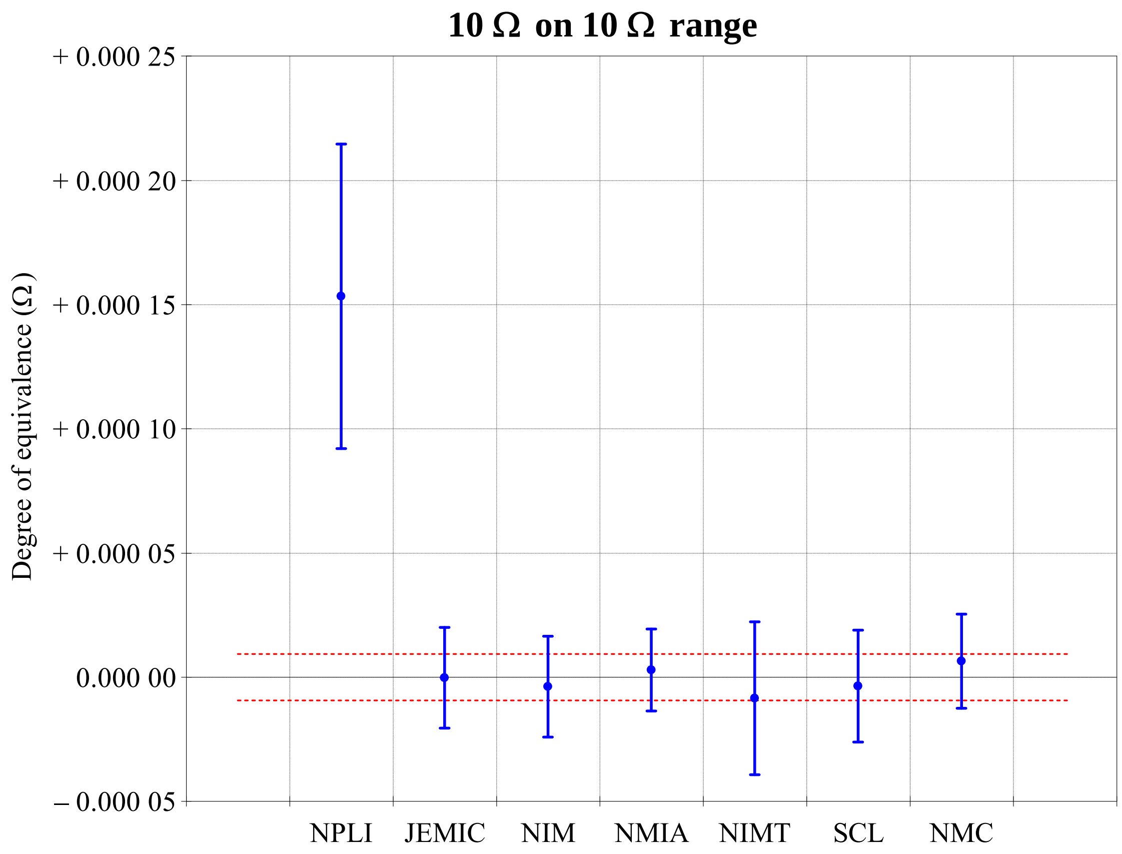

1 mA at 5 kHz on 1 mA range
+ 0.000 4
+ 0.000 2
0.000 0
– 0.000 2
– 0.000 4
– 0.000 6
– 0.000 8
– 0.001 0
Degree of equivalence (mA)
NPLI
NIM
NMIA
NIMT
SCL
NMC

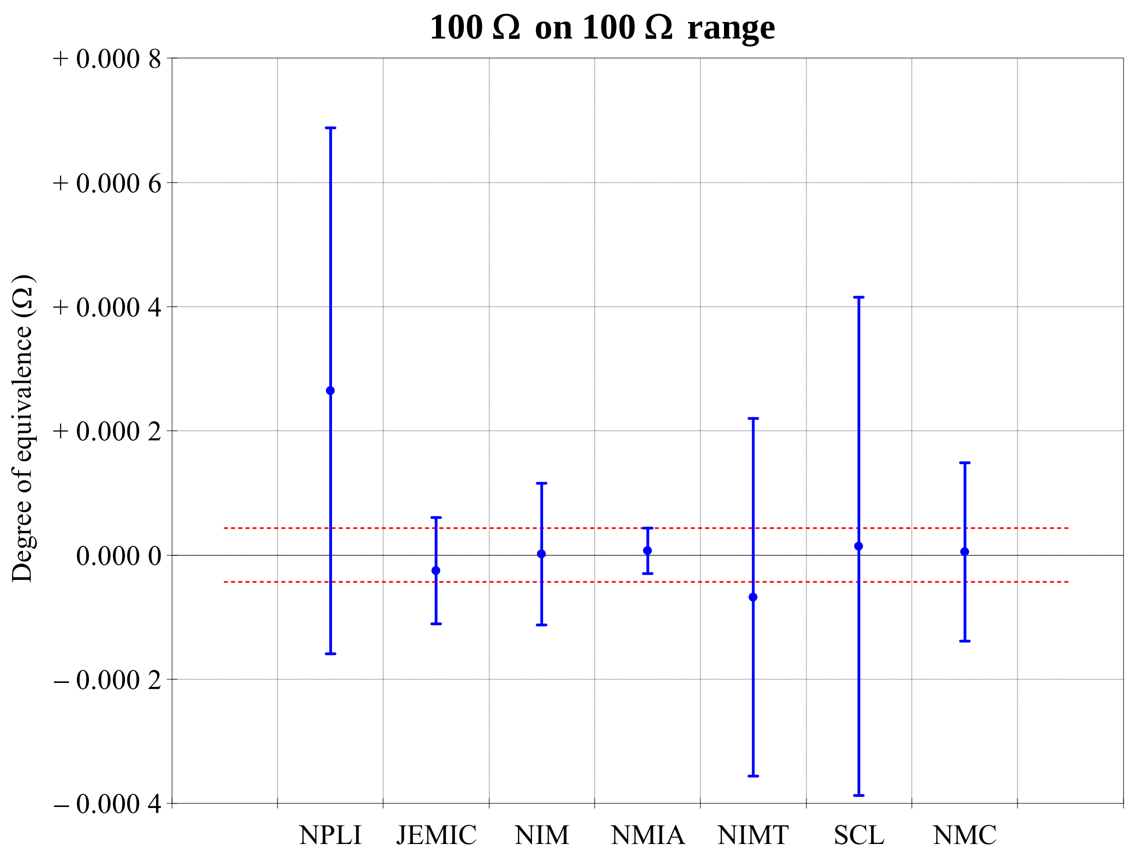

1 A at 55 Hz on 1 A range
+ 0.000 10
+ 0.000 05
0.000 00
– 0.000 05
– 0.000 10
– 0.000 15
– 0.000 20
Degree of equivalence (A)
NPLI
NIM
NMIA
NIMT
SCL
NMC

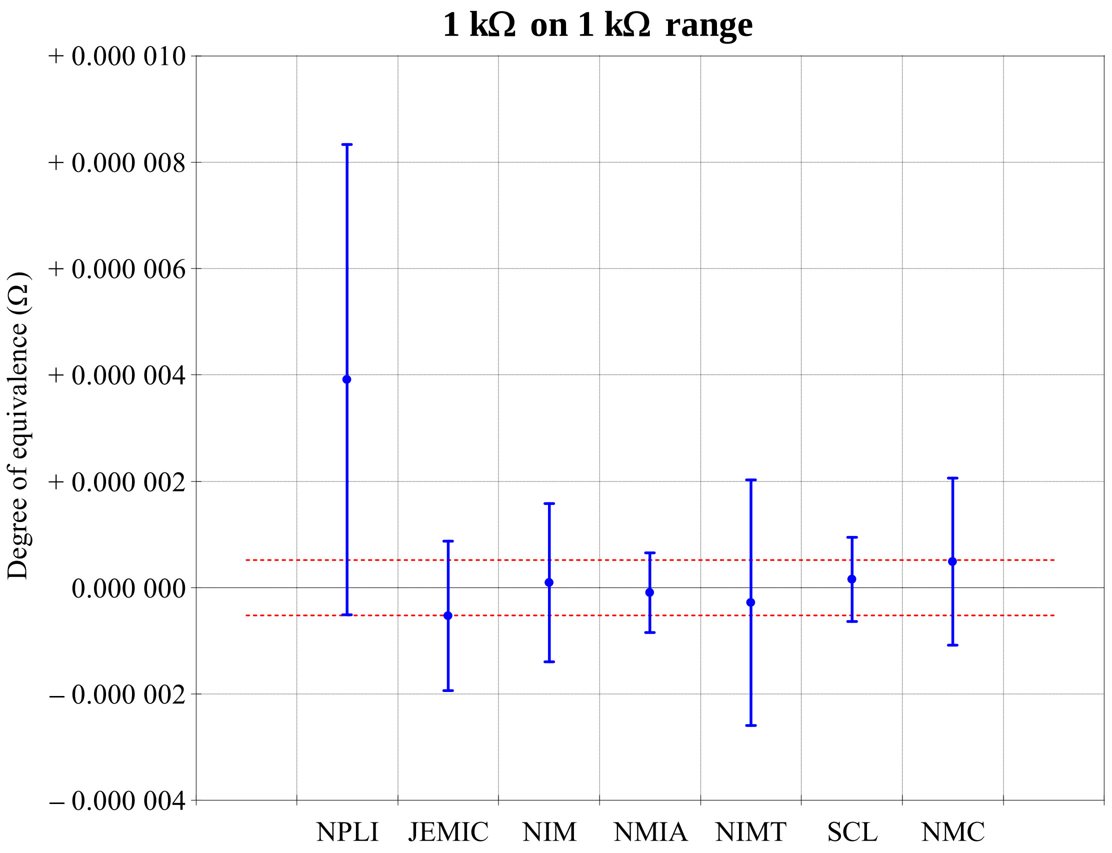

1 A at 1.005 kHz on 1 A range
Degree of equivalence (A)
+ 0.000 10
+ 0.000 05
0.000 00
– 0.000 05
– 0.000 10
– 0.000 15
– 0.000 20
– 0.000 25
NPLI
NIM
NMIA
NIMT
SCL
NMC


1 A at 5 kHz on 1 A range
Degree of equivalence (A)
+ 0.000 2
0.000 0
– 0.000 2
– 0.000 4
– 0.000 6
– 0.000 8
– 0.001 0
NPLI
NIM
NMIA
NIMT
SCL
NMC

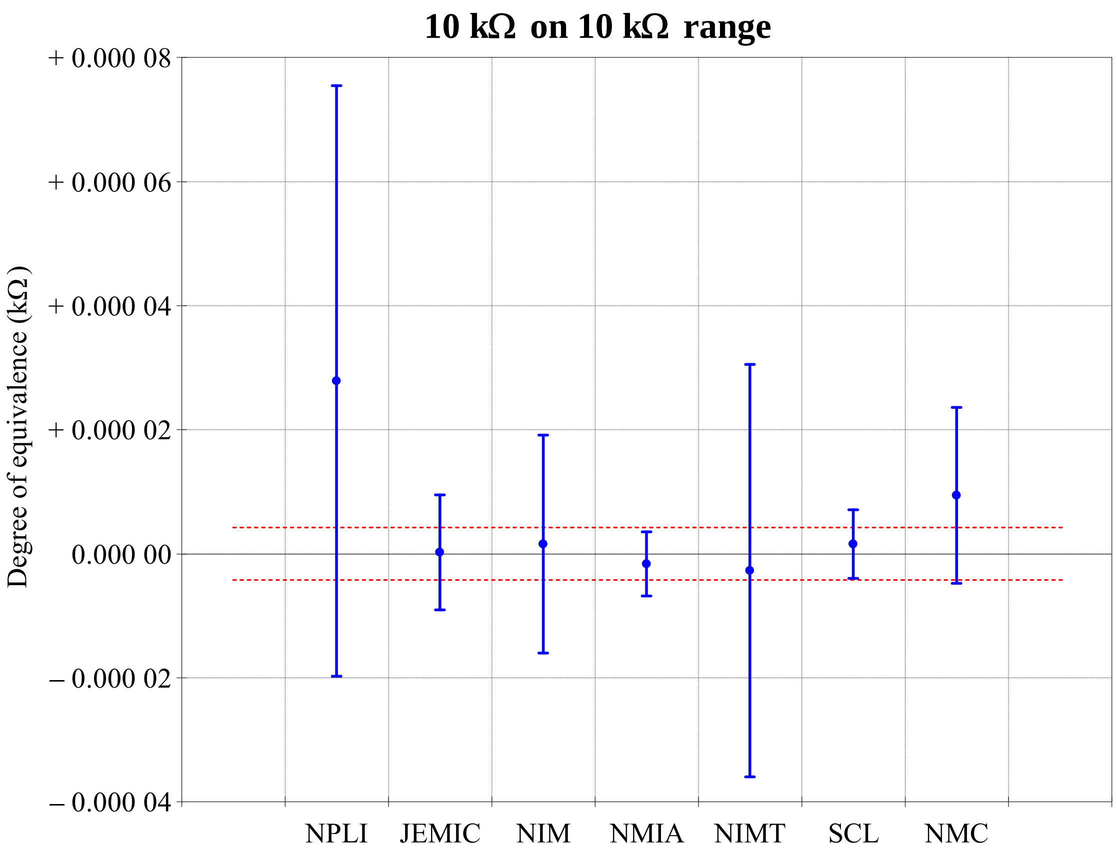
Resistance


10 Ω on 10 Ω range
Degree of equivalence (Ω)
+ 0.000 25
+ 0.000 20
+ 0.000 15
+ 0.000 10
+ 0.000 05
0.000 00
– 0.000 05
NPLI
JEMIC
NIM
NMIA
NIMT
SCL
NMC


100 Ω on 100 Ω range
Degree of equivalence (Ω)
+ 0.000 8
+ 0.000 6
+ 0.000 4
+ 0.000 2
0.000 0
– 0.000 2
– 0.000 4
NPLI
JEMIC
NIM
NMIA
NIMT
SCL
NMC

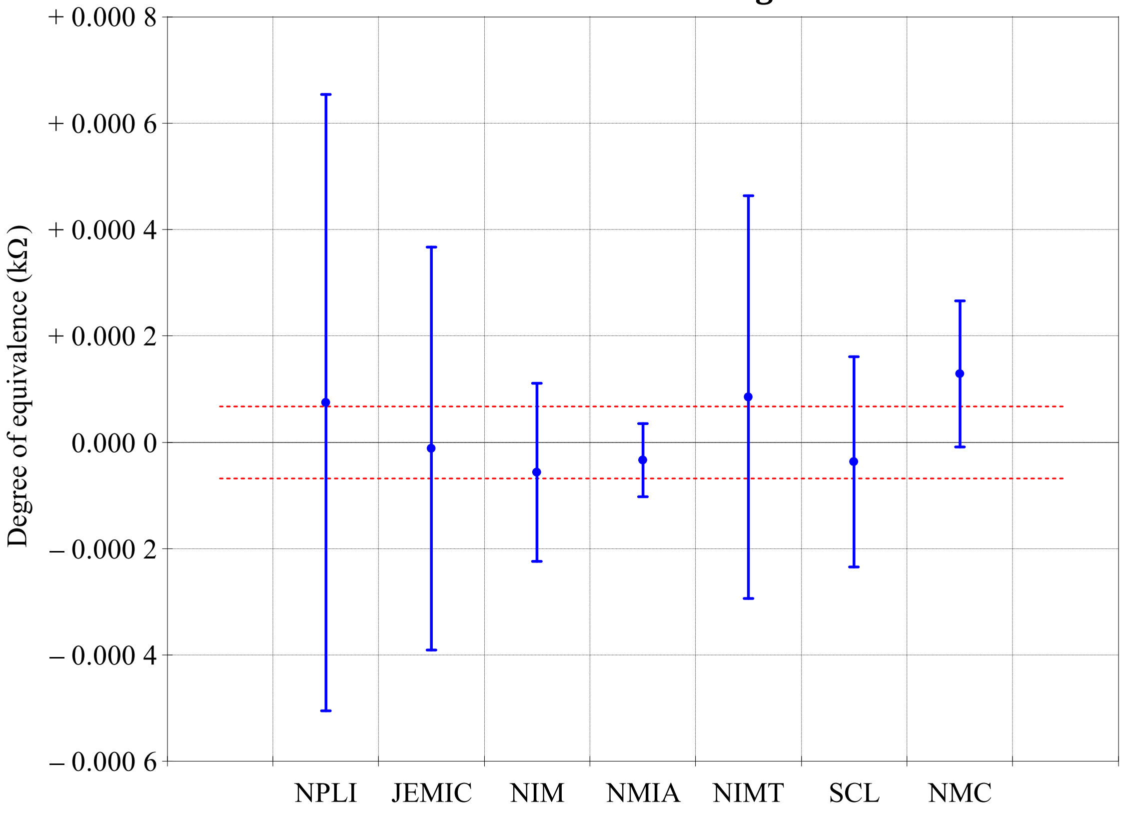


1 kΩ on 1 kΩ range
+ 0.000 010
+ 0.000 008
+ 0.000 006
+ 0.000 004
+ 0.000 002
0.000 000
– 0.000 002
– 0.000 004
Degree of equivalence (Ω)
NPLI
JEMIC
NIM
NMIA
NIMT
SCL
NMC

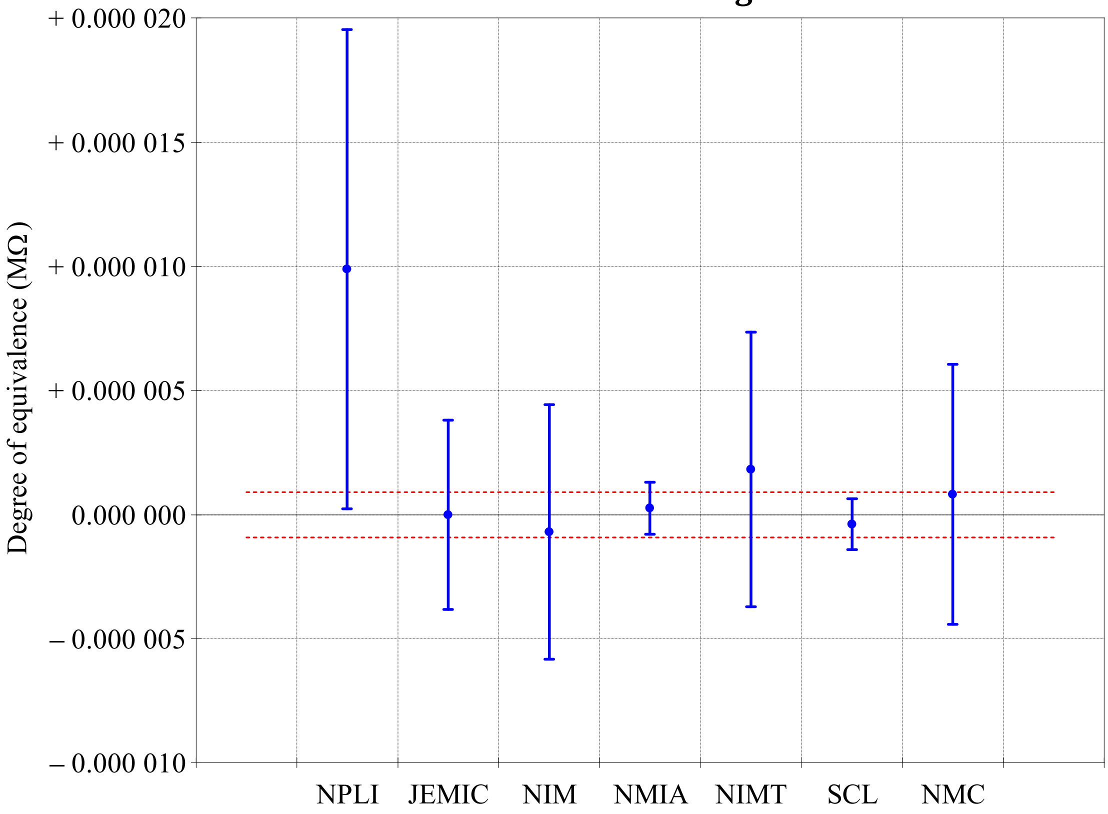


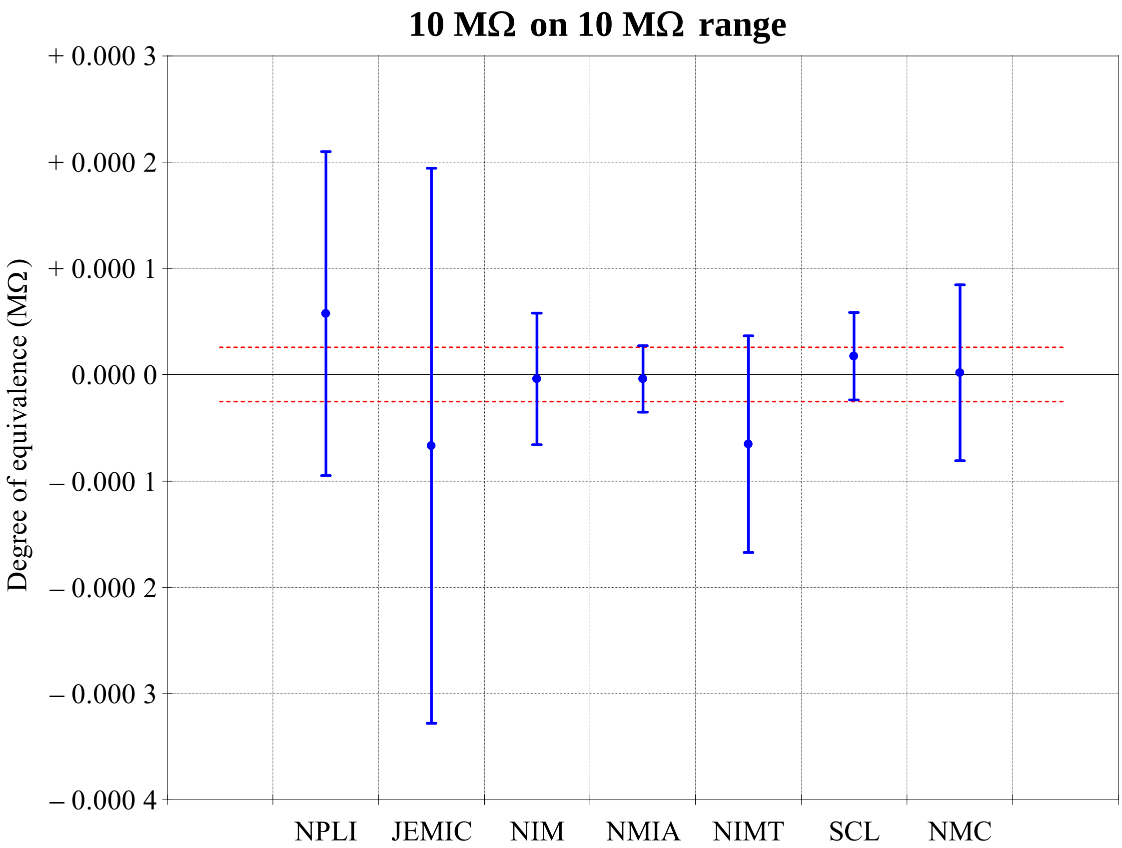
10 kΩ on 10 kΩ range
+ 0.000 08
+ 0.000 06
+ 0.000 04
+ 0.000 02
0.000 00
– 0.000 02
– 0.000 04
Degree of equivalence (kΩ)
NPLI
JEMIC
NIM
NMIA
NIMT
SCL
NMC

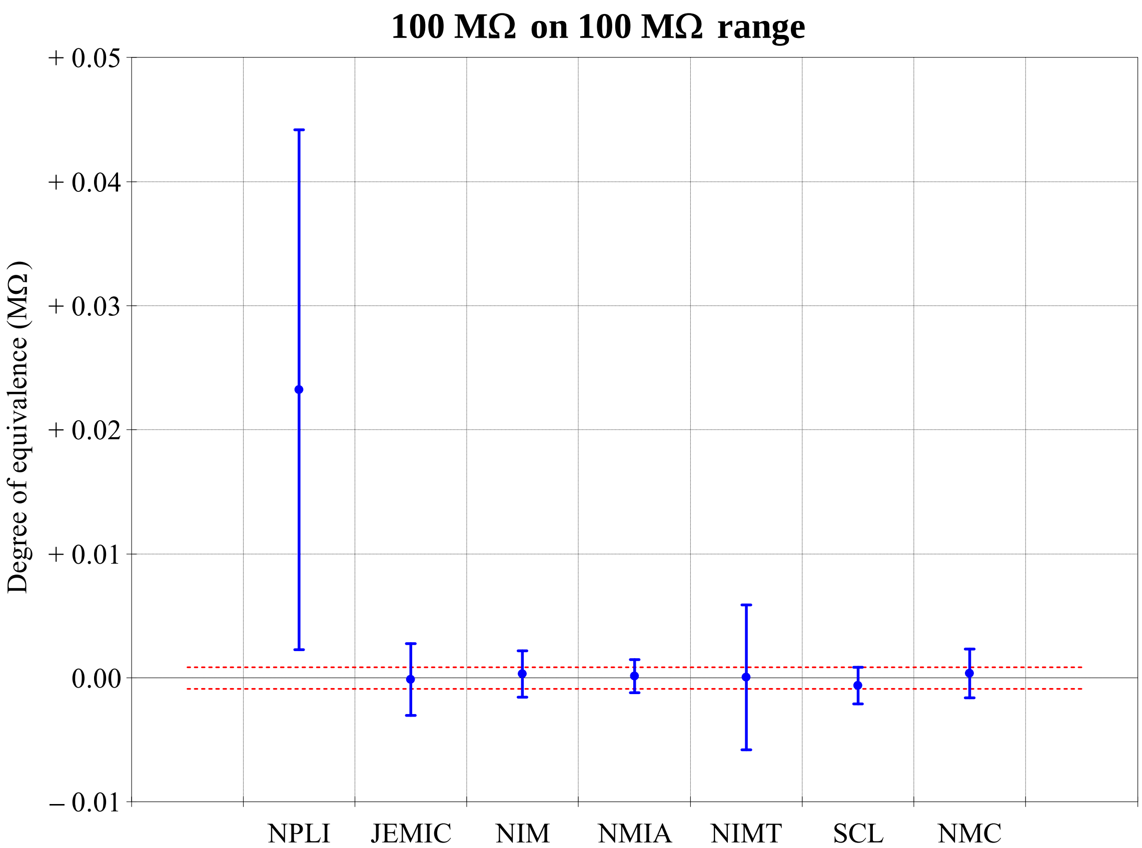
100 kΩ on 100 kΩ range



1 MΩ on 1 MΩ range




10 MΩ on 10 MΩ range
+ 0.000 3
+ 0.000 2
+ 0.000 1
0.000 0
– 0.000 1
– 0.000 2
– 0.000 3
– 0.000 4
Degree of equivalence (MΩ)
NPLI
JEMIC
NIM
NMIA
NIMT
SCL
NMC


100 MΩ on 100 MΩ range
+ 0.05
+ 0.04
+ 0.03
+ 0.02
+ 0.01
0.00
– 0.01
Degree of equivalence (MΩ)
NPLI
JEMIC
NIM
NMIA
NIMT
SCL
NMC

Appendix III: Temperature coefficients

Function	Range	Nominal Value	Nominal Frequency	Temperature Coefficient	Standard Uncertainty (at 40 °C)
Direct Voltage	100 mV	100 mV	–	– 0.048 µV/°C	± 0.000 10 mV
Direct Voltage	1 V	1 V	–	– 0.21 µV/°C	± 0.000 000 5 V
Direct Voltage	10 V	10 V	–	– 3.9 µV/°C	± 0.000 001 V
Direct Voltage	10 V	19 V	–	– 7.4 µV/°C	± 0.000 002 V
Direct Voltage	100 V	100 V	–	– 37 µV/°C	± 0.000 03 V
Direct Voltage	1000 V	1000 V	–	– 461 µV/°C	± 0.000 1 V
Direct Current	1 mA	1 mA	–	– 0.002 2 µA/°C	± 0.000 000 8 mA
Alternating Voltage	0.01 V	0.01 V	10 Hz	– 0.007 7 µV/°C	± 0.000 3 mV
Alternating Voltage	0.01 V	0.01 V	55 Hz	+ 0.001 2 µV/°C	± 0.000 1 mV
Alternating Voltage	0.01 V	0.01 V	1.005 kHz	+ 0.002 7 µV/°C	± 0.000 0 mV
Alternating Voltage	0.01 V	0.01 V	20 kHz	– 0.002 9 µV/°C	± 0.000 0 mV
Alternating Voltage	0.01 V	0.01 V	50 kHz	– 0.023 µV/°C	± 0.000 1 mV
Alternating Voltage	0.1 V	0.1 V	10 Hz	– 0.17 µV/°C	± 0.000 4 mV
Alternating Voltage	0.1 V	0.1 V	55 Hz	– 0.20 µV/°C	± 0.000 4 mV
Alternating Voltage	0.1 V	0.1 V	1.005 kHz	– 0.22 µV/°C	± 0.000 4 mV
Alternating Voltage	0.1 V	0.1 V	20 kHz	– 0.31 µV/°C	± 0.000 7 mV
Alternating Voltage	0.1 V	0.1 V	50 kHz	– 0.42 µV/°C	± 0.000 6 mV
Alternating Voltage	1 V	1 V	10 Hz	– 0.3 µV/°C	± 0.000 002 V
Alternating Voltage	1 V	1 V	55 Hz	– 0.5 µV/°C	± 0.000 002 V
Alternating Voltage	1 V	1 V	1.005 kHz	– 0.7 µV/°C	± 0.000 001 V
Alternating Voltage	1 V	1 V	20 kHz	– 1.2 µV/°C	± 0.000 001 V
Alternating Voltage	1 V	1 V	50 kHz	– 1.6 µV/°C	± 0.000 001 V
Alternating Voltage	1 V	1 V	1 MHz	+ 16.6 µV/°C	± 0.000 04 V
Alternating Voltage	10 V	10 V	10 Hz	– 11.7 µV/°C	± 0.000 02 V
Alternating Voltage	10 V	10 V	55 Hz	– 12.6 µV/°C	± 0.000 02 V
Alternating Voltage	10 V	10 V	1.005 kHz	– 11.5 µV/°C	± 0.000 02 V
Alternating Voltage	10 V	10 V	20 kHz	– 16.6 µV/°C	± 0.000 01 V
Alternating Voltage	10 V	10 V	50 kHz	– 18.7 µV/°C	± 0.000 01 V
Alternating Voltage	10 V	10 V	1 MHz	+ 604 µV/°C	± 0.000 5 V
Alternating Voltage	10 V	19 V	1.005 kHz	– 2.7 µV/°C	± 0.000 02 V
Alternating Voltage	100 V	100 V	10 Hz	– 59 µV/°C	± 0.000 2 V
Alternating Voltage	100 V	100 V	55 Hz	– 69 µV/°C	± 0.000 2 V
Alternating Voltage	100 V	100 V	1.005 kHz	– 69 µV/°C	± 0.000 1 V
Alternating Voltage	100 V	100 V	20 kHz	– 101 µV/°C	± 0.000 1 V
Alternating Voltage	100 V	100 V	50 kHz	– 143 µV/°C	± 0.000 1 V
Alternating Voltage	1000 V	700 V	55 Hz	– 1.7 mV/°C	± 0.002 V
Alternating Voltage	1000 V	700 V	1.005 kHz	– 1.4 mV/°C	± 0.001 V
Alternating Voltage	1000 V	700 V	20 kHz	– 1.5 mV/°C	± 0.001 V
Alternating Voltage	1000 V	700 V	50 kHz	– 1.4 mV/°C	± 0.001 V

Function	Range	Nominal Value	Nominal Frequency	Temperature Coefficient	Standard Uncertainty (at 40 °C)
Alternating Current	1 mA	1 mA	55 Hz	– 0.005 0 µA/°C	± 0.000 003 mA
Alternating Current	1 mA	1 mA	1.005 kHz	– 0.003 2 µA/°C	± 0.000 003 mA
Alternating Current	1 mA	1 mA	5 kHz	– 0.003 8 µA/°C	± 0.000 003 mA
Alternating Current	1 A	1 A	55 Hz	– 9.6 µA/°C	± 0.000 003 A
Alternating Current	1 A	1 A	1.005 kHz	– 7.3 µA/°C	± 0.000 004 A
Alternating Current	1 A	1 A	5 kHz	– 9.6 µA/°C	± 0.000 004 A
Resistance	10 Ω	10 Ω	–	– 0.7 µΩ/°C	± 0.000 008 Ω
Resistance	100 Ω	100 Ω	–	+ 11.0 µΩ/°C	± 0.000 02 Ω
Resistance	1 kΩ	1 kΩ	–	– 205 µΩ/°C	± 0.000 000 3 kΩ
Resistance	10 kΩ	10 kΩ	–	+ 0.8 mΩ/°C	± 0.000 002 kΩ
Resistance	100 kΩ	100 kΩ	–	– 3.4 mΩ/°C	± 0.000 01 kΩ
Resistance	1 MΩ	1 MΩ	–	– 0.99 Ω/°C	± 0.000 000 1 MΩ
Resistance	10 MΩ	10 MΩ	–	+ 33 Ω/°C	± 0.000 012 MΩ
Resistance	100 MΩ	100 MΩ	–	– 1104 Ω/°C	± 0.000 4 MΩ

Appendix IV: Drift of the travelling standard

Function	Range	Nominal Value	Nominal Frequency	Drift	Standard Uncertainty
Direct Voltage	100 mV	100 mV	–	+ 0.000 152 μV/day	± 0.000 06 mV
Direct Voltage	1 V	1 V	–	– 0.000 563 μV/day	± 0.000 000 3 V
Direct Voltage	10 V	10 V	–	– 0.000 208 μV/day	± 0.000 006 V
Direct Voltage	10 V	19 V	–	– 0.027 5 μV/day	± 0.000 008 V
Direct Voltage	100 V	100 V	–	– 0.017 4 μV/day	± 0.000 03 V
Direct Voltage	1000 V	1000 V	–	– 2.55 μV/day	± 0.000 5 V
Direct Current	1 mA	1 mA	–	– 0.002 90 nA/day	± 0.000 001 9 mA
Alternating Voltage	0.01 V	0.01 V	10 Hz	– 0.000 261 μV/day	± 0.000 1 mV
Alternating Voltage	0.01 V	0.01 V	55 Hz	– 0.000 206 μV/day	± 0.000 2 mV
Alternating Voltage	0.01 V	0.01 V	1.005 kHz	– 0.000 030 μV/day	± 0.000 1 mV
Alternating Voltage	0.01 V	0.01 V	20 kHz	+ 0.000 054 μV/day	± 0.000 1 mV
Alternating Voltage	0.01 V	0.01 V	50 kHz	+ 0.000 201 μV/day	± 0.000 2 mV
Alternating Voltage	0.1 V	0.1 V	10 Hz	+ 0.016 6 μV/day	± 0.001 7 mV
Alternating Voltage	0.1 V	0.1 V	55 Hz	+ 0.016 7 μV/day	± 0.001 3 mV
Alternating Voltage	0.1 V	0.1 V	1.005 kHz	+ 0.017 3 μV/day	± 0.001 4 mV
Alternating Voltage	0.1 V	0.1 V	20 kHz	+ 0.017 2 μV/day	± 0.001 4 mV
Alternating Voltage	0.1 V	0.1 V	50 kHz	+ 0.018 7 μV/day	± 0.001 8 mV
Alternating Voltage	1 V	1 V	10 Hz	– 0.005 21 μV/day	± 0.000 002 V
Alternating Voltage	1 V	1 V	55 Hz	– 0.008 95 μV/day	± 0.000 002 V
Alternating Voltage	1 V	1 V	1.005 kHz	– 0.007 95 μV/day	± 0.000 002 V
Alternating Voltage	1 V	1 V	20 kHz	– 0.007 53 μV/day	± 0.000 002 V
Alternating Voltage	1 V	1 V	50 kHz	– 0.007 51 μV/day	± 0.000 002 V
Alternating Voltage	1 V	1 V	1 MHz	+ 0.073 6 μV/day	± 0.000 04 V
Alternating Voltage	10 V	10 V	10 Hz	– 0.058 7 μV/day	± 0.000 01 V
Alternating Voltage	10 V	10 V	55 Hz	– 0.025 1 μV/day	± 0.000 01 V
Alternating Voltage	10 V	10 V	1.005 kHz	– 0.012 8 μV/day	± 0.000 02 V
Alternating Voltage	10 V	10 V	20 kHz	– 0.004 6 μV/day	± 0.000 02 V
Alternating Voltage	10 V	10 V	50 kHz	+ 0.001 3 μV/day	± 0.000 02 V
Alternating Voltage	10 V	10 V	1 MHz	+ 0.021 0 μV/day	± 0.000 3 V
Alternating Voltage	10 V	19 V	1.005 kHz	+ 0.071 6 μV/day	± 0.000 02 V
Alternating Voltage	100 V	100 V	10 Hz	– 0.175 μV/day	± 0.000 1 V
Alternating Voltage	100 V	100 V	55 Hz	– 0.157 μV/day	± 0.000 2 V
Alternating Voltage	100 V	100 V	1.005 kHz	– 0.235 μV/day	± 0.000 2 V
Alternating Voltage	100 V	100 V	20 kHz	+ 0.056 μV/day	± 0.000 3 V
Alternating Voltage	100 V	100 V	50 kHz	– 0.022 μV/day	± 0.000 2 V
Alternating Voltage	1000 V	700 V	55 Hz	– 7.58 μV/day	± 0.001 V
Alternating Voltage	1000 V	700 V	1.005 kHz	– 11.20 μV/day	± 0.001 V
Alternating Voltage	1000 V	700 V	20 kHz	– 9.88 μV/day	± 0.001 V
Alternating Voltage	1000 V	700 V	50 kHz	– 8.40 μV/day	± 0.004 V

Function	Range	Nominal Value	Nominal Frequency	Drift	Standard Uncertainty
Alternating Current	1 mA	1 mA	55 Hz	+ 0.153 nA/day	± 0.000 024 mA
Alternating Current	1 mA	1 mA	1.005 kHz	+ 0.110 nA/day	± 0.000 030 mA
Alternating Current	1 mA	1 mA	5 kHz	+ 0.094 nA/day	± 0.000 033 mA
Alternating Current	1 A	1 A	55 Hz	+ 0.112 µA/day	± 0.000 013 A
Alternating Current	1 A	1 A	1.005 kHz	+ 0.113 µA/day	± 0.000 015 A
Alternating Current	1 A	1 A	5 kHz	+ 0.091 µA/day	± 0.000 027 A
Resistance	10 Ω	10 Ω	–	– 0.019 0 µΩ/day	± 0.000 004 Ω
Resistance	100 Ω	100 Ω	–	– 0.071 4 µΩ/day	± 0.000 02 Ω
Resistance	1 kΩ	1 kΩ	–	– 0.001 05 mΩ/day	± 0.000 000 3 kΩ
Resistance	10 kΩ	10 kΩ	–	– 0.012 7 mΩ/day	± 0.000 002 kΩ
Resistance	100 kΩ	100 kΩ	–	– 0.089 mΩ/day	± 0.000 03 kΩ
Resistance	1 MΩ	1 MΩ	–	– 0.001 19 Ω/day	± 0.000 000 2 MΩ
Resistance	10 MΩ	10 MΩ	–	– 0.033 2 Ω/day	± 0.000 015 MΩ
Resistance	100 MΩ	100 MΩ	–	+ 1.62 Ω/day	± 0.000 7 MΩ

Appendix V: Comparison protocol

Technical Protocol

Version 1.5 (21 June 2016)

P1-APMP.EM-S12
Comparison of Standards for the Calibration of Voltage, Current and Resistance Meters

Coordinated by:

Louis Marais

National Measurement Institute

36 Bradfield Rd, West Lindfield
NSW 2070, Australia

Contents

Technical Protocol

P1-APMP.EM-S12
Comparison of Standards for the Calibration of Voltage, Current and Resistance Meters

1. Introduction

The 14th Meeting of the APMP Technical Committee on Electricity and Magnetism, held on 5 December 2011 in Kobe, Japan, decided to hold a comparison of standards for the calibration of voltage, current and resistance meters at the lowest attainable level of uncertainty. This comparison complements the APMP.EM-S8 comparison using a 6.5 digit multimeter and the following comparisons of primary standards that provide traceability for the calibration of voltage, current and resistance meters: APMP.EM-K2: DC high resistance at 10 MΩ, 1 GΩ (in progress); APMP.EM.BIPM-K11.3: DC voltage, 10 V and 1.018 V (in progress); APMP.EM-K6.a : AC/DC transfer at 3 V (completed); APMP.EM-K9: AC/DC transfer at 500 V, 1000 V (completed). The National Measurement Institute, Australia (NMIA) has been appointed the pilot laboratory.

2. Travelling Standard

2.1 Description of the Standard

The travelling standard is a Wavetek model 4950 Multifunction Transfer Standard (MTS), serial number 33528. The primary purpose of this instrument is to calibrate precision multifunction calibrators, where the MTS is sent to the client by a calibration authority, used to calibrate the calibrator, and then returned to the calibration authority. The instrument has been designed to withstand shipping, and is ideal for this comparison. In preparation for the comparison, the temperature sensitivity of each function of the MTS was determined, and a correction will be applied to correct for temperature differences between participants. The effect of humidity was investigated in the relative humidity range from 30% to 70%. The response of the instrument was affected very slightly by the change in humidity. A decision on whether to apply a correction will be taken after analysis of the comparison results. For any corrections applied, the uncertainty associated with the correction will be added by the pilot laboratory.

The travelling standard will be shipped in a ruggedized transit case with dimensions 75 cm × 58 cm × 29 cm. The weight of the packed travelling standard in its case is 27 kg. A temperature monitor and a temperature and humidity logger will accompany the travelling standard. The monitor records the maximum and minimum temperature that the package is subjected to during transport.

Figure 1. Wavetek 4950 Multifunction Transfer Standard.

2.2 Quantities to be Measured

The quantities to be measured are direct voltage, direct current, resistance, alternating voltage and alternating current. Appendix I contains details of the measurement points.

2.3 Calculating the Comparison Reference Value

The Comparison Reference Value (CRV) will be calculated as a weighted mean of the results from laboratories with independent realisations of relevant primary standards [2] – [4]. Drift of the standard will be calculated from repeated measurements at NMIA.

3. Organisation of Comparison

3.1 Coordinator and Support Group

NMIA will coordinate the comparison.

Address for correspondence	Address for dispatching of standard
Mr Louis Marais National Measurement Institute PO Box 264 Lindfield NSW 2070 Australia	Mr Louis Marais National Measurement Institute 36 Bradfield Road West Lindfield NSW 2070 Australia
Tel: +61 2 8467 3543 Fax: +61 2 8467 3655 Email: louis.marais@measurement.gov.au	Tel: +61 2 8467 3543 Fax: +61 2 8467 3655 Email: louis.marais@measurement.gov.au

Support group:
The Measurement Standards Laboratory of New Zealand (MSL) has agreed to support this comparison.

3.2 Participants

A list of participating institutes with persons responsible for the comparison is given in Appendix II.

3.3 Comparison Schedule

The comparison schedule is given in Appendix III. The period between measurements by the participants is about five weeks. This allows four weeks for measurements, and one week for shipping to the next participant. Should a participant require more time for shipping to the next participant, the measurement time must be shortened.

If unforeseen circumstances prevent a laboratory from carrying out its measurements within the allocated time, it must send the travelling standard to the next participant without delay. The pilot laboratory must be informed in such a case. If time allows, the laboratory may be able to carry out measurements towards the end.

3.4 Transportation and Handling

The travelling standard will be transported using an **ATA Carnet** for custom clearance where possible. Each participant is responsible for arranging transport and insurance from their institute to the next participant. The travelling standard must be sent using an express service with door-to-door delivery service or it must be hand-carry and delivered to the next participant.

The travelling standard can be shipped as freight. Extreme temperatures, pressure and humidity changes as well as violent impacts should be avoided. The travelling standard is equipped with a Shockwatch device that will indicate if it is mishandled.

When the travelling standard arrives at your institute, complete the Receipt form (Appendix IV) and send it to the pilot laboratory by fax or email.

Note that the travelling standard is enclosed within a plastic cover with a packet of desiccant. Make sure that the packet of desiccant is kept dry by sealing it inside the plastic cover after removing the instrument.

When preparing the travelling standard for shipment, complete the Dispatch form (Appendix V) and send a copy to the pilot laboratory and to the next participant by fax or email.

Place a packet of desiccant in the plastic cover before sealing the instrument inside it. If there is doubt about the condition of the desiccant, use a fresh packet. Do not throw away the used packet of desiccant as it can be reactivated and reused.

The travelling standard is accompanied by a temperature monitor that stores the minimum and maximum temperatures. The minimum and maximum temperatures must be recorded on the Packing List form (appendix VII) on receipt of the travelling standard. Instructions on how to extract the information from the temperature monitor is given in appendix VI.

In addition to the temperature monitor, a temperature and humidity logger is located in the travelling standard case. This logger must not be removed or disturbed in any way.

Please resend any forms that are not acknowledged by the pilot laboratory.

3.5 Failure of Travelling Standard

In case of damage or malfunction of the travelling standard the pilot laboratory must be notified immediately.

3.6 Financial Aspects

Each participant institute is responsible for its own costs for the measurements, transportation to the next participant, insurance of the shipment, and any customs charges as well as any damage that may occur within its country.

4. Measurement Instructions

4.1 Tests before Measurements

CHECK THE MAINS VOLTAGE SETTING
BEFORE TURNING ON THE INSTRUMENT!

Upon arrival of the travelling standard:

- Check the contents of the package against the packing list, on the underside of the transit case lid. (A copy of the packing list is shown in Appendix VII.)
- Check the travelling standard and its accessories for any physical damage.
- Record the maximum and minimum temperatures stored in the temperature and humidity monitor, and then reset these values. (See Appendix VI for instructions.)
- Complete the Receipt form (Appendix IV) and send it to the pilot laboratory.

- **Ensure that the mains voltage setting of the travelling standard is changed to match the local mains voltage using switch S1 (figure 2). Refer to page 2-4 of the User's Handbook [5]. Fuse F1 must be changed in accordance with the selected line voltage (figure 2). A set of fuses with the correct ratings is included in the package.**

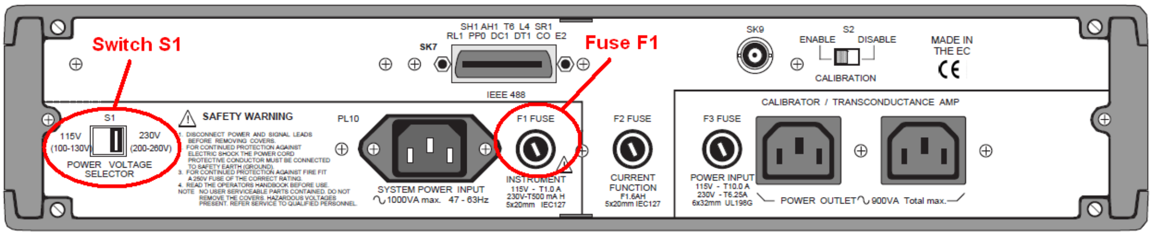


Figure 2. Rear panel of Wavetek 4950 Multifunction Transfer Standard.

- Allow the travelling standard to acclimatise and then warm up with the travelling standard switched on for at least 24 hours in a controlled environment.
- Check that the travelling standard is functioning correctly. Perform the "Confidence Self-test" as detailed on page 8-4 of the handbook [5]. Three self-test errors may pause the confidence self-test. These are:
    - 2106: Outside 30 day cal period;
    - 2107: Outside 30 day cal period; and
    - 2108: Outside 30 day cal period.
- If these errors occur, press the Continue (Cont) soft-key to proceed with confidence tests.
- If the 4950 displays any other four-figure number starting with 2 (Confidence Test Unsuccessful) during the confidence self-test the instrument probably has a fault. In this case, note the number and contact the pilot laboratory.

4.2 Measurements

Before starting measurements familiarise yourself with the travelling standard. A copy of the handbook [5] is on the CD that accompanies the travelling standard. The handbook will also be emailed to all participants at the start of the comparison.

The travelling standard must be set up carefully before each measurement. A summary of the instrument settings to be applied is given in Appendix VIII. Sections 3 and 4 of the handbook [5] have detailed instructions on applying these settings.

4.2.1 Environmental Conditions

The environmental conditions (temperature and humidity) during the measurement must be recorded. The recommended conditions are 23 °C and 50 %RH.

4.2.2 Travelling Standard Internal Temperature

The internal temperature of the travelling standard must be recorded before each measurement. This is done following the instructions on page 4-6 of the handbook [5].

4.2.3 Measurement Lead

The measurement lead supplied with the instrument (serial number 33528) must be used for all measurements. Due to the design of the instrument, the definition of input quantities includes the measurement lead. Corrections for this lead are stored in the instrument, and applied by the instrument while the measurement is performed.

Inspect the measurement lead connectors to ensure that they are clean before starting measurements. The connectors should be cleaned if required.

A type-N to banana adapter (serial number 4BN-002) is included with the travelling standard. This adapter should be used for all alternating voltage measurements (see figure VIII-3).

4.2.4 Resetting the Travelling Standard

The travelling standard should be reset before starting measurements on a new function. This is required to ensure that the travelling standard is in a well-defined state before starting measurements on a new function.

4.2.5 Applying the Test Signal

The function and range must be selected on the travelling standard before applying a test signal. Failure to do this can seriously damage the instrument.

4.2.6 Zeroing

Zeroing must be done for each range of the direct voltage, direct current and resistance measurements (lead connections for zeroing are given on page 5-45 in the handbook [5]). (The zero offset can also be removed by subtracting the instrument indication with zero signal applied from the instrument indication with the required signal applied.) Note that the measurand is defined as the change in the reading when the required change in the applied quantity is made.

4.2.7 Settling Time

The minimum settling time given in Table 1 should be used after first application of the test signal. For zeroing, the minimum settling time for all functions is 5 minutes. For alternating voltage and alternating current measurements, the settling time apply to the first frequency, after which a shorter settling time may be used for subsequent frequencies, but only if the signal is continuously applied.

Table 1: Minimum settling times after application of test signal.

Function	**Nominal Value**	**Settling time**
Direct voltage	0.1 V on 0.1 V range	5 minutes
	1 V on 1 V range	5 minutes
	10 V on 10 V range	5 minutes
	19 V on 10 V range	5 minutes
	100 V on 100 V range	5 minutes
	1000 V on 1000 V range	5 minutes
Direct current	1 mA on 1 mA range	10 minutes
	1 A on 1 A range	60 minutes
Alternating voltage, initial frequency	10 mV on 10 mV range	5 minutes
	100 mV on 100 mV range	5 minutes
	1 V on 1 V range	5 minutes
	10 V on 10 V range	5 minutes
	19 V on 10 V range	5 minutes
	100 V on 100 V range	5 minutes
	700 V on 1000 V range	5 minutes
Alternating current, initial frequency	1 mA on 1 mA range	10 minutes
	1 A on 1 A range	60 minutes

Table 1 (continued): Minimum settling times after application of test signal.

Function	Nominal Value	Settling time
Resistance	10 Ω on 10 Ω range	5 minutes
	100 Ω on 100 Ω range	5 minutes
	1 kΩ on 1 kΩ range	5 minutes
	10 kΩ on 10 kΩ range	5 minutes
	100 kΩ on 100 kΩ range	5 minutes
	1 MΩ on 1 MΩ range	5 minutes
	10 MΩ on 10 MΩ range	10 minutes
	100 MΩ on 100 MΩ range	10 minutes

4.2.8 Guarding

All measurements must be performed with Remote Guard turned ON. The guard terminal of the measurement lead must be connected to ground at an appropriate location in the measurement setup. Refer to appendix VIII for measurement lead connections.

4.2.9 Accuracy Setting

All measurements must be performed with the Accuracy set to HIGH.

4.2.10 Measurement Band Limit

All measurements, except for the 700 V alternating voltage measurements, should be performed with the Measurement Band Limit setting ON. The Measurement Band should be set to 0% for zero measurements, 100% for full range measurements, and 190% for 19 V direct and alternating voltage measurements on the 10 V range. For the alternating voltage function, only the 1 kHz at 10 V has a measurement band selection. The other alternating voltage ranges and the alternating current function do not have a measurement band selection.

4.2.11 Frequency Band

For alternating voltage and current measurements, the Frequency Band must be set to the frequency being measured. The frequency of the source used must be measured and reported at every measurement frequency. The uncertainty of the frequency measurement must also be reported. Note that the frequency accuracy of the source can be determined before the start of measurements using an appropriate output level. The frequency stability of modern sources is excellent and should remain constant throughout the measurement period.

4.2.12 Wiring Configuration

The wiring configurations for the different measurements are shown in Appendix VIII. For alternating voltage measurements at 1 V and 10 V and 1 MHz, **4wCct** must be selected in the ACV Configuration menu (this is the default setting after resetting the instrument). Note that the figures in Appendix VIII are indicative only and do not mandate the instruments or setups to use for performing measurements for this comparison.

4.2.13 2-wire Ohms Lead Serial Number

In order to perform 2-wire resistance measurements, the serial number of the measurement lead must be entered. The procedure for entering the lead serial number is described in detail in [5] on page 4-17.

4.2.14 Standardisation of Measurements

All measurements will be standardised to the same internal temperature of the travelling standard (40.0 °C). If the humidity varies significantly across participant's measurements, it will be standardised to 50 %RH. This will be done by the pilot laboratory, and an uncertainty will be added to the participant's result to account for the corrections.

5. Uncertainty of Measurement

5.1 Uncertainty Components

All contributions to the measurement uncertainty should be listed in the report submitted by each participant.

5. 2 Uncertainty Budget

The uncertainty must be calculated according to *JCGM 100:2008 – Evaluation of measurement data – Guide to the expression of uncertainty in measurement* [6] for a 95% level of confidence. In uncertainty evaluations, all uncertainty components taken into account should be included. The coverage factor and the effective degrees of freedom should be reported.

6. Measurement Results of the Laboratories

A detailed comparison report should be prepared according to the guidelines below, and sent to the pilot laboratory within one calendar month of completing the measurements. An early report helps in evaluating the behaviour of the travelling standard.

The comparison report should contain (for each function, and for each measurement method used):

- A detailed description of the method;
- A detailed description of the traceability of the method; and
- The conditions of the measurement: ambient temperature and humidity.

For each measurement point, the report should contain:

- Internal temperature of the travelling standard;
- Actual frequency of voltage / current source for alternating voltage / current measurements, and its uncertainty;
- The measurement result (correction for the travelling standard; an example is shown below); and
- A detailed uncertainty budget.

The correction of the travelling standard must be reported in the unit of measurement that apply to the parameter being measured. For example: The travelling standard is set to measure alternating voltage on its 10 V range. The indication on its display is 10.000 50 V. The applied voltage is 10.000 09 V. The correction is then 10.000 09 V – 10.000 50 V = – 0.000 41 V. The value to be reported is the correction, which for the example is – 0.000 41 V. The uncertainty of measurement should be reported in the same units as the correction.

The results of the measurements must also be entered into the results spreadsheet and sent to the pilot laboratory with the measurement report. The spreadsheet format is shown in Appendix IX. A copy will be sent to all participants before the start of the comparison.

If an anomalous result is identified, the laboratory will be informed and invited to check their results for numerical errors. If no numerical error is found the result stands and the complete set of results is sent to all participants.

7. Final Report of the Comparison

At the conclusion of circulation of the travelling standard the pilot laboratory will prepare a first draft (draft A) of the final report and will send it to the participants. This draft will be confidential. The draft will be prepared within 4 months after the end of circulation of the standard.

The participants will have two months for comments on draft A. If an institute's result is anomalous, it can decide to withdraw its result with the agreement of the other participants [1].

On the basis of the comments received, the pilot laboratory prepares a second draft (draft B), where the withdrawn results will not appear. Draft B will be submitted to the APMP TCEM and, after approval, will become the Final Report. The Final Report will form the basis for the publication of results, if any.

References

[1] Guidelines for CIPM key comparisons, available on the BIPM website: http://www.bipm.org/pdf/guidelines.pdf.

[2] Randa, J., "Update to proposal for KCRV & degree of equivalence for GTRF key comparisons," February 2005, available on the BIPM website: http://www.bipm.org/wg/CCEM/GT-RF/Allowed/18/GTRF-05-04.pdf.

[3] Cox M. G., "The evaluation of key comparison data: An introduction," *Metrologia*, 2002, 39, 587-589.

[4] Cox M. G., "The evaluation of key comparison data," *Metrologia*, 2002, 39, 589-595.

[5] Instrument User's Manual for Model 4950 Multifunction Transfer Standard, Issue 4, December 1998. Supplied on compact disk accompanying the travelling standard.

[6] JCGM 100:2008 – Evaluation of measurement data – Guide to the expression of uncertainty in measurement, September 2008, available on the BIPM website: http://www.bipm.org/utils/common/documents/jcgm/JCGM_100_2008_E.pdf

Amendments

No	Date	Version number	Changes
0	21 March 2015	1.0	Original version
1	7 July 2015	1.1	1. Slight change of wording in paragraph 4.1. 2. Corrected serial number of the type-N to banana adapter in paragraph 4.2.3. 3. Amended comparison schedule.
2	7 October 2015	1.3	1. Note that version number 1.2 was skipped in order to keep the version of the protocol the same as that of the comparison schedule. 2. Amended comparison schedule.
3	8 January 2016	1.4	1. Amended comparison schedule.
4	21 June 2016	1.5	1. Amended comparison schedule – NMC (Singapore) requested to remeasure the artefact. They suffered an equipment breakdown at the end of their first set of measurements.

Appendix I Measurement Points

Direct Voltage

+ 0.1 V, + 1 V, + 10 V, + 19 V, + 100 V, + 1000 V

Alternating Voltage

Frequency	Voltage						
	10 mV	100 mV	1 V	10 V	19 V	100 V	700 V
10 Hz	×	×	×	×		×	
55 Hz	×	×	×	×		×	×
1.005 kHz	×	×	×	×	×	×	×
20 kHz	×	×	×	×		×	×
50 kHz	×	×	×	×		×	×
1 MHz	×	×	×	×			

Direct Current

+ 1 mA, + 1 A

Alternating current

Frequency	Current	
	1 mA	1 A
55 Hz	×	×
1.005 kHz	×	×
5 kHz	×	×

Four-wire Resistance

10 Ω, 100 Ω, 1 kΩ, 10 kΩ

Two-wire Resistance

100 kΩ, 1 MΩ, 10 MΩ, 100 MΩ

Appendix II List of Participants

Country	Institute acronym	Contact person	Institute address	Shipping address
Australia	NMIA	Louis Marais	National Measurement Institute, PO Box 264, Lindfield, NSW 2070, Australia	National Measurement Institute, Receiving store, 36 Bradfield Rd, West Lindfield, NSW 2070, Australia
		Contact details:	Tel: +61 2 8467 3543 Fax: +61 2 8467 3655	Email: louis.marais@measurement.gov.au
China	NIM	LIU Yue	Room 210, Building 2, No.18 Bei San Huan Dong Lu, Chaoyang District, Beijing, China	Room 210, Building 2, No.18 Bei San Huan Dong Lu, Chaoyang District, Beijing, China
		Contact details:	Tel: 86-10-64524524 Fax: 86-10-64524524	Email: Liuyue@nim.ac.cn
Hong Kong	SCL	Dr. Steven Yang	Standards and Calibration Laboratory, 36/F, Immigration Tower, 7 Gloucester Road, Wan Chai, Hong Kong	Standards and Calibration Laboratory, 36/F, Immigration Tower, 7 Gloucester Road, Wan Chai, Hong Kong
		Contact details:	Tel: (852) 2829 4855 Fax: (852) 2829 4865	Email: steven.yang@itc.gov.hk

Appendix II List of Participants (continued)

Country	Institute acronym	Contact person	Institute address	Shipping address
India	NPLI	Mr. Thomas John Mr. P.S. Negi	National Physical Laboratory, Dr. K. S. Krishnan Road, New Delhi-110012 India	Director, National Physical Laboratory, Dr. K. S. Krishnan Road, New Delhi-110012 India
		Contact details:	Tel: 91-11-4560 8233 91-11-4560 9344 Fax: 91-11-4560 9310	Email: tjohn@nplindia.org psnegi@nplindia.org
Japan	JEMIC	Mr. Hiroaki Sakuma	Japan Electric Meters Inspection Corporation, 15-7, 4-chome, Shibaura, Minato-ku, Tokyo, 108-0023, JAPAN	Japan Electric Meters Inspection Corporation, 15-7, 4-chome, Shibaura, Minato-ku, Tokyo, 108-0023, JAPAN
		Contact details:	Tel: +81-3-3451-6762 Fax: +81-3-3451-1497	Email: h-sakuma@jemic.go.jp

Appendix II List of Participants (continued)

Country	Institute acronym	Contact person	Institute address	Shipping address
New Zealand	MSL	Murray Early	Measurement Standards Laboratory, Callaghan Innovation, P O Box 31-310, Lower Hutt, 5040, New Zealand	Measurement Standards Laboratory, Inwards Goods Store, Callaghan Innovation, 69 Gracefield Rd, Lower Hutt, 5040, New Zealand
		Contact details:	Tel: +64 4 931-3192 Fax: +64 4 931-3194	Email: m.early@irl.cri.nz
Singapore	NMC	Chua Sze Wey	National Metrology Centre, 1 Science Park Drive, Singapore 118221, Republic of Singapore	National Metrology Centre, 1 Science Park Drive, Singapore 118221, Republic of Singapore
		Contact details:	Tel: +65 6279 1909 Fax: +65 6279 1993	Email: chua_sze_wey@nmc.a-star.edu.sg
Thailand	NIMT	Chalit Kumtawee Yaowaret Pimsut	National Institute of Metrology (Thailand), 3/4-5 Moo 3, Klong 5, Klongluang, Pathumthani 12120, Thailand	National Institute of Metrology (Thailand), Electrical Metrology Department, 3/4-5 Moo 3, Klong 5, Klongluang, Pathumthani 12120, Thailand
		Contact details:	Tel: +66 2577 5100 ext. 1234 Fax: +66 2577 5093	Email: chalit@nimt.or.th yaowaret@nimt.or.th

Appendix III Comparison Schedule

Institute	Receipt of standard	Departure of standard	Report due date
Round 1			
NMIA, Australia	–	27 March 2015	–
NPLI, India	6 April 2015	8 June 2015	13 July 2015
NMC, Singapore	6 July 2015	4 August 2015	7 September 2015
JEMIC, Japan	17 August 2015	17 September 2015	19 October 2015
NMIA, Australia	21 September 2015	–	–
Round 2 (non – Carnet)			
NMIA, Australia	–	14 October 2015	–
NIM, China	3 November 2015	12 December 2015	15 January 2016
NMIA, Australia	15 December 2015	–	–
Round 3			
NMIA, Australia	–	26 January 2016	–
NIMT, Thailand	10 February 2016	7 March 2016	11 April 2016
SCL, Hong Kong	11 March 2016	8 April 2016	13 May 2016
MSL, New Zealand	14 April 2016	3 June 2016	8 July 2016
NMIA, Australia	15 June 2016	–	–
Round 4 (non – Carnet)			
NMIA, Australia	–	15 July 2016	–
NMC, Singapore	22 July 2016	19 August 2016	22 September 2016
NMIA, Australia	26 August 2016	–	–

Appendix IV Receipt Form

When the package is received, complete this form, and send it to the pilot laboratory.

To: Name: Louis Marais

Institute: National Measurement Institute, Australia

Fax: +61 2 8467 3655

Email: louis.marais@measurement.gov.au

From: Name:

Institute:

Fax:

Email:

Arrival date:

Is there any damage to the package? ☐ NO ☐ YES

If there is damage to the package, please send photographs of the damage to the pilot laboratory.

Briefly describe the damage here:

Check the content of the package against the packing list.

Is the content of the package complete? ☐ YES ☐ NO

If NO, what is missing?

Please record the maximum and minimum temperatures recorded during shipment (refer to appendix VI):

Maximum °C

Minimum °C

Reset the maximum and minimum temperatures.

What is the colour of the "Shockwatch" phial on the rear panel? ☐ WHITE ☐ RED

After changing the voltage selector for the local mains voltage, and changing fuse L1:

Is the instrument functioning correctly? ☐ YES ☐ NO

If NO, please describe the malfunction briefly:

Appendix V Dispatch Form

When the package is ready for shipment, complete this form and send a copy to the pilot laboratory, and send a copy to the recipient laboratory.

To: Name: ....

Institute: ....

Fax: ....

Email: ....

From: Name: ....

Institute: ....

Fax: ....

Email: ....

Dispatch date: ....

Comments on performance of the standard: ....

....

....

Courier (if applicable) .... Tracking no. ....

Airline .... Flight no .... Dated ....

Other details of Courier Company (if applicable):

Contact person: ....

Address: ....

Tel: ....

Fax: ....

Email: ....

Website: ....

Confirm that the minimum and maximum temperatures have been reset: ☐

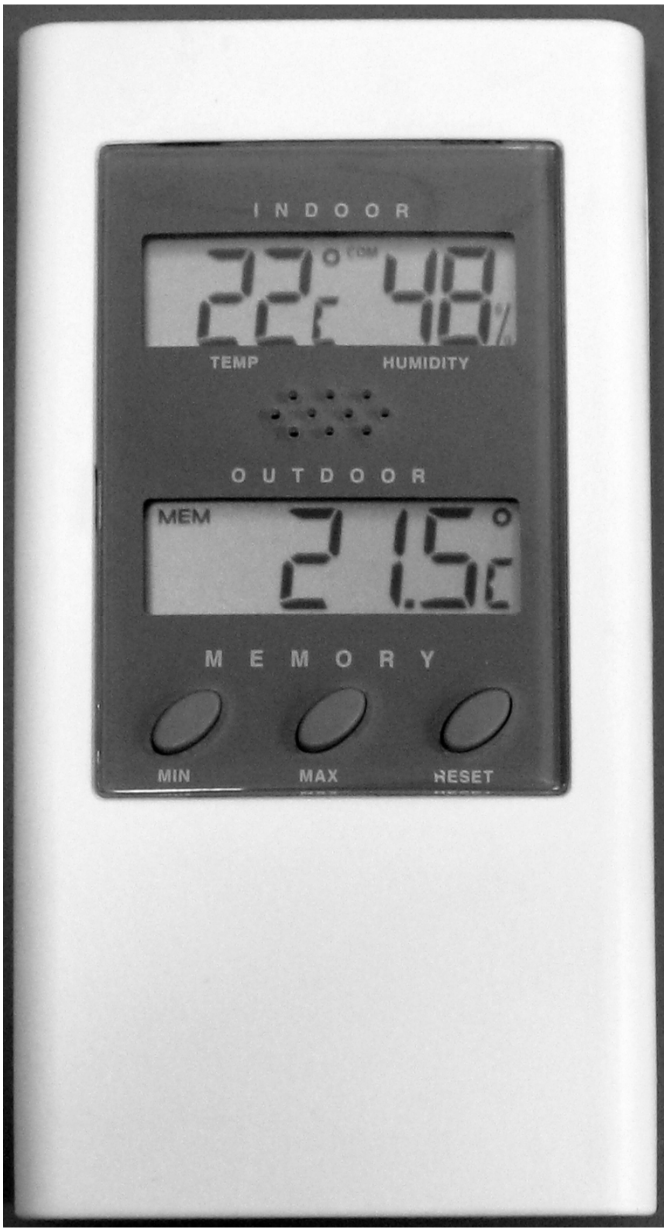
Confirm that the package content is complete as shown on packing list: ☐

Confirm that an activated desiccant bag has been placed in the zipper bag with the travelling standard: ☐

Signature of person completing this form: ....

Appendix VI Temperature Monitor Instructions

When the package is received, record the maximum and minimum temperatures during transit on the Receipt form (Appendix IV).



Record the maximum and minimum temperatures:

MAX	Press the **MAX** button once so that **MAX** is displayed on the OUTDOOR (bottom) readout. Record the temperature. Pressing **MAX** again shows the current temperature reading.
MIN	Press the **MIN** button once so that **MIN** is displayed on the OUTDOOR (bottom) readout. Record the temperature. Pressing **MIN** again shows the current temperature reading.

Reset the maximum and minimum temperatures:

MAX	Press the **MAX** button once so that **MAX** is displayed on the OUTDOOR (bottom) readout. Press the **RESET** button. Pressing **MAX** again shows the current temperature reading.
MIN	Press the **MIN** button once so that **MIN** is displayed on the OUTDOOR (bottom) readout. Press the **RESET** button. Pressing **MIN** again shows the current temperature reading.

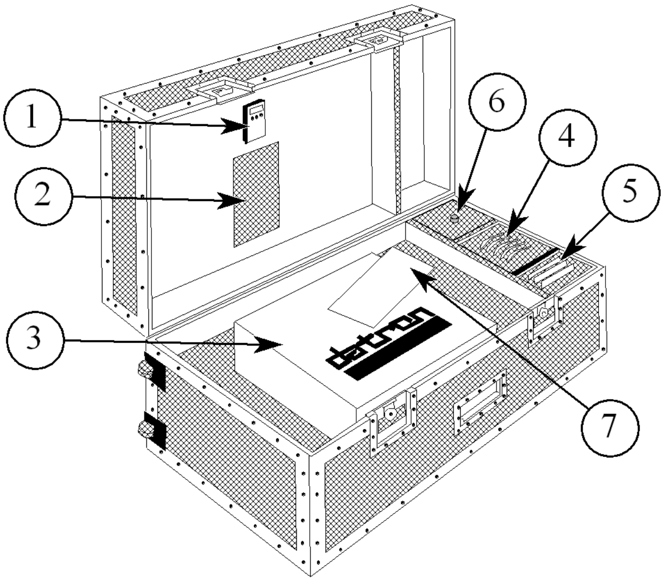
Appendix VII Packing List

The packing list can be found on the underside of the lid of the travelling standard transit case.

PACKING LIST	**IMPORTANT:** Check the contents of the travelling standard transit case against this list, complete the Receipt form, and send it to the pilot laboratory.

Items:

1. Temperature monitor, serial number 33528.
2. Packing list (this document).
3. Travelling standard: Wavetek model 4950 serial number 33528, in zipper bag.
4. Connecting cable, serial number 33528 and 4 banana to type-N adapter serial number 4BN-002.
5. Desiccant.
6. Environmental logger (do not disturb)
7. Folder with instrument manual on CD, and fuses for either 200-260 V or 100-130 V operation.



Institute: ....

Receipt date: ....

Name: ....

<u>Checks to be performed</u> (See Appendix VI for instructions)

Maximum recorded temperature since closing the transit case: .... °C

Minimum recorded temperature since closing the transit case: .... °C

Record of handling during transit – state of "Shockwatch" phial:
(White – Normal, Red – Rough) ....

Reset the temperature recorder: ....

Please remember to complete the Receipt form (Appendix IV)

Appendix VIII Summary of Instrument Settings

The following settings apply to all measurements:
- Remote Guard ON.
- Accuracy set to HIGH.

Function	Range	Nominal Value	Measurement Frequency	Settings: Band Limit Percent	Settings: Measurement Band Limit	Settings: Wiring Diagram	Settings: Frequency Band
Direct Voltage	0.1 V	0 V	–	0%	ON	–	–
		0.1 V	–	100%	ON	VIII-1	–
	1 V	0 V	–	0%	ON	–	–
		1 V	–	100%	ON	VIII-1	–
	10 V	0 V	–	0%	ON	–	–
		10 V	–	100%	ON	VIII-1	–
		19 V	–	190%	ON	VIII-1	–
	100 V	0 V	–	0%	ON	–	–
		100 V	–	100%	ON	VIII-1	–
	1000 V	0 V	–	0%	ON	–	–
		1000 V	–	100%	ON	VIII-1	–
Direct Current	0.001 A	0 A	–	0%	ON	–	–
		0.001 A	–	100%	ON	VIII-2	–
	1 A	0 A	–	0%	ON	–	–
		1 A	–	100%	ON	VIII-2	–
Alternating Voltage	0.01 V	0.01 V	10 Hz	–	ON	VIII-3	10 Hz
		0.01 V	55 Hz	–	ON	VIII-3	55 Hz
		0.01 V	1.005 kHz	–	ON	VIII-3	1 kHz
		0.01 V	20 kHz	–	ON	VIII-3	20 kHz
		0.01 V	50 kHz	–	ON	VIII-3	50 kHz
		0.01 V	1 MHz	–	ON	VIII-3	1 MHz
	0.1 V	0.1 V	10 Hz	–	ON	VIII-3	10 Hz
		0.1 V	55 Hz	–	ON	VIII-3	55 Hz
		0.1 V	1.005 kHz	–	ON	VIII-3	1 kHz
		0.1 V	20 kHz	–	ON	VIII-3	20 kHz
		0.1 V	50 kHz	–	ON	VIII-3	50 kHz
		0.1 V	1 MHz	–	ON	VIII-3	1 MHz
	1 V	1 V	10 Hz	–	ON	VIII-3	10 Hz
		1 V	55 Hz	–	ON	VIII-3	55 Hz
		1 V	1.005 kHz	–	ON	VIII-3	1 kHz
		1 V	20 kHz	–	ON	VIII-3	20 kHz
		1 V	50 kHz	–	ON	VIII-3	50 kHz
		1 V *	1 MHz	–	ON	VIII-3	1 MHz
	10 V	10 V	10 Hz	–	ON	VIII-3	10 Hz
		10 V	55 Hz	–	ON	VIII-3	55 Hz
		10 V	1.005 kHz	100%	ON	VIII-3	1 kHz
		10 V	20 kHz	–	ON	VIII-3	20 kHz
		10 V	50 kHz	–	ON	VIII-3	50 kHz
		10 V *	1 MHz	–	ON	VIII-3	1 MHz

* For 1 MHz measurements at 1 V and 10 V, select the 4wCct function in the ACV CONFIG menu.

Appendix VIII Summary of Instrument Settings (continued)

Function	Range	Nominal Value	Measurement Frequency	Settings			
				Band Limit Percent	Measurement Band Limit	Wiring Diagram	Frequency Band
Alternating Voltage	10 V	19 V	1.005 kHz	190%	ON	VIII-3	1 kHz
	100 V	100 V	10 Hz	–	ON	VIII-3	10 Hz
		100 V	55 Hz	–	ON	VIII-3	55 Hz
		100 V	1.005 kHz	–	ON	VIII-3	1 kHz
		100 V	20 kHz	–	ON	VIII-3	20 kHz
		100 V	50 kHz	–	ON	VIII-3	50 kHz
	1000 V	700 V	55 Hz	–	OFF	VIII-3	55 Hz
		700 V	1.005 kHz	–	OFF	VIII-3	1 kHz
		700 V	20 kHz	–	OFF	VIII-3	20 kHz
		700 V	50 kHz	–	OFF	VIII-3	50 kHz
Alternating Current	0.001 A	0.001 A	55 Hz	–	ON	VIII-2	55 Hz
		0.001 A	1.005 kHz	–	ON	VIII-2	1 kHz
		0.001 A	5 kHz	–	ON	VIII-2	5 kHz
	1 A	1 A	55 Hz	–	ON	VIII-2	55 Hz
		1 A	1.005 kHz	–	ON	VIII-2	1 kHz
		1 A	5 kHz	–	ON	VIII-2	5 kHz
Resistance	10 Ω	0 Ω	–	0%	ON	–	–
		10 Ω	–	100%	ON	VIII-4	–
	100 Ω	0 Ω	–	0%	ON	–	–
		100 Ω	–	100%	ON	VIII-4	–
	1 kΩ	0 Ω	–	0%	ON	–	–
		1 kΩ	–	100%	ON	VIII-4	–
	10 kΩ	0 Ω	–	0%	ON	–	–
		10 kΩ	–	100%	ON	VIII-4	–
	100 kΩ	0 Ω	–	0%	ON	–	–
		100 kΩ	–	100%	ON	VIII-5	–
	1 MΩ	0 Ω	–	0%	ON	–	–
		1 MΩ	–	100%	ON	VIII-5	–
	10 MΩ	0 Ω	–	0%	ON	–	–
		10 MΩ	–	100%	ON	VIII-5	–
	100 MΩ	0 Ω	–	0%	ON	–	–
		100 MΩ	–	100%	ON	VIII-5	–

Appendix VIII Summary of Instrument Settings (continued)

Figure VIII-1: Wiring diagram for direct voltage measurements

Figure VIII-2: Wiring diagram for current measurements

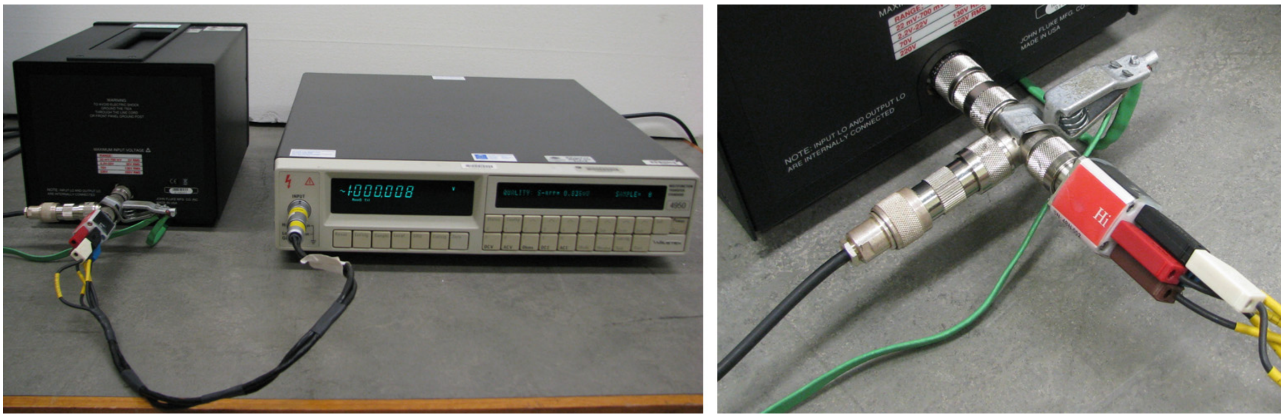


Figure VIII-3: Wiring diagram for alternating voltage measurements

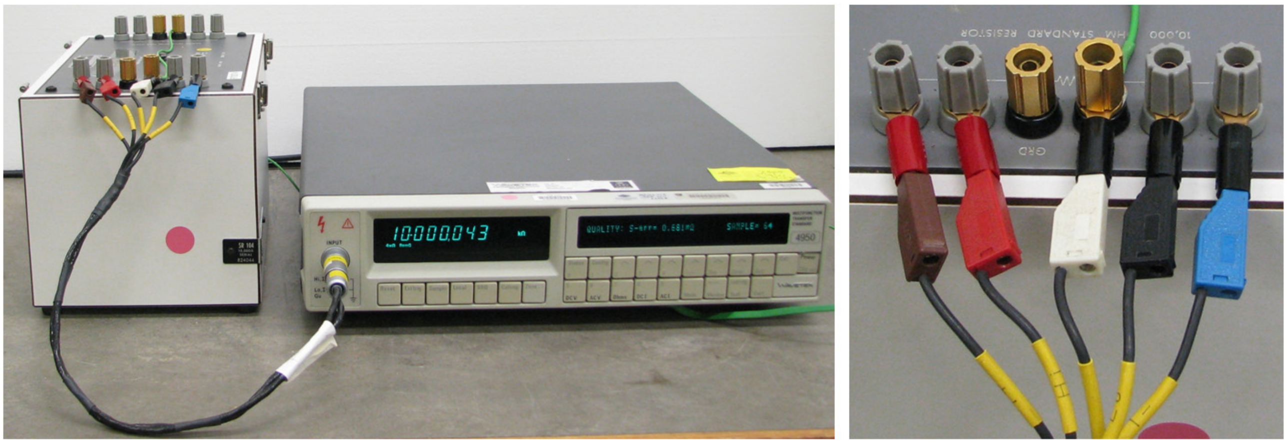


Figure VIII-4: Wiring diagram for four wire resistance measurements

Figure VIII-5: Wiring diagram for two wire resistance measurements

Appendix IX Format of Measurement Results

All participants will receive a spreadsheet for entering their summary results.

Spreadsheet extract:

P1-APMP.EM-S12 Comparison of standards for the calibration of Voltage, Current and Resistance meters

Country: ....
Institute name: ....
Institute acronym: ....

Contact person: ....
Tel: ....
Fax: ....
Email: ....

Environment during measurements:
Temperature:
Average: ________ Maximum: ________ Minimum: ________
Humidity:
Average: ________ Maximum: ________ Minimum: ________

Dates of measurements:
From: ________ To: ________

Summary results:

Function	Range	Nominal Value	Nominal Frequency	Measured Frequency	Frequency Uncertainty	Measu[illegible]es of Resu[illegible]dom	4950 Internal Temperature	Humidity
Direct Voltage	0.1 V	0.1 V	–	–	–			
Direct Voltage	1 V	1 V	–	–	–			
Direct Voltage	10 V	10 V	–	–	–			
Direct Voltage	10 V	19 V	–	–	–			

Appendix IX Format of Measurement Results (continued)

Function	Range	Nominal Value	Nominal Frequency	Measured Frequency	Frequency Uncertainty	Measu[illegible]es of Resu[illegible]dom	4950 Internal Temperature	Humidity
Direct Voltage	100 V	100 V	–	–	–			
Direct Voltage	1000 V	1000 V	–	–	–			
Direct Current	0.001 A	0.001 A	–	–	–			
Direct Current	1 A	1 A	–	–	–			
Alternating Voltage	0.01 V	0.01 V	10 Hz					
Alternating Voltage	0.01 V	0.01 V	55 Hz					
Alternating Voltage	0.01 V	0.01 V	1.005 kHz					
Alternating Voltage	0.01 V	0.01 V	20 kHz					
Alternating Voltage	0.01 V	0.01 V	50 kHz					
Alternating Voltage	0.01 V	0.01 V	1 MHz					
Alternating Voltage	0.1 V	0.1 V	10 Hz					
Alternating Voltage	0.1 V	0.1 V	55 Hz					
Alternating Voltage	0.1 V	0.1 V	1.005 kHz					
Alternating Voltage	0.1 V	0.1 V	20 kHz					
Alternating Voltage	0.1 V	0.1 V	50 kHz					
Alternating Voltage	0.1 V	0.1 V	1 MHz					
Alternating Voltage	1 V	1 V	10 Hz					
Alternating Voltage	1 V	1 V	55 Hz					
Alternating Voltage	1 V	1 V	1.005 kHz					
Alternating Voltage	1 V	1 V	20 kHz					
Alternating Voltage	1 V	1 V	50 kHz					
Alternating Voltage	1 V	1 V	1 MHz					
Alternating Voltage	10 V	10 V	10 Hz					
Alternating Voltage	10 V	10 V	55 Hz					
Alternating Voltage	10 V	10 V	1.005 kHz					
Alternating Voltage	10 V	10 V	20 kHz					
Alternating Voltage	10 V	10 V	50 kHz					
Alternating Voltage	10 V	10 V	1 MHz					
etc.	…	…	…					

Appendix VI: Laboratory reports

Report on

Measurements performed for APMP.EM-S12 Comparison of Standards for the Calibration of Voltage, Current and Resistance Meters

Measurements performed on

Wavetek 4950 serial number 33528

From 16 June 2016 to 6 July 2016

Performed by

National Measurement Institute
36 Bradfield Rd, West Lindfield
NSW 2070, Australia

Report by

Louis Marais

Introduction

The APMP.EM-S12 comparison protocol requires that the travelling standard, a Wavetek model 4950 serial number 33528 (the Unit under Test – UUT), be measured at a number of points for each of its measurement functions. These are direct voltage, direct current, alternating voltage, alternating current and resistance. The measurement points are detailed in the comparison protocol.

The instrument was received on 13 June 2016. The fuse (F1) and mains voltage selection switch (S1) was checked before applying power. The UUT was allowed to stabilise for 24 hours with the power turned on before any measurements were made. The instrument's confidence test was performed and completed without errors.

The measurements were performed from 16 June 2016 to 6 July 2016. The instrument packed for shipment to the National Metrology Centre (Singapore) on 7 July 2016.

Direct Voltage

Test methods:

Direct voltage was measured using three methods:

1. For 100 mV the correction of the UUT was determined by comparing the UUT reading to that obtained with Hewlett-Packard model 34420A nanovoltmeters. For 1 V and 10 V the correction of the UUT was determined by direct connection of the UUT to a calibrated Fluke model 732A zener voltage reference standard.
2. For 19 V to 1000 V the correction of the UUT was determined by direct connection of the UUT to a calibrated Fluke model 5720A multifunction calibrator.

See figure 1.1 for the direct voltage measurement setups.

The 'Remote Guard' function was turned on for all the measurements, and the guard terminal and low voltage terminal were connected to a common ground point. The low current terminal was connected to the low voltage terminal and the high current terminal was connected to the high voltage terminal for all measurements.

Traceability:

All the test methods described for direct voltage was traceable to the Australian national measurement standard for voltage, a Josephson voltage standard. See figure 2.1 for the direct voltage traceability chart.

Conditions of measurement:

During the direct voltage measurements, the following conditions of measurement prevailed:

Ambient temperature:	20.9 °C ± 0.5 °C
Relative humidity:	50 %RH ± 5 %RH

Measurement results:

Range (V)	Nominal Voltage (V)	Correction (V)	Uncertainty (V)	Internal Temperature (°C)
0.1	0.1	– 0.000 000 68	± 0.000 000 28	39.2
1	1	− 0.000 002 9	± 0.000 001 7	39.2
10	10	– 0.000 020	± 0.000 017	39.2
10	19	− 0.000 046	± 0.000 036	39.2
100	100	– 0.000 19	± 0.000 32	39.2
1000	1000	– 0.001 9	± 0.002 5	39.2

Detailed uncertainty budgets for the direct voltage measurements are shown in appendix 3.1.

Direct Current

Test methods:

Direct current was measured the following method:

The correction of the UUT was determined by comparing its readings to the calculated value of the applied current. A calibrated current shunt was connected in series with the UUT. The voltage drop across the current shunt was measured with a calibrated voltmeter. The applied current was calculated from the resistance of the shunt and the measured voltage.

See figure 1.2 for the direct current measurement setup.

The ‘Remote Guard’ function was turned on for all the measurements, and the guard terminal and low current terminal were connected to a common ground point. The low voltage and high voltage terminals were connected to the same ground point.

Traceability:

The resistance of the shunt was traceable to the resistance scale maintained by the Resistance project of the National Measurement Institute, Australia (NMIA). This resistance scale is traceable to the calculable capacitor. See figure 2.2 for the resistance traceability chart.

The direct voltage was traceable to the Australian national measurement standard for voltage, a Josephson voltage standard. See figure 2.1 for the direct voltage traceability chart.

Conditions of measurement:

During the direct current measurements, the following conditions of measurement prevailed:

Ambient temperature: 20.9 °C ± 0.5 °C
Relative humidity: 50 %RH ± 5 %RH

Measurement results:

Range	Nominal Current	Correction	Uncertainty	Internal Temperature (°C)
1 mA	1 mA	+ 0.000 001 mA	± 0.000 008 mA	38.7
1 A	1 A	− 0.000 043 A	± 0.000 009 A	38.7

A settling time of more than 5 minutes was allowed after applying 1 mA to the instrument before starting measurements. For the 1A measurements a settling time of more than 60 minutes was allowed before starting measurements.

Detailed uncertainty budgets for the direct current measurements are shown in appendix 3.2.

Alternating Voltage

Test methods:

Alternating voltage was measured using two methods:

1. For 10 mV and 100 mV the correction of the UUT was determined by comparing the UUT reading to that obtained from an ac-dc difference measurement with a micropot. The micropot consisted of a thermal current converter with a nominal current rating of 10 mA and a current shunt. For 10 mV a 1 Ω shunt was used as the resistive element of the micropot. For the 100 mV measurements, a 10 Ω shunt was used. The applied alternating voltage was calculated from the direct voltage and the ac-dc difference. The applied voltage was corrected for the loading caused by the input impedance of the UUT.
2. For measurements from 1 V to 700 V the correction of the UUT was determined by comparing the UUT reading to that obtained from an ac-dc difference measurement with a Fluke 792A thermal transfer standard. The applied alternating voltage was calculated from the direct voltage measured by the UUT and the ac-dc difference.

See figure 1.3 for the alternating voltage measurement setups.

The ‘Remote Guard’ function was turned on for all the measurements. The input connectors were attached to a 4 banana to type-N adapter, serial number 4BN-002. The guard connector was connected into the rear of the low voltage connector.

As specified by the protocol, the 1 MHz measurements at 1 V and 10 V was done with 4wCct (the default setting) selected.

For the 10 mV and 100 mV measurements, the reference point was the midpoint of a type-N male to male adapter placed between the 4 banana to type-N adapter and the current shunt, and for the measurements from 1 V to 700 V the reference point was the middle of a type-N tee connecting the thermal transfer standard to the 4 banana to type-N adapter. The reference point was connected to the common ground using a copper ground strap.

Traceability:

For the measurements at 10 mV and 100 mV the direct voltage traceability was obtained from the direct current output of the source and the resistance of the shunt. The ac-dc traceability was obtained from the ac-dc difference of the thermal current converter and the ac-dc difference of the shunts. The ac-dc differences were traceable to the primary set of thermal converters maintained by the Low Frequency Standard project of the NMIA.

For the measurements from 1 V to 700 V the direct voltage traceability was obtained from the direct voltage calibration of the UUT. The ac-dc differences were traceable to the primary set of thermal converters maintained by the low frequency project.

The ac-dc differences of the primary converters have been investigated theoretically and their ac-dc differences evaluated in the frequency range from 10 Hz to 1 MHz. They have been used in CCEM Key comparisons and also inter-compared at several voltage ranges.

See figure 2.3 for the ac-dc difference traceability chart.

Conditions of measurement:

During the alternating voltage measurements, the following conditions of measurement prevailed:

Ambient temperature: 20.9 °C ± 0.5 °C
Relative humidity: 50 %RH ± 5 %RH

Measurement results:

Range (V)	Nominal Voltage (V)	Frequency (kHz)	Correction (V)	Uncertainty (V)	Internal Temperature (°C)
0.01	0.01	0.010	0.000 000 0	± 0.000 001 2	38.8
		0.055	– 0.000 000 6	± 0.000 001 2	38.8
		1.005	– 0.000 000 4	± 0.000 001 2	38.8
		20	– 0.000 000 5	± 0.000 001 2	38.8
		50	– 0.000 000 1	± 0.000 001 2	38.8
		1000	– 0.000 055	± 0.000 010	38.8
0.1	0.1	0.010	+ 0.000 005 6	± 0.000 003 0	38.8
		0.055	+ 0.000 010 1	± 0.000 002 6	38.8
		1.005	+ 0.000 010 6	± 0.000 002 6	38.8
		20	+ 0.000 011 7	± 0.000 002 7	38.8
		50	+ 0.000 009 2	± 0.000 003 1	38.8
		1000	− 0.000 346	± 0.000 042	38.8
1	1	0.010	– 0.000 022	± 0.000 030	38.8
		0.055	– 0.000 009 0	± 0.000 008 0	38.8
		1.005	– 0.000 004 2	± 0.000 008 0	38.8
		20	+ 0.000 003	± 0.000 010	38.8
		50	– 0.000 021	± 0.000 016	38.8
		1000	− 0.006 83	± 0.000 15	38.8

Measurement results (continued):

Range (V)	Nominal Voltage (V)	Frequency (kHz)	Correction (V)	Uncertainty (V)	Internal Temperature (°C)
10	10	0.010	– 0.000 56	± 0.000 30	38.8
		0.055	+ 0.000 07	± 0.000 11	38.8
		1.005	+ 0.000 18	± 0.000 11	38.8
		20	+ 0.000 14	± 0.000 13	38.8
		50	+ 0.000 16	± 0.000 18	38.8
		1000	− 0.064 5	± 0.001 4	38.8
10	19	1.005	+ 0.000 39	± 0.000 23	38.8
100	100	0.010	– 0.005 3	± 0.003 1	38.8
		0.055	+ 0.001 0	± 0.001 6	38.8
		1.005	+ 0.001 2	± 0.001 6	38.8
		20	+ 0.001 6	± 0.001 7	38.8
		50	+ 0.000 2	± 0.002 2	38.8
1000	700	0.055	− 0.013	± 0.014	38.8
		1.005	– 0.010	± 0.014	38.8
		20	– 0.003	± 0.017	38.8
		50	+ 0.044	± 0.029	38.8

Detailed uncertainty budgets for the alternating voltage measurements are shown in appendix 3.3.

Alternating Current

Test methods:

Alternating current was measured using the following method:

The correction of the UUT was determined by comparing its readings to the calculated value of the applied current. A current shunt was connected in series with the UUT. The voltage drop across the current shunt was measured with an alternating voltage measurement standard. The applied current was calculated from the resistance and ac-dc differences of the shunts, and the measured voltage.

See figure 1.4 for the alternating current measurement setup.

The ‘Remote Guard’ function was turned on for all the measurements, and the guard terminal and low current terminal were connected to a common ground point.

Traceability:

The resistance of the shunts was traceable to the NMIA resistance scale. The alternating voltage measurement standard and the ac-dc differences of the shunts are traceable to the primary set of thermal converters.

See figure 2.2 for the resistance traceability chart and figure 2.3 for the ac-dc difference traceability chart.

Conditions of measurement:

During the alternating current measurements, the following conditions of measurement prevailed:

Ambient temperature: 20.9 °C ± 0.5 °C
Relative humidity: 50 %RH ± 5 %RH

Measurement results:

Range	Nominal Current	Frequency (kHz)	Correction	Uncertainty	Internal Temperature (°C)
1 mA	1 mA	0.055	+ 0.000 208 mA	± 0.000 040 mA	38.6
		1.005	+ 0.000 194 mA	± 0.000 043 mA	38.6
		5	+ 0.000 185 mA	± 0.000 045 mA	38.6
1 A	1 A	0.055	+ 0.000 101 A	± 0.000 018 A	38.6
		1.005	+ 0.000 136 A	± 0.000 018 A	38.6
		5	+ 0.000 720 A	± 0.000 030 A	38.6

A settling time of more than 5 minutes was allowed after applying 1 mA to the instrument before starting measurements. At 1 A a settling time of more than 60 minutes was allowed before starting measurements

Detailed uncertainty budgets for the alternating current measurements are shown in appendix 3.4.

Resistance

Test methods:

The correction of the UUT was determined by comparing its readings to a set of standard resistors.

See figure 1.5 for the resistance measurement setup.

The 'Remote Guard' function was turned on for all the measurements, and the guard terminal and low voltage terminal were connected to a common ground point. For 2-wire measurements the low current terminal and the high current terminal were connected to the common ground point.

Traceability:

The values of the standard resistors are traceable to the NMIA resistance scale.

See figure 2.2 for the resistance traceability chart.

Conditions of measurement:

During the resistance measurements, the following conditions of measurement prevailed:

Ambient temperature: 20.0 °C ± 1.0 °C

Relative humidity: 50 %RH ± 15 %RH

4-wire measurement results:

Range	Nominal Resistance	Correction	Uncertainty	Internal Temperature (°C)
10 Ω	10 Ω	– 0.000 008 Ω	± 0.000 010 Ω	38.4
100 Ω	100 Ω	– 0.000 27 Ω	± 0.000 004 Ω	38.4
1 kΩ	1 kΩ	+ 0.000 000 1 kΩ	± 0.000 000 4 kΩ	38.4
10 kΩ	10 kΩ	– 0.000 010 kΩ	± 0.000 004 kΩ	38.4

2-wire measurement results:

Range	Nominal Resistance	Correction	Uncertainty	Internal Temperature (°C)
100 kΩ	100 kΩ	− 0.000 14 kΩ	± 0.000 012 kΩ	38.4
1 MΩ	1 MΩ	+ 0.000 000 2 MΩ	± 0.000 002 1 MΩ	38.4
10 MΩ	10 MΩ	– 0.000 096 MΩ	± 0.000 020 MΩ	38.4
100 MΩ	100 MΩ	– 0.002 4 MΩ	± 0.000 6 MΩ	39.3

Detailed uncertainty budgets for the resistance measurements are shown in appendix 3.5.

Frequency

The protocol requires that the frequency of the sources used for alternating voltage and alternating current be measured and reported.

Test methods:

Two different calibrators were used to measure alternating voltage and alternating current. For the alternating voltage measurements, a Fluke model 5700A was used, and for alternating voltage a Fluke model 5720A was used. The correction of the calibrators was determined by measuring the frequency for an output of 1 V with a frequency counter referenced to the national frequency standard (NFS).

A measurement with a 1 V output only is sufficient to cover all the ranges and functions as the same time-base is used to generate the frequency for all output voltages and currents.

See figure 1.6 for the frequency measurement setup.

The ‘External Guard’ function of the calibrator was turned off for all the measurements, and the guard terminal was connected to a common ground point. This was done to provide the measurement circuit with a reference point because the counter input was floating.

Traceability:

The frequency measurements were traceable to the national frequency standard maintained by the Time and Frequency project of the NMIA.

See figure 2.4 for the frequency traceability chart.

Conditions of measurement:

During the frequency measurements, the following conditions of measurement prevailed:

Ambient temperature: 20.9 °C ± 0.5 °C
Relative humidity: 50 %RH ± 5 %RH

Frequency measurement results:

For Fluke 5700A serial number 9355607 used for voltage measurements:

Nominal Frequency	Correction	Uncertainty
10 Hz	− 0.000 034 Hz	± 0.000 045 Hz
55 Hz	− 0.000 193 Hz	± 0.000 045 Hz
1.005 kHz	− 0.003 542 Hz	± 0.000 043 Hz
20 kHz	− 0.070 51 Hz	± 0.000 75 Hz
50 kHz	− 0.175 99 Hz	± 0.001 93 Hz
1 MHz	− 3.603 Hz	± 0.399 Hz

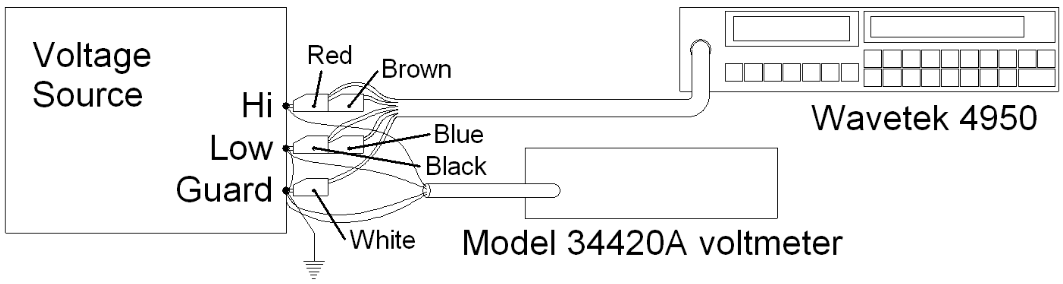
For Fluke 5720A serial number 1306206 used for current measurements:

Nominal Frequency	Correction	Uncertainty
55 Hz	+ 0.000 515 Hz	± 0.000 030 Hz
1.005 kHz	+ 0.009 396 Hz	± 0.000 043 Hz
5 kHz	+ 0.046 80 Hz	± 0.000 19 Hz

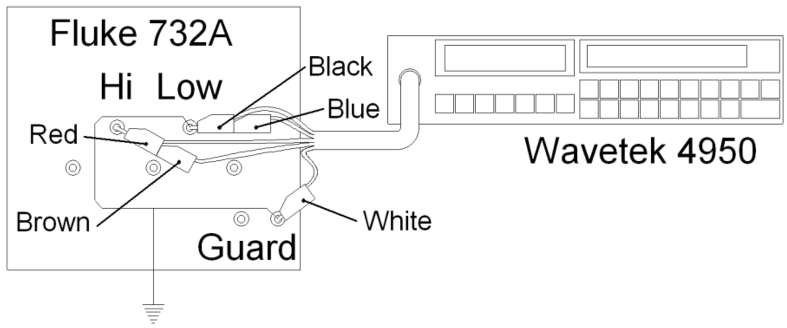
Detailed uncertainty budgets for the frequency measurements are shown in appendix 3.6.

Appendix 1: Measurement setups

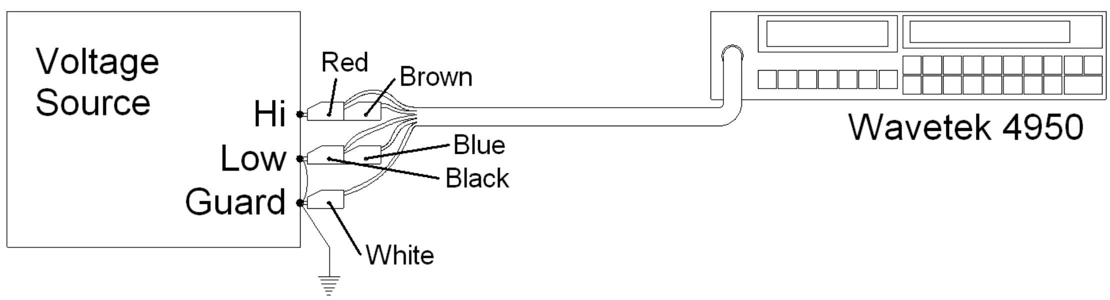
Direct Voltage



(a) 100 mV measurement



(b) 1 V and 10 V measurements



(c) 19 V to 1000 V measurements

Figure 1.1: Direct voltage measurement setups

Direct Current

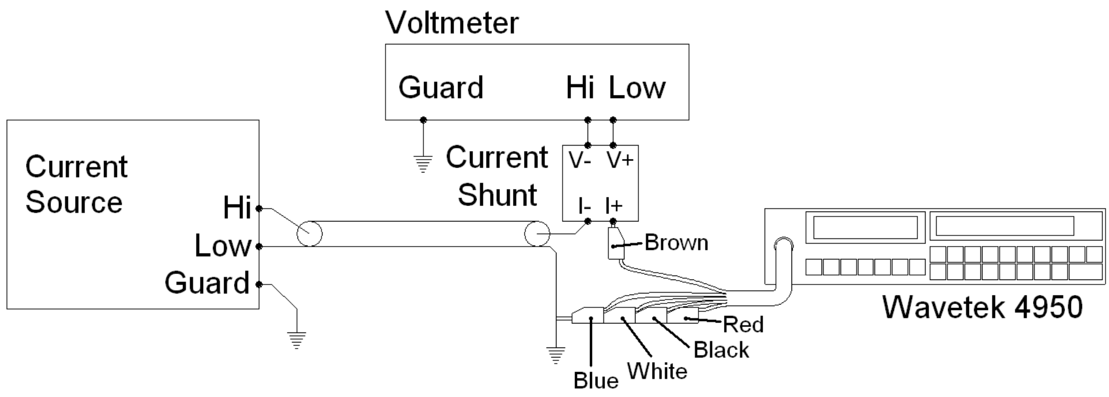
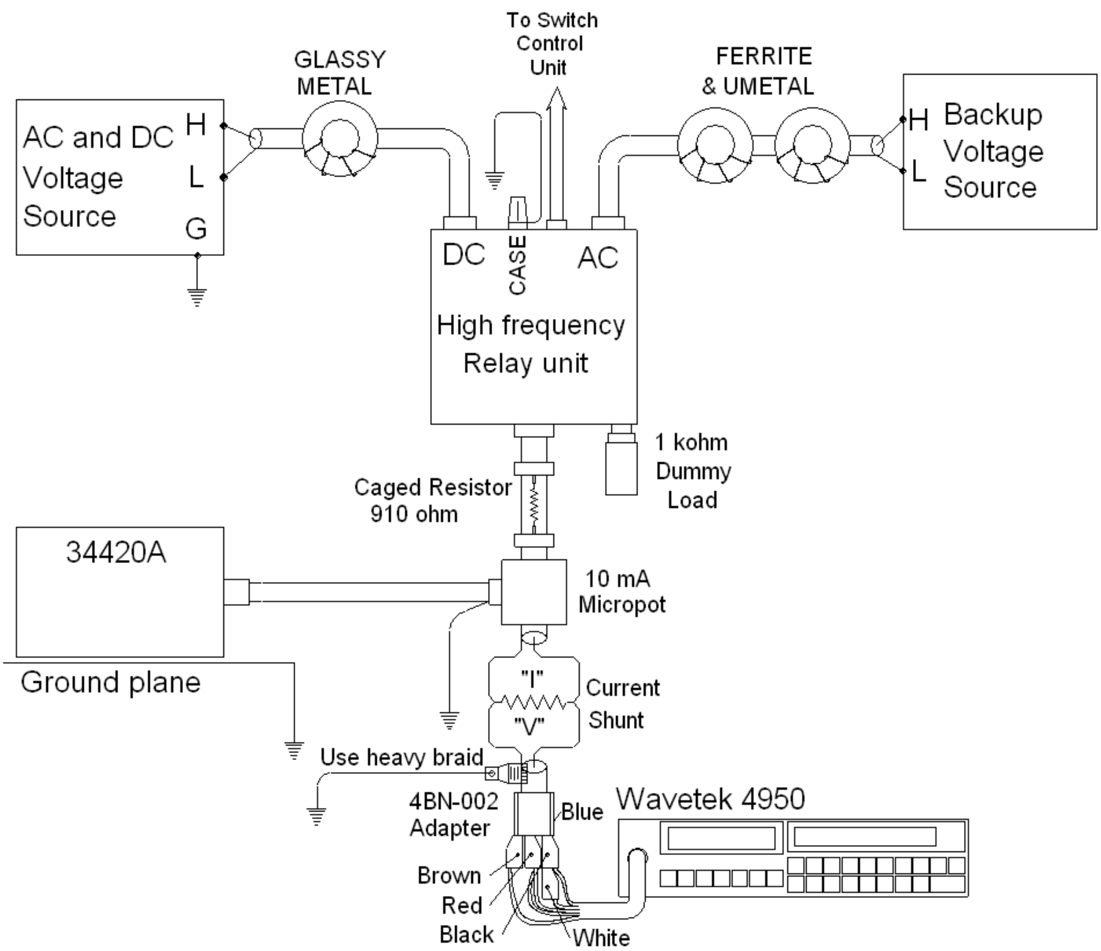
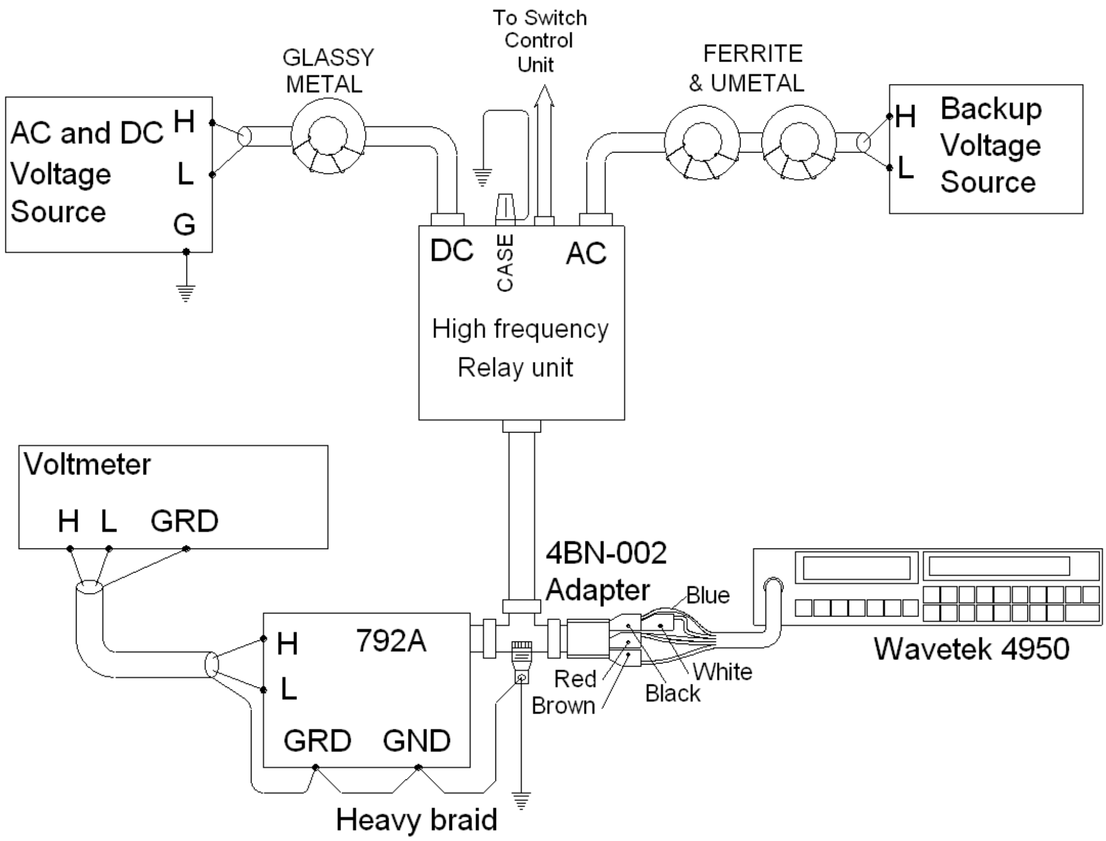


Figure 1.2: Direct current measurement setup

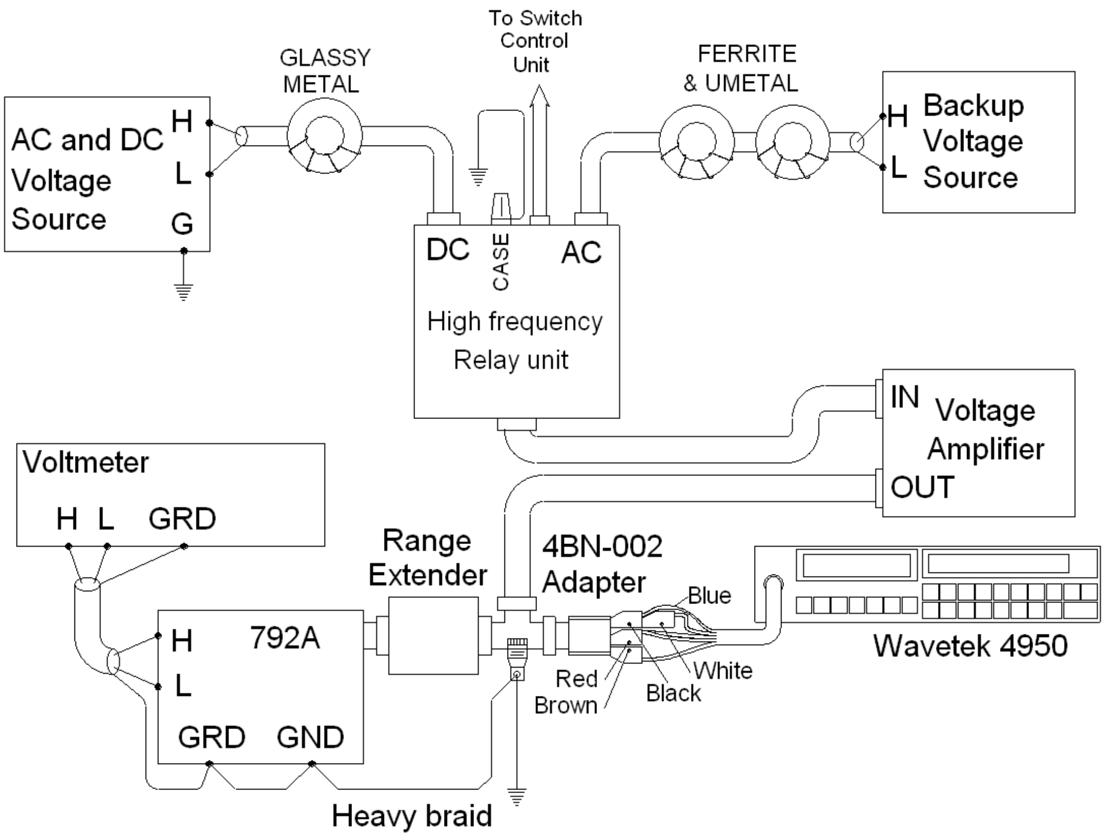
Alternating Voltage



(a) 10 mV and 100 mV



(b) 1 V to 100 V



(c) 700 V

Figure 1.3: Alternating voltage measurement setups

Alternating Current

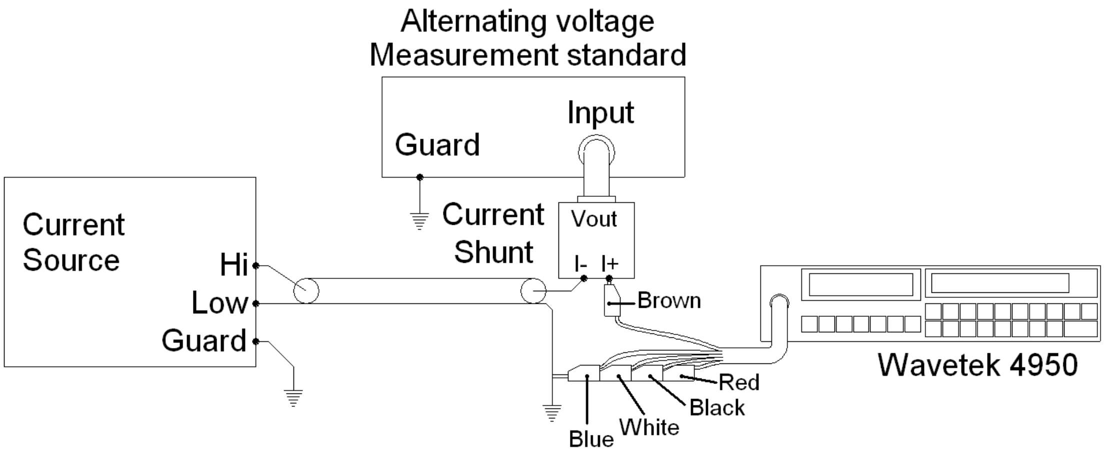
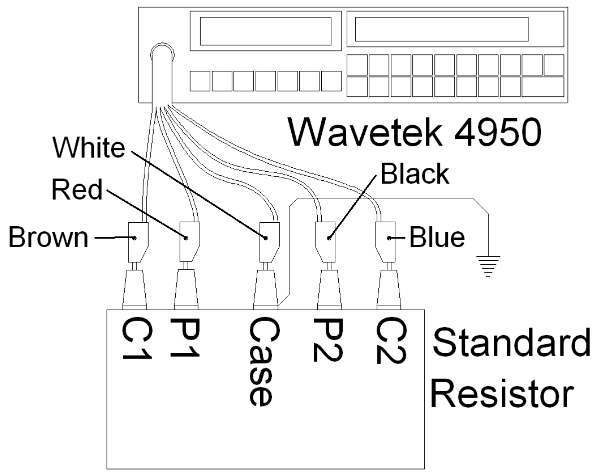
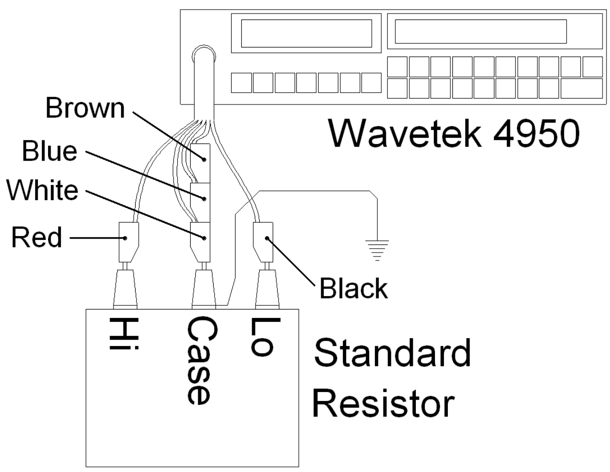


Figure 1.4: Alternating current measurement setup

Resistance



(a) Four wire resistance



(b) Two wire resistance

Figure 1.5: Resistance measurement setups

Frequency

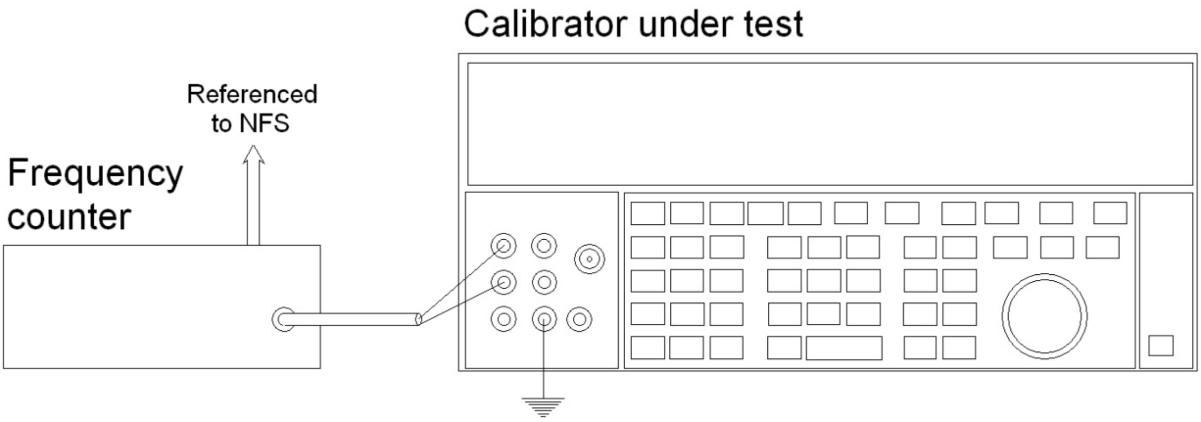


Figure 1.6: Frequency measurement setup

Appendix 2: Traceability charts

Direct Voltage

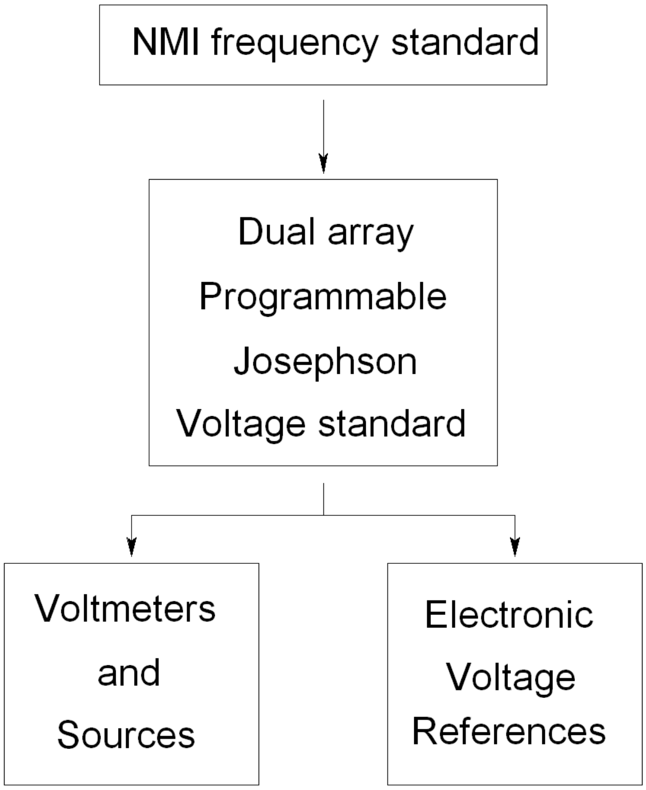


Figure 2.1: Direct voltage traceability

Resistance

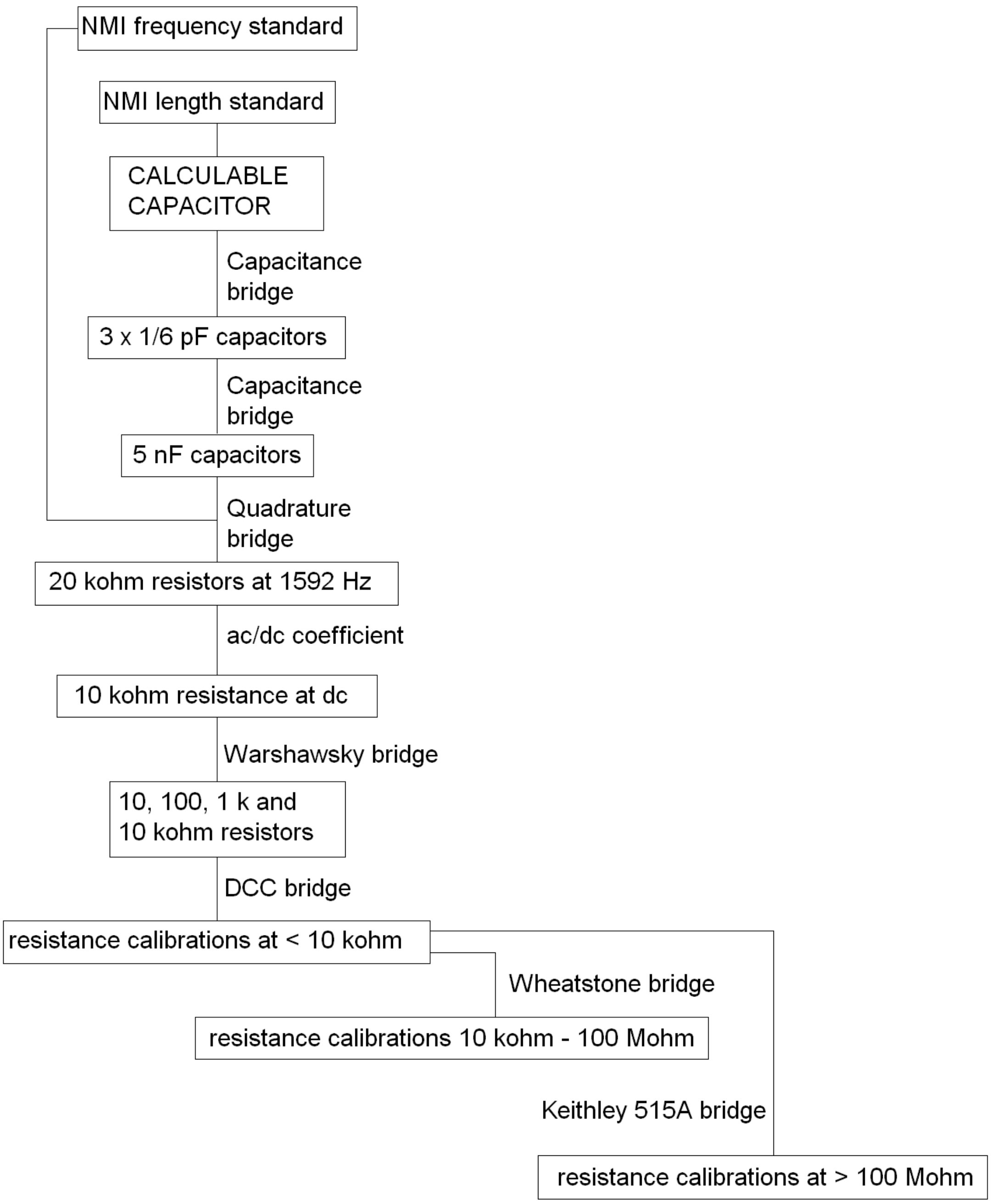


Figure 2.2: Resistance traceability

Ac-dc difference

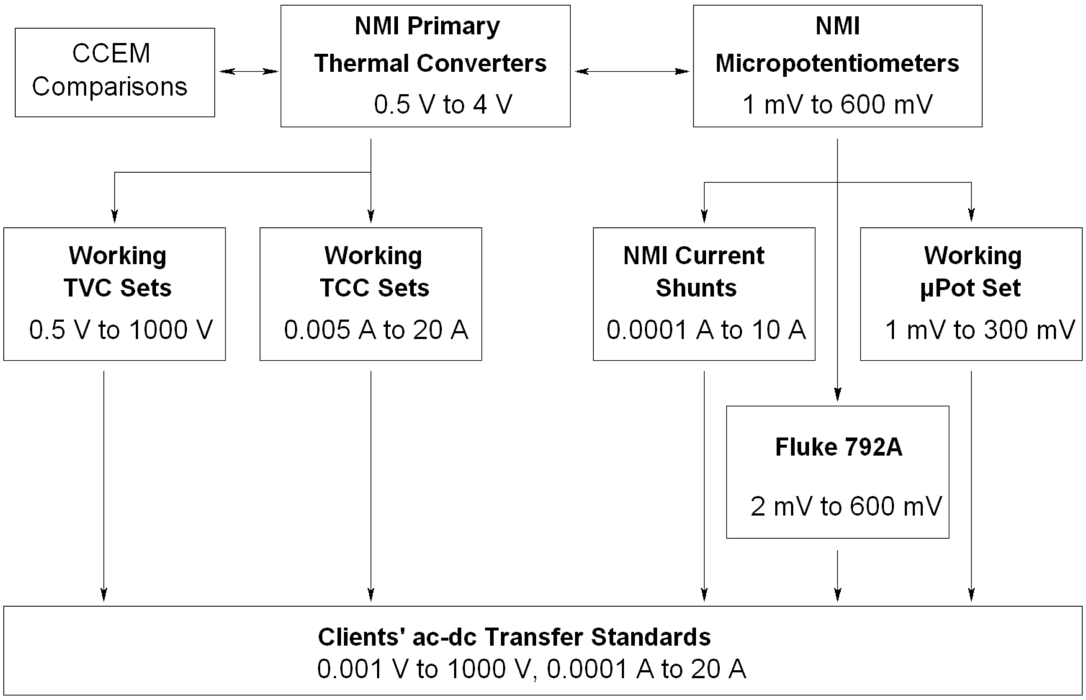


Figure 2.3: Ac-dc difference traceability

Frequency

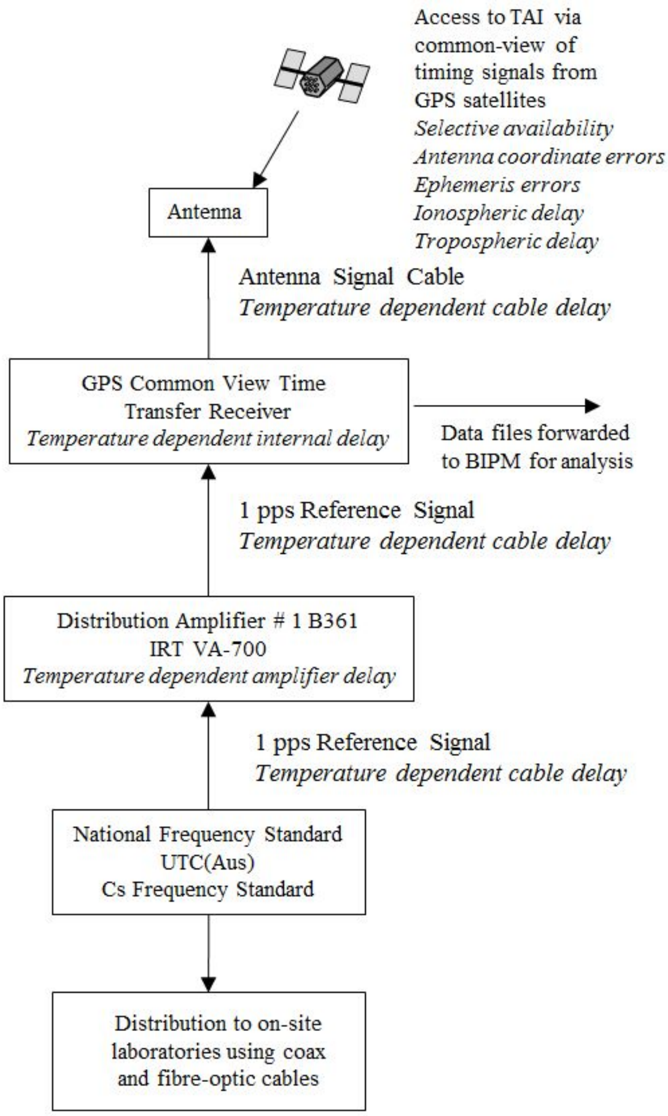


Figure 2.4: Frequency traceability

Appendix 3: Uncertainty budgets

3.1 Direct Voltage

For direct voltage at 100 mV the following components contribute to the uncertainty of measurement:

- Reference voltmeter uncertainty: From the last calibration report of the voltmeter.
- Reference voltmeter drift since last calibration: From the history of the voltmeter.
- Reference voltmeter resolution: From the specification of the voltmeter
- Reference voltmeter repeatability: From the observed data
- Unit under test resolution: From the UUT specification
- Unit under test repeatability: From the observed data
- Unit under test stability: From tests repeated several times during the period that the instrument spent in our laboratory
- Rounding of reported value: To ensure that the reported value encompasses the calculated range of possible values

Uncertainty budget:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Reference voltmeter uncertainty	B	0.140	µV	1.960	0.0714	1	0.0714	100
Reference voltmeter drift since last calibration	B	0.160	µV	1.732	0.0924	1	0.0924	30
Reference voltmeter resolution	B	0.005	µV	1.732	0.0029	1	0.0029	100
Reference voltmeter repeatability	A	0.007	µV	1.000	0.0066	1	0.0066	9
Unit under test resolution	B	0.005	µV	1.732	0.0029	1	0.0029	100
Unit under test repeatability	A	0.004	µV	1.000	0.0045	1	0.0045	9
Unit under test stability	B	0.120	µV	1.732	0.0693	1	0.0693	3
Rounding of reported value	B	0.010	µV	1.732	0.0058	1	0.0058	100
						Combined standard uncertainty	0.1362	µV
						Effective degrees of freedom	33.2	
						Coverage factor	2.035	
						Expanded uncertainty	0.2771	µV
						Expanded uncertainty	2.771	µV/V

For direct voltage at 1 V and 10 V the following components contribute to the uncertainty of measurement:

- Fluke 732A uncertainty: From the last calibration report
- Fluke 732A drift: From the history of the electronic voltage reference
- Un-cancelled thermal voltages: Estimated from the difference in zero readings before and after measurement at the nominal voltage
- Unit under test repeatability: From the observed data
- Unit under test resolution: From the unit under test specifications
- Unit under test stability: From tests repeated several times during the period that the instrument spent in our laboratory
- Rounding of reported value: To ensure that the reported value encompasses the calculated range of possible values

Uncertainty budget for 1 V measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Voltage reference	B	0.25	µV	1.960	0.1276	1	0.1276	100
Voltage reference drift	B	0.3	µV	1.732	0.1732	1	0.1732	30
Un-cancelled thermal voltages	B	0.06	µV	1.732	0.0346	1	0.0346	100
Unit under test resolution	B	0.05	µV	1.732	0.0289	1	0.0289	100
Unit under test repeatability	A	0.018	µV	1.000	0.0180	1	0.0180	9
Unit under test stability	B	0.96	µV	1.732	0.5543	1	0.5543	3
Rounding of reported value	B	0.1	µV	1.732	0.0577	1	0.0577	100
Combined standard uncertainty							0.5993	µV
Effective degrees of freedom							4.1	
Coverage factor							2.776	
Expanded uncertainty							1.6640	µV
Expanded uncertainty							1.6640	µV/V

Uncertainty budget for 10 V measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Voltage reference	B	2.57	µV	1.960	1.3112	1	1.3112	100
Voltage reference drift	B	1.1	µV	1.732	0.6351	1	0.6351	30
Un-cancelled thermal voltages	B	0.1	µV	1.732	0.0577	1	0.0577	100
Unit under test resolution	B	0.5	µV	1.732	0.2887	1	0.2887	100
Unit under test repeatability	A	0.6	µV	1.000	0.6000	1	0.6000	9
Unit under test stability	B	8.5	µV	1.732	4.9076	1	4.9076	3
Rounding of reported value	B	1	µV	1.732	0.5774	1	0.5774	100
						Combined standard uncertainty	5.195	µV
						Effective degrees of freedom	3.8	
						Coverage factor	3.182	
						Expanded uncertainty	16.533	µV
						Expanded uncertainty	1.653	µV/V

For direct voltage from 19 V to 1000 V the following components contribute to the uncertainty of measurement:

- Calibrator uncertainty: From the last calibration report
- Calibrator drift: From the history of the electronic voltage reference
- Zero offset cancellation: Estimated from the difference in zero readings before and after measurement at the nominal voltage
- Unit under test repeatability: From the observed data
- Unit under test resolution: From the unit under test specifications
- Unit under test stability: From tests repeated several times during the period that the instrument spent in our laboratory
- Rounding of reported value: To ensure that the reported value encompasses the calculated range of possible values

Uncertainty budget for 19 V measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Calibrator uncertainty	B	29.2	µV	1.960	14.90	1	14.90	100
Calibrator drift	B	12	µV	1.732	6.93	1	6.93	30
Zero offset cancellation	B	7.9	µV	1.732	4.56	1	4.56	100
Unit under test resolution	B	0.5	µV	1.732	0.29	1	0.29	100
Unit under test repeatability	A	0.8	µV	1.000	0.80	1	0.80	9
Unit under test stability	B	9	µV	1.732	5.20	1	5.20	3
Rounding of reported value	B	1	µV	1.732	0.58	1	0.58	100
Combined standard uncertainty							17.86	µV
Effective degrees of freedom							124.4	
Coverage factor							1.979	
Expanded uncertainty							35.34	µV
Expanded uncertainty							1.860	µV/V

Uncertainty budget for 100 V measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Calibrator uncertainty	B	193.1	μV	1.960	98.5	1	98.5	100
Calibrator drift	B	86	μV	1.732	49.7	1	49.7	30
Zero offset cancellation	B	11	μV	1.732	6.4	1	6.4	100
Unit under test resolution	B	5	μV	1.732	2.9	1	2.9	100
Unit under test repeatability	A	11	μV	1.000	11.0	1	11.0	9
Unit under test stability	B	170	μV	1.732	98.2	1	98.2	3
Rounding of reported value	B	10	μV	1.732	5.8	1	5.8	100
						Combined standard uncertainty	148.4	μV
						Effective degrees of freedom	15.1	
						Coverage factor	2.131	
						Expanded uncertainty	316.2	μV
						Expanded uncertainty	3.162	μV/V

Uncertainty budget for 1000 V measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Calibrator uncertainty	B	2002	μV	1.960	1021	1	1021	100
Calibrator drift	B	405	μV	1.732	234	1	234	30
Zero offset cancellation	B	80	μV	1.732	46	1	46	100
Unit under test resolution	B	50	μV	1.732	29	1	29	100
Unit under test repeatability	A	130	μV	1.000	130	1	130	9
Unit under test stability	B	1000	μV	1.732	577	1	577	3
Rounding of reported value	B	100	μV	1.732	58	1	58	100
						Combined standard uncertainty	1206	μV
						Effective degrees of freedom	44.0	
						Coverage factor	2.015	
						Expanded uncertainty	2431	μV
						Expanded uncertainty	2.431	μV/V

3.2 Direct Current

For direct current the following components contribute to the uncertainty of measurement:

- Shunt uncertainty: From the last calibration report
- Shunt drift: From the history of the shunt
- Voltmeter uncertainty: From the last calibration report
- Voltmeter drift: From the history of the voltmeter
- Voltmeter resolution: From the voltmeter specifications
- Voltmeter repeatability: From the observed data
- Unit under test repeatability: From the observed data
- Unit under test resolution: From the unit under test specifications
- Unit under test stability: From tests repeated several times during the period that the instrument spent in our laboratory
- Rounding of reported value: To ensure that the reported value encompasses the calculated range of possible values

Uncertainty budget for 1 mA measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Shunt uncertainty	B	1.8	µΩ/Ω	1.960	0.92	1	0.92	100
Shunt drift	B	0.68	µΩ/Ω	1.732	0.39	1	0.39	30
Voltmeter uncertainty	B	6.6	µV/V	1.960	3.37	1	3.37	100
Voltmeter drift	B	1.8	µV/V	1.732	1.04	1	1.04	30
Voltmeter resolution	B	0.05	µV/V	1.732	0.03	1	0.03	100
Voltmeter repeatability	A	0.122	µV/V	1.000	0.12	1	0.12	9
Unit under test resolution	B	0.5	µA/A	1.732	0.29	1	0.29	100
Unit under test repeatability	A	0.163	µA/A	1.000	0.16	1	0.16	9
Unit under test stability	B	1.3	µA/A	1.732	0.75	1	0.75	3
Rounding of reported value	B	1	µA/A	1.732	0.58	1	0.58	100
						Combined standard uncertainty	3.80	µA/A
						Effective degrees of freedom	144.8	
						Coverage factor	1.977	
						Expanded uncertainty	7.51	µA/A
						Expanded uncertainty	0.0075	µA

Uncertainty budget for 1 A measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Shunt uncertainty	B	3	μΩ/Ω	1.960	1.53	1	1.53	100
Shunt drift	B	0.7	μΩ/Ω	1.732	0.40	1	0.40	30
Voltmeter uncertainty	B	2.072	μV/V	1.960	1.06	1	1.06	100
Voltmeter drift	B	0.85	μV/V	1.732	0.49	1	0.49	30
Voltmeter resolution	B	0.005	μV/V	1.732	0.00	1	0.00	100
Voltmeter repeatability	A	0.047	μV/V	1.000	0.05	1	0.05	9
Unit under test resolution	B	0.5	μA/A	1.732	0.29	1	0.29	100
Unit under test repeatability	A	0.1	μA/A	1.000	0.10	1	0.10	9
Unit under test stability	B	5.2	μA/A	1.732	3.00	1	3.00	3
Rounding of reported value	B	1	μA/A	1.732	0.58	1	0.58	100
						Combined standard uncertainty	3.65	μA/A
						Effective degrees of freedom	6.5	
						Coverage factor	2.447	
						Expanded uncertainty	8.93	μA/A
						Expanded uncertainty	8.9	μA

3.3 Alternating Voltage

Two methods were used to perform alternating voltage measurements. For 10 mV and 100 mV the measurements were done against a micropot consisting of a thermal current converter and a precision shunt. The measurements from 1 V to 700 V were done against a thermal transfer standard. A sample uncertainty budget for each range is shown below, and the rest of the uncertainties for that range are shown in a combined table to save space.

For alternating voltage at 10 mV and 100 mV the following components contribute to the uncertainty of measurement:

- Direct current source uncertainty and drift: From the last calibration report and history of the source
- Shunt dc resistance and drift: From the last calibration report and history of the shunt
- Shunt ac-dc difference: From the last calibration report (the ac-dc difference are typically very stable, so no drift component is applied)
- Micropot ac-dc difference: From the last calibration report
- Micropot drift: The micropot has only been in use a short time, so a drift component is included based on an assessment of its stability
- Micropot loading: The input impedance of the unit under test loads the resistive component of the micropot, and this must be corrected for. To calculate this correction, the input impedance of the unit under test must be measured. This component includes the uncertainty of the loading correction and the uncertainty of the determination of the unit under test input impedance
- Cables and connectors: At higher frequencies this can be significant – an experiment was performed to estimate the effect of cables and connectors
- Ac-dc transfer repeatability: From the observed data
- Unit under test repeatability: From the observed data
- Unit under test resolution: From the unit under test specifications
- Unit under test stability: From tests repeated several times during the period that the instrument spent in our laboratory
- Rounding of reported value: To ensure that the reported value encompasses the calculated range of possible values

Uncertainty budget for 10 mV and 1.005 kHz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Direct current source	B	10	μA/A	1.960	5.10	1	5.10	100
Shunt resistance	B	3	μΩ/Ω	1.960	1.53	1	1.53	100
Shunt ac-dc difference	B	3.4	μΩ/Ω	1.960	1.73	1	1.73	100
Micropot ac-dc difference	B	7.3	μV/V	1.960	3.72	1	3.72	100
Micropot drift	B	1.6	μV/V	1.732	0.92	1	0.92	30
Micropot loading	B	0.5	μV/V	1.732	0.29	1	0.29	30
Cables and connectors	B	1.8	μV/V	1.732	1.04	1	1.04	30
ac-dc difference repeatability	A	0.3	μV/V	1.000	0.30	1	0.30	4
Unit under test repeatability	A	0.7	μV/V	1.000	0.70	1	0.70	4
Unit under test resolution	B	5	μV/V	1.732	2.89	1	2.89	100
Unit under test stability	B	60	μV/V	1.732	34.64	1	34.64	3
Rounding of reported value	B	10	μV/V	1.732	5.77	1	5.77	100
						Combined standard uncertainty	35.91	μV/V
						Effective degrees of freedom	3.5	
						Coverage factor	3.182	
						Expanded uncertainty	114.28	μV/V
						Expanded uncertainty	1.143	μV

10 mV range uncertainties

The table below summarises the uncertainty estimates for the 10 mV measurements. Only the standard uncertainties after reduction of the input values are shown. The degrees of freedom assigned to each component are the same as those assigned to the components in the budget for 10 mV and 1.005 kHz shown on the previous page.

								Standard uncertainties												
Range (V)	Nominal Voltage (V)	Frequency (kHz)	Expanded uncertainty (µV)	Expanded uncertainty (µV/V)	Coverage factor	Effective degrees of freedom	Combined standard uncertainty (µV/V)	Direct current source (µA/A)	Shunt resistance (µΩ/Ω)	Shunt ac-dc difference (µΩ/Ω)	Micropot ac-dc difference (µV/V)	Micropot drift (µV/V)	Micropot loading (µV/V)	Cables and connectors (µV/V)	Ac-dc difference repeatability (µV/V)	Unit under test repeatability (µV/V)	Unit under test resolution (µV/V)	Unit under test stability (µV/V)	Rounding of reported value (µV/V)
0.01	0.01	0.01	1.17	116.6	3.182	3.8	36.6	5.1	1.5	3.4	6.3	1.6	0.3	0.6	4.3	0.7	2.9	35	5.8
		0.055	1.14	114.3	3.182	3.5	35.9	5.1	1.5	1.7	3.7	0.9	0.3	0.6	0.5	0.4	2.9	35	5.8
		1.005	1.14	114.3	3.182	3.5	35.9	5.1	1.5	1.7	3.7	0.9	0.3	1.0	0.3	0.7	2.9	35	5.8
		20	1.19	118.6	3.182	4.0	37.3	5.1	1.5	3.5	4.0	1.0	0.3	0.6	9.4	0.3	2.9	35	5.8
		50	1.15	115.2	3.182	3.6	36.2	5.1	1.5	4.0	4.5	1.1	0.3	1.8	0.2	0.5	2.9	35	5.8
		1000	9.08	907.6	3.182	3.1	285.2	5.1	1.5	27	11	2.8	9.8	11	7	7	2.9	283	5.8

Uncertainty budget for 100 mV and 1.005 kHz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Direct current source	B	10	µA/A	1.960	5.10	1	5.10	100
Shunt resistance	B	5.0	µΩ/Ω	1.960	2.55	1	2.55	100
Shunt ac-dc difference	B	3.6	µΩ/Ω	1.960	1.82	1	1.82	100
Micropot ac-dc difference	B	7.3	µV/V	1.960	3.72	1	3.72	100
Micropot drift	B	1.6	µV/V	1.732	0.92	1	0.92	30
Micropot loading	B	4.8	µV/V	1.732	2.78	1	2.78	30
Cables and connectors	B	1.0	µV/V	1.732	0.58	1	0.58	30
ac-dc difference repeatability	A	0.8	µV/V	1.000	0.81	1	0.81	4
Unit under test repeatability	A	0.6	µV/V	1.000	0.64	1	0.64	4
Unit under test resolution	B	0.5	µV/V	1.732	0.29	1	0.29	100
Unit under test stability	B	15	µV/V	1.732	8.43	1	8.43	3
Rounding of reported value	B	1.0	µV/V	1.732	0.58	1	0.58	100
						Combined standard uncertainty	11.45	µV/V
						Effective degrees of freedom	10.1	
						Coverage factor	2.228	
						Expanded uncertainty	25.52	µV/V
						Expanded uncertainty	2.552	µV

100 mV range uncertainties

The table below summarises the uncertainty estimates for the 100 mV measurements. Only the standard uncertainties after reduction of the input values are shown. The degrees of freedom assigned to each component are the same as those assigned to the components in the budget for 100 mV and 1.005 kHz shown on the previous page.

								Standard uncertainties											
Range (V)	Nominal Voltage (V)	Frequency (kHz)	Expanded uncertainty (µV)	Expanded uncertainty (µV/V)	Coverage factor	Effective degrees of freedom	Combined standard uncertainty (µV/V)	Direct current source (µA/A)	Shunt resistance (µΩ/Ω)	Shunt ac-dc difference (µΩ/Ω)	Micropot ac-dc difference (µV/V)	Micropot drift (µV/V)	Micropot loading (µV/V)	Cables and connectors (µV/V)	Ac-dc difference repeatability (µV/V)	Unit under test repeatability (µV/V)	Unit under test resolution (µV/V)	Unit under test stability (µV/V)	Rounding of reported value (µV/V)
0.1	0.1	0.01	2.98	29.8	2.145	14.8	13.9	5.1	2.6	3.6	6.3	1.6	2.8	0.6	3.0	1.2	1.0	9	0.6
		0.055	2.55	25.5	2.228	10.2	11.4	5.1	2.6	1.9	3.7	0.9	2.8	0.6	0.6	0.4	0.3	8	0.6
		1.005	2.55	25.5	2.228	10.2	11.5	5.1	2.6	1.8	3.7	0.9	2.8	0.6	0.8	0.7	0.6	8	0.6
		20	2.65	26.5	2.201	11.5	12.0	5.1	2.6	3.5	4.0	1.0	2.8	0.6	0.6	0.3	0.3	9	0.6
		50	3.08	30.8	2.262	9.5	13.6	5.1	2.6	4.0	4.5	1.1	2.8	1.8	0.3	0.3	0.3	10	0.6
		1000	41.9	419	2.086	20.8	201	5.1	2.6	23	11	2.8	163	11	7	3	7.1	113	0.6

For alternating voltage from 1 V to 700 V the following components contribute to the uncertainty of measurement:

- Reference ac-dc difference: From the last calibration report and history of the thermal transfer standard
- Reference drift: From history of the thermal transfer standard
- Cables and connectors: At higher frequencies this can be significant – an experiment was performed to estimate the effect of cables and connectors
- Ac-dc transfer repeatability: From the observed data
- Unit under test DCV accuracy: The unit under test direct voltage readings are used with the ac-dc differences to calculate the applied alternating voltage, and from this the unit under test correction is calculated. The DCV corrections and uncertainties are obtained from a recent measurement, or calibration report.
- Unit under test DCV repeatability: From the observed data
- Unit under test ACV repeatability: From the observed data
- Unit under test resolution: From the unit under test specifications
- Unit under test stability: From tests repeated several times during the period that the instrument spent in our laboratory
- Rounding of reported value: To ensure that the reported value encompasses the calculated range of possible values

Uncertainty budget for 1 V and 1.005 kHz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Reference ac-dc difference	B	5.0	µV/V	1.960	2.57	1	2.57	100
Reference drift	B	0.5	µV/V	1.732	0.31	1	0.31	100
Cables and connectors	B	2.0	µV/V	1.732	1.18	1	1.18	30
ac-dc difference repeatability	A	0.2	µV/V	1.000	0.20	1	0.20	4
Unit under test direct voltage	B	2.2	µV/V	1.960	1.13	1	1.13	100
Unit under test DCV repeatability	A	0.1	µV/V	1.000	0.14	1	0.14	4
Unit under test ACV repeatability	A	0.2	µV/V	1.000	0.16	1	0.16	4
Unit under test resolution	B	0.5	µV/V	1.732	0.29	1	0.29	100
Unit under test stability	B	3.9	µV/V	1.732	2.25	1	2.25	3
Rounding of reported value	B	1.0	µV/V	1.732	0.58	1	0.58	100
						Combined standard uncertainty	3.86	µV/V
						Effective degrees of freedom	24.5	
						Coverage factor	2.064	
						Expanded uncertainty	7.97	µV/V
						Expanded uncertainty	7.97	µV

1 V range uncertainties

The table below summarises the uncertainty estimates for the 1 V measurements. Only the standard uncertainties after reduction of the input values are shown. The degrees of freedom assigned to each component are the same as those assigned to the components in the budget for 1 V and 1.005 kHz shown on the previous page.

								Standard uncertainties									
Range (V)	Nominal Voltage (V)	Frequency (kHz)	Expanded uncertainty (µV)	Expanded uncertainty (µV/V)	Coverage factor	Effective degrees of freedom	Combined standard uncertainty (µV/V)	Reference ac-dc difference (µV/V)	Reference drift (µV/V)	Cables and connectors (µV/V)	ac-dc difference repeatability (µV/V)	Unit under test direct voltage (µV/V)	Unit under test DCV repeatability (µV/V)	Unit under test ACV repeatability (µV/V)	Unit under test resolution (µV/V)	Unit under test stability (µV/V)	Rounding of reported result (µV/V)
1	1	0.01	30.0	30.0	1.984	99.4	15.1	14.1	0.15	1.18	2.05	1.13	0.13	1.43	0.29	4.34	0.58
		0.055	8.0	8.0	2.037	32.3	3.9	2.69	0.12	1.18	0.42	1.13	0.13	0.54	0.29	2.11	0.58
		1.005	8.0	8.0	2.064	24.5	3.9	2.57	0.31	1.18	0.20	1.13	0.14	0.16	0.29	2.25	0.58
		20	10.0	10.0	2.052	27.2	4.9	3.47	0.26	1.48	0.29	1.13	0.13	0.23	0.29	2.75	0.58
		50	16.0	16.0	2.010	49.7	8.0	5.48	3.57	2.10	0.12	1.13	0.08	0.15	0.29	3.80	0.58
		1000	114.8	114.8	2.447	6.2	46.9	21.1	5.10	11.0	6.28	1.13	0.16	6.42	0.29	39.1	0.58

Uncertainty budget for 10 V and 1.005 kHz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Reference ac-dc difference	B	7.8	µV/V	1.960	3.99	1	3.99	100
Reference drift	B	0.5	µV/V	1.732	0.27	1	0.27	100
Cables and connectors	B	2.0	µV/V	1.732	1.18	1	1.18	30
ac-dc difference repeatability	A	0.3	µV/V	1.000	0.28	1	0.28	4
Unit under test direct voltage	B	2.6	µV/V	1.960	1.34	1	1.34	100
Unit under test DCV repeatability	A	0.0	µV/V	1.000	0.03	1	0.03	4
Unit under test ACV repeatability	A	0.3	µV/V	1.000	0.27	1	0.27	4
Unit under test resolution	B	0.5	µV/V	1.732	0.29	1	0.29	100
Unit under test stability	B	4.4	µV/V	1.732	2.55	1	2.94	3
Rounding of reported value	B	1.0	µV/V	1.732	0.58	1	0.58	100
Combined standard uncertainty							5.33	µV/V
Effective degrees of freedom							29.3	
Coverage factor							2.045	
Expanded uncertainty							10.90	µV/V
Expanded uncertainty							109	µV

10 V range uncertainties

The table below summarises the uncertainty estimates for the 10 V and 19 V measurements. Only the standard uncertainties after reduction of the input values are shown. The degrees of freedom assigned to each component are the same as those assigned to the components in the budget for 10 V and 1.005 kHz shown on the previous page.

								Standard uncertainties									
Range (V)	Nominal Voltage (V)	Frequency (kHz)	Expanded uncertainty (µV)	Expanded uncertainty (µV/V)	Coverage factor	Effective degrees of freedom	Combined standard uncertainty (µV/V)	Reference ac-dc difference (µV/V)	Reference drift (µV/V)	Cables and connectors (µV/V)	ac-dc difference repeatability (µV/V)	Unit under test direct voltage (µV/V)	Unit under test DCV repeatability (µV/V)	Unit under test ACV repeatability (µV/V)	Unit under test resolution (µV/V)	Unit under test stability (µV/V)	Rounding of reported result (µV/V)
10	10	0.01	298	29.8	1.983	105.3	15.1	14.3	0.57	1.18	1.28	1.34	0.06	1.31	0.29	3.72	0.58
		0.055	109	10.9	2.018	42.3	5.4	4.22	0.70	1.18	0.34	1.34	0.03	0.28	0.29	2.67	0.58
		1.005	109	10.9	2.045	29.3	5.3	3.99	0.27	1.18	0.28	1.34	0.03	0.27	0.29	2.94	0.58
		20	127	12.7	2.018	42.9	6.3	4.84	1.47	1.48	0.23	1.34	0.03	0.32	0.29	3.11	0.58
		50	177	17.7	2.060	25.1	8.6	5.91	2.71	2.10	0.36	1.34	0.02	0.19	0.29	4.97	0.58
		1000	1366	136.6	2.447	6.1	55.8	23.3	13.5	11.0	6.89	1.34	0.04	6.22	0.29	46.7	0.58
10	19	1.005	229	12.0	2.056	26.2	5.9	4.42	0.57	1.18	0.11	1.34	0.06	0.26	0.15	3.33	0.30

Uncertainty budget for 100 V and 1.005 kHz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Reference ac-dc difference	B	14.0	μV/V	1.960	7.14	1	7.14	100
Reference drift	B	0.7	μV/V	1.732	0.41	1	0.41	100
Cables and connectors	B	2.0	μV/V	1.732	1.18	1	1.18	30
ac-dc difference repeatability	A	0.3	μV/V	1.000	0.33	1	0.33	4
Unit under test direct voltage	B	2.1	μV/V	1.960	1.07	1	1.07	100
Unit under test DCV repeatability	A	0.0	μV/V	1.000	0.02	1	0.02	4
Unit under test ACV repeatability	A	0.2	μV/V	1.000	0.22	1	0.22	4
Unit under test resolution	B	0.5	μV/V	1.732	0.29	1	0.29	100
Unit under test stability	B	4.4	μV/V	1.732	2.55	1	2.11	3
Rounding of reported value	B	1.0	μV/V	1.732	0.58	1	0.58	100
Combined standard uncertainty							7.66	μV/V
Effective degrees of freedom							105.5	
Coverage factor							1.983	
Expanded uncertainty							15.19	μV/V
Expanded uncertainty							1.52	mV

100 V range uncertainties

The table below summarises the uncertainty estimates for the 100 V measurements. Only the standard uncertainties after reduction of the input values are shown. The degrees of freedom assigned to each component are the same as those assigned to the components in the budget for 100 V and 1.005 kHz shown on the previous page.

								Standard uncertainties										
Range (V)	Nominal Voltage (V)	Frequency (kHz)	Expanded uncertainty (mV)	Expanded uncertainty (μV/V)	Coverage factor	Effective degrees of freedom	Combined standard uncertainty (μV/V)	Reference ac-dc difference (μV/V)	Reference drift (μV/V)	Cables and connectors (μV/V)	ac-dc difference repeatability (μV/V)	Unit under test direct voltage (μV/V)	Unit under test DCV repeatability (μV/V)	Unit under test ACV repeatability (μV/V)	Unit under test resolution (μV/V)	Unit under test stability (μV/V)	Rounding of reported result (μV/V)
100	100	0.01	3.10	31.0	1.982	109.0	15.7	15.2	1.20	1.18	1.68	1.07	0.03	0.51	0.29	2.35	0.58
		0.055	1.56	15.6	1.983	103.9	7.9	7.31	0.71	1.18	0.25	1.07	0.02	0.27	0.29	2.24	0.58
		1.005	1.52	15.2	1.983	105.5	7.7	7.14	0.41	1.18	0.33	1.07	0.02	0.22	0.29	2.11	0.58
		20	1.64	16.4	1.997	66.4	8.2	7.19	0.64	1.48	0.26	1.07	0.01	0.37	0.29	3.33	0.58
		50	2.19	21.9	2.030	35.3	10.8	8.85	0.77	2.10	0.58	1.07	0.02	0.53	0.29	5.58	0.58

Uncertainty budget for 700 V and 1.005 kHz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Reference ac-dc difference	B	17	µV/V	1.960	8.65	1	8.65	100
Reference drift	B	1.0	µV/V	1.732	0.56	1	0.56	100
Cables and connectors	B	2.0	µV/V	1.732	1.18	1	1.18	30
ac-dc difference repeatability	A	0.4	µV/V	1.000	0.37	1	0.37	4
Unit under test direct voltage	B	2.2	µV/V	1.960	1.13	1	1.13	100
Unit under test DCV repeatability	A	0.1	µV/V	1.000	0.07	1	0.07	4
Unit under test ACV repeatability	A	0.3	µV/V	1.000	0.28	1	0.28	4
Unit under test resolution	B	0.7	µV/V	1.732	0.41	1	0.41	100
Unit under test stability	B	6.3	µV/V	1.732	3.63	1	3.63	3
Rounding of reported value	B	1.4	µV/V	1.732	0.82	1	0.82	100
						Combined standard uncertainty	9.59	µV/V
						Effective degrees of freedom	74.3	
						Coverage factor	1.993	
						Expanded uncertainty	19.11	µV/V
						Expanded uncertainty	13.4	mV

1000 V range uncertainties

The table below summarises the uncertainty estimates for the 700 V measurements. Only the standard uncertainties after reduction of the input values are shown. The degrees of freedom assigned to each component are the same as those assigned to the components in the budget for 700 V and 1.005 kHz shown on the previous page.

								Standard uncertainties										
Range (V)	Nominal Voltage (V)	Frequency (kHz)	Expanded uncertainty (mV)	Expanded uncertainty (µV/V)	Coverage factor	Effective degrees of freedom	Combined standard uncertainty (µV/V)	Reference ac-dc difference (µV/V)	Reference drift (µV/V)	Cables and connectors (µV/V)	ac-dc difference repeatability (µV/V)	Unit under test direct voltage (µV/V)	Unit under test DCV repeatability (µV/V)	Unit under test ACV repeatability (µV/V)	Unit under test resolution (µV/V)	Unit under test stability (µV/V)	Rounding of reported result (µV/V)
1000	700	0.055	13.92	19.9	1.990	81.5	10.0	8.93	1.21	1.18	0.48	1.13	0.18	1.30	0.41	3.63	0.82
		1.005	13.50	19.3	1.995	68.4	9.7	8.65	0.56	1.18	0.37	1.13	0.07	0.28	0.41	3.83	0.82
		20	16.96	24.2	2.002	57.0	12.1	10.7	0.91	1.48	0.17	1.13	0.05	0.21	0.41	5.21	0.82
		50	28.51	40.7	2.045	29.0	19.9	16.4	1.70	2.10	0.44	1.13	0.05	0.46	0.41	10.9	0.82

3.4 Alternating Current

For alternating current the following components contribute to the uncertainty of measurement:

- ACV reference uncertainty: A Fluke 5790A alternating voltage measurement standard is used to determine the voltage drop across the shunt - its uncertainty is obtained from the latest calibration report
- ACV reference loading: The effective resistance of the current shunt is reduced due to the input impedance of the alternating voltage measurement standard – a loading correction is applied to compensate for this error and this is the associated uncertainty
- ACV reference drift: From the history of the Fluke 5790A
- ACV reference resolution: From the specification of the Fluke 5790A
- ACV reference repeatability: From the observed data
- Current shunt resistance: From the latest calibration report – this component includes drift of the shunt
- Current shunt ac-dc difference: From the latest calibration report
- Cables and connectors: An experiment was performed to estimate the effect of cables and connectors
- Unit under test resolution: From the specifications of the unit under test
- Unit under test repeatability: From the observed data
- Unit under test stability: From tests repeated several times during the period that the instrument spent in our laboratory
- Rounding of reported value: To ensure that the reported value encompasses the calculated range of possible values

Uncertainty budget for 1 mA and 1.005 kHz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
ACV reference uncertainty	B	26	µV/V	1.960	13.3	1	13.3	100
ACV reference loading	B	0.9	µV/V	1.732	0.50	1	0.50	30
ACV reference drift	B	1.8	µV/V	1.732	1.02	1	1.02	30
ACV reference resolution	B	0.5	µV/V	1.732	0.29	1	0.29	100
ACV reference repeatability	A	0.7	µV/V	1.000	0.74	1	0.74	9
Current shunt resistance	B	1.8	µΩ/Ω	1.960	0.92	1	0.92	100
Current shunt ac-dc difference	B	4.7	µΩ/Ω	1.960	2.41	1	2.41	100
Cables and connectors	B	8.0	µA/A	1.732	4.62	1	4.62	30
Unit under test resolution	B	0.5	µA/A	1.732	0.29	1	0.29	100
Unit under test repeatability	A	1.0	µA/A	1.000	1.03	1	1.03	9
Unit under test stability	B	23	µA/A	1.732	13.5	1	13.5	3
Rounding of reported value	B	1.0	µA/A	1.732	0.58	1	0.58	100
Combined standard uncertainty							19.7	µA/A
Effective degrees of freedom							13.3	
Coverage factor							2.160	
Expanded uncertainty							42.6	µA/A
Expanded uncertainty							42.6	nA

1 mA range uncertainties

The table below summarises the uncertainty estimates for the 1 mA measurements. Only the standard uncertainties after reduction of the input values are shown. The degrees of freedom assigned to each component are the same as those assigned to the components in the budget for 1 mA and 1.005 kHz shown on the previous page.

								Standard uncertainties											
Range (mA)	Nominal Voltage (mA)	Frequency (kHz)	Expanded uncertainty (nA)	Expanded uncertainty (µA/A)	Coverage factor	Effective degrees of freedom	Combined standard uncertainty (µA/A)	ACV reference uncertainty (µV/V)	ACV reference loading (µV/V)	ACV reference drift (µV/V)	ACV reference resolution (µV/V)	ACV reference repeatability (µV/V)	Current shunt resistance (µΩ/Ω)	Current shunt ac-dc difference (µΩ/Ω)	Cables and connectors (µA/A)	Unit under test resolution (µA/A)	Unit under test repeatability (µA/A)	Unit under test stability (µA/A)	Rounding of reported value (µA/A)
1	1	0.055	39.8	39.8	2.101	18.9	18.9	13.4	0.49	1.02	0.29	2.83	0.92	2.34	4.62	0.29	1.57	11.8	0.58
		1.005	42.6	42.6	2.160	13.3	19.7	13.3	0.50	1.02	0.29	0.74	0.92	2.41	4.62	0.29	1.03	13.5	0.58
		5	44.9	44.9	2.093	19.8	21.4	13.7	0.58	1.02	0.29	1.43	0.87	3.86	8.66	0.29	1.67	13.2	0.58

Uncertainty budget for 1 A and 1.005 kHz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
ACV reference uncertainty	B	7.7	μV/V	1.960	3.94	1	3.94	100
ACV reference loading	B	0.0	μV/V	1.732	0.01	1	0.01	30
ACV reference drift	B	1.1	μV/V	1.732	0.66	1	0.66	30
ACV reference resolution	B	0.5	μV/V	1.732	0.29	1	0.29	100
ACV reference repeatability	A	0.4	μV/V	1.000	0.42	1	0.42	9
Current shunt resistance	B	3.0	μΩ/Ω	1.960	1.53	1	1.53	100
Current shunt ac-dc difference	B	3.4	μΩ/Ω	1.960	1.73	1	1.73	100
Cables and connectors	B	8.7	μA/A	1.732	5.00	1	5.00	30
Unit under test resolution	B	0.5	μA/A	1.732	0.29	1	0.29	100
Unit under test repeatability	A	0.8	μA/A	1.000	0.84	1	0.84	9
Unit under test stability	B	8.8	μA/A	1.732	5.10	1	5.10	3
Rounding of reported value	B	1.0	μA/A	1.732	0.58	1	0.58	100
						Combined standard uncertainty	8.6	μA/A
						Effective degrees of freedom	21.8	
						Coverage factor	2.080	
						Expanded uncertainty	17.9	μA/A
						Expanded uncertainty	17.9	μA

1 A range uncertainties

The table below summarises the uncertainty estimates for the 1 A measurements. Only the standard uncertainties after reduction of the input values are shown. The degrees of freedom assigned to each component are the same as those assigned to the components in the budget for 1 A and 1.005 kHz shown on the previous page.

								Standard uncertainties												
Range (A)	Nominal Voltage (A)	Frequency (kHz)	Expanded uncertainty (μA)	Expanded uncertainty (μA/A)	Coverage factor	Effective degrees of freedom	Combined standard uncertainty (μA/A)	ACV reference uncertainty (μV/V)	ACV reference loading (μV/V)	ACV reference drift (μV/V)	ACV reference resolution (μV/V)	ACV reference repeatability (μV/V)	Current shunt resistance (μΩ/Ω)	Current shunt ac-dc difference (μΩ/Ω)	Cables and connectors (μA/A)	Unit under test resolution (μA/A)	Unit under test repeatability (μA/A)	Unit under test stability (μA/A)	Rounding of reported value (μA/A)
1	1	0.055	17.9	17.9	2.064	24.6	8.70	4.05	0.00	0.66	0.29	0.72	1.53	1.73	5.00	0.29	1.55	5.00	0.58
		1.005	17.9	17.9	2.080	21.8	8.59	3.94	0.01	0.66	0.29	0.42	1.53	1.73	5.00	0.29	0.84	5.10	0.58
		5	29.7	29.7	2.365	7.5	12.6	3.94	0.01	0.66	0.29	0.40	1.53	2.62	5.00	0.29	2.79	9.95	0.58

3.5 Resistance

For resistance the following components contribute to the uncertainty of measurement:

- Reference resistor: The certified correction of the reference resistor from its latest calibration report – this component includes the uncertainty of the correction applied for the drift of the resistor from its last calibration
- Uncorrected zero offset: The zero is measured before and after the calibration of a resistance range of the instrument and the average of the two zero readings is used as a correction – this is the uncertainty component of the average zero determination
- Unit under test resolution: From the specifications of the unit under test
- Unit under test repeatability: From the observed data
- Unit under test stability: From tests repeated several times during the period that the instrument spent in our laboratory
- Rounding of reported value: To ensure that the reported value encompasses the calculated range of possible values

Uncertainty budget for 10 kΩ 4-wire measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Reference resistor	B	0.284	μΩ/Ω	1.960	0.145	1	0.145	97
Uncorrected zero offset	B	0.136	μΩ/Ω	1.732	0.079	1	0.079	18
Unit under test resolution	B	0.050	μΩ/Ω	1.732	0.029	1	0.029	100
Unit under test repeatability	A	0.013	μΩ/Ω	1.000	0.013	1	0.013	9
Unit under test stability	B	0.150	μΩ/Ω	1.732	0.087	1	0.087	3
Rounding of reported value	B	0.100	μΩ/Ω	1.732	0.058	1	0.058	100
						Combined standard uncertainty	0.198	μΩ/Ω
						Effective degrees of freedom	59.3	
						Coverage factor	2.001	
						Expanded uncertainty	0.395	μΩ/Ω
						Expanded uncertainty	3.95	mΩ

Resistance function uncertainties

The table below summarises the uncertainty estimates for the resistance measurements. Only the standard uncertainties after reduction of the input values are shown. The degrees of freedom assigned to each component are the same as those assigned to the components in the budget for 10 kΩ measurement shown on the previous page, except for the degrees of freedom associated with the uncertainty of the standard resistor. The degrees of freedom for the standard resistors varied from 3 to 114.

								Standard uncertainties					
Range	Nominal Resistance	Wiring Configuration	Expanded uncertainty	Expanded uncertainty (µΩ/Ω)	Coverage factor	Effective degrees of freedom	Combined standard uncertainty (µΩ/Ω)	Reference resistor (µΩ/Ω)	Uncorrected zero offset (µΩ/Ω)	Unit under test resolution (µΩ/Ω)	Unit under test repeatability (µΩ/Ω)	Unit under test stability (µΩ/Ω)	Rounding of reported value (µΩ/Ω)
10 Ω	10 Ω	4W	9.97 µΩ	0.997	2.365	8.0	0.421	0.286	0.136	0.029	0.035	0.268	0.058
100 Ω	100 Ω	4W	39.7 µΩ	0.397	2.032	34.8	0.195	0.137	0.066	0.029	0.015	0.103	0.058
1 kΩ	1 kΩ	4W	0.395 mΩ	0.395	2.010	49.9	0.197	0.143	0.073	0.029	0.016	0.092	0.058
10 kΩ	10 kΩ	4W	3.95 mΩ	0.395	2.001	59.3	0.198	0.145	0.079	0.029	0.013	0.087	0.058
100 kΩ	100 kΩ	2W	119 mΩ	1.194	1.995	68.1	0.598	0.545	0.057	0.029	0.000	0.231	0.058
1 MΩ	1 MΩ	2W	2.10 Ω	2.096	1.987	88.4	1.055	1.024	0.057	0.029	0.010	0.238	0.058
10 MΩ	10 MΩ	2W	19.9 Ω	1.988	2.056	26.4	0.967	0.914	0.057	0.029	0.017	0.304	0.058
100 MΩ	100 MΩ	2W	600 Ω	5.996	2.074	22.4	2.891	2.371	0.057	0.029	0.082	1.65	0.058

3.6 Frequency

For frequency the following components contribute to the uncertainty of measurement:

- Reference time-base: The specified frequency accuracy of the national frequency standard at the observation time used for the measurement (typically 2000 seconds)
- Counter accuracy: Calculated using the formulae supplied by the manufacturer
- Counter resolution: The manufacturer calls this the Least Significant Digit Displayed – it was calculated using the formula supplied by the manufacturer
- Unit under test repeatability: From the observed data – for some frequency points the data was time correlated (the data distribution did not follow a normal probability distribution); for these points the repeatability is estimated using the Allan Deviation (ADEV) calculated at approximately 1/6th of the observation time extrapolated for the complete observation. A random walk frequency noise process was assumed for the extrapolation.
- Unit under test stability: From repeated tests
- Rounding of reported value: To ensure that the reported value encompasses the calculated range of possible values

Uncertainty budget for 1.005 kHz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Reference time-base	B	1.00E-12	Hz/Hz	1.960	5.10E-13	1	5.10E-13	100
Counter accuracy	B	2.24E-08	Hz/Hz	1.732	1.29E-08	1	1.29E-08	100
Counter resolution	B	6.50E-11	Hz/Hz	1.732	3.75E-11	1	3.75E-11	100
Unit under test repeatability	A	9.48E-09	Hz/Hz	1.000	9.48E-09	1	9.48E-09	98
Unit under test stability	B	2.10E-08	Hz/Hz	1.732	1.21E-08	1	1.21E-08	3
Rounding of reported value	B	1.00E-08	Hz/Hz	1.732	5.77E-09	1	5.77E-09	100
						Combined standard uncertainty	2.09E-08	Hz/Hz
						Effective degrees of freedom	25.2	
						Coverage factor	2.060	
						Expanded uncertainty	4.31E-08	Hz/Hz
						Expanded uncertainty	43.3	μHz

Calibrator frequency uncertainties

The tables below summarise the uncertainty estimates for the calibrator frequencies. Only the standard uncertainties after reduction of the input values are shown. The degrees of freedom assigned to each component are the same as those assigned to the components in the budget for 1.005 kHz measurement shown on the previous page.

For alternating voltage measurements (Fluke 5700A serial number 9355607):

						Standard uncertainties					
Nominal frequency	Expanded uncertainty	Expanded uncertainty (Hz/Hz)	Coverage factor	Effective degrees of freedom	Combined standard uncertainty (Hz/Hz)	Reference time-base (Hz/Hz)	Counter accuracy (Hz/Hz)	Counter resolution (Hz/Hz)	Unit under test repeatability (Hz/Hz)	Unit under test stability (Hz/Hz)	Rounding of reported value (Hz/Hz)
10 Hz	45.2 µHz	4.52E-06	1.972	202.7	2.29E-06	5.10E-13	1.30E-06	3.75E-11	1.80E-06	1.21E-08	5.77E-07
55 Hz	45.3 µHz	8.24E-07	1.973	182.6	4.18E-07	5.10E-13	2.36E-07	3.75E-11	3.40E-07	1.21E-08	5.77E-08
1.005 kHz	43.3 µHz	4.31E-08	2.060	25.2	2.09E-08	5.10E-13	1.29E-08	3.75E-11	9.48E-09	1.21E-08	5.77E-09
20 kHz	0.754 mHz	3.77E-08	2.201	11.7	1.71E-08	5.10E-13	6.55E-10	3.75E-11	1.06E-08	1.21E-08	5.77E-09
50 kHz	1.93 mHz	3.87E-08	2.145	14.2	1.80E-08	5.10E-13	2.72E-10	3.75E-11	1.20E-08	1.21E-08	5.77E-09
1 MHz	0.399 Hz	3.99E-07	1.981	116.3	2.02E-07	5.10E-13	8.26E-11	3.75E-11	1.93E-07	1.21E-08	5.77E-08

For alternating current measurements (Fluke 5720A serial number 1306206):

						Standard uncertainties					
Nominal frequency	Expanded uncertainty	Expanded uncertainty (Hz/Hz)	Coverage factor	Effective degrees of freedom	Combined standard uncertainty (Hz/Hz)	Reference time-base (Hz/Hz)	Counter accuracy (Hz/Hz)	Counter resolution (Hz/Hz)	Unit under test repeatability (Hz/Hz)	Unit under test stability (Hz/Hz)	Rounding of reported value (Hz/Hz)
55 Hz	30.3 μHz	5.51E-07	1.974	174.7	2.79E-07	5.10E-13	2.36E-07	3.75E-11	1.37E-07	1.21E-08	5.77E-08
1.005 kHz	43.3 μHz	4.31E-08	2.060	25.2	2.09E-08	5.10E-13	1.29E-08	3.75E-11	9.48E-09	1.21E-08	5.77E-09
5 kHz	0.186 mHz	3.72E-08	2.262	10.0	1.64E-08	5.10E-13	2.60E-09	3.75E-11	9.10E-09	1.21E-08	5.77E-09

Report on

Measurements performed for APMP.EM-S12 Comparison of Standards for the Calibration of Voltage, Current and Resistance Meters

Measurements performed on

Wavetek 4950 serial number 33528

From 3 Nov., 2015 to 2 Dec., 2015

Performed by

National Institute of Metrology
No.18 Bei San Huan Dong Lu, Chaoyang District,
Beijing, China

Report by

LIU Yue

Introduction

The APMP.EM-S12 comparison protocol requires that the travelling standard, a Wavetek model 4950 serial number 33528 (the Unit under Test – UUT), be measured at a number of points for each of its measurement functions. These are direct voltage, direct current, alternating voltage, alternating current and resistance. The measurement points are detailed in the comparison protocol.

The instrument was received on 3 Nov. 2015. The fuse (F1) and mains voltage selection switch (S1) was checked before applying power. The UUT was allowed to stabilise for 24 hours with the power turned on before any measurements were made. The instrument's confidence test was performed and completed without any errors.

The measurements were performed from 5 Nov. 2015 to 3 Dec. 2015. The instrument was sent to NMIA on 4 Dec. 2015.

Direct Voltage

Test methods:

Direct voltage was measured using three methods:

1. For 100 mV and 1 V the correction of the UUT was determined by direct connection of the UUT to the output of the divider (4902S) using the ratio of 100:1 or 10:1 with the divider input connecting Fluke 5720A and Agilent 3458A in parallel. Agilent 3458A was calibrated against 10V (732A zener reference).The voltage ratio of the divider was calibrated by a set of differential detectors with wireless output.
2. For 10 V the correction of the UUT was determined by direct connection of the UUT to a calibrated Fluke model 732A zener reference, calibrated against a Josephson voltage standard.
3. For 19 V to 1000 V the correction of the UUT was determined by direct connection of the UUT and Fluke 5720A in parallel connection to the input of the divider (4902S) using the ratio from 2:1 to 100:1 with the divider output connecting Agilent 3458A calibrated against 10V (732A zener reference).The divider was calibrated by a set of differential detectors with wireless output. For 19V Agilent 3458A was calibrated against 10V to obtain the correction of its reading of 9.5V.

See figure 1.1 for the direct voltage measurement setups.

The 'Remote Guard' function was turned on for all the measurements, and the guard terminal and low voltage terminal were connected to a common ground point. The low current terminal was connected to the low voltage terminal and the high current terminal was connected to the high voltage terminal for all measurements.

Traceability:

All the test methods described for direct voltage was traceable to Chinese national measurement standard for voltage, a Josephson voltage standard. See figure 2.1 for the direct voltage traceability chart.

Conditions of measurement:

During the direct voltage measurements, the following conditions of measurement prevailed:

Ambient temperature: 20.5 °C ± 0.5 °C
Relative humidity: 40%RH to 45 %RH

Measurement results:

Range (V)	Nominal Voltage (V)	Correction (V)	Uncertainty (V)	Internal Temperature (°C)
0.1	0.1	− 0.000 001 03	± 0.000 000 31	38.3
1	1	− 0.000 002 8	± 0.000 000 5	38.3
10	10	− 0.000 026	± 0.000 005	38.1
10	19	− 0.000 048	± 0.000 020	39.1
100	100	− 0.000 19	± 0.000 12	38.3
1000	1000	− 0.003 4	± 0.001 4	38.3

Detailed uncertainty budgets for the direct voltage measurements are shown in appendix 3.1.

Direct Current

Test methods:

Direct current was measured the following method:

The correction of the UUT was determined by comparing its readings to the calculated value of the applied current. A calibrated current shunt was connected in series with the UUT. The voltage drop across the current shunt was measured with a calibrated voltmeter. The applied current was calculated from the resistance of the shunts and the measured voltage.

See figure 1.2 for the direct current measurement setup.

The ‘Remote Guard’ function was turned on for all the measurements, and the guard terminal and low current terminal were connected to a common ground point. The low voltage and high voltage terminals were connected to the same ground point.

Traceability:

The resistance of the shunt was traceable to primary resistance standard and DCC bridge maintained in NIM, China.

See figure 2.1 and 2.2 for the direct voltage and resistance traceability chart.

Conditions of measurement:

During the direct current measurements, the following conditions of measurement prevailed:

Ambient temperature: 20.5 °C ± 0.5 °C

Relative humidity: 40%RH to 45 %RH

Measurement results:

Range	Nominal Current	Correction	Uncertainty	Internal Temperature (°C)
1 mA	1 mA	+ 0.000 003 mA	± 0.000 006 mA	41.4
1 A	1 A	+ 0.000 017 A	± 0.000 007 A	41.2

Detailed uncertainty budgets for the direct current measurements are shown in appendix 3.2.

Alternating Voltage

Test methods:

Alternating voltage was measured using three methods:

1. For 10 mV and 100 mV the correction of the UUT was determined by comparing the UUT reading to that obtained from the output of ac divider with the ratio of 10:1 (500 Ω: 50 Ω) and 100:1 (5 kΩ: 50 Ω). The ac divider consisted of chip resistors. The input of the divider was 5720A and 5790A connected in parallel, and 1V of 5790A was calibrated by thermal converter. The output AC voltage of the divider was calculated from the DC voltage ratio of the divider, ac-dc difference of the divider and the AC voltage measured by 5790A.
   For 19 V the correction of the UUT was determined by comparing the UUT reading to that obtained from the ac divider (the ratio of 19:1). The input and output connections were reversed against that of 10 mV and 100mV.

   About AC voltage buffer(should be used in each measurement):
   (a) ACV buffer was connected to the output of the divider, and the output of the buffer was connected Agilent 3458A. The input of the divider was 5720A and calibrated 5790A in parallel connection. Record the reading of 3458A (UUT 4950 unconnected).
   (b) Connect UUT (4950) to the output of the divider, with the buffer in parallel. Adjust the output of 5720A to make the output of the buffer (the reading of 3458A) the same as that in condition(a). Then actual value of the output of the divider could be calculated by the DC voltage ratio of the divider, ac-dc difference of the divider and the AC voltage measured by 5790A.
2. For 1 V and 10 V the correction of the UUT was determined by thermal converter. The applied alternating voltage was calculated from the direct voltage measured by the UUT and the ac-dc difference. The input of thermal converter was 5720A and 4950 in parallel connection.
3. For measurements from 100 V to 700 V the correction of the UUT was determined by comparing the UUT reading to that obtained from Fluke 792A thermal transfer standard. The applied alternating voltage was calculated from the direct voltage measured by the UUT and the ac-dc difference.

See figure 1.3 for the alternating voltage measurement setups.

The ‘Remote Guard’ function was turned on for all the measurements. The input connectors were attached to a 4 banana to type-N adapter, serial number 4BN-002. The guard connector was connected into the rear of the low voltage connector.

As specified by the protocol, the 1 MHz measurements at 1 V and 10 V was done with 4wCct (the default setting) selected.

Traceability:

For the measurements at 10 mV, 100 mV and 19 V ac-dc difference of the divider (newly developed) compared with 792A by measuring the same AC voltage.

For the measurements from 100 V to 700 V the direct voltage traceability was obtained from the direct voltage calibration of the UUT. The ac-dc differences of 792A were traceable to the primary set of thermal converters maintained in NIM, China.

See figure 2.3 for the ac-dc difference traceability chart.

Conditions of measurement:

During the alternating voltage measurements, the following conditions of measurement prevailed:

Ambient temperature: 20.5 °C ± 0.5 °C
Relative humidity: 40%RH to 45 %RH

Measurement results:

Range (V)	Nominal Voltage (V)	Frequency (kHz)	Correction (V)	Uncertainty (V)	Internal Temperature (°C)
0.01	0.01	0.010	+ 0.000 000 1	± 0.000 001 8	40.9
		0.055	− 0.000 000 5	± 0.000 001 6	40.9
		1.005	− 0.000 000 1	± 0.000 001 1	40.9
		20	− 0.000 000 2	± 0.000 001 5	40.9
		50	+ 0.000 000 3	± 0.000 001 7	40.9
		1000	− 0.000 015	± 0.000 012	41.0
0.1	0.1	0.010	+ 0.000 002 7	± 0.000 004 4	40.9
		0.055	+ 0.000 007 2	± 0.000 003 6	40.9
		1.005	+ 0.000 008 3	± 0.000 003 5	40.9
		20	+ 0.000 008 9	± 0.000 003 6	41.0
		50	+ 0.000 007 3	± 0.000 004 9	40.9
		1000	− 0.000 303	± 0.000 102	41.0
1	1	0.010	− 0.000 042	± 0.000 027	41.1
		0.055	− 0.000 016	± 0.000 019	41.0
		1.005	− 0.000 009	± 0.000 014	41.1
		20	− 0.000 007	± 0.000 021	41.1
		50	− 0.000 030	± 0.000 042	41.1
		1000	− 0.007 25	± 0.000 42	41.0
10	10	0.010	− 0.000 71	± 0.000 26	39.7
		0.055	− 0.000 01	± 0.000 17	39.9

		1.005	+ 0.000 09	± 0.000 11	40.0
		20	+ 0.000 03	± 0.000 16	39.7
		50	+ 0.000 07	± 0.000 31	40.0
		1000	− 0.066 7	± 0.002 6	39.7
10	19	1.005	− 0.000 24	± 0.000 60	40.9
100	100	0.010	− 0.012 2	± 0.021 0	41.3
		0.055	+ 0.001 0	± 0.003 2	41.3
		1.005	+ 0.000 9	± 0.003 1	41.3
		20	+ 0.001 2	± 0.003 2	41.3
		50	− 0.000 4	± 0.006 6	41.3
1000	700	0.055	− 0.010	± 0.028	38.9
		1.005	− 0.007	± 0.026	38.9
		20	+ 0.005	± 0.029	38.8
		50	+ 0.053	± 0.047	38.8

Detailed uncertainty budgets for the alternating voltage measurements are shown in appendix 3.3.

Alternating Current

Test methods:

Alternating current was measured the following method:

The correction of the UUT was determined by comparing its readings to the calculated value of the applied current. A calibrated current shunt was connected in series with the UUT. The voltage drop across the current shunt was measured with a calibrated alternating voltage measurement standard. The applied current was calculated from the resistance and ac-dc differences of the shunts, and the measured voltage.

See figure 1.4 for the alternating current measurement setup.

The 'Remote Guard' function was turned on for all the measurements, and the guard terminal and low current terminal were connected to a common ground point. The low voltage and high voltage terminals were connected to the same ground point.

Traceability:

The alternating voltage measurement standard and the ac-dc differences of the shunts are traceable to the primary set of thermal convertors maintained by NIM, China.

See figure 2.2 for the resistance traceability chart and figure 2.3 for the ac-dc difference traceability chart.

Conditions of measurement:

During the alternating current measurements, the following conditions of measurement prevailed:

Ambient temperature: 20.5 °C ± 0.5 °C
Relative humidity: 40%RH to 45 %RH

Measurement results:

Range	Nominal Current	Frequency (kHz)	Correction	Uncertainty	Internal Temperature (°C)
1 mA	1 mA	0.055	+ 0.000 191 mA	± 0.000 049 mA	38.7
		1.005	+ 0.000 199 mA	± 0.000 047 mA	38.7
		5	+ 0.000 299 mA	± 0.000 050 mA	38.7
1 A	1 A	0.055	+ 0.000 134 A	± 0.000 039 A	41.5
		1.005	+ 0.000 159 A	± 0.000 033 A	41.6
		5	+ 0.000 702 A	± 0.000 042 A	41.6

Detailed uncertainty budgets for the alternating current measurements are shown in appendix 3.4.

Resistance

Test methods:

The correction of the UUT was determined by comparing its readings to a set of standard resistors.

See figure 1.5 for the resistance measurement setup.

The ‘Remote Guard’ function was turned on for all the measurements, and the guard terminal and low voltage terminal were connected to a common ground point. For 2-wire measurements the low current terminal and the high current terminal were connected to the common ground point.

Traceability:

The values of the standard resistors are traceable to primary standard of resistance maintained by NIM, China.

See figure 2.2 for the resistance traceability chart.

Conditions of measurement:

During the resistance measurements, the following conditions of measurement prevailed:

Ambient temperature: 20.5 °C ± 0.5 °C
Relative humidity: 40%RH to 45 %RH

4-wire measurement results:

Range	Nominal Resistance	Correction	Uncertainty	Internal Temperature (°C)
10 **Ω**	10 **Ω**	− 0.000 004 **Ω**	± 0.000 014 **Ω**	41.4
100 **Ω**	100 **Ω**	− 0.000 28 **Ω**	± 0.000 11 **Ω**	41.4
1 k**Ω**	1 k**Ω**	+ 0.000 002 2 k**Ω**	± 0.000 001 3 k**Ω**	41.4

10 kΩ	10 kΩ	− 0.000 006 kΩ	± 0.000 017 kΩ	41.4

2-wire measurement results:

Range	Nominal Resistance	Correction	Uncertainty	Internal Temperature (°C)
100 kΩ	100 kΩ	− 0.000 16 kΩ	± 0.000 17 kΩ	41.4
1 MΩ	1 MΩ	+ 0.000 002 3 MΩ	± 0.000 005 2 MΩ	41.4
10 MΩ	10 MΩ	− 0.000 183 MΩ	± 0.000 055 MΩ	41.4
100 MΩ	100 MΩ	− 0.003 4 MΩ	± 0.001 4 MΩ	38.5

Detailed uncertainty budgets for the resistance measurements are shown in appendix 3.5.

Frequency

The protocol requires that the frequency of the sources used for alternating voltage and alternating current be measured and reported.

Test methods:

A Fluke model 5720A was used to measure alternating voltage and alternating current. The correction of the calibrators was determined by measuring the frequency for an output of 1 V or 10mA (using an ACI meter as load) using a frequency counter.

See figure 1.6 for the frequency measurement setup.

The ‘External Guard’ function of the calibrator was turned off, and the guard terminal was connected to a common ground point.

Traceability:

The frequency measurements were traceable to the national frequency standard maintained by NIM, China.

See figure 2.4 for the frequency traceability chart.

Conditions of measurement:

During the frequency measurements, the following conditions of measurement prevailed:

Ambient temperature: 20.5 °C ± 0.5 °C
Relative humidity: 40%RH to 45 %RH

Frequency measurement results:

For Fluke 5720A serial number 1579203 used for voltage measurements & current measurements:

Nominal Frequency	Correction	Uncertainty
10 Hz	+ 0.000 056 Hz	± 0.000 008 Hz
55 Hz	+ 0.000 31 Hz	± 0.000 060 Hz
1.005 kHz	+ 0.005 8 Hz	± 0.000 53 Hz
20 kHz	+ 0.119 Hz	± 0.011 Hz
50 kHz	+ 0.29 Hz	± 0.030 Hz
1 MHz	+ 5.9 Hz	± 0.6 Hz

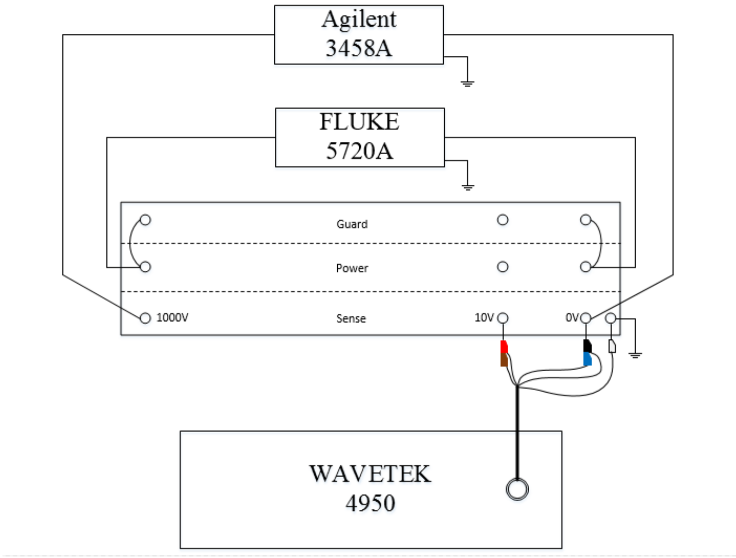
For Fluke 5720A serial number 1579203 used for current measurements:

Nominal Frequency	Correction	Uncertainty
55 Hz	+ 0.000 32 Hz	± 0.000 060 Hz
1.005 kHz	+ 0.005 6 Hz	± 0.000 6 Hz
5 kHz	+ 0.027 Hz	± 0.003 Hz

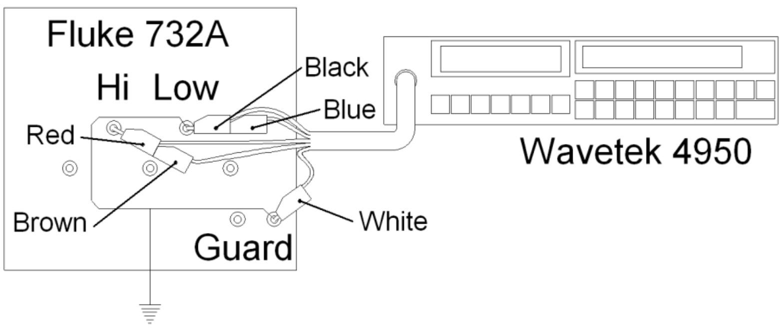
Detailed uncertainty budgets for the frequency measurements are shown in appendix 3.6.

Appendix 1: Measurement setups

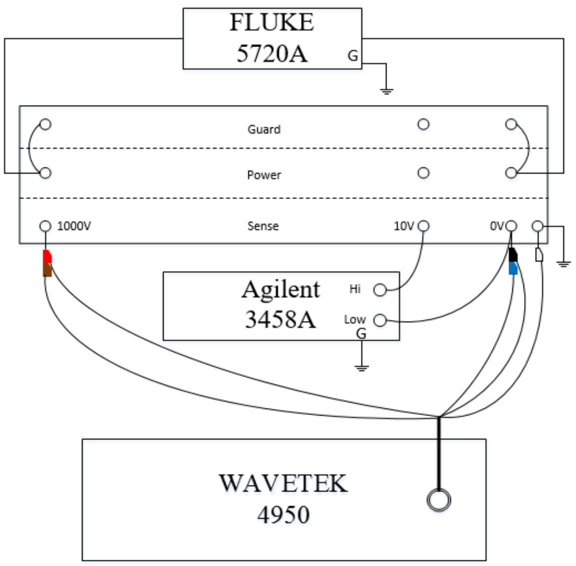
Direct Voltage



(a) 100 mV and 1 V measurement



(b) 10 V measurements



(c) 19 V to 1000 V measurements

Figure 1.1: Direct voltage measurement setups

Direct Current

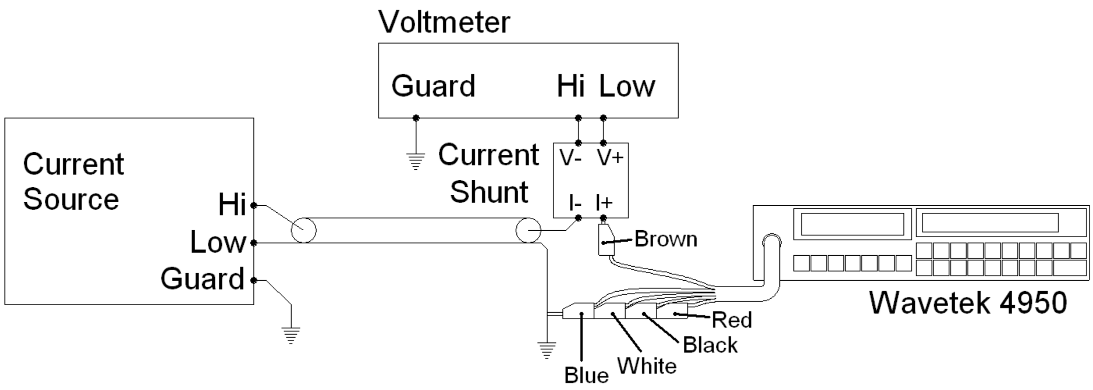
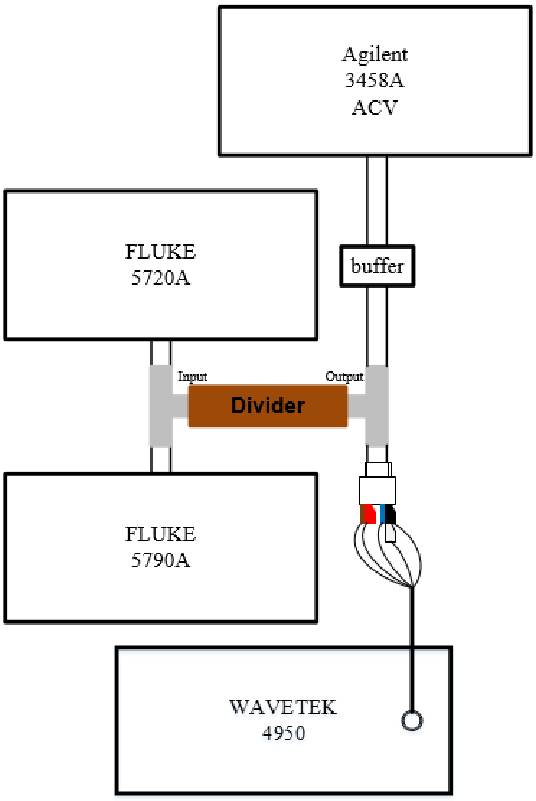
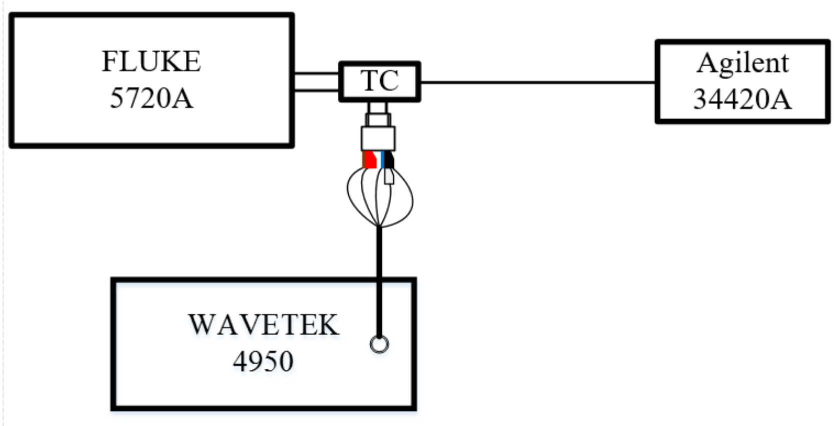


Figure 1.2: Direct current measurement setup

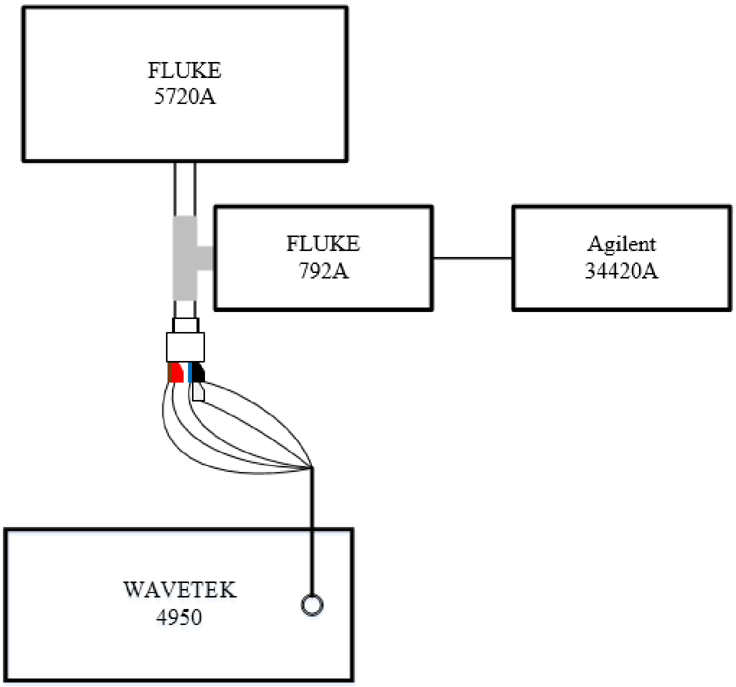
Alternating Voltage

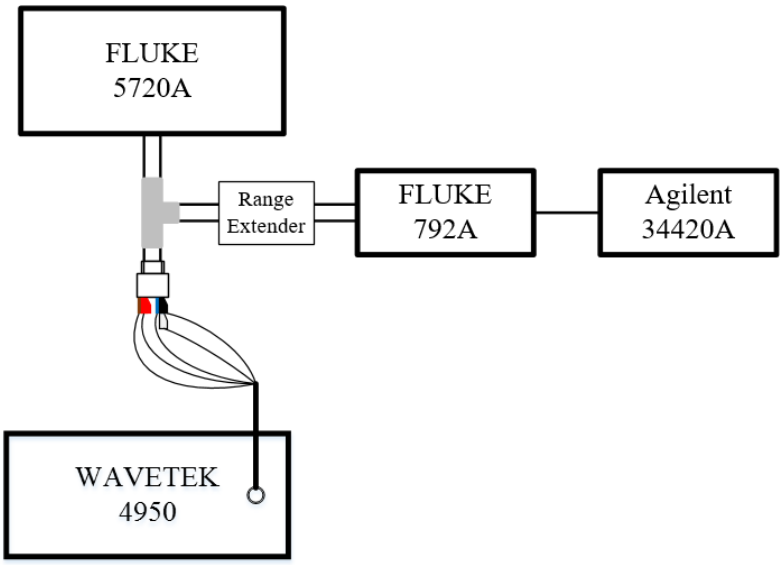


(a) 10 mV, 100 mV and 19V



(b) 1 V to 100 V





(c) 100 V to 700 V

Figure 1.3: Alternating voltage measurement setups

Alternating Current

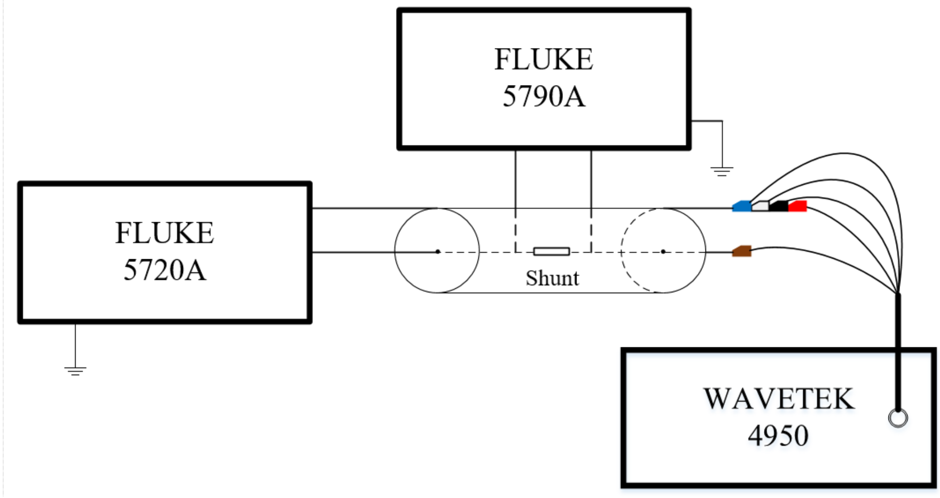


Figure 1.4: Alternating current measurement setup

Resistance

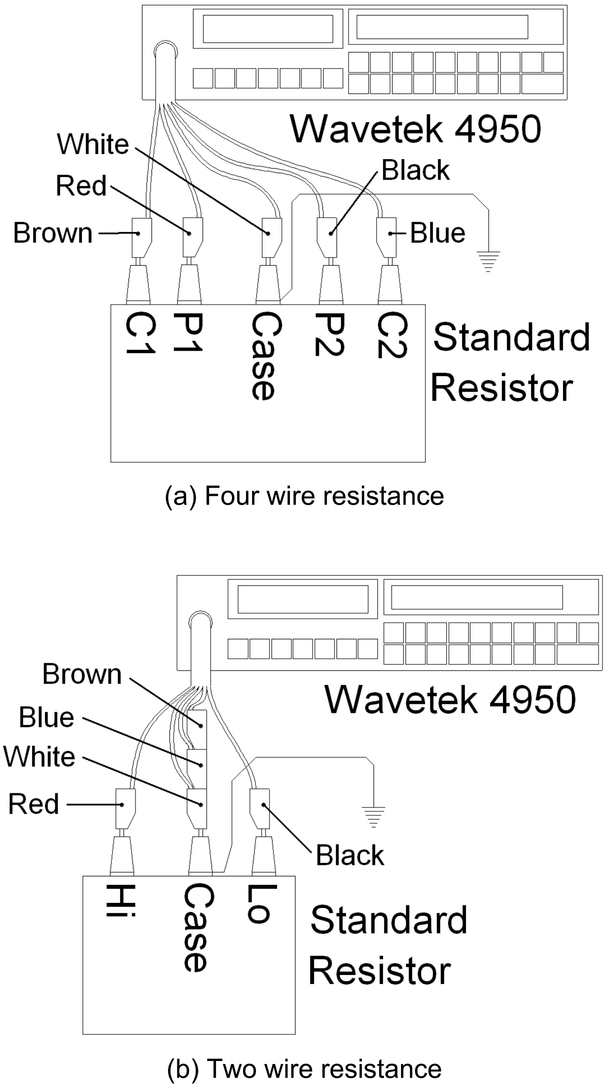


Figure 1.5: Resistance measurement setups

Frequency

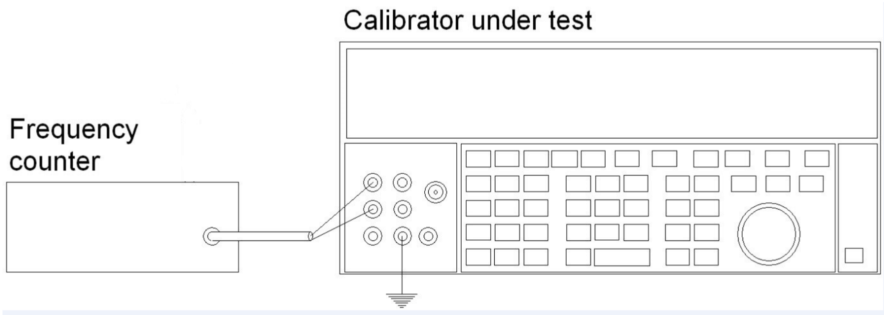


Figure 1.6: Frequency measurement setup

Appendix 2: Traceability charts

Direct Voltage

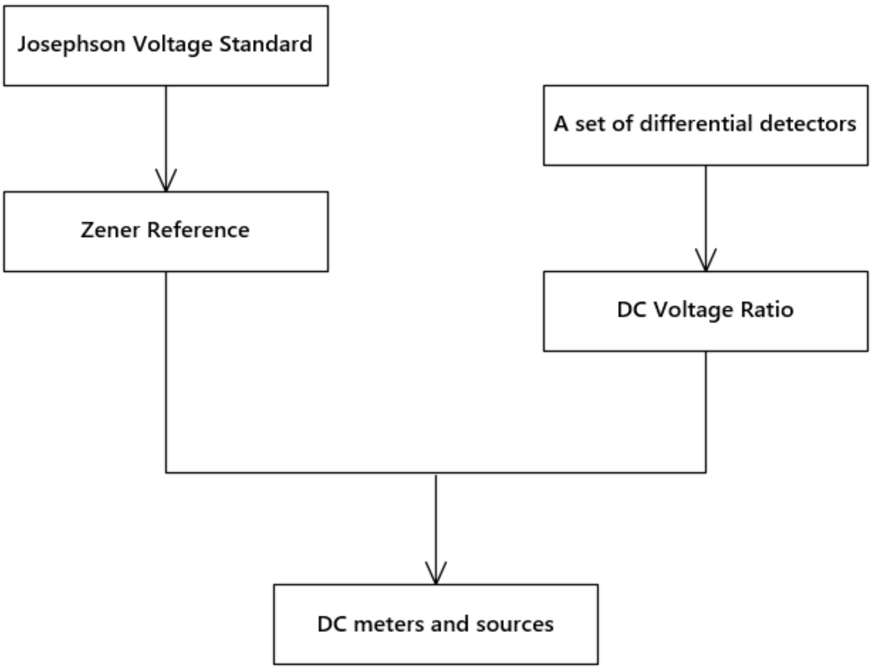


Figure 2.1: Direct voltage traceability

Resistance

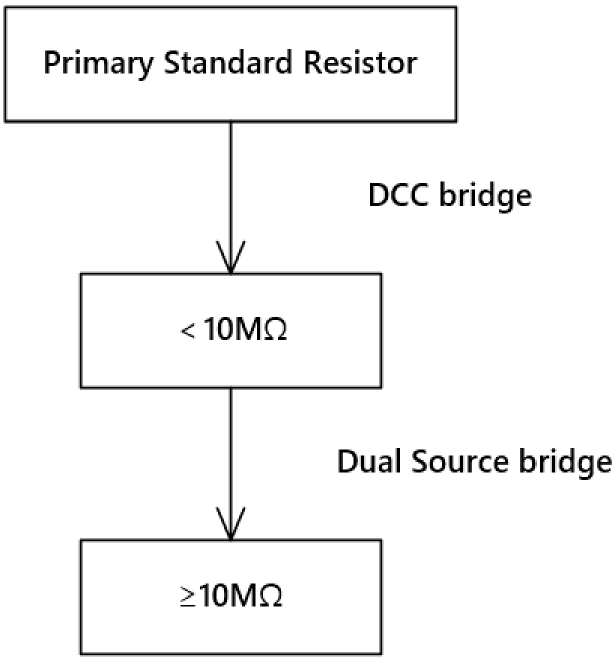


Figure 2.2: Resistance traceability

Ac-dc difference

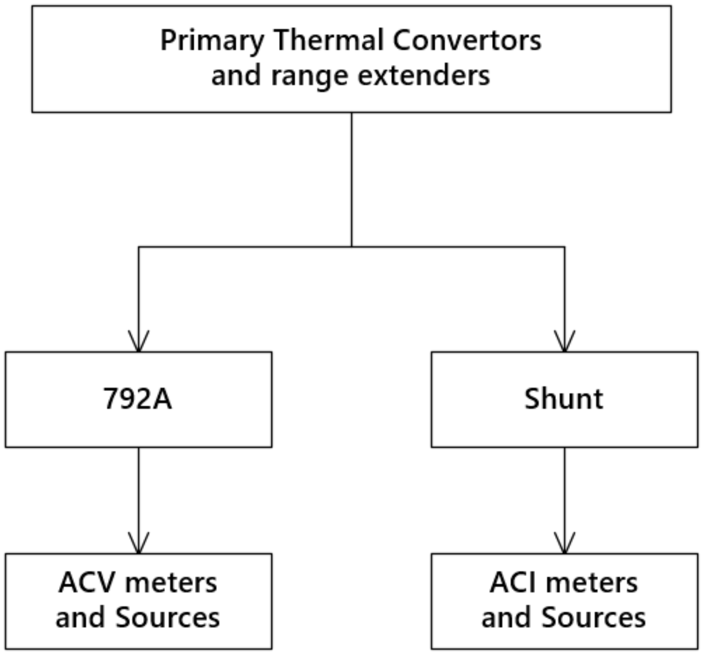


Figure 2.3: Ac-dc difference traceability

Frequency

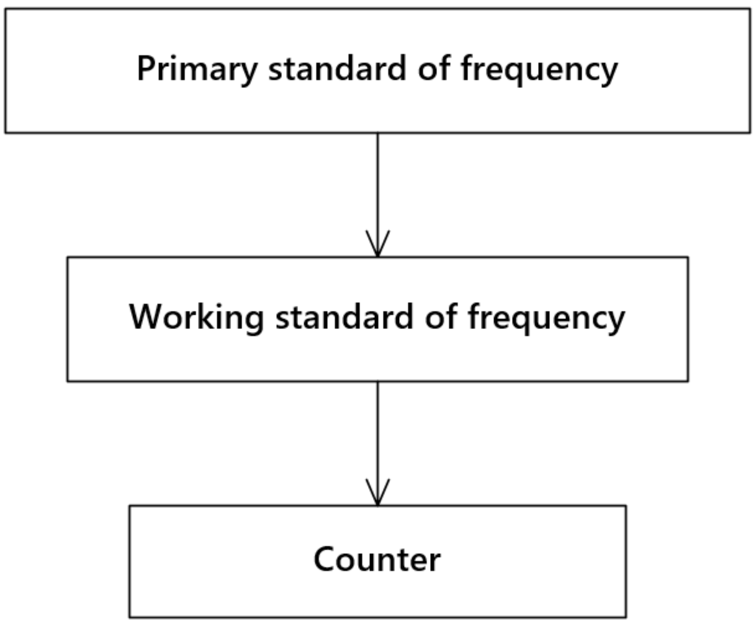


Figure 2.4: Frequency traceability

Appendix 3: Uncertainty budgets

3.1 Direct Voltage

For direct voltage at 100 mV & 1 V

$$\Delta = V_X - V_S \cdot K$$

Δ: Measurement error of UUT
V_X: Indication of UUT
V_S: Indication of reference voltmeter (3458A)
K: Voltage ratio of divider (4902S), (0<K<1)

For direct voltage at 100 mV &1 V the following components contribute to the uncertainty of measurement:

- Reference voltmeter uncertainty: From the calibration by 10 V of 732A.
- Reference voltmeter transfer accuracy: From the specification of the voltmeter.
- Reference voltmeter resolution: From the specification of the voltmeter
- Reference voltmeter repeatability: From the observed data
- Voltage ratio uncertainty: From the calibration report
- Voltage ratio drift since last calibration: From the history of the divider
- Voltage ratio temp. coefficient: From the specification of the divider
- UUT resolution: From the UUT specification
- UUT repeatability: From the observed data
- UUT stability: From measurement repeated 4 times during the period that UUT spent in our laboratory

Uncertainty budget for 100 mV measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Reference voltmeter uncertainty	B	0.15	µV/V	2	0.08	1	0.08	50
Reference voltmeter transfer accuracy	B	0.1	µV/V	1.732	0.06	1	0.06	50
Reference voltmeter resolution	B	0.05	µV/V	1.732	0.03	1	0.03	50
Reference voltmeter repeatability	A	0.07	µV/V	1	0.07	1	0.07	9
Voltage ratio uncertainty	B	2	ppm	2	1.00	1	1.00	50
Voltage ratio drift since last calibration	B	0.1	ppm	1.732	0.06	1	0.06	50
Voltage ratio temp. coefficient	B	0.1	ppm	1.732	0.06	1	0.06	50
UUT resolution	B	0.05	µV/V	1.732	0.03	1	0.03	50
UUT repeatability	A	1.2	µV/V	1.69	0.71	1	0.71	1.8
UUT stability	A	1.6	µV/V	2.06	0.78	1	0.78	2.7
						Combined standard uncertainty	1.46	µV/V
						Effective degrees of freedom	15.3	
						Coverage factor	2.13	
						Expanded uncertainty	3.11	µV/V
						Expanded uncertainty	0.31	µV

Uncertainty budget for 1 V measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Reference voltmeter uncertainty	B	0.15	µV/V	2	0.08	1	0.08	50
Reference voltmeter transfer accuracy	B	0.1	µV/V	1.732	0.06	1	0.06	50
Reference voltmeter resolution	B	0.05	µV/V	1.732	0.03	1	0.03	50
Reference voltmeter repeatability	A	0.07	µV/V	1	0.07	1	0.07	9
Voltage ratio uncertainty	B	0.2	ppm	2	0.10	1	0.10	50

Voltage ratio drift since last calibration	B	0.1	ppm	1.732	0.06	1	0.06	50
Voltage ratio temp. coefficient	B	0.1	ppm	1.732	0.06	1	0.06	50
UUT resolution	B	0.05	µV/V	1.732	0.03	1	0.03	50
UUT repeatability	A	0.1	µV/V	1.69	0.06	1	0.06	1.8
UUT stability	A	0.3	µV/V	2.06	0.15	1	0.15	2.7
						Combined standard uncertainty	0.24	µV/V
						Effective degrees of freedom	18.0	
						Coverage factor	2.1	
						Expanded uncertainty	0.50	µV/V
						Expanded uncertainty	0.50	µV

For direct voltage at 10 V the following components contribute to the uncertainty of measurement:

- Voltage reference (Fluke 732A) uncertainty: From the last calibration report
- Voltage reference (Fluke 732A) drift: From the history data
- UUT repeatability: From the observed data
- UUT t resolution: From UUT specifications
- UUT stability: From measurement repeated 4 times during the period that UUT spent in our laboratory

Uncertainty budget for 10 V measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Voltage reference	B	0.15	µV/V	2	0.08	1	0.08	50
Voltage reference drift	B	0.1	µV/V	1.732	0.06	1	0.06	50
UUT resolution	B	0.05	µV/V	1.732	0.03	1	0.03	50
UUT repeatability	A	0.1	µV/V	1.69	0.06	1	0.06	1.8
UUT stability	A	0.3	µV/V	2.06	0.15	1	0.15	2.7
						Combined standard uncertainty	0.19	µV/V
						Effective degrees of freedom	6.8	

Coverage factor	2.45	
Expanded uncertainty	0.46	μV/V
Expanded uncertainty	4.55	μV

For direct voltage from 19 V to 1000 V the following components contribute to the uncertainty of measurement:

- Reference voltmeter uncertainty: From the calibration by 10 V of 732A .
- Reference voltmeter transfer accuracy: From the specification of the voltmeter.
- Reference voltmeter linearity（only for 19V）: From the specification of the voltmeter.
- Reference voltmeter resolution: From the specification of the voltmeter
- Reference voltmeter repeatability: From the observed data
- Voltage ratio uncertainty: From the calibration report
- Voltage ratio drift since last calibration: From the history of the divider
- Voltage ratio temp. coefficient: From the specification of the divider
- UUT resolution: From the UUT specification
- UUT repeatability: From the observed data
- UUT stability: From measurement repeated 4 times during the period that UUT spent in our laboratory

Uncertainty budget for 19 V measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Reference voltmeter uncertainty	B	0.15	μV/V	2	0.08	1	0.08	50
Reference voltmeter transfer accuracy	B	0.1	μV/V	1.732	0.06	1	0.06	50
Reference voltmeter linearity	B	0.1	μV/V	1.732	0.06	1	0.06	50
Reference voltmeter resolution	B	0.05	μV/V	1.732	0.03	1	0.03	50
Reference voltmeter repeatability	A	0.07	μV/V	1	0.07	1	0.07	9
Voltage ratio uncertainty	B	0.2	ppm	2	0.10	1	0.10	50
Voltage ratio drift since last calibration	B	0.1	ppm	1.732	0.06	1	0.06	50
Voltage ratio temp. coefficient	B	0.1	ppm	1.732	0.06	1	0.06	50

UUT resolution	B	0.05	µV/V	1.732	0.03	1	0.03	50
UUT repeatability	A	0.2	µV/V	1.69	0.12	1	0.12	1.8
UUT stability	A	0.7	µV/V	2.06	0.34	1	0.34	2.7
						Combined standard uncertainty	0.41	µV/V
						Effective degrees of freedom	5.4	
						Coverage factor	2.57	
						Expanded uncertainty	1.04	µV/V
						Expanded uncertainty	19.83	µV

Uncertainty budget for 100 V measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Reference voltmeter uncertainty	B	0.15	µV/V	2	0.08	1	0.08	50
Reference voltmeter transfer accuracy	B	0.1	µV/V	1.732	0.06	1	0.06	50
Reference voltmeter resolution	B	0.05	µV/V	1.732	0.03	1	0.03	50
Reference voltmeter repeatability	A	0.07	µV/V	1	0.07	1	0.07	9
Voltage ratio uncertainty	B	0.2	ppm	2	0.10	1	0.10	50
Voltage ratio drift since last calibration	B	0.1	ppm	1.732	0.06	1	0.06	50
Voltage ratio temp. coefficient	B	0.1	ppm	1.732	0.06	1	0.06	50
UUT resolution	B	0.05	µV/V	1.732	0.03	1	0.03	50
UUT repeatability	A	0.3	µV/V	1.69	0.18	1	0.18	1.8
UUT stability	A	0.8	µV/V	2.06	0.39	1	0.39	2.7
						Combined standard uncertainty	0.46	µV/V
						Effective degrees of freedom	5.1	
						Coverage factor	2.57	
						Expanded uncertainty	1.19	µV/V
						Expanded uncertainty	119.03	µV

Uncertainty budget for 1000 V measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Reference voltmeter uncertainty	B	0.15	µV/V	2	0.08	1	0.08	50
Reference voltmeter transfer accuracy	B	0.1	µV/V	1.732	0.06	1	0.06	50
Reference voltmeter resolution	B	0.05	µV/V	1.732	0.03	1	0.03	50
Reference voltmeter repeatability	A	0.07	µV/V	1	0.07	1	0.07	9
Voltage ratio uncertainty	B	0.2	ppm	2	0.10	1	0.10	50
Voltage ratio drift since last calibration	B	0.1	ppm	1.732	0.06	1	0.06	50
Voltage ratio temp. coefficient	B	0.1	ppm	1.732	0.06	1	0.06	50
UUT resolution	B	0.05	µV/V	1.732	0.03	1	0.03	50
UUT repeatability	A	0.4	µV/V	1.69	0.24	1	0.24	1.8
UUT stability	A	0.9	µV/V	2.06	0.44	1	0.44	2.7
						Combined standard uncertainty	0.53	µV/V
						Effective degrees of freedom	5.1	
						Coverage factor	2.57	
						Expanded uncertainty	1.36	µV/V
						Expanded uncertainty	1.36	mV

3.2 Direct Current

For direct current the following components contribute to the uncertainty of measurement:

- Shunt uncertainty and power coefficient: From the last calibration report
- Shunt drift: From the history data
- Voltmeter uncertainty: From the last calibration report
- Voltmeter drift: From the history data
- Voltmeter resolution: From the voltmeter specifications
- Voltmeter repeatability: From the observed data
- UUT resolution: From the unit under test specifications
- UUT repeatability: From the observed data
- UUT stability: From measurement repeated 4 times during the period that UUT spent in our laboratory
-

Uncertainty budget for 1 mA measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Shunt uncertainty and power coeff.	B	5	μΩ/Ω	2	2.50	1	2.50	50
Shunt drift	B	0.5	μΩ/Ω	1.732	0.29	1	0.29	50
Voltmeter uncertainty	B	1	μV/V	2	0.50	1	0.50	50
Voltmeter drift	B	0.1	μV/V	1.732	0.06	1	0.06	50
Voltmeter resolution	B	0.05	μV/V	1.732	0.03	1	0.03	50
Voltmeter repeatability	A	0.16	μV/V	1	0.16	1	0.16	9
UUT resolution	B	0.5	μA/A	1.732	0.29	1	0.29	50
UUT repeatability	A	1	μA/A	1.69	0.59	1	0.59	1.8
UUT stability	A	3	μA/A	2.06	1.46	1	1.46	2.7
Combined standard uncertainty							3.03	μA/A
Effective degrees of freedom							33.4	
Coverage factor							2.04	

Expanded uncertainty	6.18	µA/A
Expanded uncertainty	6.2	nA

Uncertainty budget for 1 A measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Shunt uncertainty and power coeff.	B	5	µΩ/Ω	2	2.5	1	2.50	50
Shunt drift	B	0.4	µΩ/Ω	1.732	0.230946882	1	0.23	50
Voltmeter uncertainty	B	4	µV/V	2	2	1	2.00	50
Voltmeter drift	B	0.1	µV/V	1.732	0.057736721	1	0.06	50
Voltmeter resolution	B	0.05	µV/V	1.732	0.02886836	1	0.03	50
Voltmeter repeatability	A	0.31	µV/V	1	0.31	1	0.31	9
UUT resolution	B	0.5	µA/A	1.732	0.288683603	1	0.29	50
UUT repeatability	A	1	µA/A	1.69	0.591715976	1	0.59	1.8
UUT stability	A	3	µA/A	2.06	1.45631068	1	1.46	2.7
						Combined standard uncertainty	3.60	µA/A
						Effective degrees of freedom	59.2	
						Coverage factor	2.01	
						Expanded uncertainty	7.24	µA/A
						Expanded uncertainty	7.2	µA

3.3 Alternating Voltage

Three methods were used to perform alternating voltage measurements. For 10 mV 100 mV and 19V the measurements were done against an AC divider. The measurements from 1 V and 10 V were done against thermal convertors (TVC). The measurements from 100 V to 700 V were done against a thermal transfer standard (792A).

For alternating voltage at 10 mV 100 mV & 19 V the following components contribute to the uncertainty of measurement:

- Divider DC ratio uncertainty and drift: From the last calibration report and history data
- Divider ac-dc difference: From the compared results against 792A
- AC Voltmeter uncertainty: From the last calibration report
- AC Voltmeter drift or transfer accuracy: From the history data
- AC Voltmeter resolution: From the voltmeter specifications
- AC Voltmeter repeatability: From the observed data
- AC buffer influence(for 1 MHz only): Estimate the influence of the reference point voltage when adding 1 or 2 buffers reading the difference of the output of the buffer
- UUT repeatability: From the observed data
- UUT resolution: From UUT specifications
- UUT stability: From measurement repeated 5 times during the period that UUT spent in our laboratory

Uncertainty budget for 10 mV and 10 Hz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Divider DC ratio uncertainty and drift	B	10	μΩ/Ω	2	5.00	1	5.00	50
Divider ac-dc difference	B	10	μΩ/Ω	2	5.00	1	5.00	50
AC Voltmeter uncertainty	B	30	μV/V	2	15.00	1	15.00	50
AC Voltmeter drift or transfer accuracy	B	20	μV/V	1.732	11.55	1	11.55	50
AC Voltmeter resolution	B	0.5	μV/V	1.732	0.29	1	0.29	50
AC Voltmeter repeatability	A	4.6	μV/V	1	4.60	1	4.60	9
UUT resolution	B	5	μV/V	1.732	2.89	1	2.89	50
UUT repeatability	A	80	μV/V	1.69	47.34	1	47.34	1.8
UUT stability	A	50	μV/V	2.33	21.46	1	21.46	3.6
						Combined standard uncertainty	56.03	μV/V
						Effective degrees of freedom	3.5	
						Coverage factor	3.18	
						Expanded uncertainty	178.17	μV/V
						Expanded uncertainty	1.8	μV

Uncertainty budget for 10 mV and 55 Hz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Divider DC ratio uncertainty and drift	B	10	μΩ/Ω	2	5.00	1	5.00	50
Divider ac-dc difference	B	10	μΩ/Ω	2	5.00	1	5.00	50
AC Voltmeter uncertainty	B	20	μV/V	2	10.00	1	10.00	50
AC Voltmeter drift or transfer accuracy	B	20	μV/V	1.732	11.55	1	11.55	50
AC Voltmeter resolution	B	0.5	μV/V	1.732	0.29	1	0.29	50
AC Voltmeter repeatability	A	5.2	μV/V	1	5.20	1	5.20	9
UUT resolution	B	5	μV/V	1.732	2.89	1	2.89	50
UUT repeatability	A	70	μV/V	1.69	41.42	1	41.42	1.8

UUT stability	A	50	µV/V	2.33	21.46	1	21.46	3.6
						Combined standard uncertainty	49.95	µV/V
						Effective degrees of freedom	3.7	
						Coverage factor	3.18	
						Expanded uncertainty	158.84	µV/V
						Expanded uncertainty	1.6	µV

Uncertainty budget for 10 mV and 1.005 kHz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Divider DC ratio uncertainty and drift	B	10	µΩ/Ω	2	5.00	1	5.00	50
Divider ac-dc difference	B	10	µΩ/Ω	2	5.00	1	5.00	50
AC Voltmeter uncertainty	B	15	µV/V	2	7.50	1	7.50	50
AC Voltmeter drift or transfer accuracy	B	20	µV/V	1.732	11.55	1	11.55	50
AC Voltmeter resolution	B	0.5	µV/V	1.732	0.29	1	0.29	50
AC Voltmeter repeatability	A	1.1	µV/V	1	1.10	1	1.10	9
UUT resolution	B	5	µV/V	1.732	2.89	1	2.89	50
UUT repeatability	A	50	µV/V	1.69	29.59	1	29.59	1.8
UUT stability	A	30	µV/V	2.33	12.88	1	12.88	3.6
						Combined standard uncertainty	35.92	µV/V
						Effective degrees of freedom	3.8	
						Coverage factor	3.18	
						Expanded uncertainty	114.23	µV/V
						Expanded uncertainty	1.1	µV

Uncertainty budget for 10 mV and 20 kHz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Divider DC ratio uncertainty and drift	B	10	µΩ/Ω	2	5.00	1	5.00	50
Divider ac-dc difference	B	10	µΩ/Ω	2	5.00	1	5.00	50

AC Voltmeter uncertainty	B	25	µV/V	2	12.50	1	12.50	50
AC Voltmeter drift or transfer accuracy	B	20	µV/V	1.732	11.55	1	11.55	50
AC Voltmeter resolution	B	0.5	µV/V	1.732	0.29	1	0.29	50
AC Voltmeter repeatability	A	1.1	µV/V	1	1.10	1	1.10	9
UUT resolution	B	5	µV/V	1.732	2.89	1	2.89	50
UUT repeatability	A	70	µV/V	1.69	41.42	1	41.42	1.8
UUT stability	A	70	µV/V	2.33	30.04	1	30.04	3.6
						Combined standard uncertainty	54.47	µV/V
						Effective degrees of freedom	4.7	
						Coverage factor	2.78	
						Expanded uncertainty	151.44	µV/V
						Expanded uncertainty	1.5	µV

Uncertainty budget for 10 mV and 50 kHz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Divider DC ratio uncertainty and drift	B	10	µΩ/Ω	2	5.00	1	5.00	50
Divider ac-dc difference	B	10	µΩ/Ω	2	5.00	1	5.00	50
AC Voltmeter uncertainty	B	45	µV/V	2	22.50	1	22.50	50
AC Voltmeter drift or transfer accuracy	B	20	µV/V	1.732	11.55	1	11.55	50
AC Voltmeter resolution	B	0.5	µV/V	1.732	0.29	1	0.29	50
AC Voltmeter repeatability	A	2.3	µV/V	1	2.30	1	2.30	9
UUT resolution	B	5	µV/V	1.732	2.89	1	2.89	50
UUT repeatability	A	80	µV/V	1.69	47.34	1	47.34	1.8
UUT stability	A	70	µV/V	2.33	30.04	1	30.04	3.6
						Combined standard uncertainty	62.02	µV/V
						Effective degrees of freedom	4.9	
						Coverage factor	2.78	
						Expanded uncertainty	172.42	µV/V
						Expanded uncertainty	1.7	µV

Uncertainty budget for 10 mV and 1 MHz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Divider DC ratio uncertainty and drift	B	10	µΩ/Ω	2	5.00	1	5.00	50
Divider ac-dc difference	B	200	µΩ/Ω	2	100.00	1	100.00	50
AC Voltmeter uncertainty	B	750	µV/V	2	375.00	1	375.00	50
AC Voltmeter drift or transfer accuracy	B	50	µV/V	1.732	28.87	1	28.87	50
AC Voltmeter resolution	B	0.5	µV/V	1.732	0.29	1	0.29	50
AC Voltmeter repeatability	A	23	µV/V	1	23.00	1	23.00	9
AC voltage buffer	B	220	µV/V	1.732	127.02	1	127.02	50
UUT resolution	B	0.5	µV/V	1.732	0.29	1	0.29	50
UUT repeatability	A	180	µV/V	2.06	87.38	1	87.38	1.8
UUT stability	A	850	µV/V	2.33	364.81	1	364.81	3.6
						Combined standard uncertainty	555.76	µV/V
						Effective degrees of freedom	17.8	
						Coverage factor	2.11	
						Expanded uncertainty	1172.65	µV/V
						Expanded uncertainty	11.7	µV

Uncertainty budget for 100 mV and 10 Hz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Divider DC ratio uncertainty and drift	B	10	µΩ/Ω	2	5.00	1	5.00	50
Divider ac-dc difference	B	10	µΩ/Ω	2	5.00	1	5.00	50
AC Voltmeter uncertainty	B	30	µV/V	2	15.00	1	15.00	50
AC Voltmeter drift or transfer accuracy	B	20	µV/V	1.732	11.55	1	11.55	50
AC Voltmeter resolution	B	0.5	µV/V	1.732	0.29	1	0.29	50
AC Voltmeter repeatability	A	1	µV/V	1	1.00	1	1.00	9

UUT resolution	B	0.5	µV/V	1.732	0.29	1	0.29	50
UUT repeatability	A	11	µV/V	2.06	5.34	1	5.34	1.8
UUT stability	A	15	µV/V	2.33	6.44	1	6.44	3.6
						Combined standard uncertainty	21.90	µV/V
						Effective degrees of freedom	99.0	
						Coverage factor	2.01	
						Expanded uncertainty	44.01	µV/V
						Expanded uncertainty	4.4	µV

Uncertainty budget for 100 mV and 55 Hz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Divider DC ratio uncertainty and drift	B	10	µΩ/Ω	2	5.00	1	5.00	50
Divider ac-dc difference	B	10	µΩ/Ω	2	5.00	1	5.00	50
AC Voltmeter uncertainty	B	20	µV/V	2	10.00	1	10.00	50
AC Voltmeter drift or transfer accuracy	B	20	µV/V	1.732	11.55	1	11.55	50
AC Voltmeter resolution	B	0.5	µV/V	1.732	0.29	1	0.29	50
AC Voltmeter repeatability	A	1	µV/V	1	1.00	1	1.00	9
UUT resolution	B	0.5	µV/V	1.732	0.29	1	0.29	50
UUT repeatability	A	9	µV/V	2.06	4.37	1	4.37	1.8
UUT stability	A	13	µV/V	2.33	5.58	1	5.58	3.6
						Combined standard uncertainty	18.30	µV/V
						Effective degrees of freedom	106.5	
						Coverage factor	1.984	
						Expanded uncertainty	36.30	µV/V
						Expanded uncertainty	3.6	µV

Uncertainty budget for 100 mV and 1.005 kHz measurement:

Component	Type	Value	Unit	Divisor	Standard	Sensitivity	Uncertainty	Degrees of

					uncertainty	coefficient	contribution	Freedom
Divider DC ratio uncertainty and drift	B	10	μΩ/Ω	2	5.00	1	5.00	50
Divider ac-dc difference	B	10	μΩ/Ω	2	5.00	1	5.00	50
AC Voltmeter uncertainty	B	15	μV/V	2	7.50	1	7.50	50
AC Voltmeter drift or transfer accuracy	B	20	μV/V	1.732	11.55	1	11.55	50
AC Voltmeter resolution	B	0.5	μV/V	1.732	0.29	1	0.29	50
AC Voltmeter repeatability	A	1	μV/V	1	1.00	1	1.00	9
UUT resolution	B	0.5	μV/V	1.732	0.29	1	0.29	50
UUT repeatability	A	8	μV/V	2.06	3.88	1	3.88	1.8
UUT stability	A	16	μV/V	2.33	6.87	1	6.87	3.6
						Combined standard uncertainty	17.41	μV/V
						Effective degrees of freedom	77.3	
						Coverage factor	2.01	
						Expanded uncertainty	34.99	μV/V
						Expanded uncertainty	3.5	μV

Uncertainty budget for 100 mV and 20 kHz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Divider DC ratio uncertainty and drift	B	10	μΩ/Ω	2	5.00	1	5.00	50
Divider ac-dc difference	B	10	μΩ/Ω	2	5.00	1	5.00	50
AC Voltmeter uncertainty	B	20	μV/V	2	10.00	1	10.00	50
AC Voltmeter drift or transfer accuracy	B	20	μV/V	1.732	11.55	1	11.55	50
AC Voltmeter resolution	B	0.5	μV/V	1.732	0.29	1	0.29	50
AC Voltmeter repeatability	A	1	μV/V	1	1.00	1	1.00	9
UUT resolution	B	0.5	μV/V	1.732	0.29	1	0.29	50
UUT repeatability	A	10	μV/V	2.06	4.85	1	4.85	1.8
UUT stability	A	11	μV/V	2.33	4.72	1	4.72	3.6

Combined standard uncertainty	18.18	µV/V
Effective degrees of freedom	106.2	
Coverage factor	1.984	
Expanded uncertainty	36.06	µV/V
Expanded uncertainty	3.6	µV

Uncertainty budget for 100 mV and 50 kHz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Divider DC ratio uncertainty and drift	B	10	µΩ/Ω	2	5.00	1	5.00	50
Divider ac-dc difference	B	10	µΩ/Ω	2	5.00	1	5.00	50
AC Voltmeter uncertainty	B	35	µV/V	2	17.50	1	17.50	50
AC Voltmeter drift or transfer accuracy	B	20	µV/V	1.732	11.55	1	11.55	50
AC Voltmeter resolution	B	0.5	µV/V	1.732	0.29	1	0.29	50
AC Voltmeter repeatability	A	1	µV/V	1	1.00	1	1.00	9
UUT resolution	B	0.5	µV/V	1.732	0.29	1	0.29	50
UUT repeatability	A	12	µV/V	2.06	5.83	1	5.83	1.8
UUT stability	A	21	µV/V	2.33	9.01	1	9.01	3.6
Combined standard uncertainty							24.62	µV/V
Effective degrees of freedom							77.6	
Coverage factor							2.01	
Expanded uncertainty							49.48	µV/V
Expanded uncertainty							4.9	µV

Uncertainty budget for 100 mV and 1 MHz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Divider DC ratio uncertainty and drift	B	10	µΩ/Ω	2	5.00	1	5.00	50
Divider ac-dc difference	B	200	µΩ/Ω	2	100.00	1	100.00	50

AC Voltmeter uncertainty	B	500	µV/V	2	250.00	1	250.00	50
AC Voltmeter drift or transfer accuracy	B	50	µV/V	1.732	28.87	1	28.87	50
AC Voltmeter resolution	B	0.5	µV/V	1.732	0.29	1	0.29	50
AC Voltmeter repeatability	A	23	µV/V	1	23.00	1	23.00	9
AC voltage buffer	B	220	µV/V	1.732	127.02	1	127.02	50
UUT resolution	B	0.5	µV/V	1.732	0.29	1	0.29	50
UUT repeatability	A	175	µV/V	2.06	84.95	1	84.95	1.8
UUT stability	A	800	µV/V	2.33	343.35	1	343.35	3.6
						Combined standard uncertainty	463.82	µV/V
						Effective degrees of freedom	11.7	
						Coverage factor	2.2	
						Expanded uncertainty	1020.40	µV/V
						Expanded uncertainty	102.0	µV

Uncertainty budget for 19 V and 1.005 kHz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Divider DC ratio uncertainty and drift	B	10	μΩ/Ω	2	5.00	1	5.00	50
Divider ac-dc difference	B	10	μΩ/Ω	2	5.00	1	5.00	50
AC Voltmeter uncertainty	B	15	μV/V	2	7.50	1	7.50	50
AC Voltmeter drift or transfer accuracy	B	20	μV/V	1.732	11.55	1	11.55	50
AC Voltmeter resolution	B	0.5	μV/V	1.732	0.29	1	0.29	50
AC Voltmeter repeatability	A	1	μV/V	1	1.00	1	1.00	9
UUT resolution	B	0.5	μV/V	1.732	0.29	1	0.29	50
UUT repeatability	A	4	μV/V	2.06	1.94	1	1.94	1.8
UUT stability	A	7	μV/V	2.33	3.00	1	3.00	3.6
						Combined standard uncertainty	15.92	μV/V
						Effective degrees of freedom	135.5	
						Coverage factor	1.984	
						Expanded uncertainty	31.59	μV/V
						Expanded uncertainty	600.2	μV

For alternating voltage 1 V and 10 V the following components contribute to the uncertainty of measurement:

- TVC Reference ac-dc difference: From the last calibration report and history of the thermal convertor
- Ac-dc transfer repeatability: From the observed data
- UUT DCV accuracy: The UUT direct voltage readings are used with the ac-dc differences to calculate the applied alternating voltage, and from this the UUT correction is calculated. The DCV corrections and uncertainties are obtained from a recent measurement.
- UUT DCV repeatability: From the observed data
- UUT ACV repeatability: From the observed data
- UUT resolution: From the UUT specifications
- UUT stability: From measurement repeated 5 times during the period that UUT spent in our laboratory

Uncertainty budget for 1 V and 10 Hz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
TVC Reference ac-dc difference	B	10	µV/V	2	5.00	1	5.00	50
ac-dc difference repeatability	A	6.9	µV/V	1	6.90	1	6.90	5
UUT DCV accuracy	B	2	µV/V	2	1.00	1	1.00	50
UUT DCV repeatability	A	1	µV/V	1.69	0.59	1	0.59	1.8
UUT ACV repeatability	A	12	µV/V	2.53	4.74	1	4.74	4.5
UUT resolution	B	0.5	µV/V	1.732	0.29	1	0.29	50
UUT stability	B	18	µV/V	2.33	7.73	1	7.73	3.6
						Combined standard uncertainty	12.50	µV/V
						Effective degrees of freedom	15.6	
						Coverage factor	2.13	
						Expanded uncertainty	26.62	µV/V
						Expanded uncertainty	26.6	µV

Uncertainty budget for 1 V and 55 Hz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
TVC Reference ac-dc difference	B	5	µV/V	2	2.50	1	2.50	50
ac-dc difference repeatability	A	4.2	µV/V	1	4.20	1	4.20	5
UUT DC voltage	B	2	µV/V	2	1.00	1	1.00	50
UUT DCV repeatability	A	1	µV/V	1.69	0.59	1	0.59	1.8
UUT ACV repeatability	A	10	µV/V	2.53	3.95	1	3.95	4.5
UUT resolution	B	0.5	µV/V	1.732	0.29	1	0.29	50
UUT stability	B	14	µV/V	2.33	6.01	1	6.01	3.6
						Combined standard uncertainty	8.78	µV/V
						Effective degrees of freedom	12.4	

Coverage factor	2.18	
Expanded uncertainty	19.14	μV/V
Expanded uncertainty	19.1	μV

Uncertainty budget for 1 V and 1.005 kHz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
TVC Reference ac-dc difference	B	5	μV/V	2	2.50	1	2.50	50
ac-dc difference repeatability	A	3.6	μV/V	1	3.60	1	3.60	5
UUT DC voltage	B	2	μV/V	2	1.00	1	1.00	50
UUT DCV repeatability	A	1	μV/V	1.69	0.59	1	0.59	1.8
UUT ACV repeatability	A	7	μV/V	2.53	2.77	1	2.77	4.5
UUT resolution	B	0.5	μV/V	1.732	0.29	1	0.29	50
UUT stability	B	9	μV/V	2.33	3.86	1	3.86	3.6
Combined standard uncertainty							6.57	μV/V
Effective degrees of freedom							17.1	
Coverage factor							2.11	
Expanded uncertainty							13.87	μV/V
Expanded uncertainty							13.9	μV

Uncertainty budget for 1 V and 20 kHz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
TVC Reference ac-dc difference	B	10	μV/V	2	5.00	1	5.00	50
ac-dc difference repeatability	A	4.3	μV/V	1	4.30	1	4.30	5
UUT DC voltage	B	2	μV/V	2	1.00	1	1.00	50
UUT DCV repeatability	A	1	μV/V	1.69	0.59	1	0.59	1.8
UUT ACV repeatability	A	9	μV/V	2.53	3.56	1	3.56	4.5
UUT resolution	B	0.5	μV/V	1.732	0.29	1	0.29	50

UUT stability	B	15	µV/V	2.33	6.44	1	6.44	3.6
						Combined standard uncertainty	9.95	µV/V
						Effective degrees of freedom	16.5	
						Coverage factor	2.12	
						Expanded uncertainty	21.10	µV/V
						Expanded uncertainty	21.1	µV

Uncertainty budget for 1 V and 50 kHz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
TVC Reference ac-dc difference	B	25	µV/V	2	12.50	1	12.50	50
ac-dc difference repeatability	A	12.1	µV/V	1	12.10	1	12.10	5
UUT DC voltage	B	2	µV/V	2	1.00	1	1.00	50
UUT DCV repeatability	A	1	µV/V	1.69	0.59	1	0.59	1.8
UUT ACV repeatability	A	8	µV/V	2.53	3.16	1	3.16	4.5
UUT resolution	B	0.5	µV/V	1.732	0.29	1	0.29	50
UUT stability	B	21	µV/V	2.33	9.01	1	9.01	3.6
						Combined standard uncertainty	19.88	µV/V
						Effective degrees of freedom	23.6	
						Coverage factor	2.09	
						Expanded uncertainty	41.55	µV/V
						Expanded uncertainty	41.6	µV

Uncertainty budget for 1 V and 1 MHz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
TVC Reference ac-dc difference	B	365	µV/V	2	182.50	1	182.50	50
ac-dc difference repeatability	A	72	µV/V	1	72.00	1	72.00	5
UUT DC voltage	B	2	µV/V	2	1.00	1	1.00	50

UUT DCV repeatability	A	1	µV/V	1.69	0.59	1	0.59	1.8
UUT ACV repeatability	A	52	µV/V	2.53	20.55	1	20.55	4.5
UUT resolution	B	0.5	µV/V	1.732	0.29	1	0.29	50
UUT stability	B	150	µV/V	2.33	64.38	1	64.38	3.6
						Combined standard uncertainty	207.51	µV/V
						Effective degrees of freedom	57.3	
						Coverage factor	2.01	
						Expanded uncertainty	417.09	µV/V
						Expanded uncertainty	417.1	µV

Uncertainty budget for 10 V and 10 Hz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
TVC Reference ac-dc difference	B	10	µV/V	2	5.00	1	5.00	50
ac-dc difference repeatability	A	7.7	µV/V	1	7.70	1	7.70	5
UUT DC voltage	B	2	µV/V	2	1.00	1	1.00	50
UUT DCV repeatability	A	1	µV/V	1.69	0.59	1	0.59	1.8
UUT ACV repeatability	A	12	µV/V	2.53	4.74	1	4.74	4.5
UUT resolution	B	0.5	µV/V	1.732	0.29	1	0.29	50
UUT stability	B	15	µV/V	2.33	6.44	1	6.44	3.6
						Combined standard uncertainty	12.23	µV/V
						Effective degrees of freedom	17.2	
						Coverage factor	2.11	
						Expanded uncertainty	25.81	µV/V
						Expanded uncertainty	258	µV

Uncertainty budget for 10 V and 55 Hz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom

TVC Reference ac-dc difference	B	5	µV/V	2	2.50	1	2.50	50
ac-dc difference repeatability	A	4.1	µV/V	1	4.10	1	4.10	5
UUT DC voltage	B	2	µV/V	2	1.00	1	1.00	50
UUT DCV repeatability	A	1	µV/V	1.69	0.59	1	0.59	1.8
UUT ACV repeatability	A	9	µV/V	2.53	3.56	1	3.56	4.5
UUT resolution	B	0.5	µV/V	1.732	0.29	1	0.29	50
UUT stability	B	12	µV/V	2.33	5.15	1	5.15	3.6
Combined standard uncertainty							7.98	µV/V
Effective degrees of freedom							14.1	
Coverage factor							2.14	
Expanded uncertainty							17.08	µV/V
Expanded uncertainty							171	µV

Uncertainty budget for 10 V and 1.005 kHz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
TVC Reference ac-dc difference	B	5	µV/V	2	2.50	1	2.50	50
ac-dc difference repeatability	A	3.4	µV/V	1	3.40	1	3.40	5
UUT DC voltage	B	2	µV/V	2	1.00	1	1.00	50
UUT DCV repeatability	A	1	µV/V	1.69	0.59	1	0.59	1.8
UUT ACV repeatability	A	6	µV/V	2.53	2.37	1	2.37	4.5
UUT resolution	B	0.5	µV/V	1.732	0.29	1	0.29	50
UUT stability	B	5	µV/V	2.33	2.15	1	2.15	3.6
Combined standard uncertainty							5.43	µV/V
Effective degrees of freedom							21.4	
Coverage factor							2.09	
Expanded uncertainty							11.35	µV/V
Expanded uncertainty							113	µV

Uncertainty budget for 10 V and 20 kHz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
TVC Reference ac-dc difference	B	10	µV/V	2	5.00	1	5.00	50
ac-dc difference repeatability	A	3.9	µV/V	1	3.90	1	3.90	5
UUT DC voltage	B	2	µV/V	2	1.00	1	1.00	50
UUT DCV repeatability	A	1	µV/V	1.69	0.59	1	0.59	1.8
UUT ACV repeatability	A	6	µV/V	2.53	2.37	1	2.37	4.5
UUT resolution	B	0.5	µV/V	1.732	0.29	1	0.29	50
UUT stability	B	8	µV/V	2.33	3.43	1	3.43	3.6
Combined standard uncertainty							7.68	µV/V
Effective degrees of freedom							33.4	
Coverage factor							2.04	
Expanded uncertainty							15.68	µV/V
Expanded uncertainty							157	µV

Uncertainty budget for 10 V and 50 kHz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
TVC Reference ac-dc difference	B	15	µV/V	2	7.50	1	7.50	50
ac-dc difference repeatability	A	9.3	µV/V	1	9.30	1	9.30	5
UUT DC voltage	B	2	µV/V	2	1.00	1	1.00	50
UUT DCV repeatability	A	1	µV/V	1.69	0.59	1	0.59	1.8
UUT ACV repeatability	A	8	µV/V	2.53	3.16	1	3.16	4.5
UUT resolution	B	0.5	µV/V	1.732	0.29	1	0.29	50
UUT stability	B	19	µV/V	2.33	8.15	1	8.15	3.6
Combined standard uncertainty							14.85	µV/V
Effective degrees of freedom							17.3	
Coverage factor							2.11	

Expanded uncertainty	31.34	µV/V
Expanded uncertainty	313	µV

Uncertainty budget for 10 V and 1 MHz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
TVC Reference ac-dc difference	B	100	µV/V	2	50.00	1	50.00	50
ac-dc difference repeatability	A	58	µV/V	1	58.00	1	58.00	5
UUT DC voltage	B	2	µV/V	2	1.00	1	1.00	50
UUT DCV repeatability	A	1	µV/V	1.69	0.59	1	0.59	1.8
UUT ACV repeatability	A	45	µV/V	2.53	17.79	1	17.79	4.5
UUT resolution	B	0.5	µV/V	1.732	0.29	1	0.29	50
UUT stability	B	200	µV/V	2.33	85.84	1	85.84	3.6
Combined standard uncertainty							116.40	µV/V
Effective degrees of freedom							10.5	
Coverage factor							2.23	
Expanded uncertainty							259.58	µV/V
Expanded uncertainty							2596	µV

For alternating voltage from 100 V to 700 V the following components contribute to the uncertainty of measurement:

- Reference ac-dc difference: From the last calibration report and history of the thermal transfer standard
- Reference drift: From history of the thermal transfer standard
- Cables and connectors: Estimate the effect of cables and connectors
- Ac-dc transfer repeatability: From the observed data
- UUT DCV accuracy: The UUT direct voltage readings are used with the ac-dc differences to calculate the applied alternating voltage, and from this the UUT correction is calculated. The DCV corrections and uncertainties are obtained from a recent measurement, or calibration report.
- UUT DCV repeatability: From the observed data

- UUT t ACV repeatability: From the observed data
- UUT resolution: From the UUT specifications
- UUT stability: From measurement repeated 5 times during the period that UUT spent in our laboratory

Uncertainty budget for 100 V and 10 Hz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Reference ac-dc difference	B	190	µV/V	2	95.00	1	95.00	50
Cables and connectors	B	5	µV/V	1.732	2.89	1	2.89	50
ac-dc difference repeatability	A	35	µV/V	1	35.00	1	35.00	5
UUT DC voltage	B	2	µV/V	2	1.00	1	1.00	50
UUT DCV repeatability	A	1	µV/V	1.69	0.59	1	0.59	1.8
UUT ACV repeatability	A	47	µV/V	2.53	18.58	1	18.58	4.5
UUT resolution	B	0.5	µV/V	1.732	0.29	1	0.29	50
UUT stability	B	39	µV/V	2.33	16.74	1	16.74	3.6
						Combined standard uncertainty	104.33	µV/V
						Effective degrees of freedom	59.9	
						Coverage factor	2.01	
						Expanded uncertainty	209.71	µV/V
						Expanded uncertainty	21.0	mV

Uncertainty budget for 100 V and 55 Hz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Reference ac-dc difference	B	30	µV/V	2	15.00	1	15.00	50
Cables and connectors	B	5	µV/V	1.732	2.89	1	2.89	50
ac-dc difference repeatability	A	2	µV/V	1	2.00	1	2.00	5
UUT DC voltage	B	2	µV/V	2	1.00	1	1.00	50

UUT DCV repeatability	A	1	µV/V	1.69	0.59	1	0.59	1.8
UUT ACV repeatability	A	6	µV/V	2.53	2.37	1	2.37	4.5
UUT resolution	B	0.5	µV/V	1.732	0.29	1	0.29	50
UUT stability	B	5	µV/V	2.33	2.15	1	2.15	3.6
						Combined standard uncertainty	15.78	µV/V
						Effective degrees of freedom	60.2	
						Coverage factor	2.01	
						Expanded uncertainty	31.72	µV/V
						Expanded uncertainty	3.2	mV

Uncertainty budget for 100 V and 1.005 kHz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Reference ac-dc difference	B	30	µV/V	2	15.00	1	15.00	50
Cables and connectors	B	5	µV/V	1.732	2.89	1	2.89	50
ac-dc difference repeatability	A	1	µV/V	1	1.00	1	1.00	5
UUT DC voltage	B	2	µV/V	2	1.00	1	1.00	50
UUT DCV repeatability	A	1	µV/V	1.69	0.59	1	0.59	1.8
UUT ACV repeatability	A	3	µV/V	2.53	1.19	1	1.19	4.5
UUT resolution	B	0.5	µV/V	1.732	0.29	1	0.29	50
UUT stability	B	5	µV/V	2.33	2.15	1	2.15	3.6
						Combined standard uncertainty	15.55	µV/V
						Effective degrees of freedom	57.3	
						Coverage factor	2.01	
						Expanded uncertainty	31.25	µV/V
						Expanded uncertainty	3.1	mV

Uncertainty budget for 100 V and 20 kHz measurement:

Component	Type	Value	Unit	Divisor	Standard	Sensitivity	Uncertainty	Degrees of

					uncertainty	coefficient	contribution	Freedom
Reference ac-dc difference	B	30	µV/V	2	15.00	1	15.00	50
Cables and connectors	B	5	µV/V	1.732	2.89	1	2.89	50
ac-dc difference repeatability	A	2	µV/V	1	2.00	1	2.00	5
UUT DC voltage	B	2	µV/V	2	1.00	1	1.00	50
UUT DCV repeatability	A	1	µV/V	1.69	0.59	1	0.59	1.8
UUT ACV repeatability	A	5	µV/V	2.53	1.98	1	1.98	4.5
UUT resolution	B	0.5	µV/V	1.732	0.29	1	0.29	50
UUT stability	B	8	µV/V	2.33	3.43	1	3.43	3.6
						Combined standard uncertainty	15.95	µV/V
						Effective degrees of freedom	61.1	
						Coverage factor	2.01	
						Expanded uncertainty	32.06	µV/V
						Expanded uncertainty	3.2	mV

Uncertainty budget for 100 V and 50 kHz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Reference ac-dc difference	B	65	µV/V	2	32.50	1	32.50	50
Cables and connectors	B	5	µV/V	1.732	2.89	1	2.89	50
ac-dc difference repeatability	A	2	µV/V	1	2.00	1	2.00	5
UUT DC voltage	B	2	µV/V	2	1.00	1	1.00	50
UUT DCV repeatability	A	1	µV/V	1.69	0.59	1	0.59	1.8
UUT ACV repeatability	A	6	µV/V	2.53	2.37	1	2.37	4.5
UUT resolution	B	0.5	µV/V	1.732	0.29	1	0.29	50
UUT stability	B	10	µV/V	2.33	4.29	1	4.29	3.6
						Combined standard uncertainty	33.08	µV/V
						Effective degrees of freedom	53.4	

Coverage factor	2.01	
Expanded uncertainty	66.48	µV/V
Expanded uncertainty	6.6	mV

Uncertainty budget for 700 V and 55 Hz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Reference ac-dc difference	B	35	µV/V	2	17.50	1	17.50	50
Cables and connectors	B	5	µV/V	1.732	2.89	1	2.89	50
ac-dc difference repeatability	A	2	µV/V	1	2.00	1	2.00	5
UUT DC voltage	B	2.9	µV/V	2	1.45	1	1.45	50
UUT DCV repeatability	A	2.9	µV/V	1.69	1.72	1	1.72	1.8
UUT ACV repeatability	A	12.9	µV/V	2.53	5.10	1	5.10	4.5
UUT resolution	B	0.5	µV/V	1.732	0.29	1	0.29	50
UUT stability	B	14.3	µV/V	2.33	6.14	1	6.14	3.6
Combined standard uncertainty							19.68	µV/V
Effective degrees of freedom							61.8	
Coverage factor							2.01	
Expanded uncertainty							39.56	µV/V
Expanded uncertainty							27.7	mV

Uncertainty budget for 700 V and 1.005 kHz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Reference ac-dc difference	B	35	µV/V	2	17.50	1	17.50	50
Cables and connectors	B	5	µV/V	1.732	2.89	1	2.89	50
ac-dc difference repeatability	A	2	µV/V	1	2.00	1	2.00	5
UUT DC voltage	B	2.9	µV/V	2	1.45	1	1.45	50
UUT DCV repeatability	A	2.9	µV/V	1.69	1.72	1	1.72	1.8

UUT ACV repeatability	A	7.1	μV/V	2.53	2.81	1	2.81	4.5
UUT resolution	B	0.5	μV/V	1.732	0.29	1	0.29	50
UUT stability	B	8.6	μV/V	2.33	3.69	1	3.69	3.6
						Combined standard uncertainty	18.58	μV/V
						Effective degrees of freedom	61.1	
						Coverage factor	2.01	
						Expanded uncertainty	37.35	μV/V
						Expanded uncertainty	26.1	mV

Uncertainty budget for 700 V and 20 kHz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Reference ac-dc difference	B	35	μV/V	2	17.50	1	17.50	50
Cables and connectors	B	5	μV/V	1.732	2.89	1	2.89	50
ac-dc difference repeatability	A	2	μV/V	1	2.00	1	2.00	5
UUT DC voltage	B	2.9	μV/V	2	1.45	1	1.45	50
UUT DCV repeatability	A	2.9	μV/V	1.69	1.72	1	1.72	1.8
UUT ACV repeatability	A	15.7	μV/V	2.53	6.21	1	6.21	4.5
UUT resolution	B	0.5	μV/V	1.732	0.29	1	0.29	50
UUT stability	B	17.1	μV/V	2.33	7.34	1	7.34	3.6
						Combined standard uncertainty	20.40	μV/V
						Effective degrees of freedom	57.3	
						Coverage factor	2.01	
						Expanded uncertainty	41.00	μV/V
						Expanded uncertainty	28.7	mV

Uncertainty budget for 700 V and 50 kHz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom

Reference ac-dc difference	B	63	µV/V	2	31.50	1	31.50	50
Cables and connectors	B	5	µV/V	1.732	2.89	1	2.89	50
ac-dc difference repeatability	A	2	µV/V	1	2.00	1	2.00	5
UUT DC voltage	B	2.9	µV/V	2	1.45	1	1.45	50
UUT DCV repeatability	A	2.9	µV/V	1.69	1.72	1	1.72	1.8
UUT ACV repeatability	A	15.7	µV/V	2.53	6.21	1	6.21	4.5
UUT resolution	B	0.5	µV/V	1.732	0.29	1	0.29	50
UUT stability	B	18.6	µV/V	2.33	7.98	1	7.98	3.6
						Combined standard uncertainty	33.35	µV/V
						Effective degrees of freedom	58.4	
						Coverage factor	2.01	
						Expanded uncertainty	67.03	µV/V
						Expanded uncertainty	46.9	mV

3.4 Alternating Current

For alternating current the following components contribute to the uncertainty of measurement:

- ACV reference uncertainty: Obtained from the latest calibration report
- ACV reference loading: The effective resistance of the current shunt is reduced due to the input impedance of the alternating voltage measurement standard
- ACV reference drift: From the history data
- ACV reference resolution: From the specification
- ACV reference repeatability: From the observed data
- Current shunt resistance: From the latest calibration report – this component includes drift of the shunt
- Current shunt ac-dc difference: From the latest calibration report
- Cables and connectors: Estimate the effect of cables and connectors
- UUT resolution: From the specifications of the UUT
- UUT t repeatability: From the observed data
- UUT stability: From measurement repeated 4 times during the period that UUT spent in our laboratory

Uncertainty budget for 1 mA and 55 Hz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
ACV reference uncertainty	B	35	µV/V	2	17.50	1	17.50	50
ACV reference loading	B	2	µV/V	1.732	1.15	1	1.15	50
ACV reference drift	B	20	µV/V	1.732	11.55	1	11.55	50
ACV reference resolution	B	0.5	µV/V	1.732	0.29	1	0.29	50
ACV reference repeatability	A	8.5	µV/V	1	8.50	1	8.50	9
Current shunt resistance	B	5	µΩ/Ω	2	2.50	1	2.50	50
Current shunt ac-dc difference	B	10	µΩ/Ω	2	5.00	1	5.00	50
Cables and connectors	B	5	µA/A	1.732	2.89	1	2.89	50
UUT resolution	B	0.5	µA/A	1.732	0.29	1	0.29	50
UUT repeatability	A	7	µA/A	1.69	4.14	1	4.14	1.8
UUT stability	A	14	µA/A	2.06	6.796116505	1	6.80	2.7
						Combined standard uncertainty	24.82	µA/A
						Effective degrees of freedom	100.5	
						Coverage factor	1.984	
						Expanded uncertainty	49.25	µA/A
						Expanded uncertainty	49.3	nA

Uncertainty budget for 1 mA and 1.005 kHz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
ACV reference uncertainty	B	35	µV/V	2	17.50	1	17.50	50
ACV reference loading	B	2	µV/V	1.732	1.15	1	1.15	50
ACV reference drift	B	20	µV/V	1.732	11.55	1	11.55	50
ACV reference resolution	B	0.5	µV/V	1.732	0.29	1	0.29	50
ACV reference repeatability	A	5.7	µV/V	1	5.70	1	5.70	9

Current shunt resistance	B	5	μΩ/Ω	2	2.50	1	2.50	50
Current shunt ac-dc difference	B	10	μΩ/Ω	2	5.00	1	5.00	50
Cables and connectors	B	5	μA/A	1.732	2.89	1	2.89	50
UUT resolution	B	0.5	μA/A	1.732	0.29	1	0.29	50
UUT repeatability	A	3	μA/A	1.69	1.78	1	1.78	1.8
UUT stability	A	14	μA/A	2.06	6.80	1	6.80	2.7
						Combined standard uncertainty	23.72	μA/A
						Effective degrees of freedom	100.2	
						Coverage factor	1.984	
						Expanded uncertainty	47.05	μA/A
						Expanded uncertainty	47.1	nA

Uncertainty budget for 1 mA and 5 kHz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
ACV reference uncertainty	B	35	μV/V	2	17.50	1	17.50	50
ACV reference loading	B	2	μV/V	1.732	1.15	1	1.15	50
ACV reference drift	B	20	μV/V	1.732	11.55	1	11.55	50
ACV reference resolution	B	0.5	μV/V	1.732	0.29	1	0.29	50
ACV reference repeatability	A	1.8	μV/V	1	1.80	1	1.80	9
Current shunt resistance	B	5	μΩ/Ω	2	2.50	1	2.50	50
Current shunt ac-dc difference	B	10	μΩ/Ω	2	5.00	1	5.00	50
Cables and connectors	B	5	μA/A	1.732	2.89	1	2.89	50
UUT resolution	B	0.5	μA/A	1.732	0.29	1	0.29	50
UUT repeatability	A	9	μA/A	1.69	5.33	1	5.33	1.8
UUT stability	A	22	μA/A	2.06	10.68	1	10.68	2.7
						Combined standard uncertainty	25.03	μA/A
						Effective degrees of freedom	52.2	

Coverage factor	2.01	
Expanded uncertainty	50.30	µA/A
Expanded uncertainty	50.3	nA

Uncertainty budget for 1 A and 55 Hz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
ACV reference uncertainty	B	20	µV/V	2	10.00	1	10.00	50
ACV reference drift	B	20	µV/V	1.732	11.55	1	11.55	50
ACV reference resolution	B	0.5	µV/V	1.732	0.29	1	0.29	50
ACV reference repeatability	A	6.1	µV/V	1	6.10	1	6.10	9
Current shunt resistance	B	5	µΩ/Ω	2	2.50	1	2.50	50
Current shunt ac-dc difference	B	10	µΩ/Ω	2	5.00	1	5.00	50
Cables and connectors	B	5	µA/A	1.732	2.89	1	2.89	50
UUT resolution	B	0.5	µA/A	1.732	0.29	1	0.29	50
UUT repeatability	A	7	µA/A	1.69	4.14	1	4.14	1.8
UUT stability	A	13	µA/A	2.06	6.31	1	6.31	2.7
Combined standard uncertainty							19.16	µA/A
Effective degrees of freedom							91.5	
Coverage factor							2.01	
Expanded uncertainty							38.52	µA/A
Expanded uncertainty							38.5	µA

Uncertainty budget for 1 A and 1.005 kHz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
ACV reference uncertainty	B	15	µV/V	2	7.50	1	7.50	50
ACV reference drift	B	20	µV/V	1.732	11.55	1	11.55	50
ACV reference resolution	B	0.5	µV/V	1.732	0.29	1	0.29	50

ACV reference repeatability	A	2.7	µV/V	1	2.70	1	2.70	9
Current shunt resistance	B	5	µΩ/Ω	2	2.50	1	2.50	50
Current shunt ac-dc difference	B	10	µΩ/Ω	2	5.00	1	5.00	50
Cables and connectors	B	5	µA/A	1.732	2.89	1	2.89	50
UUT resolution	B	0.5	µA/A	1.732	0.29	1	0.29	50
UUT repeatability	A	4	µA/A	1.69	2.37	1	2.37	1.8
UUT stability	A	11	µA/A	2.06	5.34	1	5.34	2.7
						Combined standard uncertainty	16.45	µA/A
						Effective degrees of freedom	96.7	
						Coverage factor	2.01	
						Expanded uncertainty	33.07	µA/A
						Expanded uncertainty	33.1	µA

Uncertainty budget for 1 A and 5 kHz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
ACV reference uncertainty	B	15	µV/V	2	7.50	1	7.50	50
ACV reference drift	B	20	µV/V	1.732	11.55	1	11.55	50
ACV reference resolution	B	0.5	µV/V	1.732	0.29	1	0.29	50
ACV reference repeatability	A	3.6	µV/V	1	3.60	1	3.60	9
Current shunt resistance	B	5	µΩ/Ω	2	2.50	1	2.50	50
Current shunt ac-dc difference	B	10	µΩ/Ω	2	5.00	1	5.00	50
Cables and connectors	B	5	µA/A	1.732	2.89	1	2.89	50
UUT resolution	B	0.5	µA/A	1.732	0.29	1	0.29	50
UUT repeatability	A	9	µA/A	1.69	5.33	1	5.33	1.8
UUT stability	A	23	µA/A	2.06	11.17	1	11.17	2.7
						Combined standard uncertainty	19.88	µA/A
						Effective degrees of freedom	23.5	

Coverage factor	2.09	
Expanded uncertainty	41.55	μA/A
Expanded uncertainty	41.6	μA

3.5 Resistance

For resistance the following components contribute to the uncertainty of measurement:

- Reference resistor: The certified correction of the reference resistor from its latest calibration report
- Reference resistor drift: From the history data
- Reference resistor temp. coefficient: From the specification of the reference resistor
- UUT resolution: From the specifications of the UUT
- UUT repeatability: From the observed data
- UUT stability: From measurement repeated 4 times during the period that UUT spent in our laboratory

Uncertainty budget for 10 Ω 4-wire measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Reference resistor	B	0.5	μΩ/Ω	2	0.25	1	0.25	50
Reference resistor drift	B	0.2	μΩ/Ω	1.732	0.12	1	0.12	50
Reference resistor temp. coefficient	B	0.3	μΩ/Ω	1.732	0.17	1	0.17	50
UUT resolution	B	0.05	μΩ/Ω	1.732	0.03	1	0.03	50
UUT repeatability	A	0.5	μΩ/Ω	1.69	0.30	1	0.30	1.8
UUT stability	A	0.9	μΩ/Ω	2.06	0.44	1	0.44	2.7
						Combined standard uncertainty	0.62	μΩ/Ω
						Effective degrees of freedom	8.3	
						Coverage factor	2.31	
						Expanded uncertainty	1.43	μΩ/Ω
						Expanded uncertainty	14.3	μΩ

Uncertainty budget for 100 Ω 4-wire measurement:

Component	Type	Value	Unit	Divisor	Standard	Sensitivity	Uncertainty	Degrees of

					uncertainty	coefficient	contribution	Freedom
Reference resistor	B	0.5	μΩ/Ω	2	0.25	1	0.25	50
Reference resistor drift	B	0.6	μΩ/Ω	1.732	0.35	1	0.35	50
Reference resistor temp. coefficient	B	0.1	μΩ/Ω	1.732	0.06	1	0.06	50
UUT resolution	B	0.05	μΩ/Ω	1.732	0.03	1	0.03	50
UUT repeatability	A	0.3	μΩ/Ω	1.69	0.18	1	0.18	1.8
UUT stability	A	0.6	μΩ/Ω	2.06	0.29	1	0.29	2.7
Combined standard uncertainty							0.55	μΩ/Ω
Effective degrees of freedom							25.6	
Coverage factor							2.06	
Expanded uncertainty							1.13	μΩ/Ω
Expanded uncertainty							113.4	μΩ

Uncertainty budget for 1 kΩ 4-wire measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Reference resistor	B	1	μΩ/Ω	2	0.50	1	0.50	50
Reference resistor drift	B	0.5	μΩ/Ω	1.732	0.29	1	0.29	50
Reference resistor temp. coefficient	B	0.1	μΩ/Ω	1.732	0.06	1	0.06	50
UUT resolution	B	0.05	μΩ/Ω	1.732	0.03	1	0.03	50
UUT repeatability	A	0.2	μΩ/Ω	1.69	0.12	1	0.12	1.8
UUT stability	A	0.5	μΩ/Ω	2.06	0.24	1	0.24	2.7
Combined standard uncertainty							0.64	μΩ/Ω
Effective degrees of freedom							60.5	
Coverage factor							2.01	
Expanded uncertainty							1.29	μΩ/Ω
Expanded uncertainty							1.3	m Ω

Uncertainty budget for 10 kΩ 4-wire measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Reference resistor	B	1.5	μΩ/Ω	2	0.75	1	0.75	50
Reference resistor drift	B	0.5	μΩ/Ω	1.732	0.29	1	0.29	50
Reference resistor temp. coefficient	B	0.1	μΩ/Ω	1.732	0.06	1	0.06	50
UUT resolution	B	0.05	μΩ/Ω	1.732	0.03	1	0.03	50
UUT repeatability	A	0.3	μΩ/Ω	1.69	0.18	1	0.18	1.8
UUT stability	A	0.4	μΩ/Ω	2.06	0.19	1	0.19	2.7
						Combined standard uncertainty	0.85	μΩ/Ω
						Effective degrees of freedom	68.6	
						Coverage factor	2.01	
						Expanded uncertainty	1.70	μΩ/Ω
						Expanded uncertainty	17.0	m Ω

Uncertainty budget for 100 kΩ 2-wire measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Reference resistor	B	1.5	μΩ/Ω	2	0.75	1	0.75	50
Reference resistor drift	B	0.3	μΩ/Ω	1.732	0.17	1	0.17	50
Reference resistor temp. coefficient	B	0.1	μΩ/Ω	1.732	0.06	1	0.06	50
UUT resolution	B	0.05	μΩ/Ω	1.732	0.03	1	0.03	50
UUT repeatability	A	0.4	μΩ/Ω	1.69	0.24	1	0.24	1.8
UUT stability	A	0.6	μΩ/Ω	2.06	0.29	1	0.29	2.7
						Combined standard uncertainty	0.86	μΩ/Ω
						Effective degrees of freedom	50.6	
						Coverage factor	2.01	

Expanded uncertainty	1.73	μΩ/Ω
Expanded uncertainty	172.6	m Ω

Uncertainty budget for 1 MΩ 2-wire measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Reference resistor	B	5	μΩ/Ω	2	2.50	1	2.50	50
Reference resistor drift	B	0.3	μΩ/Ω	1.732	0.17	1	0.17	50
Reference resistor temp. coefficient	B	0.1	μΩ/Ω	1.732	0.06	1	0.06	50
UUT resolution	B	0.05	μΩ/Ω	1.732	0.03	1	0.03	50
UUT repeatability	A	0.5	μΩ/Ω	1.69	0.30	1	0.30	1.8
UUT stability	A	1	μΩ/Ω	2.06	0.49	1	0.49	2.7
						Combined standard uncertainty	2.57	μΩ/Ω
						Effective degrees of freedom	54.2	
						Coverage factor	2.01	
						Expanded uncertainty	5.17	μΩ/Ω
						Expanded uncertainty	5.2	Ω

Uncertainty budget for 10 MΩ 2-wire measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Reference resistor	B	5	μΩ/Ω	2	2.50	1	2.50	50
Reference resistor drift	B	1	μΩ/Ω	1.732	0.58	1	0.58	50
Reference resistor temp. coefficient	B	0.5	μΩ/Ω	1.732	0.29	1	0.29	50
UUT resolution	B	0.05	μΩ/Ω	1.732	0.03	1	0.03	50
UUT repeatability	A	0.6	μΩ/Ω	1.69	0.36	1	0.36	1.8
UUT stability	A	1.8	μΩ/Ω	2.06	0.87	1	0.87	2.7

Combined standard uncertainty	2.75	μΩ/Ω
Effective degrees of freedom	56.6	
Coverage factor	2.01	
Expanded uncertainty	5.53	μΩ/Ω
Expanded uncertainty	55.3	Ω

Uncertainty budget for 100 MΩ 2-wire measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Reference resistor	B	10	μΩ/Ω	2	5.00	1	5.00	50
Reference resistor drift	B	5	μΩ/Ω	1.732	2.89	1	2.89	50
Reference resistor temp. coefficient	B	5	μΩ/Ω	1.732	2.89	1	2.89	50
UUT resolution	B	0.05	μΩ/Ω	1.732	0.03	1	0.03	50
UUT repeatability	A	1.4	μΩ/Ω	1.69	0.83	1	0.83	1.8
UUT stability	A	4.3	μΩ/Ω	2.06	2.09	1	2.09	2.7
Combined standard uncertainty							6.83	μΩ/Ω
Effective degrees of freedom							96.7	
Coverage factor							2.01	
Expanded uncertainty							13.74	μΩ/Ω
Expanded uncertainty							1373.8	Ω

3.6 Frequency

For Calibrator frequency the following components contribute to the uncertainty of measurement:

- Counter accuracy and drift: From the latest calibration report
- Counter resolution: Using 7.5 digits display
- UUT repeatability: From the observed data
- UUT stability: From repeated tests

Uncertainty budget for 10 Hz measurement (ACV):

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Counter accuracy and drift	B	5.00E-07	Hz/Hz	2	2.50E-07	1	2.50E-07	50
Counter resolution	B	5.00E-08	Hz/Hz	1.732	2.89E-08	1	2.89E-08	50
UUT repeatability	A	4.00E-07	Hz/Hz	1.69	2.37E-07	1	2.37E-07	1.8
UUT stability	A	2.00E-07	Hz/Hz	2.06	9.71E-08	1	9.71E-08	2.7
						Combined standard uncertainty	3.59E-07	Hz/Hz
						Effective degrees of freedom	8.94	
						Coverage factor	2.31	
						Expanded uncertainty	8.29E-07	Hz/Hz
						Expanded uncertainty	8.29	µHz

Uncertainty budget for 55 Hz measurement (ACV):

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Counter accuracy and drift	B	5.00E-07	Hz/Hz	2	2.50E-07	1	2.50E-07	50
Counter resolution	B	5.00E-08	Hz/Hz	1.732	2.89E-08	1	2.89E-08	50
UUT repeatability	A	5.40E-07	Hz/Hz	1.69	3.20E-07	1	3.20E-07	1.8
UUT stability	A	3.60E-07	Hz/Hz	2.06	1.75E-07	1	1.75E-07	2.7

Combined standard uncertainty	4.43E-07	Hz/Hz
Effective degrees of freedom	6.18	
Coverage factor	2.45	
Expanded uncertainty	1.08E-06	Hz/Hz
Expanded uncertainty	59.65	µHz

Uncertainty budget for 1.005 kHz measurement (ACV):

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Counter accuracy and drift	B	5.00E-07	Hz/Hz	2	2.50E-07	1	2.50E-07	50
Counter resolution	B	5.00E-08	Hz/Hz	1.732	2.89E-08	1	2.89E-08	50
UUT repeatability	A	1.00E-07	Hz/Hz	1.69	5.92E-08	1	5.92E-08	1.8
UUT stability	A	1.00E-07	Hz/Hz	2.06	4.85E-08	1	4.85E-08	2.7
						Combined standard uncertainty	2.63E-07	Hz/Hz
						Effective degrees of freedom	55.02	
						Coverage factor	2.01	
						Expanded uncertainty	5.29E-07	Hz/Hz
						Expanded uncertainty	528.71	µHz

Uncertainty budget for 20 kHz measurement (ACV):

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Counter accuracy and drift	B	5.00E-07	Hz/Hz	2	2.50E-07	1	2.50E-07	50
Counter resolution	B	5.00E-08	Hz/Hz	1.732	2.89E-08	1	2.89E-08	50
UUT repeatability	A	1.00E-07	Hz/Hz	1.69	5.92E-08	1	5.92E-08	1.8
UUT stability	A	2.00E-07	Hz/Hz	2.06	9.71E-08	1	9.71E-08	2.7
						Combined standard uncertainty	2.76E-07	Hz/Hz
						Effective degrees of freedom	49.35	
						Coverage factor	2.01	
						Expanded uncertainty	5.55E-07	Hz/Hz

Expanded uncertainty	11.10	mHz

Uncertainty budget for 50 kHz measurement (ACV):

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Counter accuracy and drift	B	5.00E-07	Hz/Hz	2	2.50E-07	1	2.50E-07	50
Counter resolution	B	5.00E-08	Hz/Hz	1.732	2.89E-08	1	2.89E-08	50
UUT repeatability	A	2.00E-07	Hz/Hz	1.69	1.18E-07	1	1.18E-07	1.8
UUT stability	A	2.00E-07	Hz/Hz	2.06	9.71E-08	1	9.71E-08	2.7
Combined standard uncertainty							2.95E-07	Hz/Hz
Effective degrees of freedom							34.22	
Coverage factor							2.04	
Expanded uncertainty							6.01E-07	Hz/Hz
Expanded uncertainty							30.04	mHz

Uncertainty budget for 1 MHz measurement (ACV):

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Counter accuracy and drift	B	5.00E-07	Hz/Hz	2	2.50E-07	1	2.50E-07	50
Counter resolution	B	5.00E-08	Hz/Hz	1.732	2.89E-08	1	2.89E-08	50
UUT repeatability	A	2.00E-07	Hz/Hz	1.69	1.18E-07	1	1.18E-07	1.8
UUT stability	A	2.00E-07	Hz/Hz	2.06	9.71E-08	1	9.71E-08	2.7
Combined standard uncertainty							2.95E-07	Hz/Hz
Effective degrees of freedom							34.22	
Coverage factor							2.04	
Expanded uncertainty							6.01E-07	Hz/Hz
Expanded uncertainty							0.60	Hz

Uncertainty budget for 55 Hz measurement (ACI):

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Counter accuracy and drift	B	5.00E-07	Hz/Hz	2	2.50E-07	1	2.50E-07	50
Counter resolution	B	5.00E-08	Hz/Hz	1.732	2.89E-08	1	2.89E-08	50
UUT repeatability	A	5.40E-07	Hz/Hz	1.69	3.20E-07	1	3.20E-07	1.8
UUT stability	A	3.60E-07	Hz/Hz	2.06	1.75E-07	1	1.75E-07	2.7
						Combined standard uncertainty	4.43E-07	Hz/Hz
						Effective degrees of freedom	6.18	
						Coverage factor	2.45	
						Expanded uncertainty	1.08E-06	Hz/Hz
						Expanded uncertainty	59.65	µHz

Uncertainty budget for 1.005 kHz measurement (ACI):

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Counter accuracy and drift	B	5.00E-07	Hz/Hz	2	2.50E-07	1	2.50E-07	50
Counter resolution	B	5.00E-08	Hz/Hz	1.732	2.89E-08	1	2.89E-08	50
UUT repeatability	A	1.00E-07	Hz/Hz	1.69	5.92E-08	1	5.92E-08	1.8
UUT stability	A	2.00E-07	Hz/Hz	2.06	9.71E-08	1	9.71E-08	2.7
						Combined standard uncertainty	2.76E-07	Hz/Hz
						Effective degrees of freedom	49.35	
						Coverage factor	2.01	
						Expanded uncertainty	5.55E-07	Hz/Hz
						Expanded uncertainty	555.07	µHz

Uncertainty budget for 5 kHz measurement (ACI):

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Counter accuracy and drift	B	5.00E-07	Hz/Hz	2	2.50E-07	1	2.50E-07	50

Counter resolution	B	5.00E-08	Hz/Hz	1.732	2.89E-08	1	2.89E-08	50
UUT repeatability	A	2.00E-07	Hz/Hz	1.69	1.18E-07	1	1.18E-07	1.8
UUT stability	A	2.00E-07	Hz/Hz	2.06	9.71E-08	1	9.71E-08	2.7
						Combined standard uncertainty	2.95E-07	Hz/Hz
						Effective degrees of freedom	34.22	
						Coverage factor	2.04	
						Expanded uncertainty	6.01E-07	Hz/Hz
						Expanded uncertainty	3.00	mHz

Report on

Measurements performed for
APMP.EM-S12
Comparison of Standards for the Calibration of Voltage, Current and Resistance Meters

Measurements performed on

Wavetek 4950 serial number 33528

From 17 March 2016 to 8 April 2016

Performed by

Standards and Calibration Laboratory (SCL)
LF Lab, 36/F, Immigration Tower,
7 Gloucester Road, Wan Chai,
Hong Kong

Report by

Dr. Steven YANG

Introduction

The APMP.EM-S12 comparison protocol requires that the travelling standard, a Wavetek model 4950 serial number 33528 (the Unit under Test – UUT), be measured at a number of points for each of its measurement functions. These are direct voltage, direct current, alternating voltage, alternating current and resistance. The measurement points are detailed in the comparison protocol.

The instrument was received on 11 March 2016. The fuse (F1) and mains voltage selection switch (S1) was checked before applying power. The UUT was allowed to stabilise for 24 hours with the power turned on before any measurements were made. The instrument's confidence test was performed and completed without any errors.

The measurements were performed from 17 March 2016 to 8 April 2016. The instrument was sent to the MSL, New Zealand on 8 April 2016.

Some of the alternating voltage measurements required by the protocol were excluded due to limited capability. They are marked in the following table.

Frequency	Alternating voltage – SCL excluded measurement points				
	10 mV	100 mV	1 V	10 V	100 V
10 Hz	x	x	x	x	x
1 MHz	x	x			

Direct Voltage

Test methods:

Direct voltage was measured using three methods:

1. For 100 mV, the correction of the UUT was determined by comparing the UUT reading to the voltage generated from a Guildline 9930 Direct Current Comparator Potentiometer used in conjunction with a Fluke 732B zener voltage reference standard.
2. For 1 V and 10 V, the correction of the UUT was determined by direct connection of the UUT to a calibrated Fluke 732A zener voltage reference standard, calibrated against a Josephson voltage standard.
3. For 19 V to 1000 V, test voltages were applied in parallel to the input of the Guildline 9700PL Voltage Ratio Box (VRB) and the UUT. The scaled down test voltages were measured by a Guildline 9930 DCC Potentiometer used in conjunction with a Fluke 732B zener voltage reference standard. The test voltage was calculated as the product of the measured scaled down voltage and the voltage ratio of the VRB. The correction of the UUT was determined by comparing the UUT reading to the calculated test voltage.

See figure 1.1 for the direct voltage measurement setups.

The 'Remote Guard' function was turned on for all the measurements, and the guard terminal and low voltage terminal were connected to a common ground point. The low current terminal was connected to the low voltage terminal and the high current terminal was connected to the high voltage terminal for all measurements.

Traceability:

All the test methods described for direct voltage was metrological traceable to the Standards and Calibration Laboratory's (SCL) Josephson Array voltage standard. See figure 2.1 for the direct voltage traceability chart.

Conditions of measurement:

During the direct voltage measurements, the following conditions of measurement prevailed:

Ambient temperature: 23 °C ± 1 °C
Relative humidity: 45 %RH ± 8 %RH

Measurement results:

Range (V)	Nominal Voltage (V)	Correction (V)	Uncertainty (V)	Internal Temperature (°C)
0.1	0.1	- 0.000 000 66	± 0.000 000 17	41.2
1	1	- 0.000 001 88	± 0.000 000 82	41.4
10	10	- 0.000 008 0	± 0.000 001 7	41.5
10	19	- 0.000 008	± 0.000 025	41.6
100	100	0.000 00	± 0.000 13	41.7
1000	1000	- 0.000 9	± 0.002 1	41.7

Detailed uncertainty budgets for the direct voltage measurements are shown in appendix 3.1.

Direct Current

Test methods:

Direct current was measured by the following method:

The correction of the UUT was determined by comparing its readings to the calculated value of the applied current. A calibrated current shunt was connected in series with the UUT. The voltage drop across the current shunt was measured with a calibrated voltmeter. The applied current was calculated from the resistance of the shunts and the measured voltage.

See figure 1.2 for the direct current measurement setup.

The 'Remote Guard' function was turned on for all the measurements, and the guard terminal and low current terminal were connected to a common ground point. The low voltage and high voltage terminals were connected to the same ground point.

Traceability:

The resistance of the current shunt was traceable to the 100 Ω standard resistor maintained by the SCL. The 100 Ω standard resistor was directly traceable to the

National Physical Laboratory (NPL, UK). See figure 2.2 for the resistance traceability chart.

The direct voltage was metrological traceable to the SCL's Josephson Array voltage standard. See figure 2.1 for the direct voltage traceability chart.

Conditions of measurement:

During the direct current measurements, the following conditions of measurement prevailed:

Ambient temperature: 23 °C ± 1 °C
Relative humidity: 45 %RH ± 8 %RH

Measurement results:

Range	Nominal Current	Correction	Uncertainty	Internal Temperature (°C)
1 mA	1 mA	+ 0.000 001 mA	± 0.000 002 mA	40.7
1 A	1 A	− 0.000 033 A	± 0.000 009 A	40.9

Detailed uncertainty budgets for the direct current measurements are shown in appendix 3.2.

Alternating Voltage

Test methods:

Alternating voltage was measured using two methods:
1. For 10 mV and 100 mV, the correction of the UUT was determined by comparing the UUT reading to the voltage generated by an NL-1A inductive voltage divider with the 1 V AC input voltage measured by a Fluke 5790A precision AC voltmeter.
2. For 1 V to 700 V, the correction of the UUT was determined by comparing the UUT reading to the voltage obtained from an ac-dc difference measurement with a Fluke 792A thermal transfer standard. The applied alternating voltage was calculated from the applied DC voltage and the ac-dc difference.

See figure 1.3 for the alternating voltage measurement setups.

The 'Remote Guard' function was turned on for all the measurements. The input connectors were attached to a 4 banana to type-N adapter, serial number 4BN-002. The guard connector was connected into the rear of the low voltage connector.

As specified by the protocol, the 1 MHz measurements at 1 V and 10 V was done with 4wCct (the default setting) selected.

Traceability:

For 10 mV and 100 mV, the AC voltage was traceable to the following quantities: the voltage ratios of the SCL's NL-1A inductive voltage divider which were calibrated by NPL (UK), the ac-dc difference of Fluke 792A were calibrated by SCL's thermal voltage converters which were calibrated by NPL (UK), and the DC voltage quantity was traceable to SCL's JAVS system.
For 1 V to 700 V, the AC voltage was traceable to the following quantities: the ac-dc difference of Fluke 792A were calibrated by SCL's thermal voltage converters which were calibrated by NPL (UK), the DC voltage quantity were traceable to SCL's JAVS system.

See figure 2.3 for the ac-dc difference traceability chart.

Conditions of measurement:

During the alternating voltage measurements, the following conditions of measurement prevailed:

Ambient temperature: 23 °C ± 1 °C
Relative humidity: 45 %RH ± 8 %RH

Measurement results:

Range (V)	Nominal Voltage (V)	Frequency (kHz)	Correction (V)	Uncertainty (V)	Internal Temperature (°C)
0.01	0.01	0.010	N/A	N/A	N/A
		0.055	- 0.000 000 48	± 0.000 000 32	41.2
		1.005	- 0.000 000 28	± 0.000 000 30	41.2
		20	- 0.000 000 11	± 0.000 000 70	41.1
		50	- 0.000 000 7	± 0.000 001 6	41.1
		1000	N/A	N/A	N/A
0.1	0.1	0.010	N/A	N/A	N/A
		0.055	+ 0.000 007 6	± 0.000 002 8	41.1
		1.005	+ 0.000 008 4	± 0.000 002 8	41.0
		20	+ 0.000 009 3	± 0.000 002 9	41.1
		50	+ 0.000 004 3	± 0.000 005 6	41.0
		1000	N/A	N/A	N/A
1	1	0.010	N/A	N/A	N/A
		0.055	+ 0.000 022	± 0.000 040	40.7
		1.005	+ 0.000 019	± 0.000 016	40.6
		20	+ 0.000 026	± 0.000 017	40.6
		50	0.000 000	± 0.000 018	40.6
		1000	− 0.007 21	± 0.000 10	40.6
10	10	0.010	N/A	N/A	N/A
		0.055	+ 0.000 18	± 0.000 13	40.7
		1.005	+ 0.000 22	± 0.000 12	40.4
		20	+ 0.000 18	± 0.000 12	40.4
		50	+ 0.000 17	± 0.000 12	40.4
		1000	− 0.069 8	± 0.001 1	40.5
10	19	1.005	+ 0.000 23	± 0.000 22	40.5
100	100	0.010	N/A	N/A	N/A
		0.055	+ 0.001 2	± 0.001 6	41.0

		1.005	+ 0.000 8	± 0.001 4	40.9
		20	+ 0.001 3	± 0.001 5	40.8
		50	- 0.000 2	± 0.001 5	40.7
1000	700	0.055	− 0.005	± 0.014	41.0
		1.005	− 0.004	± 0.012	40.7
		20	+ 0.003	± 0.020	40.7
		50	+ 0.049	± 0.029	40.7

Detailed uncertainty budgets for the alternating voltage measurements are shown in appendix 3.3.

Alternating Current

Test methods:

Alternating current was measured by the following method:

The correction of the UUT was determined by comparing its readings to the calculated value of the applied current. A calibrated current shunt was connected in series with the UUT. The voltage drop across the current shunt was measured with a calibrated alternating voltage measurement standard. The applied current was calculated from the DC resistance and the ac-dc differences of the shunt, and the measured voltage across the shunt.

See figure 1.4 for the alternating current measurement setup.

The ‘Remote Guard’ function was turned on for all the measurements, and the guard terminal and low current terminal were connected to a common ground point. The low voltage and high voltage terminals were connected to the same ground point.

Traceability:

The DC resistance of the current shunt was traceable to the 100 Ω standard resistor maintained by the SCL. The 100 Ω standard resistor was directly traceable to the National Physical Laboratory (NPL, UK). The ac-dc resistance difference of the current shunts was traceable to the standard resistors of SCL which were calibrated by the National Physical Laboratory (UK).

The DC voltage quantities were traceable to SCL’s JAVS system. The ac-dc difference of Fluke 792A was calibrated by SCL’s thermal voltage converters which were calibrated by NPL (UK).

See figure 2.2 for the resistance traceability chart and figure 2.3 for the ac-dc difference traceability chart.

Conditions of measurement:

During the alternating current measurements, the following conditions of measurement prevailed:

Ambient temperature: 23 °C ± 1 °C
Relative humidity: 45 %RH ± 8 %RH

Measurement results:

Range	Nominal Current	Frequency (kHz)	Correction	Uncertainty	Internal Temperature (°C)
1 mA	1 mA	0.055	+ 0.000 166 mA	± 0.000 030 mA	41.0
		1.005	+ 0.000 144 mA	± 0.000 030 mA	41.0
		5	+ 0.000 134 mA	± 0.000 033 mA	40.9
1 A	1 A	0.055	+ 0.000 124 A	± 0.000 048 A	41.2
		1.005	+ 0.000 138 A	± 0.000 039 A	41.3
		5	+ 0.000 63 A	± 0.000 15 A	41.3

Detailed uncertainty budgets for the alternating current measurements are shown in appendix 3.4.

Resistance

Test methods:

The correction of the UUT was determined by comparing its readings to a set of standard resistors.

See figure 1.5 for the resistance measurement setup.

The ‘Remote Guard’ function was turned on for all the measurements, and the guard terminal and low voltage terminal were connected to a common ground point. For 2-wire measurements the low current terminal and the high current terminal were connected to the common ground point.

Traceability:

The DC resistance of the standard resistors was traceable to the 100 Ω standard resistor maintained by the SCL. The 100 Ω standard resistor was directly traceable to the National Physical Laboratory (NPL, UK).

See figure 2.2 for the resistance traceability chart.

Conditions of measurement:

During the resistance measurements, the following conditions of measurement prevailed:

Ambient temperature: 23 °C ± 1 °C
Relative humidity: 45 %RH ± 8 %RH

4-wire measurement results:

Range	Nominal Resistance	Correction	Uncertainty	Internal Temperature (°C)
10 **Ω**	10 Ω	− 0.000 006 **Ω**	± 0.000 017 **Ω**	40.9

100 Ω	100 Ω	− 0.000 27 Ω	± 0.000 40 Ω	41.0
1 kΩ	1 kΩ	+ 0.000 002 1 kΩ	± 0.000 000 3 kΩ	41.1
10 kΩ	10 kΩ	− 0.000 007 kΩ	± 0.000 003 kΩ	41.1

2-wire measurement results:

Range	Nominal Resistance	Correction	Uncertainty	Internal Temperature (°C)
100 kΩ	100 kΩ	− 0.000 15 kΩ	± 0.000 20 kΩ	41.2
1 MΩ	1 MΩ	+ 0.000 002 1 MΩ	± 0.000 001 3 MΩ	41.0
10 MΩ	10 MΩ	− 0.000 155 MΩ	± 0.000 030 MΩ	41.1
100 MΩ	100 MΩ	- 0.001 28 MΩ	± 0.000 74 MΩ	41.1

Detailed uncertainty budgets for the resistance measurements are shown in appendix 3.5.

Frequency

The protocol requires that the frequency of the sources used for alternating voltage and alternating current be measured and reported.

Test methods:

The frequency correction of the Fluke 5720A calibrators was determined by measuring the frequency for an output of 1 V using a frequency counter locked to a 10 MHz reference from the SCL's Caesium Beam Frequency Standard.

See figure 1.6 for the frequency measurement setup.

The 'External Guard' function of the calibrator was turned off for all the measurements, and the guard terminal was connected to a common ground point. This was done to provide the measurement circuit with a common reference point because the counter input was floating.

Traceability:

Frequency measurement was traceable to the SCL's Caesium Beam Frequency Standard.

See figure 2.4 for the frequency traceability chart.

Conditions of measurement:

During the frequency measurements, the following conditions of measurement prevailed:

Ambient temperature: 23 °C ± 1 °C
Relative humidity: 45 %RH ± 8 %RH

Frequency measurement results:

Fluke 5720A (serial number: 2150201) was used for voltage measurements:

Nominal Frequency	Correction	Uncertainty
10 Hz	N/A	N/A
55 Hz	+ 0.000 93 Hz	± 0.000 56 Hz
1.005 kHz	+ 0.018 Hz	± 0.010 Hz
20 kHz	+ 0.36 Hz	± 0.20 Hz
50 kHz	+ 0.90 Hz	± 0.50 Hz
1 MHz	+ 18 Hz	± 10 Hz

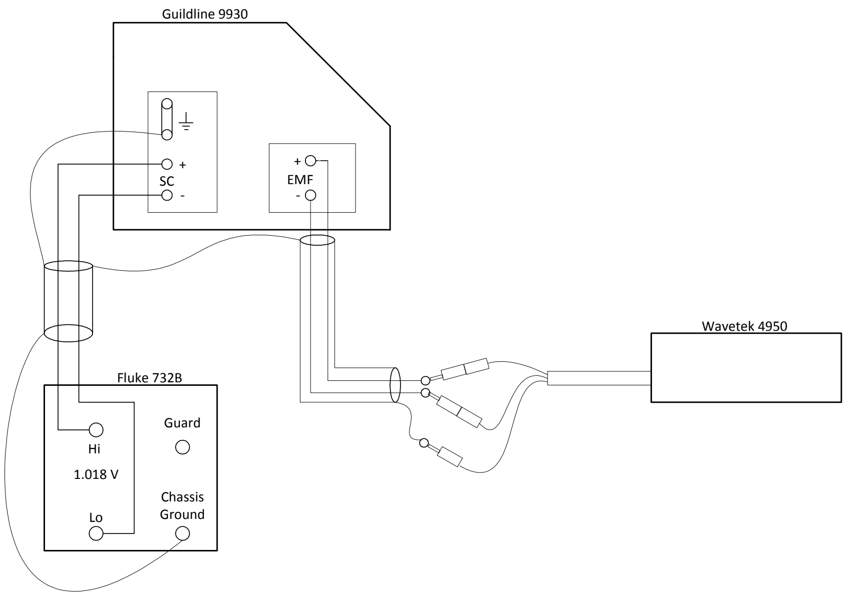
Fluke 5720A (serial number 7245202) was used for current measurements:

Nominal Frequency	Correction	Uncertainty
55 Hz	+ 0.000 72 Hz	± 0.000 56 Hz
1.005 kHz	+ 0.014 Hz	± 0.010 Hz
5 kHz	+0.068 Hz	± 0.050 Hz

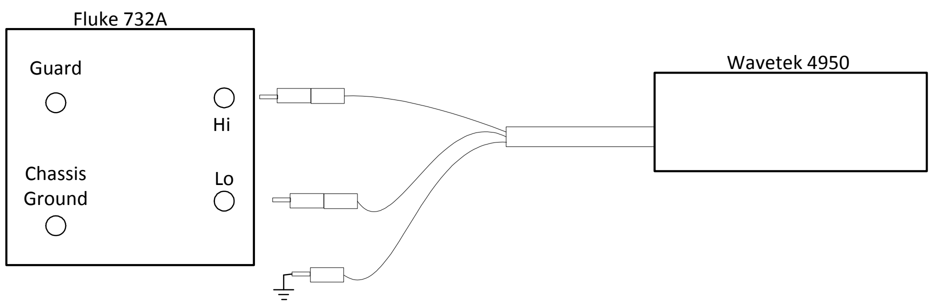
Detailed uncertainty budgets for the frequency measurements are shown in appendix 3.6.

Appendix 1: Measurement setups

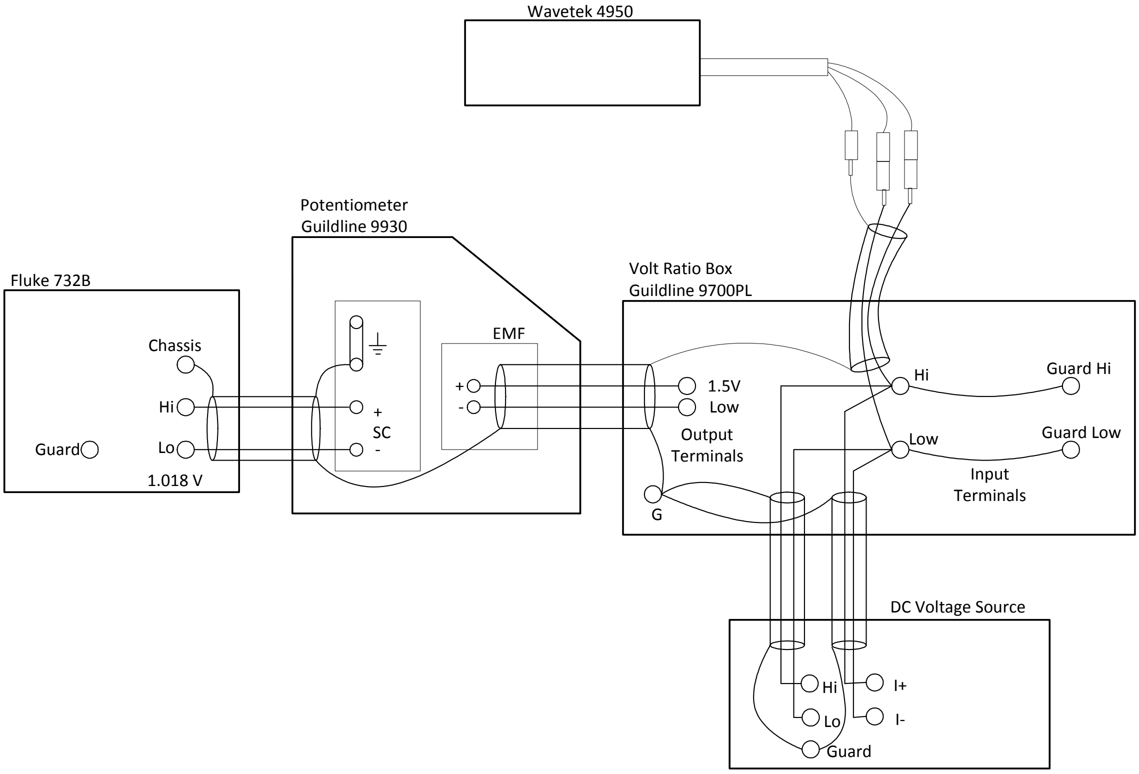
Direct Voltage



(a) 100 mV measurement



(b) 1 V and 10 V measurements



(c) 19 V to 1000 V measurements

Figure 1.1: Direct voltage measurement setups

Direct Current

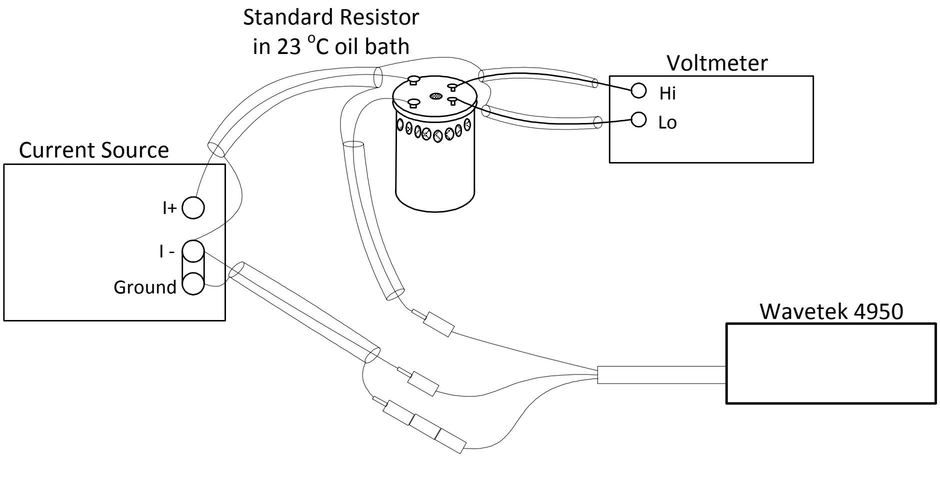
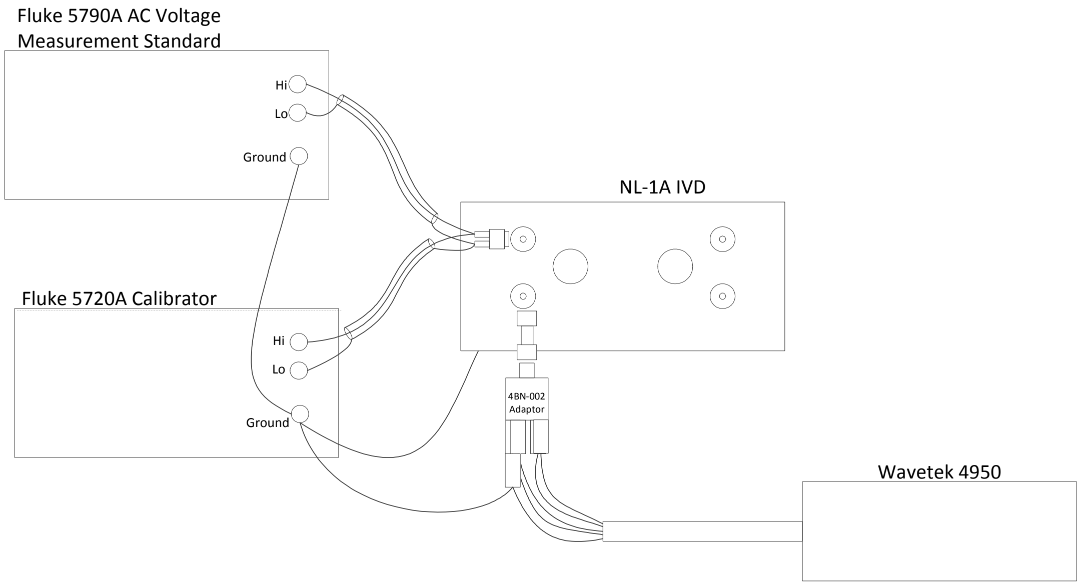
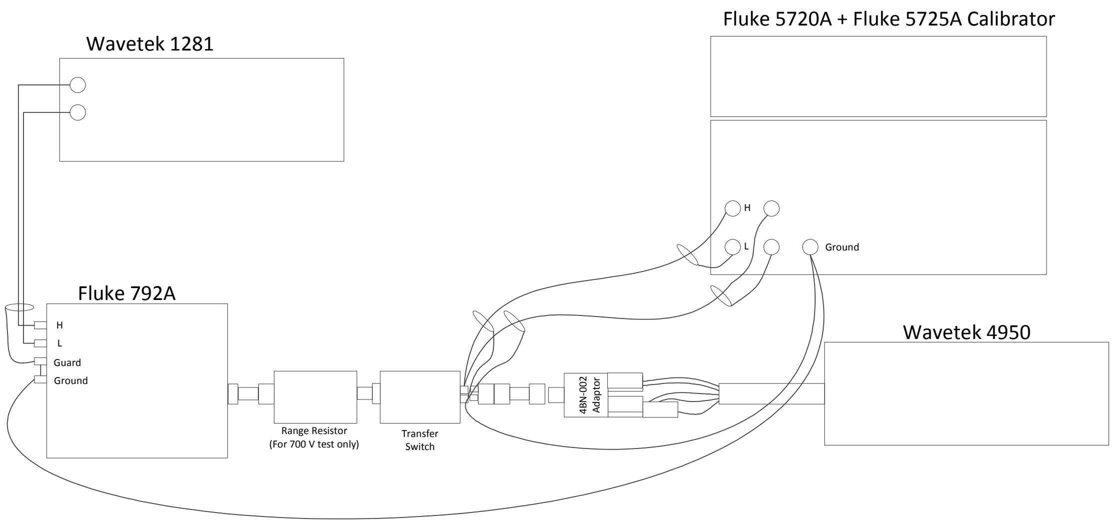


Figure 1.2: Direct current measurement setup

Alternating Voltage



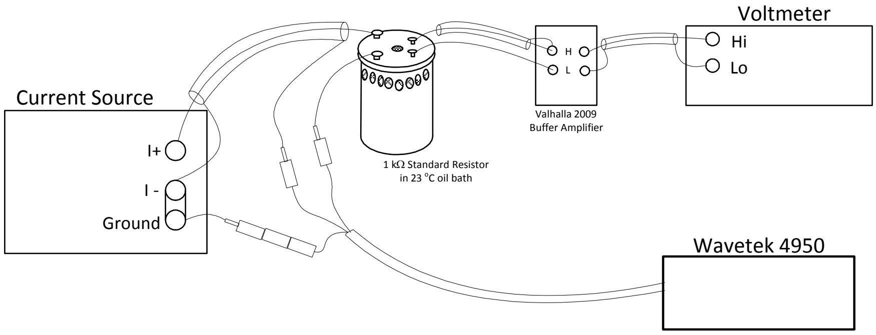
(a) 10 mV and 100 mV



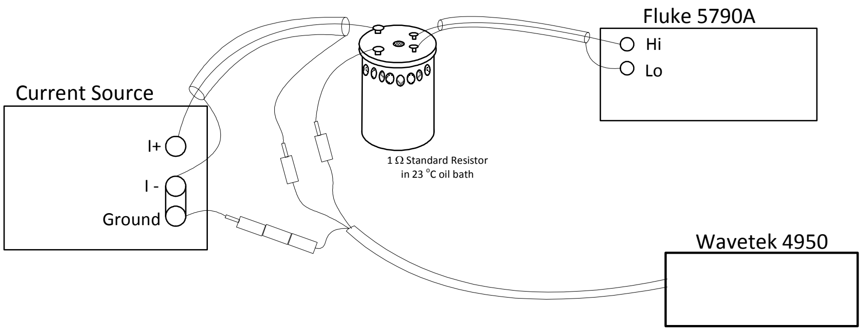
(b) 1 V to 700 V

Figure 1.3: Alternating voltage measurement setups

Alternating Current



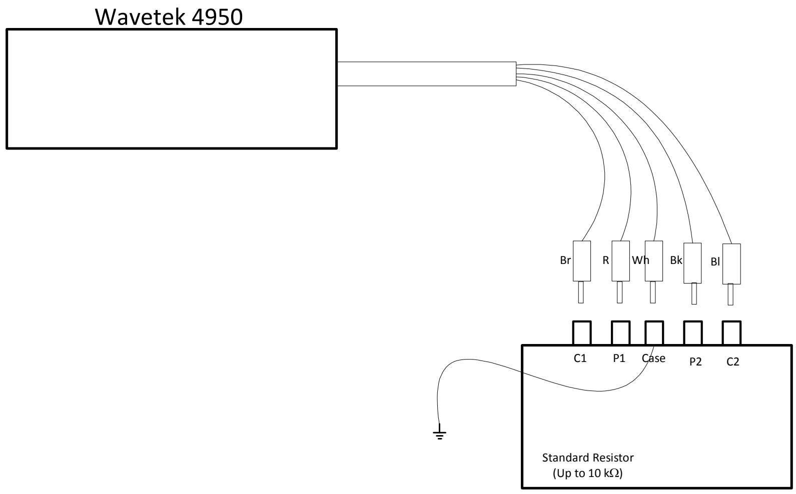
(a) AC 1 mA



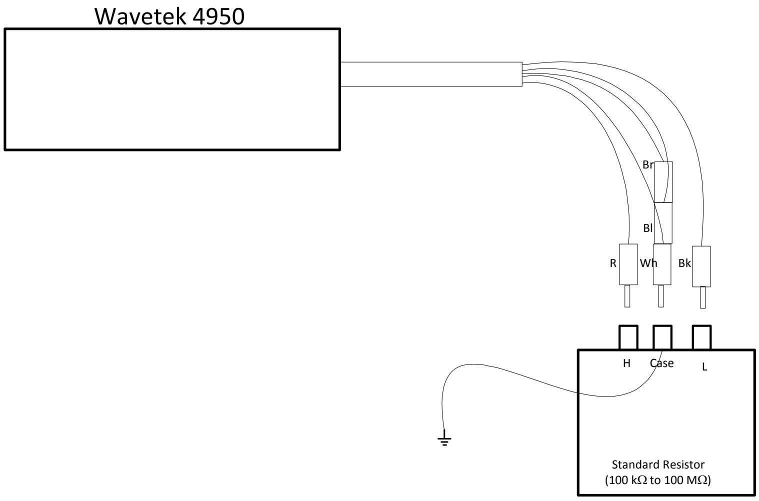
(b) AC 1 A

Figure 1.4: Alternating current measurement setup

Resistance



(a) Four wire resistance



(b) Two wire resistance

Figure 1.5: Resistance measurement setups

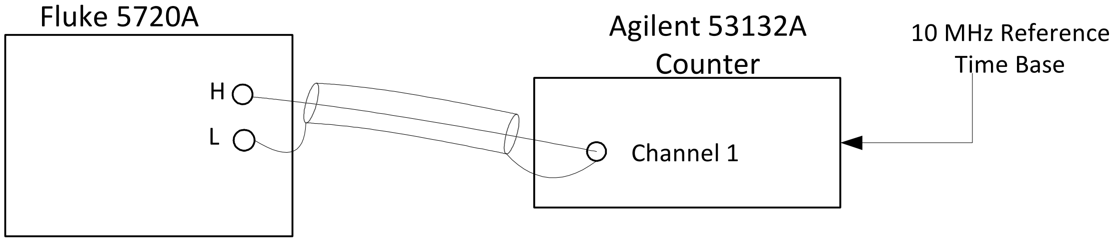


Figure 1.6: Frequency measurement setup

Appendix 2: Traceability charts

Direct Voltage

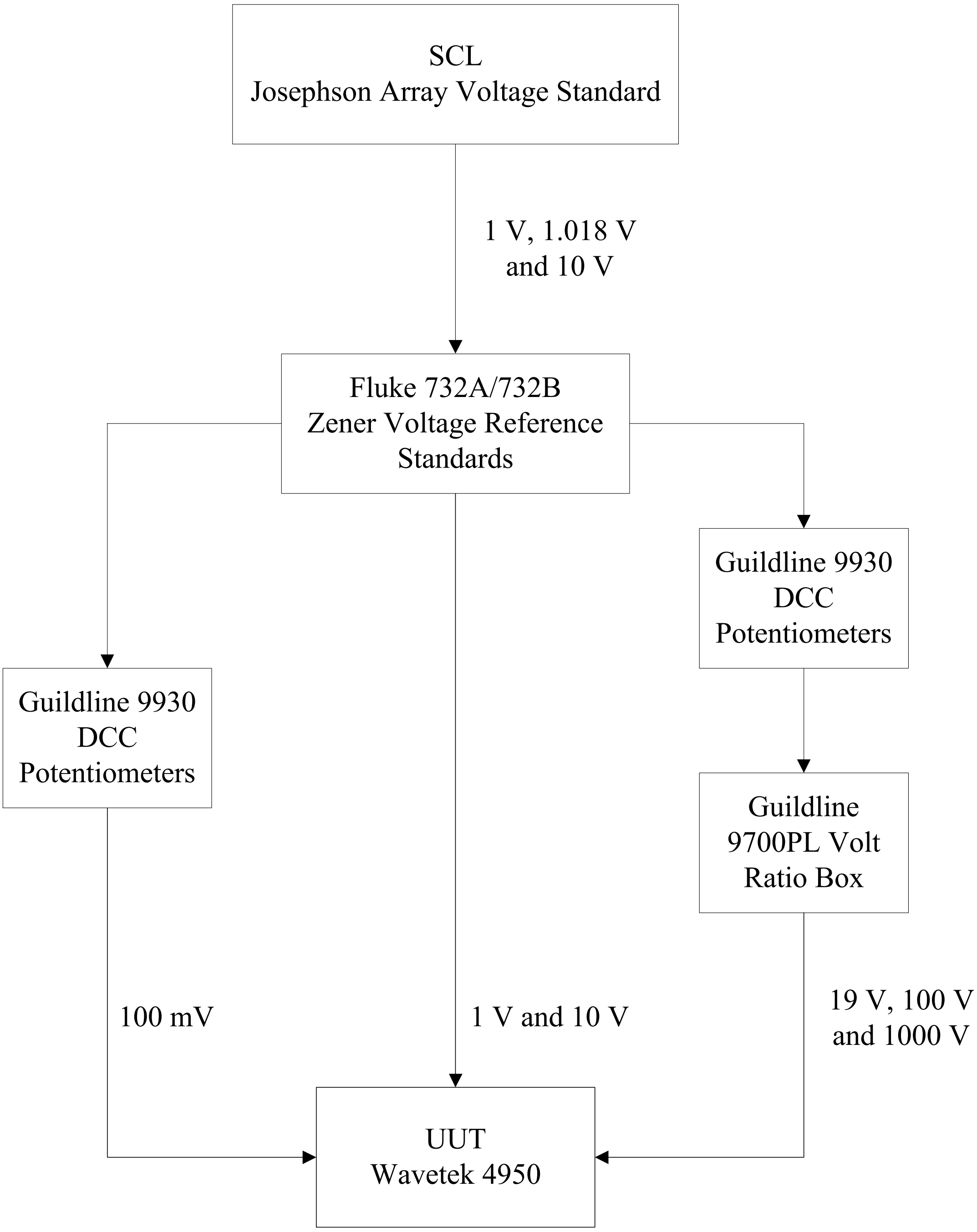


Figure 2.1: Direct voltage traceability

Resistance

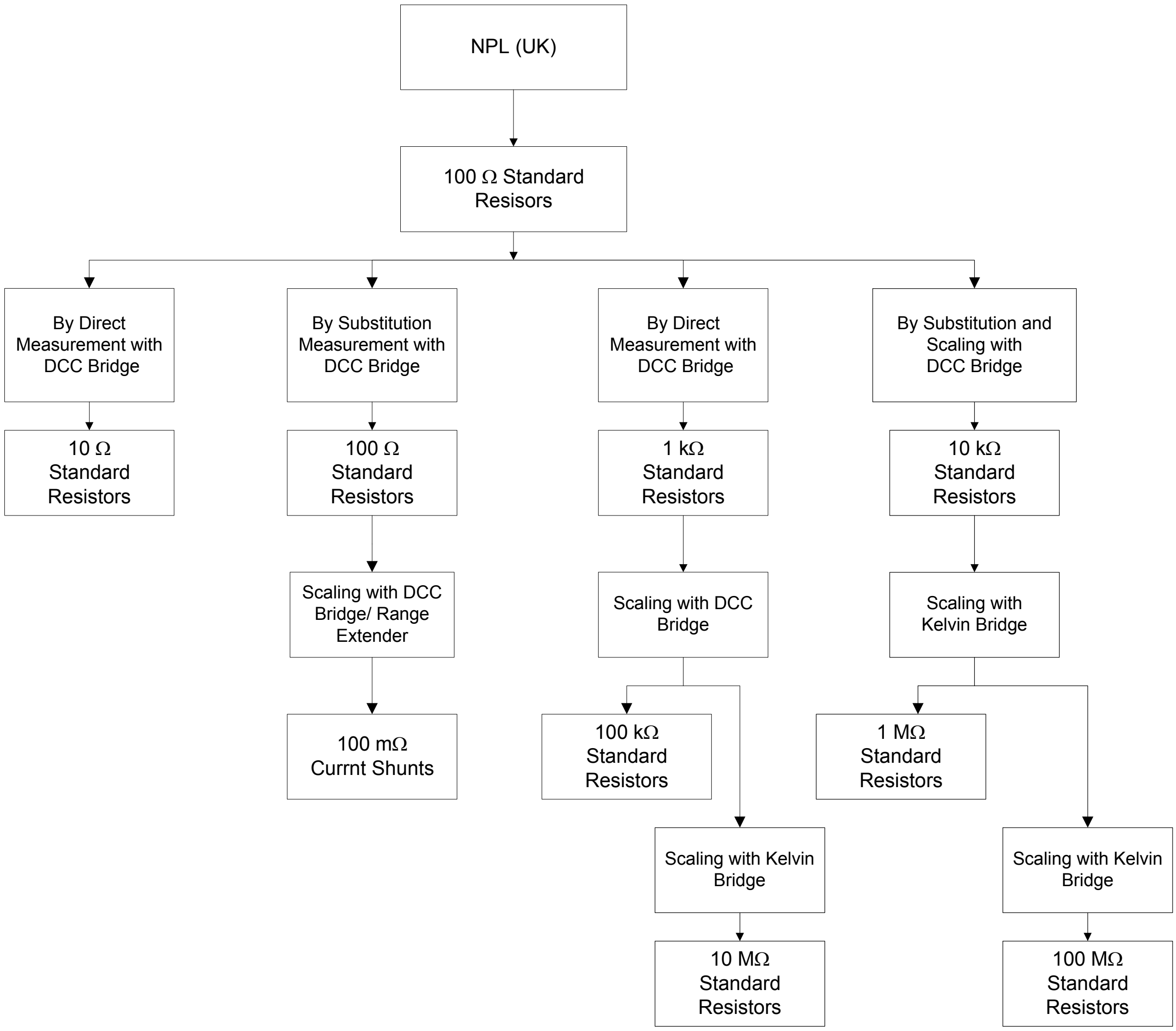


Figure 2.2: Resistance traceability

Ac-dc difference

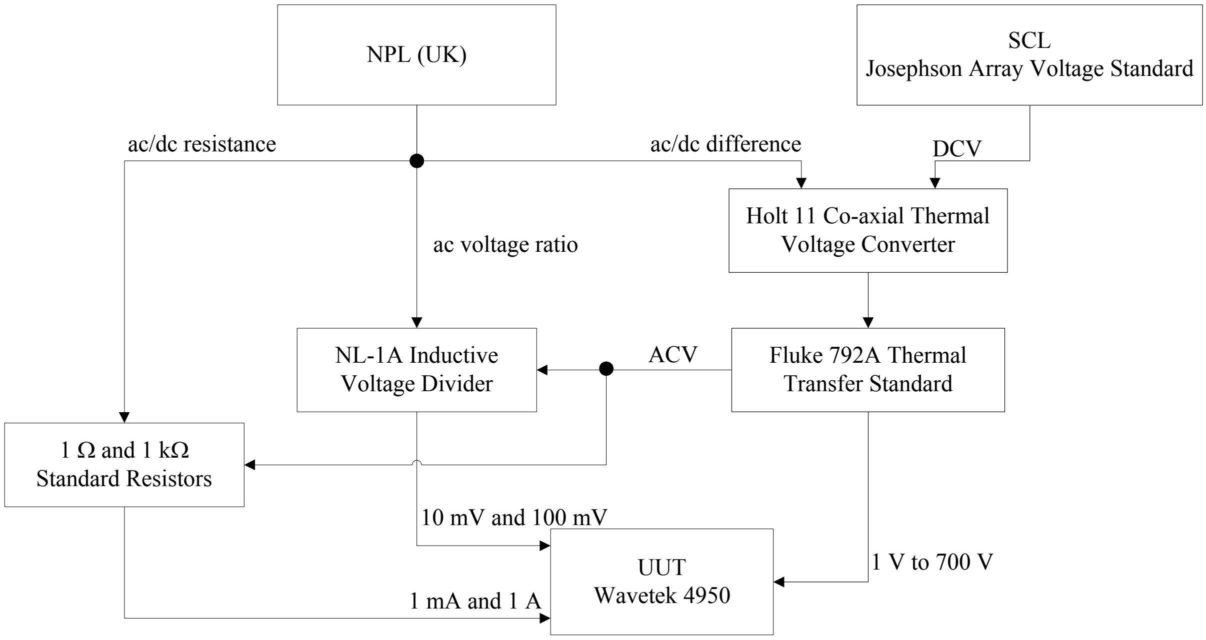


Figure 2.3: AC-DC difference traceability

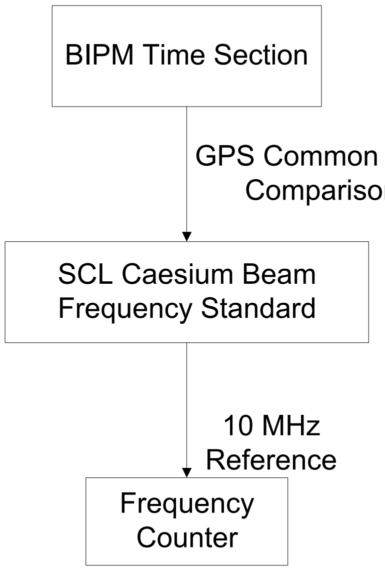


Figure 2.4: Frequency traceability

Appendix 3: Uncertainty budgets

For direct voltage at 100 mV the following components contribute to the uncertainty of measurement:

- DC voltage reference standard: From the last calibration report of the voltage standard
- Measurement uncertainty of the Potentiometer
- UUT resolution: From the UUT specification
- UUT repeatability: From the observed data
- UUT stability: From repeated tests during the measurement period at the SCL

Uncertainty budget for DC 100 mV measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
DC reference voltage uncertainty	B	0.6	μV/V	2.0	0.3	1	0.3	200
Measurement uncertainty of Potentiometer	B	0.594	μV/V	1	0.594	1	0.594	∞
Unit under test repeatability	A	0.12	μV/V	1	0.12	1	0.12	9
Unit under test resolution	B	0.05	μV/V	√3	0.0289	1	0.0289	∞
Unit under test stability	B	0.85	μV/V	√3	0.491	1	0.491	∞
						Combined standard uncertainty	0.84	μV/V
						Effective degrees of freedom	7698	
						Coverage factor	2.0	
						Expanded uncertainty	1.7	μV/V
						Expanded uncertainty	0.17	μV

For direct voltage at 1 V and 10 V the following components contribute to the uncertainty of measurement:

- Fluke 732A uncertainty: From the last calibration report
- UUT repeatability: From the observed data
- UUT resolution: From the unit under test specifications
- UUT stability: From repeated tests during the measurement period at the SCL

Uncertainty budget for DC 1 V and 10 V measurement:

Component	Type	Value		Unit	Divisor	Standard uncertainty		Sensitivity coefficient	Uncertainty contribution		Degrees of Freedom	
		1 V	10 V			1 V	10 V		1 V	10 V	1 V	10 V
DC reference voltage uncertainty	B	0.19	0.11	µV/V	2.0	0.096	0.056	1	0.096	0.056	1970	2994
Unit under test resolution	A	0.022	0.017	µV/V	1	0.022	0.017	1	0.022	0.017	9	9
Unit under test repeatability	B	0.05	0.05	µV/V	√3	0.0289	0.0289	1	0.0289	0.0289	∞	∞
Unit under test stability	B	0.69	0.09	µV/V	√3	0.398	0.052	1	0.398	0.052	∞	∞
Combined standard uncertainty									0.41	0.083	µV/V	
Effective degrees of freedom									4.1E5	3840		
Coverage factor									2.0	2.0		
Expanded uncertainty									0.82	0.17	µV/V	
Expanded uncertainty									0.82	1.7	µV	

For direct voltage from 19 V to 1000 V the following components contribute to the uncertainty of measurement:

- DC voltage reference standard: From the last calibration report of the voltage standard
- Measurement uncertainty of the Potentiometer
- Measurement uncertainty of the voltage ratio box
- UUT resolution: From the UUT specification
- UUT repeatability: From the observed data
- UUT stability: From repeated tests during the measurement period at the SCL

Uncertainty budget for DC 19 V to 1 kV measurement:

Component	Type	Value			Unit	Divisor	Standard uncertainty			Sensitivity coefficient	Uncertainty contribution			Degrees of Freedom		
		19 V	100 V	1 kV			19 V	100 V	1 kV		19 V	100 V	1 kV	19 V	100 V	1 kV
DC reference voltage uncertainty	B	0.6	0.6	0.6	µV/V	2.0	0.3	0.3	0.3	1	0.3	0.3	0.3	200	200	200
Measurement uncertainty of Potentiometer	B	0.12	0.12	0.12	µV/V	√3	0.069	0.069	0.069	1	0.069	0.069	0.069	∞	∞	∞
Measurement uncertainty of voltage ratio box	B	0.58	0.64	1.1	µV/V	2.0	0.29	0.32	0.55	1	0.29	0.32	0.55	200	200	200
Unit under test resolution	B	0.026	0.05	0.05	µV/V	√3	0.015	0.029	0.029	1	0.015	0.029	0.029	∞	∞	∞
Unit under test repeatability	A	0.016	0.021	0.022	µV/V	1	0.016	0.021	0.022	1	0.016	0.021	0.022	9	9	9
Unit under test stability	B	0.82	0.75	1.4	µV/V	√3	0.47	0.43	0.81	1	0.47	0.43	0.81	∞	∞	∞
Combined standard uncertainty											0.64	0.62	1.03	µV/V		
Effective degrees of freedom											2237	1674	2258			
Coverage factor											2.0	2.0	2.0			
Expanded uncertainty											1.3	1.3	2.1	µV/V		
Expanded uncertainty											25 µV	0.13 mV	2.1 mV			

3.2 Direct Current

For direct current the following components contribute to the uncertainty of measurement:

- Measurement uncertainty of voltmeter for voltage drop
- Voltmeter repeatability: From the observed data
- Shunt resistance uncertainty: From the last calibration report
- UUT repeatability: From the observed data
- UUT resolution: From the UUT specifications
- UUT stability: From repeated tests during the measurement period at the SCL

Uncertainty budget for DC 1 mA and 1 A measurement:

Component	Type	Value		Unit	Divisor	Standard uncertainty		Sensitivity coefficient	Uncertainty contribution		Degrees of Freedom	
		1 mA	1 A			1 mA	1 A		1 mA	1 A	1 mA	1 A
Uncertainty of voltmeter for voltage drop	B	0.319	0.717	μV/V	1	0.319	0.717	1	0.319	0.717	255	956
Voltmeter repeatability	A	0.28	0.36	μV/V	1	0.28	0.36	1	0.28	0.36	9	9
Shunt resistance uncertainty	B	0.19	1.8	μΩ/Ω	2.0	0.095	0.90	1	0.095	0.90	500	500
Unit under test resolution	B	0.5	0.5	μA/A	√3	0.29	0.29	1	0.29	0.29	∞	∞
Unit under test repeatability	A	0.13	0.33	μA/A	1	0.13	0.33	1	0.13	0.33	9	9
Unit under test stability	B	1.5	7	μA/A	√3	0.87	4.0	1	0.87	4.0	∞	∞
Combined standard uncertainty									1.02	4.24	μA/A	
Effective degrees of freedom									1430	67731		
Coverage factor									2.0	2.0		
Expanded uncertainty									2.0	8.5	μA/A	
Expanded uncertainty									2.0 nA	8.5 μA		

3.3 Alternating Voltage

For alternating voltage at 10 mV and 100 mV the following components contribute to the uncertainty of measurement:

- (a) Uncertainty of input voltage to inductive voltage divider: From the specification of the AC Volt measurement standard
- (b) AC voltameter standard repeatability: From the observed data
- (c) AC voltameter standard resolution: From the unit under test specifications
- (d) Uncertainty of voltage ratio of the inductive voltage divider:
- (e) UUT repeatability: From the observed data
- (f) UUT resolution: From the unit under test specifications
- (g) UUT stability: From repeated tests during the measurement period at the SCL

Uncertainty budget for AC 10 mV measurement:

Component	Type	Value				Unit	Divisor	Standard uncertainty				Sensitivity coefficient	Uncertainty contribution				Degrees of Freedom			
		55 Hz	1.005 kHz	20 kHz	50 kHz			55 Hz	1.005 kHz	20 kHz	50 kHz		55 Hz	1.005 kHz	20 kHz	50 kHz	55 Hz	1.005 kHz	20 kHz	50 kHz
(a)	B	24	24	24	46	μV/V	√3	13.9	13.9	13.9	26.6	1	13.9	13.9	13.9	26.6	∞	∞	∞	∞
(b)	A	0.21	0.20	0.31	0.10	μV/V	1	0.21	0.20	0.31	0.10	1	0.21	0.20	0.31	0.10	9	9	9	9
(c)	B	0.05	0.05	0.05	0.05	μV/V	√3	0.029	0.029	0.029	0.029	1	0.029	0.029	0.029	0.029	∞	∞	∞	∞
(d)	B	13	7	64	150	μV/V	2.0	6.5	3.5	32	75	1	6.5	3.5	32	75	77	6136	123	120
(e)	A	0.31	0.66	0.37	0.3	μV/V	1	0.31	0.66	0.37	0.30	1	0.31	0.66	0.37	0.30	9	9	9	9
(f)	B	0.5	0.5	0.5	0.5	μV/V	√3	0.29	0.29	0.29	0.29	1	0.29	0.29	0.29	0.29	∞	∞	∞	∞
(g)	B	5.4	4.6	5.9	6.3	μV/V	√3	3.1	2.7	3.4	3.6	1	3.1	2.7	3.4	3.6	∞	∞	∞	∞
Combined standard uncertainty													16	15	35	80	μV/V			
Effective degrees of freedom													2572	9.8E5	176	152				
Coverage factor													2.0	2.0	2.0	2.0				
Expanded uncertainty													32	30	70	160	μV/V			
Expanded uncertainty													0.32	0.30	0.70	1.6	μV			

Uncertainty budget for AC 100 mV measurement:

Component	Type	Value				Unit	Divisor	Standard uncertainty				Sensitivity coefficient	Uncertainty contribution				Degrees of Freedom			
		55 Hz	1.005 kHz	20 kHz	50 kHz			55 Hz	1.005 kHz	20 kHz	50 kHz		55 Hz	1.005 kHz	20 kHz	50 kHz	55 Hz	1.005 kHz	20 kHz	50 kHz
(a)	B	24	24	24	46	µV/V	√3	13.9	13.9	13.9	26.6	1	13.9	13.9	13.9	26.6	∞	∞	∞	∞
(b)	A	0.20	0.26	0.28	0.14	µV/V	1	0.20	0.26	0.28	0.14	1	0.20	0.26	0.28	0.14	9	9	9	9
(c)	B	0.05	0.05	0.05	0.05	µV/V	√3	0.029	0.029	0.029	0.029	1	0.02	0.029	0.02	0.029	∞	∞	∞	∞
(d)	B	1.6	2.0	7.0	18	µV/V	2.0	0.80	1.0	3.5	9.0	1	0.80	1.0	3.5	9.0	191	2.1E4	159	250
(e)	A	0.33	0.50	0.29	0.22	µV/V	1	0.33	0.50	0.29	0.220	1	0.33	0.50	0.29	0.22.	9	9	9	9
(f)	B	0.5	0.5	0.5	0.5	µV/V	√3	0.29	0.29	0.29	0.29	1	0.29	0.29	0.29	0.29	∞	∞	∞	∞
(g)	B	2.4	1.5	0.4	1.2	µV/V	√3	1.4	0.87	0.23	0.69	1	1.4	0.87	0.23	0.69	∞	∞	∞	∞
												Combined standard uncertainty	14.0	14.0	14.3	28.1	µV/V			
												Effective degrees of freedom	1E7	5E6	4E4	2E4				
												Coverage factor	2.0	2.0	2.0	2.0				
												Expanded uncertainty	28	28	29	56	µV/V			
												Expanded uncertainty	2.8	2.8	2.9	5.6	µV			

For alternating voltage from 1 V to 700 V the following components contribute to the uncertainty of measurement:

- (a) Uncertainty of applied DC voltage: From the specification of the DC Voltage calibrator
- (b) Reference ac-dc difference: From the last calibration report of the Fluke 792A
- (c) Unit under test ac-dc difference repeatability: From the observed data
- (d) Uncertainty of DMM for Fluke 792A output measurement: From the DMM specifications
- (e) UUT repeatability: From the observed data
- (f) UUT resolution: From the UUT specifications
- (g) UUT stability: From repeated tests during the measurement period at the SCL

Uncertainty budget for AC 1 V measurement:

Component	Type	Value			Unit	Divisor	Standard uncertainty			Sensitivity coefficient	Uncertainty contribution			Degrees of Freedom		
		55 Hz	1.005 kHz	20 kHz			55 Hz	1.005 kHz	20 kHz		55 Hz*	1.005 kHz	20 kHz	55 Hz	1.005 kHz	20 kHz
(a)	B	6.8	6.8	6.8	μV/V	√3	3.9	3.9	3.9	1	3.9	3.9	3.9	∞	∞	∞
(b)	B	12	11	12	μV/V	2.0	6.0	5.5	6.0	1	6.0	5.5	6.0	200	200	200
(c)	A	0.34	0.40	0.29	μV/V	1	0.34	0.40	0.29	1	0.34	0.40	0.29	3	3	3
(d)	B	0.59	0.59	0.59	μV/V	√3	0.34	0.34	0.34	1	0.34	0.34	0.34	∞	∞	∞
(e)	A	036	0.16	0.13	μV/V	1	036	0.16	0.13	1	0.36	0.16	0.13	3	3	3
(f)	B	0.5	0.5	0.5	μV/V	√3	0.29	0.29	0.29	1	0.29	0.29	0.29	∞	∞	∞
(g)	B	8.4	7.4	7.5	μV/V	√3	4.9	4.3	4.3	1	4.9	4.3	4.3	∞	∞	∞
Combined standard uncertainty											8.70	8.02	8.40	μV/V		
Effective degrees of freedom											875	902	765			
Coverage factor											2.0	2.0	2.0			
Expanded uncertainty											18	16	17	μV/V		
Expanded uncertainty											18	16	17	μV		

*The expanded uncertainty for 1 V 55 Hz is quoted as 40 μV to align with SCL's CMC.

Uncertainty budget for AC 1 V measurement: (Cont'd)

Component	Type	Value		Unit	Divisor	Standard uncertainty		Sensitivity coefficient	Uncertainty contribution		Degrees of Freedom	
		50 kHz	1 MHz			50 kHz	1 MHz		50 kHz	1 MHz	50 kHz	1 MHz
(a)	B	6.8	6.8	μV/V	√3	3.9	3.9	1	3.9	3.9	∞	∞
(b)	B	13	87	μV/V	2.0	6.5	44	1	6.5	44	200	200
(c)	A	0.41	2.5	μV/V	1	0.41	2.5	1	0.41	2.5	3	3
(d)	B	0.59	0.59	μV/V	√3	0.34	0.34	1	0.34	0.34	∞	∞
(e)	A	0.19	2.3	μV/V	1	0.19	2.3	1	0.19	2.3	3	3
(f)	B	0.5	0.5	μV/V	√3	0.29	0.29	1	0.29	0.29	∞	∞
(g)	B	8.1	41	μV/V	√3	4.7	24	1	4.7	24	∞	∞
Combined standard uncertainty									8.94	50.0	μV/V	
Effective degrees of freedom									715	345		
Coverage factor									2.0	2.0		
Expanded uncertainty									18	100	μV/V	
Expanded uncertainty									18 μV	0.10 mV		

Uncertainty budget for AC 10 V and 19 V measurement:

Component	Type	Value			Unit	Divisor	Standard uncertainty			Sensitivity coefficient	Uncertainty contribution			Degrees of Freedom		
		10 V / 55 Hz	10 V / 1.005 kHz	10 V / 20 kHz			10 V / 55 Hz	10 V / 1.005 kHz	10 V / 20 kHz		10 V / 55 Hz	10 V / 1.005 kHz	10 V / 20 kHz	10 V / 55 Hz	10 V / 1.005 kHz	10 V / 20 kHz
(a)	B	4.3	4.3	4.3	μV/V	√3	2.5	2.5	2.5	1	2.5	2.5	2.5	∞	∞	∞
(b)	B	12	11	10	μV/V	2.0	6.0	5.5	5.0	1	6.0	5.5	5.0	200	200	200
(c)	A	0.43	0.26	0.47	μV/V	1	0.43	0.26	0.47	1	0.43	0.26	0.47	3	3	3
(d)	B	0.55	0.55	0.55	μV/V	√3	0.32	0.32	0.32	1	0.32	0.32	0.32	∞	∞	∞
(e)	A	0.68	0.19	0.17	μV/V	1	0.68	0.19	0.17	1	0.68	0.19	0.17	3	3	3
(f)	B	0.5	0.5	0.5	μV/V	√3	0.29	0.29	0.29	1	0.29	0.29	0.29	∞	∞	∞
(g)	B	0.27	1.3	1.4	μV/V	√3	0.16	0.75	0.81	1	0.16	0.75	0.81	∞	∞	∞
Combined standard uncertainty											6.56	6.10	5.68	μV/V		
Effective degrees of freedom											281	303	331			
Coverage factor											2.0	2.0	2.0			
Expanded uncertainty											13	12	12	μV/V		
Expanded uncertainty											0.13	0.12	0.12	mV		

Uncertainty budget for AC 10 V and 19 V measurement: (Cont'd)

Component	Type	Value			Unit	Divisor	Standard uncertainty			Sensitivity coefficient	Uncertainty contribution			Degrees of Freedom		
		10 V / 55 Hz	10 V / 1 MHz	19 V / 1.005 kHz			10 V / 55 Hz	10 V / 1 MHz	19 V / 1.005 kHz		10 V / 55 Hz	10 V / 1 MHz	19 V / 1.005 kHz	10 V / 55 Hz	10 V / 1 MHz	19 V / 1.005 kHz
(a)	B	4.3	4.3	4.3	μV/V	√3	2.5	2.5	2.5	1	2.5	2.5	2.5	∞	∞	∞
(b)	B	11	85	10	μV/V	2.0	5.5	43	5.0	1	5.5	43	5.0	200	200	200
(c)	A	0.45	5.7	0.66	μV/V	1	0.45	5.7	0.66	1	0.45	5.7	0.66	3	3	3
(d)	B	0.55	0.55	0.29	μV/V	√3	0.32	0.32	0.17	1	0.32	0.32	0.17	∞	∞	∞
(e)	A	0.16	6.0	0.31	μV/V	1	0.16	6.0	0.31	1	0.16	6.0	0.31	3	3	3
(f)	B	0.5	0.5	0.26	μV/V	√3	0.29	0.29	0.15	1	0.29	0.29	0.15	∞	∞	∞
(g)	B	1.3	53	1.6	μV/V	√3	0.75	30	0.92	1	0.75	30	0.92	∞	∞	∞
Combined standard uncertainty											6.11	53.0	5.71	μV/V		
Effective degrees of freedom											304	461	333			
Coverage factor											2.0	2.0	2.0			
Expanded uncertainty											12	106	11.4	μV/V		
Expanded uncertainty											0.12	1.1	0.22	mV		

Uncertainty budget for AC 100 V measurement:

Component	Type	Value				Unit	Divisor	Standard uncertainty				Sensitivity coefficient	Uncertainty contribution				Degrees of Freedom			
		55 Hz	1.005 kHz	20 kHz	50 kHz			55 Hz	1.005 kHz	20 kHz	50 kHz		55 Hz	1.005 kHz	20 kHz	50 kHz	55 Hz	1.005 kHz	20 kHz	50 kHz
(a)	B	6.5	6.5	6.5	6.5	μV/V	√3	3.8	3.8	3.8	3.8	1	3.8	3.8	3.8	3.8	∞	∞	∞	∞
(b)	B	14	12	13	12	μV/V	2.0	7.0	6.0	6.5	6.0	1	7.0	6.0	6.5	6.0	200	200	200	200
(c)	A	0.36	0.43	0.40	0.94	μV/V	1	0.36	0.43	0.40	0.94	1	0.36	0.43	0.40	0.94	3	3	3	3
(d)	B	0.55	0.55	0.55	0.55	μV/V	√3	0.32	0.32	0.32	0.32	1	0.32	0.32	0.32	0.32	∞	∞	∞	∞
(e)	A	0.15	0.074	0.30	0.81	μV/V	1	0.15	0.074	0.30	0.81	1	0.15	0.074	0.30	0.81	3	3	3	3
(f)	B	0.5	0.5	0.5	0.5	μV/V	√3	0.29	0.29	0.29	0.29	1	0.29	0.29	0.29	0.29	∞	∞	∞	∞
(g)	B	0.3	0.3	0.2	0.2	μV/V	√3	0.17	0.17	0.12	0.12	1	0.17	0.17	0.12	0.12	∞	∞	∞	∞
Combined standard uncertainty													8.0	7.1	7.6	7.2	μV/V			
Effective degrees of freedom													335	392	360	390				
Coverage factor													2.0	2.0	2.0	2.0				
Expanded uncertainty													16	14	15	15	μV/V			
Expanded uncertainty													1.6	1.4	1.5	1.5	mV			

Uncertainty budget for AC 700 V measurement:

Component	Type	Value				Unit	Divisor	Standard uncertainty				Sensitivity coefficient	Uncertainty contribution				Degrees of Freedom			
		55 Hz	1.005 kHz	20 kHz	50 kHz			55 Hz	1.005 kHz	20 kHz	50 kHz		55 Hz	1.005 kHz	20 kHz	50 kHz	55 Hz	1.005 kHz	20 kHz	50 kHz
(a)	B	8.7	8.7	8.7	8.7	μV/V	√3	5.0	5.0	5.0	5.0	1	5.0	5.0	5.0	5.0	∞	∞	∞	∞
(b)	B	17	13	25	39	μV/V	2.0	8.5	6.5	12.5	19.5	1	8.5	6.5	12.5	19.5	200	200	200	200
(c)	A	0.40	0.16	0.90	1.9	μV/V	1	0.4	0.16	0.90	1.9	1	0.4	0.16	0.90	1.9	3	3	3	3
(d)	B	0.4	0.4	0.4	0.4	μV/V	√3	0.23	0.23	0.23	0.23	1	0.23	0.23	0.23	0.23	∞	∞	∞	∞
(e)	A	0.33	0.22	0.18	0.86	μV/V	1	0.33	0.22	0.18	0.86	1	0.33	0.22	0.18	0.86	3	3	3	3
(f)	B	0.71	0.71	0.71	0.71	μV/V	√3	0.41	0.41	0.41	0.41	1	0.41	0.41	0.41	0.41	∞	∞	∞	∞
(g)	B	1.4	4.2	4.6	6.3	μV/V	√3	0.81	2.4	2.7	3.6	1	0.81	2.4	2.7	3.6	∞	∞	∞	∞
Combined standard uncertainty													10	8.6	14	21	μV/V			
Effective degrees of freedom													372	607	293	246				
Coverage factor													2.0	2.0	2.0	2.0				
Expanded uncertainty													20	17	28	42	μV/V			
Expanded uncertainty													14	12	20	29	mV			

3.4 Alternating Current

For alternating current the following components contribute to the uncertainty of measurement:

- (a) ACV measurement uncertainty: A Fluke 5790A AC voltage measurement standard is used to determine the voltage drop across the shunt. From the specification of the Fluke 5790A
- (b) ACV reference repeatability: From the observed data
- (c) ACV reference resolution: From the specification of the Fluke 5790A
- (d) Uncertainty of AC voltage drop measurement between measurement and verification: From the specification of the Wavetek 1281 (For 1 mA test only)
- (e) Current shunt impedance: From the latest calibration report
- (f) UUT repeatability: From the observed data
- (g) UUT resolution: From the specifications of the UUT
- (h) UUT stability: From repeated tests during the measurement period at the SCL

Uncertainty budget for AC 1 mA measurement:

Component	Type	Value			Unit	Divisor	Standard uncertainty			Sensitivity coefficient	Uncertainty contribution			Degrees of Freedom		
		55 Hz	1.005 kHz	5 kHz			55 Hz	1.005 kHz	5 kHz		55 Hz	1.005 kHz	5 kHz	55 Hz	1.005 kHz	5 kHz
(a)	B	24	24	24	μV/V	√3	13.9	13.9	13.9	1	13.9	13.9	13.9	∞	∞	∞
(b)	A	0.40	0.23	0.33	μV/V	1	0.40	0.23	0.33	1	0.40	0.23	0.33	9	9	9
(c)	B	0.05	0.05	0.05	μV/V	√3	0.029	0.029	0.029	1	0.029	0.029	0.029	∞	∞	∞
(d)	B	5	5	5	μV/V	√3	2.9	2.9	2.9	1	2.9	2.9	2.9	∞	∞	∞
(e)	B	9	9	9	μΩ/Ω	2.0	4.5	4.5	4.5	1	4.5	4.5	4.5	200	200	200
(f)	A	0.75	0.45	0.31	μA/A	1	0.75	0.45	0.31	1	0.75	0.45	0.31	9	9	9
(g)	B	0.5	0.5	0.5	μA/A	√3	0.29	0.29	0.29	1	0.29	0.29	0.29	∞	∞	∞
(h)	B	1.5	4	12	μA/A	√3	0.87	2.3	6.9	1	0.87	2.3	6.9	∞	∞	∞
Combined standard uncertainty											14.9	15.0	16.4	μA/A		
Effective degrees of freedom											2.3E4	2.4E4	3.5E4			
Coverage factor											2.0	2.0	2.0			
Expanded uncertainty											30	30	33	μA/A		
Expanded uncertainty											0.030	0.030	0.033	μA		

Uncertainty budget for AC 1 A measurement:

Component	Type	Value			Unit	Divisor	Standard uncertainty			Sensitivity coefficient	Uncertainty contribution			Degrees of Freedom		
		55 Hz	1.005 kHz	5 kHz			55 Hz	1.005 kHz	5 kHz		55 Hz	1.005 kHz	5 kHz	55 Hz	1.005 kHz	5 kHz
(a)	B	24	24	24	µV/V	√3	13.9	13.9	13.9	1	13.9	13.9	13.9	∞	∞	∞
(b)	A	0.21	0.94	0.33	µV/V	1	0.21	0.94	0.33	1	0.21	0.94	0.33	9	9	9
(c)	B	0.05	0.05	0.05	µV/V	√3	0.029	0.029	0.029	1	0.029	0.029	0.029	∞	∞	∞
(e)	B	26	27	120	µΩ/Ω	2.0	13	13.5	60	1	13	13.5	60	200	200	200
(f)	A	0.43	1.5	2.8	µA/A	1	0.43	1.5	2.8	1	0.43	1.5	2.8	9	9	9
(g)	B	0.5	0.5	0.5	µA/A	√3	0.29	0.29	0.29	1	0.29	0.29	0.29	∞	∞	∞
(h)	B	25	2.1	65	µA/A	√3	14.4	1.21	67.5	1	14.4	1.21	38	∞	∞	∞
Combined standard uncertainty											23.9	19.5	72.4	µA/A		
Effective degrees of freedom											2272	861	418			
Coverage factor											2.0	2.0	2.0			
Expanded uncertainty											48	39	145	µA/A		
Expanded uncertainty											0.048	0.039	0.15	mA		

3.5 Resistance

For resistance the following components contribute to the uncertainty of measurement:

- Reference resistor: From the latest calibration report (For 4-wire resistors) or laboratory's measurement results (For 2-wire resistors)
- UUT repeatability: From the observed data
- UUT resolution: From the specifications of the UUT
- UUT stability: From repeated tests during the measurement period at the SCL

Uncertainty budget for Resistance measurement:

Component	Type	Value			Unit	Divisor	Standard uncertainty			Sensitivity coefficient	Uncertainty contribution			Degrees of Freedom		
		10 Ω	100 Ω	1 kΩ			10 Ω	100 Ω	1 kΩ		10 Ω	100 Ω	1 kΩ	10 Ω	100 Ω	1 kΩ
Uncertainty of reference resistance	B	0.15	0.075	0.10	µΩ/Ω	1	0.15	0.075	0.10	1	0.15	0.075	0.10	500	500	500
Unit under test repeatability	A	0.09	0.15	0.016	µΩ/Ω	1	0.09	0.15	0.016	1	0.09	0.15	0.016	9	9	9
Unit under test resolution	B	0.05	0.05	0.05	µΩ/Ω	√3	0.029	0.029	0.029	1	0.029	0.029	0.029	∞	∞	∞
Unit under test stability	B	1.4	0.15	0.15	µΩ/Ω	√3	0.81	0.087	0.087	1	0.81	0.087	0.087	∞	∞	∞
Combined standard uncertainty											0.829	0.191	0.137	µΩ/Ω		
Effective degrees of freedom											4.8E4	23	1839			
Coverage factor											2.0	2.1	2.0			
Expanded uncertainty											1.7	0.40	0.27	µΩ/Ω		
Expanded uncertainty											0.017	0.040	0.27	mΩ		

Uncertainty budget for Resistance measurement: (Cont'd)

Component	Type	Value			Unit	Divisor	Standard uncertainty			Sensitivity coefficient	Uncertainty contribution			Degrees of Freedom		
		10 kΩ	100 kΩ	1 MΩ			10 kΩ	100 kΩ	1 MΩ		10 kΩ	100 kΩ	1 MΩ	10 kΩ	100 kΩ	1 MΩ
Uncertainty of reference resistance	B	0.12	0.92	0.60	µΩ/Ω	1	0.12	0.92	0.60	1	0.12	0.92	0.60	500	46	193
Unit under test repeatability	A	0.016	0.010	0.010	µΩ/Ω	1	0.016	0.010	0.010	1	0.016	0.010	0.010	9	9	9
Unit under test resolution	B	0.05	0.05	0.05	µΩ/Ω	√3	0.029	0.029	0.029	1	0.029	0.029	0.029	∞	∞	∞
Unit under test stability	B	0.15	0.55	0.45	µΩ/Ω	√3	0.087	0.318	0.26	1	0.087	0.318	0.26	∞	∞	∞
Combined standard uncertainty											0.152	0.974	0.655	µΩ/Ω		
Effective degrees of freedom											1342	57	272			
Coverage factor											2.0	2.1	2.0			
Expanded uncertainty											0.30	2.0	1.3	µΩ/Ω		
Expanded uncertainty											3.0 mΩ	0.20 Ω	1.3 Ω			

Uncertainty budget for Resistance measurement: (Cont'd)

Component	Type	Value		Unit	Divisor	Standard uncertainty		Sensitivity coefficient	Uncertainty contribution		Degrees of Freedom	
		10 MΩ	100 MΩ			10 MΩ	100 MΩ		10 MΩ	100 MΩ	10 MΩ	100 MΩ
Uncertainty of reference resistance	B	1.07	2.85	μΩ/Ω	1	1.07	2.85	1	1.07	2.85	327	180
Unit under test repeatability	A	0.04	0.25	μΩ/Ω	1	0.04	0.25	1	0.04	0.25	9	9
Unit under test resolution	B	0.05	0.05	μΩ/Ω	√3	0.029	0.029	1	0.029	0.029	∞	∞
Unit under test stability	B	1.7	4.0	μΩ/Ω	√3	0.981	2.31	1	0.981	2.31	∞	∞
								Combined standard uncertainty	1. 5	3.7	μΩ/Ω	
								Effective degrees of freedom	1108	497		
								Coverage factor	2.0	2.0		
								Expanded uncertainty	3.0	7.4	μΩ/Ω	
								Expanded uncertainty	30 Ω	0.74 kΩ		

3.6 Frequency

For frequency the following components contribute to the uncertainty of measurement:

- Counter accuracy: From the latest calibration report
- Counter repeatability: From the observed data
- Counter resolution: From the specifications of the counter

Calibrator frequency uncertainties

For ACV measurements (Fluke 5720A serial number 2150201):

Component	Type	Value			Unit	Divisor	Standard uncertainty			Sensitivity coefficient	Uncertainty contribution			Degrees of Freedom		
		55 Hz	1.005 kHz	20 kHz			55 Hz	1.005 kHz	20 kHz		55 Hz	1.005 kHz	20 kHz	55 Hz	1.005 kHz	20 kHz
Uncertainty of reference counter	B	0.55	10.1	200	mHz	2.0	0.28	5.05	100	1	0.28	5.1	100	500	500	500
Counter repeatability	A	32	0.35	40.9	μHz	1	32	0.35	40.9	1	32	0.35	40.9	19	19	19
Resolution of counter	B	0.005	0.005	0.05	μHz	√3	0.0029	0.0029	0.029	1	0.0029	0.0029	0.029	∞	∞	∞
Combined standard uncertainty											0.28	5.1	100	mHz		
Effective degrees of freedom											511	500	500			
Coverage factor											2.0	2.0	2.0			
Expanded uncertainty											0.56	10	200	mHz		
Expanded uncertainty											10	10	10	μHz/Hz		

For ACV measurements (Fluke 5720A serial number 2150201): (Cont'd)

Component	Type	Value		Unit	Divisor	Standard uncertainty		Sensitivity coefficient	Uncertainty contribution		Degrees of Freedom	
		50 kHz	1 MHz			50 kHz	1 MHz		50 kHz	1 MHz	50 kHz	1 MHz
Uncertainty of reference counter	B	0.5	10	Hz	2.0	0.25	5	1	0.25	5	500	500
Counter repeatability	A	0.0465	32.4	mHz	1	0.0465	32.4	1	0.0465	32.4	19	19
Resolution of counter	B	0.05	0.5	μHz	√3	0.029	0.29	1	0.029	0.29	∞	∞
Combined standard uncertainty									0.25	5.0	Hz	
Effective degrees of freedom									500	500		
Coverage factor									2.0	2.0		
Expanded uncertainty									0.50	10	Hz	
Expanded uncertainty									10	10	μHz/Hz	

For ACI measurements (Fluke 5720A serial number 7245202):

Component	Type	Value			Unit	Divisor	Standard uncertainty			Sensitivity coefficient	Uncertainty contribution			Degrees of Freedom		
		55 Hz	1.005 kHz	5 kHz			55 Hz	1.005 kHz	5 kHz		55 Hz	1.005 kHz	5 kHz	55 Hz	1.005 kHz	5 kHz
Uncertainty of reference counter	B	0.55	10.1	50	mHz	2.0	0.28	5.05	25	1	0.28	5.05	25	500	500	500
Counter repeatability	A	28.7	3.24	5.1	µHz	1	28.7	3.24	5.1	1	28.7	3.24	5.1	19	19	19
Resolution of counter	B	0.005	0.005	0.05	µHz	√3	0.0029	0.0029	0.029	1	0.0029	0.0029	0.029	∞	∞	∞
Combined standard uncertainty											0.28	5.1	25	mHz		
Effective degrees of freedom											511	500	500			
Coverage factor											2.0	2.0	2.0			
Expanded uncertainty											0.56	10	50	mHz		
Expanded uncertainty											10	10	10	µHz/Hz		

-END-

Report on

Measurements performed for
APMP.EM-S12
Comparison of Standards for the Calibration of Voltage, Current and Resistance Meters

Measurements performed on

Wavetek 4950 serial number 33528

From 13 May 2015 to 21 May 2015

Performed by

CSIR- National Physical Laboratory
Dr K S Krishnan Road, New Delhi 110012
India

Report by

LF HF Impedance & DC Standards

Introduction

The APMP.EM-S12 comparison protocol requires that the travelling standard, a Wavetek model 4950 serial number 33528 (the Unit under Test – UUT), be measured at a number of points for each of its measurement functions. These are direct voltage, direct current, alternating voltage, alternating current and resistance. The measurement points are detailed in the comparison protocol.

The instrument was received on 8 May 2015. The fuse (F1) and mains voltage selection switch (S1) was checked before applying power. The UUT was allowed to stabilise for 24 hours with the power turned on before any measurements were made. The instrument's confidence test was performed and completed without any errors.

The measurements were performed from 13 May 2015 to 21 May 2015. The instrument was handed over for the AC parameter measurements on 22 May 2015.

Direct Voltage

Test methods:

Direct voltage was measured using three methods:

1. For 100 mV the correction of the UUT was determined by comparing the UUT reading to that obtained with a reference DMM Fluke 8508A calibrated with Fluke 5720A which itself is calibrated against the Josephson Voltage Standard at NPL.
2. For 1 V and 10 V the correction of the UUT was determined by direct connection of the UUT to a calibrated Fluke model 732B zener voltage reference standard, calibrated against the Josephson voltage standard at NPL.
3. For 19 V to 1000 V the correction of the UUT was determined by direct connection of the UUT to a calibrated Fluke model 5720A multifunction calibrator, calibrated against the Josephson voltage standard at NPL.

See figure 1.1 for the direct voltage measurement setups.

The 'Remote Guard' function was turned on for all the measurements, and the guard terminal and low voltage terminal were connected to a common ground point. The low current terminal was connected to the low voltage terminal and the high current terminal was connected to the high voltage terminal for all measurements.

Traceability:

All the test methods described for direct voltage was traceable to the Indian national measurement standard for voltage, a Josephson voltage standard. See figure 2.1 for the direct voltage traceability chart.

Conditions of measurement:

During the direct voltage measurements, the following conditions of measurement prevailed:

Ambient temperature: 25 °C ± 1 °C
Relative humidity: 50 %RH ± 10 %RH

Measurement results:

Range (V)	Nominal Voltage (V)	Correction	Uncertainty	Internal Temperature (°C)
0.1	0.1	-0.588 µV	± 1.51 µV	40.6
1	1	-3.166 µV	± 1.82 µV	40.5
10	10	-0.006 mV	± 17.9 µV	40.7
10	19	-0.005 mV	± 34.85 µV	41.6
100	100	2.826 mV	± 237.20 µV	40.8
1000	1000	12.886 mV	±7025.38 µV	41.8

Detailed uncertainty budgets for the direct voltage measurements are shown in appendix 3.1.

Direct Current

Test methods:

Direct current was measured the following method:

The correction of the UUT was determined by comparing its readings to the calculated value of the applied current. A calibrated current shunt was connected in series with the UUT. The voltage drop across the current shunt was measured with a calibrated voltmeter. The applied current was calculated from the resistance of the shunts and the measured voltage.

See figure 1.2 for the direct current measurement setup.

The ‘Remote Guard’ function was turned on for all the measurements, and the guard terminal and low current terminal were connected to a common ground point. The low voltage and high voltage terminals were connected to the same ground point.

Traceability:

The resistance of the shunt was traceable to the resistance scale maintained by NPL India. This resistance scale is directly traceable to the Quantum Hall Resistance (QHR) Standard. See figure 2.2 for the resistance traceability chart.

The direct voltage was traceable to the Josephson voltage standard. See figure 2.1 for the direct voltage traceability chart.

Conditions of measurement:

During the direct current measurements, the following conditions of measurement prevailed:

Ambient temperature: 25 °C ± 1 °C
Relative humidity: 50 %RH ± 10 %RH

Measurement results:

Range	Nominal Current	Correction	Uncertainty	Internal Temperature (°C)
1 mA	1 mA	0.002 μA	± 0.0084 μA	40.5
1 A	1 A	0.000 010 A	± 22.6 μA	40.3

Detailed uncertainty budgets for the direct current measurements are shown in appendix 3.2.

Resistance

Test methods:

The correction of the UUT was determined by comparing its readings to a set of standard resistors.

See figure 1.5 for the resistance measurement setup.

The 'Remote Guard' function was turned on for all the measurements, and the guard terminal and low voltage terminal were connected to a common ground point. For 2-wire measurements the low current terminal and the high current terminal were connected to the common ground point.

Traceability:

The values of the standard resistors are traceable to the resistance standards (a bank of 1kΩ resistors) traceable to QHR maintained by NPL India.

See figure 2.2 for the resistance traceability chart.

Conditions of measurement:

During the resistance measurements, the following conditions of measurement prevailed:

Ambient temperature: 25 °C ± 1 °C
Relative humidity: 50 %RH ± 10 %RH

4-wire measurement results:

Range	Nominal Resistance	Correction	Uncertainty	Internal Temperature (°C)
10 Ω	10 Ω	0.00016 Ω	± 0.000 058Ω	40.6
100 Ω	100 Ω	0.000 002 Ω	± 0.000 42 Ω	41.2
1 kΩ	1 kΩ	0.000 006 kΩ	± 0.000 0040 kΩ	40.4
10 kΩ	10 kΩ	0.000 023 kΩ	± 0.000 044 kΩ	40.9

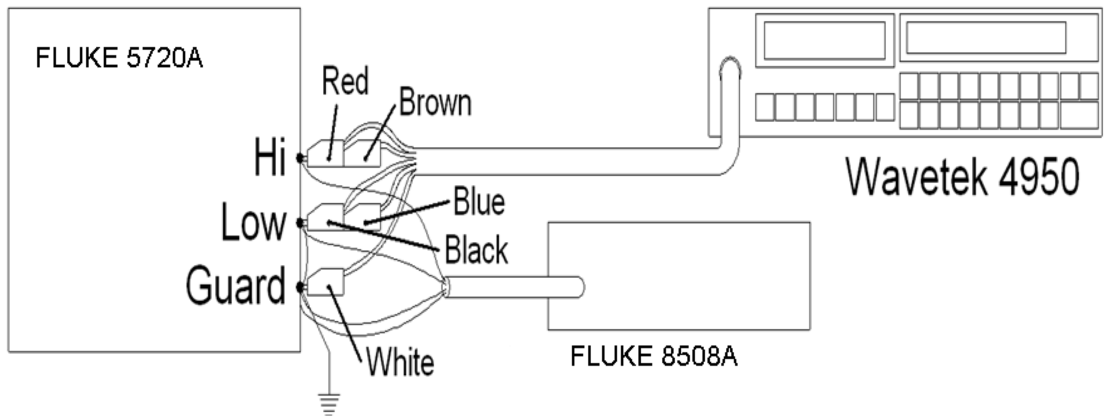
2-wire measurement results:

Range	Nominal Resistance	Correction	Uncertainty	Internal Temperature (°C)
100 kΩ	100 kΩ	0.000 02 kΩ	± 0.000 58 kΩ	40.6
1 MΩ	1 MΩ	+ 0.000 012 MΩ	± 0.000 009 6 MΩ	40.3
10 MΩ	10 MΩ	-0.000 10 MΩ	± 0.000 15 MΩ	40.8
100 MΩ	100 MΩ	0.022 21 MΩ	± 0.020 9 MΩ	41.2

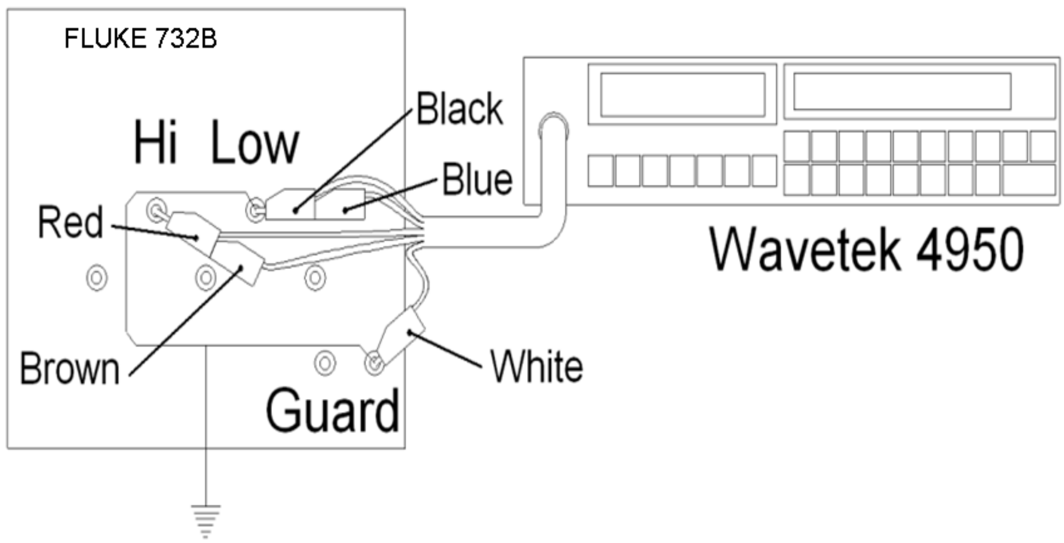
Detailed uncertainty budgets for the resistance measurements are shown in appendix 3.5.

Appendix 1: Measurement setups

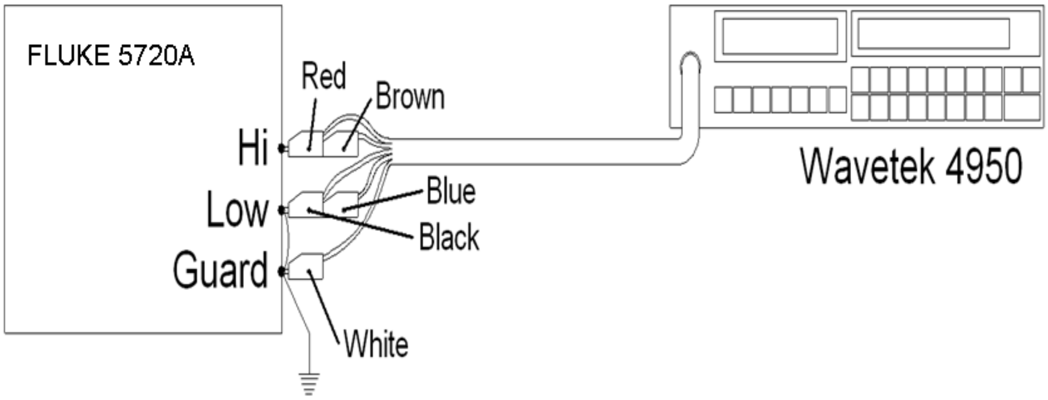
Direct Voltage



(a) 100 mV measurement



(b) 1 V and 10 V measurements



(c) 19 V to 1000 V measurements

Figure 1.1: Direct voltage measurement setups

Direct Current

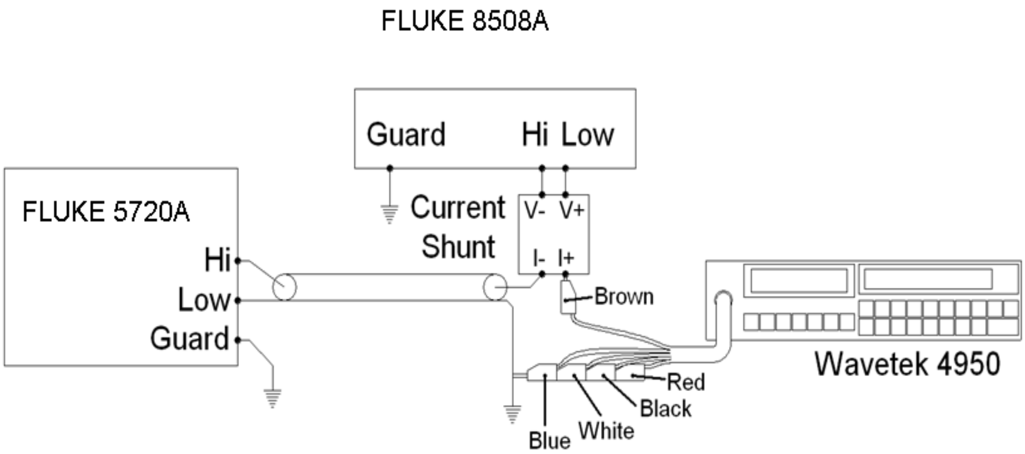
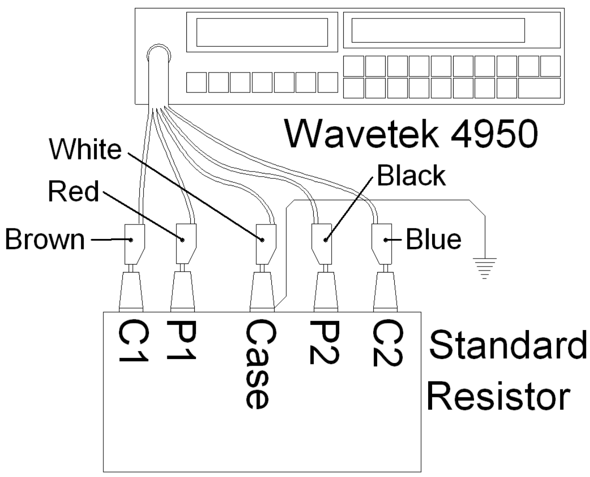
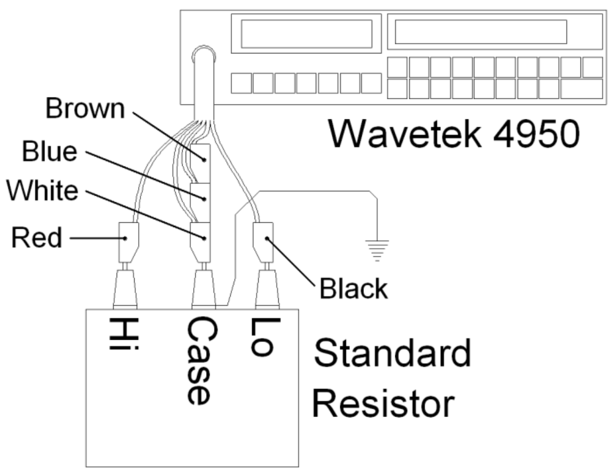


Figure 1.2: Direct current measurement setup

Resistance



(a) Four wire resistance



(b) Two wire resistance

Figure 1.5: Resistance measurement setups

Appendix 2: Traceability charts

Direct Voltage

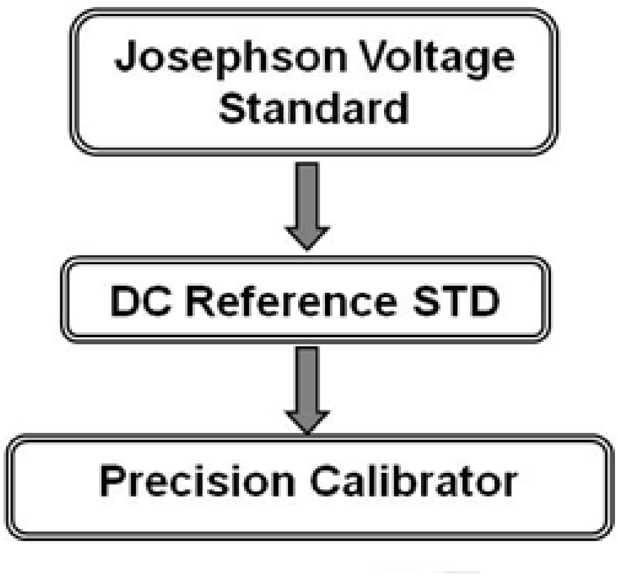


Figure 2.1: Direct voltage traceability

Resistance

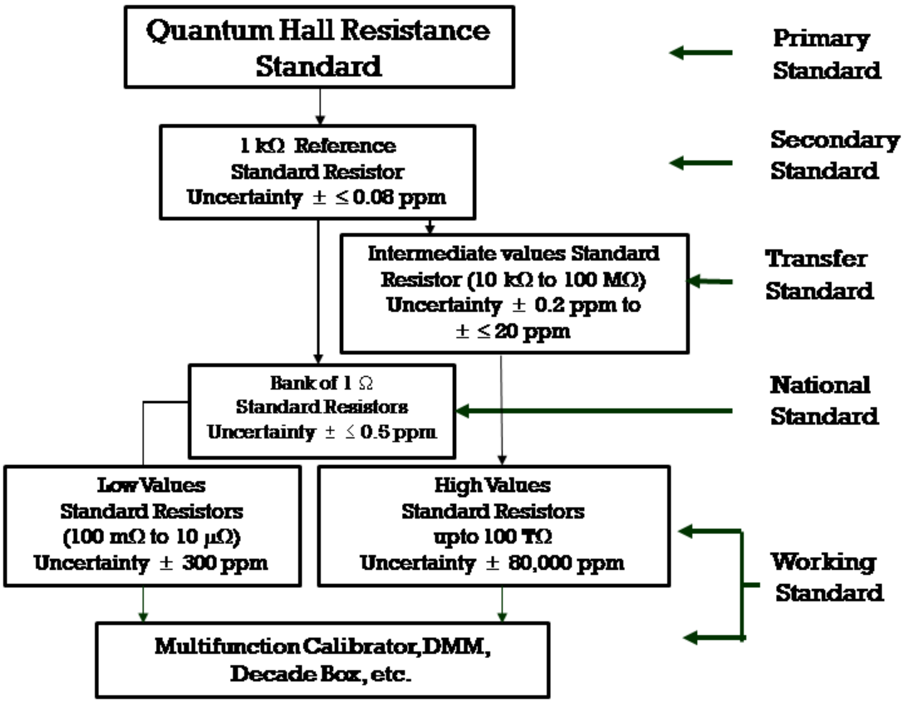


Figure 2.2: Resistance traceability

Appendix 3: Uncertainty budgets

3.1 Direct Voltage

For direct voltage at 100 mV the following components contribute to the uncertainty of measurement:

- Reference voltmeter(calibrator 5720A) uncertainty: From the last calibration report of the voltmeter.
- Reference voltmeter(calibrator 5720A) resolution: From the specification of the voltmeter
- Reference voltmeter(calibrator 5720A) repeatability: From the observed data
- Unit under test resolution: From the UUT specification
- Unit under test repeatability: From the observed data
- Unit under test stability: From tests repeated several times during the period that the instrument spent in our laboratory
- Rounding of reported value: To ensure that the reported value encompasses the calculated range of possible values

Uncertainty budget:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Reference voltmeter(calibrator 5720A) uncertainty	B	1.3	µv	2	6.50E-001	1	6.50E-01	∞
Reference voltmeter(calibrator 5720A) resolution	B	0.005	µv	1.732	0.002886836	1	2.89E-03	∞
Unit under test resolution	B	0.005	µv	1.732	0.002886836	1	2.89E-03	∞
Unit under test repeatability	A	3.46E-01	µv	1	3.46E-01	1	3.46E-01	6
Unit under test stability	B	0.3	µv	1.732	1.73E-001	1	1.73E-01	∞
Rounding of reported value	B	0.01	µv	1.732	0.0057736721	1	5.77E-03	∞
					Combined standard uncertainty		7.57E-01	µv
					Effective degrees of freedom		136.914	
					Coverage factor		1.98	
					Expanded uncertainty		1.50E+00	µv
					Expanded uncertainty		15.0	µv/v

For direct voltage at 1 V and 10 V the following components contribute to the uncertainty of measurement:

- Fluke 732A uncertainty: From the last calibration report
- Fluke 732A drift: From the history of the electronic voltage reference
- Un-cancelled thermal voltages: Estimated from the difference in zero readings before and after measurement at the nominal voltage
- Unit under test repeatability: From the observed data
- Unit under test resolution: From the unit under test specifications
- Unit under test stability: From tests repeated several times during the period that the instrument spent in our laboratory
- Rounding of reported value: To ensure that the reported value encompasses the calculated range of possible values

Uncertainty budget for 1 V measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Fluke732Auncertainty	B	0.2	µv	1.96	1.02E-001	1	1.02E-01	∞
Fluke 732A drift	B	0.1059	µv	1.732	0.0611431871	1	6.11E-02	∞
Un-cancelled thermal voltages	B	0.1	µv	1.732	0.0577367206	1	5.77E-02	∞
Unit under test resolution	B	0.05	µv	1.732	0.0288683603	1	2.89E-02	∞
Unit under test repeatability	A	2.36E-01	µv	1	**2.36E-01**	1	2.36E-01	6
Unit under test stability	B	1.5	µv	1.732	8.66E-001	1	8.66E-01	∞
Rounding of reported value	B	0.1	µv	1.732	0.0577367206	1	5.77E-02	∞
						Combined standard uncertainty	9.10E-01	
						Effective degrees of freedom	1323.936	
						Coverage factor	1.96	
						Expanded uncertainty	1.78E+00	µv
						Expanded uncertainty	1.78	µv/v

Uncertainty budget for 10 V measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Fluke732Auncertainty	B	0.35	µv	1.96	1.79E-001	1	1.79E-01	∞
Fluke 732A drift	B	-3.53	µv	1.732	-2.0381062356	1	-2.04E+00	∞
Un-cancelled thermal voltages	B	0.1	µv	1.732	0.0577367206	1	5.77E-02	∞
Unit under test resolution	B	0.5	µv	1.732	0.2886836028	1	2.89E-01	∞
Unit under test repeatability	A	1.98E+00	µv	1	**1.98E+00**	1	1.98E+00	6
Unit under test stability	B	15	µv	1.732	8.66E+000	1	8.66E+00	∞
Rounding of reported value	B	1	µv	1.732	0.5773672055	1	5.77E-01	∞
						Combined standard uncertainty	9.139	
						Effective degrees of freedom	2743.312	
						Coverage factor	1.961	
						Expanded uncertainty	17.92	µv
						Expanded uncertainty	1.792	µv/v

For direct voltage from 19 V to 1000 V the following components contribute to the uncertainty of measurement:

- Calibrator uncertainty: From the last calibration report
- Resolution of Calibrator
- Unit under test repeatability: From the observed data
- Unit under test resolution: From the unit under test specifications
- Unit under test stability: From tests repeated several times during the period that the instrument spent in our laboratory
- Rounding of reported value: To ensure that the reported value encompasses the calculated range of possible values

Uncertainty budget for 19 V measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
uncertainty contribution of Calibrator	B	6.00E+00	µV	2	3.00E+000	1	3.00E+00	∞
Resolution of Calibrator	B	**0.5**	µV	1.732	0.28868	1	2.89E-01	∞
drift since last calibration	B	0	µV	1.732	0	1	0.00E+00	∞
Unit under test resolution	B	**0.5**	µV	1.732	0.28868	1	2.89E-01	∞
Unit under test repeatability	A	**4.83E+00**	µV	1	4.83398	1	4.83E+00	6
Unit under test stability	B	**28.5**	µV	1.732	16.45497	1	1.65E+01	∞
Rounding of reported value	B	**1**	µV	1.732	0.5774	1	5.77E-01	∞
						Combined standard uncertainty	1.74E+01	
						Effective degrees of freedom	1013.051	
						Coverage factor	2	
						Expanded uncertainty	34.850	µV
						Expanded uncertainty	1.8342184889	ppm

Uncertainty budget for 100 V measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
uncertainty contribution of Calibrator	B	1.00E+01	µV	2	5.00E+000	1	5.00E+00	∞
Resolution of Calibrator	B	**5**	µV	1.732	2.8868360277	1	2.89E+00	∞
drift since last calibration	B	0	µV	1.732	0	1	0.00E+00	∞
Unit under test resolution	B	**5**	µV	1.732	2.8868360277	1	2.89E+00	∞
Unit under test repeatability	A	**2.56E+01**	µV	1	**2.56E+01**	1	2.56E+01	6
Unit under test stability	B	**200**	µV	1.732	1.15E+002	1	1.15E+02	∞
Rounding of reported value	B	**10**	µV	1.732	5.7736720554	1	5.77E+00	∞
						Combined standard uncertainty	1.19E+02	
						Effective degrees of freedom	2754.525	
						Coverage factor	2	
						Expanded uncertainty	237.196805	µV
						Expanded uncertainty	2.3719680538	ppm

Uncertainty budget for 1000 V measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
uncertainty contribution of Calibrator	B	6.00E+02	µV	2	3.00E+002	1	3.00E+02	∞
Resolution of Calibrator	B	**5**	µV	1.732	2.8868360277	1	2.89E+00	∞
drift since last calibration	B	0	µV	1.732	0	1	0.00E+00	∞
Unit under test resolution	B	**5**	µV	1.732	2.8868360277	1	2.89E+00	∞
Unit under test repeatability	A	**5.00E+02**	µV	1	**5.00E+02**	1	5.00E+02	6
Unit under test stability	B	**2000**	µV	1.732	3.46E+003	1	3.46E+03	∞
Rounding of reported value	B	**10**	µV	1.732	5.7736720554	1	5.77E+00	∞
						Combined standard uncertainty	3.51E+03	
						Effective degrees of freedom	14654.703	
						Coverage factor	2	
						Expanded uncertainty	7025.387	µV
						Expanded uncertainty	7.0253873206	ppm

3.2Direct Current

For direct current the following components contribute to the uncertainty of measurement:

- Shunt uncertainty: From the last calibration report
- Shunt drift: From the history of the shunt
- Voltmeter uncertainty: From the last calibration report
- Voltmeter drift: From the history of the voltmeter
- Voltmeter resolution: From the voltmeter specifications
- Voltmeter repeatability: From the observed data
- Unit under test repeatability: From the observed data
- Unit under test resolution: From the unit under test specifications
- Unit under test stability: From tests repeated several times during the period that the instrument spent in our laboratory
- Rounding of reported value: To ensure that the reported value encompasses the calculated range of possible values

Uncertainty budget for 1 mA measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Shunt uncertainty	B	0.4	ppm	1.96	0.20	1	0.20	∞
Shunt drift	B	0.1	ppm	1.732	0.06	1	0.06	∞
Voltmeter uncertainty	B	1	ppm	1.96	0.51	1	0.51	∞
Voltmeter drift	B	0.85	ppm	1.732	0.49	1	0.49	∞
Voltmeter resolution	B	0.05	ppm	1.732	0.03	1	0.03	∞
Voltmeter repeatability	A	0.31	ppm	1	0.31	1	0.31	7
Unit under test resolution	B	0.5	ppm	1.732	0.29	1	0.29	∞
Unit under test repeatability	A	0.43	ppm	1	0.43	1	0.43	7
Unit under test stability	B	7	ppm	1.732	4.04	1	4.04	∞
Rounding of reported value	B	1	ppm	1.732	0.58	1	0.58	∞
						Combined standard uncertainty	4.19	ppm
						Effective degrees of freedom	209124.727	
						Coverage factor	2	
						Expanded uncertainty	8.38	ppm
						Expanded uncertainty	8.3848030471	nA

Uncertainty budget for 1 A measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Shunt uncertainty	B	2	ppm	1.96	1.02	1	1.02	∞
Shunt drift	B	0.1	ppm	1.732	0.06	1	0.06	∞
Voltmeter uncertainty	B	13	ppm	1.96	6.63	1	6.63	∞
Voltmeter drift	B	0.85	ppm	1.732	0.49	1	0.49	∞
Voltmeter resolution	B	0.05	ppm	1.732	0.03	1	0.03	∞
Voltmeter repeatability	A	2.30	ppm	1	2.30	1	2.30	7
Unit under test resolution	B	0.5	ppm	1.732	0.29	1	0.29	∞
Unit under test repeatability	A	1.41	ppm	1	1.41	1	1.41	7
Unit under test stability	B	15	ppm	1.732	8.66	1	8.66	∞
Rounding of reported value	B	1	ppm	1.732	0.58	1	0.58	∞
						Combined standard uncertainty	11.31	μA/A
						Effective degrees of freedom	3526.356	
						Coverage factor	2	
						Expanded uncertainty	22.62	μA/A
						Expanded uncertainty	22.62	μA

3.5 Resistance

For resistance the following components contribute to the uncertainty of measurement:

- Reference resistor: The certified correction of the reference resistor from its latest calibration report – this component includes the uncertainty of the correction applied for the drift of the resistor from its last calibration
- Unit under test resolution: From the specifications of the unit under test
- Unit under test repeatability: From the observed data
- Unit under test stability: From tests repeated several times during the period that the instrument spent in our laboratory
- Rounding of reported value: To ensure that the reported value encompasses the calculated range of possible values

Uncertainty budget for 10 kΩ 4-wire measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Reference resistor	B	0.3	ppm	1.96	0.1530612245	1	0.1530612245	∞
Uncorrected zero offset	B	0	ppm	1.732	0	1	0	∞
Unit under test resolution	B	0.05	ppm	1.732	0.0288683603	1	0.0288683603	∞
Unit under test repeatability	A	1.34917	ppm	1	1.34917	1	1.34917	6
Unit under test stability	B	3	ppm	1.732	1.7321016166	1	1.7321016166	∞
Rounding of reported value	B	0.1	ppm	1.732	0.0577367206	1	0.0577367206	∞
						Combined standard uncertainty	2.2018243229	ppm
						Effective degrees of freedom	42.561	
						Coverage factor	2.02	
						Expanded uncertainty	4.4434613788	ppm
						Expanded uncertainty	44.4346137881	mΩ

Resistance function uncertainties

The table below summarises the uncertainty estimates for the resistance measurements. Only the standard uncertainties after reduction of the input values are shown. The degrees of freedom assigned to each component are the same as those assigned to the components in the budget for 10 kΩ measurement shown on the previous page, except for the degrees of freedom associated with the uncertainty of the standard resistor. The degrees of freedom for the standard resistors is above 100 in all cases (coverage factor k=2)

								Standard uncertainties					
Range	Nominal Resistance	Wiring Configuration	Expanded uncertainty	Expanded uncertainty (μΩ/Ω)	Coverage factor	Effective degrees of freedom	Combined standard uncertainty (μΩ/Ω)	Reference resistor (μΩ/Ω)	Uncorrected zero offset (μΩ/Ω)	Unit under test resolution (μΩ/Ω)	Unit under test repeatability (μΩ/Ω)	Unit under test stability (μΩ/Ω)	Rounding of reported value (μΩ/Ω)
10 Ω	10 Ω	4W	57.83 μΩ	5.78	2	3436	2.94	0.35	0	0.05	0.57	5	0.1
100 Ω	100 Ω	4W	418μΩ	4.18	2	63	2.09	0.3	0	0.05	1.37	3	0.1
1 kΩ	1 kΩ	4W	4.02 mΩ	4.02	2	90	2.338	0.4	0	0.05	1.027	3	0.1
10 kΩ	10 kΩ	4W	44.4 mΩ	4.44	2.02	42	2.201	0.3	0	0.05	1.34	3	0.1
100 kΩ	100 kΩ	2W	0.58mΩ	5. 8	2	9030424	2.9	0.5	0	0.005	0.1	5	0.1
1 MΩ	1 MΩ	2W	9.6 Ω	9.6	2	32357	4.8	2.3	0	0.05	0.7	8	0.1
10 MΩ	10 MΩ	2W	149.5 Ω	14.95	2	9923	7.475	5.0	0	0.05	1.4	12	0.1
100 MΩ	100 MΩ	2W	20.882 kΩ	208.82	2	603179	104.41	16	0	0.005	7	180	0.01

Report on

Measurements performed for
APMP.EM-S12
Comparison of Standards for the Calibration of AC Voltage and Current

Measurements performed on

Wavetek 4950 serial number 33528

From 22/05/2015 to 04/06/2015

Performed by

National Physical Laboratory
Dr. K.S. Krishnan Marg
New Delhi-110012

Report by

Sunidhi Luthra and Saood Ahmad
LF & HF Voltage and Current

Introduction

The APMP.EM-S12 comparison protocol requires that the travelling standard, a Wavetek model 4950 serial number 33528 (the Unit under Test – UUT), be measured at a number of points for each of its measurement functions. These are direct voltage, direct current, alternating voltage, alternating current and resistance. The measurement points are detailed in the comparison protocol.

The instrument was received on 22/05/2015. The fuse (F1) and mains voltage selection switch (S1) was checked before applying power. The UUT was allowed to stabilise for 24 hours with the power turned on before any measurements were made. The instrument's confidence test was performed and completed without any errors.

1mA is not covered in our CMC although we have performed measurements at 1mA in Low frequency range.

The measurements were performed from 22/05/2015 to 04/06/2015. The instrument was sent to the SCL, Hong Kong on 05/06/2015.

Alternating Voltage

Test methods:

Given below are the details of the test methods used by the National Physical Laboratory, India.

Alternating voltage was measured using two methods:

1. For 10 mV and 100 mV the correction of the UUT was determined by comparing the UUT reading to that obtained from an ac-dc difference measurement with a Fluke 792A thermal transfer standard using Low Voltage Thermal Voltage Converter (LVTVC) as a sourcing device. The LVTVC is used to generate an accurately known source of AC Voltage in voltage range from 2mV to 200mV. The operating principle of LVTVC is similar to that of a micropotentiometer. It incorporates 7 output ranges having full scale output voltages of 2mV, 5mV, 10mV, 20mV, 50mV, 100mV and 200mV. For a full scale output a 10V input is applied at LVTVC. The applied alternating voltage was calculated from the direct voltage and the ac-dc difference.

2. For measurements from 1V to700V the correction of the UUT was determined by comparing the UUT reading to that obtained from an ac-dc difference measurement with a Fluke 792A thermal transfer standard. The applied alternating voltage was calculated from the direct voltage measured by the UUT and the ac-dc difference.

See figure 1.1 for the alternating voltage measurement setups.

The 'Remote Guard' function was turned on for all the measurements. The input connectors were attached to a 4 banana to type-N adapter, serial number 4BN-002. The guard connector was connected into the rear of the low voltage connector.

As specified by the protocol, the 1 MHz measurements at 1V and 10V was done with 4wCct (the default setting) selected.

For the 10 mV and 100 mV measurements, the reference point was the midpoint of a type-N male to male adapter placed between the 4 banana to type-N adapter and the current shunt, and for the measurements from 1 V to 700 V the reference point was the middle of a type-N tee connecting the thermal transfer standard to the 4 banana to type-N adapter. The reference point was connected to the common ground using a copper ground strap.

Traceability:

For alternating Voltage measurements the ac-dc traceability was obtained from the ac-dc difference of set of Thermal Transfer Standard 792A used as reference standard at NPLI. The ac-dc differences for reference standard is traceable to the primary set of Multijunction thermal converters (MJTC) maintained by the LFVoltage & Current Standards at National Physical Laboratory, India.

The ac-dc differences of the primary converters have been investigated theoretically and their ac-dc differences evaluated in the frequency range from 10 Hz to 1 MHz. They have been used in CCEM Key comparisons and also inter-compared at several voltage ranges.

See figure 2.1 for traceability charts.

Conditions of measurement:

During the alternating voltage measurements, the following conditions of measurement prevailed:

Ambient temperature:	23.0 °C ± 1.0 °C
Relative humidity:	50.0 %RH ± 10.0 %RH

Measurement results: Alternating Voltage

Function	Range	Nominal Value	Nominal Frequency (kHz)	Measured Frequency (kHz)	Frequency uncertainty (± kHz)	Measurement result (correction) (V)	Uncertainty in correction (± V)	Coverage Factor	Degrees of Freedom	Internal Temp (°C)	Humidity
Alternating Voltage	0.01 V	0.01 V	0.01	0.0100076	0.0000009	0.0000085	0.0000038	2	15100	41.7	44.2
Alternating Voltage	0.01 V		0.055	0.0549966	0.0000008	0.0000017	0.0000033	2	49846	41.7	44.1
Alternating Voltage	0.01 V		1.005	1.0049904	0.00000012	0.0000028	0.0000027	2	78	41.7	44.2
Alternating Voltage	0.01 V		20	19.999823	0.000014	0.0000199	0.0000038	2	1.6E+08	41.8	44.1
Alternating Voltage	0.01 V		50	49.999558	0.000017	0.0000082	0.0000092	2	8.0E+10	41.8	43.8
Alternating Voltage	0.01 V		1000	999.99114	0.00014	0.000065	0.000041	2	2.9E+10	41.8	43.8
Alternating Voltage	0.1 V	0.1 V	0.01	0.0100070	0.0000008	0.0000071	0.0000065	2	1.1E+07	41.3	43.8
Alternating Voltage	0.1 V		0.055	0.0549986	0.0000007	0.0000045	0.0000071	2	3.1E+06	41.3	43.9
Alternating Voltage	0.1 V		1.005	1.0049924	0.00000017	0.0000018	0.0000071	2	2.5E+05	41.7	43.9
Alternating Voltage	0.1 V		20	19.999825	0.000013	0.0000296	0.0000073	2	6.7E+07	41.7	43.7
Alternating Voltage	0.1 V		50	49.999562	0.000015	0.0000083	0.0000122	2	2.6E+08	41.6	43.7
Alternating Voltage	0.1 V		1000	999.99116	0.00012	-0.000072	0.000052	2	3.7E+09	41.6	43.7
Alternating Voltage	1 V	1 V	0.01	0.0100052	0.0000006	0.000075	0.000051	2	5.4E+05	41.3	43.8
Alternating Voltage	1 V		0.055	0.0549986	0.0000006	0.000043	0.000045	2	3E+07	41.3	43.9
Alternating Voltage	1 V		1.005	1.0049940	0.00000010	0.000019	0.000048	2	9.8E+12	41.3	43.9
Alternating Voltage	1 V		20	19.999827	0.000010	0.000271	0.000050	2	1.6E+05	41.3	43.8
Alternating Voltage	1 V		50	49.999561	0.000010	0.000059	0.000105	2	8.9E+07	41.3	43.9
Alternating Voltage	1 V		1000	999.99117	0.00010	-0.00072	0.00061	2	1.3E+10	41.3	43.9
Alternating Voltage	10 V	10 V	0.01	0.0100090	0.0000008	0.00086	0.00054	2	5.2E+06	40.9	43.8
Alternating Voltage	10 V		0.055	0.0549940	0.0000007	-0.00010	0.00045	2	24847	40.9	43.7
Alternating Voltage	10 V		1.005	1.0049935	0.00000016	0.00032	0.00035	2	311521	40.9	43.9
Alternating Voltage	10 V		20	19.999821	0.000012	0.00023	0.00048	2	6.7E+05	40.9	43.8
Alternating Voltage	10 V		50	49.999554	0.000012	0.00013	0.00105	2	2.6E+06	40.9	43.8
Alternating Voltage	10 V		1000	999.99111	0.00015	-0.0009	0.006	2	2.5E+10	40.9	43.9
Alternating Voltage	19 V	19 V	1.005 kHz	1.0049860	0.00000016	0.00044	0.00087	2	5.1E+6	41.4	43.8
Alternating Voltage	100 V	100 V	0.01	0.0100080	0.0000015	0.0085	0.0056	2	9.5E+05	41.1	42.9
Alternating Voltage	100 V		0.055	0.0549932	0.0000010	0.0012	0.0041	2	9.6E+06	41.1	42.9
Alternating Voltage	100 V		1.005	1.0049860	0.00000018	0.0011	0.0036	2	1.8E+06	41.1	42.9
Alternating Voltage	100 V		20	19.999821	0.000015	0.0037	0.0054	2	2.5E+05	41.1	42.9
Alternating Voltage	100 V		50	49.999551	0.000015	-0.0010	0.0104	2	1.1E+08	41.1	44.2
Alternating Voltage	1000 V	700 V	0.055	0.0549890	0.0000020	0.006	0.040	2	3.3E+05	40.0	44.1
Alternating Voltage	1000 V		1.005	1.0049820	0.00000020	0.019	0.034	2	3.2E+06	40.0	44.2
Alternating Voltage	1000 V		20	19.999816	0.000021	0.009	0.043	2	4.2E+06	40.0	44.2
Alternating Voltage	1000 V		50	49.999547	0.000021	-0.105	0.055	2	7.3E+04	40.0	42.8

Table 1.1

Detailed uncertainty budgets for the alternating voltage measurements are shown in appendix 3.1.

Alternating Current

Given below are the details of the test methods used by the National Physical Laboratory, India.

The correction of the UUT was determined by comparing the UUT reading to that obtained from an ac-dc difference measurement using current shunts. The voltage drop across the current shunt was measured with a calibrated Thermal Transfer Standard along with Nanovoltmeter.

See figure 1.2 for the alternating current measurement setup.

The ‘Remote Guard’ function was turned on for all the measurements, and the guard terminal and low current terminal were connected to a common ground point. The low voltage and high voltage terminals were connected to the same ground point.

Traceability:
For alternating Current measurements the ac-dc traceability was obtained from the ac-dc difference of current shunt with Thermal Transfer Standard 792A used as reference standard at NPLI. The ac-dc differences for reference standard is traceable to the primary set of Multijunction thermal converters maintained by the low frequency Voltage & Current Standards at National Physical Laboratory, India.

The ac-dc differences of the primary converters have been investigated theoretically and their ac-dc differences evaluated in the frequency range from 10 Hz to 1 MHz. They have been used in CCEM Key comparisons and also inter-compared at several voltage ranges.

See 2.2 for the ac-dc difference traceability chart.

Conditions of measurement:

During the alternating current measurements, the following conditions of measurement prevailed:

Ambient temperature: 23.0 °C ± 1.0 °C
Relative humidity: 50.0 %RH ± 10.0 %RH

Measurement results: Alternating Current

Function	Range	Nominal Value	Nominal Frequency (kHz)	Measured Frequency (kHz)	Frequency uncertainty (kHz)	Measurement result (correction) (V)	Uncertainty (V)	Coverage Factor	Degrees of Freedom	Internal Temp (°C)	Humidity
Alternating Current	0.001 A	0.001 A	0.055	0.0549910	0.0000012	0.000000103	0.000000083	2	2.3E+07	41.8	44.5
Alternating Current	0.001 A		1.005	1.0049850	0.0000010	0.000000096	0.000000079	2	10251	41.6	44.1
Alternating Current	0.001 A		5.000	4.999986	0.0000010	-0.000000620	0.000000105	2	1.4E+06	41.8	44.3
Alternating Current	1 A	1 A	0.055	0.0549976	0.0000015	-0.000010	0.000070	2	2.6E+07	41.4	44.9
Alternating Current	1 A		1.005	1.0049960	0.0000013	-0.000013	0.000062	2	8.6E+06	41.1	44.9
Alternating Current	1 A		5.000	4.999989	0.0000013	-0.000072	0.000068	2	5.1E+07	41.3	44.9

Table 1.2

Detailed uncertainty budgets for the alternating current measurements are shown in appendix 3.2.

Frequency

The protocol requires that the frequency of the sources used for alternating voltage and alternating current be measured and reported.

Test methods:

For the alternating voltage and current measurements, a Fluke model 5720A was used. The correction of the calibrators was determined by measuring the frequency for an output of 1 V using a frequency counter referenced to the Cesium atomic standard.

A measurement with a 1 V output only is sufficient to cover all the ranges and functions as the same time-base is used to generate the frequency for all output voltages and currents.

See figure 1.3 for the frequency measurement setup and table 1.1 & 1.2 for measurement results.

The 'External Guard' function of the calibrator was turned off for all the measurements, and the guard terminal was connected to a common ground point. This was done to provide the measurement circuit with a reference point because the counter input was floating.

Traceability:

The frequency measurements were traceable to the Cesium atomic Standard maintained by the Time and Frequency project of the National Physical Laboratory, India.

Detailed uncertainty budgets for the frequency measurements are shown in appendix 3.3.

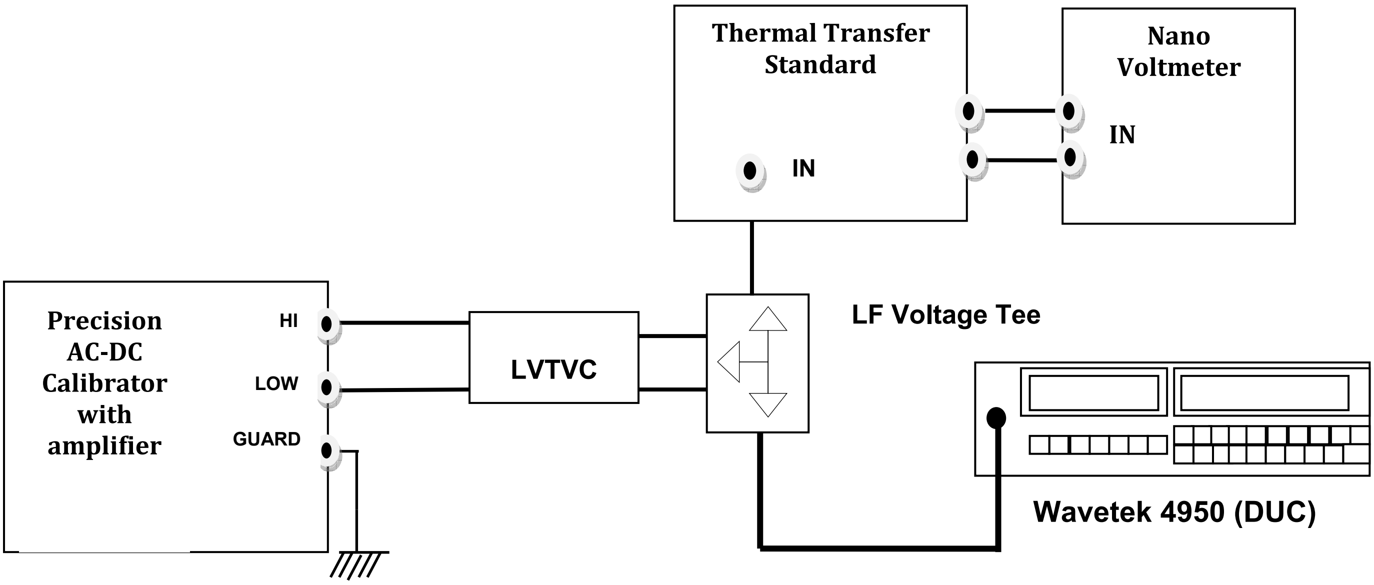
Conditions of measurement:

During the frequency measurements, the following conditions of measurement prevailed:

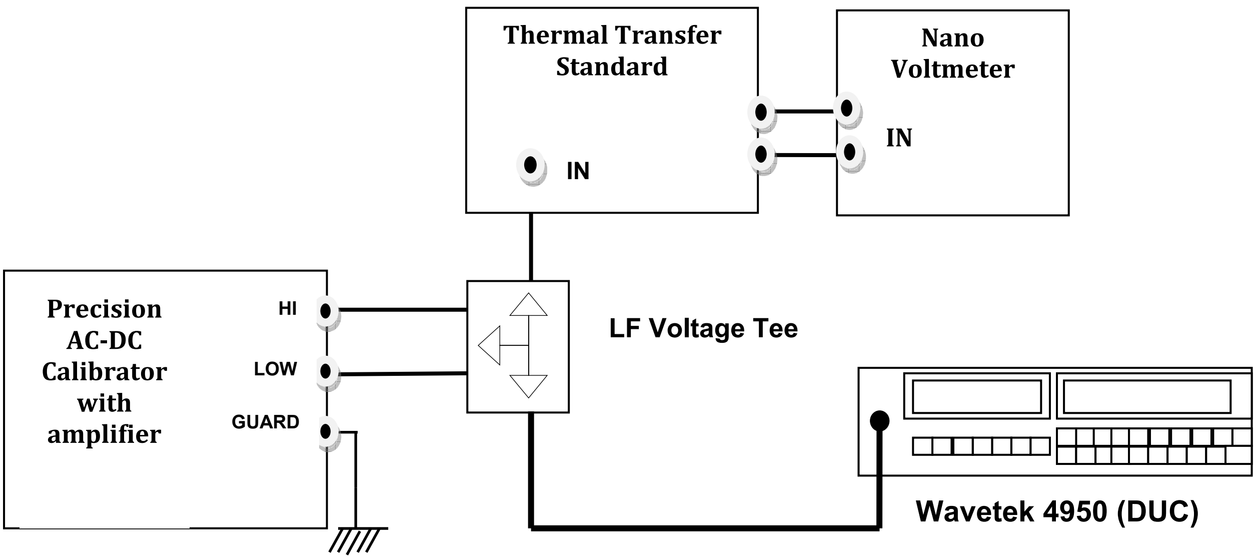
Ambient temperature:	23.0 °C ± 1.0 °C
Relative humidity:	50.0 %RH ± 10.0 %RH

Appendix 1: Measurement setups

Alternating Voltage:



(a) 10 mV and 100 mV



(b) 1 V to 700 V

Figure 1.1: Alternating voltage measurement setups

Alternating Current

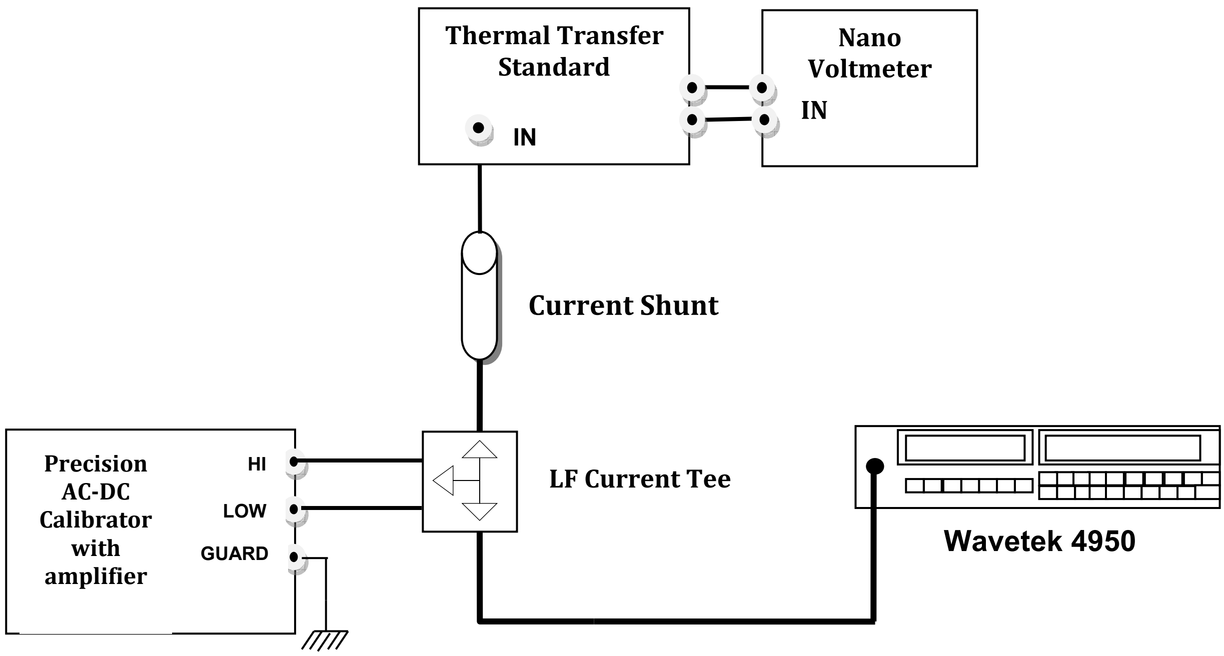


Figure 1.2: Alternating Current measurement setup

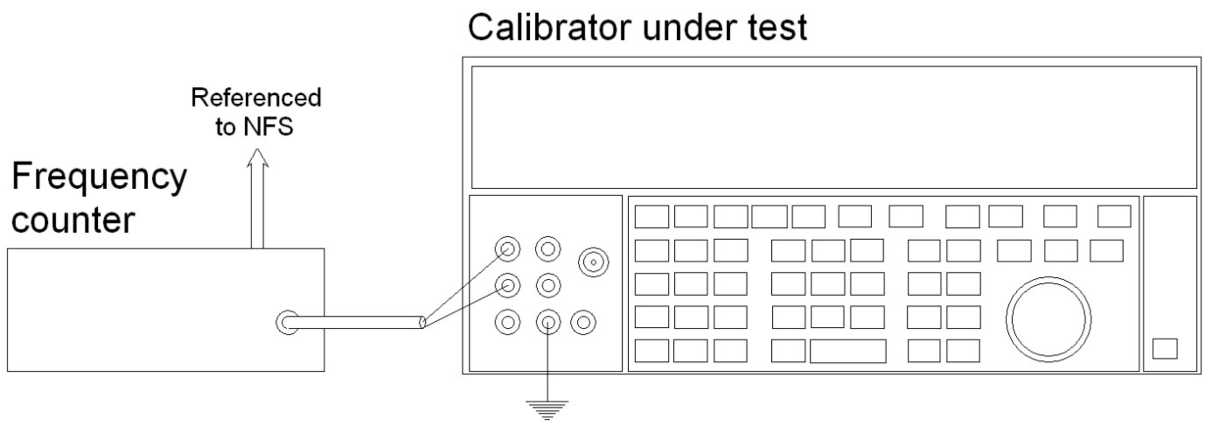


Figure 1.3: Frequency measurement setup

Appendix 2: Traceability charts

AC-DC difference traceability chart for Voltage

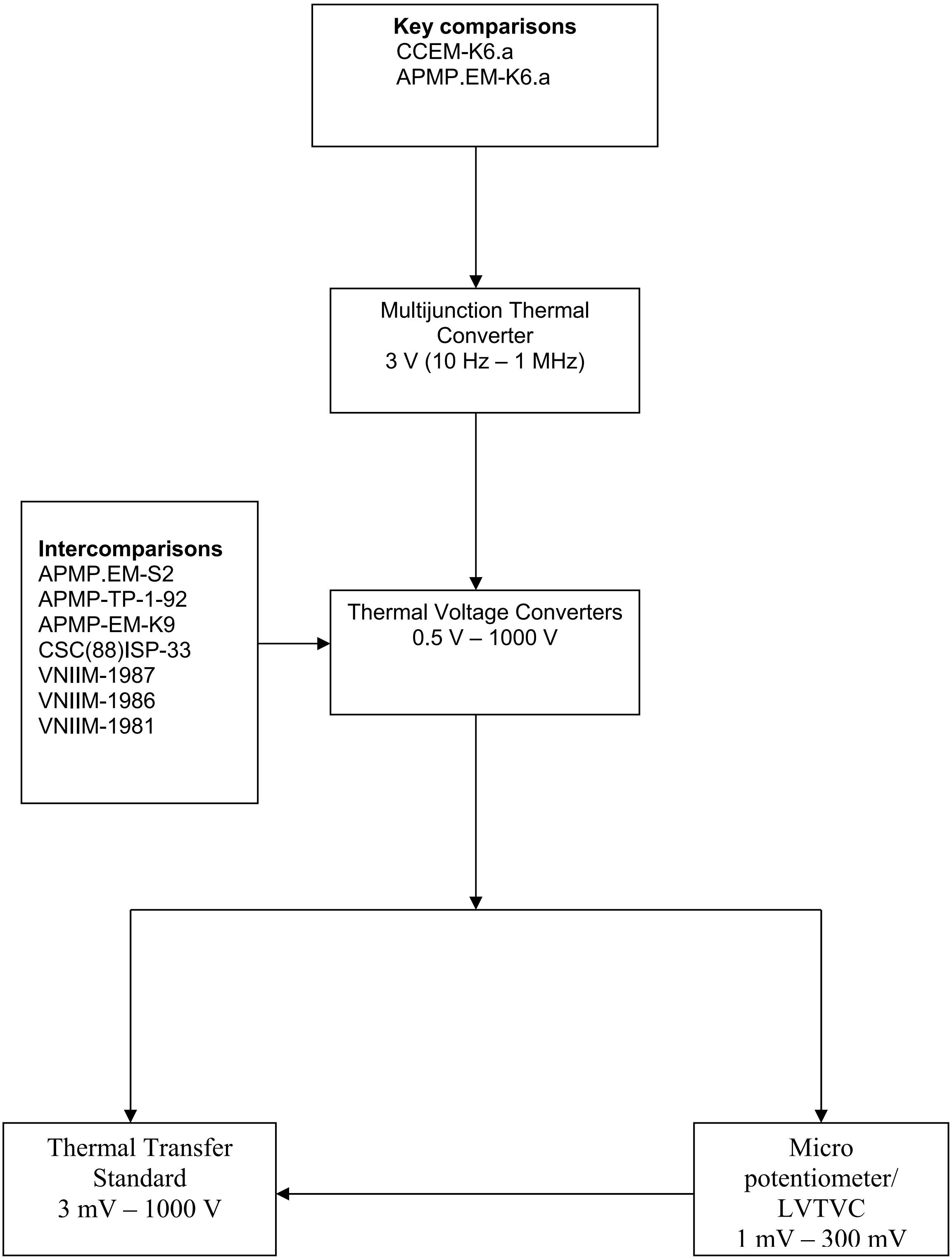


Figure 2.1 Voltage traceability chart

AC-DC difference traceability chart for Current

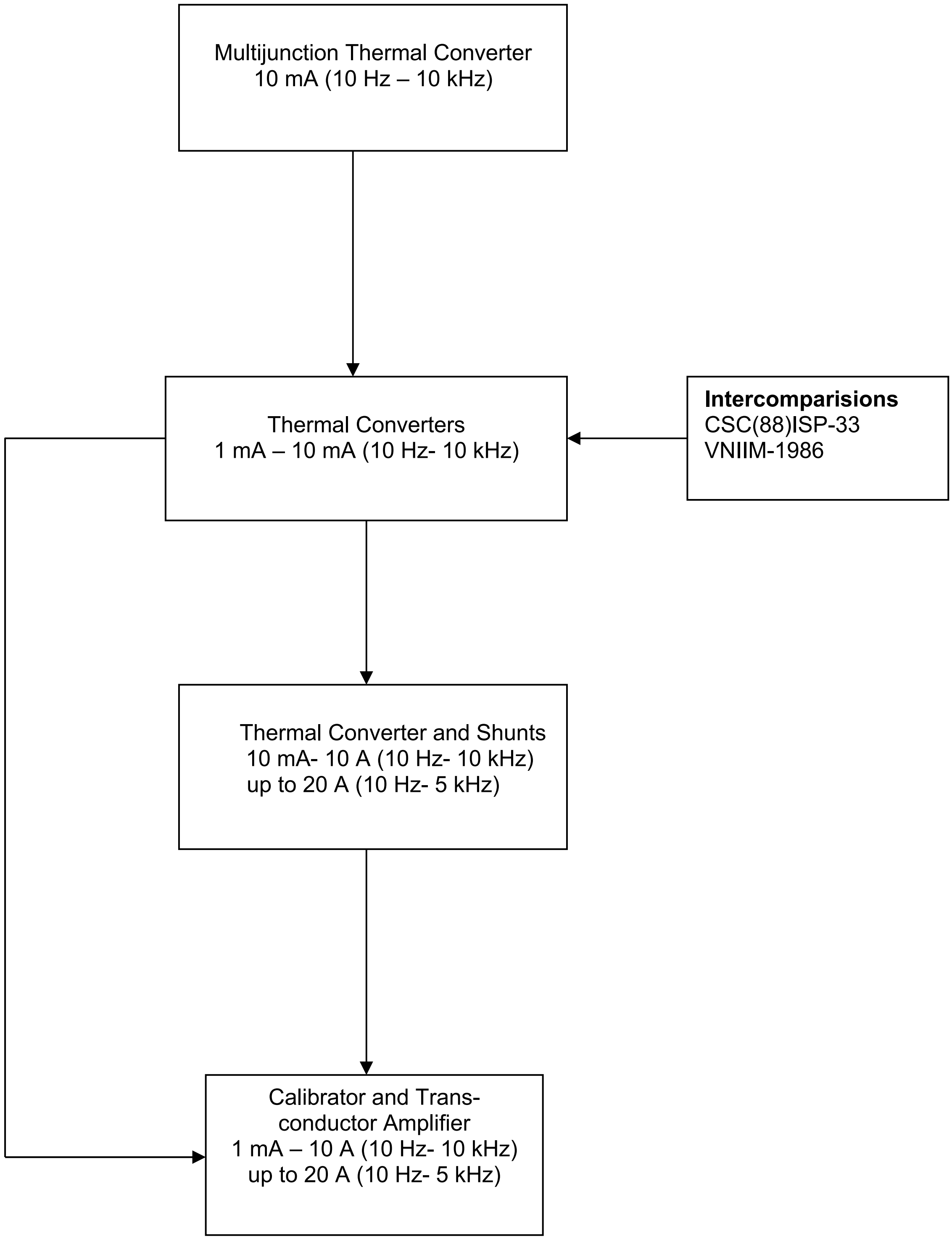


Figure 2.2Current traceability chart

Appendix 3: Uncertainty budgets

3.1Alternating Voltage

Two methods were used to perform alternating voltage measurements. For 10 mV and 100 mV the measurements were done against a thermal transfer standard and a precision shunt by using Low voltage thermal converter as sourcing device. The measurements from 1 V to 700 V were done against a thermal transfer standard.

For alternating voltage from 10 mV to 700 V the following components contribute to the uncertainty of measurement:

- Reference ac-dc difference: From the last calibration report and history of the thermal transfer standard
- Reference drift: From history of the thermal transfer standard
- Cables and connectors: At higher frequencies this can be significant – an experiment was performed to estimate the effect of cables and connectors
- Ac-dc transfer repeatability: From the observed data
- Unit under test DCV repeatability: From the observed data
- Unit under test ACV repeatability: From the observed data
- Unit under test resolution: From the unit under test specifications
- Unit under test stability: From tests repeated several times during the period
- that the instrument spent in our laboratory
- Rounding of reported value: To ensure that the reported value encompasses the calculated range of possible values

The uncertainty budget for each measurement is given below:

Uncertainty budget for 10 mV and 10 Hz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	
Unc due to Reference Std	B	44.5	µV/V	2	22.2	1	22.2	
Reference drift	B	32.0	µV/V	1.732	18.5	1	18.5	
Meas. Setup/Cables&Connectors	B	325.0	µV/V	1.732	187.6	1	187.6	
Type A uncertainty	A	24.4	µV/V	1	24.4	1	24.4	
UUT DCV repeatability	A	1.4	µV/V	1	1.4	1	1.4	
UUT ACV repeatability	A	1.6	µV/V	1	1.6	1	1.6	
UUT resolution	B	0.5	µV/V	1.732	0.3	1	0.3	
UUT stability	B	4.0	µV/V	1.732	2.3	1	2.3	
Rounding of reported value	B	0.5	µV/V	1.732	0.3	1	0.3	
nanovoltmeter std	B	1.0	µV/V	1.732	0.6	1	0.6	
n value std unc	B	2.0	µV/V	1.732	1.2	1	1.2	
						Combined standard uncertainty	191.4	µV/V
						Effective degrees of freedom	15100	
						Coverage factor	2	
						Exp. Uncertainty(V)	0.0000038	V

Uncertainty budget for 10 mV and 55 Hz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	
Unc due to Reference Std	B	37.1	µV/V	2	18.6	1	18.6	
Reference drift	B	28.0	µV/V	1.732	16.2	1	16.2	
Meas. Setup/Cables&Connectors	B	280.0	µV/V	1.732	161.7	1	161.7	
Type A uncertainty	A	15.5	µV/V	1	15.5	1	15.5	
UUT DCV repeatability	A	0.9	µV/V	1	0.9	1	0.9	
UUT ACV repeatability	A	1.3	µV/V	1	1.3	1	1.3	
UUT resolution	B	0.5	µV/V	1.732	0.3	1	0.3	
UUT stability	B	3.5	µV/V	1.732	2.0	1	2.0	
Rounding of reported value	B	0.5	µV/V	1.732	0.3	1	0.3	
nanovoltmeter std	B	1.0	µV/V	1.732	0.6	1	0.6	
n value std unc	B	2.0	µV/V	1.732	1.2	1	1.2	
Combined standard uncertainty							164.3	µV/V
Effective degrees of freedom							49846	
Coverage factor							2	
Exp. Uncertainty(V)							0.0000033	V

Uncertainty budget for 10mV 1.005 kHz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	
Unc due to Reference Std	B	36.80	µV/V	2	18.4	1	18.4	
Reference drift	B	28.0	µV/V	1.732	16.2	1	16.2	
Meas. Setup/Cables&Connectors	B	200	µV/V	1.732	115.5	1	115.5	
Type A uncertainty	A	64.0	µV/V	1	64.0	1	64.0	
UUT DCV repeatability	A	1.4	µV/V	1	1.4	1	0.8	
UUT ACV repeatability	A	0.9	µV/V	1	0.9	1	0.5	
UUT resolution	B	0.5	µV/V	1.732	0.3	1	0.3	
UUT stability	B	2.5	µV/V	1.732	1.4	1	1.4	
Rounding of reported value	B	0.5	µV/V	1.732	0.3	1	0.3	
nanovoltmeter std	B	1.0	µV/V	1.732	0.6	1	0.6	
n value std unc	B	2.0	µV/V	1.732	1.2	1	1.2	
Combined standard uncertainty							134.3	µV/V
Effective degrees of freedom							78	
Coverage factor							2	
Exp. Uncertainty(V)							0.0000027	V

Uncertainty budget for 10mV 20 kHz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	
Unc due to Reference Std	B	38.26	µV/V	2	19.1	1	19.1	
Reference drift	B	28.0	µV/V	1.732	16.2	1	16.2	
Meas. Setup/Cables&Connectors	B	330	µV/V	1.732	190.5	1	190.5	
Type A uncertainty	A	2.4	µV/V	1	2.4	1	2.4	
UUT DCV repeatability	A	1.3	µV/V	1	1.3	1	1.3	
UUT ACV repeatability	A	1.1	µV/V	1	1.1	1	1.1	
UUT resolution	B	0.5	µV/V	1.732	0.3	1	0.3	
UUT stability	B	3.0	µV/V	1.732	1.7	1	1.7	
Rounding of reported value	B	0.5	µV/V	1.732	0.3	1	0.3	
nanovoltmeter std	B	1.0	µV/V	1.732	0.6	1	0.6	
n value std unc	B	2.0	µV/V	1.732	1.2	1	1.2	
						Combined standard uncertainty	192.2	µV/V
						Effective degrees of freedom	1.6E+08	
						Coverage factor	2	
						Exp. Uncertainty(V)	0.0000038	V

Uncertainty budget for 10mV 50 kHzmeasurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	
Unc due to Reference Std	B	59.6	µV/V	2	29.8	1	19.1	
Reference drift	B	30.0	µV/V	1.732	17.3	1	16.2	
Meas. Setup/Cables&Connectors	B	795.0	µV/V	1.732	459.0	1	190.5	
Type A uncertainty	A	1.2	µV/V	1	1.2	1	2.4	
UUT DCV repeatability	A	1.1	µV/V	1	1.1	1	1.3	
UUT ACV repeatability	A	1.2	µV/V	1	1.2	1	1.1	
UUT resolution	B	0.5	µV/V	1.732	0.3	1	0.3	
UUT stability	B	3.0	µV/V	1.732	1.7	1	1.7	
Rounding of reported value	B	0.5	µV/V	1.732	0.3	1	0.3	
nanovoltmeter std	B	1.0	µV/V	1.732	0.6	1	0.6	
n value std unc	B	2.0	µV/V	1.732	1.2	1	1.2	
Combined standard uncertainty							460.3	µV/V
Effective degrees of freedom							8.0E+10	
Coverage factor							2	
Exp. Uncertainty(V)							0.0000092	V

Uncertainty budget for 10mV 1MHzmeasurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	
Unc due to Reference Std	B	165.6	µV/V	2	82.8	1	82.8	
Reference drift	B	150.0	µV/V	1.732	86.6	1	86.6	
Meas. Setup/Cables&Connectors	B	3210	µV/V	1.732	1853.3	1	1853.3	
Type A uncertainty	A	7.1	µV/V	1	7.1	1	7.1	
UUT DCV repeatability	A	1.1	µV/V	1	1.1	1	1.1	
UUT ACV repeatability	A	894.4	µV/V	1	894.4	1	894.4	
UUT resolution	B	0.5	µV/V	1.732	0.3	1	0.3	
UUT stability	B	2.5	µV/V	1.732	1.4	1	1.4	
Rounding of reported value	B	0.5	µV/V	1.732	0.3	1	0.3	
nanovoltmeter std	B	1.0	µV/V	1.732	0.6	1	0.6	
n value std unc	B	2.0	µV/V	1.732	1.2	1	1.2	
						Combined standard uncertainty	2061.3	µV/V
						Effective degrees of freedom	2.9E+10	
						Coverage factor	2	
						Exp. Uncertainty(V)	0.000041	V

Uncertainty budget for 100mV 10 Hzmeasurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	
Unc due to Reference Std	B	41.0	µV/V	2	20.5	1	20.5	
Reference drift	B	21.0	µV/V	1.732	12.1	1	12.1	
Meas. Setup/Cables&Connectors	B	30	µV/V	1.732	17.3	1	17.3	
Type A uncertainty	A	0.8	µV/V	1	0.8	1	0.8	
UUT DCV repeatability	A	2.2	µV/V	1	2.2	1	2.2	
UUT ACV repeatability	A	8.8	µV/V	1	8.8	1	8.8	
UUT resolution	B	0.5	µV/V	1.732	0.3	1	0.3	
UUT stability	B	18.5	µV/V	1.732	10.7	1	10.7	
Rounding of reported value	B	0.5	µV/V	1.732	0.3	1	0.3	
nanovoltmeter std	B	1.0	µV/V	1.732	0.6	1	0.6	
n value std unc	B	2.0	µV/V	1.732	1.2	1	1.2	
						Combined standard uncertainty	32.7	µV/V
						Effective degrees of freedom	1.1E+07	
						Coverage factor	2	
						Exp. Uncertainty(V)	0.0000065	V

Uncertainty budget for 100mV 55 Hzmeasurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	
Unc due to Reference Std	B	29.3	µV/V	2	14.6	1	14.6	
Reference drift	B	5.0	µV/V	1.732	2.9	1	2.9	
Meas. Setup/Cables&Connectors	B	55	µV/V	1.732	31.8	1	31.8	
Type A uncertainty	A	1.2	µV/V	1	1.2	1	1.2	
UUT DCV repeatability	A	2.1	µV/V	1	2.1	1	2.1	
UUT ACV repeatability	A	1.3	µV/V	1	1.3	1	1.3	
UUT resolution	B	0.5	µV/V	1.732	0.3	1	0.3	
UUT stability	B	5.5	µV/V	1.732	3.2	1	3.2	
Rounding of reported value	B	0.5	µV/V	1.732	0.3	1	0.3	
nanovoltmeter std	B	1.0	µV/V	1.732	0.6	1	0.6	
n value std unc	B	2.0	µV/V	1.732	1.2	1	1.2	
Combined standard uncertainty							35.4	µV/V
Effective degrees of freedom							3.1E+06	
Coverage factor							2	
Exp. Uncertainty(V)							0.0000071	V

Uncertainty budget for 100mV 1.005 kHzmeasurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	
Unc due to Reference Std	B	29.3	µV/V	2	14.7	1	14.7	
Reference drift	B	5.0	µV/V	1.732	2.9	1	2.9	
Meas. Setup/Cables&Connectors	B	55	µV/V	1.732	31.8	1	31.8	
Type A uncertainty	A	1.2	µV/V	1	2.2	1	2.2	
UUT DCV repeatability	A	2.1	µV/V	1	0.8	1	0.8	
UUT ACV repeatability	A	1.3	µV/V	1	1.5	1	1.5	
UUT resolution	B	0.5	µV/V	1.732	0.3	1	0.3	
UUT stability	B	4.5	µV/V	1.732	2.6	1	2.6	
Rounding of reported value	B	0.5	µV/V	1.732	0.3	1	0.3	
nanovoltmeter std	B	1.0	µV/V	1.732	0.6	1	0.6	
n value std unc	B	2.0	µV/V	1.732	1.2	1	1.2	
Combined standard uncertainty							35.3	µV/V
Effective degrees of freedom							2.5E+05	
Coverage factor							2	
Exp. Uncertainty(V)							0.0000071	V

Uncertainty budget for 100mV 20 kHz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	
Unc due to Reference Std	B	29.8	μV/V	2	14.9	1	14.9	
Reference drift	B	5.0	μV/V	1.732	2.9	1	2.9	
Meas. Setup/Cables&Connectors	B	56	μV/V	1.732	32.0	1	32.0	
Type A uncertainty	A	0.6	μV/V	1	0.6	1	0.6	
UUT DCV repeatability	A	3.0	μV/V	1	3.0	1	3.0	
UUT ACV repeatability	A	6.9	μV/V	1	6.9	1	6.9	
UUT resolution	B	0.5	μV/V	1.732	0.3	1	0.3	
UUT stability	B	0.5	μV/V	1.732	0.3	1	0.3	
Rounding of reported value	B	0.5	μV/V	1.732	0.3	1	0.3	
nanovoltmeter std	B	1.0	μV/V	1.732	0.6	1	0.6	
n value std unc	B	2.0	μV/V	1.732	1.2	1	1.2	
						Combined standard uncertainty	36.3	μV/V
						Effective degrees of freedom	6.7E+07	
						Coverage factor	2	
						Exp. Uncertainty(V)	0.0000073	V

Uncertainty budget for 100mV 50 kHzmeasurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	
Unc due to Reference Std	B	35.82	µV/V	2	17.9	1	17.9	
Reference drift	B	10.0	µV/V	1.732	5.8	1	5.8	
Meas. Setup/Cables&Connectors	B	100	µV/V	1.732	57.7	1	57.7	
Type A uncertainty	A	0.7	µV/V	1	0.7	1	0.7	
UUT DCV repeatability	A	0.7	µV/V	1	0.7	1	0.7	
UUT ACV repeatability	A	1.3	µV/V	1	1.3	1	1.3	
UUT resolution	B	0.5	µV/V	1.732	0.3	1	0.3	
UUT stability	B	5.5	µV/V	1.732	3.2	1	3.2	
Rounding of reported value	B	0.5	µV/V	1.732	0.3	1	0.3	
nanovoltmeter std	B	1.0	µV/V	1.732	0.6	1	0.6	
n value std unc	B	2.0	µV/V	1.732	1.2	1	1.2	
Combined standard uncertainty							60.9	µV/V
Effective degrees of freedom							2.6E+08	
Coverage factor							2	
Exp. Uncertainty(V)							0.0000122	V

Uncertainty budget for 100mV 1 MHz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	
Unc due to Reference Std	B	78.4	μV/V	2	39.2	1	39.2	
Reference drift	B	60	μV/V	1.732	34.6	1	34.6	
Meas. Setup/Cables&Connectors	B	440	μV/V	1.732	254.0	1	254.0	
Type A uncertainty	A	1.5	μV/V	1	1.5	1	1.5	
UUT DCV repeatability	A	2.2	μV/V	1	2.2	1	2.2	
UUT ACV repeatability	A	16.7	μV/V	1	16.7	1	16.7	
UUT resolution	B	0.5	μV/V	1.732	0.3	1	0.3	
UUT stability	B	27.0	μV/V	1.732	15.6	1	15.6	
Rounding of reported value	B	0.5	μV/V	1.732	0.3	1	0.3	
nanovoltmeter std	B	1.0	μV/V	1.732	0.6	1	0.6	
n value std unc	B	2.0	μV/V	1.732	1.2	1	1.2	
						Combined standard uncertainty	260.4	μV/V
						Effective degrees of freedom	3.7E+09	
						Coverage factor	2	
						Exp. Uncertainty(V)	0.000052	V

Uncertainty budget for 1V 10Hz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	
Unc due to Reference Std	B	10.1	µV/V	2	5.0	1	39.2	
Reference drift	B	19	µV/V	1.732	11.0	1	34.6	
Meas. Setup/Cables&Connectors	B	39	µV/V	1.732	22.5	1	254.0	
Type A uncertainty	A	1.3	µV/V	1	1.3	1	1.5	
UUT DCV repeatability	A	0.2	µV/V	1	0.2	1	2.2	
UUT ACV repeatability	A	1.2	µV/V	1	1.2	1	16.7	
UUT resolution	B	0.5	µV/V	1.732	0.3	1	0.3	
UUT stability	B	3.5	µV/V	1.732	2.0	1	15.6	
Rounding of reported value	B	0.5	µV/V	1.732	0.3	1	0.3	
nanovoltmeter std	B	1.0	µV/V	1.732	0.6	1	0.6	
n value std unc	B	2.0	µV/V	1.732	1.2	1	1.2	
Combined standard uncertainty							25.7	µV/V
Effective degrees of freedom							5.4E+05	
Coverage factor							2	
Exp. Uncertainty(V)							0.000051	V

Uncertainty budget for 1V 55Hz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	
Unc due to Reference Std	B	7.6	µV/V	2	3.8	1	3.8	
Reference drift	B	3	µV/V	1.732	1.7	1	1.7	
Meas. Setup/Cables&Connectors	B	38	µV/V	1.732	21.9	1	21.9	
Type A uncertainty	A	0.4	µV/V	1	0.4	1	0.4	
UUT DCV repeatability	A	0.1	µV/V	1	0.1	1	0.1	
UUT ACV repeatability	A	0.7	µV/V	1	0.7	1	0.7	
UUT resolution	B	0.5	µV/V	1.732	0.3	1	0.3	
UUT stability	B	2.5	µV/V	1.732	1.4	1	1.4	
Rounding of reported value	B	0.5	µV/V	1.732	0.3	1	0.3	
nanovoltmeter std	B	1.0	µV/V	1.732	0.6	1	0.6	
n value std unc	B	2.0	µV/V	1.732	1.2	1	1.2	
Combined standard uncertainty							22.5	µV/V
Effective degrees of freedom							3E+07	
Coverage factor							2	
Exp. Uncertainty(V)							0.000045	V

Uncertainty budget for 1V 1.005 kHz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	
Unc due to Reference Std	B	7.6	µV/V	2	3.8	1	3.8	
Reference drift	B	2	µV/V	1.732	0.9	1	0.9	
Meas. Setup/Cables&Connectors	B	41	µV/V	1.732	23.7	1	23.7	
Type A uncertainty	A	0.02	µV/V	1	0.02	1	0.0	
UUT DCV repeatability	A	0.1	µV/V	1	0.1	1	0.1	
UUT ACV repeatability	A	0.6	µV/V	1	0.6	1	0.6	
UUT resolution	B	0.5	µV/V	1.732	0.3	1	0.3	
UUT stability	B	3.5	µV/V	1.732	2.0	1	2.0	
Rounding of reported value	B	0.5	µV/V	1.732	0.3	1	0.3	
nanovoltmeter std	B	1.0	µV/V	1.732	0.6	1	0.6	
n value std unc	B	2.0	µV/V	1.732	1.2	1	1.2	
						Combined standard uncertainty	24	µV/V
						Effective degrees of freedom	9.8E+12	
						Coverage factor	2	
						Exp. Uncertainty(V)	0.000048	V

Uncertainty budget for 1V 20 kHz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	
Unc due to Reference Std	B	7.55	μV/V	2	3.8	1	3.8	
Reference drift	B	2	μV/V	1.732	0.9	1	0.9	
Meas. Setup/Cables&Connectors	B	42.5	μV/V	1.732	24.5	1	24.5	
Type A uncertainty	A	0.02	μV/V	1	1.8	1	1.8	
UUT DCV repeatability	A	0.1	μV/V	1	0.1	1	0.1	
UUT ACV repeatability	A	0.6	μV/V	1	0.6	1	0.6	
UUT resolution	B	0.5	μV/V	1.732	0.3	1	0.3	
UUT stability	B	3.5	μV/V	1.732	1.4	1	1.4	
Rounding of reported value	B	0.5	μV/V	1.732	0.3	1	0.3	
nanovoltmeter std	B	1.0	μV/V	1.732	0.6	1	0.6	
n value std unc	B	2.0	μV/V	1.732	1.2	1	1.2	
						Combined standard uncertainty	25.0	μV/V
						Effective degrees of freedom	1.6E+05	
						Coverage factor	2	
						Exp. Uncertainty(V)	0.000050	V

Uncertainty budget for 1V 50 kHz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	
Unc due to Reference Std	B	10.2	µV/V	2	5.1	1	5.1	
Reference drift	B	4	µV/V	1.732	2.3	1	2.3	
Meas. Setup/Cables&Connectors	B	35	µV/V	1.732	20.2	1	20.2	
Type A uncertainty	A	0.8	µV/V	1	0.8	1	0.8	
UUT DCV repeatability	A	0.1	µV/V	1	0.1	1	0.1	
UUT ACV repeatability	A	1.2	µV/V	1	1.2	1	1.2	
UUT resolution	B	0.5	µV/V	1.732	0.3	1	0.3	
UUT stability	B	83.5	µV/V	1.732	48.2	1	48.2	
Rounding of reported value	B	0.5	µV/V	1.732	0.3	1	0.3	
nanovoltmeter std	B	1.0	µV/V	1.732	0.6	1	0.6	
n value std unc	B	2.0	µV/V	1.732	1.2	1	1.2	
						Combined standard uncertainty	52.6	µV/V
						Effective degrees of freedom	8.9E+07	
						Coverage factor	2	
						Exp. Uncertainty(V)	0.000105	V

Uncertainty budget for 1V 1MHzmeasurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	
Unc due to Reference Std	B	18.3	µV/V	2	9.2	1	9.2	
Reference drift	B	45	µV/V	1.732	26.0	1	26.0	
Meas. Setup/Cables&Connectors	B	525	µV/V	1.732	303.1	1	303.1	
Type A uncertainty	A	1.3	µV/V	1	1.3	1	1.3	
UUT DCV repeatability	A	0.1	µV/V	1	0.1	1	0.1	
UUT ACV repeatability	A	1.2	µV/V	1	1.2	1	1.2	
UUT resolution	B	0.5	µV/V	1.732	0.3	1	0.3	
UUT stability	B	3.0	µV/V	1.732	1.7	1	1.7	
Rounding of reported value	B	0.5	µV/V	1.732	0.3	1	0.3	
nanovoltmeter std	B	1.0	µV/V	1.732	0.6	1	0.6	
n value std unc	B	2.0	µV/V	1.732	1.2	1	1.2	
						Combined standard uncertainty	304.4	µV/V
						Effective degrees of freedom	1.3E+10	
						Coverage factor	2	
						Exp. Uncertainty(V)	0.00061	V

Uncertainty budget for 10V 10Hz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	
Unc due to Reference Std	B	13.99	μV/V	2	7.0	1	7.0	
Reference drift	B	19	μV/V	1.732	11.0	1	11.0	
Meas. Setup/Cables&Connectors	B	41	μV/V	1.732	23.7	1	23.7	
Type A uncertainty	A	0.8	μV/V	1	0.8	1	0.8	
UUT DCV repeatability	A	0.1	μV/V	1	0.1	1	0.1	
UUT ACV repeatability	A	1.6	μV/V	1	1.6	1	1.6	
UUT resolution	B	0.5	μV/V	1.732	0.3	1	0.3	
UUT stability	B	2.0	μV/V	1.732	1.2	1	1.2	
Rounding of reported value	B	0.5	μV/V	1.732	0.3	1	0.3	
nanovoltmeter std	B	1.0	μV/V	1.732	0.6	1	0.6	
n value std unc	B	2.0	μV/V	1.732	1.2	1	1.2	
						Combined standard uncertainty	27.1	μV/V
						Effective degrees of freedom	5.2E+06	
						Coverage factor	2	
						Exp. Uncertainty(V)	0.00054	V

Uncertainty budget for 10V 55Hz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	
Unc due to Reference Std	B	10.7	µV/V	2	5.3	1	5.3	
Reference drift	B	3	µV/V	1.732	1.7	1	1.7	
Meas. Setup/Cables&Connectors	B	38	µV/V	1.732	21.7	1	21.7	
Type A uncertainty	A	0.8	µV/V	1	0.8	1	0.8	
UUT DCV repeatability	A	0.1	µV/V	1	0.1	1	0.1	
UUT ACV repeatability	A	1.5	µV/V	1	1.5	1	1.5	
UUT resolution	B	0.5	µV/V	1.732	0.3	1	0.3	
UUT stability	B	2.5	µV/V	1.732	1.4	1	1.4	
Rounding of reported value	B	0.5	µV/V	1.732	0.3	1	0.3	
nanovoltmeter std	B	1.0	µV/V	1.732	0.6	1	0.6	
n value std unc	B	2.0	µV/V	1.732	1.2	1	1.2	
						Combined standard uncertainty	22.7	µV/V
						Effective degrees of freedom	24847	
						Coverage factor	2	
						Exp. Uncertainty(V)	0.00045	V

Uncertainty budget for 10V 1.005 kHz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	
Unc due to Reference Std	B	10.54	µV/V	2	5.3	1	5.3	
Reference drift	B	2	µV/V	1.732	1.2	1	1.2	
Meas. Setup/Cables&Connectors	B	28.5	µV/V	1.732	16.5	1	16.5	
Type A uncertainty	A	1.0	µV/V	1	1.0	1	1.0	
UUT DCV repeatability	A	0.1	µV/V	1	0.1	1	0.1	
UUT ACV repeatability	A	0.9	µV/V	1	0.9	1	0.9	
UUT resolution	B	0.5	µV/V	1.732	0.3	1	0.3	
UUT stability	B	2.5	µV/V	1.732	1.4	1	1.4	
Rounding of reported value	B	0.5	µV/V	1.732	0.3	1	0.3	
nanovoltmeter std	B	1.0	µV/V	1.732	0.6	1	0.6	
n value std unc	B	2.0	µV/V	1.732	1.2	1	1.2	
Combined standard uncertainty							17.5	µV/V
Effective degrees of freedom							311521	
Coverage factor							2	
Exp. Uncertainty(V)							0.00035	V

Uncertainty budget for 10V 20 kHz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	
Unc due to Reference Std	B	8.93	µV/V	2	4.5	1	4.5	
Reference drift	B	2	µV/V	1.732	1.2	1	1.2	
Meas. Setup/Cables&Connectors	B	40.5	µV/V	1.732	23.4	1	23.4	
Type A uncertainty	A	1.2	µV/V	1	1.2	1	1.2	
UUT DCV repeatability	A	0.1	µV/V	1	0.1	1	0.1	
UUT ACV repeatability	A	0.9	µV/V	1	0.9	1	0.9	
UUT resolution	B	0.5	µV/V	1.732	0.3	1	0.3	
UUT stability	B	3.0	µV/V	1.732	1.7	1	1.7	
Rounding of reported value	B	0.5	µV/V	1.732	0.3	1	0.3	
nanovoltmeter std	B	1.0	µV/V	1.732	0.6	1	0.6	
n value std unc	B	2.0	µV/V	1.732	1.2	1	1.2	
						Combined standard uncertainty	24.00	µV/V
						Effective degrees of freedom	6.7E+05	
						Coverage factor	2	
						Exp. Uncertainty(V)	0.00048	V

Uncertainty budget for 10V 50 kHz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	
Unc due to Reference Std	B	16.2	µV/V	2	8.1	1	8.1	
Reference drift	B	4	µV/V	1.732	2.3	1	2.3	
Meas. Setup/Cables&Connectors	B	90	µV/V	1.732	52.0	1	52.0	
Type A uncertainty	A	1.9	µV/V	1	1.9	1	1.9	
UUT DCV repeatability	A	0.1	µV/V	1	0.1	1	0.1	
UUT ACV repeatability	A	0.9	µV/V	1	0.9	1	0.9	
UUT resolution	B	0.5	µV/V	1.732	0.3	1	0.3	
UUT stability	B	2.5	µV/V	1.732	1.4	1	1.4	
Rounding of reported value	B	0.5	µV/V	1.732	0.3	1	0.3	
nanovoltmeter std	B	1.0	µV/V	1.732	0.6	1	0.6	
n value std unc	B	2.0	µV/V	1.732	1.2	1	1.2	
						Combined standard uncertainty	52.7	µV/V
						Effective degrees of freedom	2.6E+06	
						Coverage factor	2	
						Exp. Uncertainty(V)	0.00105	V

Uncertainty budget for 10V 1 MHzmeasurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	
Unc due to Reference Std	B	31.4	µV/V	2	15.7	1	15.7	
Reference drift	B	48	µV/V	1.732	27.7	1	27.7	
Meas. Setup/Cables&Connectors	B	550	µV/V	1.732	317.5	1	317.5	
Type A uncertainty	A	1.1	µV/V	1	1.1	1	1.1	
UUT DCV repeatability	A	0.1	µV/V	1	0.1	1	0.1	
UUT ACV repeatability	A	0.9	µV/V	1	0.9	1	0.9	
UUT resolution	B	0.5	µV/V	1.732	0.3	1	0.3	
UUT stability	B	2.0	µV/V	1.732	1.2	1	1.2	
Rounding of reported value	B	0.5	µV/V	1.732	0.3	1	0.3	
nanovoltmeter std	B	1.0	µV/V	1.732	0.6	1	0.6	
n value std unc	B	2.0	µV/V	1.732	1.2	1	1.2	
Combined standard uncertainty							319.1	µV/V
Effective degrees of freedom							2.5E+10	
Coverage factor							2	
Exp. Uncertainty(V)							0.006	V

Uncertainty budget for 19V 1.005 kHz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	
Unc due to Reference Std	B	10.5	μV/V	2	5.3	1	5.3	
Reference drift	B	48	μV/V	1.732	0.9	1	0.9	
Meas. Setup/Cables&Connectors	B	28.5	μV/V	1.732	22.2	1	22.2	
Type A uncertainty	A	0.7	μV/V	1	0.7	1	0.7	
UUT DCV repeatability	A	0.0	μV/V	1	0.0	1	0.0	
UUT ACV repeatability	A	0.5	μV/V	1	0.5	1	0.5	
UUT resolution	B	0.5	μV/V	1.732	0.2	1	0.2	
UUT stability	B	1.1	μV/V	1.732	0.6	1	0.6	
Rounding of reported value	B	0.5	μV/V	1.732	0.2	1	0.2	
nanovoltmeter std	B	1.0	μV/V	1.732	0.6	1	0.6	
n value std unc	B	2.0	μV/V	1.732	1.2	1	1.2	
Combined standard uncertainty							22.9	μV/V
Effective degrees of freedom							5.1E+06	
Coverage factor							2	
Exp. Uncertainty(V)							0.00087	V

Uncertainty budget for 100V 10 Hz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	
Unc due to Reference Std	B	24.3	μV/V	2	12.2	1	12.2	
Reference drift	B	19	μV/V	1.732	11.0	1	11.0	
Meas. Setup/Cables&Connectors	B	39	μV/V	1.732	22.5	1	22.5	
Type A uncertainty	A	1.3	μV/V	1	1.3	1	1.3	
UUT DCV repeatability	A	0.1	μV/V	1	0.1	1	0.1	
UUT ACV repeatability	A	1.0	μV/V	1	1.0	1	1.0	
UUT resolution	B	0.5	μV/V	1.732	0.3	1	0.3	
UUT stability	B	2.0	μV/V	1.732	1.2	1	1.2	
Rounding of reported value	B	0.5	μV/V	1.732	0.3	1	0.3	
nanovoltmeter std	B	1.0	μV/V	1.732	0.6	1	0.6	
n value std unc	B	2.0	μV/V	1.732	1.2	1	1.2	
						Combined standard uncertainty	28.0	μV/V
						Effective degrees of freedom	9.5E+05	
						Coverage factor	2	
						Exp. Uncertainty(V)	0.0056	V

Uncertainty budget for 100V 55 Hz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	
Unc due to Reference Std	B	17.9	µV/V	2	8.9	1	8.9	
Reference drift	B	3	µV/V	1.732	1.7	1	1.7	
Meas. Setup/Cables&Connectors	B	32	µV/V	1.732	18.2	1	18.2	
Type A uncertainty	A	0.5	µV/V	1	0.5	1	0.5	
UUT DCV repeatability	A	0.1	µV/V	1	0.1	1	0.1	
UUT ACV repeatability	A	0.1	µV/V	1	0.1	1	0.1	
UUT resolution	B	0.5	µV/V	1.732	0.3	1	0.3	
UUT stability	B	4.0	µV/V	1.732	2.3	1	2.3	
Rounding of reported value	B	0.5	µV/V	1.732	0.3	1	0.3	
nanovoltmeter std	B	1.0	µV/V	1.732	0.6	1	0.6	
n value std unc	B	2.0	µV/V	1.732	1.2	1	1.2	
						Combined standard uncertainty	20.5	µV/V
						Effective degrees of freedom	9.6E+06	
						Coverage factor	2	
						Exp. Uncertainty(V)	0.0041	V

Uncertainty budget for 100V 1.005 kHzmeasurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	
Unc due to Reference Std	B	17.67	µV/V	2	8.8	1	8.8	
Reference drift	B	3	µV/V	1.732	1.7	1	1.7	
Meas. Setup/Cables&Connectors	B	26	µV/V	1.732	15.0	1	15.0	
Type A uncertainty	A	0.7	µV/V	1	0.7	1	0.7	
UUT DCV repeatability	A	0.1	µV/V	1	0.1	1	0.1	
UUT ACV repeatability	A	1.3	µV/V	1	1.3	1	1.3	
UUT resolution	B	0.5	µV/V	1.732	0.3	1	0.3	
UUT stability	B	4.0	µV/V	1.732	2.3	1	2.3	
Rounding of reported value	B	0.5	µV/V	1.732	0.3	1	0.3	
nanovoltmeter std	B	1.0	µV/V	1.732	0.6	1	0.6	
n value std unc	B	2.0	µV/V	1.732	1.2	1	1.2	
Combined standard uncertainty							17.8	µV/V
Effective degrees of freedom							1.8E+06	
Coverage factor							2	
Exp. Uncertainty(V)							0.0036	V

Uncertainty budget for 100V 20 kHz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	
Unc due to Reference Std	B	19.1	µV/V	2	9.6	1	9.6	
Reference drift	B	3	µV/V	1.732	1.7	1	1.7	
Meas. Setup/Cables&Connectors	B	44	µV/V	1.732	25.1	1	25.1	
Type A uncertainty	A	1.7	µV/V	1	1.7	1	1.7	
UUT DCV repeatability	A	0.1	µV/V	1	0.1	1	0.1	
UUT ACV repeatability	A	1.1	µV/V	1	1.1	1	1.1	
UUT resolution	B	0.5	µV/V	1.732	0.3	1	0.3	
UUT stability	B	3.0	µV/V	1.732	1.7	1	1.7	
Rounding of reported value	B	0.5	µV/V	1.732	0.3	1	0.3	
nanovoltmeter std	B	1.0	µV/V	1.732	0.6	1	0.6	
n value std unc	B	2.0	µV/V	1.732	1.2	1	1.2	
Combined standard uncertainty							27.1	µV/V
Effective degrees of freedom							2.5E+05	
Coverage factor							2	
Exp. Uncertainty(V)							0.0054	V

Uncertainty budget for 100V 50 kHz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	
Unc due to Reference Std	B	24.08	µV/V	2	12.0	1	12.0	
Reference drift	B	7	µV/V	1.732	3.8	1	3.8	
Meas. Setup/Cables&Connectors	B	86.9	µV/V	1.732	50.2	1	50.2	
Type A uncertainty	A	0.7	µV/V	1	0.7	1	0.7	
UUT DCV repeatability	A	0.1	µV/V	1	0.1	1	0.1	
UUT ACV repeatability	A	0.8	µV/V	1	0.8	1	0.8	
UUT resolution	B	0.5	µV/V	1.732	0.3	1	0.3	
UUT stability	B	2.5	µV/V	1.732	1.4	1	1.4	
Rounding of reported value	B	0.5	µV/V	1.732	0.3	1	0.3	
nanovoltmeter std	B	1.0	µV/V	1.732	0.6	1	0.6	
n value std unc	B	2.0	µV/V	1.732	1.2	1	1.2	
						Combined standard uncertainty	51.8	µV/V
						Effective degrees of freedom	1.1E+08	
						Coverage factor	2	
						Exp. Uncertainty(V)	0.0104	V

Uncertainty budget for 700V 55 Hz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	
Unc due to Reference Std	B	44.4	µV/V	2	22.2	1	22.2	
Reference drift	B	4	µV/V	1.732	11.0	1	11.0	
Meas. Setup/Cables&Connectors	B	24.5	µV/V	1.732	14.1	1	14.1	
Type A uncertainty	A	1.7	µV/V	1	1.7	1	1.7	
UUT DCV repeatability	A	0.1	µV/V	1	0.1	1	0.1	
UUT ACV repeatability	A	2.0	µV/V	1	2.0	1	2.0	
UUT resolution	B	0.7	µV/V	1.732	0.4	1	0.4	
UUT stability	B	6.4	µV/V	1.732	3.7	1	3.7	
Rounding of reported value	B	0.7	µV/V	1.732	0.4	1	0.4	
nanovoltmeter std	B	1.0	µV/V	1.732	0.6	1	0.6	
n value std unc	B	2.0	µV/V	1.732	1.2	1	1.2	
						Combined standard uncertainty	28.9	µV/V
						Effective degrees of freedom	3.3E+05	
						Coverage factor	2	
						Exp. Uncertainty(V)	0.040	V

Uncertainty budget for 700V 1.005 kHz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	
Unc due to Reference Std	B	44.3	µV/V	2	22.2	1	22.2	
Reference drift	B	4	µV/V	1.732	2.3	1	2.3	
Meas. Setup/Cables&Connectors	B	15	µV/V	1.732	8.7	1	8.7	
Type A uncertainty	A	0.8	µV/V	1	0.8	1	0.8	
UUT DCV repeatability	A	0.1	µV/V	1	0.1	1	0.1	
UUT ACV repeatability	A	2.6	µV/V	1	2.6	1	2.6	
UUT resolution	B	0.7	µV/V	1.732	0.4	1	0.4	
UUT stability	B	4.3	µV/V	1.732	2.5	1	2.5	
Rounding of reported value	B	0.7	µV/V	1.732	0.4	1	0.4	
nanovoltmeter std	B	1.0	µV/V	1.732	0.6	1	0.6	
n value std unc	B	2.0	µV/V	1.732	1.2	1	1.2	
Combined standard uncertainty							24.2	µV/V
Effective degrees of freedom							3.2E+06	
Coverage factor							2	
Exp. Uncertainty(V)							0.034	V

Uncertainty budget for 700V 20 kHz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	
Unc due to Reference Std	B	51.86	µV/V	2	25.9	1	25.9	
Reference drift	B	4	µV/V	1.732	2.3	1	2.3	
Meas. Setup/Cables&Connectors	B	28	µV/V	1.732	16.2	1	16.2	
Type A uncertainty	A	1.0	µV/V	1	1.0	1	1.0	
UUT DCV repeatability	A	0.1	µV/V	1	0.1	1	0.1	
UUT ACV repeatability	A	1.7	µV/V	1	1.7	1	1.7	
UUT resolution	B	0.7	µV/V	1.732	0.4	1	0.4	
UUT stability	B	4.3	µV/V	1.732	2.5	1	2.5	
Rounding of reported value	B	0.7	µV/V	1.732	0.4	1	0.4	
nanovoltmeter std	B	1.0	µV/V	1.732	0.6	1	0.6	
n value std unc	B	2.0	µV/V	1.732	1.2	1	1.2	
Combined standard uncertainty							30.9	µV/V
Effective degrees of freedom							4.2E+06	
Coverage factor							2	
Exp. Uncertainty(V)							0.043	V

Uncertainty budget for 700V 50 kHz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	
Unc due to Reference Std	B	51.86	µV/V	2	25.9	1	25.9	
Reference drift	B	7	µV/V	1.732	3.8	1	3.8	
Meas. Setup/Cables&Connectors	B	28	µV/V	1.732	28.9	1	28.9	
Type A uncertainty	A	3.4	µV/V	1	3.4	1	3.4	
UUT DCV repeatability	A	0.2	µV/V	1	0.2	1	0.2	
UUT ACV repeatability	A	1.7	µV/V	1	1.7	1	1.7	
UUT resolution	B	0.7	µV/V	1.732	0.4	1	0.4	
UUT stability	B	4.3	µV/V	1.732	2.5	1	2.5	
Rounding of reported value	B	0.7	µV/V	1.732	0.4	1	0.4	
nanovoltmeter std	B	1.0	µV/V	1.732	0.6	1	0.6	
n value std unc	B	2.0	µV/V	1.732	1.2	1	1.2	
Combined standard uncertainty							39.3	µV/V
Effective degrees of freedom							73329	
Coverage factor							2	
Exp. Uncertainty(V)							0.055	V

3.2Alternating Current

For alternating current the following components contribute to the uncertainty of measurement:

- ACV reference uncertainty: A Fluke 5790A alternating voltage measurement standard is used to determine the voltage drop across the shunt - its uncertainty is obtained from the latest calibration report
- ACV reference drift: From the history of the Fluke 5790A
- ACV reference resolution: From the specification of the Fluke 5790A
- ACV reference repeatability: From the observed data
- Current shunt ac-dc difference: From the latest calibration report
- Cables and connectors: An experiment was performed to estimate the effect of cables and connectors
- Unit under test resolution: From the specifications of the unit under test
- Unit under test repeatability: From the observed data
- Unit under test stability: From tests repeated several times during the period that the instrument spent in our laboratory
- Rounding of reported value: To ensure that the reported value encompasses the calculated range of possible values

Uncertainty budget for 1mA 55 Hz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	
Unc due to Reference Std	B	10.9	µA/A	2	5.5	1	5.5	
Reference drift	B	32	µA/A	1.732	18.5	1	18.5	
Meas. Setup/Cables&Connectors	B	63	µA/A	1.732	36.4	1	36.4	
Type A uncertainty	A	0.8	µA/A	1	0.8	1	0.8	
UUT DCV repeatability	A	0.2	µA/A	1	0.2	1	0.2	
UUT ACV repeatability	A	3.4	µA/A	1	3.4	1	3.4	
UUT resolution	B	0.5	µA/A	1.732	0.3	1	0.3	
UUT stability	B	0.5	µA/A	1.732	0.3	1	0.3	
Rounding of reported value	B	0.5	µA/A	1.732	0.3	1	0.3	
nanovoltmeter std	B	1.0	µA/A	1.732	0.6	1	0.6	
n value std unc	B	2.0	µA/A	1.732	1.2	1	1.2	
						Combined standard uncertainty	41.3	µA/A
						Effective degrees of freedom	2.3E+7	
						Coverage factor	2	
						Exp. Uncertainty(A)	0.000000083	A

Uncertainty budget for 1mA 1.005 kHz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	
Unc due to Reference Std	B	11.9	µA/A	2	6.0	1	6.0	
Reference drift	B	28	µA/A	1.732	16.2	1	16.2	
Meas. Setup/Cables&Connectors	B	60.5	µA/A	1.732	34.9	1	34.9	
Type A uncertainty	A	5.5	µA/A	1	5.5	1	5.5	
UUT DCV repeatability	A	0.2	µA/A	1	0.2	1	0.2	
UUT ACV repeatability	A	0.0	µA/A	1	0.0	1	0.0	
UUT resolution	B	0.5	µA/A	1.732	0.0	1	0.0	
UUT stability	B	5.0	µA/A	1.732	2.9	1	0.0	
Rounding of reported value	B	0.5	µA/A	1.732	0.0	1	0.0	
nanovoltmeter std	B	1.0	µA/A	1.732	0.6	1	0.6	
n value std unc	B	2.0	µA/A	1.732	1.2	1	1.2	
						Combined standard uncertainty	39.4	µA/A
						Effective degrees of freedom	10251	
						Coverage factor	2	
						Exp. Uncertainty(A)	0.000000079	A

Uncertainty budget for 1mA 5 kHz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	
Unc due to Reference Std	B	18.1	µA/A	2	9.0	1	9.0	
Reference drift	B	28	µA/A	1.732	16.2	1	16.2	
Meas. Setup/Cables&Connectors	B	85	µA/A	1.732	49.1	1	49.1	
Type A uncertainty	A	2.2	µA/A	1	2.2	1	2.2	
UUT DCV repeatability	A	0.0	µA/A	1	0.0	1	0.0	
UUT ACV repeatability	A	0.0	µA/A	1	0.0	1	0.0	
UUT resolution	B	0.5	µA/A	1.732	0.0	1	0.0	
UUT stability	B	7.5	µA/A	1.732	4.3	1	0.1	
Rounding of reported value	B	0.5	µA/A	1.732	0.0	1	0.0	
nanovoltmeter std	B	1.0	µA/A	1.732	0.6	1	0.6	
n value std unc	B	2.0	µA/A	1.732	1.2	1	1.2	
Combined standard uncertainty							52.5	µA/A
Effective degrees of freedom							1.4E+06	
Coverage factor							2	
Exp. Uncertainty(A)							0.000000105	A

Uncertainty budget for 1A 55 Hzmeasurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	
Unc due to Reference Std	B	59.1	µA/A	2	29.6	1	29.6	
Reference drift	B	19	µA/A	1.732	11.0	1	11.0	
Meas. Setup/Cables&Connectors	B	27	µA/A	1.732	15.6	1	15.6	
Type A uncertainty	A	0.7	µA/A	1	0.7	1	0.7	
UUT DCV repeatability	A	0.2	µA/A	1	0.2	1	0.2	
UUT ACV repeatability	A	0.8	µA/A	1	0.8	1	0.8	
UUT resolution	B	0.5	µA/A	1.732	0.3	1	0.3	
UUT stability	B	1.5	µA/A	1.732	0.9	1	0.9	
Rounding of reported value	B	0.5	µA/A	1.732	0.3	1	0.3	
nanovoltmeter std	B	1.0	µA/A	1.732	0.6	1	0.6	
n value std unc	B	2.0	µA/A	1.732	1.2	1	1.2	
						Combined standard uncertainty	35.2339166	µA/A
						Effective degrees of freedom	2.6E+07	
						Coverage factor	2	
						Exp. Uncertainty(A)	0.000070	A

Uncertainty budget for 1A 1.005 kHz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	
Unc due to Reference Std	B	54.2	µA/A	2	27.1	1	27.1	
Reference drift	B	3	µA/A	1.732	1.7	1	1.7	
Meas. Setup/Cables&Connectors	B	25	µA/A	1.732	14.4	1	14.4	
Type A uncertainty	A	0.8	µA/A	1	0.8	1	0.8	
UUT DCV repeatability	A	1.0	µA/A	1	1.0	1	1.0	
UUT ACV repeatability	A	1.2	µA/A	1	1.2	1	1.2	
UUT resolution	B	0.5	µA/A	1.732	0.3	1	0.3	
UUT stability	B	4.5	µA/A	1.732	2.6	1	2.6	
Rounding of reported value	B	0.5	µA/A	1.732	0.3	1	0.3	
nanovoltmeter std	B	1.0	µA/A	1.732	0.6	1	0.6	
n value std unc	B	2.0	µA/A	1.732	1.2	1	1.2	
Combined standard uncertainty							30.9526957	µA/A
Effective degrees of freedom							8.6E+06	
Coverage factor							2	
Exp. Uncertainty(A)							0.000062	A

Uncertainty budget for 1A 5 kHz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	
Unc due to Reference Std	B	58.4	µA/A	2	29.2	1	29.2	
Reference drift	B	2	µA/A	1.732	0.9	1	0.9	
Meas. Setup/Cables&Connectors	B	30	µA/A	1.732	17.3	1	17.3	
Type A uncertainty	A	0.6	µA/A	1	0.6	1	0.6	
UUT DCV repeatability	A	1.0	µA/A	1	1.0	1	1.0	
UUT ACV repeatability	A	3.3	µA/A	1	3.3	1	3.3	
UUT resolution	B	0.5	µA/A	1.732	0.3	1	0.3	
UUT stability	B	3.5	µA/A	1.732	2.0	1	2.0	
Rounding of reported value	B	0.5	µA/A	1.732	0.3	1	0.3	
nanovoltmeter std	B	1.0	µA/A	1.732	0.6	1	0.6	
n value std unc	B	2.0	µA/A	1.732	1.2	1	1.2	
						Combined standard uncertainty	34.2	µA/A
						Effective degrees of freedom	5.1E+07	
						Coverage factor	2	
						Exp. Uncertainty(A)	0.000068	A

3.3 Frequency

For frequency the following components contribute to the uncertainty of measurement:

- Reference time-base: The specified frequency accuracy of the national frequency standard at the observation time used for the measurement (typically 2000 seconds)
- Counter accuracy: Calculated using the formulae supplied by the manufacturer
- Counter resolution: The manufacturer calls this the Least Significant Digit Displayed – it was calculated using the formula supplied by the manufacturer
- Unit under test repeatability: From the observed data – for some frequency points the data was time correlated (the data distribution did not follow a normal probability distribution); for these points the repeatability is estimated using the Allan Deviation (ADEV) calculated at approximately 1/6th of the observation time extrapolated for the complete observation. A random walk frequency noise process was assumed for the extrapolation.
- Unit under test stability: From repeated tests
- Rounding of reported value: To ensure that the reported value encompasses the calculated range of possible values

Uncertainty budget for 1.005 kHz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	
Reference standard	B	5.00E-11	Hz/Hz	2.000	2.50E-11	1	2.50E-11	
Counter accuracy	B	5.00E-07	Hz/Hz	2.000	2.50E-07	1	2.50E-07	
Counter resolution	B	5.00E-07	Hz/Hz	1.732	2.89E-07	1	2.89E-07	
Unit under test repeatability	A	2.45E-07	Hz/Hz	1.000	2.45E-07	1	2.45E-07	
Unit under test stability	B	5.00E-07	Hz/Hz	1.732	2.89E-07	1	2.89E-07	
Rounding of reported value	B	5.00E-07	Hz/Hz	1.732	2.89E-07	1	2.89E-07	
						Combined standard uncertainty	6.10E-08	Hz/Hz
						Effective degrees of freedom	154.2	
						Coverage factor	2	
						Expanded uncertainty	1.22E-07	Hz/Hz

Report on

Measurements performed for APMP.EM-S12 Comparison of Standards for the Calibration of Voltage, Current and Resistance Meters

Measurements performed on

Wavetek 4950 serial number 33528

From 17 August 2015 to 14 September 2015

Performed by

Japan Electric Meters Inspection Corporation,
15-7, 4-chome, Shibaura, Minato-ku,
Tokyo, 108-0023, JAPAN

Report by

Yasuhiro Noguchi
Calibration Laboratory

Introduction

The APMP.EM-S12 comparison protocol requires that the travelling standard, a Wavetek model 4950 serial number 33528 (the Unit under Test – UUT), be measured at a number of points for each of its measurement functions. These are direct voltage, direct current, alternating voltage, alternating current and resistance. The measurement points are detailed in the comparison protocol.

The instrument was received on 17 August 2015. The fuse (F1) and mains voltage selection switch (S1) was changed before applying power. The UUT was allowed to stabilise for 24 hours with the power turned on before any measurements were made. The instrument's confidence test was performed and completed without any errors.

The measurements were performed from 18 August 2015 to 14 September 2015. The instrument was sent to the NMIA on 14 September 2015.

The capabilities of our institute are limited. This means that some of the measurements required by the protocol could not be performed. These were direct voltage (DCV), direct current (DCI), Resistance.

Direct Voltage

Test methods:

Direct voltage was measured using three methods:

1. For 100 mV and 1 V the correction of the UUT was determined by measuring Guildline model 9930's (Direct Current Comparator Potentiometer: DCCP) output voltage. We used DCCP as a generator.

2. For 10 V the correction of the UUT was determined by DC voltage measurement system (Fluke model 720A, 845AB, 5700A) connection of the UUT to a calibrated Fluke model 732B zener voltage reference standard.

3. For 19 V to 1000 V the correction of the UUT was determined by DC voltage measurement system (Fluke model 720A, 752A, 845AB, 5700A, 732B) connection of the UUT.

See figure 1.1 for the direct voltage measurement setups.

The 'Remote Guard' function was turned on for all the measurements, and the guard terminal and low voltage terminal were connected to a common ground point. The low current terminal was connected to the low voltage terminal and the high current terminal was connected to the high voltage terminal for all measurements.

Traceability:

All the test methods described for direct voltage was traceable to the NMIJ(National Metrology Institute of Japan) measurement standard. See figure 2.1 for the direct voltage traceability chart.

Conditions of measurement:

During the direct voltage measurements, the following conditions of measurement prevailed:

Ambient temperature: 23.0 °C ± 0.5 °C
Relative humidity: 55 %RH ± 5 %RH

Measurement results:

Range	Nominal Voltage	Correction	Uncertainty	Internal Temperature (°C)
100 mV	100 mV	− 0.000 49 mV	± 0.000 30 mV	41.4
1 V	1 V	− 0.000 001 5 V	± 0.000 001 7 V	41.4
10 V	10 V	− 0.000 005 V	± 0.000 014 V	41.4
10 V	19 V	− 0.000 014 V	± 0.000 043 V	41.5
100 V	100 V	− 0.000 09 V	± 0.000 21 V	41.5
1000 V	1000 V	− 0.000 7 V	± 0.002 9 V	41.5

Detailed uncertainty budgets for the direct voltage measurements are shown in appendix 3.1.

Direct Current

Test methods:

Direct current was measured the following method:

The correction of the UUT was determined by comparing its readings to the calculated value of the applied current. A calibrated current shunt (or standard resister) was connected in series with the UUT. The voltage drop across the current shunt was measured with a calibrated voltmeter. The applied current was calculated from the resistance of the shunts and the measured voltage.

See figure 1.2 for the direct current measurement setup.

The 'Remote Guard' function was turned on for all the measurements, and the guard terminal and low current terminal were connected to a common ground point. The low voltage and high voltage terminals were connected to the same ground point.

Traceability:

See figure 2.2 for the direct current traceability chart.

The resistance of the shunt (or standard resistor) was traceable to the NMIJ. See figure 2.3 for the resistance traceability chart.

The direct voltage was traceable to the NMIJ for voltage, a Josephson voltage standard. See figure 2.1 for the direct voltage traceability chart.

Conditions of measurement:

During the direct current measurements, the following conditions of measurement prevailed:

Ambient temperature: 23.0 °C ± 0.5 °C
Relative humidity: 55 %RH ± 5 %RH

Measurement results:

Range	Nominal Current	Correction	Uncertainty	Internal Temperature (°C)
1 mA	1 mA	+ 0.000 007 mA	± 0.000 005 mA	41.4
1 A	1 A	+ 0.000 012 A	± 0.000 006 A	41.2

Detailed uncertainty budgets for the direct current measurements are shown in appendix 3.2.

Resistance

Test methods:

The correction of the UUT was determined by comparing its readings to a set of standard resistors (from 10 Ω to 1 MΩ). In addition, we use precision resistance measuring system (242C) and resistance transfer standard (SR1050) at 10 MΩ and 100 MΩ. The UUT setting is below.

- From 10 Ω to 10 kΩ range: “4W”
- From 100 kΩ to 100 MΩ range: “2W”

See figure 1.3 for the resistance measurement setups.

The ‘Remote Guard’ function was turned on for all the measurements, and the guard terminal and low voltage terminal were connected to a common ground point. For 2wire measurements the low current terminal and the high current terminal were connected to the common ground point.

Traceability:

The resistance of the shunt (or standard resistor) was traceable to the NMIJ.

See figure 2.3 for the resistance traceability chart.

Conditions of measurement:

During the resistance measurements, the following conditions of measurement prevailed:

Ambient temperature: 23.0 °C ± 0.5 °C
Relative humidity: 55 %RH ± 5 %RH

4-wire measurement results:

Range	Nominal Resistance	Correction	Uncertainty	Internal Temperature (°C)
10 Ω	10 Ω	+ 0.000 001 Ω	± 0.000 014 Ω	41.4
100 Ω	100 Ω	− 0.000 30 Ω	± 0.000 08 Ω	41.3
1 kΩ	1 kΩ	+0.000 001 6 kΩ	± 0.000 001 2 kΩ	41.1
10 kΩ	10 kΩ	− 0.000 006 kΩ	± 0.000 008 kΩ	41.0

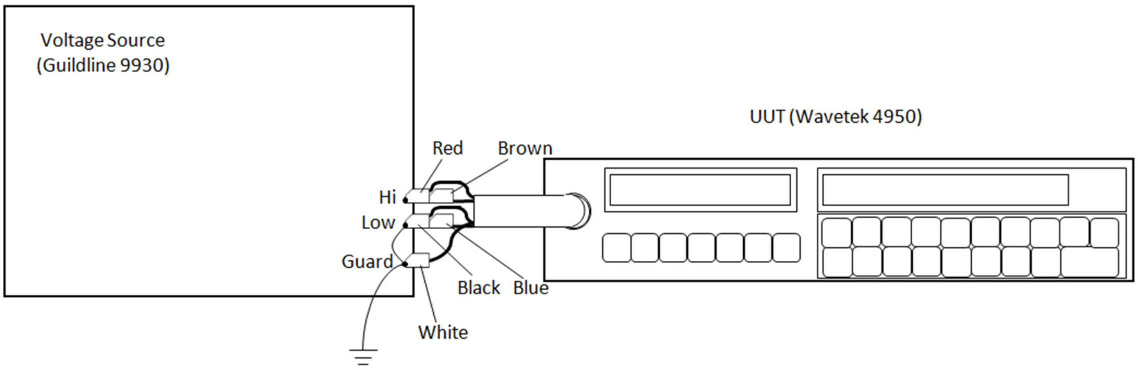
2-wire measurement results:

Range	Nominal Resistance	Correction	Uncertainty	Internal Temperature (°C)
100 kΩ	100 kΩ	− 0.000 11 kΩ	± 0.000 38 kΩ	41.0
1 MΩ	1 MΩ	+ 0.000 002 7 MΩ	± 0.000 003 9 MΩ	41.0
10 MΩ	10 MΩ	− 0.000 240 MΩ	± 0.000 26 MΩ	41.3
100 MΩ	100 MΩ	− 0.000 89 MΩ	± 0.002 6 MΩ	41.3

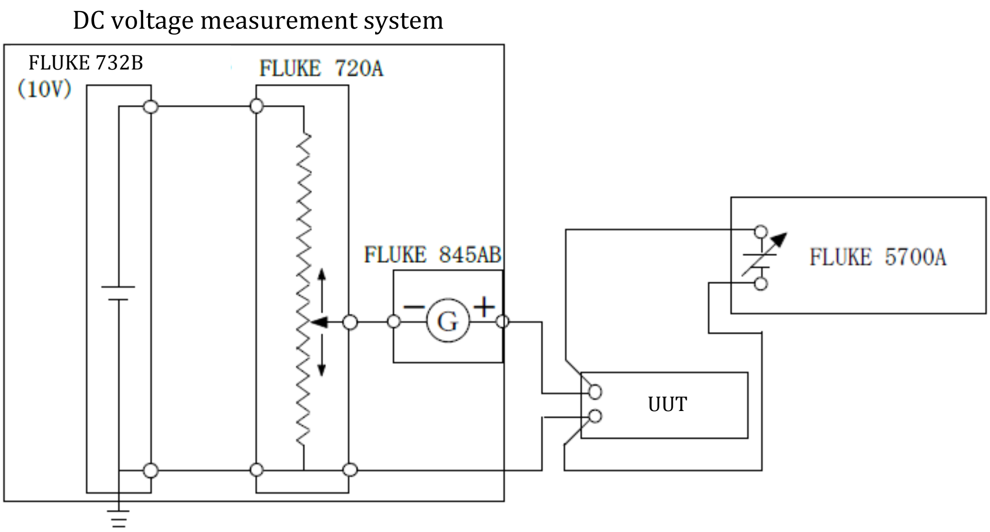
Detailed uncertainty budgets for the resistance measurements are shown in appendix 3.3.

Appendix 1: Measurement setups

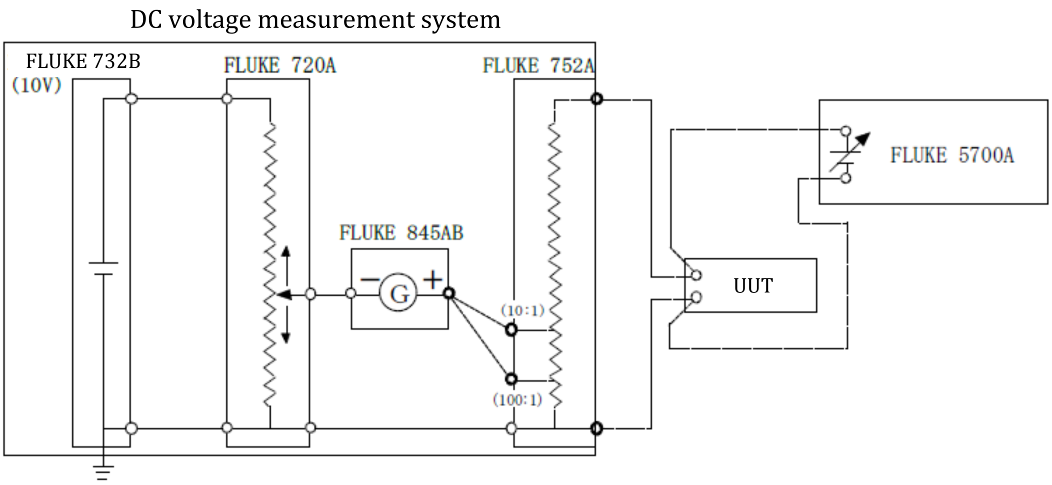
Direct Voltage



(a) 100 mV and 1 V measurement



(b) 10 V measurements



(c) 19 V to 1000 V measurements

Figure 1.1: Direct voltage measurement setups

Direct Current

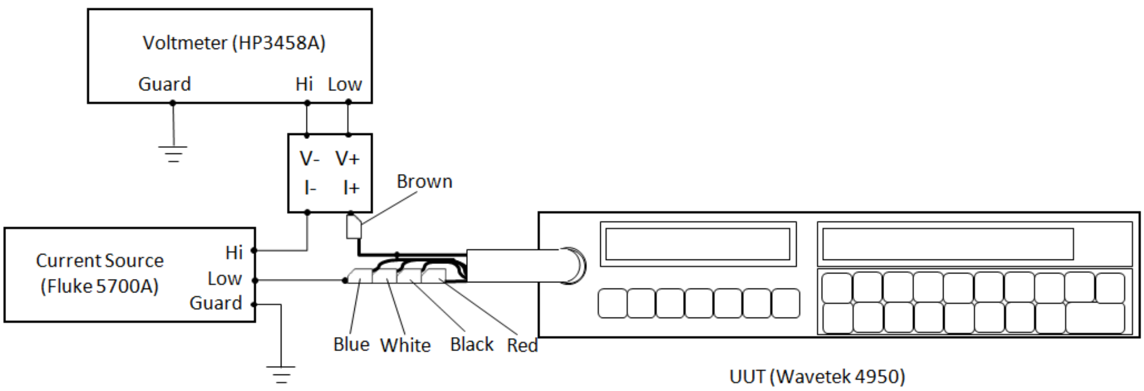
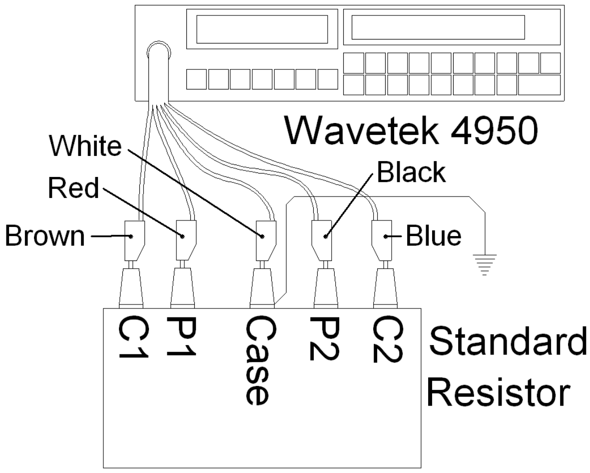
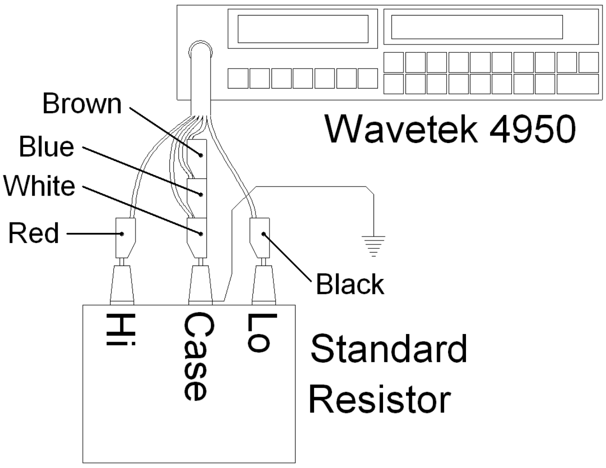


Figure 1.2: Direct current measurement setup

Resistance



(a) Four wire resistance



(b) Two wire resistance

Figure 1.3: Resistance measurement setups

Appendix 2: Traceability charts

Direct Voltage

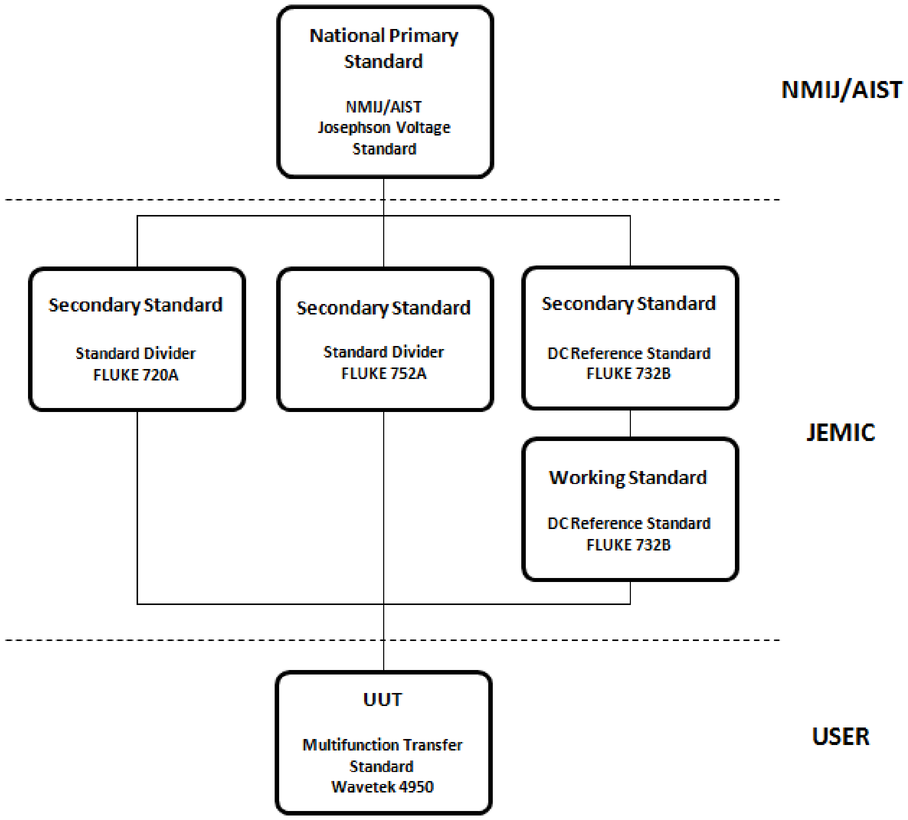


Figure 2.1: Direct voltage traceability

Direct Current

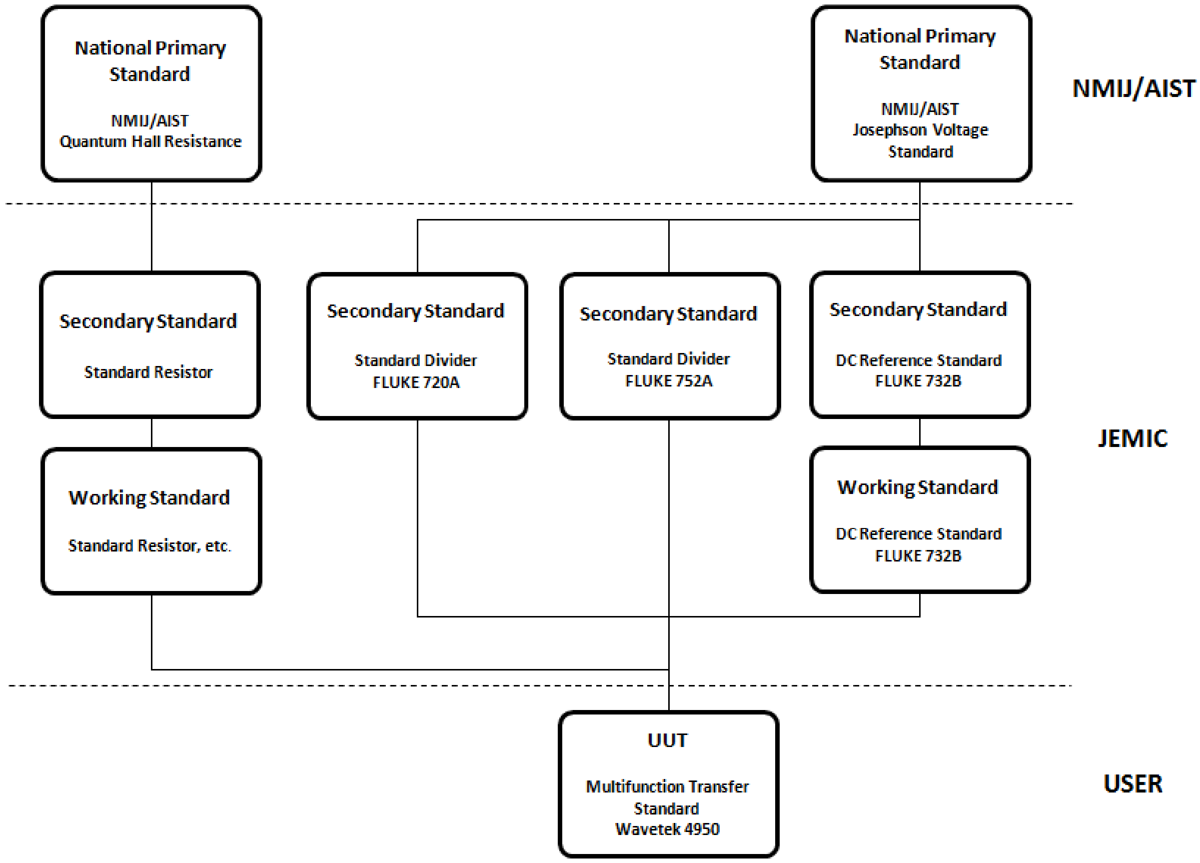


Figure 2.2: Direct current traceability

Resistance

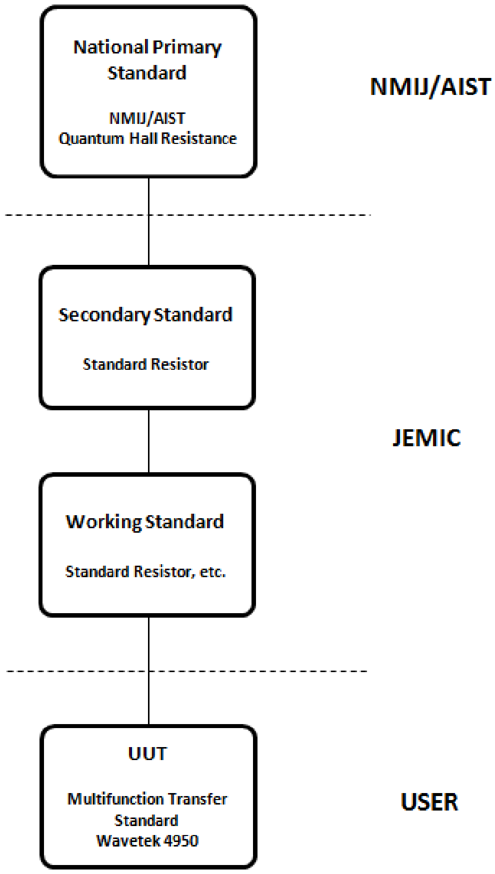


Figure 2.3: Resistance traceability

Appendix 3: Uncertainty budgets

3.1 Direct Voltage

For direct voltage at 100 mV and 1 V the following components contribute to the uncertainty of measurement:

- DC voltage standard (model 732B): Uncertainty of measurement by the reference standard, drift, temperature dependence.
- Direct Current Comparator Potentiometer (DCCP: model 9930): Resolution, sensitivity of detection, linearity.
  Measurement circuit: Thermal electromotive force, repeatability, unit under test resolution.

Uncertainty budget (100 mV):

Component	Type	Standard uncertainty	Unit	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
DC voltage standard: uncertainty	B	0.102	µV	0.1	0.0102	infinity
DC voltage standard: drift	B	0.577	µV	0.1	0.0577	infinity
DC voltage standard: temperature dependence	B	0.588	µV	0.1	0.0588	infinity
DCCP: resolution	B	0.029	µV	1	0.029	infinity
DCCP: sensitivity of detection	B	0.009	µV	1	0.009	infinity
DCCP: linearity	B	0.014	µV	1	0.014	infinity
Measurement circuit: Thermal electromotive force	B	0.115	µV	-1	0.115	infinity
Measurement circuit: Repeatability	A	0.014	µV	-1	0.014	4
Measurement circuit: Unit under test resolution	B	0.003	µV	-1	0.003	infinity
				Combined standard uncertainty	0.146	µV
				Effective degrees of freedom	15594.0	

Coverage factor	2	
Expanded uncertainty	0.293	µV
Expanded uncertainty	3.0	µV/V

Uncertainty budget (1 V):

Component	Type	Standard uncertainty	Unit	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
DC voltage standard: uncertainty	B	0.102	µV	1	0.102	infinity
DC voltage standard: drift	B	0.577	µV	1	0.577	infinity
DC voltage standard: temperature dependence	B	0.588	µV	1	0.588	infinity
DCCP: resolution	B	0.029	µV	1	0.029	infinity
DCCP: sensitivity of detection	B	0.009	µV	1	0.009	infinity
DCCP: linearity	B	0.014	µV	1	0.014	infinity
Measurement circuit: Thermal electromotive force	B	0.115	µV	-1	0.115	infinity
Measurement circuit: Repeatability	A	0.025	µV	-1	0.025	4
Measurement circuit: Unit under test resolution	B	0.029	µV	-1	0.029	infinity
Combined standard uncertainty					0.840	µV
Effective degrees of freedom					21449.7	
Coverage factor					2	
Expanded uncertainty					1.679	µV
Expanded uncertainty					1.7	µV/V

For direct voltage at 10 V, 19 V, 100 V and 1000 V the following components contribute to the uncertainty of measurement:

– DC voltage standard (model 732B): Uncertainty of measurement by the reference standard, drift, temperature dependence
– DC voltage divider (model 720A, 752A): Uncertainty of measurement by the reference standard, etc.
– Measurement circuit: Thermal electromotive force, etc.

Uncertainty budget (10 V):

Component	Type	Standard uncertainty	Unit	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
DC voltage standard: uncertainty	B	0.1	µV	1	0.1	infinity
DC voltage standard: drift	B	4.04	µV	1	4.04	infinity
DC voltage standard: temperature dependence	B	0.289	µV	1	0.289	infinity
DC voltage standard: cable contact	B	0.577	µV	1	0.577	infinity
720 standard: uncertainty	B	0.529	µV	10	5.29	infinity
720 standard: linearity	B	0.058	µV	10	0.58	infinity
Measurement circuit: Thermal electromotive force	B	0.029	µV	-1	0.029	infinity
Measurement circuit: Repeatability	A	0	µV	-1	0	4
Measurement circuit: Unit under test resolution	B	0.289	µV	-1	0.289	infinity
				Combined standard uncertainty	6.720	µV
				Effective degrees of freedom	19421.8	
				Coverage factor	2	

Expanded uncertainty	13.4	μV
Expanded uncertainty	1.4	μV/V

Uncertainty budget (19 V):

Component	Type	Standard uncertainty	Unit	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
DC voltage standard: uncertainty	B	0.1	μV	1.9	0.19	infinity
DC voltage standard: drift	B	4.04	μV	1.9	7.676	infinity
DC voltage standard: temperature dependence	B	0.289	μV	1.9	0.5491	infinity
DC voltage standard: cable contact	B	0.577	μV	1.9	1.0963	infinity
720 standard: uncertainty	B	0.124	μV	100	12.4	infinity
720 standard: linearity	B	0.058	μV	100	5.8	infinity
752 standard: uncertainty	B	7.5	μV	1.9	14.25	infinity
Measurement circuit: Thermal electromotive force	B	0.029	μV	-1	0.029	infinity
Measurement circuit: Repeatability	A	0.245	μV	-1	0.245	4
Measurement circuit: Unit under test resolution	B	0.289	μV	-1	0.289	infinity
Combined standard uncertainty					21.238	μV
Effective degrees of freedom					29279.1	
Coverage factor					2	
Expanded uncertainty					42.479	μV
Expanded uncertainty					2.3	μV/V

Uncertainty budget (100 V):

Component	Type	Standard uncertainty	Unit	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
DC voltage standard: uncertainty	B	0.1	µV	10	1	infinity
DC voltage standard: drift	B	4.04	µV	10	40.4	infinity
DC voltage standard: temperature dependence	B	0.289	µV	10	2.89	infinity
DC voltage standard: cable contact	B	0.577	µV	10	5.77	infinity
720 standard: uncertainty	B	0.529	µV	100	52.9	infinity
720 standard: linearity	B	0.058	µV	100	5.8	infinity
752 standard: uncertainty	B	7.5	µV	10	75	infinity
Measurement circuit: Thermal electromotive force	B	0.0289	µV	-1	0.0289	infinity
Measurement circuit: Repeatability	A	0	µV	-1	0	4
Measurement circuit: Unit under test resolution	B	2.89	µV	-1	2.89	infinity
				Combined standard uncertainty	100.699	µV
				Effective degrees of freedom	24401.7	
				Coverage factor	2	
				Expanded uncertainty	201.4	µV
				Expanded uncertainty	2.1	µV/V

Uncertainty budget (1000 V):

Component	Type	Standard uncertainty	Unit	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
DC voltage standard: uncertainty	B	0.1	µV	100	10	infinity
DC voltage standard: drift	B	4.04	µV	100	404	infinity
DC voltage standard: temperature dependence	B	0.289	µV	100	28.9	infinity
DC voltage standard: cable contact	B	0.577	µV	100	57.7	infinity
720 standard: uncertainty	B	0.529	µV	1000	529	infinity
720 standard: linearity	B	0.058	µV	1000	58	infinity
752 standard: uncertainty	B	125	µV	10	1250	infinity
Measurement circuit: Thermal electromotive force	B	0.0289	µV	-1	0.0289	infinity
Measurement circuit: Repeatability	A	0	µV	-1	0	4
Measurement circuit: Unit under test resolution	B	28.9	µV	-1	28.9	infinity
				Combined standard uncertainty	1419.162	µV
				Effective degrees of freedom	15929.6	
				Coverage factor	2	
				Expanded uncertainty	2838.550	µV
				Expanded uncertainty	2.9	µV/V

3.2 Direct Current

For direct current the following components contribute to the uncertainty of measurement:

- Shunt(Standard resister) uncertainty: Uncertainty of measurement by the reference standard, drift, temperature dependence
- Voltmeter uncertainty: Uncertainty of measurement by the reference standard, drift, temperature dependence
- Unit under test uncertainty: Repeatability, sensitivity of detection

Uncertainty budget for 1 mA measurement:

Component	Type	Standard uncertainty	Unit	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Standard resister: uncertainty	B	25	μΩ	0.00001	0.00025	infinity
Standard resister: temperature and current dependence	B	11.5	μΩ	0.00001	0.000115	infinity
Standard resister: drift	B	40.5	μΩ	0.00001	0.000405	infinity
Voltmeter: uncertainty	B	0.2	μV	-0.01	0.002	infinity
Voltmeter: effect of compensation	B	0.0289	μV	-0.01	0.000289	infinity
Voltmeter: drift	B	0.0577	μV	-0.01	0.000577	infinity
Voltmeter: repeatability	A	0	μV	-0.01	0	4
Voltmeter: resolution	B	0.0289	μV	-0.01	0.000289	infinity
UUT: repeatability	A	0.0002	μV	1	0.0002	4
UUT: resolution	B	0.000289	μV	1	0.000289	infinity
Combined standard uncertainty					0.0022	μA
Effective degrees of freedom					11730.1	
Coverage factor					2	

Expanded uncertainty	0.0044	µA
Expanded uncertainty	5	µA/A

Uncertainty budget for 1 A measurement:

Component	Type	Standard uncertainty	Unit	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Standard resister: uncertainty	B	0.045	µΩ	10	0.45	infinity
Standard resister: temperature dependence	B	0.073	µΩ	10	0.73	infinity
Standard resister: drift	B	0.133	µΩ	10	1.33	infinity
Voltmeter: uncertainty	B	0.2	µV	-10	2	infinity
Voltmeter: effect of compensation	B	0.0289	µV	-10	0.289	infinity
Voltmeter: drift	B	0.0577	µV	-10	0.577	infinity
Voltmeter: repeatability	A	0	µV	-10	0	4
Voltmeter: resolution	B	0.0289	µV	-10	0.289	infinity
UUT: repeatability	A	0	µA	1	0	4
UUT: resolution	B	0.289	µA	1	0.289	infinity
Combined standard uncertainty					2.662	µA
Effective degrees of freedom					25649.6	
Coverage factor					2	
Expanded uncertainty					5.325	µA
Expanded uncertainty					6	µA/A

3.3 Resistance

For resistance at 10 Ω, 100 Ω, 1 kΩ, 10 kΩ, 100 kΩ and 1 MΩ the following components contribute to the uncertainty of measurement:

– Standard resister uncertainty: Uncertainty of measurement by the reference standard, drift, temperature dependence, power dependence
– Unit under test uncertainty: Repeatability, resolution

Uncertainty budget for 10 Ω 4-wire measurement:

Component	Type	Standard uncertainty	Unit	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Standard resister: uncertainty	B	0.40	µΩ/Ω	1	0.40	infinity
Standard resister: drift	B	0.54	µΩ/Ω	1	0.54	infinity
Standard resister: temperature dependence	B	0.12	µΩ/Ω	1	0.12	infinity
Standard resister: power dependence	B	0.03	µΩ/Ω	1	0.03	infinity
UUT: repeatability	A	0.11	µΩ/Ω	1	0.11	4
UUT: resolution	B	0.03	µΩ/Ω	1	0.03	infinity
				Combined standard uncertainty	0.6924	µΩ/Ω
				Effective degrees of freedom	5138.8	
				Coverage factor	2	
				Expanded uncertainty	1.385	µΩ/Ω
				Expanded uncertainty	1.4	µΩ/Ω

Uncertainty budget for 100 Ω 4-wire measurement:

Component	Type	Standard uncertainty	Unit	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Standard resister: uncertainty	B	0.25	μΩ/Ω	1	0.25	infinity
Standard resister: drift	B	0.29	μΩ/Ω	1	0.29	infinity
Standard resister: temperature dependence	B	0.12	μΩ/Ω	1	0.12	infinity
Standard resister: power dependence	B	0.03	μΩ/Ω	1	0.03	infinity
UUT: repeatability	A	0.02	μΩ/Ω	1	0.02	4
UUT: resolution	B	0.03	μΩ/Ω	1	0.03	infinity
				Combined standard uncertainty	0.4040	μΩ/Ω
				Effective degrees of freedom	22984.3	
				Coverage factor	2	
				Expanded uncertainty	0.808	μΩ/Ω
				Expanded uncertainty	0.8	μΩ/Ω

Uncertainty budget for 1 kΩ 4-wire measurement:

Component	Type	Standard uncertainty	Unit	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Standard resister: uncertainty	B	0.50	μΩ/Ω	1	0.50	infinity
Standard resister: drift	B	0.29	μΩ/Ω	1	0.29	infinity
Standard resister: temperature dependence	B	0.12	μΩ/Ω	1	0.12	infinity
Standard resister: power dependence	B	0.03	μΩ/Ω	1	0.03	infinity

UUT: repeatability	A	0.02	μΩ/Ω	1	0.02	4
UUT: resolution	B	0.03	μΩ/Ω	1	0.03	infinity
				Combined standard uncertainty	0.5924	μΩ/Ω
				Effective degrees of freedom	17420.4	
				Coverage factor	2	
				Expanded uncertainty	1.185	μΩ/Ω
				Expanded uncertainty	1.2	μΩ/Ω

Uncertainty budget for 10 kΩ 4-wire measurement:

Component	Type	Standard uncertainty	Unit	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Standard resister: uncertainty	B	0.30	μΩ/Ω	1	0.30	infinity
Standard resister: drift	B	0.16	μΩ/Ω	1	0.16	infinity
Standard resister: temperature dependence	B	0.12	μΩ/Ω	1	0.12	infinity
Standard resister: power dependence	B	0.01	μΩ/Ω	1	0.01	infinity
UUT: repeatability	A	0.04	μΩ/Ω	1	0.04	4
UUT: resolution	B	0.03	μΩ/Ω	1	0.03	infinity
				Combined standard uncertainty	0.3639	μΩ/Ω
				Effective degrees of freedom	12644.6	
				Coverage factor	2	
				Expanded uncertainty	0.728	μΩ/Ω
				Expanded uncertainty	0.8	μΩ/Ω

Uncertainty budget for 100 kΩ 2-wire measurement:

Component	Type	Standard uncertainty	Unit	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Standard resister: uncertainty	B	0.75	μΩ/Ω	1	0.75	infinity
Standard resister: drift	B	1.73	μΩ/Ω	1	1.73	infinity
Standard resister: temperature dependence	B	0.12	μΩ/Ω	1	0.12	infinity
Standard resister: power dependence	B	0.00	μΩ/Ω	1	0.00	infinity
UUT: repeatability	A	0.00	μΩ/Ω	1	0.00	4
UUT: resolution	B	0.03	μΩ/Ω	1	0.03	infinity
				Combined standard uncertainty	1.8896	μΩ/Ω
				Effective degrees of freedom	13747.9	
				Coverage factor	2	
				Expanded uncertainty	3.780	μΩ/Ω
				Expanded uncertainty	3.8	μΩ/Ω

Uncertainty budget for 1 MΩ 2-wire measurement:

Component	Type	Standard uncertainty	Unit	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Standard resister: uncertainty	B	0.85	μΩ/Ω	1	0.85	infinity
Standard resister: drift	B	1.73	μΩ/Ω	1	1.73	infinity
Standard resister: temperature dependence	B	0.12	μΩ/Ω	1	0.12	infinity
Standard resister: power dependence	B	0.00	μΩ/Ω	1	0.00	infinity

UUT: repeatability	A	0.00	µΩ/Ω	1	0.00	4
UUT: resolution	B	0.03	µΩ/Ω	1	0.03	infinity
				Combined standard uncertainty	1.9315	µΩ/Ω
				Effective degrees of freedom	14682.1	
				Coverage factor	2	
				Expanded uncertainty	3.863	µΩ/Ω
				Expanded uncertainty	3.9	µΩ/Ω

For resistance at 10 MΩ and 100 MΩ the following components contribute to the uncertainty of measurement:

- Precision resistance measuring equipment (242C): Uncertainty of measurement point, drift, repeatability, resolution
- Unit under test uncertainty: Repeatability, resolution

Uncertainty budget for 10 MΩ 2-wire measurement:

Component	Type	Standard uncertainty	Unit	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Resistance measuring equipment(242 C): uncertainty of measurement point	B	11.55	µΩ/Ω	1	11.55	infinity
242 C : drift	B	5.43	µΩ/Ω	1	5.43	infinity
242 C : repeatability	A	0.15	µΩ/Ω	1	0.15	89
242 C : resolution	B	0.29	µΩ/Ω	1	0.29	infinity
UUT: repeatability	A	0.06	µΩ/Ω	1	0.06	4
UUT: resolution	B	0.03	µΩ/Ω	1	0.03	infinity
				Combined standard uncertainty	12.7659	µΩ/Ω
				Effective degrees of freedom	14229.8	

Coverage factor	2	
Expanded uncertainty	25.534	μΩ/Ω
Expanded uncertainty	0.026	mΩ/Ω

Uncertainty budget for 100 MΩ 2-wire measurement:

Component	Type	Standard uncertainty	Unit	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Resistance measuring equipment(242 C): uncertainty of measurement point	B	11.55	μΩ/Ω	1	11.55	infinity
242 C : drift	B	5.43	μΩ/Ω	1	5.43	infinity
242 C : repeatability	A	0.28	μΩ/Ω	1	0.28	89
242 C : resolution	B	0.29	μΩ/Ω	1	0.29	infinity
UUT: repeatability	A	0.29	μΩ/Ω	1	0.29	4
UUT: resolution	B	0.03	μΩ/Ω	1	0.03	infinity
Combined standard uncertainty					12.7711	μΩ/Ω
Effective degrees of freedom					14240.0	
Coverage factor					2	
Expanded uncertainty					25.545	μΩ/Ω
Expanded uncertainty					0.026	mΩ/Ω

Report on

Measurements performed for
APMP.EM-S12
Comparison of Standards for the Calibration of Voltage, Current and Resistance Meters

Measurements performed on

Wavetek 4950 serial number 33528

From 22 July 2016 to 19 August 2016

Performed by

National Metrology Centre, A*STAR
1 Science Park Drive
Singapore 118221

Report by

Ms Tay Siew Choon
Dr Chua Sze Wey

Electrical Metrology

Introduction

The APMP.EM-S12 comparison protocol requires that the travelling standard, a Wavetek model 4950 serial number 33528 (Unit Under Test – UUT), be measured at a number of points for each of its measurement functions. These are direct voltage, direct current, alternating voltage, alternating current and resistance. The measurement points are detailed in the comparison protocol.

The instrument was received on 20 July 2016. The fuse (F1) and mains voltage selection switch (S1) were checked before applying power. The UUT was allowed to stabilise for 24 hours with the power turned on before any measurements were made. The instrument's confidence test was performed and completed without any error.

The measurements were performed from 22th July 2016 to 19th August 2016. The instrument was sent to the NMI, Australia on 22nd August 2016.

Direct Voltage

Test methods:

1. For 100 mV, 19 V, 100 V and 1 000 V measurements, the correction of the UUT was determined by direct comparison against a characterized Calibrator. The Calibrator was characterized using a voltage measuring system consisting of a DC Voltage Standard and two Reference DC Voltage Dividers. The DC Voltage Standard was calibrated by a Josephson Array Voltage Standard.
2. For 1 V and 10 V measurements, the correction of the UUT was determined by direct comparison against DC Voltage Standards respectively which were calibrated by a Josephson Array Voltage Standard.

The 'Remote Guard' function was turned on for all the measurements, and the guard terminal and low voltage terminal were connected to a common ground point. The low current terminal was connected to the low voltage terminal and the high current terminal was connected to the high voltage terminal for all measurements.

See Figure 1.1 for the direct voltage measurement setups.

Traceability:

All the measurements described for Direct Voltage are traceable to Josephson Array Voltage Standard and Reference DC Voltage Dividers maintained by the National Metrology Centre, Singapore.

See Figure 2.1 for the Direct Voltage traceability chart.

Conditions of measurement:

During the direct voltage measurements, the following conditions of measurement prevailed:

Ambient temperature: (23.4 ± 0.2) °C
Relative humidity: (56 ± 1) % relative humidity

Measurement results:

Range (V)	Nominal Voltage (V)	Correction (V)	Uncertainty (V)	Internal Temperature (°C)
0.1	0.1	- 0.000 000 79	0.000 000 46	40.9
1	1	- 0.000 002 6	0.000 000 3	40.9
10	10	- 0.000 001	0.000 003	40.9
10	19	0.000 000	0.000 023	40.8
100	100	- 0.000 06	0.000 11	40.9
1000	1000	- 0.000 3	0.001 2	40.9

Detailed uncertainty budgets for the direct voltage measurements are shown in Appendix 3.1.

Direct Current

Test methods:

The correction of the UUT was determined by comparing its readings to the applied current. The UUT was connected in series with a calibrated resistor and a current source. The voltage drop across the resistor was measured by a calibrated voltmeter. The applied current was determined from the measured voltage divided by the resistance value of the resistor.

See Figure 1.2 for the direct current measurement setups.

The 'Remote Guard' function was turned on for all the measurements, and the guard terminal and low current terminal were connected to a common ground point. The low voltage and high voltage terminals were connected to the same ground point.

Traceability:

The traceability of dc current measurement is derived from dc voltage and resistance. The resistance value of the resistor is traceable to the resistance scale maintained by the National Metrology Centre, Singapore. This resistance scale is traceable to BIPM. The DC voltage measurement is traceable to Josephson Array Voltage Standard and DC voltage measurement standard maintained at the National Metrology Centre, Singapore.

See Figure 2.1 and 2.2 for the voltage traceability chart and resistance traceability chart respectively.

Conditions of measurement:

During the DC current measurements, the following conditions of measurement prevailed:

Ambient temperature: (22.9 ± 0.1) °C
Relative humidity: (57 ± 1) % relative humidity

Measurement results:

Range	Nominal Current	Correction	Uncertainty	Internal Temperature (°C)
1 mA	1 mA	0.000 002 mA	0.000 004 mA	40.8
1 A	1 A	- 0.000 030 A	0.000 007 A	40.8

Detailed uncertainty budgets for the direct current measurements are shown in Appendix 3.2.

Alternating Voltage

Test methods:

For AC measurements from 10 mV to 700 V, the correction of the UUT was determined by comparing the UUT reading to that obtained from an ac-dc difference measurement with a Thermal Transfer Standard. The applied alternating voltage was calculated from the characterised direct voltage of a Calibrator and the ac-dc difference of the Thermal Transfer Standard.

The calibrator output was directly connected to a type-N tee connector through a type-N adaptor. One end of the type N-tee connector was connected to Thermal Transfer Standard through a type-N adaptor while the other end of the type-N tee connector was directly connected to a 4 banana to type-N adapter, serial number 4BN-002. The UUT test lead was then attached to the 4 banana to type-N adaptor.

The ‘Remote Guard’ function of the UUT was turned on for all the measurements.

As specified by the protocol, the 1 MHz measurements at 1 V and 10 V was done with 4wCct (the default setting) selected.

The reference point was the middle of a type-N tee connecting the thermal transfer standard to the 4 banana to type-N adapter.

See Figure 1.3 for the alternating voltage measurement setups.

Traceability:

The traceability of ac voltage is derived from ac-dc difference and dc voltage. The direct voltage is traceable to Josephson Array Voltage Standard and Reference Voltage Dividers maintained by the National Metrology Centre, Singapore whereas the ac-dc voltage differences are traceable to the National Physical Laboratory (NPL), UK and the Physikalisch-Technische Bundesanstalt, Germany (PTB).

See Figure 2.3 for the ac-dc difference traceability chart.

Conditions of measurement:

During the alternating voltage measurements, the following conditions of measurement prevailed:

Ambient temperature: (23.2 ± 0.2) °C
Relative humidity: (56 ± 1) % relative humidity

Measurement results:

Range (V)	Nominal Voltage (V)	Frequency (kHz)	Correction (V)	Uncertainty (V)	Internal Temperature (°C)
0.01	0.01	0.010	- 0.000 000 41	0.000 001 7	40.7
		0.055	- 0.000 000 54	0.000 000 56	40.4
		1.005	- 0.000 000 36	0.000 000 74	40.6
		20	- 0.000 000 39	0.000 000 67	40.5
		50	- 0.000 000 34	0.000 000 68	40.5
		1 000	- 0.000 010 76	0.000 006 3	40.4
0.1	0.1	0.010	+ 0.000 003 9	0.000 002 2	40.7
		0.055	+ 0.000 008 2	0.000 001 9	40.6
		1.005	+ 0.000 008 8	0.000 002 0	40.6
		20	+ 0.000 009 2	0.000 001 6	40.6
		50	+ 0.000 006 6	0.000 002 6	40.6
		1 000	- 0.000 209 7	0.000 028	40.4
1	1	0.010	- 0.000 015	0.000 012	40.7
		0.055	- 0.000 003	0.000 007	40.7
		1.005	+ 0.000 007	0.000 011	40.8
		20	+ 0.000 012	0.000 011	40.8
		50	- 0.000 012	0.000 011	40.8
		1 000	- 0.007 025	0.000 082	40.6
10	10	0.010	- 0.000 55	0.000 12	40.8
		0.055	+ 0.000 06	0.000 08	40.7
		1.005	+ 0.000 09	0.000 08	40.6
		20	+ 0.000 06	0.000 11	40.6
		50	+ 0.000 07	0.000 10	40.6
		1 000	- 0.067 58	0.000 71	40.6
10	19	1.005	+ 0.000 03	0.000 17	40.5
100	100	0.010	- 0.007 0	0.001 8	40.9
		0.055	- 0.000 4	0.001 7	40.8
		1.005	- 0.000 3	0.001 7	40.8
		20	0.000 0	0.001 5	40.7
		50	- 0.001 5	0.001 4	40.7
1000	700	0.055	- 0.016	0.013	40.9
		1.005	- 0.015	0.016	40.9
		20	- 0.001	0.018	40.9
		50	+ 0.046	0.022	40.9

Detailed uncertainty budgets for the alternating voltage measurements are shown in Appendix 3.3.

Alternating Current

Test methods:

The correction of the UUT was determined by comparing its readings to that obtained from an ac-dc current difference measurement with a calibrated current system consisted of a current shunt and a Thermal Transfer Standard. The applied alternating current was calculated from the characterised direct current of the calibrator and the ac-dc current difference of the calibrated current system.

The UUT was connected in series with a current source and a current system with a voltmeter connected to its output.

The 'Remote Guard' function of the UUT was turned on for all the measurements. The guard terminal, the low current terminal, the low voltage terminal and high voltage terminal were connected to a common ground point.

See Figure 1.4 for the alternating current measurement setups.

Traceability:

The traceability of ac current is derived from ac-dc difference and dc current. The direct current is traceable to Josephson Array Voltage Standard and Reference Voltage Dividers maintained by the National Metrology Centre, Singapore whereas the ac-dc current differences are traceable to the Physikalisch-Technische Bundesanstalt, Germany (PTB).

See Figure 2.3 for the ac-dc current difference traceability chart.

Conditions of measurement:

During the alternating current measurements, the following conditions of measurement prevailed:

Ambient temperature: (23.0 ± 0.3) °C
Relative humidity: (56 ± 1) % relative humidity

Measurement results:

Range	Nominal Current	Frequency (kHz)	Correction	Uncertainty	Internal Temperature (°C)
1 mA	1 mA	0.055	+ 0.000 214 mA	0.000 039 mA	40.5
		1.005	+ 0.000 211 mA	0.000 039 mA	40.5
		5	+ 0.000 198 mA	0.000 039 mA	40.5
1 A	1 A	0.055	+ 0.000 138 A	0.000 030 A	40.9
		1.005	+ 0.000 174 A	0.000 031 A	40.9
		5	+ 0.000 736 A	0.000 031 A	40.9

Detailed uncertainty budgets for the alternating current measurements are shown in Appendix 3.4.

Resistance

Test methods:

The correction of the UUT was determined by comparing its readings to a set of standard resistors.

The ‘Remote Guard’ function of the UUT was turned on for all the measurements.

For 4-wire measurement, the guard terminal and low voltage terminal were connected to a common ground point.

For 2-wire measurement, the guard terminal, the low current terminal and the high current terminal were connected to a common ground point.

See Figure 1.5 for the resistance measurement setups.

Traceability:

The values of the standard resistors are traceable to BIPM through a resistance scale maintained by the National Metrology Centre, Singapore.

See Figure 2.2 for the resistance traceability chart.

Conditions of measurement:

During the resistance measurements, the following conditions of measurement prevailed:

Ambient temperature: (23.3 ± 0.2) °C
Relative humidity: (56 ± 1) % relative humidity

4-wire measurement results:

Range	Nominal Resistance	Correction	Uncertainty	Internal Temperature (°C)
10 Ω	10 Ω	+ 0.000 001 Ω	0.000 012 Ω	40.9
100 Ω	100 Ω	- 0.000 29 Ω	0.000 14 Ω	40.9
1 kΩ	1 kΩ	+ 0.000 002 2 kΩ	0.000 001 4 kΩ	40.8
10 kΩ	10 kΩ	- 0.000 001 kΩ	0.000 012 kΩ	40.9

2-wire measurement results:

Range	Nominal Resistance	Correction	Uncertainty	Internal Temperature (°C)
100 kΩ	100 kΩ	0.000 00 kΩ	0.000 14 kΩ	40.9
1 MΩ	1 MΩ	+ 0.000 003 0 MΩ	0.000 005 3 MΩ	40.9
10 MΩ	10 MΩ	- 0.000 166 MΩ	0.000 078 MΩ	40.8
100 MΩ	100 MΩ	- 0.000 27 MΩ	0.001 5 MΩ	40.9

Detailed uncertainty budgets for the resistance measurements are shown in Appendix 3.5.

Frequency

Test methods:

A calibrator was used as a source for the measurements of alternating voltage and alternating current. The correction of the calibrator was determined by measuring the frequency for an output of 1 V at 100 s gate time using a Frequency Counter referenced to a Frequency Primary Standard.

A measurement with a 1 V output only was sufficient to cover all the ranges and functions as the same time-based was used to generate the frequency for all output voltages and currents.

See Figure 1.6 for the frequency measurement setup.

The ‘External Guard’ function of the calibrator was turned off for all the measurements and the guard terminal was connected to a common ground point. This was done to provide the measurement circuit with a reference point because the counter input was floating.

Traceability:

The frequency measurements are traceable to the national frequency standard maintained by the National Metrology Centre, Singapore.

See Figure 2.4 for the frequency traceability chart.

Conditions of measurement:

During the frequency measurements, the following conditions of measurement prevailed:

Ambient temperature: (23.0 ± 0.4) °C
Relative humidity: (56 ± 1) % relative humidity

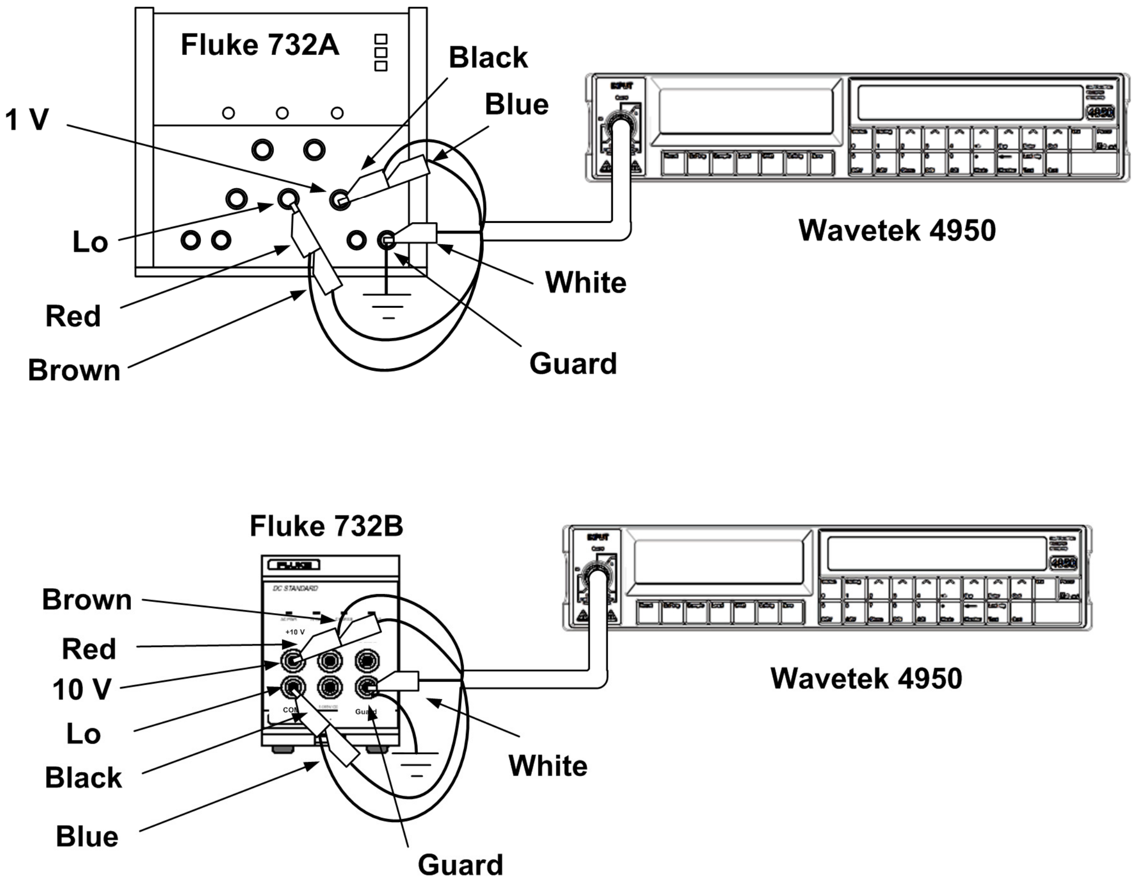
Frequency measurement results:

Nominal Frequency	Correction	Uncertainty
10 Hz	+ 0.000 273 3 Hz	0.000 003 1 Hz
55 Hz	+ 0.001 501 Hz	0.000 004 Hz
1.005 kHz	+ 0.027 41 Hz	0.000 02 Hz
5 kHz	+ 0.136 58 Hz	0.000 04 Hz
20 kHz	+ 0.546 1 Hz	0.001 0 Hz
50 kHz	+ 1.372 Hz	0.009 Hz
1 MHz	+ 27.41 Hz	0.17 Hz

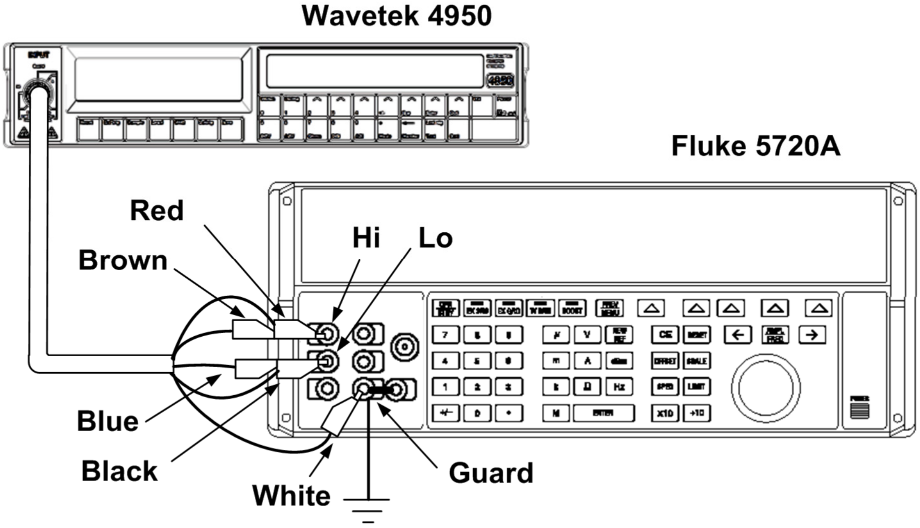
Detailed uncertainty budgets for the frequency measurements are shown in Appendix 3.6.

Appendix 1: Measurement setups

Direct Voltage



(a) 1 V and 10 V measurements



(b) 100 mV, 19 V, 100 V and 1000 V measurements

Figure 1.1: Direct voltage measurement setups

Direct Current

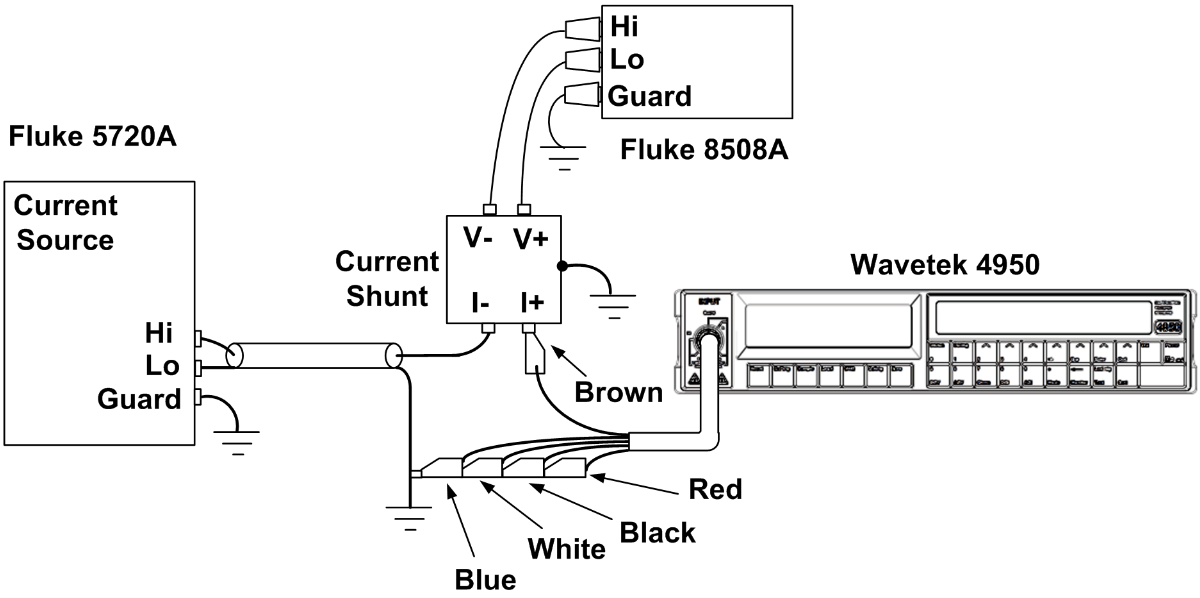
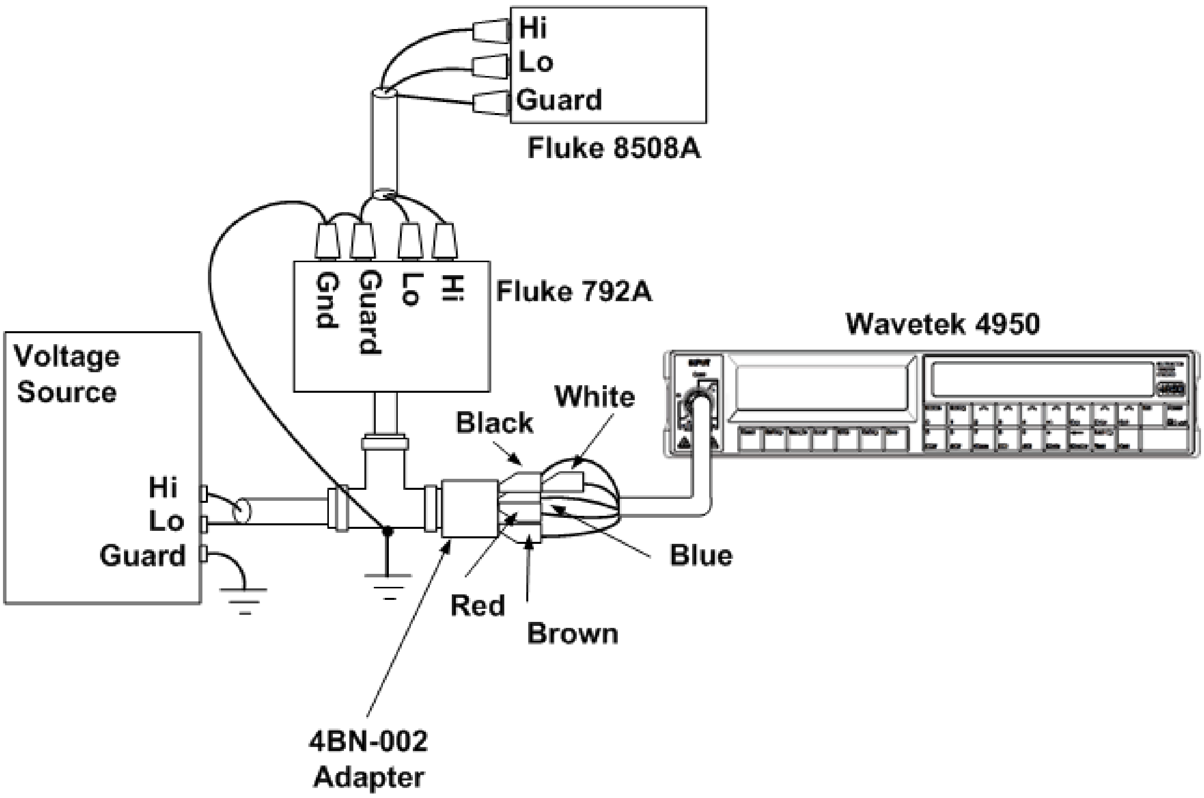
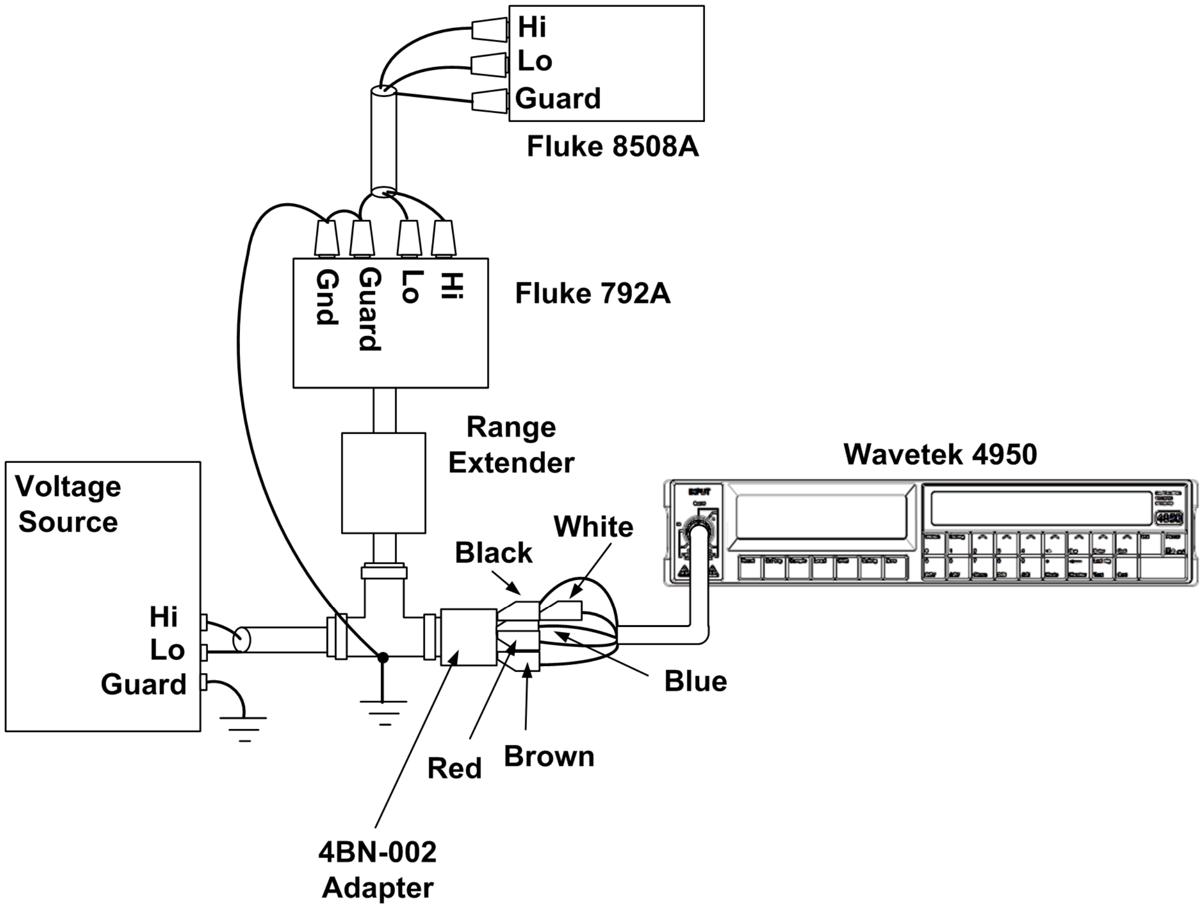


Figure 1.2: Direct current measurement setup

Alternating Voltage



(a) 10 mV to 100 V measurements



(b) 700 V measurement

Figure 1.3: Alternating voltage measurement setups

Alternating Current

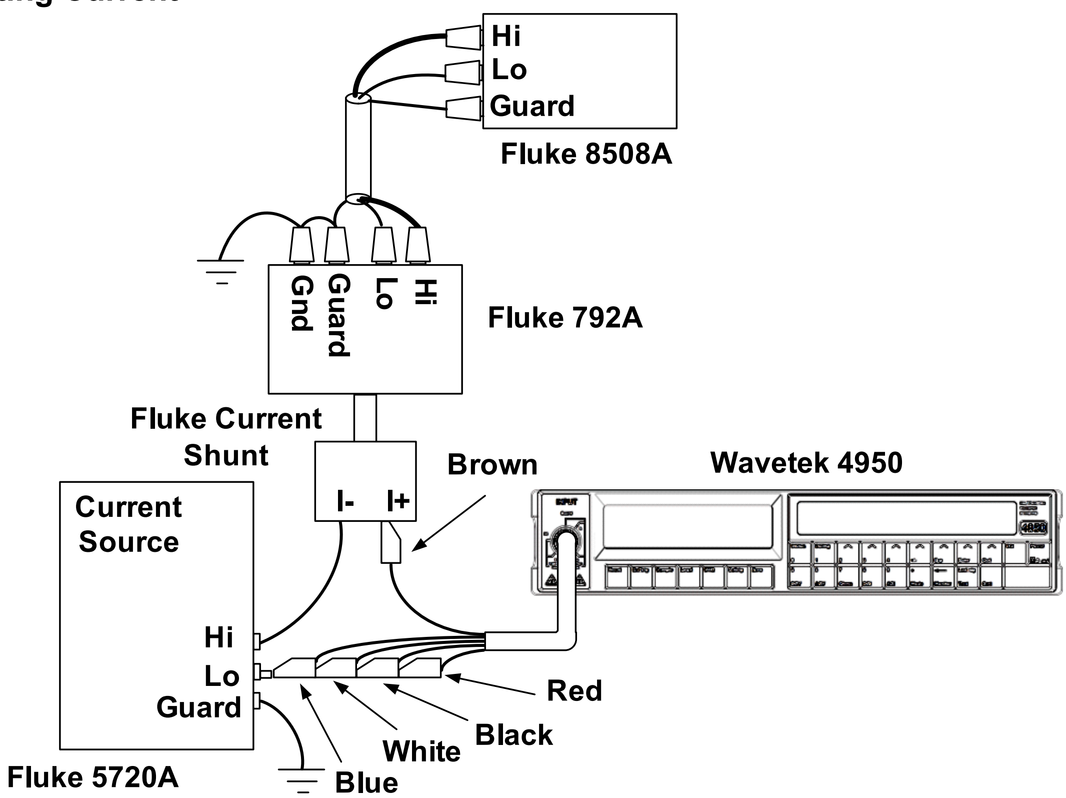
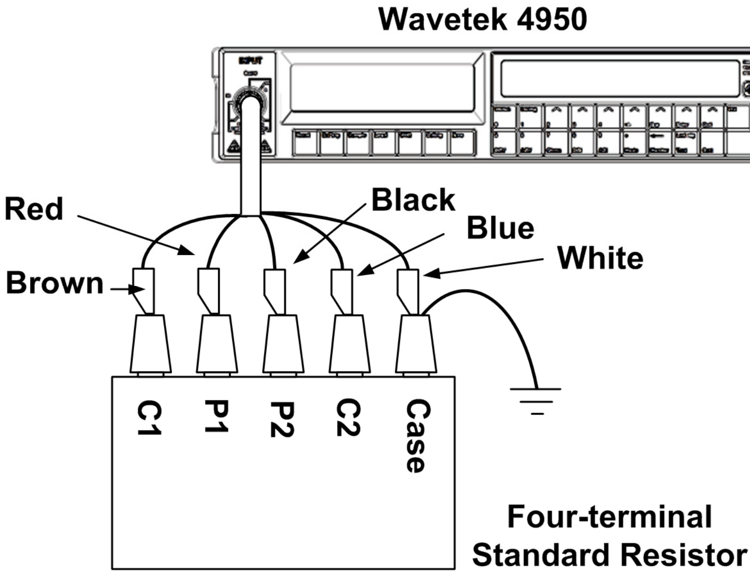
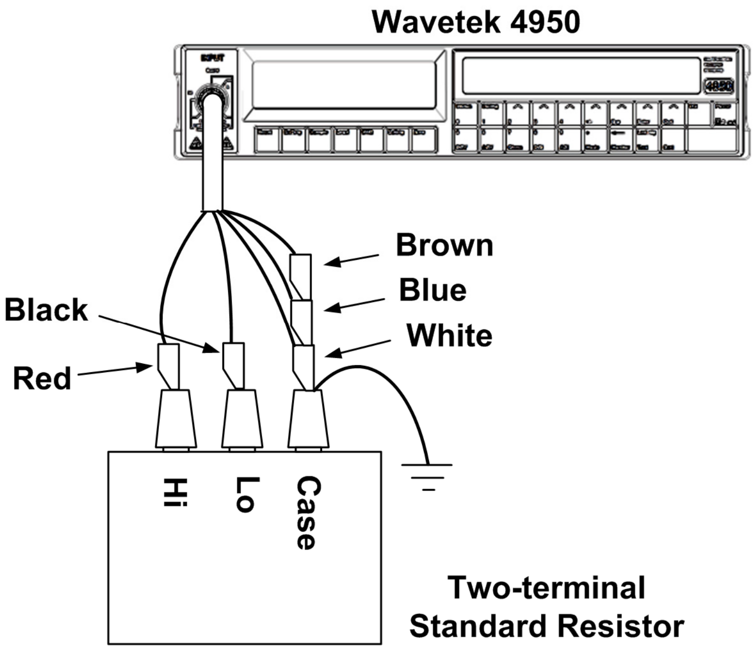


Figure 1.4: Alternating current measurement setup

Resistance



(a) Four wire resistance measurement



(b) Two wire resistance measurement

Figure 1.5: Resistance measurement setups

Frequency

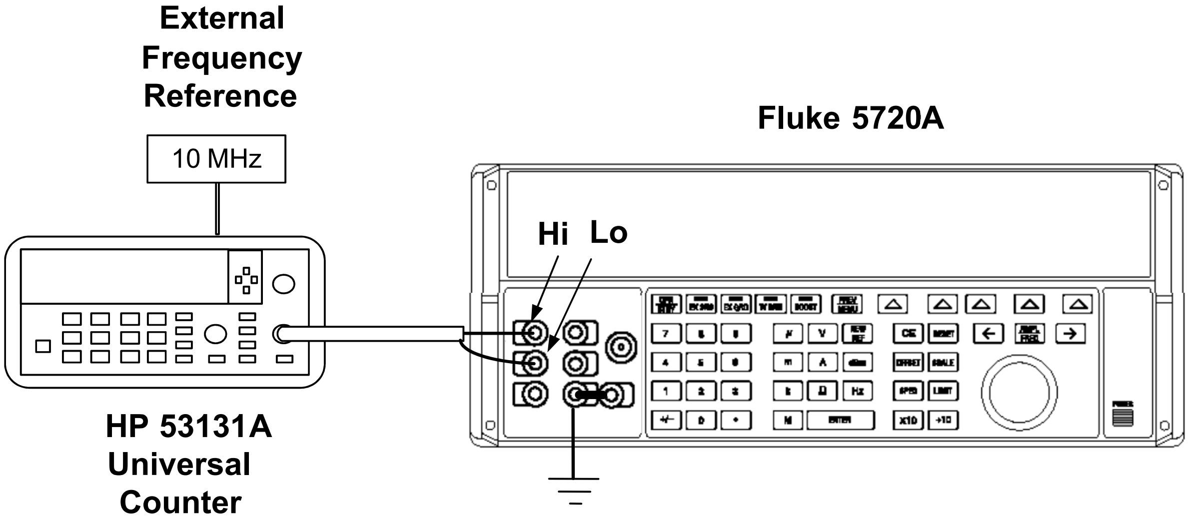


Figure 1.6 Frequency measurement setup.

Appendix 2: Traceability charts

Direct Voltage

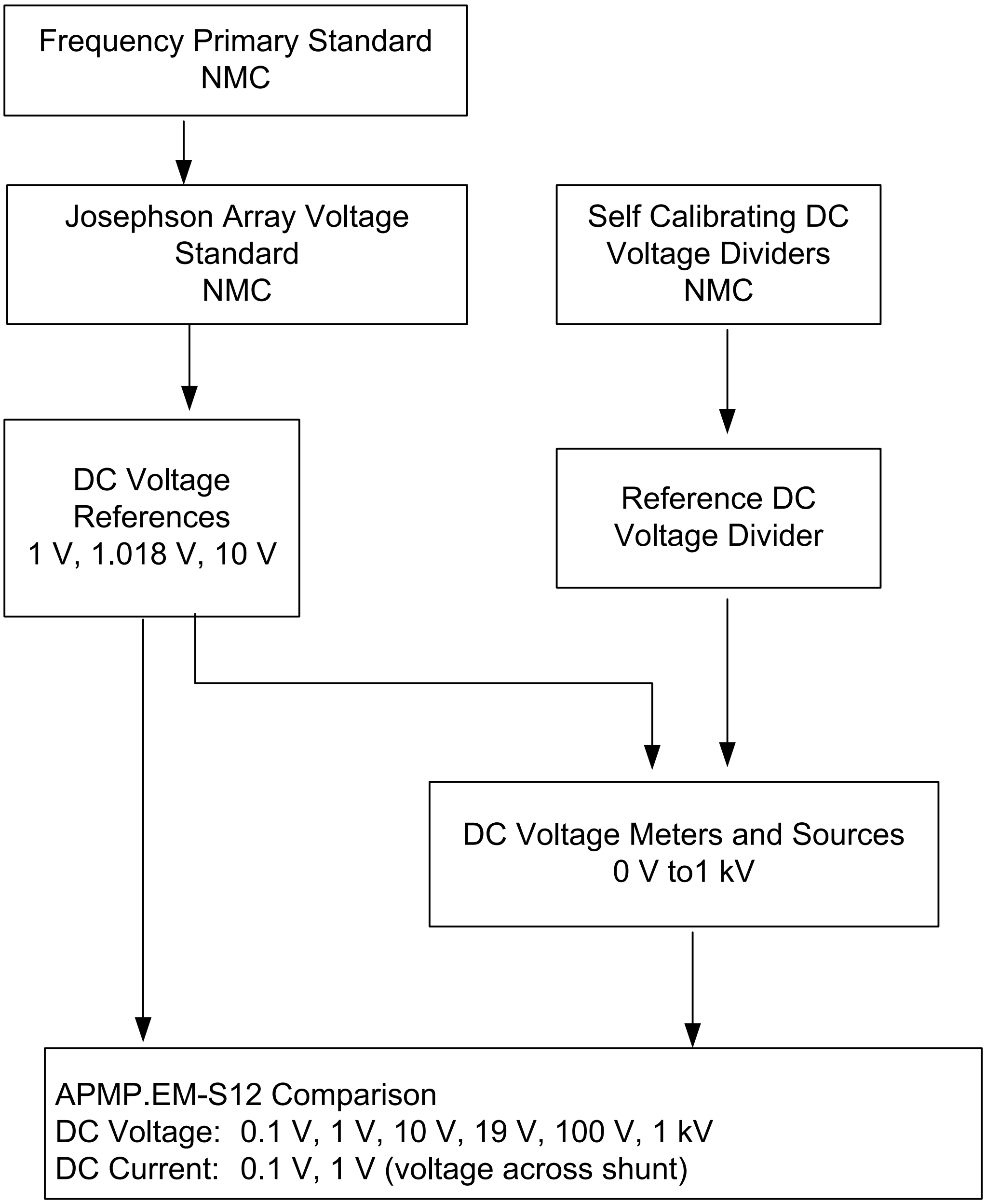


Figure 2.1: Direct voltage traceability

Resistance

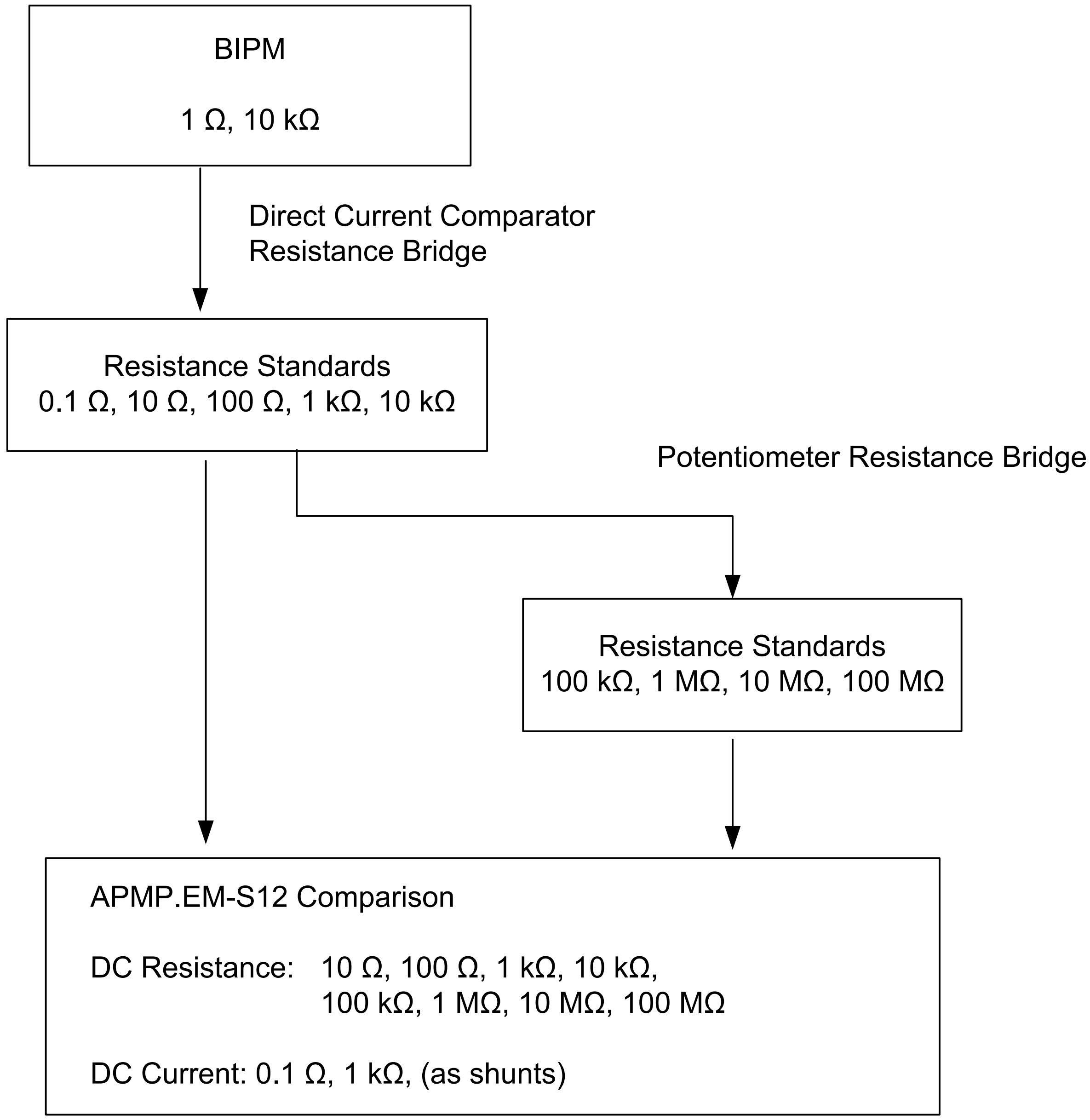


Figure 2.2: Resistance traceability

Ac-dc difference

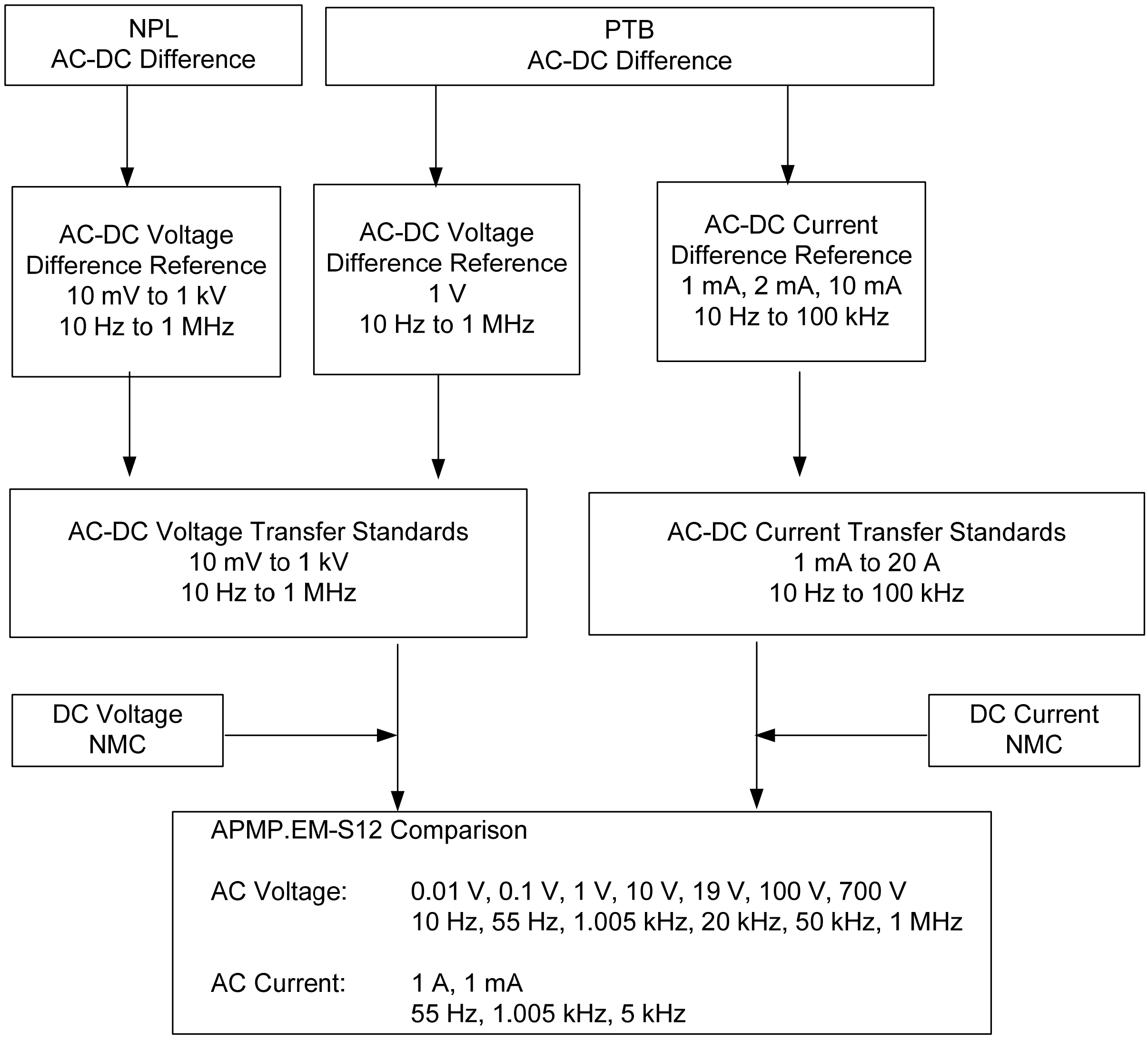


Figure 2.3: Ac-dc difference traceability

Frequency

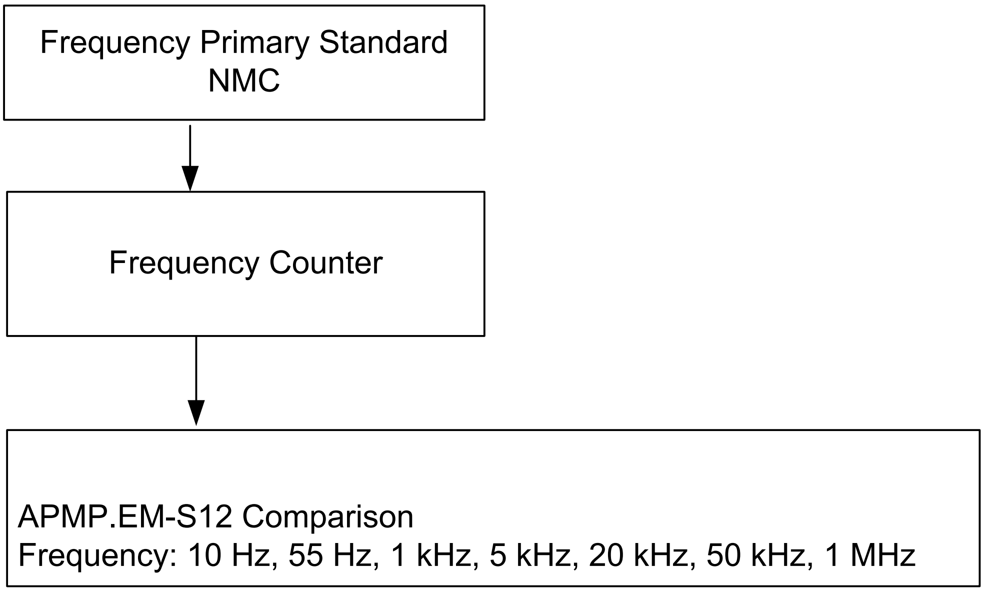


Figure 2.4 Frequency traceability

Appendix 3: Uncertainty budgets

3.1 Direct Voltage

For direct voltage at 100 mV, the following components contribute to the uncertainty of measurement:

- Calibrator Uncertainty: From the latest calibration report
- Calibrator Stability: From the specification of the calibrator
- Zero Offset Cancellation: From the difference in zero readings before and after measurement at the nominal voltage
- Unit Under Test Repeatability: From the observed data
- Unit Under Test Stability: From tests repeated several times during the period that the instrument spent in our laboratory
- Unit Under Test Resolution: The least displayed digit on the unit under test

Uncertainty budget for 100 mV measurement:

Source Of Uncertainty	**Type**	**Value (µV/V)**	**Sensitivity Coefficient**	**Divisor**	**Standard Uncertainty (µV/V)**	**Degrees Of Freedom**
Calibrator Uncertainty	B	3	1	2.000	1.50	infinity
Calibrator Stability	B	3.3	1	2.576	1.28	infinity
Zero Offset Thermal Voltages	B	0.39	1	1.732	0.23	infinity
Unit Under Test Repeatability	A	1.09	1	1.000	1.09	14
Unit Under Test Stability	B	0.5	1	1.732	0.29	infinity
Unit Under Test Resolution	B	0.05	1	1.732	0.03	Infinity
Combined Uncertainty				-	2.28	273
Expanded Uncertainty				2.01	4.58	273
					(µV)	
Expanded Uncertainty				2.01	0.458	273

For direct voltage at 1 V and 10 V, the following components contribute to the uncertainty of measurement:

– Voltage Reference Uncertainty: From the latest calibration report
– Voltage Reference Drift: From the history of the voltage reference
– Zero Offset Thermal Voltages: From the difference in zero readings before and after measurement at the nominal voltage
– Unit Under Test Repeatability: From the observed data
– Unit Under Test Stability: From tests repeated several times during the period that the instrument spent in our laboratory
– Unit Under Test Resolution: The least displayed digit on the unit under test

Uncertainty budget for 1 V measurement:

Source Of Uncertainty	**Type**	**Value (µV/V)**	**Sensitivity Coefficient**	**Divisor**	**Standard Uncertainty (µV/V)**	**Degrees Of Freedom**
Voltage Reference Uncertainty	B	0.1	1	2.000	0.05	infinity
Voltage Reference Drift	B	0.17	1	2.140	0.08	19
Zero Offset Thermal Voltages	B	0.08	1	1.732	0.05	infinity
Unit Under Test Repeatability	A	0.02	1	1.000	0.02	14
Unit Under Test Stability	B	0.1	1	1.732	0.06	infinity
Unit Under Test Resolution	B	0.05	1	1.732	0.03	Infinity
Combined Uncertainty				-	0.12	116
Expanded Uncertainty				2.02	0.25	116
					(µV)	
Expanded Uncertainty				2.02	0.25	116

Uncertainty budget for 10 V measurement:

Source Of Uncertainty	Type	Value (µV/V)	Sensitivity Coefficient	Divisor	Standard Uncertainty (µV/V)	Degrees Of Freedom
Voltage Reference Uncertainty	B	0.1	1	2.000	0.05	infinity
Voltage Reference Drift	B	0.04	1	2.140	0.02	19
Zero Offset Thermal Voltages	B	0.04	1	1.732	0.02	infinity
Unit Under Test Repeatability	A	0.01	1	1.000	0.01	14
Unit Under Test Stability	B	0.19	1	1.732	0.11	infinity
Unit Under Test Resolution	B	0.05	1	1.732	0.03	Infinity
Combined Uncertainty				-	0.13	33598
Expanded Uncertainty				2.00	0.26	33598
					(µV)	
Expanded Uncertainty				2.00	2.6	33598

For direct voltage at 19 V to 1 000 V, the following components contribute to the uncertainty of measurement:

– Calibrator Uncertainty: From the latest calibration report
– Calibrator Stability: From the specification of the calibrator
– Zero Offset Thermal Voltages: From the difference in zero readings before and after measurement at the nominal voltage
– Unit Under Test Repeatability: From the observed data
– Unit Under Test Stability: From tests repeated several times during the period that the instrument spent in our laboratory
– Unit Under Test Resolution: The least displayed digit on the unit under test

Uncertainty budget for 19 V measurement:

Source Of Uncertainty	Type	Value (μV/V)	Sensitivity Coefficient	Divisor	Standard Uncertainty (μV/V)	Degrees Of Freedom
Calibrator Uncertainty	B	0.7	1	2.000	0.35	infinity
Calibrator Stability	B	0.66	1	2.576	0.26	infinity
Zero Offset Thermal Voltages	B	0.03	1	1.732	0.02	infinity
Unit Under Test Repeatability	A	0.01	1	1.000	0.01	14
Unit Under Test Stability	B	0.71	1	1.732	0.41	infinity
Unit Under Test Resolution	B	0.03	1	1.732	0.02	Infinity
Combined Uncertainty				-	0.60	9.56×10^{7}
Expanded Uncertainty				2.00	1.20	9.56×10^{7}
					(μV)	
Expanded Uncertainty				2.00	22.8	9.56×10^{7}

Uncertainty budget for 100 V measurement:

Source Of Uncertainty	Type	Value (μV/V)	Sensitivity Coefficient	Divisor	Standard Uncertainty (μV/V)	Degrees Of Freedom
Calibrator Uncertainty	B	0.45	1	2.000	0.23	infinity
Calibrator Stability	B	0.9	1	2.576	0.35	infinity
Zero Offset Thermal Voltages	B	0.15	1	1.732	0.08	infinity
Unit Under Test Repeatability	A	0.01	1	1.000	0.01	14
Unit Under Test Stability	B	0.55	1	1.732	0.32	infinity
Unit Under Test Resolution	B	0.05	1	1.732	0.03	Infinity
Combined Uncertainty	B	-	-	-	0.53	5.67×10^{8}
Expanded Uncertainty	B	-	-	2.00	1.06	5.67×10^{8}
					(mV)	
Expanded Uncertainty				2.00	0.106	5.67×10^{8}

Uncertainty budget for 1000 V measurement:

Source Of Uncertainty	Type	Value (μV/V)	Sensitivity Coefficient	Divisor	Standard Uncertainty (μV/V)	Degrees Of Freedom
Calibrator Uncertainty	B	0.85	1	2.000	0.43	infinity
Calibrator Stability	B	0.7	1	2.576	0.27	infinity
Zero offset Thermal Voltages	B	0	1	1.732	0.00	infinity
Unit Under Test Repeatability	A	0.01	1	1.000	0.01	14
Unit Under Test Stability	B	0.58	1	1.732	0.33	infinity
Unit Under Test Resolution	B	0.05	1	1.732	0.03	Infinity
Combined Uncertainty				-	0.61	5.99×10^{7}
Expanded Uncertainty				2.00	1.21	5.99×10^{7}
					(mV)	
Expanded Uncertainty				2.00	1.21	5.99×10^{7}

3.2 Direct Current

For direct current, the following components contribute to the uncertainty of measurement:

- Shunt Uncertainty: From the latest calibration report
- Shunt Drift: From the regression calculation based on the past calibration reports of the shunt
- Shunt Temperature Coefficient : From varying of the temperature to determine the temperature coefficient of the shunt
- Voltmeter Uncertainty: From the voltmeter specifications
- Voltmeter Resolution: The least displayed digit on the voltmeter
- Voltmeter Loading: From the calculation based on the measured value of input impedance of the voltmeter
- Voltmeter Repeatability: From the observed data
- Unit Under Test Repeatability: From the observed data
- Unit Under Test Stability: From tests repeated several times during the period that the instrument spent in our laboratory
- Unit Under Test Resolution: The least displayed digit on the unit under test

Uncertainty budget for 1 mA measurement:

Source Of Uncertainty	**Type**	**Value**	**Unit**	**Sensitivity Coefficient**	**Divisor**	**Standard Uncertainty**	**Unit**	**Degrees Of Freedom**
Shunt Uncertainty	B	1	µΩ/Ω	1	2.000	0.50	µΩ/Ω	Infinity
Shunt Drift	B	0.65	µΩ/Ω	1	2.080	0.31	µΩ/Ω	31
Shunt Temperature Coefficient	B	0.1	µΩ/Ω	1	1.732	0.06	µΩ/Ω	Infinity
Voltmeter Uncertainty	B	4.5	µV/V	1	2.576	1.75	µV/V	Infinity
Voltmeter Resolution	B	0.05	µV/V	1	1.732	0.03	µV/V	Infinity
Voltmeter Loading	B	0	µV/V	1	1.732	0.00	µV/V	Infinity
Voltmeter Repeatability	A	0.04	µV/V	1	1.000	0.04	µV/V	14
Unit Under Test Repeatability	A	0.07	µA/A	1	1.000	0.07	µA/A	14
Unit Under Test Stability	B	1	µA/A	1	1.732	0.58	µA/A	Infinity
Unit Under Test Resolution	B	0.5	µA/A	1	1.732	0.29	µA/A	Infinity
Combined Uncertainty					-	1.96	µA/A	47342
Expanded Uncertainty					2.00	3.91	µA/A	47342
Expanded Uncertainty					2.00	3.91	nA	47342

Uncertainty budget for 1 A measurement:

Source Of Uncertainty	Type	Value	Unit	Sensitivity Coefficient	Divisor	Standard Uncertainty	Unit	Degrees Of Freedom
Shunt Uncertainty	B	2	μΩ/Ω	1	2.000	1.00	μΩ/Ω	Infinity
Shunt Drift	B	0.15	μΩ/Ω	1	2.230	0.07	μΩ/Ω	12
Shunt Temperature Coefficient	B	0.1	μΩ/Ω	1	1.732	0.06	μΩ/Ω	Infinity
Voltmeter Uncertainty	B	7.2	μV/V	1	2.576	2.80	μV/V	Infinity
Voltmeter Resolution	B	0.05	μV/V	1	1.732	0.03	μV/V	Infinity
Voltmeter Loading	B	0	μV/V	1	1.732	0.00	μV/V	Infinity
Voltmeter Repeatability	A	0.09	μV/V	1	1.000	0.09	μV/V	14
Unit Under Test Repeatability	A	0.13	μA/A	1	1.000	0.13	μA/A	14
Unit Under Test Stability	B	2	μA/A	1	1.732	1.15	μA/A	Infinity
Unit Under Test Resolution	B	0.5	μA/A	1	1.732	0.29	μA/A	Infinity
Combined Uncertainty					-	3.20	μA/A	3.58×10^{6}
Expanded Uncertainty					2.00	6.41	μA/A	3.58×10^{6}
Expanded Uncertainty					2.00	6.41	μA	3.58×10^{6}

3.3 Alternating Voltage

For alternating voltage from 10 mV to 700 V the following components contribute to the uncertainty of measurement:

- DC Reference Uncertainty: From the uncertainty calculation of the characterised dc voltage of the calibrator at the time of calibration. This source of uncertainty includes the stability and the resolution of the calibrator
- Connector Loading: Measure the impedance of the connecting assembly which consisted of 2 type N adaptors and a type-N tee connector using an LCR meter. Calculate the effect of the connecting assembly.
- Voltmeter Short Term Stability: From the specification of the voltmeter
- Thermal Transfer Uncertainty : From the latest calibration report
- Thermal Transfer Drift: From the history of the thermal transfer standard
- Voltmeter ac-dc Difference: The difference of the measured voltages at the Thermal Transfer Output when switching from dc to ac
- Voltmeter dc Repeatability: From the observed data of the measured voltage at dc
- Voltmeter ac Repeatability: From the observed data of the measured voltage at ac
- Unit Under Test Repeatability: From the observed data
- Unit Under Test Stability: From tests repeated several times during the period that the instrument spent in our laboratory
- Unit Under Test Resolution: The least displayed digit on the unit under test

Uncertainty budget for 10 mV and 1.005 kHz measurement:

Source Of Uncertainty	**Type**	**Value (μV/V)**	**Sensitivity Coefficient**	**Divisor**	**Standard Uncertainty (μV/V)**	**Degrees Of Freedom**
DC Reference Uncertainty	B	40	1	2.000	20.00	infinity
Connector Loading	B	0	1	1.732	0.00	infinity
Voltmeter Short Term Stability	B	0.34	1	2.576	0.13	infinity
Thermal Transfer Uncertainty	B	31	1	2.000	15.50	infinity
Thermal Transfer Drift	B	41	1	1.732	23.67	infinity
Voltmeter ac-dc Difference	B	2.65	1	1.732	1.53	infinity
Voltmeter dc Repeatability	A	3.85	1	1.000	3.85	14
Voltmeter ac Repeatability	A	0.2	1	1.000	0.20	14
Unit Under Test Repeatability	A	0.45	1	1.000	0.45	14
Unit Under Test Stability	B	18	1	1.732	10.39	infinity
Unit Under Test Resolution	B	5	1	1.732	2.89	Infinity
Combined Uncertainty				-	36.53	113916
Expanded Uncertainty				2.00	73.06	113916
					(μV)	
Expanded Uncertainty				2.00	0.731	113916

10 mV range uncertainties

The table below summarises the uncertainty estimates for the 10 mV measurements. Only the standard uncertainties after reduction of the input values are shown. The degrees of freedom assigned to each component are the same as those assigned to the components in the budget for 10 mV and 1.005 kHz shown on the previous page.

								Standard uncertainties											
Range (V)	Nominal Voltage (V)	Frequency (kHz)	Expanded uncertainty (µV)	Expanded uncertainty (µV/V)	Coverage factor	Effective degrees of freedom	Combined standard uncertainty (µV/V)	DC Reference Uncertainty (µV/V)	Connector Loading (µV/V)	Voltmeter Short Term Stability (µV/V)	Thermal Transfer Uncertainty (µV/V)	Thermal Transfer Drift (µV/V)	Voltmeter ac-dc difference (µV/V)	Voltmeter dc Repeatability (µV/V)	Voltmeter ac Repeatability (µV/V)	Unit Under Test Repeatability (µV/V)	Unit Under Test Stability (µV/V)	Unit Under Test Resolution (µV/V)
0.01	0.01	0.01	1.647	164.7	2.00	3.60×10^{6}	82.35	20.00	0.00	0.13	15.50	76.79	14.64	3.66	0.18	0.19	3.00	2.89
		0.055	0.557	55.70	2.00	5.09×10^{4}	27.85	20.00	0.00	0.13	16.00	6.35	5.97	3.58	0.88	0.28	4.66	2.89
		1.005	0.731	73.06	2.00	1.14×10^{5}	36.53	20.00	0.00	0.13	15.50	23.67	1.53	3.85	0.20	0.45	10.39	2.89
		20	0.665	66.54	2.00	1.02×10^{5}	33.27	20.00	0.01	0.13	15.50	4.62	8.47	3.60	0.31	0.36	18.76	2.89
		50	0.680	67.99	2.00	1.04×10^{5}	33.99	20.00	0.04	0.13	17.50	2.31	8.91	3.66	0.18	0.19	18.51	2.89
		1000	6.220	621.3	2.00	1.73×10^{9}	310.65	20.00	30.16	0.13	204.0	214.2	4.80	2.94	0.11	0.79	87.48	2.88

Uncertainty budget for 100 mV and 1.005 kHz measurement:

Source Of Uncertainty	Type	Value (µV/V)	Sensitivity Coefficient	Divisor	Standard Uncertainty (µV/V)	Degrees Of Freedom
DC Reference Uncertainty	B	5	1	2.000	2.50	infinity
Connector Loading	B	0	1	1.732	0.00	infinity
Voltmeter Short Term Stability	B	0.34	1	2.576	0.13	infinity
Thermal Transfer Uncertainty	B	10	1	2.000	5.00	infinity
Thermal Transfer Drift	B	14	1	1.732	8.08	infinity
Voltmeter ac-dc difference	B	1.59	1	1.732	0.92	infinity
Voltmeter dc Repeatability	A	0.31	1	1.000	0.31	14
Voltmeter ac Repeatability	A	0.17	1	1.000	0.17	14
Unit Under Test Repeatability	A	0.37	1	1.000	0.37	14
Unit Under Test Stability	B	2	1	1.732	1.41	infinity
Unit Under Test Resolution	B	0.5	1	1.732	0.29	Infinity
Combined Uncertainty				-	9.99	4802561
Expanded Uncertainty				2.00	19.98	4802561
					(µV)	
Expanded Uncertainty				2.00	1.998	4802561

100 mV range uncertainties

The table below summarises the uncertainty estimates for the 100 mV measurements. Only the standard uncertainties after reduction of the input values are shown. The degrees of freedom assigned to each component are the same as those assigned to the components in the budget for 100 mV and 1.005 kHz shown on the previous page.

								Standard uncertainties										
Range (V)	Nominal Voltage (V)	Frequency (kHz)	Expanded uncertainty (µV)	Expanded uncertainty (µV/V)	Coverage factor	Effective degrees of freedom	Combined standard uncertainty (µV/V)	DC Reference Uncertainty (µV/V)	Connector Loading (µV/V)	Voltmeter Short Term Stability (µV/V)	Thermal Transfer Uncertainty (µV/V)	Thermal Transfer Drift (µV/V)	Voltmeter ac-dc difference (µV/V)	Voltmeter dc Repeatability (µV/V)	Voltmeter ac Repeatability (µV/V)	Unit Under Test Repeatability (µV/V)	Unit Under Test Stability (µV/V)	Unit Under Test Resolution (µV/V)
0.1	0.1	0.01	2.14	21.40	2.00	9.81×10^{3}	10.70	2.50	0.00	0.13	5.00	8.08	2.86	1.74	1.74	0.78	1.70	0.29
		0.055	1.84	18.38	2.00	3.50×10^{6}	9.19	2.50	0.00	0.13	6.00	6.35	1.04	0.28	0.26	0.37	0.66	0.29
		1.005	2.00	19.98	2.00	4.80×10^{6}	9.99	2.50	0.00	0.13	5.00	8.08	0.92	0.31	0.17	0.37	1.41	0.29
		20	1.56	15.60	2.00	1.14×10^{6}	7.80	2.50	0.01	0.13	5.00	4.04	2.38	0.45	0.10	0.26	2.68	0.29
		50	2.59	25.84	2.00	4.05×10^{3}	12.92	2.50	0.04	0.13	6.00	5.20	1.96	0.34	0.06	3.13	9.15	0.29
		1000	27.79	277.34	2.00	6.30×10^{11}	138.7	2.50	30.16	0.13	60.5	116.1	1.28	0.28	0.10	0.21	34.41	0.29

Uncertainty budget for 1 V and 1.005 kHz measurement:

Source Of Uncertainty	Type	Value (µV/V)	Sensitivity Coefficient	Divisor	Standard Uncertainty (µV/V)	Degrees Of Freedom
DC Reference Uncertainty	B	1	1	2.000	0.50	infinity
Connector Loading	B	0	1	1.732	0.00	infinity
Voltmeter Short Term Stability	B	0.35	1	2.576	0.14	infinity
Thermal Transfer Uncertainty	B	7	1	2.000	3.50	infinity
Thermal Transfer Drift	B	7	1	1.732	4.04	infinity
Voltmeter ac-dc difference	B	1.96	1	1.732	1.13	infinity
Voltmeter dc Repeatability	A	0.06	1	1.000	0.06	14
Voltmeter ac Repeatability	A	0.13	1	1.000	0.13	14
Unit Under Test Repeatability	A	0.33	1	1.000	0.33	14
Unit Under Test Stability	B	0.27	1	1.732	0.15	infinity
Unit Under Test Resolution	B	0.5	1	1.732	0.29	Infinity
Combined Uncertainty				-	5.51	1055538
Expanded Uncertainty				2.00	11.02	1055538
					(µV)	
Expanded Uncertainty				2.00	11.02	1055538

1 V range uncertainties

The table below summarises the uncertainty estimates for the 1 V measurements. Only the standard uncertainties after reduction of the input values are shown. The degrees of freedom assigned to each component are the same as those assigned to the components in the budget for 1 V and 1.005 kHz shown on the previous page.

								Standard uncertainties										
Range (V)	Nominal Voltage (V)	Frequency (kHz)	Expanded uncertainty (µV)	Expanded uncertainty (µV/V)	Coverage factor	Effective degrees of freedom	Combined standard uncertainty (µV/V)	DC Reference Uncertainty (µV/V)	Connector Loading (µV/V)	Voltmeter Short Term Stability (µV/V)	Thermal Transfer Uncertainty (µV/V)	Thermal Transfer Drift (µV/V)	Voltmeter ac-dc difference (µV/V)	Voltmeter dc Repeatability (µV/V)	Voltmeter ac Repeatability (µV/V)	Unit Under Test Repeatability (µV/V)	Unit Under Test Stability (µV/V)	Unit Under Test Resolution (µV/V)
1	1	0.01	11.24	11.24	2.00	8.37×10^{5}	5.62	0.50	0.00	0.14	3.50	2.31	3.38	0.31	0.06	0.29	1.42	0.29
		0.055	6.94	6.94	2.00	5.61×10^{4}	4.04	0.50	0.00	0.14	3.00	1.15	0.70	0.06	0.41	0.29	0.77	0.29
		1.005	11.02	11.02	2.00	1.06×10^{6}	5.51	0.50	0.00	0.14	3.50	4.04	1.13	0.06	0.13	0.33	0.15	0.29
		20	10.29	10.29	2.00	5.29×10^{4}	5.14	0.50	0.01	0.14	3.00	3.46	1.47	0.66	0.07	0.13	1.58	0.29
		50	11.00	11.00	2.00	1.10×10^{7}	5.50	0.50	0.04	0.14	4.04	1.11	1.11	0.07	0.08	0.18	0.12	0.29
		1000	81.36	80.79	2.00	1.11×10^{11}	40.40	0.50	30.16	0.14	26.00	4.04	1.86	0.08	0.13	0.23	5.12	0.29

Uncertainty budget for 10 V and 1.005 kHz measurement:

Source Of Uncertainty	**Type**	**Value (µV/V)**	**Sensitivity Coefficient**	**Divisor**	**Standard Uncertainty (µV/V)**	**Degrees Of Freedom**
DC Reference Uncertainty	B	1	1	2.000	0.50	infinity
Connector Loading	B	0	1	1.732	0.00	infinity
Voltmeter Short Term Stability	B	0.33	1	2.576	0.13	infinity
Thermal Transfer Uncertainty	B	6	1	2.000	3.00	infinity
Thermal Transfer Drift	B	4	1	1.732	2.31	infinity
Voltmeter ac-dc difference	B	0.58	1	1.732	0.33	infinity
Voltmeter dc Repeatability	A	0.06	1	1.000	0.06	14
Voltmeter ac Repeatability	A	0.15	1	1.000	0.15	14
Unit Under Test Repeatability	A	0.37	1	1.000	0.37	14
Unit Under Test Stability	B	0.7	1	1.732	0.38	infinity
Unit Under Test Resolution	B	0.5	1	1.732	0.29	Infinity
Combined Uncertainty				-	3.89	174715
Expanded Uncertainty				2.00	7.78	174715
					(µV)	
Expanded Uncertainty				2.00	77.8	174715

10 V range uncertainties

The table below summarises the uncertainty estimates for the 10 V and 19 V measurements. Only the standard uncertainties after reduction of the input values are shown. The degrees of freedom assigned to each component are the same as those assigned to the components in the budget for 10 V and 1.005 kHz shown on the previous page.

								Standard uncertainties										
Range (V)	Nominal Voltage (V)	Frequency (kHz)	Expanded uncertainty (µV)	Expanded uncertainty (µV/V)	Coverage factor	Effective degrees of freedom	Combined standard uncertainty (µV/V)	DC Reference Uncertainty (µV/V)	Connector Loading (µV/V)	Voltmeter Short Term Stability (µV/V)	Thermal Transfer Uncertainty (µV/V)	Thermal Transfer Drift (µV/V)	Voltmeter ac-dc difference (µV/V)	Voltmeter dc Repeatability (µV/V)	Voltmeter ac Repeatability (µV/V)	Unit Under Test Repeatability (µV/V)	Unit Under Test Stability (µV/V)	Unit Under Test Resolution (µV/V)
10	10	0.01	114.5	11.45	2.00	9.00×10^{4}	5.72	0.50	0.00	0.13	3.00	4.62	1.21	0.07	0.34	0.63	0.35	0.29
		0.055	78.4	7.84	2.00	1.08×10^{5}	3.92	0.50	0.00	0.13	3.00	2.31	0.59	0.06	0.34	0.36	0.23	0.29
		1.005	77.8	7.78	2.00	1.75×10^{5}	3.89	0.50	0.00	0.13	3.00	2.31	0.33	0.06	0.15	0.37	0.38	0.29
		20	101.5	10.15	2.00	1.29×10^{7}	5.07	0.50	0.01	0.13	3.00	4.04	0.09	0.08	0.08	0.16	0.04	0.29
		50	93.1	9.31	2.00	1.92×10^{7}	4.65	0.50	0.04	0.13	3.00	3.46	0.15	0.07	0.09	0.13	0.50	0.29
		1000	708.5	70.37	2.00	1.39×10^{9}	35.19	0.50	30.16	0.13	16.00	5.77	2.79	0.06	0.17	0.35	5.58	0.29
10	19	1.005	164.0	8.63	2.00	9.35×10^{6}	4.32	0.75	0.00	0.09	3.00	2.89	0.15	0.04	0.07	0.15	0.81	0.15

Uncertainty budget for 100 V and 1.005 kHz measurement:

Source Of Uncertainty	Type	Value (µV/V)	Sensitivity Coefficient	Divisor	Standard Uncertainty (µV/V)	Degrees Of Freedom
DC Reference Uncertainty	B	1.5	1	2.000	0.75	infinity
Connector Loading	B	0	1	1.732	0.00	infinity
Voltmeter Short Term Stability	B	0.33	1	2.576	0.13	infinity
Thermal Transfer Uncertainty	B	7	1	2.000	3.50	infinity
Thermal Transfer Drift	B	13	1	1.732	7.51	infinity
Voltmeter ac-dc difference	B	1.51	1	1.732	0.87	infinity
Voltmeter dc Repeatability	A	0.06	1	1.000	0.06	14
Voltmeter ac Repeatability	A	0.14	1	1.000	0.14	14
Unit Under Test Repeatability	A	0.13	1	1.000	0.13	14
Unit Under Test Stability	B	0.93	1	1.732	0.54	infinity
Unit Under Test Resolution	B	0.5	1	1.732	0.29	Infinity
Combined Uncertainty				-	8.89	9.87×10^{7}
Expanded Uncertainty				2.00	16.77	9.87×10^{7}
					(mV)	
Expanded Uncertainty				2.00	1.68	9.87×10^{7}

100 V range uncertainties

The table below summarises the uncertainty estimates for the 100 V measurements. Only the standard uncertainties after reduction of the input values are shown. The degrees of freedom assigned to each component are the same as those assigned to the components in the budget for 100 V and 1.005 kHz shown on the previous page.

								Standard uncertainties										
Range (V)	Nominal Voltage (V)	Frequency (kHz)	Expanded uncertainty (mV)	Expanded uncertainty (µV/V)	Coverage factor	Effective degrees of freedom	Combined standard uncertainty (µV/V)	DC Reference Uncertainty (µV/V)	Connector Loading (µV/V)	Voltmeter Short Term Stability (µV/V)	Thermal Transfer Uncertainty (µV/V)	Thermal Transfer Drift (µV/V)	Voltmeter ac-dc difference (µV/V)	Voltmeter dc Repeatability (µV/V)	Voltmeter ac Repeatability (µV/V)	Unit Under Test Repeatability (µV/V)	Unit Under Test Stability (µV/V)	Unit Under Test Resolution (µV/V)
100	100	0.01	1.74	17.40	2.00	1.75×10^5	8.70	0.75	0.00	0.13	5.00	6.35	2.77	0.06	0.71	0.67	1.00	0.29
		0.055	1.68	16.72	2.00	5.83×10^5	8.36	0.75	0.00	0.13	3.50	7.51	0.54	0.07	0.18	0.58	0.08	0.29
		1.005	1.68	16.77	2.00	9.87×10^7	8.39	0.75	0.00	0.13	3.50	7.51	0.87	0.06	0.14	0.13	0.54	0.29
		20	1.47	14.64	2.00	4.30×10^6	8.33	0.75	0.01	0.13	3.50	6.35	0.35	0.16	0.26	0.26	0.19	0.29
		50	1.37	13.70	2.00	2.35×10^6	6.85	0.75	0.02	0.13	3.50	5.77	0.65	0.07	0.33	0.20	0.31	0.29

Uncertainty budget for 700 V and 1.005 kHz measurement:

Source Of Uncertainty	**Type**	**Value (µV/V)**	**Sensitivity Coefficient**	**Divisor**	**Standard Uncertainty (µV/V)**	**Degrees Of Freedom**
DC Reference Uncertainty	B	1.5	1	2.000	0.75	infinity
Connector Loading	B	0	1	1.732	0.00	infinity
Voltmeter Short Term Stability	B	0.27	1	2.576	0.11	infinity
Thermal Transfer Uncertainty	B	9	1	2.000	4.50	infinity
Thermal Transfer Drift	B	17	1	1.732	9.82	infinity
Voltmeter ac-dc difference	B	0.91	1	1.732	0.53	infinity
Voltmeter dc Repeatability	A	0.06	1	1.000	0.06	14
Voltmeter ac Repeatability	A	0.24	1	1.000	0.24	14
Unit Under Test Repeatability	A	0.29	1	1.000	0.29	14
Unit Under Test Stability	B	0.1	1	1.732	0.06	infinity
Unit Under Test Resolution	B	0.71	1	1.732	0.41	Infinity
Combined Uncertainty				-	10.85	1.97×10^{7}
Expanded Uncertainty				2.00	21.70	1.97×10^{7}
					(mV)	
Expanded Uncertainty				2.00	15.19	1.97×10^{7}

1000 V range uncertainties

The table below summarises the uncertainty estimates for the 700 V measurements. Only the standard uncertainties after reduction of the input values are shown. The degrees of freedom assigned to each component are the same as those assigned to the components in the budget for 700 V and 1.005 kHz shown on the previous page.

								Standard uncertainties											
Range (V)	Nominal Voltage (V)	Frequency (kHz)	Expanded uncertainty (mV)	Expanded uncertainty (µV/V)	Coverage factor	Effective degrees of freedom	Combined standard uncertainty (µV/V)	DC Reference Uncertainty (µV/V)	Connector Loading (µV/V)	Voltmeter Short Term Stability (µV/V)	Thermal Transfer Uncertainty (µV/V)	Thermal Transfer Drift (µV/V)	Voltmeter ac-dc difference (µV/V)	Voltmeter dc Repeatability (µV/V)	Voltmeter ac Repeatability (µV/V)	Unit Under Test Repeatability (µV/V)	Unit Under Test Stability (µV/V)	Unit Under Test Resolution (µV/V)
1 000	700	0.055	12.16	17.38	2.00	1.11×10^{7}	8.69	0.75	0.00	0.11	5.00	6.93	0.41	0.06	0.18	0.28	1.21	0.41
		1.005	15.19	21.70	2.00	1.97×10^{7}	10.85	0.75	0.00	0.11	4.50	9.82	0.53	0.06	0.24	0.29	0.51	0.41
		20	17.64	25.20	2.00	4.57×10^{7}	12.60	0.75	0.01	0.11	9.50	8.08	0.94	0.08	0.21	0.27	1.15	0.41
		50	21.37	30.53	2.00	1.52×10^{5}	15.26	0.75	0.04	0.11	14.50	4.04	0.59	0.06	1.49	0.44	1.70	0.41

3.4 Alternating Current

For alternating current the following components contribute to the uncertainty of measurement:

- DC Reference Uncertainty: From the uncertainty calculation of the characterised dc current of the calibrator at the time of calibration. This source of uncertainty includes the stability and the resolution of the calibrator.
- Current Shunt Transfer Uncertainty: From the latest calibration report
- Current Shunt Stability: From the specification of the shunt
- Voltmeter Short Term Stability: From the specification of the voltmeter
- Voltmeter dc Repeatability: From the observed data of the measured voltage at dc
- Voltmeter ac Repeatability: From the observed data of the measured voltage at ac
- Voltmeter ac-dc difference: The difference of the measured voltages at the thermal transfer when switching from dc to ac
- Cable Loading: An experiment was performed to estimate the effect of cable
- Unit Under Test Repeatability: From the observed data
- Unit Under Test Stability: From tests repeated several times during the period that the instrument spent in our laboratory
- Unit Under Test Resolution: The least displayed digit on the unit under test

Uncertainty budget for 1 mA and 1.005 kHz measurement:

Source Of Uncertainty	**Type**	**Value**	**Unit**	**Sensitivity Coefficient**	**Divisor**	**Standard Uncertainty**	**Unit**	**Degrees Of Freedom**
DC Calibrator Uncertainty	B	10	µA/A	1	2.000	5.00	µA/A	infinity
Current Shunt Transfer Uncertainty	B	30	µΩ/Ω	1	2.000	15.00	µΩ/Ω	infinity
Current Shunt Stability	B	18	µΩ/Ω	1	1.732	10.39	µΩ/Ω	infinity
Voltmeter Short Term Stability	B	0.41	µV/V	1	2.576	0.16	µV/V	infinity
Voltmeter dc Repeatability	A	0.13	µV/V	1	1.000	0.13	µV/V	14
Voltmeter ac Repeatability	A	0.17	µV/V	1	1.000	0.17	µV/V	14
Voltmeter ac/dc Difference	B	5.78	µV/V	1	1.732	3.34	µV/V	infinity
Connector Loading	B	0.93	µA/A	1	1.732	0.54	µA/A	infinity
Unit Under Test Repeatability	A	0.27	µA/A	1	1.000	0.27	µA/A	14
Unit Under Test Stability	B	0.93	µA/A	1	1.732	0.54	µA/A	infinity
Unit Under Test Resolution	B	0.5	µA/A	1	1.732	0.29	µA/A	Infinity
Combined Uncertainty					-	19.23	µA/A	2.8781×10^{8}
Expanded Uncertainty					2.00	38.47	µA/A	2.8781×10^{8}
Expanded Uncertainty					2.00	38.46	nA	2.8781×10^{8}

1 mA range uncertainties

The table below summarises the uncertainty estimates for the 1 mA measurements. Only the standard uncertainties after reduction of the input values are shown. The degrees of freedom assigned to each component are the same as those assigned to the components in the budget for 1 mA and 1.005 kHz shown on the previous page.

								Standard uncertainties										
Range (mA)	Nominal Voltage (mA)	Frequency (kHz)	Expanded uncertainty (nA)	Expanded uncertainty (µA/A)	Coverage factor	Effective degrees of freedom	Combined standard uncertainty (µA/A)	DC Reference Uncertainty (µA/A)	Current Shunt Transfer Uncertainty (µΩ/Ω)	Current Shunt Stability (µΩ/Ω)	Voltmeter Short Term Stability (µV/V)	Voltmeter dc Repeatability (µV/V)	Voltmeter ac Repeatability (µV/V)	Voltmeter ac/dc Difference (µV/V)	Cable Loading (µA/A)	Unit Under Test Repeatability (µA/A)	Unit Under Test Stability (µA/A)	Unit Under Test Resolution (µA/A)
1	1	0.055	38.6	38.6	2.00	5.482×10^{8}	19.29	5.00	15.00	10.39	0.16	0.19	0.19	3.69	0.19	0.18	0.19	0.29
		1.005	38.5	38.5	2.00	2.878×10^{8}	19.23	5.00	15.00	10.39	0.16	0.13	0.17	3.34	0.54	0.27	0.54	0.29
		5	38.9	38.9	2.00	3.827×10^{8}	19.45	5.00	15.00	10.39	0.16	0.18	0.21	3.95	1.50	0.22	1.50	0.29

Uncertainty budget for 1 A and 1.005 kHz measurement:

Source Of Uncertainty	Type	Value	Unit	Sensitivity Coefficient	Divisor	Standard Uncertainty	Unit	Degrees Of Freedom
DC Reference Uncertainty	B	16	µA/A	1	2.000	8.00	µA/A	infinity
Current Shunt Transfer Uncertainty	B	22	µΩ/Ω	1	2.000	11.00	µΩ/Ω	infinity
Current Shunt Drift	B	10	µΩ/Ω	1	1.732	5.77	µΩ/Ω	infinity
Voltmeter Short Term stability	B	0.28	µV/V	1	2.576	0.11	µV/V	infinity
Voltmeter dc Repeatability	A	0.12	µV/V	1	1.000	0.12	µV/V	14
Voltmeter ac Repeatability	A	0.09	µV/V	1	1.000	0.09	µV/V	14
Voltmeter ac/dc difference	B	0.15	µV/V	1	1.732	0.09	µV/V	infinity
Cable Loading	B	3.9	µA/A	1	1.732	2.27	µA/A	infinity
Unit Under Test Repeatability	A	0.86	µA/A	1	1.000	0.86	µA/A	14
Unit Under Test Stability	B	2.9	µA/A	1	1.732	1.66	µA/A	infinity
Unit Under Test Resolution	B	0.5	µA/A	1	1.732	0.29	µA/A	Infinity
Combined Uncertainty					-	15.07	µA/A	1306956
Expanded Uncertainty					2.00	30.14	µA/A	1306956
Expanded Uncertainty					2.00	30.14	µA	1306956

1 A range uncertainties

The table below summarises the uncertainty estimates for the 1 A measurements. Only the standard uncertainties after reduction of the input values are shown. The degrees of freedom assigned to each component are the same as those assigned to the components in the budget for 1 A and 1.005 kHz shown on the previous page.

								Standard uncertainties										
Range (A)	Nominal Voltage (A)	Frequency (kHz)	Expanded uncertainty (µA)	Expanded uncertainty (µA/A)	Coverage factor	Effective degrees of freedom	Combined standard uncertainty (µA/A)	DC Reference Uncertainty (µA/A)	Current Shunt Transfer Uncertainty (µΩ/Ω)	Current Shunt Stability (µΩ/Ω)	Voltmeter Short Term Stability (µV/V)	Voltmeter dc Repeatability (µV/V)	Voltmeter ac Repeatability (µV/V)	Voltmeter ac/dc Difference (µV/V)	Cable Loading (µA/A)	Unit Under Test Repeatability (µA/A)	Unit Under Test Stability (µA/A)	Unit Under Test Resolution (µA/A)
1	1	0.055	29.76	29.76	2.00	2701762	14.88	8.00	11.00	3.46	0.11	0.09	0.21	2.11	0.22	0.71	4.39	0.29
		1.005	30.14	30.14	2.00	1306956	15.07	8.00	11.00	5.77	0.11	0.12	0.09	0.09	2.27	0.86	1.66	0.29
		5	30.68	30.68	2.00	341711	15.34	8.00	11.00	1.73	0.11	0.10	0.07	2.31	4.37	1.23	4.27	0.29

3.5 Resistance

For resistance the following components contribute to the uncertainty of measurement:

- Resistor Uncertainty: From the latest calibration report
- Resistor Drift: From the regression calculation based on the past calibration reports of the resistor
- Resistor Temperature Coefficient: From varying of the temperature to determine the temperature coefficient of the resistor
- Uncorrected Zero Offset: The zero is measured before and after measuring of a resistance range on the Unit Under Test The average of the two zero readings is used as a correction and this uncertainty component of the average zero determination
- Unit Under Test Repeatability: From the observed data
- Unit Under Test Stability: From tests repeated several times during the period that the instrument spent in our laboratory
- Unit Under Test Resolution: The least displayed digit on the unit under test

Uncertainty budget for 10 kΩ 4-wire measurement:

Source Of Uncertainty	**Type**	**Value** (μΩ/Ω)	**Sensitivity Coefficient**	**Divisor**	**Standard Uncertainty** (μΩ/Ω)	**Degrees Of Freedom**
Resistor Uncertainty	B	1	1	2.000	0.500	Infinity
Resistor Drift	B	0.55	1	2.080	0.264	34
Resistor Temp Coefficient	B	0.1	1	1.732	0.058	Infinity
Uncorrected Zero Offset	B	0.027	1	1.732	0.015	Infinity
Unit Under Test Repeatability	A	0.011	1	1.000	0.011	14
Unit Under Test Stability	B	0.213	1	1.732	0.123	Infinity
Unit Under Test Resolution	B	0.05	1	1.732	0.029	Infinity
Combined Uncertainty				-	0.583	802
Expanded Uncertainty				2.00	1.167	802
					(Ω)	
Expanded Uncertainty				2.00	0.01167	802

Resistance function uncertainties

The table below summarises the uncertainty estimates for the resistance measurements. Only the standard uncertainties after reduction of the input values are shown. The degrees of freedom assigned to each component are the same as those assigned to the components in the budget for 10 kΩ measurement shown on the previous page, except for the degrees of freedom associated with the uncertainty of the standard resistor. The degrees of freedom for the standard resistors varied from 165 to 14204.

								Standard uncertainties						
Range	Nominal Resistance	Wiring Configuration	Expanded uncertainty	Expanded uncertainty (µΩ/Ω)	Coverage factor	Effective degrees of freedom	Combined standard uncertainty (µΩ/Ω)	Resistor Uncertainty (µΩ/Ω)	Resistor Drift t (µΩ/Ω)	Resistor Temp Coefficient (µΩ/Ω)	Uncorrected Zero Offset (µΩ/Ω)	Unit Under Test Repeatability (µΩ/Ω)	Unit Under Test Stability (µΩ/Ω)	Unit Under Test Resolution (µΩ/Ω)
10 Ω	10 Ω	4W	11.7 µΩ	1.17	2.00	3717.6	0.584	0.500	0.135	0.058	0.114	0.131	0.196	0.029
100 Ω	100 Ω	4W	13.9 µΩ	1.39	2.00	1868.1	0.691	0.500	0.250	0.058	0.021	0.013	0.400	0.029
1 kΩ	1 kΩ	4W	1.39 mΩ	1.39	2.00	740.7	0.691	0.500	0.313	0.058	0.000	0.012	0.354	0.029
10 kΩ	10 kΩ	4W	11.7 mΩ	1.17	2.00	802.1	0.583	0.500	0.264	0.058	0.015	0.011	0.123	0.029
100 kΩ	100 kΩ	2W	0.138 Ω	1.38	2.01	199.3	0.684	0.500	0.433	0.115	0.115	0.050	0.007	0.029
1 MΩ	1 MΩ	2W	5.24 Ω	5.24	2.00	4518.1	2.615	2.500	0.756	0.115	0.058	0.112	0.007	0.029
10 MΩ	10 MΩ	2W	77.6 Ω	7.76	2.02	128.2	3.842	2.500	2.627	0.693	0.086	1.060	0.008	0.029
100 MΩ	100 MΩ	2W	1.48 kΩ	14.80	2.01	283.5	7.367	4.500	3.698	2.887	0.058	3.464	0.066	0.029

3.6 Frequency

For frequency, the following components contribute to the uncertainty of measurement:

- Frequency Standard Uncertainty: The specified frequency accuracy of the national frequency standard maintained in Singapore
- Counter Resolution: The least significant digit displayed on the counter
- Calibrator Repeatability: Estimated using the Allan Deviation (ADEV)
- Calibrator Stability : From the repeated tests

Uncertainty budget for 1.005 kHz measurement:

Source Of Uncertainty	**Type**	**Value**	**Sensitivity Coefficient**	**Divisor**	**Standard Uncertainty**	**Degrees Of Freedom**
Frequency Standard Uncertainty	B	1.00×10^{-13}	1	2.000	5.00×10^{-14}	infinity
Counter Resolution	B	4.97×10^{-12}	1	1.732	2.87×10^{-12}	infinity
Calibrator Repeatability	A	2.79×10^{-10}	1	1.000	6.79×10^{-10}	13
Calibrator Stability	B	8.87×10^{-9}	1	1.732	5.12×10^{-9}	infinity
Combined Uncertainty				-	5.16×10^{-9}	2.58×10^{2}
Expanded Uncertainty				2.00	1.04×10^{-8}	2.58×10^{2}
					(mHz)	
Expanded Uncertainty				2.00	0.011	2.58×10^{2}

Calibrator frequency uncertainties

The table below summarises the uncertainty estimates for the calibrator measurements. Only the standard uncertainties after reduction of the input values are shown. The degrees of freedom assigned to each component are the same as those assigned to the components in the budget for 1.005 kHz measurement shown on the previous page.

						Standard uncertainties			
Nominal Frequency	Expanded uncertainty	Expanded uncertainty	Coverage factor	Effective degrees of freedom	Combined standard uncertainty	Frequency Standard Uncertainty	Counter Resolution	Calibrator Repeatability	Calibrator Stability
10 Hz	3.07 µHz	$3.07×10^{-7}$	2.00	$3.04×10^{4}$	$3.07×10^{-7}$	$5.00×10^{-14}$	$2.89×10^{-12}$	$6.12×10^{-9}$	$1.53×10^{-7}$
55 Hz	3.66 µHz	$6.66×10^{-8}$	2.00	$3.52×10^{4}$	$3.33×10^{-8}$	$5.00×10^{-14}$	$5.25×10^{-13}$	$1.28×10^{-9}$	$3.38×10^{-8}$
1.005 kHz	0.011 mHz	$1.04×10^{-8}$	2.00	$2.58×10^{2}$	$5.16×10^{-9}$	$5.00×10^{-14}$	$2.87×10^{-12}$	$6.79×10^{-10}$	$5.12×10^{-9}$
5 kHz	0.037 mHz	$7.42×10^{-9}$	2.00	$3.95×10^{1}$	$3.59×10^{-9}$	$5.00×10^{-14}$	$5.77×10^{-13}$	$7.54×10^{-10}$	$3.51×10^{-9}$
20 kHz	1.01 mHz	$5.07×10^{-8}$	2.00	$7.82×10^{5}$	$2.53×10^{-8}$	$5.00×10^{-14}$	$1.44×10^{-12}$	$4.49×10^{-10}$	$2.53×10^{-8}$
50 kHz	9.00 mHz	$1.80×10^{-7}$	2.00	$4.53×10^{6}$	$8.99×10^{-8}$	$5.00×10^{-14}$	$5.77×10^{-13}$	$1.03×10^{-9}$	$8.99×10^{-8}$
1 MHz	0.170 Hz	$1.70×10^{-7}$	2.00	$3.24×10^{6}$	$8.48×10^{-8}$	$5.00×10^{-14}$	$2.89×10^{-12}$	$1.05×10^{-9}$	$8.47×10^{-8}$

Report on

Measurements performed for
APMP.EM-S12
Comparison of Standards for the Calibration of Voltage, Current and Resistance Meters

Measurements performed on

Wavetek 4950 serial number 33528

From 13 February 2016 to 6 March 2016

Performed by

National Institute of Metrology (Thailand)
3/4-5 Moo 3, Klong 5, Klong Luang,
Pathumthani 12120, Thailand

Report by

Yaowaret Pimsut, Metrologist
and Chalit Kumtawee, Head of Electrical laboratory
Electrical Metrology Department

Revision date: 11 July 2017

Introduction

The APMP.EM-S12 comparison protocol requires that the travelling standard, a Wavetek model 4950 serial number 33528 (the Unit under Test – UUT), be measured at a number of points for each of its measurement functions. These are direct voltage, direct current, alternating voltage, alternating current and resistance. The measurement points are detailed in the comparison protocol.

The instrument was received on 10 February 2016 The fuse (F1) and mains voltage selection switch (S1) was checked before applying power. The UUT was allowed to stabilise for 24 hours with the power turned on before any measurements were made. The instrument's confidence test was performed and completed without any errors.

The measurements were performed from 13 February 2016 to 6 march. The instrument was sent to the SCL, Hong Kong on 7 March 2016.

Direct Voltage

Test methods:

Direct voltage was measured using three methods:

1. For 100 mV the correction of the UUT was determined by comparing the UUT reading to that obtained with a Keithley model 2182A nanovoltmeter calibrated against a Josephson Voltage Standard.
2. For 1 V and 10 V the correction of the UUT was determined by direct connection of the UUT to a calibrated Fluke model 732A zener voltage reference standard, calibrated against a Josephson voltage standard.
3. For 19 V to 1000 V the correction of the UUT was determined by direct connection of the UUT to a calibrated Fluke model 5720A multifunction calibrator, the calibrator was traceable to dc reference standard maintained by the DC voltage and current laboratory of the National Institute of metrology, Thailand.

See figure 1.1 for the direct voltage measurement setups.

The 'Remote Guard' function was turned on for all the measurements, and the guard terminal and low voltage terminal were connected to a common ground point. The low current terminal was connected to the low voltage terminal and the high current terminal was connected to the high voltage terminal for all measurements.

Traceability:

All the test methods described for direct voltage was traceable to the Thailand national measurement standard for voltage, a Josephson voltage standard. See figure 2.1 for the direct voltage traceability chart.

Conditions of measurement:

During the direct voltage measurements, the following conditions of measurement prevailed:

Ambient temperature: 23.0 °C ± 0.3 °C
Relative humidity: 52 %RH ± 3 %RH

Measurement results:

Range (V)	Nominal Voltage (V)	Correction (V)	Uncertainty (V)	Internal Temperature (°C)
0.1	0.1	-0.000 000 12	±0.000 000 49	40.6
1	1	-0.000 002 5	±0.000 001 6	40.7
10	10	-0.000 011	±0.000 011	40.6
10	19	-0.000 025	±0.000 026	40.7
100	100	-0.000 20	±0.000 20	40.8
1000	1000	-0.001 4	±0.002 0	40.8

Detailed uncertainty budgets for the direct voltage measurements are shown in appendix 3.1.

Direct Current

Test methods:

Direct current was measured the following method:

The correction of the UUT was determined by comparing its readings to the calculated value of the applied current. A calibrated current shunt was connected in series with the UUT. The voltage drop across the current shunt was measured with a calibrated voltmeter. The applied current was calculated from the resistance of the shunts and the measured voltage.

See figure 1.2 for the direct current measurement setup.

The 'Remote Guard' function was turned on for all the measurements, and the guard terminal and low current terminal were connected to a common ground point. The low voltage and high voltage terminals were connected to the same ground point.

Traceability:

The resistance of the shunt was traceable to the resistance resistors maintained by the Resistance laboratory of the National Institute of metrology, Thailand. These resistance resistors are traceable to the BIPM resistors. See figure 2.2 for the resistance traceability chart.

The direct voltage was traceable to the Thailand national measurement standard for voltage, a Josephson voltage standard. See figure 2.1 for the direct voltage traceability chart.

Conditions of measurement:

During the direct current measurements, the following conditions of measurement prevailed:

Ambient temperature: 23.4 °C ± 0.7 °C
Relative humidity: 53 %RH ± 2 %RH

Measurement results:

Range	Nominal Current	Correction	Uncertainty	Internal Temperature (°C)
1 mA	1 mA	+ 0.000 003 mA	±0.000 009 mA	40.5
1 A	1 A	− 0.000 017 A	±0.000 009 A	40.6

Detailed uncertainty budgets for the direct current measurements are shown in appendix 3.2.

Alternating Voltage

Test methods:

Alternating voltage was measured the following method:

The correction of the UUT was determined by comparing the UUT reading to that obtained from an ac-dc voltage difference measurement with a Fluke 792A ac/dc transfer standard. The applied alternating voltage was calculated from the direct voltage measured by the UUT and the ac-dc voltage difference.

See figure 1.3 for the alternating voltage measurement setups.

The 'Remote Guard' function was turned on for all the measurements. The input connectors were attached to a 4 banana to type-N adapter, serial number 4BN-002. The guard connector was connected into the rear of the low voltage connector.

As specified by the protocol, the 1 MHz measurements at 1 V and 10 V was done with 4wCct (the default setting) selected.

The reference point was the middle of a type-N tee connecting the thermal transfer standard to the 4 banana to type-N adapter. The reference point was connected to the common ground using a copper ground strap.

Traceability:

The ac-dc voltage difference traceability was obtained from the ac-dc voltage difference of the ac/dc transfer standard maintained by the AC voltage and current laboratory of the National Institute of Metrology, Thailand. The ac-dc differences were traceable to the PTB standards.

See figure 2.3 for the ac-dc difference traceability chart.

Conditions of measurement:

During the alternating voltage measurements, the following conditions of measurement prevailed:

Ambient temperature:	23.6 °C ± 0.4 °C
Relative humidity:	49 %RH ± 5 %RH

Measurement results:

Range (V)	Nominal Voltage (V)	Frequency (kHz)	Correction (V)	Uncertainty (V)	Internal Temperature (°C)
0.01	0.01	0.010	-0.000 007 77	±0.000 001 10	40.5
		0.055	-0.000 008 38	±0.000 000 90	40.5
		1.005	-0.000 008 01	±0.000 000 90	40.5
		20	-0.000 008 57	±0.000 000 90	40.5
		50	-0.000 008 38	±0.000 000 90	40.5
		1000	-0.000 020 09	±0.000 003 00	40.5
0.1	0.1	0.010	+0.000 003 2	±0.000 002 8	40.2
		0.055	+0.000 007 9	±0.000 002 3	40.2
		1.005	+0.000 008 8	±0.000 002 3	40.2
		20	+0.000 010 1	±0.000 002 3	40.2
		50	+0.000 007 8	±0.000 003 1	40.2
		1000	-0.000 305 1	±0.000 022 0	40.2
1	1	0.010	-0.000 019	±0.000 015	40.5
		0.055	-0.000 009	±0.000 011	40.5
		1.005	-0.000 009	±0.000 011	40.5
		20	0.000 000	±0.000 011	40.5
		50	-0.000 025	±0.000 013	40.5
		1000	+0.000 017	±0.000 300	40.5
10	10	0.010	-0.000 51	±0.000 16	40.5
		0.055	+0.000 05	±0.000 12	40.5
		1.005	+0.000 13	±0.000 12	40.5
		20	+0.000 11	±0.000 12	40.5
		50	+0.000 13	±0.000 15	40.5
		1000	-0.001 95	±0.003 50	40.5
10	19	1.005	+0.000 05	±0.000 23	40.5
100	100	0.010	-0.005 6	±0.001 9	40.4
		0.055	+0.000 6	±0.001 6	40.4
		1.005	+0.000 4	±0.001 6	40.4
		20	+0.000 8	±0.001 6	40.4
		50	-0.000 4	±0.002 2	40.4
1000	700	0.055	-0.010	±0.024	40.4
		1.005	-0.008	±0.020	40.4
		20	0.000	±0.020	40.4
		50	+0.049	±0.030	40.4

Detailed uncertainty budgets for the alternating voltage measurements are shown in appendix 3.3.

Alternating Current

Test methods:

Alternating current was measured the following method:

The correction of the UUT was determined by comparing the UUT reading to that obtained from an ac-dc current difference measurement with a set of Fluke 792A ac/dc transfer standard and a current shunt. The applied alternating current was calculated from the direct current measured by the UUT and the ac-dc current difference.

See figure 1.4 for the alternating current measurement setup.

The ‘Remote Guard’ function was turned on for all the measurements, and the guard terminal and low current terminal were connected to a common ground point. The low voltage and high voltage terminals were connected to the same ground point.

Traceability:

The ac-dc current difference traceability was obtained from the ac-dc current difference of the ac/dc transfer standard with current shunt maintained by the AC voltage and current laboratory of the National Institute of Metrology, Thailand. The ac-dc differences at 1 mA were traceable to the NMIA standards and .ac-dc differences at 1 A were traceable to the PTB standards.

See figure 2.2 for the resistance traceability chart and figure 2.3 for the ac-dc difference traceability chart.

Conditions of measurement:

During the alternating current measurements, the following conditions of measurement prevailed:

Ambient temperature: 23.7 °C ± 0.2 °C
Relative humidity: 51 %RH ± 3 %RH

Measurement results:

Range	Nominal Current	Frequency (kHz)	Correction	Uncertainty	Internal Temperature (°C)
1 mA	1 mA	0.055	+ 0.000 156 mA	±0.000 100 mA	40.5
		1.005	+ 0.000 136 mA	±0.000 100 mA	40.5
		5	+ 0.000 107 mA	±0.000 100 mA	40.5
1 A	1 A	0.055	+ 0.000 122 A	±0.000 075 A	40.5
		1.005	+ 0.000 148 A	±0.000 072 A	40.5
		5	+ 0.000 720 A	±0.000 075 A	40.5

Detailed uncertainty budgets for the alternating current measurements are shown in appendix 3.4.

Resistance

Test methods:

The correction of the UUT was determined by comparing its readings to a set of standard resistors.

See figure 1.5 for the resistance measurement setup.

The 'Remote Guard' function was turned on for all the measurements, and the guard terminal and low voltage terminal were connected to a common ground point. For 2-wire measurements the low current terminal and the high current terminal were connected to the common ground point.

Traceability:

The resistance of the set of standard resistors was traceable to the resistance resistors maintained by the Resistance laboratory of the National Institute of metrology, Thailand. These resistance resistors are traceable to the BIPM resistors.

See figure 2.2 for the resistance traceability chart.

Conditions of measurement:

During the resistance measurements, the following conditions of measurement prevailed:

Ambient temperature: 23.4 °C ± 0.1 °C
Relative humidity: 48 %RH ± 2 %RH

4-wire measurement results:

Range	Nominal Resistance	Correction	Uncertainty	Internal Temperature (°C)
10 Ω	10 Ω	-0.000 011 Ω	±0.000 027 Ω	40.8
100 Ω	100 Ω	-0.000 35 Ω	±0.000 28 Ω	40.8
1 kΩ	1 kΩ	+0.000 001 6 kΩ	±0.000 002 2 kΩ	40.8
10 kΩ	10 kΩ	-0.000 011 kΩ	±0.000 033 kΩ	40.8

2-wire measurement results:

Range	Nominal Resistance	Correction	Uncertainty	Internal Temperature (°C)
100 kΩ	100 kΩ	-0.000 03 kΩ	±0.000 38 kΩ	40.8
1 MΩ	1 MΩ	+0.000 004 1 MΩ	±0.000 005 6 MΩ	40.8
10 MΩ	10 MΩ	-0.000 228 MΩ	±0.000 098 MΩ	40.8
100 MΩ	100 MΩ	-0.000 97 MΩ	±0.005 725 3 MΩ	40.8

Detailed uncertainty budgets for the resistance measurements are shown in appendix 3.5.

Frequency

The protocol requires that the frequency of the sources used for alternating voltage and alternating current be measured and reported.

Test methods:

A Fluke model 5720A was used to measure alternating voltage and alternating current. The correction of the calibrators was determined by measuring the frequency for an output of 1 V using a frequency counter referenced to the national frequency standard.

A measurement with a 1 V output only is sufficient to cover all the ranges and functions as the same time-base is used to generate the frequency for all output voltages and currents.

See figure 1.6 for the frequency measurement setup.

The ‘External Guard’ function of the calibrator was turned off for all the measurements, and the guard terminal was connected to a common ground point. This was done to provide the measurement circuit with a reference point because the counter input was floating.

Traceability:

The frequency measurements were traceable to the national frequency standard maintained by the Time and Frequency of the National Institute of Measurement, Thailand.

See figure 2.4 for the frequency traceability chart.

Conditions of measurement:

During the frequency measurements, the following conditions of measurement prevailed:

Ambient temperature: 23.2 °C ± 0.4 °C
Relative humidity: 45 %RH ± 3 %RH

Frequency measurement results:

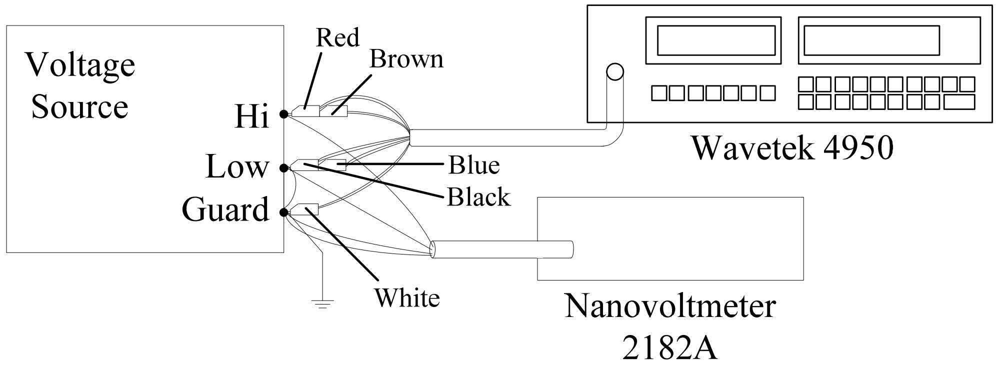
For Fluke 5720A serial number 2440202 used for voltage and current measurements:

Nominal Frequency	Correction	Uncertainty
10 Hz	+0.000 052 Hz	±0.000 156 Hz
55 Hz	+0.000 500 Hz	±0.000 018 Hz
1.005 kHz	+0.008 873 Hz	±0.000 290 Hz
5 kHz	+0.044 169 Hz	±0.001 443 Hz
20 kHz	+0.146 01 Hz	±0.005 77 Hz
50 kHz	+0.399 05 Hz	±0.027 47 Hz
1 MHz	+8.614 Hz	±0.501 Hz

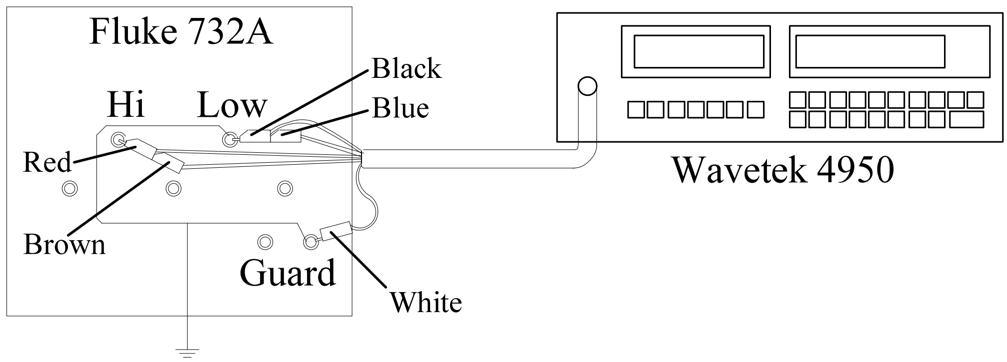
Detailed uncertainty budgets for the frequency measurements are shown in appendix 3.6.

Appendix 1: Measurement setups

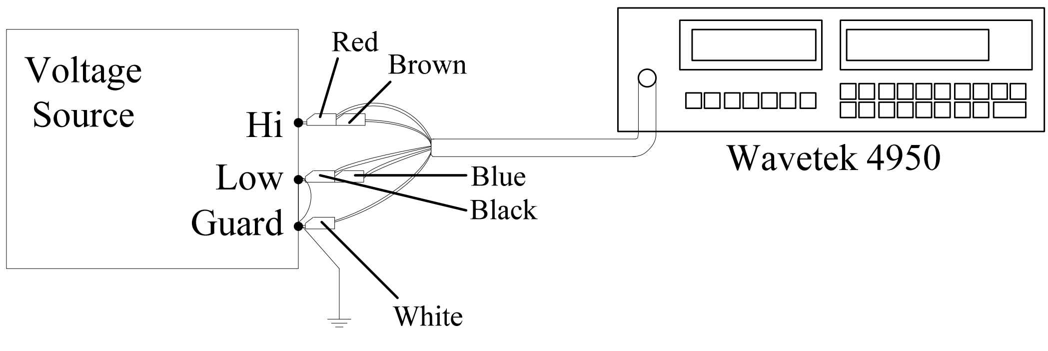
Direct Voltage



(a) 100 mV measurement



(b) 1 V and 10 V measurements



(c) 19 V to 1000 V measurements

Figure 1.1: Direct voltage measurement setups

Direct Current

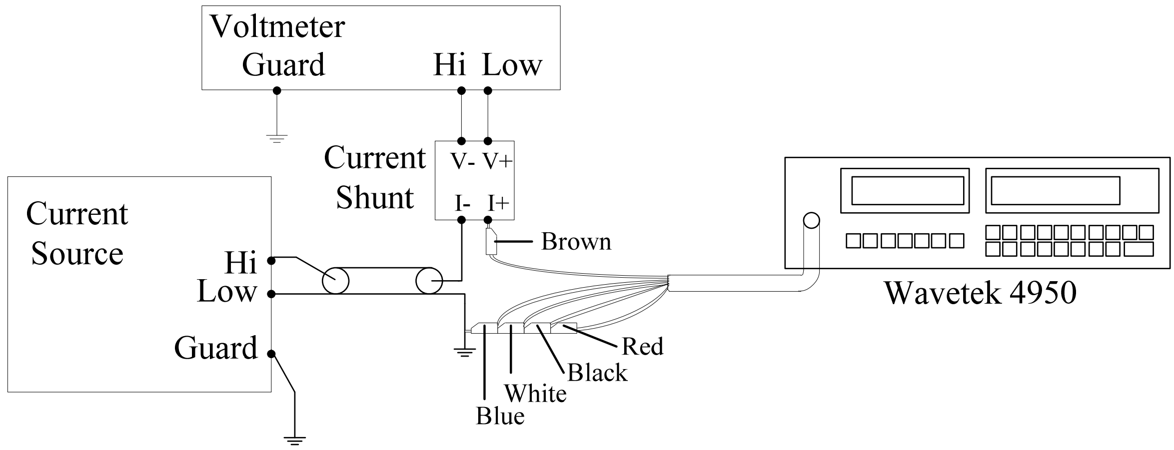
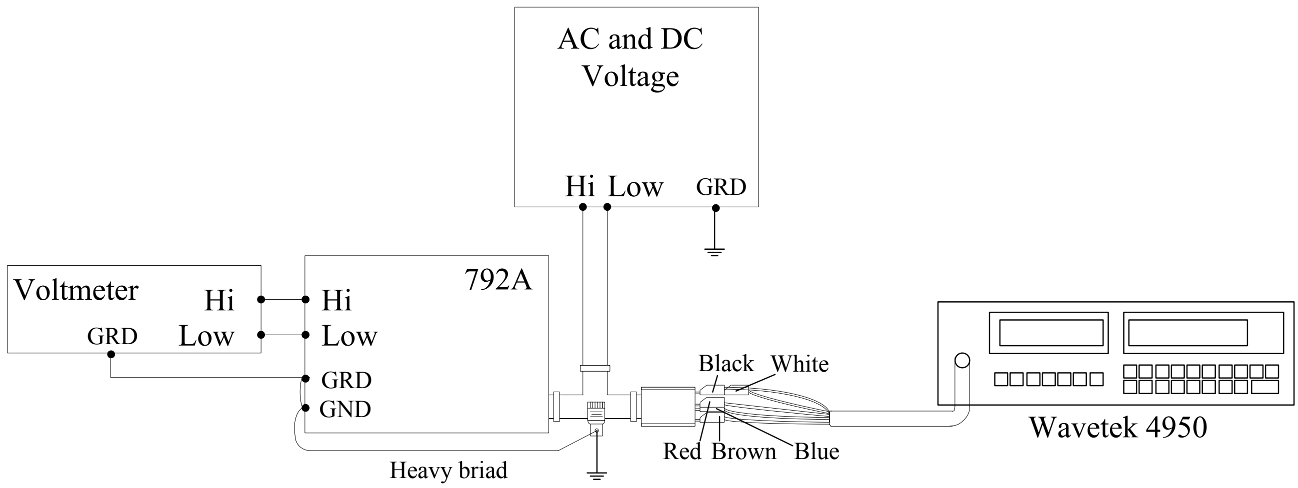
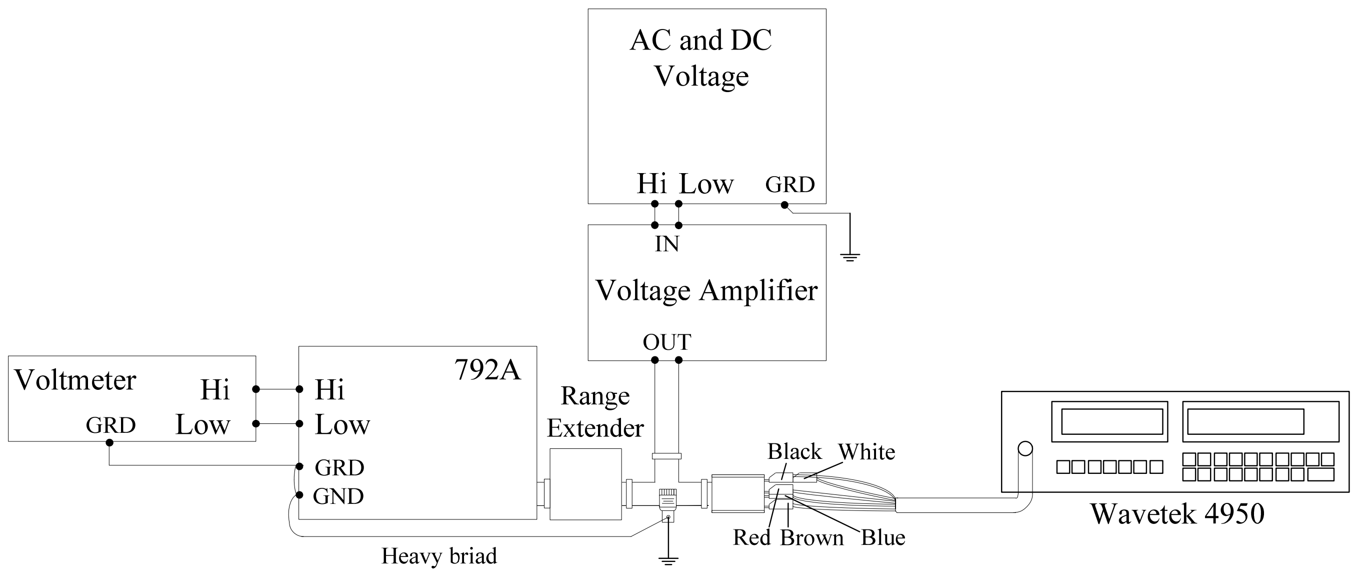


Figure 1.2: Direct current measurement setup

Alternating Voltage



(a) 10 mV to 100 V



(b) 700 V

Figure 1.3: Alternating voltage measurement setups

Alternating Current

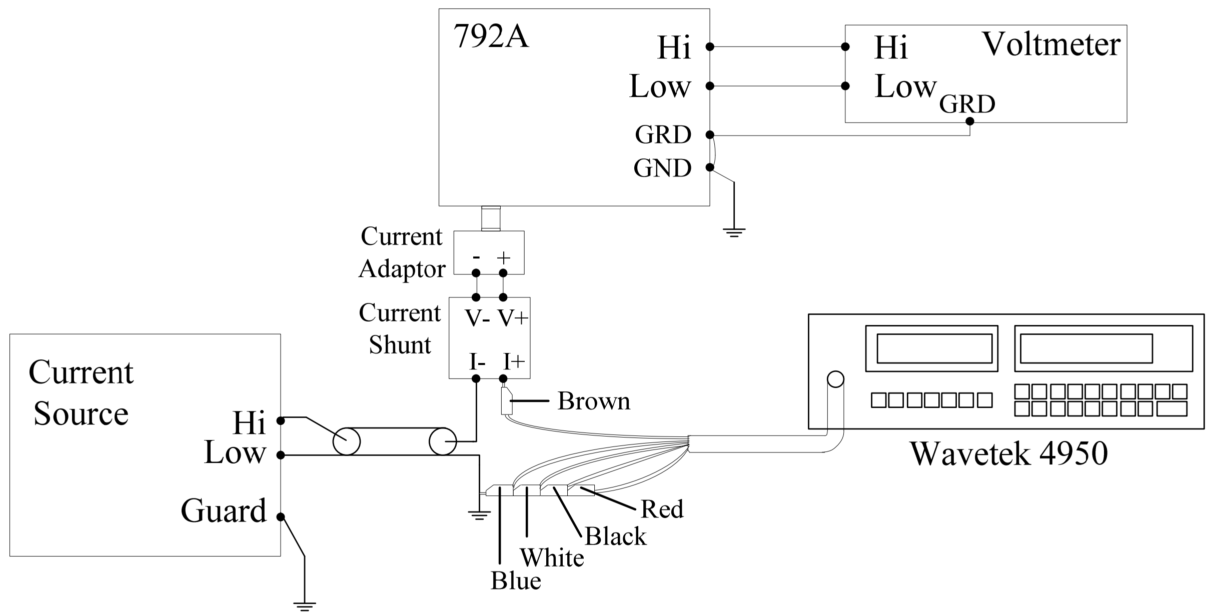
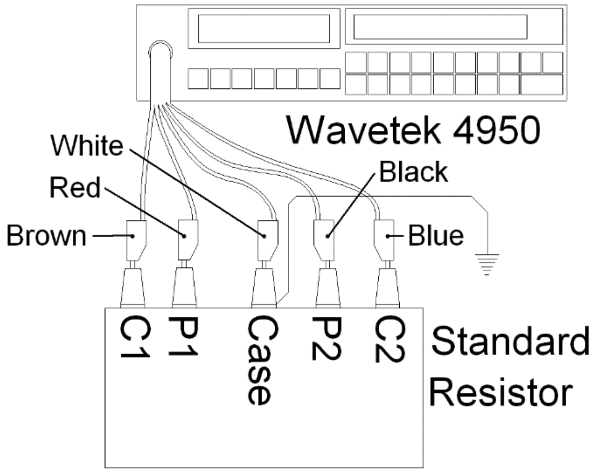
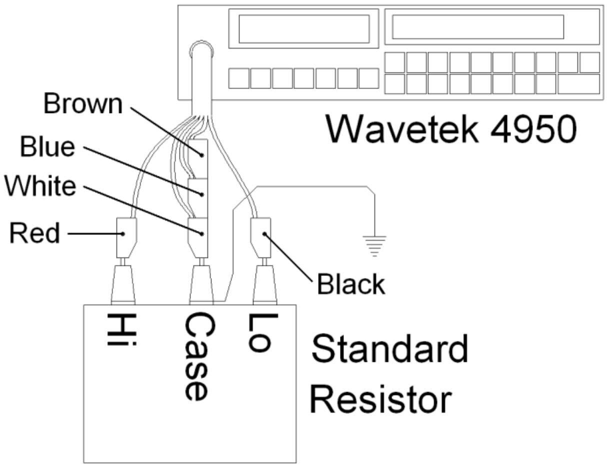


Figure 1.4: Alternating current measurement setup

Resistance



(a) Four wire resistance



(b) Two wire resistance

Figure 1.5: Resistance measurement setups

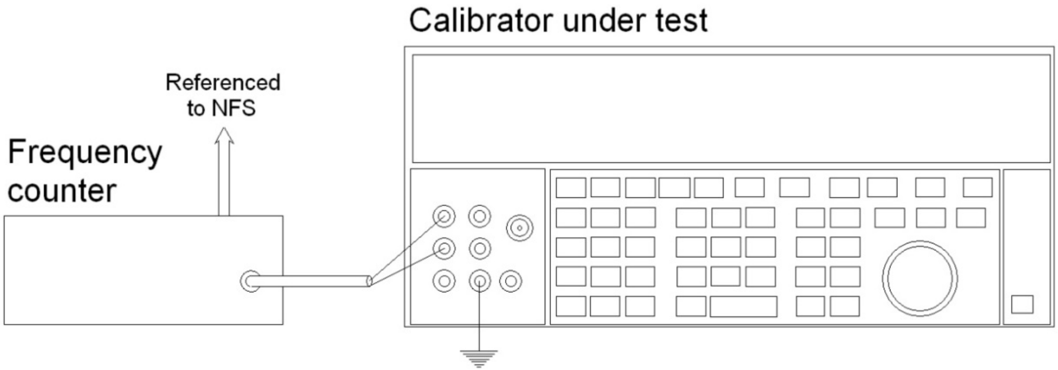


Figure 1.6: Frequency measurement setup

Appendix 2: Traceability charts

Direct Voltage

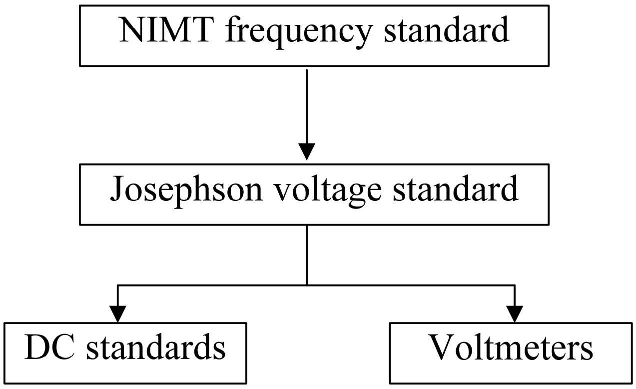


Figure 2.1: Direct voltage traceability

Resistance

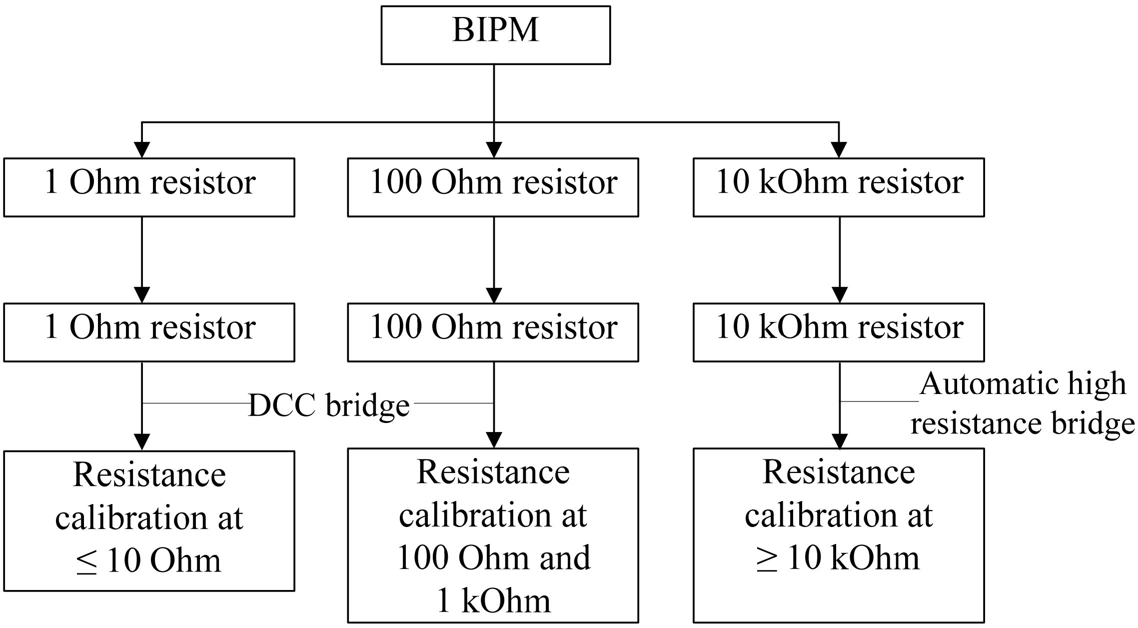
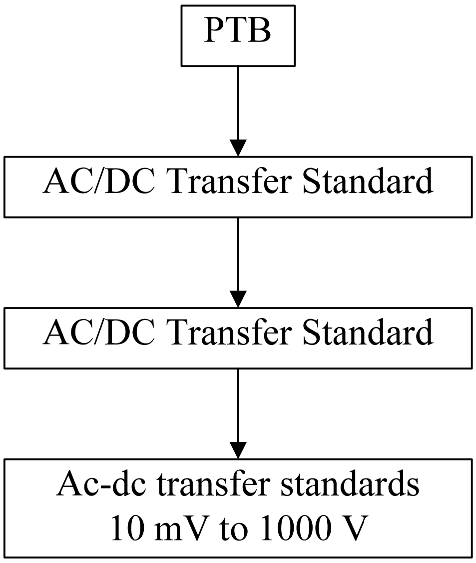
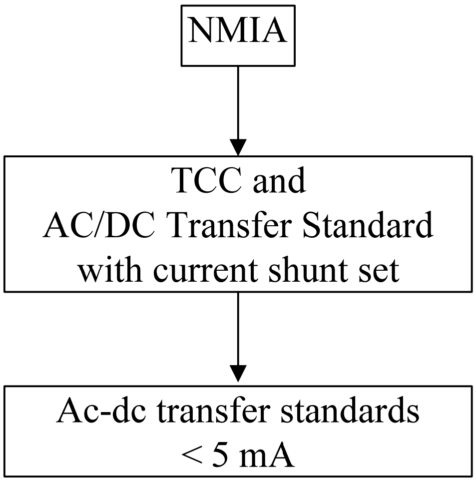


Figure 2.2: Resistance traceability

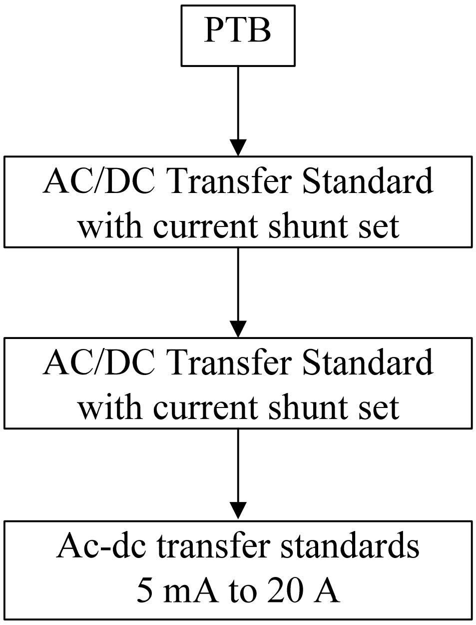
Ac-dc difference



(a) ac voltage 10 mV to 700 V



(b) ac current 1 mA



(c) ac current 1 A

Figure 2.3: Ac-dc difference traceability

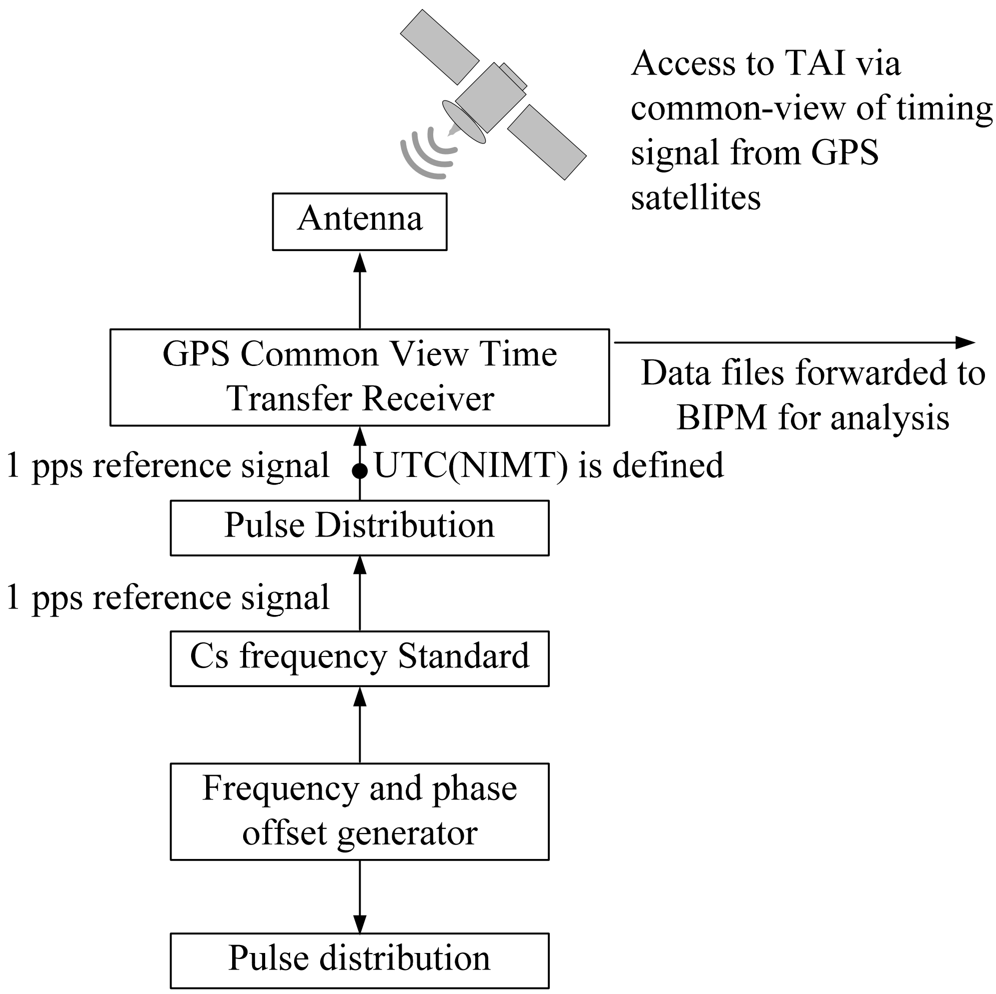


Figure 2.4: Frequency traceability

Appendix 3: Uncertainty budgets

3.1 Direct Voltage

For direct voltage at 100 mV the following components contribute to the uncertainty of measurement:

- Reference voltmeter uncertainty: From the last calibration report of the voltmeter.
- Reference voltmeter drift since last calibration: From the history of the voltmeter.
- Reference voltmeter resolution: From the specification of the voltmeter
- Reference voltmeter repeatability: From the observed data
- Unit under test resolution: From the UUT specification
- Unit under test repeatability: From the observed data
- Unit under test stability: From tests repeated several times during the period that the instrument spent in our laboratory
- Rounding of reported value: To ensure that the reported value encompasses the calculated range of possible values

Uncertainty budget:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Reference voltmeter uncertainty	B	0.10	µV	2.000	0.0500	1	0.0500	∞
Reference voltmeter drift since last calibration	B	0.27	µV	1.732	0.1553	1	0.1553	∞
Reference voltmeter resolution	B	0.005	µV	1.732	0.0029	1	0.0029	∞
Reference voltmeter repeatability	A	0.051	µV	1.000	0.0510	1	0.0510	99
Unit under test resolution	B	0.005	µV	1.732	0.0029	1	0.0029	∞
Unit under test repeatability	A	0.009	µV	1.000	0.0090	1	0.0090	9
Unit under test stability	B	0.30	µV	1.732	0.1732	1	0.1732	∞
Rounding of reported value	B	0.01	µV	1.732	0.0058	1	0.0058	∞
Combined standard uncertainty							0.2436	µV
Effective degrees of freedom							4.83E+06	
Coverage factor							2.000	
Expanded uncertainty							0.49	µV
Expanded uncertainty							4.9	µV/V
Expanded uncertainty							0.000 000 49	V

For direct voltage at 1 V and 10 V the following components contribute to the uncertainty of measurement:

- Voltage reference uncertainty, Fluke 732A: From the last calibration report
- Voltage reference drift, Fluke 732A drift: From the history of the electronic voltage reference
- Un-cancelled thermal voltages: Estimated from the difference in zero readings before and after measurement at the nominal voltage
- Unit under test repeatability: From the observed data
- Unit under test resolution: From the unit under test specifications
- Unit under test stability: From tests repeated several times during the period that the instrument spent in our laboratory
- Rounding of reported value: To ensure that the reported value encompasses the calculated range of possible values

Uncertainty budget for 1 V measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Voltage reference uncertainty	B	0.09	µV	2.000	0.0450	1	0.0450	∞
Voltage reference drift	B	1.10	µV	1.732	0.6351	1	0.6351	∞
Un-cancelled thermal voltages	B	0.10	µV	1.732	0.0577	1	0.0577	∞
Unit under test resolution	B	0.05	µV	1.732	0.0289	1	0.0289	∞
Unit under test repeatability	A	0.15	µV	1.000	0.1500	1	0.1500	9
Unit under test stability	B	0.80	µV	1.732	0.4619	1	0.4619	∞
Rounding of reported value	B	0.10	µV	1.732	0.0577	1	0.0577	∞
						Combined standard uncertainty	0.8054	µV
						Effective degrees of freedom	7.48E+03	
						Coverage factor	2.000	
						Expanded uncertainty	1.6	µV
						Expanded uncertainty	1.6	µV/V
						Expanded uncertainty	0.000 001 6	V

Uncertainty budget for 10 V measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Voltage reference uncertainty	B	0.03	µV	2.000	0.0150	1	0.0150	∞
Voltage reference drift	B	3.50	µV	1.732	2.0208	1	2.0208	∞
Un-cancelled thermal voltages	B	0.10	µV	1.732	0.0577	1	0.0577	∞
Unit under test resolution	B	0.50	µV	1.732	0.2887	1	0.2887	∞
Unit under test repeatability	A	1.00	µV	1.000	1.0000	1	1.0000	9
Unit under test stability	B	9.00	µV	1.732	5.1963	1	5.1963	∞
Rounding of reported value	B	1.00	µV	1.732	0.5774	1	0.5774	∞
						Combined standard uncertainty	5.7014	µV
						Effective degrees of freedom	9.51E+03	
						Coverage factor	2.000	
						Expanded uncertainty	11.40	µV
						Expanded uncertainty	1.1	µV/V
						Expanded uncertainty	0.000 011	V

For direct voltage from 19 V to 1000 V the following components contribute to the uncertainty of measurement:

- Calibrator uncertainty: From the last calibration report
- Calibrator drift: From the history of the electronic voltage reference
- Zero offset cancellation: Estimated from the difference in zero readings before and after measurement at the nominal voltage
- Unit under test repeatability: From the observed data
- Unit under test resolution: From the unit under test specifications
- Unit under test stability: From tests repeated several times during the period that the instrument spent in our laboratory
- Rounding of reported value: To ensure that the reported value encompasses the calculated range of possible values

Uncertainty budget for 19 V measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Calibrator uncertainty	B	18.00	μV	2.000	9.0000	1	9.0000	∞
Calibrator drift	B	15.00	μV	1.732	8.6605	1	8.6605	∞
Zero offset cancellation	B	7.00	μV	1.732	4.0416	1	4.0416	∞
Unit under test resolution	B	0.05	μV	1.732	0.0289	1	0.0289	∞
Unit under test repeatability	A	1.00	μV	1.000	1.0000	1	1.0000	9
Unit under test stability	B	2.00	μV	1.732	1.1547	1	1.1547	∞
Rounding of reported value	B	1.00	μV	1.732	0.5774	1	0.5774	∞
						Combined standard uncertainty	13.2290	μV
						Effective degrees of freedom	2.76E+05	
						Coverage factor	2.000	
						Expanded uncertainty	26.46	μV
						Expanded uncertainty	1.4	μV/V
						Expanded uncertainty	0.000 026	V

Uncertainty budget for 100 V measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Calibrator uncertainty	B	80.00	µV	2.000	40.0000	1	40.0000	∞
Calibrator drift	B	150.00	µV	1.732	86.6051	1	86.6051	∞
Zero offset cancellation	B	30.00	µV	1.732	17.3210	1	17.3210	∞
Unit under test resolution	B	5.00	µV	1.732	2.8868	1	2.8868	∞
Unit under test repeatability	A	5.00	µV	1.000	5.0000	1	5.0000	9
Unit under test stability	B	20.00	µV	1.732	11.5473	1	11.5473	∞
Rounding of reported value	B	10.00	µV	1.732	5.7737	1	5.7737	∞
						Combined standard uncertainty	97.9820	µV
						Effective degrees of freedom	1.33E+06	
						Coverage factor	2.000	
						Expanded uncertainty	195.96	µV
						Expanded uncertainty	2.0	µV/V
						Expanded uncertainty	0.000 20	V

Uncertainty budget for 1000 V measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Calibrator uncertainty	B	1000	µV	2.000	500.0000	1	500.0000	∞
Calibrator drift	B	700	µV	1.732	404.1570	1	404.1570	∞
Zero offset cancellation	B	400	µV	1.732	230.9469	1	230.9469	∞
Unit under test resolution	B	50	µV	1.732	28.8684	1	28.8684	∞
Unit under test repeatability	A	100	µV	1.000	100.0000	1	100.0000	9
Unit under test stability	B	1200	µV	1.732	692.8406	1	692.8406	∞
Rounding of reported value	B	100	µV	1.732	57.7367	1	57.7367	∞
						Combined standard uncertainty	980.2420	µV
						Effective degrees of freedom	8.31.E+04	
						Coverage factor	2.000	
						Expanded uncertainty	1960.52	µV
						Expanded uncertainty	2.0	µV/V
						Expanded uncertainty	0.002 0	V

3.2 Direct Current

For direct current the following components contribute to the uncertainty of measurement:

- Shunt uncertainty: From the last calibration report
- Shunt drift: From the history of the shunt
- Voltmeter uncertainty: From the last calibration report
- Voltmeter drift: From the history of the voltmeter
- Voltmeter resolution: From the voltmeter specifications
- Voltmeter repeatability: From the observed data
- Unit under test repeatability: From the observed data
- Unit under test resolution: From the unit under test specifications
- Unit under test stability: From tests repeated several times during the period that the instrument spent in our laboratory
- Rounding of reported value: To ensure that the reported value encompasses the calculated range of possible values

Uncertainty budget for 1 mA measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Shunt uncertainty	B	3.10	μΩ/Ω	2.000	1.550	1	1.550	∞
Shunt drift	B	5.15	μΩ/Ω	1.732	2.973	1	2.973	∞
Voltmeter uncertainty	B	0.10	μV/V	2.000	0.050	1	0.050	∞
Voltmeter drift	B	2.20	μV/V	1.732	1.270	1	1.270	∞
Voltmeter resolution	B	0.005	μV/V	1.732	0.003	1	0.003	∞
Voltmeter repeatability	A	1.00	μV/V	1.000	1.000	1	1.000	99
Unit under test resolution	B	0.50	μA/A	1.732	0.289	1	0.289	∞
Unit under test repeatability	A	0.80	μA/A	1.000	0.800	1	0.800	9
Unit under test stability	B	4.00	μA/A	1.732	2.309	1	2.309	∞
Rounding of reported value	B	1.00	μA/A	1.732	0.577	1	0.577	∞
						Combined standard uncertainty	4.4433	μA/A
						Effective degrees of freedom	7.01E+03	
						Coverage factor	2.000	
						Expanded uncertainty	9.00	μA/A
						Expanded uncertainty	0.000 009	mA

Uncertainty budget for 1 A measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Shunt uncertainty	B	6.10	µΩ/Ω	2.000	3.050	1	3.050	∞
Shunt drift	B	4.00	µΩ/Ω	1.732	2.309	1	2.309	∞
Voltmeter uncertainty	B	0.50	µV/V	2.000	0.250	1	0.250	∞
Voltmeter drift	B	1.00	µV/V	1.732	0.577	1	0.577	∞
Voltmeter resolution	B	0.05	µV/V	1.732	0.029	1	0.029	∞
Voltmeter repeatability	A	0.50	µV/V	1.000	0.500	1	0.500	99
Unit under test resolution	B	0.50	µA/A	1.732	0.289	1	0.289	∞
Unit under test repeatability	A	0.90	µA/A	1.000	0.900	1	0.900	9
Unit under test stability	B	3.35	µA/A	1.732	1.934	1	1.934	∞
Rounding of reported value	B	1.00	µA/A	1.732	0.577	1	0.577	∞
						Combined standard uncertainty	4.5001	µA/A
						Effective degrees of freedom	5.58E+03	
						Coverage factor	2.000	
						Expanded uncertainty	9.00	µA/A
						Expanded uncertainty	0.000 009	A

3.3 Alternating Voltage

For alternating voltage from 10 mV to 700 V the following components contribute to the uncertainty of measurement:

- Reference ac-dc difference: From the last calibration report and history of the ac-dc transfer standard
- Reference drift: From history of the ac-dc transfer standard
- Measuring set-up: From cables, connectors, temperature, humidity, etc. –experiments were performed to estimate the effect of cables, connectors, temperature, humidity, etc. The values of each component were combined by root sum square calculation.
- DMM for ac-dc transfer standard output reading resolution: Resolution specifications of digital multimeter which was used to monitor output from ac-dc transfer standard.
- Ac-dc transfer repeatability: From the observed data
- Unit under test DCV accuracy: The unit under test direct voltage readings are used with the ac-dc differences to calculate the applied alternating voltage, and from this the unit under test correction is calculated. The DCV corrections and uncertainties are obtained from a recent measurement, or calibration report.
- Unit under test DCV repeatability: From the observed data
- Unit under test ACV repeatability: From the observed data
- Unit under test resolution: From the unit under test specifications
- Unit under test stability: From tests repeated several times during the period that the instrument spent in our laboratory
- Rounding of reported value: To ensure that the reported value encompasses the calculated range of possible values

Uncertainty budget for 10 mV and 1.005 kHz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Reference ac-dc transfer standard uncertainty	B	26.00	µV/V	2.000	13.00	1	13.000	∞
Reference ac-dc transfer standard drift	B	10.00	µV/V	1.732	5.77	1	5.774	∞
Measuring set-up (cables, connectors, temp., humidity, etc.)	B	51.00	µV/V	1.732	29.45	1	29.446	∞
ac-dc difference repeatability	A	5.00	µV/V	1.000	5.00	1	5.000	6
DMM for ac-dc transfer standard output reading resolution	B	0.005	µV/V	1.732	0.00	1	0.003	∞
Unit under test direct voltage measurement	B	5.20	µV/V	2.000	2.60	1	2.600	∞
Unit under test DCV repeatability	A	3.00	µV/V	1.000	3.00	1	3.000	6
Unit under test ACV repeatability	A	8.00	µV/V	1.000	8.00	1	8.000	6
Unit under test resolution	B	0.50	µV/V	1.732	0.29	1	0.289	∞
Unit under test stability	B	50.00	µV/V	1.732	28.87	1	28.868	∞
Rounding of reported value	B	1.00	µV/V	1.732	0.58	1	0.577	∞
						Combined standard uncertainty	44.810	µV/V
						Effective degrees of freedom	5037.705	
						Coverage factor	2.000	
						Expanded uncertainty	89.643	µV/V
						Expanded uncertainty	0.90	µV
						Expanded uncertainty	0.000 000 90	V

10 mV range uncertainties

The table below summarises the uncertainty estimates for the 10 mV measurements. Only the standard uncertainties after reduction of the input values are shown. The degrees of freedom assigned to each component are the same as those assigned to the components in the budget for 10 mV and 1.005 kHz shown on the previous page.

								Standard uncertainties											
Range (V)	Nominal Voltage (V)	Frequency (kHz)	Expanded uncertainty (µV)	Expanded uncertainty (µV/V)	Coverage factor	Effective degrees of freedom	Combined standard uncertainty (µV/V)	Reference ac-dc transfer standard uncertainty (µV/V)	Reference ac-dc transfer standard drift (µV/V)	Measuring set-up (cables, connectors, temp., humidity, etc.) (µV/V)	ac-dc difference repeatability (µV/V)	DMM for ac-dc transfer standard output reading resolution (µV/V)	Unit under test direct voltage measurement (µV/V)	Unit under test DCV repeatability (µV/V)	Unit under test ACV repeatability (µV/V)	Unit under test resolution (µV/V)	Unit under test stability (µV/V)	Rounding of reported value (µV/V)
0.01	0.01	0.01	1.10	109.8	2.001	2344.0	54.879	15.000	5.774	36.663	7.000	0.003	2.600	3.000	12.000	0.289	34.642	0.577
		0.055	0.90	89.9	2.000	5106.5	44.962	13.000	5.774	29.446	5.000	0.003	2.600	3.000	8.000	0.289	28.868	0.577
		1.005	0.90	89.9	2.000	5106.5	44.962	13.000	5.774	29.446	5.000	0.003	2.600	3.000	8.000	0.289	28.868	0.577
		20	0.90	89.9	2.000	5106.5	44.962	13.000	5.774	29.446	5.000	0.003	2.600	3.000	8.000	0.289	28.868	0.577
		50	0.90	89.9	2.000	5106.5	44.962	13.000	5.774	29.446	5.000	0.003	2.600	3.000	8.000	0.289	28.868	0.577
		1000	3.00	300.0	2.000	2.1E+05	150.000	50.000	14.434	75.058	8.000	0.003	2.600	4.000	10.000	0.289	118.199	0.577

Uncertainty budget for 100 mV and 1.005 kHz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Reference ac-dc transfer standard uncertainty	B	6.00	μV/V	2.000	3.00	1	3.000	∞
Reference ac-dc transfer standard drift	B	5.00	μV/V	1.732	2.89	1	2.887	∞
Measuring set-up (cables, connectors, temp., humidity, etc.)	B	12.00	μV/V	1.732	6.93	1	6.928	∞
ac-dc difference repeatability	A	2.00	μV/V	1.000	2.00	1	2.000	6
DMM for ac-dc transfer standard output reading resolution	B	0.005	μV/V	1.732	0.00	1	0.003	∞
Unit under test direct voltage measurement	B	4.90	μV/V	2.000	2.45	1	2.450	∞
Unit under test DCV repeatability	A	1.00	μV/V	1.000	1.00	1	1.000	6
Unit under test ACV repeatability	A	2.00	μV/V	1.000	2.00	1	2.000	6
Unit under test resolution	B	0.50	μV/V	1.732	0.29	1	0.289	∞
Unit under test stability	B	13.00	μV/V	1.732	7.51	1	7.506	∞
Rounding of reported value	B	1.00	μV/V	1.732	0.58	1	0.577	∞
						Combined standard uncertainty	11.709	μV/V
						Effective degrees of freedom	3417.154	
						Coverage factor	2.001	
						Expanded uncertainty	23.426	μV/V
						Expanded uncertainty	2.34	μV
						Expanded uncertainty	0.000 002 3	V

100 mV range uncertainties

The table below summarises the uncertainty estimates for the 100 mV measurements. Only the standard uncertainties after reduction of the input values are shown. The degrees of freedom assigned to each component are the same as those assigned to the components in the budget for 100 mV and 1.005 kHz shown on the previous page.

								Standard uncertainties										
Range (V)	Nominal Voltage (V)	Frequency (kHz)	Expanded uncertainty (µV)	Expanded uncertainty (µV/V)	Coverage factor	Effective degrees of freedom	Combined standard uncertainty (µV/V)	Reference ac-dc transfer standard uncertainty (µV/V)	Reference ac-dc transfer standard drift (µV/V)	Measuring set-up (cables, connectors, temp., humidity, etc.) (µV/V)	ac-dc difference repeatability (µV/V)	DMM for ac-dc transfer standard output reading resolution (µV/V)	Unit under test direct voltage measurement (µV/V)	Unit under test DCV repeatability (µV/V)	Unit under test ACV repeatability (µV/V)	Unit under test resolution (µV/V)	Unit under test stability (µV/V)	Rounding of reported value (µV/V)
0.1	0.1	0.01	2.76	27.6	2.000	6547.2	13.775	4.000	2.887	8.661	2.000	0.003	2.450	1.000	2.000	0.289	8.661	0.577
		0.055	2.34	23.4	2.001	3417.2	11.709	3.000	2.887	6.928	2.000	0.003	2.450	1.000	2.000	0.289	7.506	0.577
		1.005	2.34	23.4	2.001	3417.2	11.709	3.000	2.887	6.928	2.000	0.003	2.450	1.000	2.000	0.289	7.506	0.577
		20	2.34	23.4	2.001	3417.2	11.709	3.000	2.887	6.928	2.000	0.003	2.450	1.000	2.000	0.289	7.506	0.577
		50	3.11	31.1	2.000	10568.8	15.527	3.000	2.887	11.547	2.000	0.003	2.450	1.000	2.000	0.289	8.661	0.577
		1000	22.02	220.2	2.000	6.4E+05	110.118	7.500	8.661	23.095	6.000	0.003	2.450	1.000	3.000	0.289	106.813	0.577

Uncertainty budget for 1 V and 1.005 kHz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Reference ac-dc transfer standard uncertainty	B	1.00	µV/V	2.000	0.50	1	0.500	∞
Reference ac-dc transfer standard drift	B	0.70	µV/V	1.732	0.40	1	0.404	∞
Measuring set-up (cables, connectors, temp., humidity, etc.)	B	5.00	µV/V	1.732	2.89	1	2.887	∞
ac-dc difference repeatability	A	1.00	µV/V	1.000	1.00	1	1.000	6
DMM for ac-dc transfer standard output reading resolution	B	0.005	µV/V	1.732	0.00	1	0.003	∞
Unit under test direct voltage measurement	B	1.60	µV/V	2.000	0.80	1	0.800	∞
Unit under test DCV repeatability	A	0.50	µV/V	1.000	0.50	1	0.500	6
Unit under test ACV repeatability	A	0.80	µV/V	1.000	0.80	1	0.800	6
Unit under test resolution	B	0.50	µV/V	1.732	0.29	1	0.289	∞
Unit under test stability	B	7.40	µV/V	1.732	4.27	1	4.273	∞
Rounding of reported value	B	1.00	µV/V	1.732	0.58	1	0.577	∞
						Combined standard uncertainty	5.473	µV/V
						Effective degrees of freedom	3655.589	
						Coverage factor	2.001	
						Expanded uncertainty	10.949	µV/V
						Expanded uncertainty	10.9	µV
						Expanded uncertainty	0.000 011	V

1 V range uncertainties

The table below summarises the uncertainty estimates for the 1 V measurements. Only the standard uncertainties after reduction of the input values are shown. The degrees of freedom assigned to each component are the same as those assigned to the components in the budget for 1 V and 1.005 kHz shown on the previous page.

								Standard uncertainties											
Range (V)	Nominal Voltage (V)	Frequency (kHz)	Expanded uncertainty (µV)	Expanded uncertainty (µV/V)	Coverage factor	Effective degrees of freedom	Combined standard uncertainty (µV/V)	Reference ac-dc transfer standard uncertainty (µV/V)	Reference ac-dc transfer standard drift (µV/V)	Measuring set-up (cables, connectors, temp., humidity, etc.) (µV/V)	ac-dc difference repeatability (µV/V)	DMM for ac-dc transfer standard output reading resolution (µV/V)	Unit under test direct voltage measurement (µV/V)	Unit under test DCV repeatability (µV/V)	Unit under test ACV repeatability (µV/V)	Unit under test resolution (µV/V)	Unit under test stability (µV/V)	Rounding of reported value (µV/V)
1.00	1.00	0.01	15.0	15.0	2.003	895.7	7.489	1.000	0.924	3.176	1.500	0.003	0.800	0.300	2.000	0.289	6.062	0.577
		0.055	11.0	11.0	2.001	3166.9	5.488	0.500	0.404	2.887	1.000	0.003	0.800	0.500	0.900	0.289	4.273	0.577
		1.005	10.9	10.9	2.001	3655.6	5.473	0.500	0.404	2.887	1.000	0.003	0.800	0.500	0.800	0.289	4.273	0.577
		20	11.1	11.1	2.001	3272.2	5.533	0.500	0.404	2.887	1.000	0.003	0.800	0.500	0.900	0.289	4.330	0.577
		50	13.5	13.5	2.000	7186.2	6.736	0.500	0.577	2.887	1.000	0.003	0.800	0.500	0.900	0.289	5.774	0.577
		1000	300.0	300.0	2.000	6.0E+04	149.973	5.000	4.619	138.568	15.000	0.003	0.800	1.000	3.000	0.289	54.850	0.577

Uncertainty budget for 10 V and 1.005 kHz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Reference ac-dc transfer standard uncertainty	B	1.00	µV/V	2.000	0.50	1	0.500	∞
Reference ac-dc transfer standard drift	B	0.70	µV/V	1.732	0.40	1	0.404	∞
Measuring set-up (cables, connectors, temp., humidity, etc.)	B	7.00	µV/V	1.732	4.04	1	4.042	∞
ac-dc difference repeatability	A	1.00	µV/V	1.000	1.00	1	1.000	6
DMM for ac-dc transfer standard output reading resolution	B	0.005	µV/V	1.732	0.00	1	0.003	∞
Unit under test direct voltage measurement	B	1.10	µV/V	2.000	0.55	1	0.550	∞
Unit under test DCV repeatability	A	0.50	µV/V	1.000	0.50	1	0.500	6
Unit under test ACV repeatability	A	1.00	µV/V	1.000	1.00	1	1.000	6
Unit under test resolution	B	0.50	µV/V	1.732	0.29	1	0.289	∞
Unit under test stability	B	7.00	µV/V	1.732	4.04	1	4.042	∞
Rounding of reported value	B	1.00	µV/V	1.732	0.58	1	0.577	∞
Combined standard uncertainty							6.004	µV/V
Effective degrees of freedom							3780.898	
Coverage factor							2.001	
Expanded uncertainty							12.013	µV/V
Expanded uncertainty							120	µV
Expanded uncertainty							0.000 12	V

10 V range uncertainties

The table below summarises the uncertainty estimates for the 10 V and 19 V measurements. Only the standard uncertainties after reduction of the input values are shown. The degrees of freedom assigned to each component are the same as those assigned to the components in the budget for 10 V and 1.005 kHz shown on the previous page.

								Standard uncertainties										
Range (V)	Nominal Voltage (V)	Frequency (kHz)	Expanded uncertainty (µV)	Expanded uncertainty (µV/V)	Coverage factor	Effective degrees of freedom	Combined standard uncertainty (µV/V)	Reference ac-dc transfer standard uncertainty (µV/V)	Reference ac-dc transfer standard drift (µV/V)	Measuring set-up (cables, connectors, temp., humidity, etc.) (µV/V)	ac-dc difference repeatability (µV/V)	DMM for ac-dc transfer standard output reading resolution (µV/V)	Unit under test direct voltage measurement (µV/V)	Unit under test DCV repeatability (µV/V)	Unit under test ACV repeatability (µV/V)	Unit under test resolution (µV/V)	Unit under test stability (µV/V)	Rounding of reported value (µV/V)
10	10	0.01	161	16.1	2.000	12154.9	8.040	1.000	0.577	5.196	1.000	0.003	0.550	0.500	1.000	0.289	5.774	0.577
		0.055	120	12.0	2.001	3816.6	6.018	0.500	0.577	4.042	1.000	0.003	0.550	0.500	1.000	0.289	4.042	0.577
		1.005	120	12.0	2.001	3780.9	6.004	0.500	0.404	4.042	1.000	0.003	0.550	0.500	1.000	0.289	4.042	0.577
		20	120	12.0	2.001	3816.6	6.018	0.500	0.577	4.042	1.000	0.003	0.550	0.500	1.000	0.289	4.042	0.577
		50	153	15.3	2.000	9861.4	7.630	0.500	0.577	4.619	1.000	0.003	0.550	0.500	1.000	0.289	5.774	0.577
		1000	3500	350.0	2.000	1.5E+05	174.995	5.000	5.774	157.240	14.000	0.003	0.550	1.000	3.000	0.289	75.058	0.577
10	19	1.005	229	12.0	2.001	3820.3	6.020	0.500	0.404	4.042	1.000	0.003	0.700	0.500	1.000	0.289	4.042	0.577

Uncertainty budget for 100 V and 1.005 kHz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Reference ac-dc transfer standard uncertainty	B	5.00	µV/V	2.000	2.50	1	2.500	∞
Reference ac-dc transfer standard drift	B	3.00	µV/V	1.732	1.73	1	1.732	∞
Measuring set-up (cables, connectors, temp., humidity, etc.)	B	7.00	µV/V	1.732	4.04	1	4.042	∞
ac-dc difference repeatability	A	1.00	µV/V	1.000	1.00	1	1.000	6
DMM for ac-dc transfer standard output reading resolution	B	0.005	µV/V	1.732	0.00	1	0.003	∞
Unit under test direct voltage measurement	B	2.00	µV/V	2.000	1.00	1	1.000	∞
Unit under test DCV repeatability	A	0.40	µV/V	1.000	0.40	1	0.400	6
Unit under test ACV repeatability	A	0.70	µV/V	1.000	0.70	1	0.700	6
Unit under test resolution	B	0.50	µV/V	1.732	0.29	1	0.289	∞
Unit under test stability	B	10.00	µV/V	1.732	5.77	1	5.774	∞
Rounding of reported value	B	1.00	µV/V	1.732	0.58	1	0.577	∞
						Combined standard uncertainty	7.873	µV/V
						Effective degrees of freedom	18214.367	
						Coverage factor	2.000	
						Expanded uncertainty	15.747	µV/V
						Expanded uncertainty	1.6	mV
						Expanded uncertainty	0.001 6	V

100 V range uncertainties

The table below summarises the uncertainty estimates for the 100 V measurements. Only the standard uncertainties after reduction of the input values are shown. The degrees of freedom assigned to each component are the same as those assigned to the components in the budget for 100 V and 1.005 kHz shown on the previous page.

								Standard uncertainties											
Range (V)	Nominal Voltage (V)	Frequency (kHz)	Expanded uncertainty (mV)	Expanded uncertainty (µV/V)	Coverage factor	Effective degrees of freedom	Combined standard uncertainty (µV/V)	Reference ac-dc transfer standard uncertainty (µV/V)	Reference ac-dc transfer standard drift (µV/V)	Measuring set-up (cables, connectors, temp., humidity, etc.) (µV/V)	ac-dc difference repeatability (µV/V)	DMM for ac-dc transfer standard output reading resolution (µV/V)	Unit under test direct voltage measurement (µV/V)	Unit under test DCV repeatability (µV/V)	Unit under test ACV repeatability (µV/V)	Unit under test resolution (µV/V)	Unit under test stability (µV/V)	Rounding of reported value (µV/V)
100	100	0.01	1.94	19.4	2.000	41579.8	9.678	2.500	1.732	6.928	1.000	0.003	1.000	0.400	0.700	0.289	5.774	0.577
		0.055	1.57	15.7	2.000	18214.4	7.873	2.500	1.732	4.042	1.000	0.003	1.000	0.400	0.700	0.289	5.774	0.577
		1.005	1.57	15.7	2.000	18214.4	7.873	2.500	1.732	4.042	1.000	0.003	1.000	0.400	0.700	0.289	5.774	0.577
		20	1.57	15.7	2.000	18214.4	7.873	2.500	1.732	4.042	1.000	0.003	1.000	0.400	0.700	0.289	5.774	0.577
		50	2.20	22.0	2.000	69011.6	10.984	2.500	1.732	8.661	1.000	0.003	1.000	0.400	0.700	0.289	5.774	0.577

Uncertainty budget for 700 V and 1.005 kHz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Reference ac-dc transfer standard uncertainty	B	6.00	μV/V	2.000	3.00	1	3.000	∞
Reference ac-dc transfer standard drift	B	3.00	μV/V	1.732	1.73	1	1.732	∞
Measuring set-up (cables, connectors, temp., humidity, etc.)	B	22.00	μV/V	1.732	12.70	1	12.702	∞
ac-dc difference repeatability	A	1.00	μV/V	1.000	1.00	1	1.000	6
DMM for ac-dc transfer standard output reading resolution	B	0.01	μV/V	1.732	0.00	1	0.003	∞
Unit under test direct voltage measurement	B	2.20	μV/V	2.000	1.10	1	1.100	∞
Unit under test DCV repeatability	A	0.50	μV/V	1.000	0.50	1	0.500	6
Unit under test ACV repeatability	A	0.90	μV/V	1.000	0.90	1	0.900	6
Unit under test resolution	B	0.50	μV/V	1.732	0.29	1	0.289	∞
Unit under test stability	B	10.00	μV/V	1.732	5.77	1	5.774	∞
Rounding of reported value	B	1.00	μV/V	1.732	0.58	1	0.577	∞
						Combined standard uncertainty	14.504	μV/V
						Effective degrees of freedom	154498.142	
						Coverage factor	2.000	
						Expanded uncertainty	29.008	μV/V
						Expanded uncertainty	0.020	V

1000 V range uncertainties

The table below summarises the uncertainty estimates for the 700 V measurements. Only the standard uncertainties after reduction of the input values are shown. The degrees of freedom assigned to each component are the same as those assigned to the components in the budget for 700 V and 1.005 kHz shown on the previous page.

								Standard uncertainties											
Range (V)	Nominal Voltage (V)	Frequency (kHz)	Expanded uncertainty (mV)	Expanded uncertainty (µV/V)	Coverage factor	Effective degrees of freedom	Combined standard uncertainty (µV/V)	Reference ac-dc transfer standard uncertainty (µV/V)	Reference ac-dc transfer standard drift (µV/V)	Measuring set-up (cables, connectors, temp., humidity, etc.) (µV/V)	ac-dc difference repeatability (µV/V)	DMM for ac-dc transfer standard output reading resolution (µV/V)	Unit under test direct voltage measurement (µV/V)	Unit under test DCV repeatability (µV/V)	Unit under test ACV repeatability (µV/V)	Unit under test resolution (µV/V)	Unit under test stability (µV/V)	Rounding of reported value (µV/V)
1000	700	0.055	24.23	34.6	2.000	223531.5	17.309	3.000	1.732	14.434	1.000	0.003	1.100	0.800	1.000	0.289	8.661	0.577
		1.005	20.31	29.0	2.000	154498.1	14.504	3.000	1.732	12.702	1.000	0.003	1.100	0.500	0.900	0.289	5.774	0.577
		20	20.31	29.0	2.000	110186.3	14.504	3.000	1.732	12.679	1.000	0.003	1.100	0.800	1.000	0.289	5.774	0.577
		50	29.96	42.8	2.000	522228.2	21.400	3.000	1.732	20.208	1.000	0.003	1.100	0.800	1.000	0.289	5.774	0.577

3.4 Alternating Current

For alternating current the following components contribute to the uncertainty of measurement:

- Reference ac-dc current difference: From the last calibration report and history of the ac-dc current transfer standard
- Reference drift: From history of the ac-dc current transfer standard
- Measuring set-up: From cables, connectors, temperature, humidity, etc. –experiments were performed to estimate the effect of cables, connectors, temperature, humidity, etc. The values of each component were combined by root sum square calculation.
- DMM for ac-dc transfer standard output reading resolution: Resolution specifications of digital multimeter which was used to monitor output from ac-dc transfer standard.
- Ac-dc transfer repeatability: From the observed data
- Unit under test DCI accuracy: The unit under test direct current readings are used with the ac-dc differences to calculate the applied alternating current, and from this the unit under test correction is calculated. The DCI corrections and uncertainties are obtained from a recent measurement, or calibration report.
- Unit under test DCI repeatability: From the observed data
- Unit under test ACI repeatability: From the observed data
- Unit under test resolution: From the unit under test specifications
- Unit under test stability: From tests repeated several times during the period that the instrument spent in our laboratory
- Rounding of reported value: To ensure that the reported value encompasses the calculated range of possible values

Uncertainty budget for 1 mA and 1.005 kHz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Reference ac-dc transfer standard uncertainty	B	50.00	µA/A	2.000	25.00	1	25.000	∞
Reference ac-dc transfer standard drift	B	10.00	µA/A	1.732	5.77	1	5.774	∞
Measuring set-up (cables, connectors, temp., humidity, etc.)	B	61.93	µA/A	1.732	35.76	1	35.756	∞
ac-dc difference repeatability	A	2.00	µA/A	1.000	2.00	1	2.000	7
DMM for ac-dc transfer standard output reading resolution	B	0.01	µA/A	1.732	0.00	1	0.003	∞
Unit under test direct current measurement	B	9.00	µA/A	2.000	4.50	1	4.500	∞
Unit under test DCI repeatability	A	1.00	µA/A	1.000	1.00	1	1.000	7
Unit under test ACI repeatability	A	2.00	µA/A	1.000	2.00	1	2.000	7
Unit under test resolution	B	0.50	µA/A	1.732	0.29	1	0.289	∞
Unit under test stability	B	40.00	µA/A	1.732	23.09	1	23.095	∞
Rounding of reported value	B	1.00	µA/A	1.732	0.58	1	0.577	∞
						Combined standard uncertainty	49.999	µA/A
						Effective degrees of freedom	1.33E+06	
						Coverage factor	2.000	
						Expanded uncertainty	100.00	µA/A
						Expanded uncertainty	0.000 100	mA

1 mA range uncertainties

The table below summarises the uncertainty estimates for the 1 mA measurements. Only the standard uncertainties after reduction of the input values are shown. The degrees of freedom assigned to each component are the same as those assigned to the components in the budget for 1 mA and 1.005 kHz shown on the previous page.

								Standard uncertainties										
Range (mA)	Nominal Current (mA)	Frequency (kHz)	Expanded uncertainty (nA)	Expanded uncertainty (µA/A)	Coverage factor	Effective degrees of freedom	Combined standard uncertainty (µA/A)	Reference ac-dc transfer standard uncertainty (µA/A)	Reference ac-dc transfer standard drift (µA/A)	Measuring set-up (cables, connectors, temp., humidity, etc.) (µA/A)	ac-dc difference repeatability (µA/A)	DMM for ac-dc transfer standard output reading resolution (µA/A)	Unit under test direct current measurement (µA/A)	Unit under test DCI repeatability (µA/A)	Unit under test ACI repeatability (µA/A)	Unit under test resolution (µA/A)	Unit under test stability (µA/A)	Rounding of reported value (µA/A)
1	1	0.055	100	100	2.000	1.3E+06	50.002	15.000	8.661	40.462	2.000	0.003	4.500	1.000	2.000	0.289	23.095	0.577
		1.005	100	100	2.000	1.3E+06	49.999	25.000	5.774	35.756	2.000	0.003	4.500	1.000	2.000	0.289	23.095	0.577
		5	100	100	2.000	1.3E+06	50.000	35.000	5.774	26.051	2.000	0.003	4.500	1.000	2.000	0.289	23.095	0.577

Uncertainty budget for 1 A and 1.005 kHz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Reference ac-dc transfer standard uncertainty	B	5.00	µA/A	2.000	2.50	1	2.500	∞
Reference ac-dc transfer standard drift	B	5.00	µA/A	1.732	2.89	1	2.887	∞
Measuring set-up (cables, connectors, temp., humidity, etc.)	B	50.33	µA/A	1.732	29.06	1	29.061	∞
ac-dc difference repeatability	A	1.00	µA/A	1.000	1.00	1	1.000	4
DMM for ac-dc transfer standard output reading resolution	B	0.01	µA/A	1.732	0.00	1	0.003	∞
Unit under test direct current measurement	B	9.40	µA/A	2.000	4.70	1	4.700	∞
Unit under test DCI repeatability	A	1.00	µA/A	1.000	1.00	1	1.000	4
Unit under test ACI repeatability	A	2.00	µA/A	1.000	2.00	1	2.000	4
Unit under test resolution	B	0.50	µA/A	1.732	0.29	1	0.289	∞
Unit under test stability	B	35.00	µA/A	1.732	20.21	1	20.208	∞
Rounding of reported value	B	1.00	µA/A	1.732	0.58	1	0.577	∞
Combined standard uncertainty							36.000	µA/A
Effective degrees of freedom							3.73E+05	
Coverage factor							2.000	
Expanded uncertainty							72.00	µA/A
Expanded uncertainty							0.000 072	A

1 A range uncertainties

The table below summarises the uncertainty estimates for the 1 A measurements. Only the standard uncertainties after reduction of the input values are shown. The degrees of freedom assigned to each component are the same as those assigned to the components in the budget for 1 A and 1.005 kHz shown on the previous page.

								Standard uncertainties											
Range (A)	Nominal Current (A)	Frequency (kHz)	Expanded uncertainty (μA)	Expanded uncertainty (μA/A)	Coverage factor	Effective degrees of freedom	Combined standard uncertainty (μA/A)	Reference ac-dc transfer standard uncertainty (μA/A)	Reference ac-dc transfer standard drift (μA/A)	Measuring set-up (cables, connectors, temp., humidity, etc.) (μA/A)	ac-dc difference repeatability (μA/A)	DMM for ac-dc transfer standard output reading resolution (μA/A)	Unit under test direct current measurement (μA/A)	Unit under test DCI repeatability (μA/A)	Unit under test ACI repeatability (μA/A)	Unit under test resolution (μA/A)	Unit under test stability (μA/A)	Rounding of reported value (μA/A)
1	1	0.055	75.0	75.0	2.000	4.4E+05	37.499	2.500	2.887	28.805	1.000	0.003	4.700	1.000	2.000	0.289	23.095	0.577
		1.005	72.0	72.0	2.000	3.7E+05	36.000	2.500	2.887	29.061	1.000	0.003	4.700	1.000	2.000	0.289	20.208	0.577
		5	75.0	75.0	2.000	4.4E+05	37.500	2.500	2.887	28.806	1.000	0.003	4.700	1.000	2.000	0.289	23.095	0.577

3.5 Resistance

For resistance the following components contribute to the uncertainty of measurement:

- Reference resistor uncertainty: The certified correction of the reference resistor from its latest calibration report
- Calibrator drift: From the history of the resistor
- Uncorrected zero offset: The zero is measured before and after the calibration of a resistance range of the instrument and the average of the two zero readings is used as a correction – this is the uncertainty component of the average zero determination
- Unit under test resolution: From the specifications of the unit under test
- Unit under test repeatability: From the observed data
- Unit under test stability: From tests repeated several times during the period that the instrument spent in our laboratory
- Rounding of reported value: To ensure that the reported value encompasses the calculated range of possible values

Uncertainty budget for 10 kΩ 4-wire measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Reference resistor uncertainty	B	2.40	μΩ/Ω	2.000	1.2000	1	1.2000	∞
Resistor drift	B	1.88	μΩ/Ω	1.732	1.0855	1	1.0855	∞
Uncorrected zero offset	B	0.10	μΩ/Ω	1.732	0.0577	1	0.0577	∞
Unit under test resolution	B	0.05	μΩ/Ω	1.732	0.0289	1	0.0289	∞
Unit under test repeatability	A	0.20	μΩ/Ω	1.000	0.2000	1	0.2000	9
Unit under test stability	B	0.40	μΩ/Ω	1.732	0.2309	1	0.2309	∞
Rounding of reported value	B	0.10	μΩ/Ω	1.732	0.0577	1	0.0577	∞
Combined standard uncertainty							1.6490	μΩ/Ω
Effective degrees of freedom							4.16E+04	
Coverage factor							2.000	
Expanded uncertainty							3.30	μΩ/Ω
Expanded uncertainty							0.000 033	kΩ

Resistance function uncertainties

The table below summarises the uncertainty estimates for the resistance measurements. Only the standard uncertainties after reduction of the input values are shown. The degrees of freedom assigned to each component are the same as those assigned to the components in the budget for 10 kΩ measurement shown on the previous page.

								Standard uncertainties						
Range	Nominal Resistance	Wiring Configuration	Expanded uncertainty	Expanded uncertainty (μΩ/Ω)	Coverage factor	Effective degrees of freedom	Combined standard uncertainty (μΩ/Ω)	Reference resistor uncertainty (μΩ/Ω)	Resistor drift (μΩ/Ω)	Uncorrected zero offset (μΩ/Ω)	Unit under test resolution (μΩ/Ω)	Unit under test repeatability (μΩ/Ω)	Unit under test stability (μΩ/Ω)	Rounding of reported value (μΩ/Ω)
10 Ω	10 Ω	4W	27.0 μΩ	2.698	2.001	3673.8	1.348	1.100	0.520	0.058	0.029	0.300	0.491	0.058
100 Ω	100 Ω	4W	279.5 μΩ	2.795	2.000	21463.3	1.398	1.050	0.866	0.058	0.029	0.200	0.231	0.058
1 kΩ	1 kΩ	4W	2.199 mΩ	2.199	2.000	8213.0	1.099	1.000	0.346	0.058	0.029	0.200	0.202	0.058
10 kΩ	10 kΩ	4W	32.98 mΩ	3.298	2.000	41586.6	1.649	1.200	1.085	0.058	0.029	0.200	0.231	0.058
100 kΩ	100 kΩ	2W	0.380 Ω	3.800	2.000	14480.6	1.900	1.550	0.982	0.173	0.029	0.300	0.346	0.058
1 MΩ	1 MΩ	2W	5.60 Ω	5.602	2.000	68373.9	2.801	1.500	2.304	0.173	0.029	0.300	0.404	0.058
10 MΩ	10 MΩ	2W	98.0 Ω	9.805	2.000	6.4E+05	4.902	3.000	3.482	0.115	0.029	0.300	1.674	0.058
100 MΩ	100 MΩ	2W	5.73 kΩ	57.253	2.000	1.5E+07	28.626	20.000	20.208	0.115	0.029	0.800	3.233	0.058

3.6 Frequency

For frequency the following components contribute to the uncertainty of measurement:

- Reference time-base: The specified frequency accuracy of the national frequency standard at the observation time used for the measurement
- Counter accuracy: Calculated using the formulae supplied by the manufacturer
- Counter resolution: The manufacturer calls this the Least Significant Digit Displayed – it was calculated using the formula supplied by the manufacturer
- Unit under test repeatability: From the observed data
- Unit under test stability: From repeated tests
- Rounding of reported value: To ensure that the reported value encompasses the calculated range of possible values

Uncertainty budget for 1.005 kHz measurement:

Component	Type	Value	Unit	Divisor	Standard uncertainty	Sensitivity coefficient	Uncertainty contribution	Degrees of Freedom
Reference time-base	B	4.00E-12	Hz/Hz	2.000	2.00E-12	1	2.000E-12	∞
Counter accuracy	B	3.70E-09	Hz/Hz	1.732	2.14E-09	1	2.135E-09	∞
Counter resolution	B	5.00E-13	Hz/Hz	1.732	2.89E-13	1	2.887E-13	∞
Unit under test repeatability	A	1.28E-09	Hz/Hz	1.000	1.28E-09	1	1.276E-09	99
Unit under test stability	B	2.50E-07	Hz/Hz	1.732	1.44E-07	1	1.443E-07	∞
Rounding of reported value	B	1.00E-12	Hz/Hz	1.732	5.77E-13	1	5.774E-13	∞
						Combined standard uncertainty	1.444E-07	Hz/Hz
						Effective degrees of freedom	1.622E+10	
						Coverage factor	2.000	
						Expanded uncertainty	2.887E-07	Hz/Hz
						Expanded uncertainty	0.000290	Hz

Calibrator frequency uncertainties

The tables below summarise the uncertainty estimates for the calibrator frequencies. Only the standard uncertainties after reduction of the input values are shown. The degrees of freedom assigned to each component are the same as those assigned to the components in the budget for 1.005 kHz measurement shown on the previous page.

						Standard uncertainties					
Nominal frequency (kHz)	Expanded uncertainty	Expanded uncertainty (Hz/Hz)	Coverage factor	Effective degrees of freedom	Combined standard uncertainty (Hz/Hz)	Reference time-base (Hz/Hz)	Counter accuracy (Hz/Hz)	Counter resolution (Hz/Hz)	Unit under test repeatability (Hz/Hz)	Unit under test stability (Hz/Hz)	Rounding of reported value (Hz/Hz)
0.01	15.6 μHz	1.56E-05	2.014	1.79E+02	7.74E-06	2.00E-12	2.14E-07	2.89E-13	6.67E-06	3.92E-06	5.77E-13
0.055	0.33 μHz	3.32E-07	2.001	2.78E+03	5.77E-13	2.00E-12	3.90E-08	2.89E-13	7.21E-08	1.44E-07	5.77E-13
1.005	0.29 μHz	2.89E-07	2.000	1.62E+10	1.44E-07	2.00E-12	2.14E-09	2.89E-13	1.28E-09	1.44E-07	5.77E-13
5	0.29 μHz	2.89E-07	2.000	5.66E+10	1.44E-07	2.00E-12	4.31E-10	2.89E-13	9.33E-10	1.44E-07	5.77E-13
20	0.29 μHz	2.89E-07	2.000	2.77E+12	1.44E-07	2.00E-12	1.10E-10	2.89E-13	3.53E-10	1.44E-07	5.77E-13
50	0.55 μHz	5.49E-07	2.000	1.70E+14	2.75E-07	2.00E-12	4.53E-11	2.89E-13	2.40E-10	2.75E-07	5.77E-13
1000	0.50 μHz	5.01E-07	2.000	3.56E+13	2.51E-07	2.00E-12	4.63E-12	2.89E-13	3.24E-10	2.51E-07	5.77E-13