Key International Comparison of AC-DC Current Transfer Standards CCEM-K12

Final Report

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1. Introduction

The CIPM Mutual Recognition Arrangement (MRA) states that its technical basis is a set of results obtained in a course of time through key comparisons carried out by the Consultative Committees of the CIPM, the BIPM and the Regional Metrology Organisations (RMOs). As part of this process, the CIPM Consultative Committee for Electricity and Magnetism (CCEM) decided at its 23rd meeting in September 2002 on a Key International Comparison of AC-DC Current Transfer Standards CCEM-K12, with the National Measurement Institute, Australia (NMIA) as the pilot laboratory and the support group consisting of National Institute of Standards and Technology (NIST) and Justervesenet (JV).

The comparison measurements were conducted in the period from November 2004 to April 2007

2. Participants and organisation of the comparison

2.1. List of participants

Table 1. List of Participants

Date		Laboratory	
	to Mar 2005	***NMIA***	Dr Ilya Budovsky National Measurement Institute PO Box 264 Lindfield NSW 2070 Australia phone: (+61 2) 8467 3541 fax: (+61 2) 8467 3783 Email: ilya.budvosky@measurement.gov.au
Mar 2005 -	May 2005	***NIST***	Thomas E. Lipe National Institute of Standards and Technology100 Bureau Drive, Building 220, Room B-146, Gaithersburg, MD 20899-8171 USA Telephone: 01 301 975 4251 Fax: 01 301 926 3972Email: thomas.lipe@nist.gov
May 2005 -	Jun 2005	NRC	Dr. Peter S. Filipski Institute for National Measurement Standards National Research Council Canada 1200 Montreal Rd. Bldg. M36 Ottawa, Ontario Canada K1A 0R6 Telephone: (613) 993 2313 Fax: (613) 952 1394 Email: Peter.Filipski@nrc.ca
Jul 2005 -	Aug 2005	INTI	Dr. Ing. Hector Laiz INSTITUTO NACIONAL DE TECNOLOGIA INDUSTRIAL Av. Gral Paz 5445, San Martin, B1650KNA, Buenos Aires, Argentina Telephone: (+5411) 4724-6200 Fax: (+5411) 4724-6200 Email: laiz@inti.gov.ar
Sep 2005 -	Oct 2005	PTB	Dr. Torsten Funck Physikalisch-Technische Bundesanstalt Bundesallee 100 38116 Braunschweig Germany Telephone: ++49-531-592-2320 Fax: ++49-531-592-

			2345 Email: Torsten.Funck@ptb.de
Oct 2005 -	Oct 2005	BEV	Martin Garcocz Bundesamt für Eich- und Vermessungswesen Arltgasse 35; A-1160 VIENNA Austria Telephone: +43-1-49110-0 Fax: +43-1-4920875 Email: m.garcocz@metrologie.at
Nov 2005 -	Dec 2005	***JV***	Jeanne H. Espedalen Justervesenet Fetveien 99, N-2007 Kjeller; NORWAY Telephone: +47 64 84 84 84Fax: +47 64 84 84 85 Email: jeanne.espedalen@justervesenet.no
Jan 2006 -	Feb 2006	SP	Karl-Erik Rydler Brinellgatan 4, SE-504 62 BORAAS, Sweden Telephone: +46 33 165401 Fax: +46 33 125038 Email: karlerik.rydler@sp.se
Mar 2006 -	May 2006	***NMIA***	Dr Ilya Budovsky National Measurement Institute PO Box 264 Lindfield NSW 2070 Australia phone: (+61 2) 8467 3541 fax: (+61 2) 8467 3783
06 Jun 2006 -	Jul 2006	NMC	Dr. Sze Wey CHUA NMC 1 Science Park Drive, Singapore 118221 Tel: (65) 62791909, Fax: (65) 62791995 Email: chua_sze_wey@nmc.a-star.edu.sg
Aug 2006 -	Sep 2006	INMETRO	Giovanna Borghi Av. Nossa Senhora das Graças, 50, Xerém, Duque de Caxias, RJ, Brasil CEP 25.250-020 Telephone: (55 21) 2679-9076 Fax: (55 21) 2679-1627 Email: latce@inmetro.gov.br
Sep 2006 -	Jan 2007	NPL	MR ADRIAN WHEATON CENTRE FOR ELECTROMAGNETIC & TIME METROLOGY, MODULE 2, ROOM F2-A14, QUEENS ROAD, TEDDINGTON, MIDDLESEX. TW11 0LW Telephone: +44 20 8943 6235 / 6367Fax: +44 20 8614 0539 Email: adrian.wheaton@npl.co.uk
Mar 2007 -	Apr 2007	VNIIM	Dr. G.P. Telitchenko 19, Moskovsky pr., 198005 St. Petrsburg, Russia Telephone: 7 (812) 3239620 Fax: 7 (812) 3239620 Email: G.P.Telitchenko@vniim.ru

2.2. Comparison schedule

Table 2. Original Comparison Schedule

Dates		Laboratory
	to Mar 2005	***NMIA***
12 Apr 2005 -	23 May 2005	***NIST***
24 May 2005 -	04 Jul 2005	NRC
05 Jul 2005 -	15 Aug 2005	INTI
16 Aug 2005 -	26 Sep 2005	PTB
27 Sep 2005 -	07 Nov 2005	BEV
08 Nov 2005 -	19 Dec 2005	***JV***
20 Dec 2005 -	30 Jan 2006	SP
31 Jan 2006 -	13 Mar 2006	NPL
14 Mar 2006 -	24 Apr 2006	***NMIA***
25 Apr 2006 -	05 Jun 2006	VNIIM
06 Jun 2006 -	17 Jul 2006	NMC
18 Jul 2006 -	28 Aug 2006	INMETRO
29 Aug 2006 -	09 Oct 2006	***NMIA***

2.3. Organisation of the comparison

Prior to the comparison, a pilot comparison was organised between the pilot laboratory, National Measurement Institute, Australia (NMIA), and the support group consisting of National Institute of Standards and Technology, USA (NIST) and Justervesenet, Norway (JV). As a result of this comparison, the long term stability of the travelling standards was confirmed and preliminary reference values established.

The travelling standards were dispatched from NMIA around March 2005 and returned after the completion of each loop. The pilot laboratory was informed by fax of the arrival of the package and again when sending the package to the next participant. The next participant was also informed by e-mail or fax.

Each participating laboratory covered the costs of the measurement, transportation and customs clearance as well as for any damage that may occur within its country. The pilot laboratory covered the overall costs for the organisation of the comparison. The pilot laboratory had no insurance for any loss or damage of the travelling standard.

Due to the time constraints the participants were expected to use a recognised courier service e.g. UPS or DHL for the transport of the travelling standard and not to use a forwarding agent that does not guarantee an adequate delivery time, inclusive of the time for customs procedure. The case was transported with an ATA Carnet for customs clearance.

2.4. Unexpected incidents

After the start of the comparison, two participants, NPL and VNIIM requested that their participation be moved to the end of the circulation. This liberated two measurement slots in the middle of the schedule. The pilot laboratory approached several laboratories that originally applied to participate in the comparison but none were prepared to take the vacant positions at a relatively short notice.

In 2006 NPL chose a little known courier company to send the travelling standards to VNIIM. After the measurements at VNIIM were completed in April 2007 the same courier took possession of the standards to send them back to the pilot laboratory. Following this, all contact with the courier ceased, leading to eventual loss of the standards. Since, prior to their disappearance, the travelling standards exhibited exceptional stability, the CCEM working group on low-frequency standards decided in June 2008 to accept the results of the comparison as valid without the final measurement by NMIA.

3. Travelling standards and measurement instructions

3.1. Description of the travelling standards

- **10 mA**

The travelling standard for the current of 10 mA was a Single-Junction Thermal Converter, Serial Number 1001-2003, manufactured by NMIA. It has the following nominal parameters:

Rated Input Current:	10 mA
Heater Resistance:	25 Ω
Thermocouple Resistance:	7 Ω
Output Voltage at Rated Current:	7.6 mV

The Thermal Converter has a UHF-type input connector and a type 10SL-4S output connector.

- **5 A**

The 5 A travelling standard comprised a 0.2 Ω coaxial shunt, Serial No S10 and a 1 V single junction thermal converter, Serial Number 251 - 2003. Both were manufactured at NMIA. Their main parameters are as follows:

Current Shunt, Serial No S10

Nominal Resistance	0.2 Ω
Power coefficient of resistance	<0.5 μΩ/Ω/W
Input Connector	UHF
Output Connector	N-female

Thermal Converter, Serial No 251 - 2003

Rated Input Voltage:	1 V
Input Resistance:	475 Ω
Thermocouple Resistance:	7 Ω
Output Voltage at Rated Voltage:	6.2 mV

The 5 A travelling standard was supplied with two Perspex supports, for the Thermal Converter and for the input side of the shunt respectively. When assembled correctly the travelling standard can be positioned firmly on a flat surface (see Figure 1).

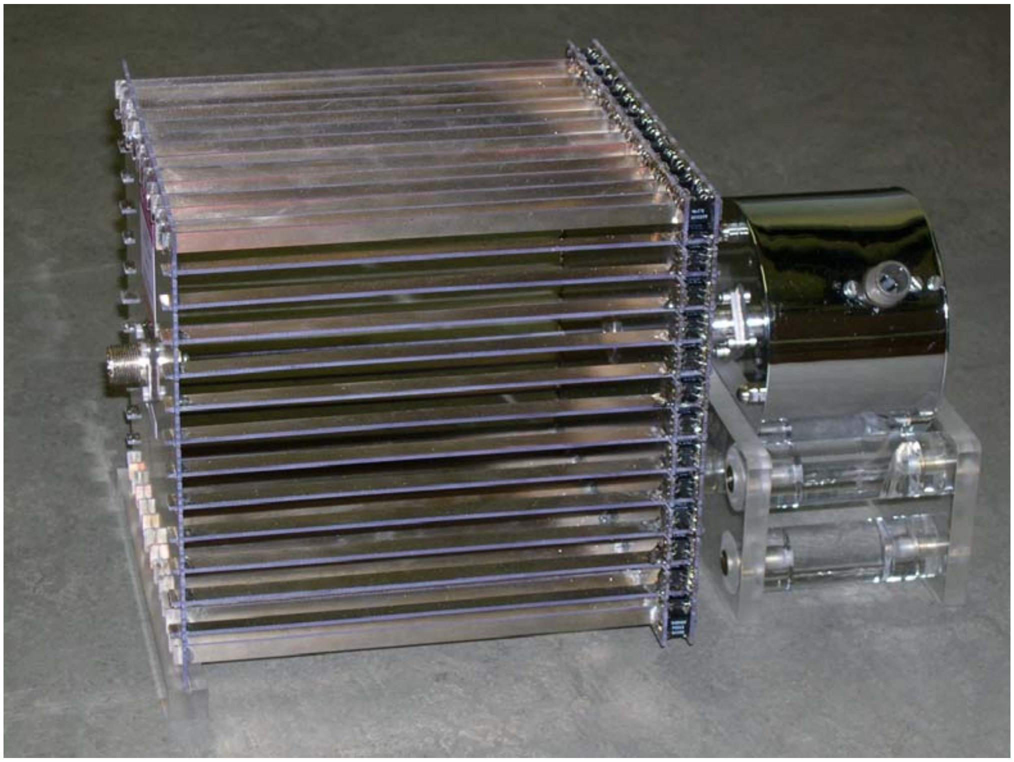


Figure 1 Physical layout of the 5A travelling standard

3.2. Quantities to be measured and measurement conditions

Ac-dc current transfer difference was defined as

$$\delta = \frac{I_{ac} - I_{dc}}{I_{dc}}$$

where

I_{ac} is an rms ac current, and
I_{dc} is a dc current which, when reversed, produces the same mean output response as the rms ac current.

Differences were expressed in microamperes per ampere (μA/A) and a positive sign signifies that more ac than dc current was required for the same output response.

3.3. Measurement instructions

The following detailed instructions were given to the participants.

- Upon receiving the package, check input and output resistances of the two thermal converters. Check also that there is a high resistance (>100 MΩ) between the input and the output. In making these preliminary measurements, make sure **not to exceed** the nominal current of the thermal converters (for input resistance), 1 mA (for output resistance) and 100 V between the heater and the thermocouple. In case of any failure, inform the pilot laboratory immediately.

- The ac-dc transfer difference is to be measured for the “Lo” position of the travelling standard, i.e. with both its input and output earthed. The connection to earth must remain at all times to protect the thermocouple.
- Care should be taken not to apply current above nominal, which may destroy the travelling standards.
- Recommended ambient conditions are temperature (23±1)°C and relative humidity (50±5)%.
- At least 30 minutes should be allowed for stabilisation after the fist application of current.
- The measurement frequency should be within 1 % of its nominal value. The frequency and its uncertainty must be reported.
- Sufficient delay time should be used between successive applications of alternating and direct current. Note that the thermal converter used in the 5A travelling standard has a time constant of approximately 4 seconds.

The ac-dc difference of each travelling standard was to be measured at its nominal current and the following frequencies:

Mandatary: 10 Hz, 55 Hz, 1 kHz, 10 kHz
Optional: 20 kHz, 50 kHz, 100 kHz.

4. Methods of measurement

Table 3. Reference standards and measurement methods at 10 mA

Laboratory	Reference Standard	Measurement Method	Source of Traceability
NMIA	Micropotentiometer SJTC	Direct Comparison	In-house
NIST	3D MJTC, SJTC	Direct Comparison	In-house
NRC	MJTC≤10kHz, CJTC≥20 kHz	Direct Comparison	In-house
INTI	PMJTC	Direct Comparison	PTB
PTB	QPMJTC	Direct Comparison	In-house
BEV	PMJTC≤1kHz, SJTC≥10 kHz	Direct Comparison	In-house
JV	PMJT	Direct Comparison	PTB
SP	MJTC≤1kHz, SJTC≥10 kHz	Direct Comparison	In-house
NMC	PMJTC	Direct Comparison	PTB
INMETRO	Fluke A40 Shunt +SJTC	Direct Comparison	PTB
NPL	Guildline MJTC	Direct Comparison	In-house
VNIIM	SJTC	Direct Comparison	In-house

Table 4. Reference standards and measurement methods at 5 A

Laboratory	Reference Standard	Measurement Method	Source of Traceability
NMIA	NMIA Shunt + SJTC	Direct Comparison	In-house
NIST	NIST Shunt + SJTC	Build-up	In-house
NRC	NRC Shunt + SJTC	Build-up	In-house
INTI	Shunt + PMJTC	Build-up	In-house
PTB	Holt Shunt + PMJTC, JV Shunt + PMJTC	Build-up	In-house
BEV	BEV Shunt + PMJTC	Build-up	In-house
JV	JV Shunt + PMJTC	Build-up	In-house
SP	SP Shunt + PMJTC	Build-up	In-house
NMC	Holt Shunt + PMJTC	Build-up	In-house
INMETRO	Fluke A40A Shunt +SJTC	Direct Comparison	PTB
NPL	Shunt + SJTC	Build-up	In-house
VNIIM	VNIIM Shunt + SJTC	Direct Comparison	In-house

5. Repeated measurements of the pilot laboratory

Tables 5 and 6 show the mean results of the measurements by the pilot laboratory for the duration of the comparison, including measurements done prior to the circulation.

Figures 2 and 3 show long-term stability measurements over three months.

Table 5. AC-DC Difference of the 10 mA Travelling Standard Measured by NMIA, in μA/A

f (kHz)	Year		
	2003	2004	2006
0.01	-0.6	-0.1	0.1
0.055	-1.5	-1.1	-1.1
1	-1.5	-1.2	-1.3
10		-1.2	-1.4
20	-1.6	-1.2	-1.5
50	-1.8	-1.3	-1.6
100	-2.1	-1.7	-1.8

Table 6. AC-DC Difference of the 5 A Travelling Standard Measured by NMIA, in μA/A

f (kHz)	Year		
	2003	2004	2006
0.01	-0.5	-0.6	-0.8
0.055	0.2	0.4	0.0
1	0.3	0.8	0.4
10	-2.62	-1.3	-2.2
20	-9.4	-8.3	-8.8
50	-37.3	-37.1	-36.7
100	-70.3	-70.5	-70.1

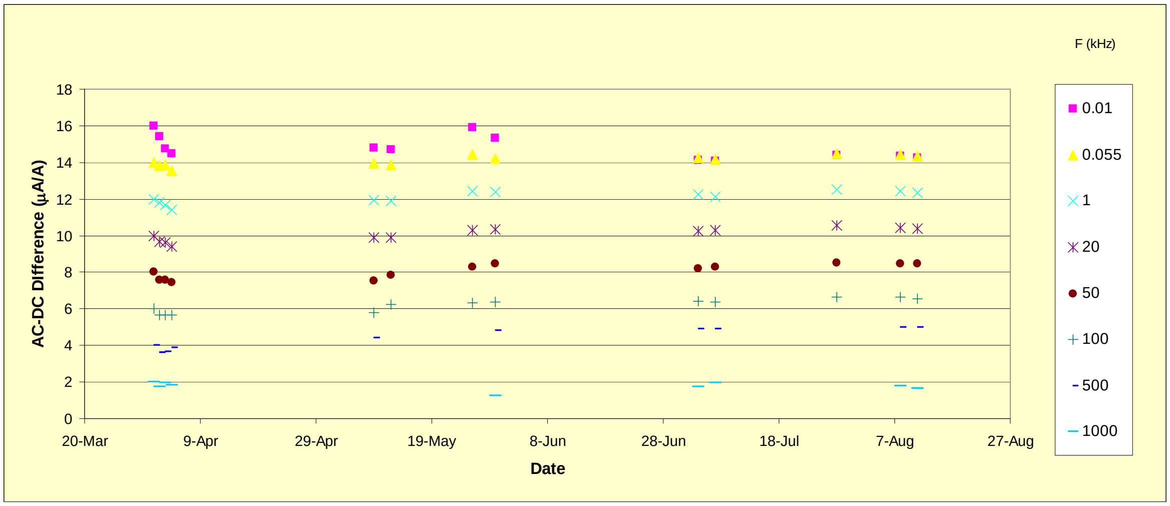


Figure 2. NMIA measurements of the 10 mA transfer standard long term stability. The values on the vertical axis have been adjusted for clarity of presentation and are, therefore, not true ac-dc difference values.

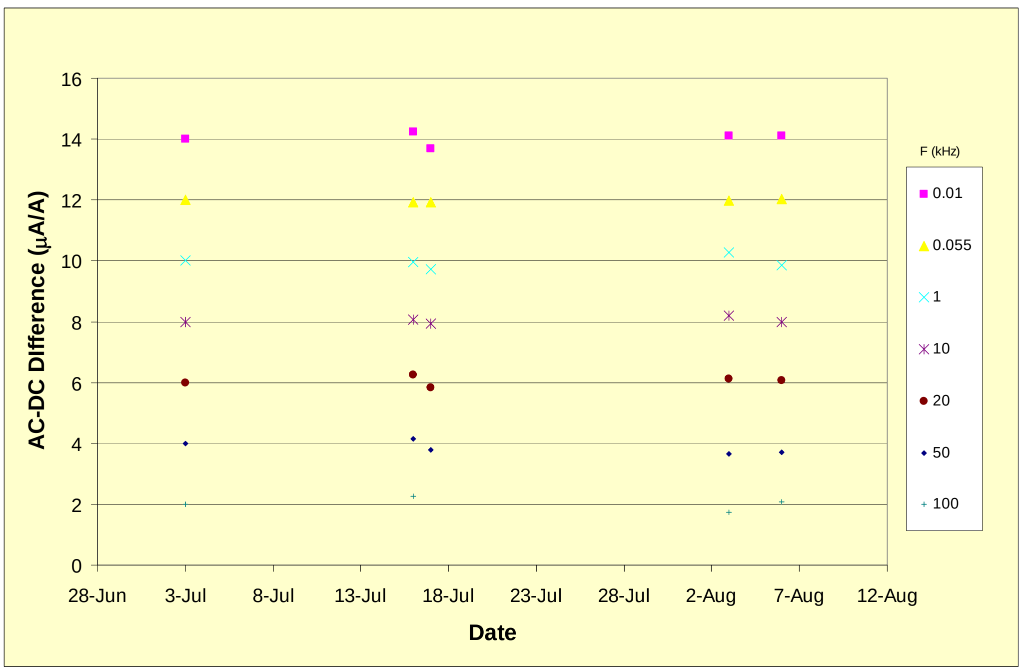


Figure 3. NMIA measurements of the 5 A transfer standard long term stability. The values on the vertical axis have been adjusted for clarity of presentation and are, therefore, not true ac-dc difference values.

On the basis of these measurements, no correction due to the long term drift of the travelling standards has been introduced into the calculations presented in Section 6.

6. Measurement results

6.1. Determination of the Reference Value

The key comparison reference value (KCRV) is based on the results of participants who have:

1. An independent realisation of primary standards for current ac-dc difference
2. The lowest reported uncertainty values.

At 10 mA, the following laboratories satisfy the above criteria: NMIA, NIST, NRC, PTB, BEV, SP, and VNIIM.

Most laboratories performed a buildup to characterise their references at 5A. The uncertainty contribution from this buildup is significantly larger than from the 10 mA reference at the starting point of the buildup. Thus, laboratories with low uncertainties at 5 A were deemed independent even if their 10 mA reference was traceable to another NMI. Therefore, the reference values at 5A were calculated using the results of, NMIA, NIST, NRC, INTI, PTB, BEV, JV (except 10 Hz), SP, NMC, and VNIIM (from 10 Hz to 10 kHz).

For each frequency, the reference value δ_{R} and its standard uncertainty u_{R} have been calculated from the results of the above laboratories as a weighted mean [1] given by:

$$\delta_{\mathrm{R}} / u^2{}_{\mathrm{R}} = \sum_i \delta_{i} / u^2{}_i \,, \tag{1}$$

where

$$1/ u^2{}_{\mathrm{R}} = \sum 1/ u^2{}_i \text{, and} \tag{2}$$

where δ_{i} and u_{i} are the ac-dc differences and uncertainties, respectively, reported by laboratory *i*.

The results submitted by the participants and the reference values are summarised in Tables 7 and 8 and, graphically, in Figures 6 and 7. The grey background in the tables indicates the results that were not included in the calculation of the KCRV.

6.2. Degree of Equivalence with the Reference Value

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

$$D_i = \delta_i - \delta_{\mathrm{R}} \tag{3}$$

For the laboratories whose results were used in the calculation of the reference value, the correlation with the reference value has been taken into account using formula (4) below to calculate the standard uncertainty $u_{i\mathrm{D}}$ of the deviation from KCDV:

$$u^2{}_{i\mathrm{D}} = u^2{}_i - u^2{}_{\mathrm{R}} \,, \tag{4}$$

where u_i are the uncertainties reported by the laboratory. For the remaining laboratories there is no such correlation. Therefore, for these laboratories,

$$u^2{}_{i\mathrm{D}} = u^2{}_i + u^2{}_{\mathrm{R}} \,. \tag{5}$$

The expanded uncertainty of the degree of equivalence has been calculated as:

$$U_{i\mathrm{D}} = k_{i\mathrm{D}} u_{i\mathrm{D}} \,, \tag{6}$$

where $k_{i\mathrm{D}}$ is the coverage factor. The coverage factor $k_{i\mathrm{D}} = 2$ has been used.

The calculated degrees of equivalence D_i with the CCEM-K12 Reference Value and expanded uncertainties (95%) U_{iD} are shown Tables 9 and 10 and, graphically, in Figures 6 and 7. The grey background in the tables indicates the results that were not included in the calculation of the reference value.

6.3. Degree of Equivalence between pairs of NMIs

The degree of equivalence between pairs of NMI results has been calculated as:

$$D_{ij} = \delta_i - \delta_j \,, \tag{7}$$

with a standard uncertainty u_{ij_D} calculated as:

$$u^2{}_{ij_D} = u^2{}_i + u^2{}_j \tag{8}$$

The expanded uncertainty U_{ij} has been calculated as:

$$U_{ij} = k_{ij_D} u_{ij\mathrm{D}} \,, \tag{9}$$

where k_{ij_D} is the coverage factor. The coverage factor $k_{ij_D} = 2$ has been used. The degrees of equivalence D_{ij} between pairs of NMIs and the associated expanded uncertainties U_{ij} are given in Appendix 1.

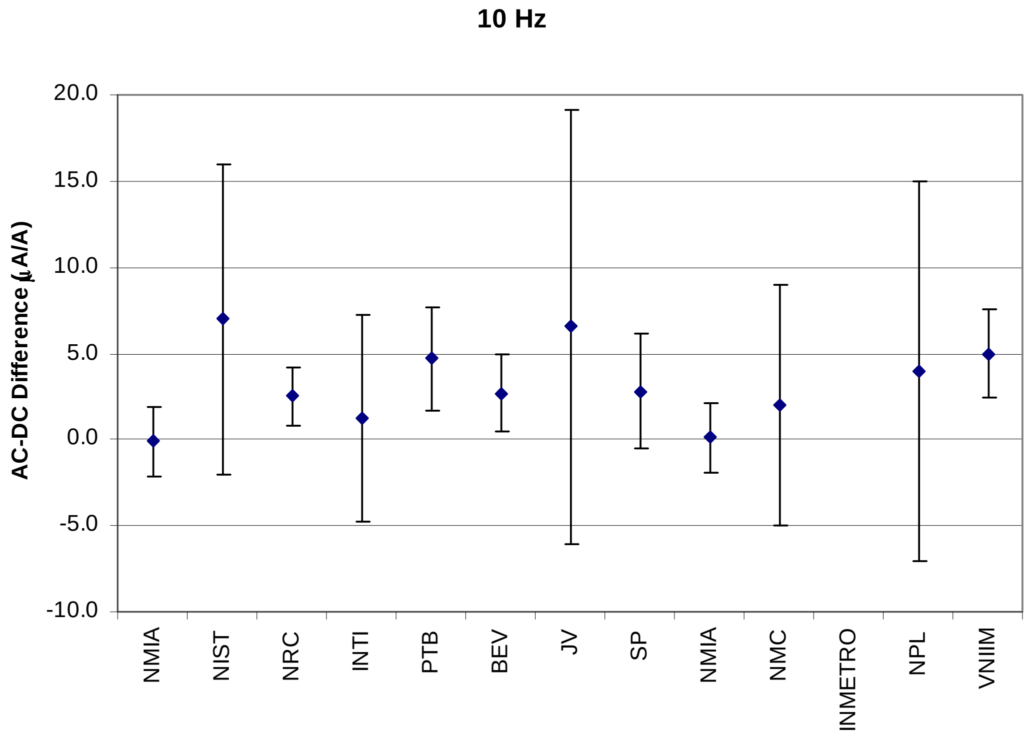
6.4. Tables and graphs of reported results

Table 7. Reported AC-DC Difference δ_i and Expanded Uncertainty (95%) U_i at 10 mA, in μA/A

Laboratory	Measurement Period	Reported Ac-dc Difference δ_i and Expanded Uncertainty (95%) U_i in μA/A													
		10 Hz		55 Hz		1 kHz		10 kHz		20 kHz		50 kHz		100 kHz	
		δ_i	U_i	δ_i	U_i	δ_i	U_i	δ_i	U_i	δ_i	U_i	δ_i	U_i	δ_i	U_i
NMIA	10/2004-2/2005	**-0.1**	2.0	**-1.1**	1.0	**-1.2**	1.0	**-1.2**	1.0	**-1.2**	1.0	**-1.3**	1.4	**-1.7**	1.8
NIST	03/2005 - 05/2005	**7.0**	9.0	**-1.0**	6.0	**-2.0**	4.0	**0.0**	4.0	**0.0**	4.0	**2.0**	7.0	**5.0**	10.0
NRC	5/2005 - 6/2005	**2.5**	1.7	**-0.9**	0.8	**-0.9**	0.8	**-1.8**	1.4	**-1.8**	1.8	**-2.1**	1.6	**-2.6**	1.6
INTI	7/2005 - 8/2005	**1.2**	6.0	**1.0**	6.0	**1.3**	3.0	**1.2**	3.0	**1.1**	5.0	**0.2**	10.0	**-1.0**	20.0
PTB	1/09/2005 - 10/2005	**4.7**	3.0	**-0.3**	3.0	**0.0**	2.0	**-0.1**	2.0	**-0.1**	2.0	**-0.4**	2.0	**-1.0**	2.0
BEV	10/2005	**2.7**	2.2	**-1.1**	2.2	**-1.0**	2.2	**-1.4**	2.2	**-1.2**	2.4	**-1.1**	2.6	**-1.4**	3.4
JV	11/2005 - 12/2005	**6.6**	12.6	**-0.5**	6.6	**-1.3**	6.6	**-1.3**	6.8	**-1.9**	8.4	**-3.0**	10.4	**-5.0**	12.5
SP	1/2006 - 2/2006	**2.8**	3.3	**-1.0**	2.2	**-1.2**	1.6	**-1.4**	2.0	**-1.1**	2.1	**-1.2**	2.5	**-1.6**	3.4
NMIA	3/2006 - 5/2006	**0.1**	2.0	**-1.1**	1.0	**-1.3**	1.0	**-1.4**	1.0	**-1.5**	1.0	**-1.6**	1.4	**-1.8**	1.8
NMC	6/2006 - 7/2006	**2.0**	7.0	**-2.0**	7.0	**-2.0**	7.0	**-2.0**	7.0	**-2.0**	7.0	**-1.0**	7.0	**0.0**	12.0
INMETRO	8/2006 - 9/2006			**-14.0**	27.0	**-14.0**	27.0	**-12.0**	36.0						
NPL	9/2006 - 1/2007	**4.0**	11.0	**-2.0**	11.0	**-1.0**	11.0	**-1.0**	13.0	**-2.0**	14.0	**0.0**	15.0	**1.0**	22.0
VNIIM	3/2007 - 4/2007	**5.0**	2.6	**2.0**	2.8	**-0.8**	2.4	**-1.0**	2.6	**-1.1**	2.6	**-1.3**	2.6	**-1.7**	2.6
NMIA Mean		**0.0**	2.0	**-1.1**	1.0	**-1.3**	1.0	**-1.3**	1.0	**-1.4**	1.0	**-1.5**	1.4	**-1.8**	1.8
KCRV		**2.6**	0.9	**-0.8**	0.6	**-1.0**	0.5	**-1.2**	0.6	**-1.2**	0.7	**-1.3**	0.8	**-1.8**	0.9

Table 8. Reported AC-DC Difference δ_i and Expanded Uncertainty (95%) U_i at 5 A, in μA/A

Laboratory	Measurement Period	10 Hz		55 Hz		1 kHz		10 kHz		20 kHz		50 kHz		100 kHz	
		δ_i	U_i	δ_i	U_i	δ_i	U_i	δ_i	U_i	δ_i	U_i	δ_i	U_i	δ_i	U_i
NMIA	10/2004-2/2005	**-0.6**	4.5	**0.4**	4.1	**0.8**	4.1	**-1.3**	4.2	**-8.3**	4.5	**-37.1**	8.0	**-70.5**	12.0
NIST	03/2005 - 05/2005	**3.0**	19.0	**4.0**	18.0	**3.0**	17.0	**6.0**	17.0	**-8.0**	21.0	**-33.0**	27.0	**-91.0**	33.0
NRC	5/2005 - 6/2005	**-0.1**	15.0	**-0.2**	14.0	**-0.6**	14.0	**-3.1**	15.0	**-8.2**	15.0	**-35.6**	20.0	**-76.6**	31.0
INTI	7/2005 - 8/2005	**1.2**	8.0	**-1.2**	7.0	**3.4**	5.0	**-2.1**	7.0	**-7.7**	8.0	**-31.1**	13.0	**-65.2**	22.0
PTB	1/09/2005 - 10/2005	**0.0**	6.0	**0.0**	4.0	**0.0**	4.0	**-4.0**	5.0	**-11.0**	7.0	**-36.0**	9.0	**-66.0**	11.0
BEV	10/2005	**0.5**	2.0	**0.0**	2.0	**0.0**	2.0	**-3.2**	9.0	**-9.0**	9.0	**-32.9**	9.6	**-59.1**	12.6
JV	11/2005 - 12/2005	**5.0**	44.6	**1.8**	13.2	**-0.5**	10.6	**-3.6**	11.0	**-10.4**	18.4	**-36.5**	25.2	**-68.8**	38.4
SP	1/2006 - 2/2006	**-0.5**	4.9	**-0.7**	4.2	**-0.9**	3.9	**-1.4**	4.3	**-6.7**	5.1	**-31.0**	10.0	**-56.0**	15.0
NMIA	3/2006 - 5/2006	**-0.8**	4.5	**0.0**	4.1	**0.4**	4.1	**-2.2**	4.2	**-10.3**	4.5	**-37.8**	8.0	**-69.9**	12.0
NMC	6/2006 - 7/2006	**-2.0**	25.0	**-1.0**	25.0	**-2.0**	25.0	**-3.0**	25.0	**-8.8**	25.0	**-36.7**	25.0	**-70.1**	44.0
INMETRO	8/2006 - 9/2006			**-1.0**	91.0	**24.0**	91.0	**118.0**	96.0						
NPL	9/2006 - 1/2007	**-26.0**	56.0	**8.0**	25.0	**-2.0**	24.0	**-9.0**	22.0	**-10.0**	53.0	**-56.0**	84.0	**-80.0**	166.0
VNIIM	3/2007 - 4/2007	**-2.0**	4.0	**-2.4**	4.0	**2.0**	3.4	**2.8**	3.2						
NMIA Mean		**-0.7**	4.5	**0.2**	4.1	**0.6**	4.1	**-1.8**	4.2	**-9.3**	4.5	**-37.5**	8.0	**-70.2**	12.0
KCRV		**-0.1**	1.5	**-0.3**	1.4	**0.5**	1.3	**-0.6**	1.8	**-8.6**	2.6	**-34.5**	4.0	**-65.3**	5.7



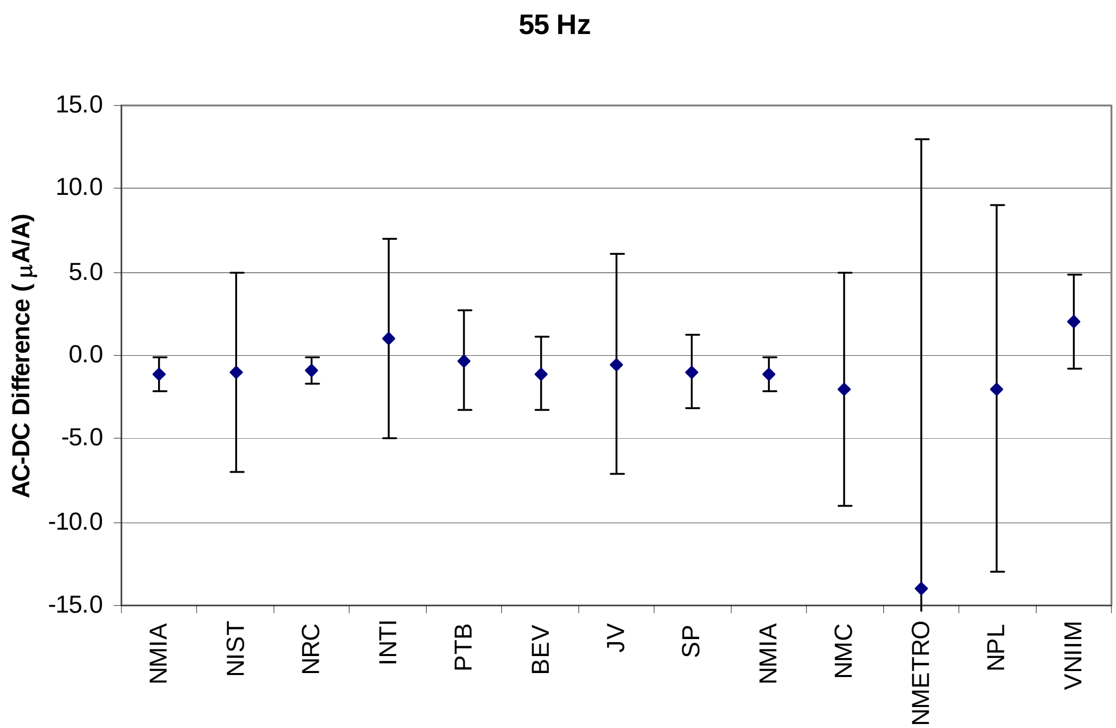
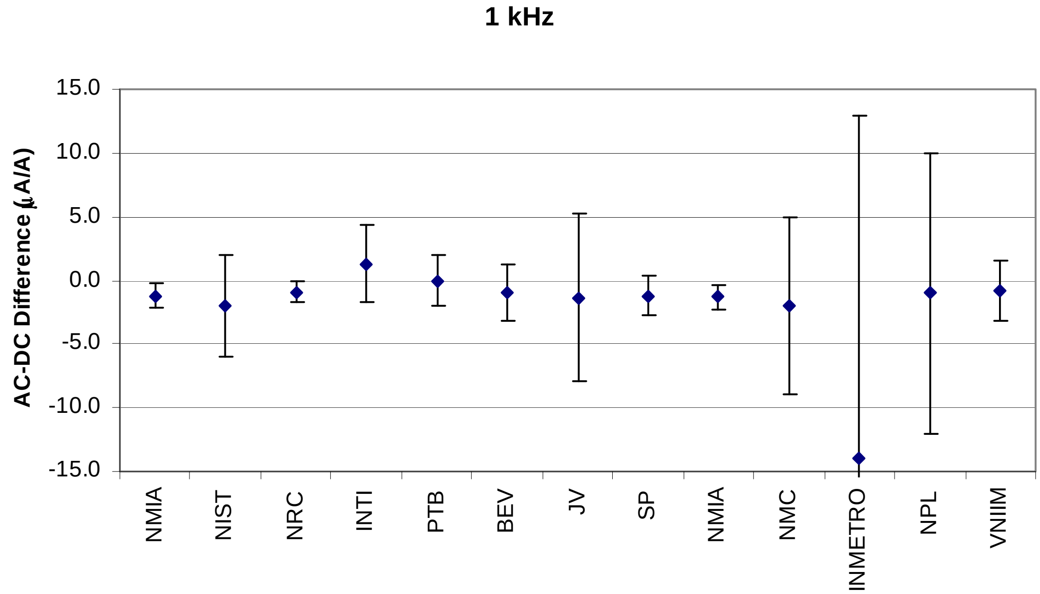


Figure 4. Reported AC-DC Difference δ_i and Expanded Uncertainty (95%) U_i at 10 mA, in μA/A



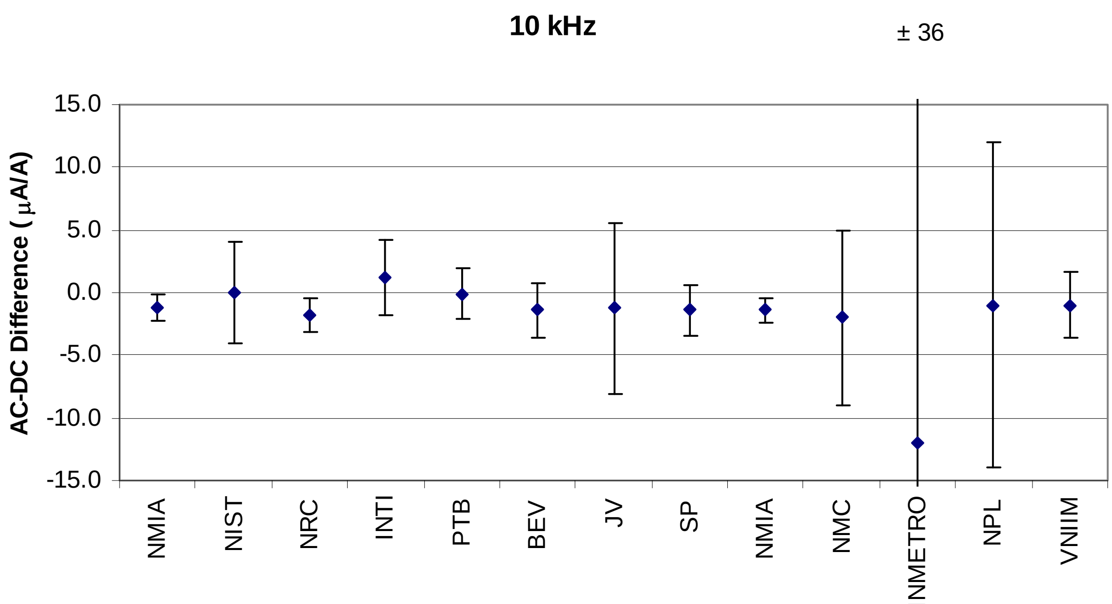
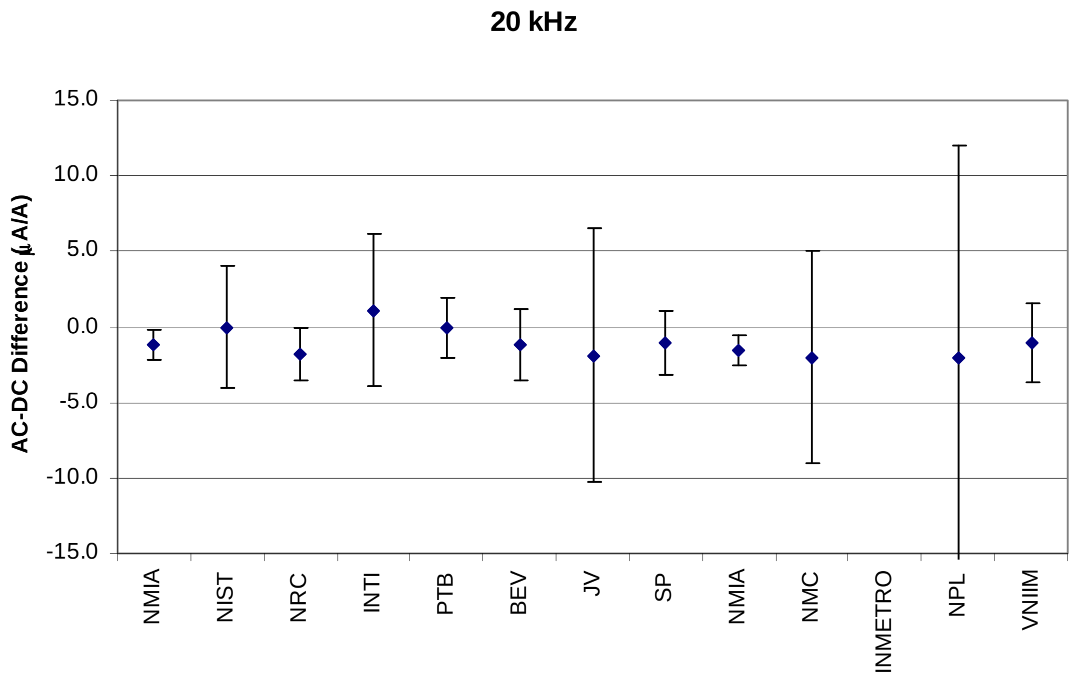


Figure 4. Reported AC-DC Difference δ_i and Expanded Uncertainty (95%) U_i at 10 mA, in μA/A (continued).



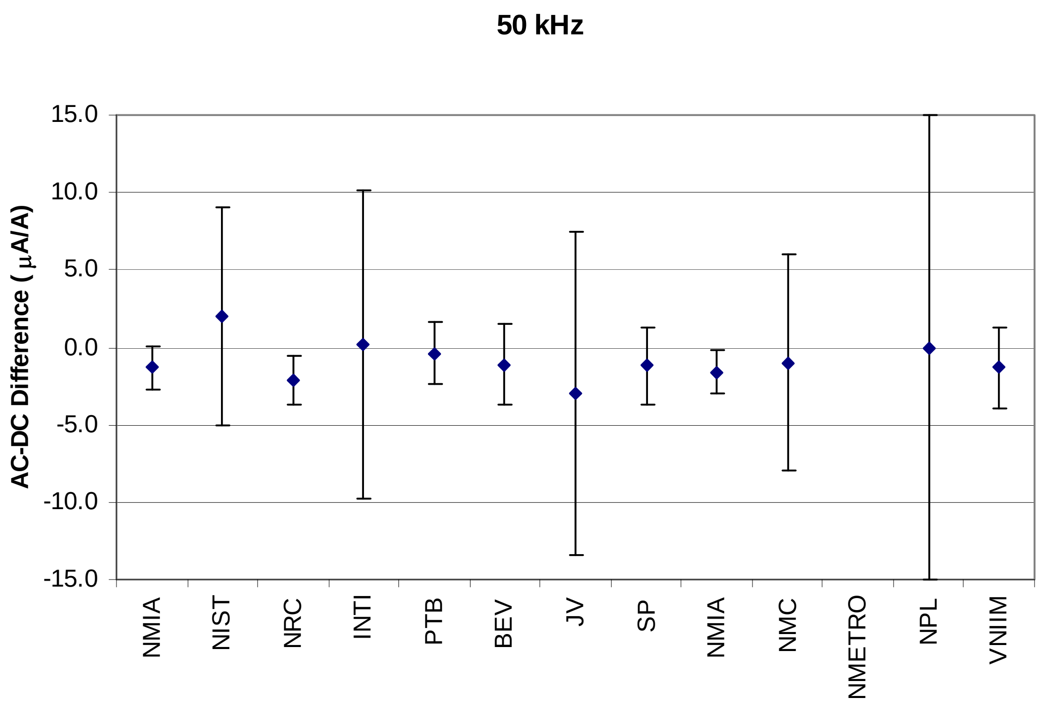


Figure 4. Reported AC-DC Difference δ_i and Expanded Uncertainty (95%) U_i at 10 mA, in μA/A (continued).

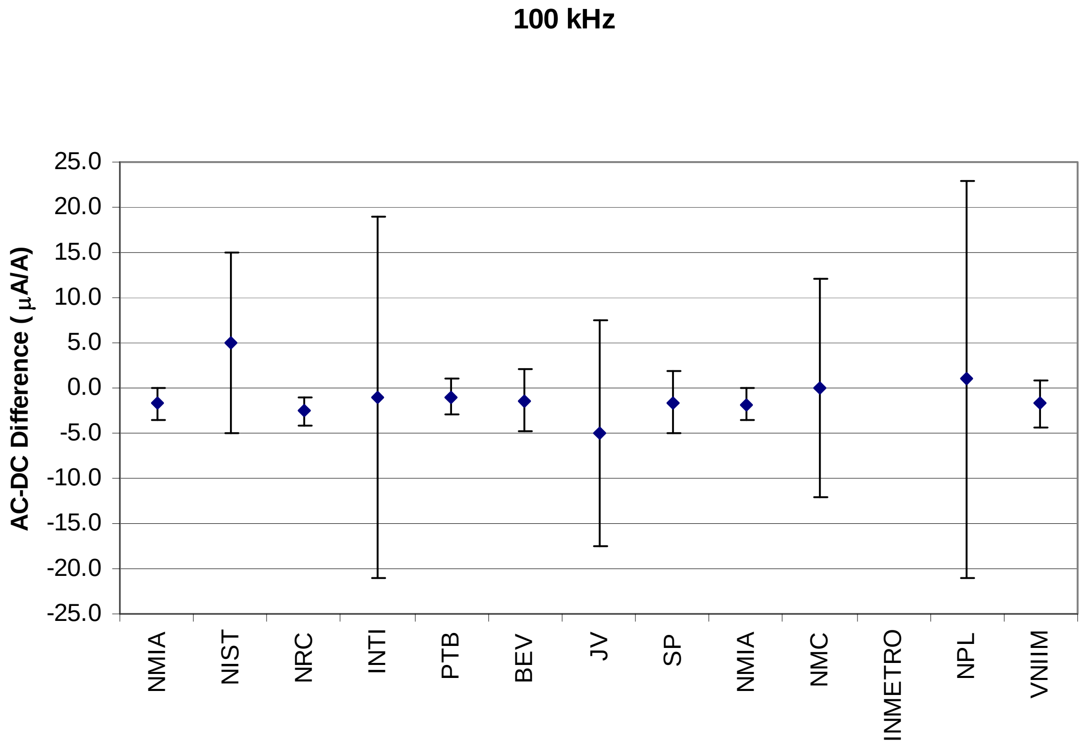


Figure 4. Reported AC-DC Difference δ_i and Expanded Uncertainty (95%) U_i at 10 mA, in μA/A (continued).

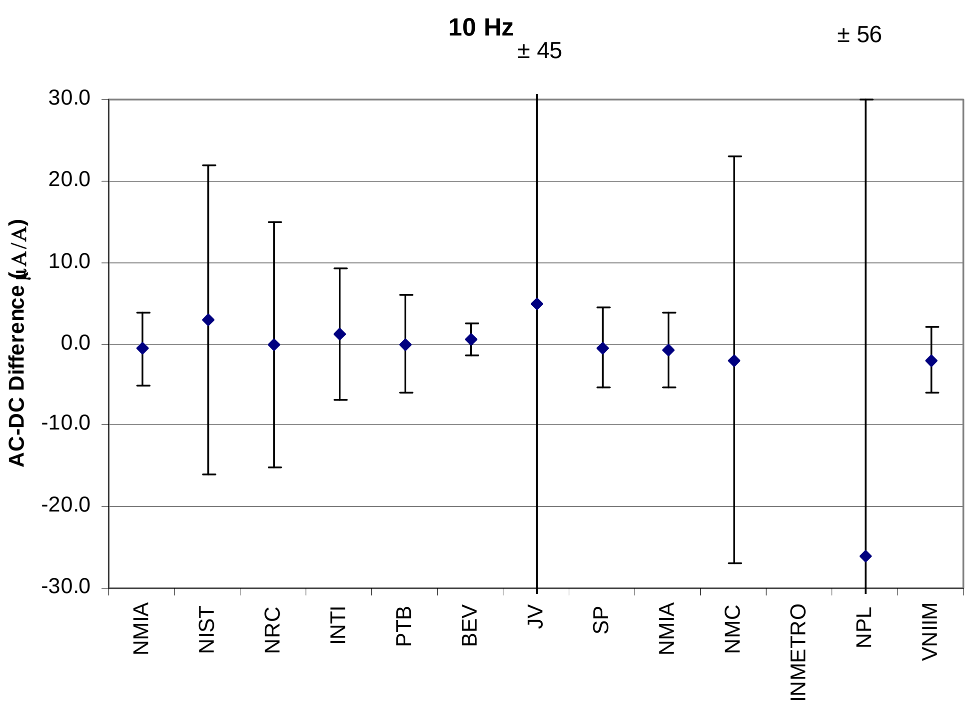


Figure 5. Reported AC-DC Difference δ_i and Expanded Uncertainty (95%) U_i at 5 A, in μA/A

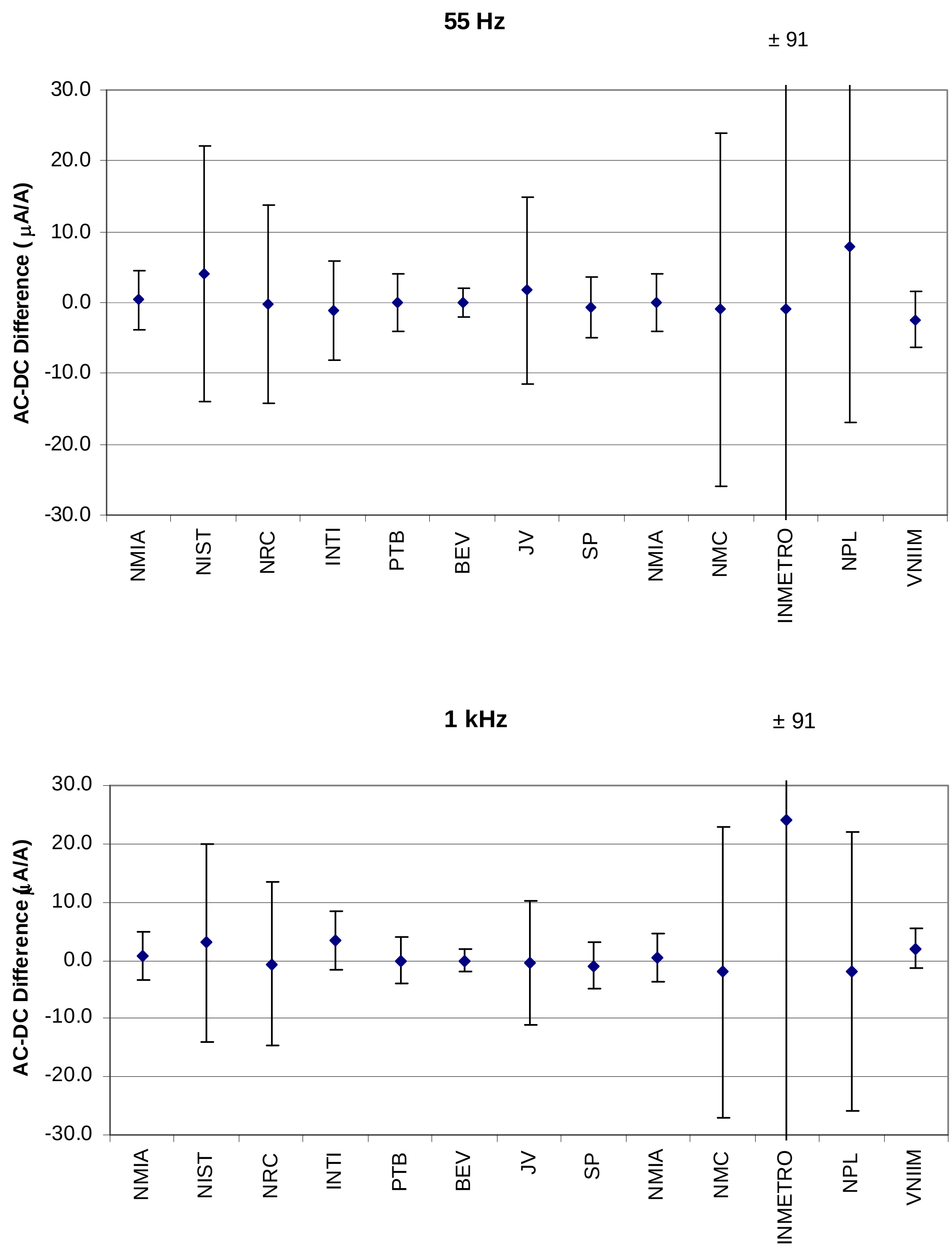
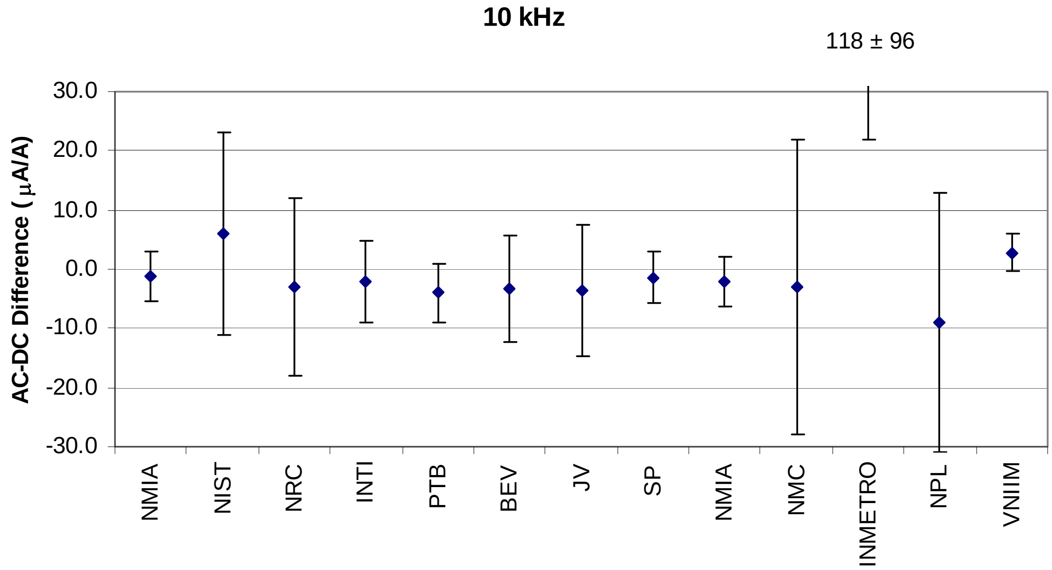


Figure 5. Reported AC-DC Difference δ_i and Expanded Uncertainty (95%) U_i at 5 A, in μA/A (continued).



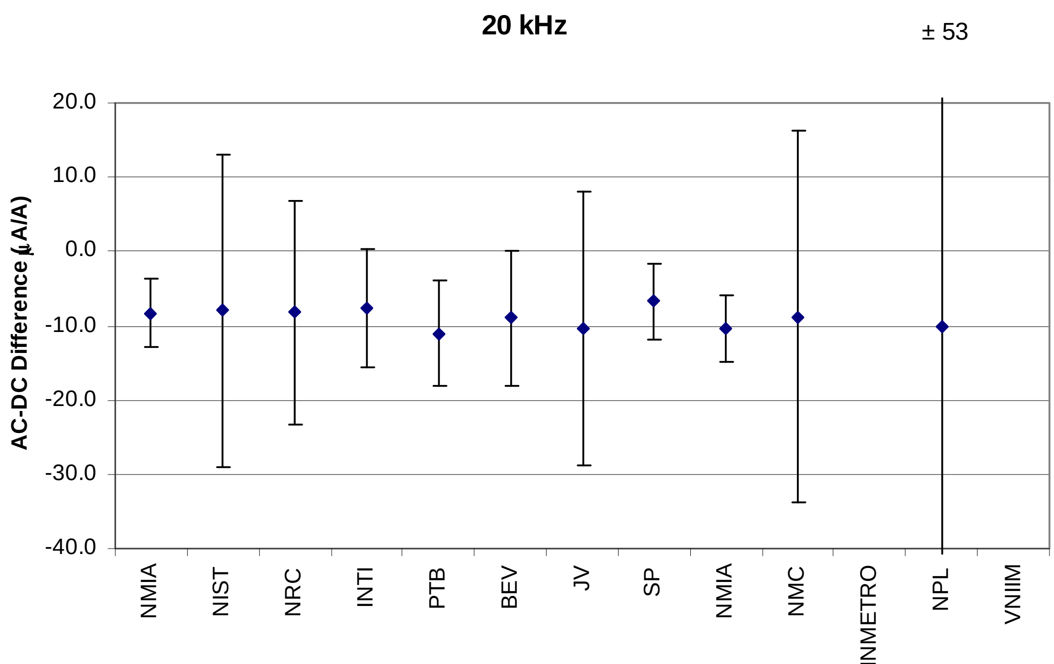
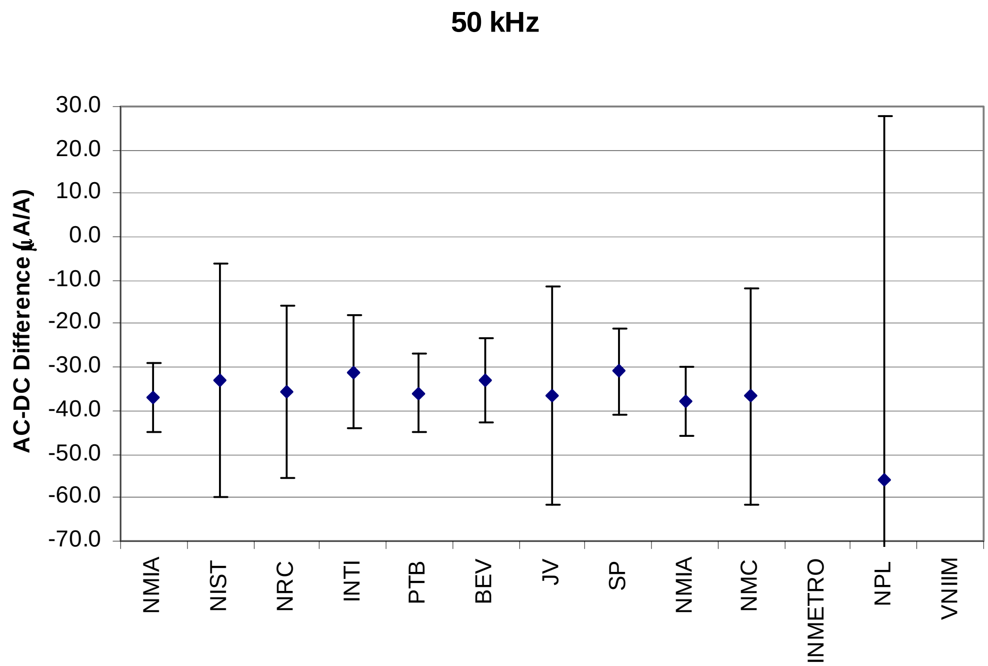


Figure 5. Reported AC-DC Difference δ_i and Expanded Uncertainty (95%) U_i at 5 A, in μA/A (continued).



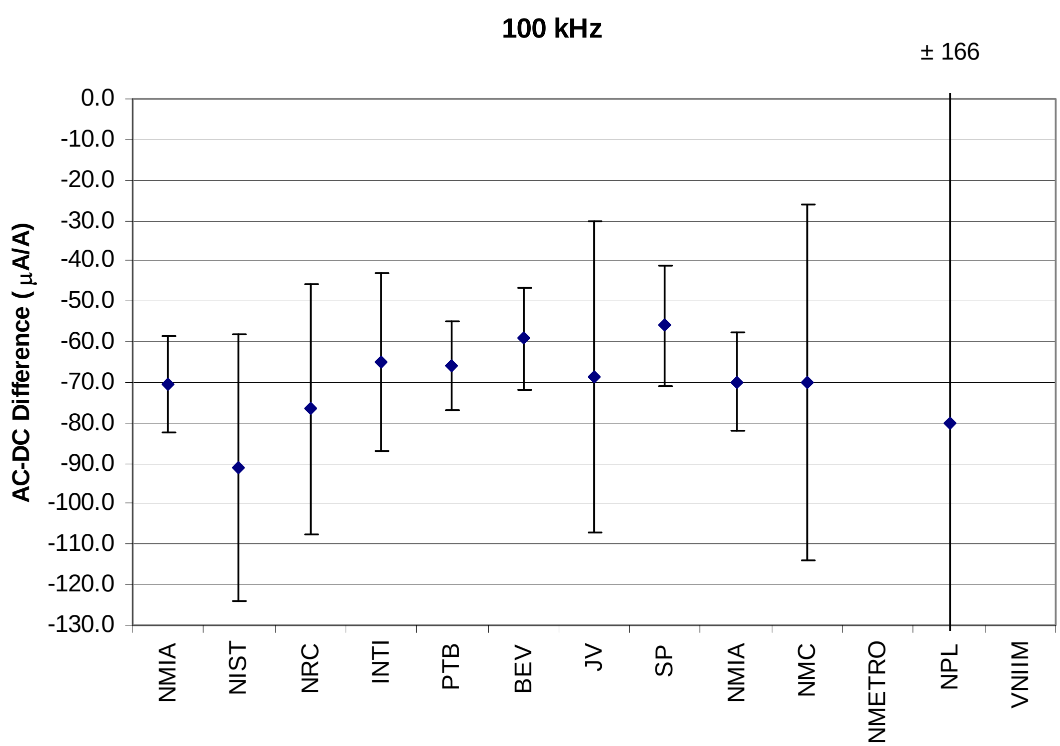


Figure 5. Reported AC-DC Difference δ_i and Expanded Uncertainty (95%) U_i at 5 A, in μA/A (continued).

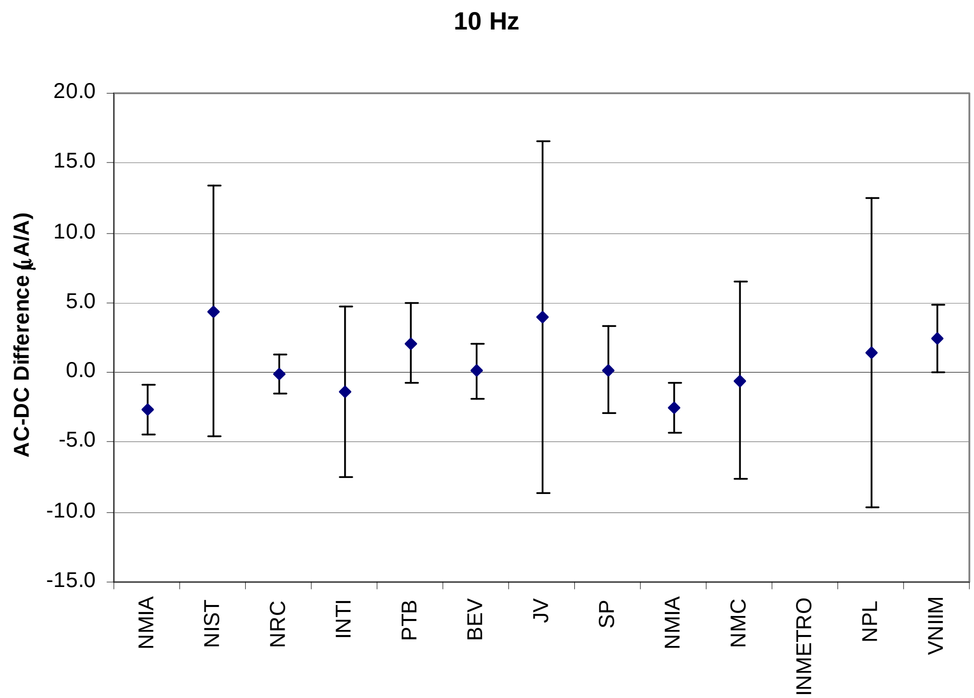
6.5. Tables and Graphs of Degrees of Equivalence with the Reference Value

Table 9. Degrees of Equivalence D_i and Expanded Uncertainty (95%) U_{iD} at 10 mA, in μA/A

Laboratory	Degrees of Equivalence with the CEEM-K12 Reference Value D_i and Expanded Uncertainty (95%) U_{iD} in μA/A													
	10 Hz		55 Hz		1 kHz		10 kHz		20 kHz		50 kHz		100 kHz	
	D_i	U_{iD}	D_i	U_{iD}	D_i	U_{iD}	D_i	U_{iD}	D_i	U_{iD}	D_i	U_{iD}	D_i	U_{iD}
NMIA	**-2.6**	1.8	**-0.3**	0.8	**-0.3**	0.9	**-0.1**	0.8	**-0.2**	0.7	**-0.1**	1.2	**0.0**	1.6
NIST	**4.4**	9.0	**-0.2**	6.0	**-1.0**	4.0	**1.2**	3.9	**1.2**	3.9	**3.3**	7.0	**6.8**	10.0
NRC	**-0.1**	1.4	**-0.1**	0.6	**0.1**	0.6	**-0.6**	1.2	**-0.6**	1.7	**-0.8**	1.4	**-0.8**	1.3
INTI	**-1.4**	6.1	**1.8**	6.0	**2.3**	3.0	**2.4**	3.1	**2.3**	5.0	**1.5**	10.0	**0.8**	20.0
PTB	**2.1**	2.9	**0.5**	2.9	**1.0**	1.9	**1.1**	1.9	**1.1**	1.9	**0.9**	1.8	**0.8**	1.8
BEV	**0.1**	2.0	**-0.3**	2.1	**0.0**	2.1	**-0.2**	2.1	**0.0**	2.3	**0.2**	2.5	**0.4**	3.3
JV	**4.0**	12.6	**0.3**	6.6	**-0.4**	6.6	**0.0**	6.8	**-0.7**	8.4	**-1.7**	10.4	**-3.2**	12.5
SP	**0.2**	3.2	**-0.2**	2.1	**-0.2**	1.5	**-0.2**	1.9	**0.1**	2.0	**0.1**	2.4	**0.2**	3.3
NMIA	**-2.5**	1.8	**-0.3**	0.8	**-0.3**	0.9	**-0.2**	0.8	**-0.3**	0.7	**-0.3**	1.2	**0.0**	1.6
NMC	**-0.6**	7.1	**-1.2**	7.0	**-1.0**	7.0	**-0.8**	7.0	**-0.8**	7.0	**0.3**	7.0	**1.8**	12.0
INMETRO			**-13.2**	27.0	**-13.0**	27.0	**-10.8**	36.0						
NPL	**1.4**	11.0	**-1.2**	11.0	**0.0**	11.0	**0.2**	13.0	**-0.8**	14.0	**1.3**	15.0	**2.8**	22.0
VNIIM	**2.4**	2.4	**2.8**	2.7	**0.2**	2.3	**0.2**	2.5	**0.1**	2.5	**0.0**	2.5	**0.1**	2.4

Table 10. Degrees of Equivalence D_i and Expanded Uncertainty (95%) U_{iD} at 5 A, in μA/A

Laboratory	Degrees of Equivalence with the CEEM-K12 Reference Value D_i and Expanded Uncertainty (95%) U_{iD} in μA/A													
	10 Hz		55 Hz		1 kHz		10 kHz		20 kHz		50 kHz		100 kHz	
	D_i	U_{iD}	D_i	U_{iD}	D_i	U_{iD}	D_i	U_{iD}	D_i	U_{iD}	D_i	U_{iD}	D_i	U_{iD}
NMIA	**-0.6**	4.2	**0.5**	3.9	**0.1**	3.9	**-1.2**	3.8	**-0.7**	3.7	**-3.0**	6.9	**-4.9**	10.6
NIST	**3.1**	18.9	**4.3**	17.9	**2.5**	16.9	**6.6**	16.9	**0.6**	20.8	**1.5**	26.7	**-25.7**	32.5
NRC	**0.0**	14.9	**0.1**	13.9	**-1.1**	13.9	**-2.5**	14.9	**0.4**	14.8	**-1.1**	19.6	**-11.3**	30.5
INTI	**1.3**	7.9	**-0.9**	6.9	**2.9**	4.8	**-1.5**	6.8	**0.9**	7.6	**3.4**	12.4	**0.1**	21.3
PTB	**0.1**	5.8	**0.3**	3.8	**-0.5**	3.8	**-3.4**	4.7	**-2.4**	6.5	**-1.5**	8.1	**-0.7**	9.4
BEV	**0.6**	1.3	**0.3**	1.5	**-0.5**	1.5	**-2.6**	8.8	**-0.4**	8.6	**1.6**	8.7	**6.2**	11.3
JV	**5.1**	44.6	**2.1**	13.3	**-1.0**	10.7	**-3.0**	11.2	**-1.8**	18.6	**-2.0**	25.5	**-3.5**	38.8
SP	**-0.4**	4.7	**-0.4**	4.0	**-1.4**	3.7	**-0.8**	3.9	**1.9**	4.4	**3.5**	9.2	**9.3**	13.9
NMIA	**-0.7**	4.2	**0.4**	3.9	**-0.1**	3.9	**-1.6**	3.8	**-1.7**	3.7	**-3.3**	6.9	**-4.6**	10.6
NMC	**-1.9**	25.0	**-0.7**	25.0	**-2.5**	25.0	**-2.4**	24.9	**-0.2**	24.9	**-2.2**	24.7	**-4.9**	43.6
INMETRO			**-0.7**	91.0	**23.5**	91.0	**118.6**	96.0						
NPL	**-25.9**	56.0	**8.3**	25.0	**-2.5**	24.0	**-8.4**	22.1	**-1.4**	53.1	**-21.5**	84.1	**-14.7**	166.1
VNIIM	**-1.9**	3.7	**-2.1**	3.8	**1.5**	3.1	**3.4**	2.6						



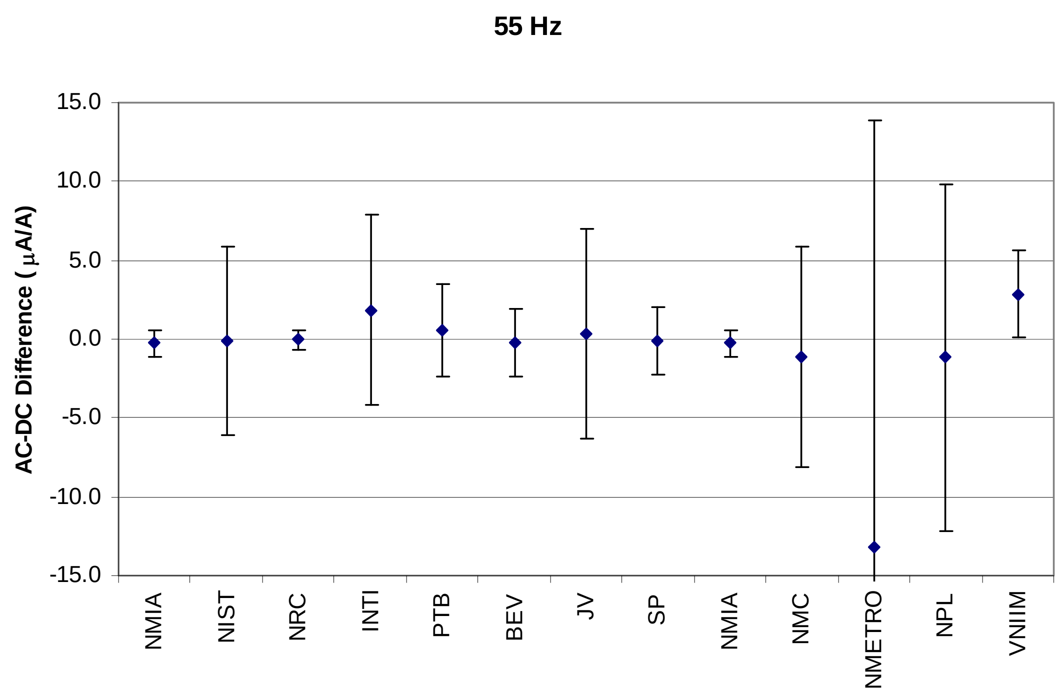
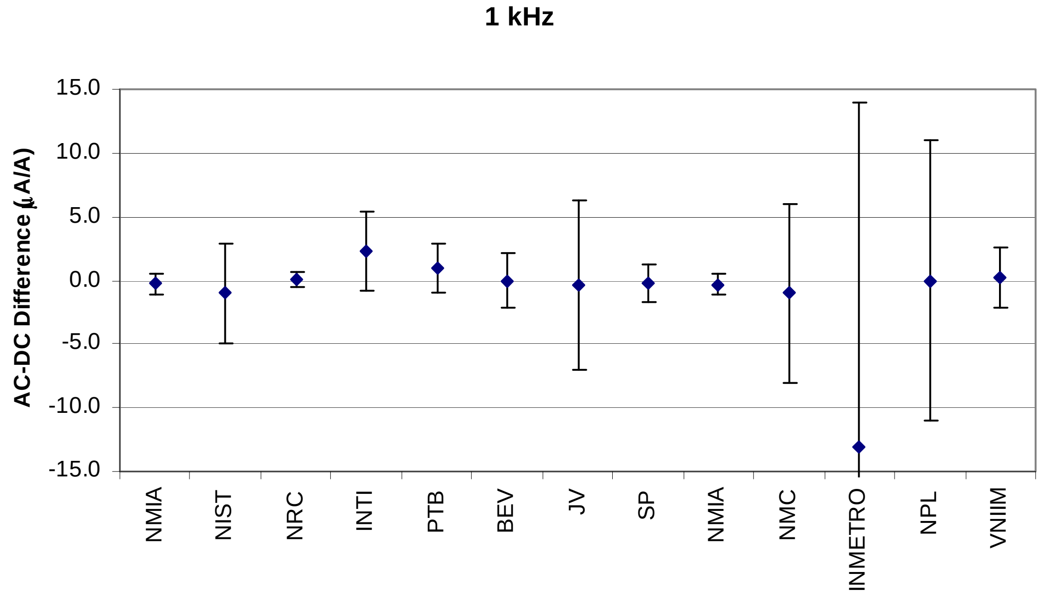


Figure 6. Degrees of Equivalence with the Reference Value D_i and Expanded Uncertainty (95%) $U_{i\mathrm{D}}$ at 10 mA, in μA/A .



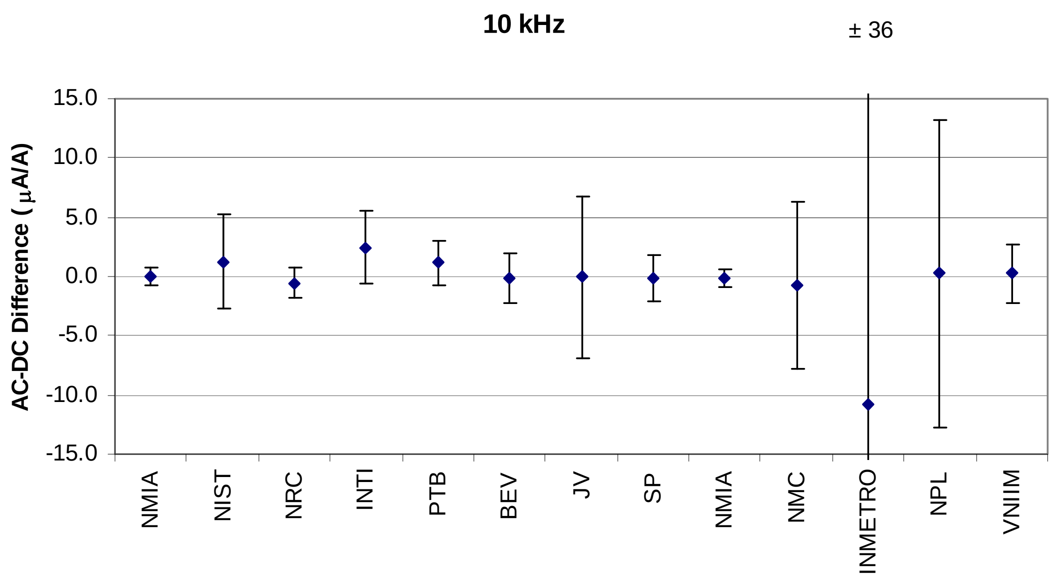
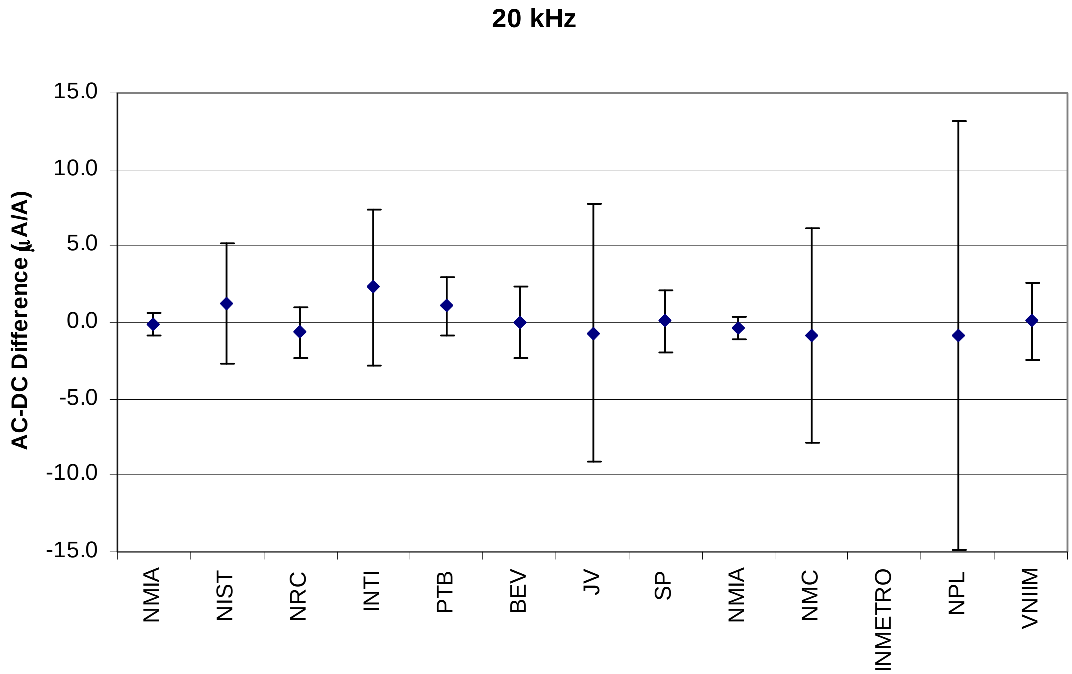


Figure 6. Degrees of Equivalence with the Reference Value D_i and Expanded Uncertainty (95%) U_{iD} at 10 mA, in μA/A (continued).



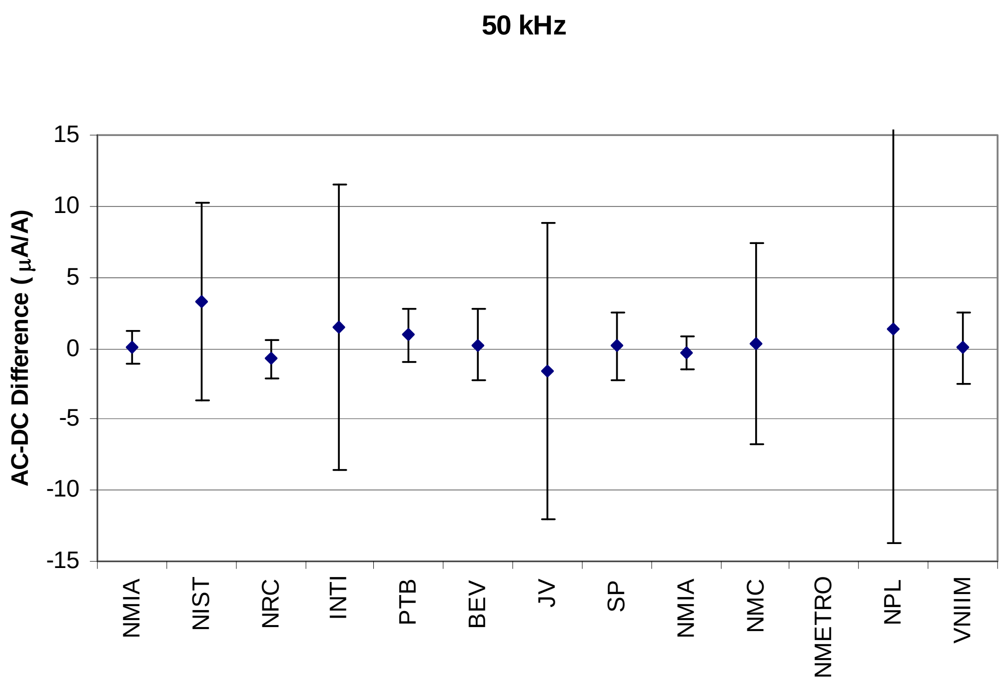


Figure 6. Degrees of Equivalence with the Reference Value D_i and Expanded Uncertainty (95%) $U_{i\mathrm{D}}$ at 10 mA, in μA/A (continued).

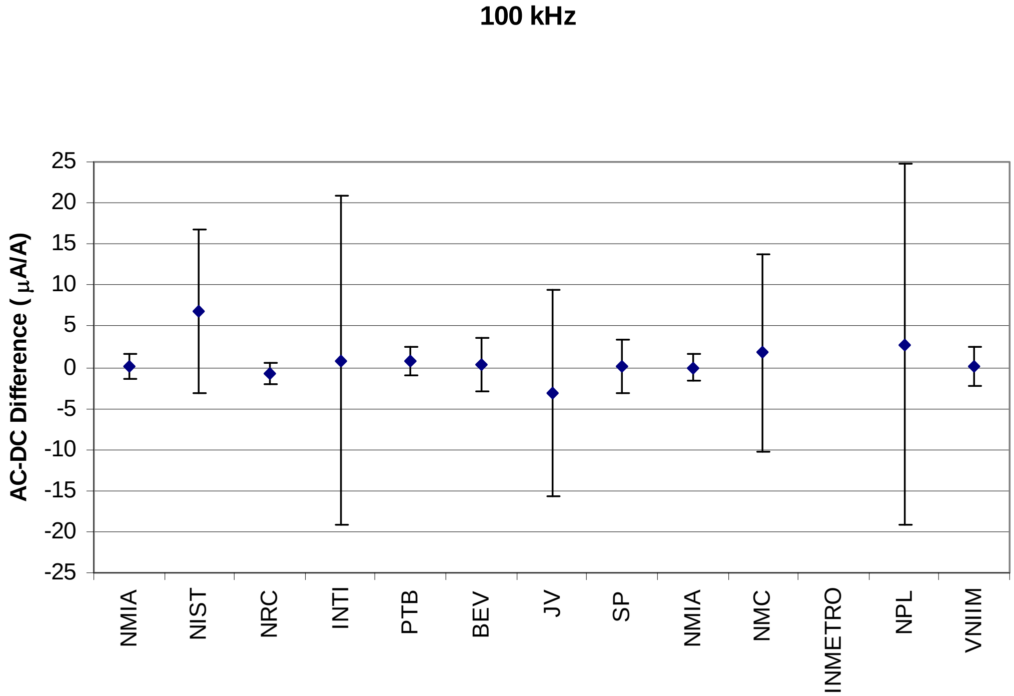


Figure 6. Degrees of Equivalence with the Reference Value D_i and Expanded Uncertainty (95%) U_{iD} at 10 mA, in μA/A (continued).

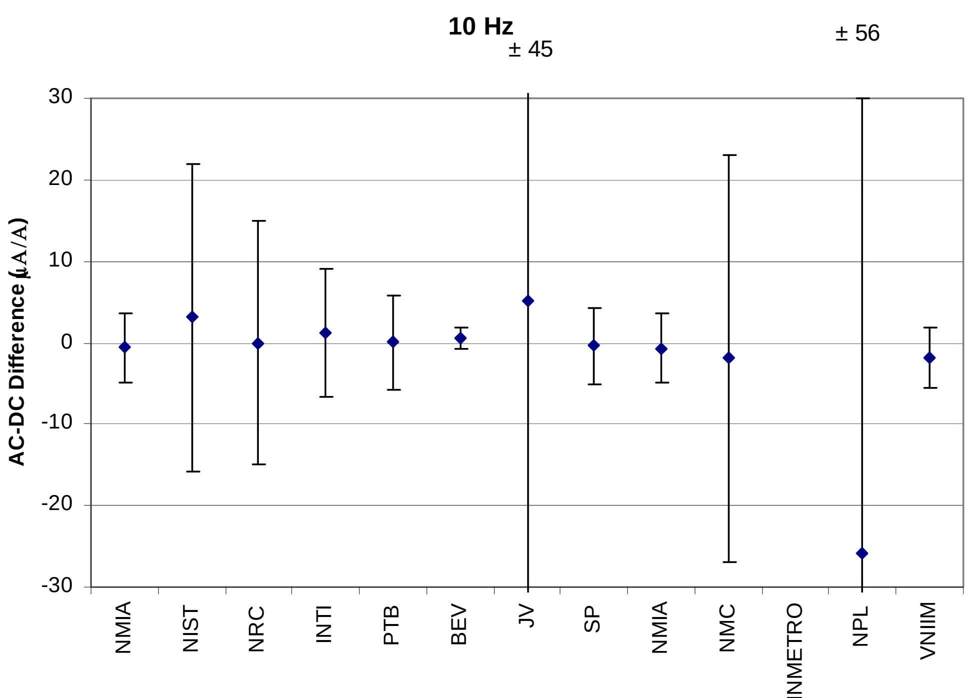
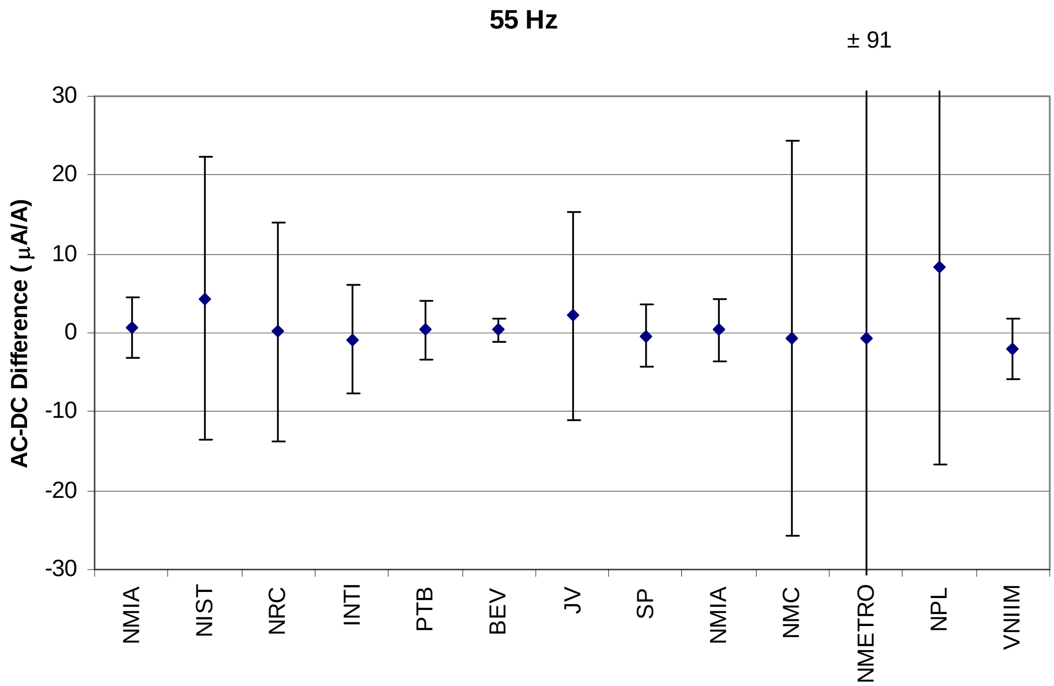


Figure 7. Degrees of Equivalence with the Reference Value D_i and Expanded Uncertainty (95%) U_{iD} at 5 A, in μA/A.



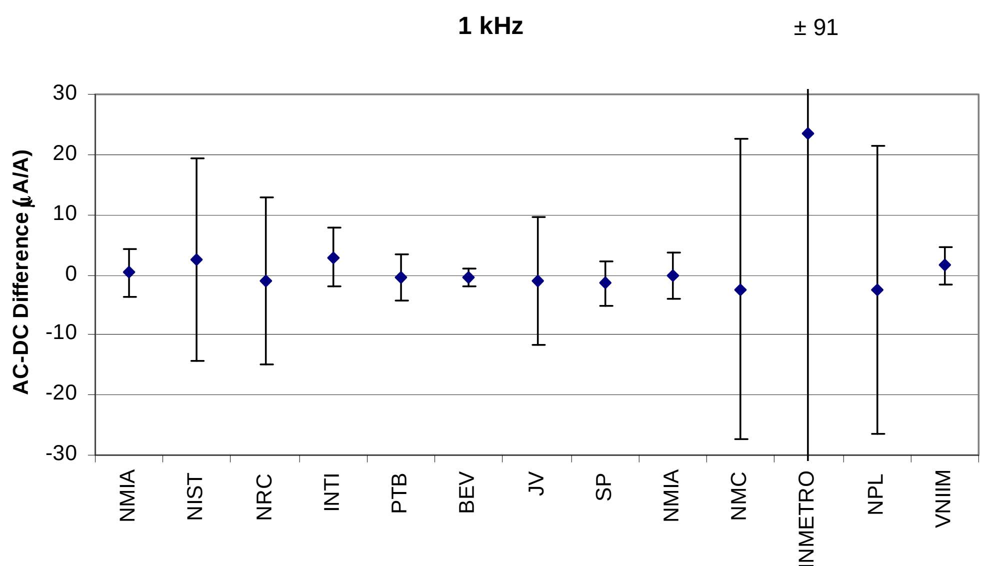
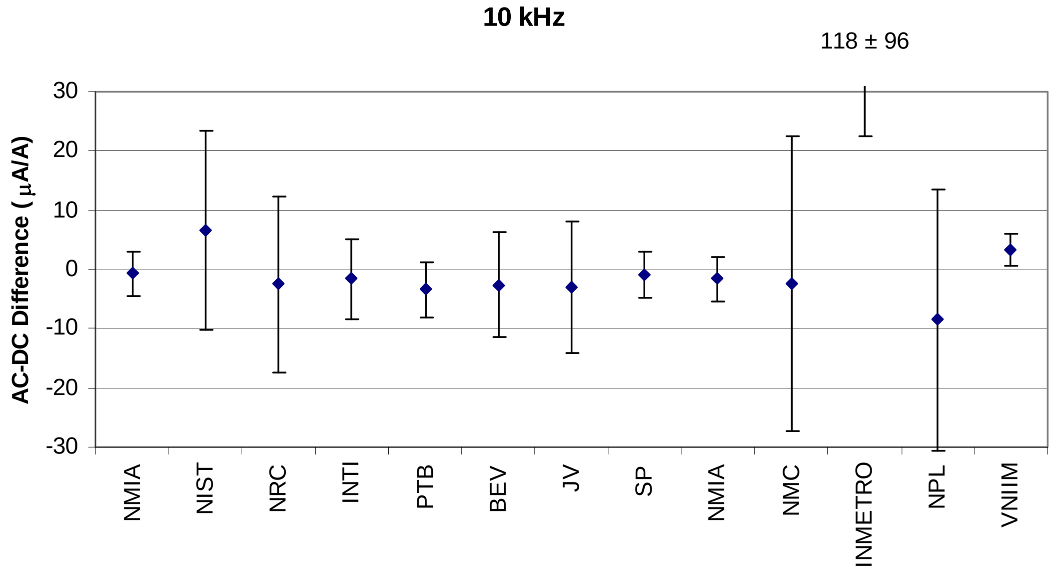


Figure 7. Degrees of Equivalence with the Reference Value D_i and Expanded Uncertainty (95%) $U_{i\mathrm{D}}$ at 5 A, in μA/A (continued).



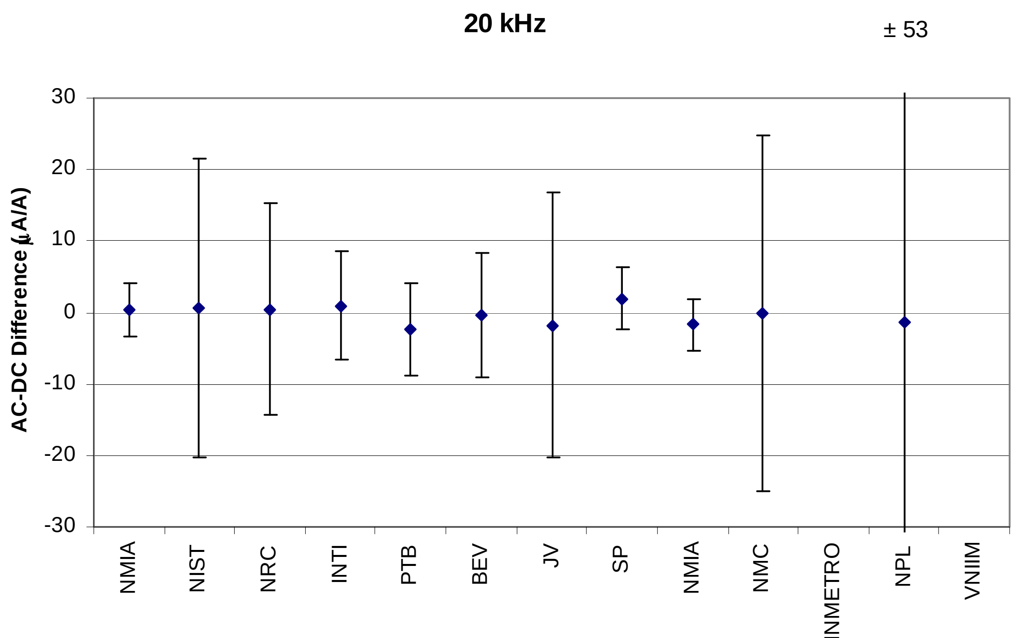
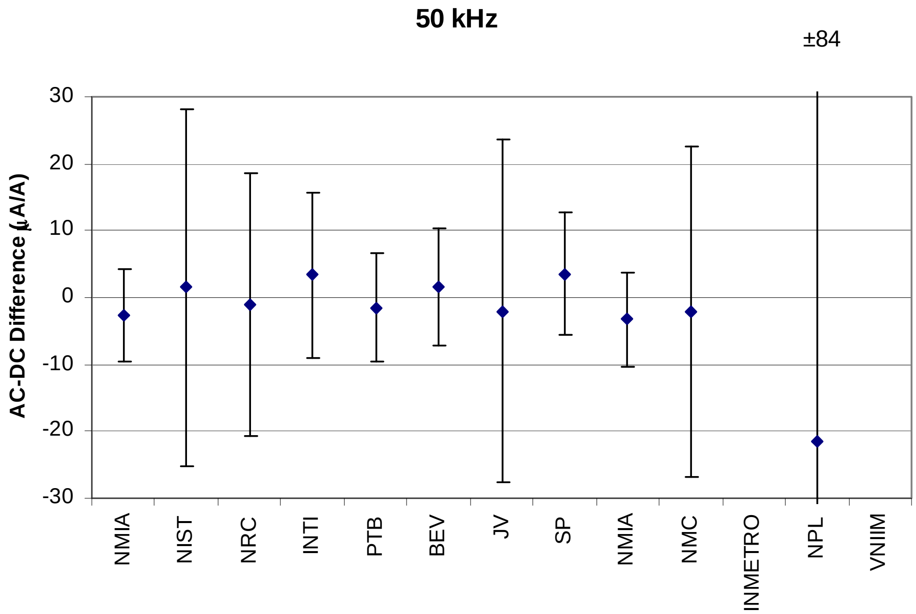


Figure 7. Degrees of Equivalence with the Reference Value D_i and Expanded Uncertainty (95%) $U_{i\mathrm{D}}$ at 5 A, in μA/A (continued).



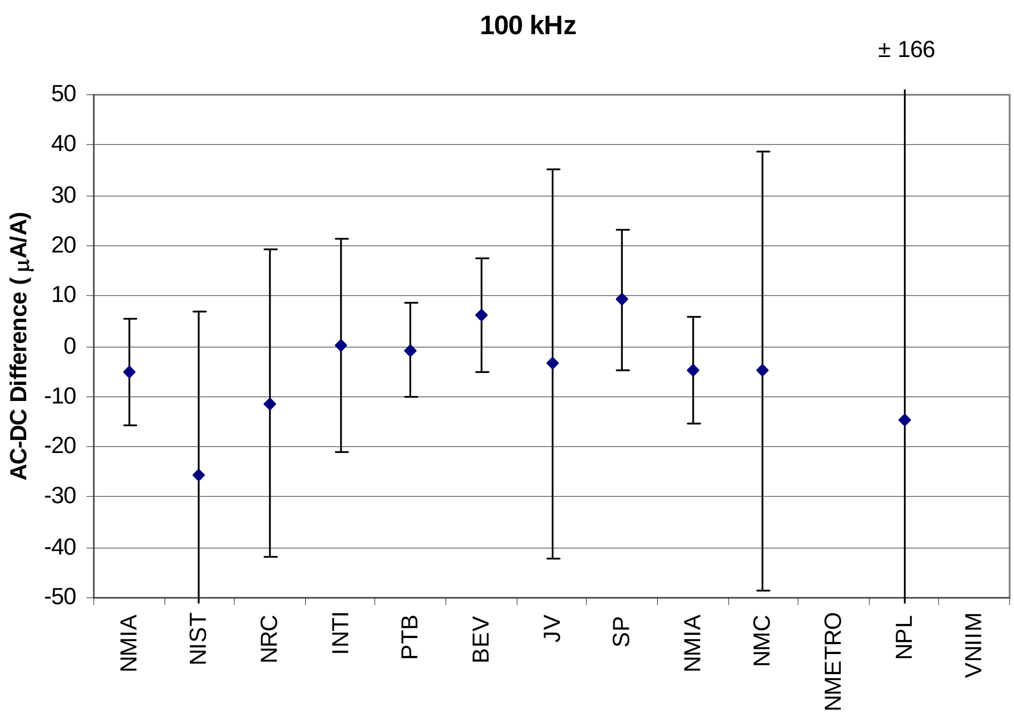


Figure 7. Degrees of Equivalence with the Reference Value D_i and Expanded Uncertainty (95%) $U_{i\mathrm{D}}$ at 5 A, in μA/A (continued).

7. Withdrawals and corrections

One NMI found a calculation error in its 5 A, 10 Hz result which was corrected at the Report A stage.

8. Follow-up comparisons

No bilateral follow-up comparisons have been requested, however most Regional Metrology Organisations (RMOs) are expected to run a regional key comparison with results linked to those presented in this report.

9. Summary and conclusions

The circulation of the travelling standards in the CIPM key comparison CCEM-K12 of ac-dc current transfer difference began in March 2005 and was completed in April 2007. The travelling standards were lost on their way from the last participant to the pilot laboratory. Since, prior to their disappearance, the travelling standards exhibited exceptional stability, the CCEM working group on low-frequencies decided in June 2008 to accept the results of the comparison as valid without the final measurement by the pilot laboratory.

The ac-dc transfer differences of the travelling standards have been measured at 10 mA and 5 A and at the frequencies 10 Hz, 55 Hz, 1 kHz, 10 kHz, 20 kHz, 50 kHz, 100 kHz. The key comparison reference values (KCRV) were calculated as the weighted mean of the results of the NMIs with independent realisations of primary standards and low reported uncertainties. The degrees of equivalence with the KCRV and between pairs of NMIs have been determined for the measurement points and show very good agreement. All but three of the calculated degrees of equivalence with the KCRV are within the limits of the expanded uncertainties.

10. References

[1] C.F. Dietrich, Uncertainty, Calibration and Probability, Adam Hilger, Bristol, UK, 1991

Appendix 1: Degrees of equivalence between pairs of NMIs

Table 1. Degrees of equivalence 10 mA, 10 Hz

	NMIA		NIST		NRC		INTI		PTB		BEV		JV		SP		NMC		NPL		VNIIM	
	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
NMIA			-7.0	9.1	-2.5	2.3	-1.2	6.3	-4.7	3.4	-2.7	2.7	-6.6	12.8	-2.8	3.6	-2.0	7.3	-4.0	11.2	-5.0	3.0
NIST	7.0	9.1			4.5	9.1	5.8	10.8	2.3	9.4	4.3	9.2	0.4	15.5	4.2	9.5	5.0	11.4	3.0	14.2	2.0	9.3
NRC	2.5	2.3	-4.5	9.1			1.3	6.2	-2.2	3.2	-0.2	2.5	-4.1	12.7	-0.3	3.5	0.5	7.2	-1.5	11.1	-2.5	2.8
INTI	1.2	6.3	-5.8	10.8	-1.3	6.2			-3.5	6.7	-1.5	6.4	-5.4	14.0	-1.6	6.8	-0.8	9.3	-2.8	12.6	-3.8	6.5
PTB	4.7	3.4	-2.3	9.4	2.2	3.2	3.5	6.7			2.0	3.5	-1.9	13.0	1.9	4.3	2.7	7.6	0.7	11.4	-0.3	3.7
BEV	2.7	2.7	-4.3	9.2	0.2	2.5	1.5	6.4	-2.0	3.5			-3.9	12.8	-0.1	3.7	0.7	7.3	-1.3	11.2	-2.3	3.1
JV	6.6	12.8	-0.4	15.5	4.1	12.7	5.4	14.0	1.9	13.0	3.9	12.8			3.8	13.0	4.6	14.5	2.6	16.8	1.6	12.9
SP	2.8	3.6	-4.2	9.5	0.3	3.5	1.6	6.8	-1.9	4.3	0.1	3.7	-3.8	13.0			0.8	7.7	-1.2	11.5	-2.2	4.0
NMC	2.0	7.3	-5.0	11.4	-0.5	7.2	0.8	9.3	-2.7	7.6	-0.7	7.3	-4.6	14.5	-0.8	7.7			-2.0	13.1	-3.0	7.5
NPL	4.0	11.2	-3.0	14.2	1.5	11.1	2.8	12.6	-0.7	11.4	1.3	11.2	-2.6	16.8	1.2	11.5	2.0	13.1			-1.0	11.3
VNIIM	5.0	3.0	-2.0	9.3	2.5	2.8	3.8	6.5	0.3	3.7	2.3	3.1	-1.6	12.9	2.2	4.0	3.0	7.5	1.0	11.3		

Table 2. Degrees of equivalence 10 mA, 55 Hz

	NMIA		NIST		NRC		INTI		PTB		BEV		JV		SP		NMC		INMETRO		NPL		VNIIM	
	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
NMIA			-0.1	6.0	-0.2	1.0	-2.1	6.1	-0.8	3.1	0.0	2.3	-0.6	6.7	-0.1	2.3	0.9	7.1	12.9	27.0	0.9	11.0	-3.1	2.9
NIST	0.1	6.0			-0.1	6.0	-2.0	8.5	-0.7	6.7	0.1	6.3	-0.5	8.9	0.0	6.3	1.0	9.2	13.0	27.7	1.0	12.5	-3.0	6.6
NRC	0.2	1.0	0.1	6.0			-1.9	6.1	-0.6	3.0	0.2	2.2	-0.4	6.6	0.1	2.2	1.1	7.0	13.1	27.0	1.1	11.0	-2.9	2.8
INTI	2.1	6.1	2.0	8.5	1.9	6.1			1.3	6.7	2.1	6.4	1.5	9.0	2.0	6.4	3.0	9.3	15.0	27.7	3.0	12.6	-1.0	6.6
PTB	0.8	3.1	0.7	6.7	0.6	3.0	-1.3	6.7			0.8	3.6	0.2	7.2	0.7	3.6	1.7	7.6	13.7	27.2	1.7	11.4	-2.3	4.0
BEV	0.0	2.3	-0.1	6.3	-0.2	2.2	-2.1	6.4	-0.8	3.6			-0.6	7.0	-0.1	3.0	0.9	7.3	12.9	27.1	0.9	11.2	-3.1	3.5
JV	0.6	6.7	0.5	8.9	0.4	6.6	-1.5	9.0	-0.2	7.2	0.6	7.0			0.5	7.0	1.5	9.7	13.5	27.8	1.5	12.9	-2.5	7.2
SP	0.1	2.3	0.0	6.3	-0.1	2.2	-2.0	6.4	-0.7	3.6	0.1	3.0	-0.5	7.0			1.0	7.3	13.0	27.1	1.0	11.2	-3.0	3.5
NMC	-0.9	7.1	-1.0	9.2	-1.1	7.0	-3.0	9.3	-1.7	7.6	-0.9	7.3	-1.5	9.7	-1.0	7.3			12.0	27.9	0.0	13.1	-4.0	7.5
INMETRO	-12.9	27.0	-13.0	27.7	-13.1	27.0	-15.0	27.7	-13.7	27.2	-12.9	27.1	-13.5	27.8	-13.0	27.1	-12.0	27.9			-12.0	29.2	-16.0	27.1
NPL	-0.9	11.0	-1.0	12.5	-1.1	11.0	-3.0	12.6	-1.7	11.4	-0.9	11.2	-1.5	12.9	-1.0	11.2	0.0	13.1	12.0	29.2			-4.0	11.4
VNIIM	3.1	2.9	3.0	6.6	2.9	2.8	1.0	6.6	2.3	4.0	3.1	3.5	2.5	7.2	3.0	3.5	4.0	7.5	16.0	27.1	4.0	11.4		

Table 3. Degrees of equivalence 10 mA, 1 kHz

	NMIA		NIST		NRC		INTI		PTB		BEV		JV		SP		NMC		INMETRO		NPL		VNIIM	
	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
NMIA			0.8	4.1	-0.4	1.0	-2.6	3.2	-1.3	2.1	-0.3	2.3	0.1	6.7	-0.1	1.7	0.8	7.1	12.8	27.0	-0.3	11.0	-0.5	2.5
NIST	-0.8	4.1			-1.1	4.0	-3.3	5.0	-2.0	4.4	-1.0	4.5	-0.7	7.7	-0.8	4.2	0.0	8.1	12.0	27.3	-1.0	11.7	-1.2	4.6
NRC	0.4	1.0	1.1	4.0			-2.2	3.1	-0.9	2.0	0.1	2.2	0.4	6.6	0.3	1.6	1.1	7.0	13.1	27.0	0.1	11.0	-0.1	2.4
INTI	2.6	3.2	3.3	5.0	2.2	3.1			1.3	3.6	2.3	3.7	2.6	7.3	2.5	3.4	3.3	7.7	15.3	27.2	2.3	11.4	2.1	3.8
PTB	1.3	2.1	2.0	4.4	0.9	2.0	-1.3	3.6			1.0	2.9	1.3	6.9	1.2	2.5	2.0	7.3	14.0	27.1	1.0	11.2	0.8	3.0
BEV	0.3	2.3	1.0	4.5	-0.1	2.2	-2.3	3.7	-1.0	2.9			0.3	7.0	0.2	2.6	1.0	7.3	13.0	27.1	0.0	11.2	-0.2	3.2
JV	-0.1	6.7	0.7	7.7	-0.4	6.6	-2.6	7.3	-1.3	6.9	-0.3	7.0			-0.1	6.8	0.7	9.6	12.7	27.8	-0.3	12.8	-0.5	7.0
SP	0.1	1.7	0.8	4.2	-0.3	1.6	-2.5	3.4	-1.2	2.5	-0.2	2.6	0.1	6.8			0.8	7.2	12.8	27.0	-0.2	11.1	-0.4	2.8
NMC	-0.8	7.1	0.0	8.1	-1.1	7.0	-3.3	7.7	-2.0	7.3	-1.0	7.3	-0.7	9.6	-0.8	7.2			12.0	27.9	-1.0	13.1	-1.2	7.4
INMETRO	-12.8	27.0	-12.0	27.3	-13.1	27.0	-15.3	27.2	-14.0	27.1	-13.0	27.1	-12.7	27.8	-12.8	27.0	-12.0	27.9			-13.0	29.2	-13.2	27.1
NPL	0.3	11.0	1.0	11.7	-0.1	11.0	-2.3	11.4	-1.0	11.2	0.0	11.2	0.3	12.8	0.2	11.1	1.0	13.1	13.0	29.2			-0.2	11.3
VNIIM	0.5	2.5	1.2	4.6	0.1	2.4	-2.1	3.8	-0.8	3.0	0.2	3.2	0.5	7.0	0.4	2.8	1.2	7.4	13.2	27.1	0.2	11.3		

Table 4. Degrees of equivalence 10 mA, 10 kHz

	NMIA		NIST		NRC		INTI		PTB		BEV		JV		SP		NMC		INMETRO		NPL		VNIIM	
	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
NMIA			-1.3	4.0	0.5	1.5	-2.5	3.2	-1.2	2.0	0.1	2.2	0.0	6.9	0.1	2.0	0.7	7.1	10.7	36.0	-0.3	13.0	-0.3	2.6
NIST	1.3	4.0			1.8	4.1	-1.2	5.0	0.1	4.4	1.4	4.5	1.3	7.9	1.4	4.4	2.0	8.1	12.0	36.2	1.0	13.6	1.0	4.7
NRC	-0.5	1.5	-1.8	4.1			-3.0	3.3	-1.7	2.3	-0.4	2.4	-0.5	6.9	-0.4	2.3	0.2	7.1	10.2	36.0	-0.8	13.1	-0.8	2.8
INTI	2.5	3.2	1.2	5.0	3.0	3.3			1.3	3.6	2.6	3.7	2.5	7.5	2.6	3.6	3.2	7.7	13.2	36.1	2.2	13.4	2.2	4.0
PTB	1.2	2.0	-0.1	4.4	1.7	2.3	-1.3	3.6			1.3	2.8	1.2	7.1	1.3	2.7	1.9	7.3	11.9	36.1	0.9	13.2	0.9	3.2
BEV	-0.1	2.2	-1.4	4.5	0.4	2.4	-2.6	3.7	-1.3	2.8			-0.1	7.1	0.0	2.8	0.6	7.3	10.6	36.1	-0.4	13.2	-0.4	3.3
JV	0.0	6.9	-1.3	7.9	0.5	6.9	-2.5	7.5	-1.2	7.1	0.1	7.1			0.1	7.1	0.7	9.8	10.7	36.6	-0.3	14.7	-0.3	7.3
SP	-0.1	2.0	-1.4	4.4	0.4	2.3	-2.6	3.6	-1.3	2.7	0.0	2.8	-0.1	7.1			0.6	7.3	10.6	36.1	-0.4	13.2	-0.4	3.2
NMC	-0.7	7.1	-2.0	8.1	-0.2	7.1	-3.2	7.7	-1.9	7.3	-0.6	7.3	-0.7	9.8	-0.6	7.3			10.0	36.7	-1.0	14.8	-1.0	7.5
INMETRO	-10.7	36.0	-12.0	36.2	-10.2	36.0	-13.2	36.1	-11.9	36.1	-10.6	36.1	-10.7	36.6	-10.6	36.1	-10.0	36.7			-11.0	38.3	-11.0	36.1
NPL	0.3	13.0	-1.0	13.6	0.8	13.1	-2.2	13.4	-0.9	13.2	0.4	13.2	0.3	14.7	0.4	13.2	1.0	14.8	11.0	38.3			0.0	13.3
VNIIM	0.3	2.6	-1.0	4.7	0.8	2.8	-2.2	4.0	-0.9	3.2	0.4	3.3	0.3	7.3	0.4	3.2	1.0	7.5	11.0	36.1	0.0	13.3		

Table 5. Degrees of equivalence 10 mA, 20 kHz

	NMIA		NIST		NRC		INTI		PTB		BEV		JV		SP		NMC		NPL		VNIIM	
	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
NMIA			-1.4	4.0	0.5	1.8	-2.5	5.1	-1.3	2.0	-0.2	2.4	0.5	8.5	-0.3	2.1	0.7	7.1	0.7	14.0	-0.3	2.6
NIST	1.4	4.0			1.8	4.3	-1.1	6.4	0.1	4.4	1.2	4.6	1.9	9.3	1.1	4.4	2.0	8.1	2.0	14.6	1.1	4.7
NRC	-0.5	1.8	-1.8	4.3			-2.9	5.3	-1.7	2.5	-0.6	2.8	0.1	8.6	-0.7	2.6	0.2	7.2	0.2	14.1	-0.7	3.0
INTI	2.5	5.1	1.1	6.4	2.9	5.3			1.2	5.4	2.3	5.5	3.0	9.8	2.2	5.4	3.1	8.7	3.1	14.9	2.2	5.6
PTB	1.3	2.0	-0.1	4.4	1.7	2.5	-1.2	5.4			1.1	3.0	1.8	8.6	1.0	2.7	1.9	7.3	1.9	14.1	1.0	3.1
BEV	0.2	2.4	-1.2	4.6	0.6	2.8	-2.3	5.5	-1.1	3.0			0.7	8.7	-0.1	3.0	0.8	7.4	0.8	14.2	-0.1	3.4
JV	-0.5	8.5	-1.9	9.3	-0.1	8.6	-3.0	9.8	-1.8	8.6	-0.7	8.7			-0.8	8.7	0.1	11.0	0.1	16.4	-0.8	8.8
SP	0.3	2.1	-1.1	4.4	0.7	2.6	-2.2	5.4	-1.0	2.7	0.1	3.0	0.8	8.7			0.9	7.3	0.9	14.2	0.0	3.2
NMC	-0.7	7.1	-2.0	8.1	-0.2	7.2	-3.1	8.7	-1.9	7.3	-0.8	7.4	-0.1	11.0	-0.9	7.3			0.0	15.7	-0.9	7.5
NPL	-0.7	14.0	-2.0	14.6	-0.2	14.1	-3.1	14.9	-1.9	14.1	-0.8	14.2	-0.1	16.4	-0.9	14.2	0.0	15.7			-0.9	14.2
VNIIM	0.3	2.6	-1.1	4.7	0.7	3.0	-2.2	5.6	-1.0	3.1	0.1	3.4	0.8	8.8	0.0	3.2	0.9	7.5	0.9	14.2		

Table 6. Degrees of equivalence 10 mA, 50 kHz

	NMIA		NIST		NRC		INTI		PTB		BEV		JV		SP		NMC		NPL		VNIIM	
	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
NMIA			-3.5	7.1	0.7	1.8	-1.7	10.1	-1.1	2.2	-0.4	2.7	1.5	10.5	-0.3	2.6	-0.5	7.1	-1.5	15.1	-0.2	2.7
NIST	3.5	7.1			4.1	7.1	1.8	12.2	2.4	7.2	3.1	7.4	5.0	12.5	3.2	7.3	3.0	9.9	2.0	16.6	3.3	7.4
NRC	-0.7	1.8	-4.1	7.1			-2.3	10.1	-1.7	2.3	-1.0	2.8	0.9	10.5	-0.9	2.8	-1.1	7.2	-2.1	15.1	-0.8	2.8
INTI	1.7	10.1	-1.8	12.2	2.3	10.1			0.6	10.2	1.3	10.3	3.2	14.5	1.4	10.3	1.2	12.3	0.2	18.1	1.5	10.3
PTB	1.1	2.2	-2.4	7.2	1.7	2.3	-0.6	10.2			0.7	3.1	2.6	10.6	0.8	3.0	0.6	7.3	-0.4	15.1	0.9	3.1
BEV	0.4	2.7	-3.1	7.4	1.0	2.8	-1.3	10.3	-0.7	3.1			1.9	10.7	0.1	3.4	-0.1	7.5	-1.1	15.2	0.2	3.5
JV	-1.5	10.5	-5.0	12.5	-0.9	10.5	-3.2	14.5	-2.6	10.6	-1.9	10.7			-1.8	10.7	-2.0	12.6	-3.0	18.3	-1.7	10.7
SP	0.3	2.6	-3.2	7.3	0.9	2.8	-1.4	10.3	-0.8	3.0	-0.1	3.4	1.8	10.7			-0.2	7.4	-1.2	15.2	0.1	3.4
NMC	0.5	7.1	-3.0	9.9	1.1	7.2	-1.2	12.3	-0.6	7.3	0.1	7.5	2.0	12.6	0.2	7.4			-1.0	16.6	0.3	7.5
NPL	1.5	15.1	-2.0	16.6	2.1	15.1	-0.2	18.1	0.4	15.1	1.1	15.2	3.0	18.3	1.2	15.2	1.0	16.6			1.3	15.2
VNIIM	0.2	2.7	-3.3	7.4	0.8	2.8	-1.5	10.3	-0.9	3.1	-0.2	3.5	1.7	10.7	-0.1	3.4	-0.3	7.5	-1.3	15.2		

Table 7. Degrees of equivalence 10 mA, 100 kHz

	NMIA		NIST		NRC		INTI		PTB		BEV		JV		SP		NMC		NPL		VNIIM	
	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
NMIA			-6.8	10.1	0.9	2.1	-0.8	20.1	-0.8	2.4	-0.4	3.6	3.2	12.6	-0.2	3.6	-1.8	12.1	-2.8	22.1	-0.1	2.9
NIST	6.8	10.1			7.6	10.0	6.0	22.4	6.0	10.1	6.4	10.5	10.0	16.0	6.6	10.5	5.0	15.6	4.0	24.2	6.7	10.3
NRC	-0.9	2.1	-7.6	10.0			-1.6	20.1	-1.6	2.2	-1.2	3.5	2.4	12.6	-1.0	3.5	-2.6	12.1	-3.6	22.1	-0.9	2.8
INTI	0.8	20.1	-6.0	22.4	1.6	20.1			0.0	20.1	0.4	20.3	4.0	23.6	0.6	20.3	-1.0	23.4	-2.0	29.8	0.7	20.2
PTB	0.8	2.4	-6.0	10.1	1.6	2.2	0.0	20.1			0.4	3.7	4.0	12.7	0.6	3.7	-1.0	12.2	-2.0	22.1	0.7	3.0
BEV	0.4	3.6	-6.4	10.5	1.2	3.5	-0.4	20.3	-0.4	3.7			3.6	13.0	0.2	4.6	-1.4	12.5	-2.4	22.3	0.3	4.1
JV	-3.2	12.6	-10.0	16.0	-2.4	12.6	-4.0	23.6	-4.0	12.7	-3.6	13.0			-3.4	13.0	-5.0	17.4	-6.0	25.3	-3.3	12.8
SP	0.2	3.6	-6.6	10.5	1.0	3.5	-0.6	20.3	-0.6	3.7	-0.2	4.6	3.4	13.0			-1.6	12.5	-2.6	22.3	0.1	4.1
NMC	1.8	12.1	-5.0	15.6	2.6	12.1	1.0	23.4	1.0	12.2	1.4	12.5	5.0	17.4	1.6	12.5			-1.0	25.1	1.7	12.3
NPL	2.8	22.1	-4.0	24.2	3.6	22.1	2.0	29.8	2.0	22.1	2.4	22.3	6.0	25.3	2.6	22.3	1.0	25.1			2.7	22.2
VNIIM	0.1	2.9	-6.7	10.3	0.9	2.8	-0.7	20.2	-0.7	3.0	-0.3	4.1	3.3	12.8	-0.1	4.1	-1.7	12.3	-2.7	22.2		

Table 8. Degrees of equivalence 5 A, 10 Hz

	NMIA		NIST		NRC		INTI		PTB		BEV		JV		SP		NMC		NPL		VNIIM	
	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
NMIA			-3.7	19.4	-0.6	15.5	-1.9	8.9	-0.7	7.2	-1.2	4.5	-5.7	44.8	-0.2	6.3	1.3	25.3	25.3	56.2	1.3	5.6
NIST	3.7	19.4			3.1	24.1	1.8	20.5	3.0	19.8	2.5	19.0	-2.0	48.5	3.5	19.5	5.0	31.3	29.0	59.1	5.0	19.3
NRC	0.6	15.5	-3.1	24.1			-1.3	16.9	-0.1	16.0	-0.6	15.0	-5.1	47.1	0.4	15.6	1.9	29.1	25.9	58.0	1.9	15.4
INTI	1.9	8.9	-1.8	20.5	1.3	16.9			1.2	9.8	0.7	8.0	-3.8	45.3	1.7	9.1	3.2	26.2	27.2	56.6	3.2	8.7
PTB	0.7	7.2	-3.0	19.8	0.1	16.0	-1.2	9.8			-0.5	6.0	-5.0	45.0	0.5	7.5	2.0	25.6	26.0	56.3	2.0	6.9
BEV	1.2	4.5	-2.5	19.0	0.6	15.0	-0.7	8.0	0.5	6.0			-4.5	44.6	1.0	4.9	2.5	25.0	26.5	56.0	2.5	4.0
JV	5.7	44.8	2.0	48.5	5.1	47.1	3.8	45.3	5.0	45.0	4.5	44.6			5.5	44.9	7.0	51.1	31.0	71.6	7.0	44.8
SP	0.2	6.3	-3.5	19.5	-0.4	15.6	-1.7	9.1	-0.5	7.5	-1.0	4.9	-5.5	44.9			1.5	25.4	25.5	56.2	1.5	6.0
NMC	-1.3	25.3	-5.0	31.3	-1.9	29.1	-3.2	26.2	-2.0	25.6	-2.5	25.0	-7.0	51.1	-1.5	25.4			24.0	61.3	0.0	25.2
NPL	-25.3	56.2	-29.0	59.1	-25.9	58.0	-27.2	56.6	-26.0	56.3	-26.5	56.0	-31.0	71.6	-25.5	56.2	-24.0	61.3			-24.0	56.1
VNIIM	-1.3	5.6	-5.0	19.3	-1.9	15.4	-3.2	8.7	-2.0	6.9	-2.5	4.0	-7.0	44.8	-1.5	6.0	0.0	25.2	24.0	56.1		

Table 9. Degrees of equivalence 5 A, 55 Hz

	NMIA		NIST		NRC		INTI		PTB		BEV		JV		SP		NMC		INMETRO		NPL		VNIIM	
	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
NMIA			-3.8	18.4	0.4	14.5	1.4	7.9	0.2	5.4	0.2	4.1	-1.6	13.8	0.9	5.5	1.2	25.3	1.2	91.1	-7.8	25.3	2.6	5.4
NIST	3.8	18.4			4.2	22.7	5.2	19.2	4.0	18.3	4.0	18.0	2.2	22.3	4.7	18.4	5.0	30.7	5.0	92.8	-4.0	30.8	6.4	18.3
NRC	-0.4	14.5	-4.2	22.7			1.0	15.5	-0.2	14.4	-0.2	14.0	-2.0	19.2	0.5	14.5	0.8	28.6	0.8	92.1	-8.2	28.7	2.2	14.4
INTI	-1.4	7.9	-5.2	19.2	-1.0	15.5			-1.2	7.8	-1.2	7.0	-3.0	14.9	-0.5	7.9	-0.2	25.9	-0.2	91.3	-9.2	26.0	1.2	7.8
PTB	-0.2	5.4	-4.0	18.3	0.2	14.4	1.2	7.8			0.0	4.0	-1.8	13.8	0.7	5.5	1.0	25.2	1.0	91.1	-8.0	25.3	2.4	5.3
BEV	-0.2	4.1	-4.0	18.0	0.2	14.0	1.2	7.0	0.0	4.0			-1.8	13.4	0.7	4.2	1.0	25.0	1.0	91.0	-8.0	25.1	2.4	4.0
JV	1.6	13.8	-2.2	22.3	2.0	19.2	3.0	14.9	1.8	13.8	1.8	13.4			2.5	13.9	2.8	28.3	2.8	92.0	-6.2	28.3	4.2	13.8
SP	-0.9	5.5	-4.7	18.4	-0.5	14.5	0.5	7.9	-0.7	5.5	-0.7	4.2	-2.5	13.9			0.3	25.3	0.3	91.1	-8.7	25.4	1.7	5.5
NMC	-1.2	25.3	-5.0	30.7	-0.8	28.6	0.2	25.9	-1.0	25.2	-1.0	25.0	-2.8	28.3	-0.3	25.3			0.0	94.4	-9.0	35.4	1.4	25.2
INMETRO	-1.2	91.1	-5.0	92.8	-0.8	92.1	0.2	91.3	-1.0	91.1	-1.0	91.0	-2.8	92.0	-0.3	91.1	0.0	94.4			-9.0	94.4	1.4	91.1
NPL	7.8	25.3	4.0	30.8	8.2	28.7	9.2	26.0	8.0	25.3	8.0	25.1	6.2	28.3	8.7	25.4	9.0	35.4	9.0	94.4			10.4	25.3
VNIIM	-2.6	5.4	-6.4	18.3	-2.2	14.4	-1.2	7.8	-2.4	5.3	-2.4	4.0	-4.2	13.8	-1.7	5.5	-1.4	25.2	-1.4	91.1	-10.4	25.3		

Table 10. Degrees of equivalence 5 A, 1 kHz

	NMIA		NIST		NRC		INTI		PTB		BEV		JV		SP		NMC		INMETRO		NPL		VNIIM	
	D_{ij}	U_{ij}	$D_{i,j}$	$U^2(D_{i,j})$	$D_{i,j}$	$U^2(D_{i,j})$	$D_{i,j}$	$U^2(D_{i,j})$	$D_{i,j}$	$U^2(D_{i,j})$	$D_{i,j}$	$U^2(D_{i,j})$	$D_{i,j}$	$U^2(D_{i,j})$	$D_{i,j}$	$U^2(D_{i,j})$	$D_{i,j}$	$U^2(D_{i,j})$	$D_{i,j}$	$U^2(D_{i,j})$	$D_{i,j}$	$U^2(D_{i,j})$	$D_{i,j}$	$U^2(D_{i,j})$
NMIA			-2.4	17.4	1.2	14.5	-2.8	6.2	0.6	5.4	0.6	4.2	1.1	11.4	1.5	5.3	2.6	25.3	-23.4	91.1	2.6	24.3	-1.4	5.0
NIST	2.4	17.4			3.6	21.9	-0.4	17.6	3.0	17.4	3.0	17.0	3.5	20.0	3.9	17.3	5.0	30.2	-21.0	92.6	5.0	29.4	1.0	17.2
NRC	-1.2	14.5	-3.6	21.9			-4.0	14.8	-0.6	14.4	-0.6	14.0	-0.1	17.6	0.3	14.4	1.4	28.6	-24.6	92.1	1.4	27.8	-2.6	14.3
INTI	2.8	6.2	0.4	17.6	4.0	14.8			3.4	6.1	3.4	5.1	3.9	11.7	4.3	6.1	5.4	25.4	-20.6	91.1	5.4	24.5	1.4	5.8
PTB	-0.6	5.4	-3.0	17.4	0.6	14.4	-3.4	6.1			0.0	4.1	0.5	11.3	0.9	5.3	2.0	25.3	-24.0	91.1	2.0	24.3	-2.0	4.9
BEV	-0.6	4.2	-3.0	17.0	0.6	14.0	-3.4	5.1	0.0	4.1			0.5	10.8	0.9	4.0	2.0	25.0	-24.0	91.0	2.0	24.1	-2.0	3.5
JV	-1.1	11.4	-3.5	20.0	0.1	17.6	-3.9	11.7	-0.5	11.3	-0.5	10.8			0.4	11.3	1.5	27.2	-24.5	91.6	1.5	26.3	-2.5	11.1
SP	-1.5	5.3	-3.9	17.3	-0.3	14.4	-4.3	6.1	-0.9	5.3	-0.9	4.0	-0.4	11.3			1.1	25.2	-24.9	91.1	1.1	24.3	-2.9	4.8
NMC	-2.6	25.3	-5.0	30.2	-1.4	28.6	-5.4	25.4	-2.0	25.3	-2.0	25.0	-1.5	27.2	-1.1	25.2			-26.0	94.4	0.0	34.7	-4.0	25.2
INMETRO	23.4	91.1	21.0	92.6	24.6	92.1	20.6	91.1	24.0	91.1	24.0	91.0	24.5	91.6	24.9	91.1	26.0	94.4			26.0	94.1	22.0	91.1
NPL	-2.6	24.3	-5.0	29.4	-1.4	27.8	-5.4	24.5	-2.0	24.3	-2.0	24.1	-1.5	26.3	-1.1	24.3	0.0	34.7	-26.0	94.1			-4.0	24.2
VNIIM	1.4	5.0	-1.0	17.2	2.6	14.3	-1.4	5.8	2.0	4.9	2.0	3.5	2.5	11.1	2.9	4.8	4.0	25.2	-22.0	91.1	4.0	24.2		

Table 11. Degrees of equivalence 5 A, 10 kHz

	NMIA		NIST		NRC		INTI		PTB		BEV		JV		SP		NMC		INMETRO		NPL		VNIIM	
	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
NMIA			-7.8	17.3	1.3	15.4	0.3	7.7	2.2	6.0	1.4	9.6	1.8	11.8	-0.4	5.4	1.2	25.2	-119.8	96.1	7.2	22.4	-4.6	4.6
NIST	7.8	17.3			9.1	22.5	8.1	18.2	10.0	17.5	9.2	19.1	9.6	20.2	7.4	17.3	9.0	30.1	-112.0	97.5	15.0	27.8	3.2	17.1
NRC	-1.3	15.4	-9.1	22.5			-1.0	16.3	0.9	15.6	0.1	17.3	0.5	18.6	-1.7	15.4	-0.1	29.0	-121.1	97.2	5.9	26.6	-5.9	15.1
INTI	-0.3	7.7	-8.1	18.2	1.0	16.3			1.9	8.2	1.1	11.1	1.5	13.0	-0.7	7.8	0.9	25.8	-120.1	96.3	6.9	23.1	-4.9	7.2
PTB	-2.2	6.0	-10.0	17.5	-0.9	15.6	-1.9	8.2			-0.8	10.0	-0.4	12.1	-2.6	6.1	-1.0	25.4	-122.0	96.1	5.0	22.6	-6.8	5.3
BEV	-1.4	9.6	-9.2	19.1	-0.1	17.3	-1.1	11.1	0.8	10.0			0.4	14.2	-1.8	9.6	-0.2	26.4	-121.2	96.4	5.8	23.8	-6.0	9.2
JV	-1.8	11.8	-9.6	20.2	-0.5	18.6	-1.5	13.0	0.4	12.1	-0.4	14.2			-2.2	11.8	-0.6	27.3	-121.6	96.7	5.4	24.7	-6.4	11.5
SP	0.4	5.4	-7.4	17.3	1.7	15.4	0.7	7.8	2.6	6.1	1.8	9.6	2.2	11.8			1.6	25.2	-119.4	96.1	7.6	22.4	-4.2	4.7
NMC	-1.2	25.2	-9.0	30.1	0.1	29.0	-0.9	25.8	1.0	25.4	0.2	26.4	0.6	27.3	-1.6	25.2			-121.0	99.2	6.0	33.3	-5.8	25.1
INMETRO	119.8	96.1	112.0	97.5	121.1	97.2	120.1	96.3	122.0	96.1	121.2	96.4	121.6	96.7	119.4	96.1	121.0	99.2			127.0	98.5	115.2	96.1
NPL	-7.2	22.4	-15.0	27.8	-5.9	26.6	-6.9	23.1	-5.0	22.6	-5.8	23.8	-5.4	24.7	-7.6	22.4	-6.0	33.3	-127.0	98.5			-11.8	22.2
VNIIM	4.6	4.6	-3.2	17.1	5.9	15.1	4.9	7.2	6.8	5.3	6.0	9.2	6.4	11.5	4.2	4.7	5.8	25.1	-115.2	96.1	11.8	22.2		

Table 12. Degrees of equivalence 5 A, 20 kHz

	NMIA		NIST		NRC		INTI		PTB		BEV		JV		SP		NMC		NPL	
	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
NMIA			-1.3	21.2	-1.1	15.2	-1.6	8.4	1.7	7.5	-0.3	9.4	1.1	18.9	-2.6	5.7	-0.5	25.1	0.7	53.2
NIST	1.3	21.2			0.2	25.5	-0.3	22.2	3.0	21.8	1.0	22.5	2.4	27.9	-1.3	21.3	0.8	32.4	2.0	57.0
NRC	1.1	15.2	-0.2	25.5			-0.5	16.6	2.8	16.1	0.8	17.1	2.2	23.7	-1.5	15.4	0.6	28.9	1.8	55.1
INTI	1.6	8.4	0.3	22.2	0.5	16.6			3.3	10.0	1.3	11.5	2.7	20.1	-1.0	8.7	1.1	26.0	2.3	53.6
PTB	-1.7	7.5	-3.0	21.8	-2.8	16.1	-3.3	10.0			-2.0	10.8	-0.6	19.7	-4.3	7.8	-2.2	25.7	-1.0	53.5
BEV	0.3	9.4	-1.0	22.5	-0.8	17.1	-1.3	11.5	2.0	10.8			1.4	20.5	-2.3	9.7	-0.2	26.3	1.0	53.8
JV	-1.1	18.9	-2.4	27.9	-2.2	23.7	-2.7	20.1	0.6	19.7	-1.4	20.5			-3.7	19.1	-1.6	31.0	-0.4	56.2
SP	2.6	5.7	1.3	21.3	1.5	15.4	1.0	8.7	4.3	7.8	2.3	9.7	3.7	19.1			2.1	25.2	3.3	53.2
NMC	0.5	25.1	-0.8	32.4	-0.6	28.9	-1.1	26.0	2.2	25.7	0.2	26.3	1.6	31.0	-2.1	25.2			1.2	58.6
NPL	-0.7	53.2	-2.0	57.0	-1.8	55.1	-2.3	53.6	1.0	53.5	-1.0	53.8	0.4	56.2	-3.3	53.2	-1.2	58.6		

Table 13. Degrees of equivalence 5 A, 50 kHz

	NMIA		NIST		NRC		INTI		PTB		BEV		JV		SP		NMC		NPL	
	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
NMIA			-4.5	27.6	-1.9	20.8	-6.4	14.2	-1.5	10.6	-4.6	11.1	-1.0	26.4	-6.5	11.5	-0.7	25.6	18.5	84.4
NIST	4.5	27.6			2.6	33.1	-1.9	29.4	3.0	27.9	-0.1	28.1	3.5	36.9	-2.0	28.2	3.7	36.4	23.0	88.2
NRC	1.9	20.8	-2.6	33.1			-4.5	23.2	0.4	21.2	-2.7	21.4	0.9	32.2	-4.6	21.6	1.1	31.5	20.4	86.3
INTI	6.4	14.2	1.9	29.4	4.5	23.2			4.9	14.8	1.8	15.1	5.4	28.4	-0.1	15.4	5.6	27.6	24.9	85.0
PTB	1.5	10.6	-3.0	27.9	-0.4	21.2	-4.9	14.8			-3.1	11.9	0.5	26.8	-5.0	12.2	0.7	26.0	20.0	84.5
BEV	4.6	11.1	0.1	28.1	2.7	21.4	-1.8	15.1	3.1	11.9			3.6	27.0	-1.9	12.6	3.8	26.2	23.1	84.5
JV	1.0	26.4	-3.5	36.9	-0.9	32.2	-5.4	28.4	-0.5	26.8	-3.6	27.0			-5.5	27.1	0.2	35.5	19.5	87.9
SP	6.5	11.5	2.0	28.2	4.6	21.6	0.1	15.4	5.0	12.2	1.9	12.6	5.5	27.1			5.7	26.3	25.0	84.6
NMC	0.7	25.6	-3.7	36.4	-1.1	31.5	-5.6	27.6	-0.7	26.0	-3.8	26.2	-0.2	35.5	-5.7	26.3			19.3	87.6
NPL	-18.5	84.4	-23.0	88.2	-20.4	86.3	-24.9	85.0	-20.0	84.5	-23.1	84.5	-19.5	87.9	-25.0	84.6	-19.3	87.6		

Table 14. Degrees of equivalence 5 A, 100 kHz

	NMIA		NIST		NRC		INTI		PTB		BEV		JV		SP		NMC		NPL	
	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}	D_{ij}	U_{ij}
NMIA			20.8	34.2	6.4	32.3	-5.0	23.7	-4.2	14.2	-11.1	15.4	-1.4	40.2	-14.2	17.5	-0.1	44.9	9.8	166.4
NIST	-20.8	34.2			-14.4	44.6	-25.8	38.8	-25.0	33.9	-31.9	34.4	-22.2	50.6	-35.0	35.4	-20.9	54.4	-11.0	169.2
NRC	-6.4	32.3	14.4	44.6			-11.4	37.2	-10.6	31.9	-17.5	32.5	-7.8	49.4	-20.6	33.5	-6.5	53.2	3.4	168.9
INTI	5.0	23.7	25.8	38.8	11.4	37.2			0.8	23.3	-6.1	24.1	3.6	44.3	-9.2	25.4	4.9	48.5	14.8	167.5
PTB	4.2	14.2	25.0	33.9	10.6	31.9	-0.8	23.3			-6.9	14.7	2.8	39.9	-10.0	16.8	4.1	44.6	14.0	166.4
BEV	11.1	15.4	31.9	34.4	17.5	32.5	6.1	24.1	6.9	14.7			9.7	40.4	-3.1	17.9	11.0	45.1	20.9	166.5
JV	1.4	40.2	22.2	50.6	7.8	49.4	-3.6	44.3	-2.8	39.9	-9.7	40.4			-12.8	41.2	1.3	58.4	11.2	170.6
SP	14.2	17.5	35.0	35.4	20.6	33.5	9.2	25.4	10.0	16.8	3.1	17.9	12.8	41.2			14.1	45.8	24.0	166.7
NMC	0.1	44.9	20.9	54.4	6.5	53.2	-4.9	48.5	-4.1	44.6	-11.0	45.1	-1.3	58.4	-14.1	45.8			9.9	171.7
NPL	-9.8	166.4	11.0	169.2	-3.4	168.9	-14.8	167.5	-14.0	166.4	-20.9	166.5	-11.2	170.6	-24.0	166.7	-9.9	171.7		

Appendix 2. Uncertainty Budgets

NMIA, Australia

Measurement Current : 10 mA

Contribution of:	Standard Uncertainty (μA/A) at frequency							Type A or B	Distribution
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz		
Reference μPot TCC	0.9	0.2	0.2	0.2	0.2	0.2	0.2	B	Normal
Type A	0.1	0.1	0.1	0.1	0.1	0.2	0.3	A	Normal
Connectors	0.4	0.3	0.3	0.3	0.3	0.3	0.3	B	Normal
Measurement Setup	0	0	0	0	0.1	0.1	0.1	B	Normal
Bead Leakage	1.0	0.4	0.4	0.4	0.4	0.4	0.5	B	Normal
Combined unc (k=1):	1.0	0.5	0.5	0.5	0.5	0.7	0.9		
Expanded unc:	2.0	1.0	1.0	1.0	1.0	1.4	1.8		

Measurement Current : 5 A

Contribution of:	Standard Uncertainty (μA/A) at frequency							Type A or B	Distribution
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz		
5 A Reference									
Reference TVC	0.6	0.4	0.4	0.4	0.4	1	1.5	B	Normal
Type A	0.2	0.2	0.2	0.2	0.2	0.2	0.2	A	Normal
Connectors	0.1	0.1	0.1	0.1	0.1	0.3	0.8	B	Normal
Measurement Setup	0.3	0.2	0.2	0.2	0.2	0.3	0.4	B	Normal
(a) TVC	0.7	0.5	0.5	0.5	0.5	1.1	1.8		
μPot Resistor	1	1	1	1	1	2.2	2.2	B	Normal
Type A	0.8	0.8	0.8	0.8	0.8	0.8	1.6	A	Normal
Measurement Setup	0.3	0.2	0.2	0.2	0.2	0.3	0.4	B	Normal
Current Dependence	0.8	0.8	0.8	0.8	0.8	1.2	1.8	B	Normal
(b) Shunt	1.5	1.5	1.5	1.5	1.5	2.6	3.3	B	Normal
(c) Loading Effect	0.1	0.1	0.1	0.1	0.5	2.0	4.0	B	Normal
(d) Stability	1	1	1	1	1	1	1	B	Normal
Comparison Measurements									
Reference Total (a)…(d)	0.2	0.2	0.2	0.2	0.2	0.2	0.2	B	Normal
Type A	0.4	0.3	0.3	0.3	0.3	0.3	0.5	A	Normal
Measurement Setup	0.2	0.3	0.3	0.3	0.3	0.3	0.5	B	Normal
Connectors	2.0	1.9	1.9	1.9	2.0	3.7	5.6	B	Normal
Combined unc (k=1):	2.3	2.0	2.0	2.1	2.3	4.0	6.0		
Expanded unc:	4.5	4.1	4.1	4.2	4.5	8.0	12.0		

NIST, USA

Remarks: 10 mA current converter calibrated using 3D multijunction thermal converter primary standard and single junction reference standard. 5 A converter calibrated using precision bifilar shunt in combination with reference thermoelement.

Measurement Current : 10 mA

Contribution of:	Standard Uncertainty / 10^{-6} at frequency							Type A or B	Distri-bution
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz		
Primary/Reference Standards (includes buildup from primary standards and frequency extension from 1 kHz)	0.58	0.42	0.42	0.42	0.89	1.64	1.80	B	Normal
Pooled Standard Deviation for primary intercomparisons and reference buildup	0.50	0.29	0.29	0.29	0.29	0.45	0.55	A	Normal
NIST Comparator System	2.20	1.11	0.68	0.68	0.68	1.06	1.31	B	Normal
Uncertainties for NIST standards									
Stability	2.50	1.70	0.75	0.75	0.75	1.70	2.00	B	Uniform
Bead	1.00	0.80	0.20	0.20	0.70	2.00	2.90	B	Uniform
Reproducibility	1.00	1.00	0.80	0.80	0.80	1.00	1.25	B	Uniform
Total contribution from NIST standards (k = 1)	3.70	2.45	1.40	1.40	1.74	3.45	4.38	B	Normal
Comparison of CCEM-K12 to NIST standards									
Pooled Standard Deviation for CCEM-K12 comparison	0.70	0.90	0.90	0.80	0.80	0.30	0.30	A	Normal
NIST Comparator System	2.20	1.11	0.68	0.68	0.68	1.06	1.31	B	Normal
Stability of CCEM-K12	0.60	0.70	0.67	0.49	0.67	0.49	1.34	B	Uniform
Combined unc (k=1)	4.40	2.92	1.92	1.82	2.14	3.65	4.77		
Expanded unc:	8.80	5.84	3.84	3.63	4.28	7.30	9.55		

Measurement Current : 5 A

Contribution of:	Standard Uncertainty / 10^{-6} at frequency							Type A or B	Distri-bution
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz		
Primary/Reference Standards (includes buildup from primary standards – 8 steps)	7.70	7.70	7.70	7.70	9.20	12.00	15.20	B	Normal
Pooled Standard Deviation for primary intercomparisons and reference buildup	1.71	1.25	0.90	1.00	1.20	2.00	2.00	A	Normal
NIST Comparator System	2.30	2.00	2.00	2.00	2.30	2.30	2.30		Normal
Uncertainties for NIST standards									
Level Coefficient	2.20	2.00	2.00	2.00	2.00	2.00	2.90	B	Uniform
Stability	2.50	1.70	0.75	0.75	0.75	1.70	2.00	B	Uniform
Bead	0.50	0.50	0.50	0.50	1.50	3.00	4.00	B	Uniform
Proximity Effect	1.00	1.00	1.00	1.00	1.00	1.00	1.25	B	Uniform
Reproducibility	1.00	1.00	0.80	0.80	0.80	1.00	1.25	B	Uniform
Total contribution from NIST standards (k = 1)	8.99	8.60	8.40	8.41	9.99	13.10	16.50	B	Normal
Comparison of CCEM-K12 to NIST standards									
Pooled Standard Deviation for CCEM-K12 comparison	0.70	0.90	0.90	0.80	0.80	0.30	0.30	A	Normal
NIST Comparator System	2.30	2.00	2.00	2.00	2.30	2.30	2.30	B	Normal
Stability of CCEM-K12	0.60	0.70	0.67	0.49	0.67	0.49	1.34	B	Uniform
Combined unc (k=1)	9.32	8.90	8.71	8.69	10.30	13.31	16.71		
Expanded unc:	18.65	17.81	17.41	17.39	20.60	26.62	33.43		

NRC, Canada

Measured current: 10 mA

Contribution of:	Standard uncertainty (µA/A) at frequency							Type A or B	Distri-bution
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz		
Reference Standard	0.2	0.2	0.2	0.2	0.2	0.2	0.2	A+B	normal
Comparison with std.	0.6	0.3	0.3	0.5	0.6	0.4	0.5	A	normal
Magnitude/n-meas.	0.5	0.2	0.2	0.4	0.6	0.6	0.6	B	uniform
CTVC LF correction	0.2	-	-	0.2	0.2	0.2	0.2	B	uniform
Combined unc. (k=1)	0.8	0.4	0.4	0.7	0.9	0.8	0.8		
Expanded unc:	1.7	0.8	0.8	1.4	1.8	1.6	1.6		

Measured current: 5 A

Contribution of:	Standard uncertainty (µA/A) at frequency							Type A or B	Distri-bution
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz		
Reference Std, Shunt	6.6	6.9	6.9	6.9	6.8	9.4	13.6	A+B	normal
Reference Std., TVC	0.8	0.5	0.5	1.0	1.0	1.0	1.4	A+B	normal
Comparison with std.	0.6	0.6	0.9	0.9	0.6	0.7	1.5	A	normal
Magnitude/n-meas.	0.4	0.3	0.3	0.3	0.3	0.5	0.7	B	uniform
Potential position	0.4	0.6	0.9	1.0	1.3	0.7	3.1	B	uniform
Guarding unc.	0.4	0.4	0.4	0.5	0.3	0.3	0.6	B	Uniform
Closure	3.2	1.2	1.1	2.3	2.4	2.5	6.8	B	uniform
Combined unc. (k=1)	7.4	7.1	7.1	7.5	7.4	9.9	15.7		
Expanded unc:	14.8	14.1	14.3	14.9	14.8	19.7	31.4		

INTI, Argentina

Measurement Current : 10 mA

Contribution of:	Standard Uncertainty (µA/A) at frequency							Type A or B	Distribution
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz		
Standard deviation of 12 measurements	0,2	0,2	0,2	0,2	0,2	0,2	0,2	A	n
AC-DC transfer difference of the standard	3,0	3,0	1,0	1,0	2,0	5,0	10,0	B	n
Measuring setup	0,4	0,4	0,4	0,6	0,9	0,8	1,5	A	n
Stability of Keithley 182-1	$6,1\cdot10^{-11}$	$6,1\cdot10^{-11}$	$6,1\cdot10^{-11}$	$6,1\cdot10^{-11}$	$6,1\cdot10^{-11}$	$6,1\cdot10^{-11}$	$6,1\cdot10^{-11}$	B	r
Stability of Keithley 182-2	$3,9\cdot10^{-11}$	$3,9\cdot10^{-11}$	$3,9\cdot10^{-11}$	$3,9\cdot10^{-11}$	$3,9\cdot10^{-11}$	$3,9\cdot10^{-11}$	$3,9\cdot10^{-11}$	B	r
AC-DC transfer difference due to connectors	0,1	0,1	0,1	0,1	0,1	0,1	0,1	B	r
Combined unc (k=1)	**3,0**	**3,0**	**1,1**	**1,2**	**2,2**	**5,0**	**10,1**		
Expanded unc:	**6,0**	**6,0**	**2,2**	**2,4**	**4,4**	**10,0**	**20,2**		

Measurement Current : 5 A

Contribution of:	Standard Uncertainty (µA/A) at frequency							Type A or B	Distribution
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz		
Standard deviation of 12 measurements	1,0	0,4	0,8	0,9	0,8	1,0	1,0	A	n
AC-DC transfer difference of the standard	3,7	3,4	2,2	3,5	3,9	6,1	10,7	B	n

Stability of Keithley 182-1	$6{,}1\cdot10^{-11}$	$6{,}1\cdot10^{-11}$	$6{,}1\cdot10^{-11}$	$6{,}1\cdot10^{-11}$	$6{,}1\cdot10^{-11}$	$6{,}1\cdot10^{-11}$	$6{,}1\cdot10^{-11}$	B	r
Stability of Keithley 182-2	$3{,}9\cdot10^{-11}$	$3{,}9\cdot10^{-11}$	$3{,}9\cdot10^{-11}$	$3{,}9\cdot10^{-11}$	$3{,}9\cdot10^{-11}$	$3{,}9\cdot10^{-11}$	$3{,}9\cdot10^{-11}$	B	r
AC-DC transfer difference due to connectors	0,1	0,1	0,1	0,2	0,2	0,3	0,5	B	r
Combined unc (k=1)	**3,8**	**3,4**	**2,3**	**3,5**	**3,9**	**6,2**	**10,7**		
Expanded unc:	**7,6**	**6,8**	**4,6**	**7,0**	**7,8**	**12,4**	**21,4**		

PTB, Germany

The following sources of uncertainties have been taken into account [3]:

Comparison at 10 mA

Model equation: $\delta = \delta_Q + \delta_C$

with
δ_Q: Transfer difference of the calculable QPMJTC
δ_C: Measured transfer difference in comparison

additional uncertainties:
u_A: Standard deviation of twelve comparisons
u_M: Maximum deviation from the mean when using different setups

At frequencies below 1kHz the transfer difference has been additionally determined as described in [4].

10 Hz

Parameter X_i	**Δx_i or s_i**	**Distribution**	**$u(x_i)$**	**c_i**	**$u_i(y)$**	**$u_i^2(y)$**	**$\nu_{eff\,i}$**	**$u_i^4(y)/\nu_{eff\,i}$**
δ_Q	0,3 µA/A	normal	0,30 µA/A	1	0,30 µA/A	0,090 (µA/A)²	50	1,620E-4 (µA/A)^4
δ_C	0,1 µA/A	normal	0,10 µA/A	1	0,10 µA/A	0,010 (µA/A)²	50	2,000E-6 (µA/A)^4
Standard deviation	0,7 µA/A	normal	0,20 µA/A	1	0,20 µA/A	0,041 (µA/A)²	11	1,516E-4 (µA/A)^4
Max. dev. from mean	2,0 µA/A	rectangular	1,15 µA/A	1	1,15 µA/A	1,333 (µA/A)²	10.000	1,778E-4 (µA/A)^4
					1,21 µA/A	1,474 (µA/A)²	**4.405**	4,934E-4 (µA/A)^4
					2,43 µA/A	***k* = 2**		

55 Hz

Parameter X_i	**Δx_i or s_i**	**Distribution**	**$u(x_i)$**	**c_i**	**$u_i(y)$**	**$u_i^2(y)$**	**$\nu_{eff\,i}$**	**$u_i^4(y)/\nu_{eff\,i}$**
δ_Q	0,2 µA/A	normal	0,20 µA/A	1	0,20 µA/A	0,040 (µA/A)²	50	3,200E-5 (µA/A)^4
δ_C	0,1 µA/A	normal	0,10 µA/A	1	0,10 µA/A	0,010 (µA/A)²	50	2,000E-6 (µA/A)^4
Standard deviation	0,7 µA/A	normal	0,20 µA/A	1	0,20 µA/A	0,041 (µA/A)²	11	1,516E-4 (µA/A)^4
Max. dev. from mean	1,0 µA/A	rectangular	0,58 µA/A	1	0,58 µA/A	0,333 (µA/A)²	10.000	1,111E-5 (µA/A)^4
					0,65 µA/A	0,424 (µA/A)²	**915**	1,967E-4 (µA/A)^4
					1,30 µA/A	***k* = 2**		

1000 Hz

Parameter X_i	**Δx_i or s_i**	**Distribution**	**$u(x_i)$**	**c_i**	**$u_i(y)$**	**$u_i^2(y)$**	**$\nu_{eff\,i}$**	**$u_i^4(y)/\nu_{eff\,i}$**
δ_Q	0,0 µA/A	normal	0,00 µA/A	1	0,00 µA/A	0,000 (µA/A)²	50	0,000E+0 (µA/A)^4
δ_C	0,1 µA/A	normal	0,10 µA/A	1	0,10 µA/A	0,010 (µA/A)²	50	2,000E-6 (µA/A)^4
Standard deviation	0,7 µA/A	normal	0,20 µA/A	1	0,20 µA/A	0,041 (µA/A)²	11	1,516E-4 (µA/A)^4
Max. dev. from mean	1,0 µA/A	rectangular	0,58 µA/A	1	0,58 µA/A	0,333 (µA/A)²	10.000	1,111E-5 (µA/A)^4
					0,62 µA/A	0,384 (µA/A)²	**896**	1,647E-4 (µA/A)^4
					1,24 µA/A	***k* = 2**		

10.000 Hz

Parameter X_i	**Δx_i or s_i**	**Distribution**	**$u(x_i)$**	**c_i**	**$u_i(y)$**	**$u_i^2(y)$**	**$\nu_{eff\,i}$**	**$u_i^4(y)/\nu_{eff\,i}$**
δ_Q	0,0 µA/A	normal	0,00 µA/A	1	0,00 µA/A	0,000 (µA/A)²	50	0,000E+0 (µA/A)^4
δ_C	0,1 µA/A	normal	0,10 µA/A	1	0,10 µA/A	0,010 (µA/A)²	50	2,000E-6 (µA/A)^4
Standard deviation	0,7 µA/A	normal	0,20 µA/A	1	0,20 µA/A	0,041 (µA/A)²	11	1,516E-4 (µA/A)^4
Max. dev. from mean	1,0 µA/A	rectangular	0,58 µA/A	1	0,58 µA/A	0,333 (µA/A)²	10.000	1,111E-5 (µA/A)^4
					0,62 µA/A	0,384 (µA/A)²	**896**	1,647E-4 (µA/A)^4
					1,24 µA/A	***k* = 2**		

Comparison at 5 A

Model equation: $\delta = \delta_Q + \delta_C$ for the first step, then
$\delta = \delta_{Step-1} + \delta_C$

with
δ_Q: Transfer difference of the calculable QPMJTC
δ_{Step-1}: Transfer difference of the step before
δ_C: Measured transfer difference in comparison

additional uncertainties:
u_{lev}: Uncertainty due to level dependence of shunts
u_{LF}: Uncertainty due to low frequency behavior of PMJTC
u_A: Standard deviation of twelve comparisons
u_M: Maximum deviation from the mean when using different step-ups

The simplified budget for the step-up to 5 A looks as follows:

Influencing quantity	Std. meas. uncertainty *u* in µA/A at the frequencies in kHz									
	0,010	**0,055**	**1**	**10**	**20**	**50**	**100**	**200**	**500**	**1.000**
Q117-ITee										
$u(\delta_{Chip})$	0,3	0,2	0,0	0,0	0,0	0,0	0,0	0,0	0,1	0,2
$u(\delta_{Connector})$	0,0	0,0	0,0	0,0	0,0	0,0	0,1	0,2	0,4	0,7
$u(\delta_S)$	**0,30**	**0,20**	**0,00**	**0,00**	**0,00**	**0,00**	**0,10**	**0,20**	**0,41**	**0,73**
$U(\delta_S)$ k=2	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**1**	**2**
30 mA (PMJTC + JV30mA vs. Q117)										
$u(\delta_{Q117})$	0,3	0,2	0,0	0,0	0,0	0,0	0,1	0,2	0,4	0,7
$u(\delta_A)$	0,4	0,2	0,2	0,2	0,2	0,2	0,2	0,2	0,2	0,3
$u(\delta_C)$	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1
$u(\delta_{10mA})$	**0,51**	**0,30**	**0,22**	**0,22**	**0,22**	**0,22**	**0,24**	**0,30**	**0,5**	**0,8**
$U(\delta_{10mA})$ k=2	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**3**	**4**
100 mA (PMJTC + JV100mA vs. Q117)										
$u(\delta_{Q117})$	0,3	0,2	0,0	0,0	0,0	0,0	0,1	0,2	0,4	0,7
$u(\delta_A)$	0,4	0,2	0,2	0,2	0,2	0,2	0,2	0,2	0,3	0,5
$u(\delta_C)$	0,2	0,2	0,2	0,2	0,2	0,2	0,2	0,2	0,2	0,3
l_{evy}	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,1	0,2	0,3
u_{LF}	0,4	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
$u(\delta_{100mA})$	**0,68**	**0,36**	**0,30**	**0,30**	**0,30**	**0,30**	**0,32**	**0,36**	**0,6**	**1,0**
$U(\delta_{100mA})$ k=2	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**3**	**5**
300 mA (PMJTC + JV300mA vs. PMJTC + JV100mA)										
$u(\delta_{Step-1})$	0,7	0,4	0,3	0,3	0,3	0,3	0,3	0,4	0,6	1,0
$u(\delta_A)$	0,4	0,2	0,2	0,2	0,2	0,2	0,2	0,2	0,3	0,5
$u(\delta_C)$	0,2	0,2	0,2	0,2	0,2	0,2	0,2	0,2	0,2	0,3
l_{evy}	0,3	0,3	0,1	0,3	0,3	0,3	0,5	0,5	0,7	1,0
u_{LF}	0,4	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
$u(\delta_{300mA})$	**1,0**	**0,55**	**0,42**	**0,51**	**0,51**	**0,51**	**0,66**	**0,68**	**1,0**	**1,5**
$U(\delta_{300mA})$ k=2	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**2**	**3**	**5**
1 A (PMJTC + JV1A vs. PMJTC + JV300mA)										
$u(\delta_{Step-1})$	1,0	0,5	0,4	0,5	0,5	0,5	0,7	0,7	1,0	1,5
$u(\delta_A)$	0,4	0,2	0,2	0,2	0,2	0,2	0,2	0,2	0,3	0,5
$u(\delta_C)$	0,2	0,2	0,2	0,2	0,2	0,2	0,2	0,2	0,2	0,3
l_{evy}	1,0	1,0	1,0	1,0	1,0	1,0	1,5	1,5	2,0	3,0
u_{LF}	0,4	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0	0,0
$u(\delta_{51A})$	**1,5**	**1,2**	**1,1**	**1,2**	**1,2**	**1,2**	**1,7**	**1,7**	**2,3**	**3,4**
$U(\delta_{1A})$ k=2	**4**	**3**	**3**	**3**	**3**	**3**	**4**	**4**	**5**	**8**
3 A (PMJTC + JV3A vs. PMJTC + JV1A)										
$u(\delta_{Step-1})$	1,5	1,2	1,1	1,2	1,2	1,2	1,7			
$u(\delta_A)$	0,4	0,2	0,2	0,2	0,2	0,2	0,2			
$u(\delta_C)$	0,2	0,2	0,2	0,2	0,2	0,2	0,2			
l_{evy}	1,0	1,0	1,0	1,5	2,0	3,0	3,5			
u_{LF}	0,4	0,0	0,0	0,0	0,0	0,0	0,0			
$u(\delta_{1A})$	**1,9**	**1,6**	**1,5**	**1,9**	**2,3**	**3,2**	**3,9**			
$U(\delta_{1A})$ k=2	**4**	**4**	**4**	**4**	**5**	**7**	**8**			

5 A (PMJTC + JV5A vs. PMJTC + JV3A)							
$u(\delta_{Step-1})$	1,9	1,6	1,5	1,9	2,3	3,2	3,9
$u(\delta_A)$	0,4	0,2	0,2	0,2	0,2	0,2	0,2
$u(\delta_C)$	0,2	0,2	0,2	0,2	0,2	0,2	0,2
l_{evy}	1,0	1,0	1,0	1,5	2,0	3,0	3,5
u_{LF}	0,4	0,0	0,0	0,0	0,0	0,0	0,0
$u(\delta_{5A})$	**2,2**	**1,9**	**1,8**	**2,4**	**3,1**	**4,4**	**5,2**
$U(\delta_{5A})$ k=2	**5**	**4**	**4**	**5**	**7**	**9**	**11**

This leads to the budgets for the comparison at 5 A:

10 Hz

Parameter X_i	**Δx_i or s_i**	**Distribution**	**$u(x_i)$**	**c_i**	**$u_i(y)$**	**$u_i^2(y)$**	**$\nu_{eff\,i}$**	**$u_i^4(y)/\nu_{eff\,i}$**
Step-up	2,2 µA/A	normal	2,20 µA/A	1	2,20 µA/A	4,840 (µA/A)²	50	4,685E-1 (µA/A)^4
δ_C	0,2 µA/A	normal	0,20 µA/A	1	0,20 µA/A	0,040 (µA/A)²	50	3,200E-5 (µA/A)^4
Standard deviation	1,4 µA/A	normal	0,40 µA/A	1	0,40 µA/A	0,163 (µA/A)²	11	2,425E-3 (µA/A)^4
Max. dev. from mean	2,0 µA/A	rectangular	1,15 µA/A	1	1,15 µA/A	1,333 (µA/A)²	10.000	1,778E-4 (µA/A)^4
					2,53 µA/A	6,377 (µA/A)²	**86**	4,711E-1 (µA/A)^4
					5,05 µA/A	***k* = 2**		

55 Hz

Parameter X_i	**Δx_i or s_i**	**Distribution**	**$u(x_i)$**	**c_i**	**$u_i(y)$**	**$u_i^2(y)$**	**$\nu_{eff\,i}$**	**$u_i^4(y)/\nu_{eff\,i}$**
Step-up	1,9 µA/A	normal	1,90 µA/A	1	1,90 µA/A	3,610 (µA/A)²	50	2,606E-1 (µA/A)^4
δ_C	0,2 µA/A	normal	0,20 µA/A	1	0,20 µA/A	0,040 (µA/A)²	50	3,200E-5 (µA/A)^4
Standard deviation	0,7 µA/A	normal	0,20 µA/A	1	0,20 µA/A	0,041 (µA/A)²	11	1,516E-4 (µA/A)^4
Max. dev. from mean	1,0 µA/A	rectangular	0,58 µA/A	1	0,58 µA/A	0,333 (µA/A)²	10.000	1,111E-5 (µA/A)^4
					2,01 µA/A	4,024 (µA/A)²	**62**	2,608E-1 (µA/A)^4
					4,01 µA/A	***k* = 2**		

1000 Hz

Parameter X_i	**Δx_i or s_i**	**Distribution**	**$u(x_i)$**	**c_i**	**$u_i(y)$**	**$u_i^2(y)$**	**$\nu_{eff\,i}$**	**$u_i^4(y)/\nu_{eff\,i}$**
Step-up	1,8 µA/A	normal	1,80 µA/A	1	1,80 µA/A	3,240 (µA/A)²	50	2,100E-1 (µA/A)^4
δ_C	0,2 µA/A	normal	0,20 µA/A	1	0,20 µA/A	0,040 (µA/A)²	50	3,200E-5 (µA/A)^4
Standard deviation	0,7 µA/A	normal	0,20 µA/A	1	0,20 µA/A	0,041 (µA/A)²	11	1,516E-4 (µA/A)^4
Max. dev. from mean	1,0 µA/A	rectangular	0,58 µA/A	1	0,58 µA/A	0,333 (µA/A)²	10.000	1,111E-5 (µA/A)^4
					1,91 µA/A	3,654 (µA/A)²	**64**	2,101E-1 (µA/A)^4
					3,82 µA/A	***k* = 2**		

10.000 Hz

Parameter X_i	**Δx_i or s_i**	**Distribution**	**$u(x_i)$**	**c_i**	**$u_i(y)$**	**$u_i^2(y)$**	**$\nu_{eff\,i}$**	**$u_i^4(y)/\nu_{eff\,i}$**
Step-up	2,4 µA/A	normal	2,40 µA/A	1	2,40 µA/A	5,760 (µA/A)²	50	6,636E-1 (µA/A)^4
δ_C	0,2 µA/A	normal	0,20 µA/A	1	0,20 µA/A	0,040 (µA/A)²	50	3,200E-5 (µA/A)^4
Standard deviation	0,7 µA/A	normal	0,20 µA/A	1	0,20 µA/A	0,041 (µA/A)²	11	1,516E-4 (µA/A)^4
Max. dev. from mean	1,0 µA/A	rectangular	0,58 µA/A	1	0,58 µA/A	0,333 (µA/A)²	10.000	1,111E-5 (µA/A)^4
					2,48 µA/A	6,174 (µA/A)²	**57**	6,637E-1 (µA/A)^4
					4,97 µA/A	***k* = 2**		

References

[1] Scarioni, L. “High Frequency Thin-Film Converter on a Quartz Crystal Chip,” Doctoral Thesis, Technical University Braunschweig, Braunschweig, Germany, 2003.

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[3] Klonz, M.; Laiz, H.; Spiegel, T.; Bittel, P., “AC-DC Current Transfer Step-Up and Step-Down Calibration and Uncertainty Calculation,” *IEEE Trans. Instrum. Meas*., 51, (2002), 2, 1027 - 1034

[4] Funck, T.; Kampik, M.; Kessler, E.; Klonz, M.; Laiz, H.; Lapuh, R., “Determination of the ac-dc voltage transfer difference of high voltage transfer standards at low frequencies“ *IEEE Trans. Instrum. Meas.* 54 (2005), 2, 807 – 809

BEV, Austria

Measurement Current : 10 mA

Contribution of:	Standard Uncertainty (μA/A) at frequency							Type A or B	Distribution
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz		
BEV - standard	0.5	0.5	0.5	0.5	0.5	0.5	0.5	B	normal
standard-deviation	0.3	0.3	0.3	0.3	0.3	0.3	0.3	A	normal
tee connector	0	0	0	0	0.1	0.1	0.1	B	rectangular
reproducibility	0.3	0.3	0.3	0.3	0.3	0.3	0.3	B	rectangular
nanovoltmeter 1	0.5	0.5	0.5	0.5	0.5	0.5	0.5	B	rectangular
nanovoltmeter 2	0.6	0.6	0.6	0.6	0.6	0.6	0.6	B	rectangular
different NVM	0	0	0	0	0.5	0.7	1.3	B	rectangular
dc effects	0.3	0.3	0.3	0.3	0.3	0.3	0.3	B	rectangular

Combined unc (k=1):	1.1	1.1	1.1	1.1	1.2	1.3	1.7
Expanded unc:	2.2	2.2	2.2	2.2	2.4	2.6	3.4

Measurement Current : 5 A

Contribution of:	Standard Uncertainty (μA/A) at frequency							Type A or B	Distribution
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz		
BEV - standard	0.3	0.3	0.3	4.3	4.3	4.6	6.1	B	normal
standard-deviation	0.3	0.3	0.3	0.3	0.3	0.3	0.3	A	normal
reproducibility	0.3	0.3	0.3	0.3	0.3	0.3	0.3	B	rectangular
nanovoltmeter 1	0.2	0.2	0.2	0.2	0.2	0.2	0.2	B	rectangular
nanovoltmeter 2	0.8	0.8	0.8	0.8	0.8	0.8	0.8	B	rectangular
sensitivity	0	0	0	0	0	0.1	0.1	B	rectangular
different NVM	0	0	0	0	0.5	0.7	1.3	B	rectangular
dc effects	0.3	0.3	0.3	0.3	0.3	0.3	0.3	B	rectangular

Combined unc (k=1):	1.0	1.0	1.0	4.5	4.5	4.8	6.3
Expanded unc:	2.0	2.0	2.0	9.0	9.0	9.6	12.6

JV, Norway

Uncertainty calculations have been performed according to the guidelines in "Guide to the Uncertainties in Measurements".

The main uncertainty contributions at each frequency are

u_{ref} uncertainty in the reference standard.
u_{step} total uncertainty resulting from current step-up.
This can be decomposed into
- s_m Standard deviation of the mean
- u_T Unsymmetry of "T" connection. This is considered to accumulate linearly.
- u_{lin} Lienarity and drift of DVM
- u_{sf} Uncertainty from scale factors
- u_P Power dependency (only relevant below 100 Hz for PMJTCs)

Smobj Standard deviation in the mean for the object measurement.

In addition one contribution from each of u_T, u_{lin} and u_{sf} for the measurement of the object.

For 10 mA, 10 Hz, the uncertainty calculation is shown in table 3, and 5 A,10 Hz in table 4.

The calculations for 5 A, 100 kHz are shown in table 5.

	Est. Value [µA/A]	Distribution	Sensitivity	Contribution	Estimated Deg. of freed.
s_m	0,49	1	1	0,49	9
u_{ref}	6	1	1	6	1,00E+02
u_{lin}	1	1	1	1	1,00E+02
u_{sf}	0,40	1	1	0,4	9
u_P	0,1	1	1	0,1	1,00E+02
u_T	0,2	1	1	0,2	1,00E+02
		Standard uncertainty (k=1):		6,32	9,1E+06

Table 3. 10 mA, 10 Hz uncertainty calculation

	Est. Value [µA/A]	Distribution	Sensitivity	Contribution	Estimated Deg. of freed.
s_m	0,40	1	1	0,40	9
$u_{ref} + u_{step}$	22,03	1	1	22,03	1,00E+03
u_{lin}	1	1	1	1	1,00E+02
u_{sf}	0,40	1	1	0,4	9
u_P	0,1	1	1	0,1	1,00E+02
u_T	0,2	1	1	0,2	1,00E+02
		Standard uncertainty (k=1):		22,26	4,2E+06

Table 4. 5A, 10 Hz uncertainty calculations.

	Est. Value [µA/A]	Distribution	Sensitivity	Contribution	Estimated Deg. of freed.
s_m	0,47	1	1	0,47	9
$u_{ref\,+}\ u_{step}$	17,30	1	1	17,30	1,00E+03
u_{lin}	1	1	1	1	1,00E+02
u_{sf}	0,40	1	1	0,4	9
u_P	0,1	1	1	0,1	1,00E+02
u_T	1,8	1	1	1,8	1,00E+02
		Standard uncertainty (k=1):		19,14	7,4E+06

Table 4. 5 A, 100 kHz uncertainty calculations.

SP, Sweden

Measurement Current : 10 mA

Contribution of:	Standard Uncertainty (μA/A) at frequency							Type A or B	Distri-bution
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz		
Ac-dc difference 10 mA of SP standard	1,2	0,8	0,5	0,8	0,8	0,9	1,2	B	Normal
Drift of standard	0,3	0,2	0,2	0,2	0,3	0,4	0,5	B	Rect.
Indicated ac-dc difference	0,3	0,2	0,2	0,2	0,2	0,2	0,3	A	Normal
Measurement set-up	1	0,7	0,5	0,5	0,5	0,7	1	B	Normal
T-connector	0	0	0	0	0	0	0,1	B	Rect.

Combined unc (*k*=1):	1,6	1,1	0,8	1,0	1,0	1,2	1,7
Expanded unc:	3,3	2,2	1,6	2,0	2,1	2,5	3,4

Measurement Current : 5 A

Contribution of:	Standard Uncertainty (μA/A) at frequency							Type A or B	Distri-bution
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz		
Ac-dc difference 5 A of SP standard	2,1	1,9	1,8	2,0	2,4	4,5	7,0	B	Normal
Drift of standard	0,6	0,4	0,4	0,4	0,6	0,8	1,0	B	Rect.
Indicated ac-dc difference	0,3	0,2	0,2	0,2	0,2	0,2	0,3	A	Normal
Measurement set-up	1	0,7	0,5	0,5	0,5	0,7	1	B	Normal
T-connector	0	0	0	0	0	0	0	B	Rect.

Combined unc (*k*=1):	2,4	2,1	1,9	2,1	2,6	4,6	7,1
Expanded unc:	4,9	4,2	3,9	4,3	5,1	10	15

NMC, Singapore

Uncertainty evaluation for 10 mA (10^{-6})

Contribution of:	Standard Uncertainty / 10^{-6} at frequency							Type A or B	D.o.F.	Distribution
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz			
Ref standard	5	5	5	5	5	5	10	B	Infinite	Normal
Drift of ref std	1	1	1	1	1	1	1	B	Infinite	Normal
Potential effect	1.0	1.2	1.3	1.2	1.1	1.2	1.2	B	21	Rectangular
“n” effect	1	1	1	1	1	1	1	B	Infinite	Normal
Type-A	0.2	0.1	0.1	0.2	0.2	0.1	0.1	A	56	Normal
Test Repeat.	1.0	1.0	1.4	1.0	0.8	0.9	1.3	A	56	Rectangular
Sys stability	1.5	1.5	1.5	1.5	1.5	1.5	1.5	B	30	Normal
Round-up	0.5	0.5	0.5	0.5	0.5	0.5	0.5	B	Infinite	Rectangular

Combined unc:	3.3	3.4	3.4	3.4	3.4	3.4	5.6	
Effective D.o.F.	549	476	388	453	500	439	2989	
Expanded unc:	**7**	**7**	**7**	**7**	**7**	**7**	**12**	k = 2

Uncertainty evaluation for 5 A (10^{-6})

Contribution of:		Standard Uncertainty / 10^{-6} at frequency							Type A or B	D.o.F.	Distribution
		10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz			
Ref standard		12	12	12	12	12	12	22	B		t-distribution
	D.o.F	288	290	280	289	289	292	223			
Potential effect		0.7	0.6	0.1	1.0	0.3	1.7	1.9	B	21	Rectangular
“n” effect		1	1	1	1	1	1	1	B	Infinite	Normal
Type-A		0.25	0.21	0.46	0.28	0.24	0.25	0.27	A	56	Normal
Test Repeat.		2.0	1.2	1.6	1.4	1.4	1.3	2.0		56	Rectangular
Sys stability		1.5	1.5	1.5	1.5	1.5	1.5	1.5	B	30	Normal
Round-up		0.5	0.5	0.5	0.5	0.5	0.5	0.5	B	Infinite	Rectangular

Combined unc:	12.0	12.0	11.9	12.0	12.0	12.2	21.8	
Effective D.o.F.	304	307	295	306	304	310	227	
Expanded unc:	**25**	**25**	**25**	**25**	**25**	**25**	**44**	k = 2

INMETRO, Brazil

Measurement Current : 10 mA

Contribution of:	Standard Uncertainty (μA/A) at frequency					Type A or B	Distribution
	55 Hz	1 kHz	10 kHz	50 kHz	100 kHz		
reproducibility	1	1	1	1	1	A	Normal
Reference standard	20	20	30	30	38	B	Normal
n coefficient of standard	50	50	50	50	50	B	Rectangular
standard drift	10	10	10	15	20	B	Rectangular
set-up procedure:							
standard voltmeter stability	0,5e-3	0,5e-3	0,5e-3	0,5e-3	0,5e-3	B	Rectangular
travel. voltmeter stability	2,2e-3	2,2e-3	2,2e-3	2,2e-3	2,2e-3	B	Rectangular
DC source uncertainty	10	10	10	3	3	B	Normal
Transconductance amplifier uncertainty				20	20	B	Rectangular
connectors AC-DC difference	7	7	10	10	12	B	Rectangular

Combined unc (*k*=1):	13,22	13,22	17,80	18,32	23,34
Expanded unc:	27	27	36	42	51

Measurement Current : 5 A

Contribution of:	Standard Uncertainty (μA/A) at frequency					Type A or B	Distribution
	55 Hz	1 kHz	10 kHz	50 kHz	100 kHz		
reproducibility	2	3	5	6	7	A	Normal
Reference standard	50	50	50	70	117	B	Normal
n coefficient of standard	50	50	50	50	50	B	Rectangular
standard drift	30	30	40	40	40	B	Rectangular
set-up procedure:							
standard voltmeter stability	0,5e-3	0,5e-3	0,5e-3	0,5e-3	0,5e-3	B	Rectangular
travel. voltmeter stability	5,5e-3	5,5e-3	5,5e-3	5,5e-3	5,5e-3	B	Rectangular
DC source uncertainty	16	16	3	3	3	B	Normal
amplifier uncertainty	55	55	50	50	50	B	Rectangular
connectors AC-DC difference	7	7	10	10	12	B	Rectangular

Combined unc (*k*=1):	31,71	31,71	42,67	49,21	68,08

Expanded unc:	91	91	96	104	141

NPL, United Kingdom

Table 1 - Break Down of Uncertainty Calculations for Current Level of 10 mA								
	Divisor	***10 Hz***	***55 Hz***	***1 kHz***	***10 kHz***	***20 kHz***	***50 kHz***	***100 kHz***
Freq Dependant Bridge Errors	Rectangular	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Typical Scatter	Normal	3.0	3.0	3.0	3.0	3.0	3.0	3.0
Freq Dependant Bridge Errors	Rectangular	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Typical Scatter	Normal	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Level Dependancy	Rectangular	0.6	0.0	0.0	0.0	0.0	0.0	0.0
Network/Potential of Housing	Rectangular	3.0	3.0	3.0	4.0	5.0	6.0	10.0
Repeatability	Normal	2.0	1.2	1.1	2.0	1.6	1.9	1.9
rss x2		**11.2**	**10.7**	**10.6**	**12.4**	**13.5**	**15.2**	**22.1**
Degrees of Freedom		**>100**	**>100**	**>100**	**>100**	**>100**	**>100**	**>100**

Table 2 - Break Down of Uncertainty Calculations for Current Level of 5 A								
	Divisor	***10 Hz***	***55 Hz***	***1 kHz***	***10 kHz***	***20 kHz***	***50 kHz***	***100 kHz***
Build Up Uncertainty	Rectangular	11.0	7.7	9.4	7.8	8.1	10.3	13.3
Level Dependancy	Rectangular	24.0	6.0	0.0	0.0	0.0	0.0	0.0
Network/Potential of Housing	Rectangular	7.0	7.0	7.0	7.0	25.0	40.0	80.0
Freq Dependant Bridge Errors	Rectangular	2.0	2.0	2.0	2.0	2.0	2.0	2.0
Typical Scatter	Normal	1.0	1.0	1.0	1.0	1.0	1.0	1.0
Repeatability	Normal	5.6	1.0	1.2	1.1	1.8	4.3	16.4
rss x2		**55.9**	**24.5**	**24.0**	**21.6**	**52.9**	**83.2**	**165.5**
Degrees of Freedom		**>100**	**>100**	**>100**	**>100**	**>100**	**>100**	**>100**

VNIIM, Russia

Measurement Current : 10 mA

Contribution of:	Standard Uncertainty (μA/A) at frequency							Type A or B	Distri-bution
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz		
Reference Standard	1.1	1.1	1.1	1.1	1.1	1.2	1.5	U_B	
Setup	0.15	0.15	0.15	0.15	0.15	0.15	0.15	U_B	
Capacitance between thermal converters	0.07	0.07	0.07	0.07	0.07	0.15	0.15	U_B	
Temperature fluctuations	0.28	0.28	0.28	0.28	0.28	0.28	0.28	U_B	
Type A	0.5	0.8	0.13	0.56	0.58	0.33	0.51	U_A	

Combined unc (*k*=1):	1.26	1.41	1.16	1.28	1.29	1.27	1.33
Expanded unc:	1.3	1.4	1.2	1.3	1.3	1.3	1.3

Measurement Current : 5 A

Contribution of:	Standard Uncertainty (μA/A) at frequency							Type A or B	Distri-bution
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz		
Reference Standard	1.5	1.5	1.5	1.5				U_B	
Setup	0.15	0.15	0.15	0.15				U_B	
Temperature fluctuations	0.28	0.28	0.28	0.28				U_B	
Capacitance between reference and shunt	0.07	0.07	0.07	0.07				U_B	
Type A	1.3	1.1	0.73	0.5				U_A	

Combined unc (*k*=1):	2.0	1.9	1.7	1.6			
Expanded unc:	2.0	2.0	1.7	1.6			

CCEM Key International Comparison of AC-DC Current Transfer Standards CCEM-K12

Technical Protocol

1. Scope

The Mutual Recognition Arrangement (MRA) states that its technical basis is a set of results obtained in a course of time through key comparisons carried out by the Consultative Committees of the CIPM, the BIPM and the Regional Metrology Organisations (RMOs). As part of this process, the CIPM Consultative Committee for Electricity and Magnetism (CCEM) decided at its 23rd meeting in September 2002 on a Key International Comparison of AC-DC Current Transfer Standards CCEM-K12, with the National Measurement Institute, Australia (NMIA) as the pilot laboratory and the support group consisting of National Institute of Standards and Technology (NIST) and Justervesenet (JV).

2. Definition of the Measurand

Ac-dc current transfer difference is defined as

$$\delta = \frac{I_{ac} - I_{dc}}{I_{dc}}$$

where

I_{ac} is an rms ac current, and
I_{dc} is a dc current which, when reversed, produces the same mean output response as the rms ac current.

Differences are expressed in microamperes per ampere (μA/A) and a positive sign signifies that more ac than dc current was required for the same output response.

3. The Travelling Standards

- **10 mA**

The travelling standard for the current of 10 mA is a Single-Junction Thermal Converter, Serial Number 1001-2003, manufactured by NMIA. It has the following nominal parameters:

Rated Input Current:	10 mA
Heater Resistance:	25 Ω
Thermocouple Resistance:	7 Ω
Output Voltage at Rated Current:	7.6 mV

The Thermal Converter has a UHF-type input connector and a type 10SL-4S output connector.

- **5 A**

The 5 ampere travelling standard comprises a 0.2 Ω coaxial shunt, Serial No S10 and a 1 V single junction thermal converter, serial number 251 - 2003. Both have been manufactured at NMIA. Their main parameters are as follows:

Current Shunt, Serial No S10

Nominal Resistance	0.2 Ω
Power coefficient of resistance	<0.5 μΩ/Ω/W
Input Connector	UHF
Output Connector	N-female

Thermal Converter, Serial No 251 - 2003

Rated Input Voltage:	1 V
Input Resistance:	475 Ω
Thermocouple Resistance:	7 Ω
Output Voltage at Rated Voltage:	6.2 mV

The 5 A travelling standard is supplied with two Perspex supports, for the Thermal Converter and for the input side of the shunt respectively. When assembled correctly the travelling standard can be positioned firmly on a flat surface (see Figure 1).

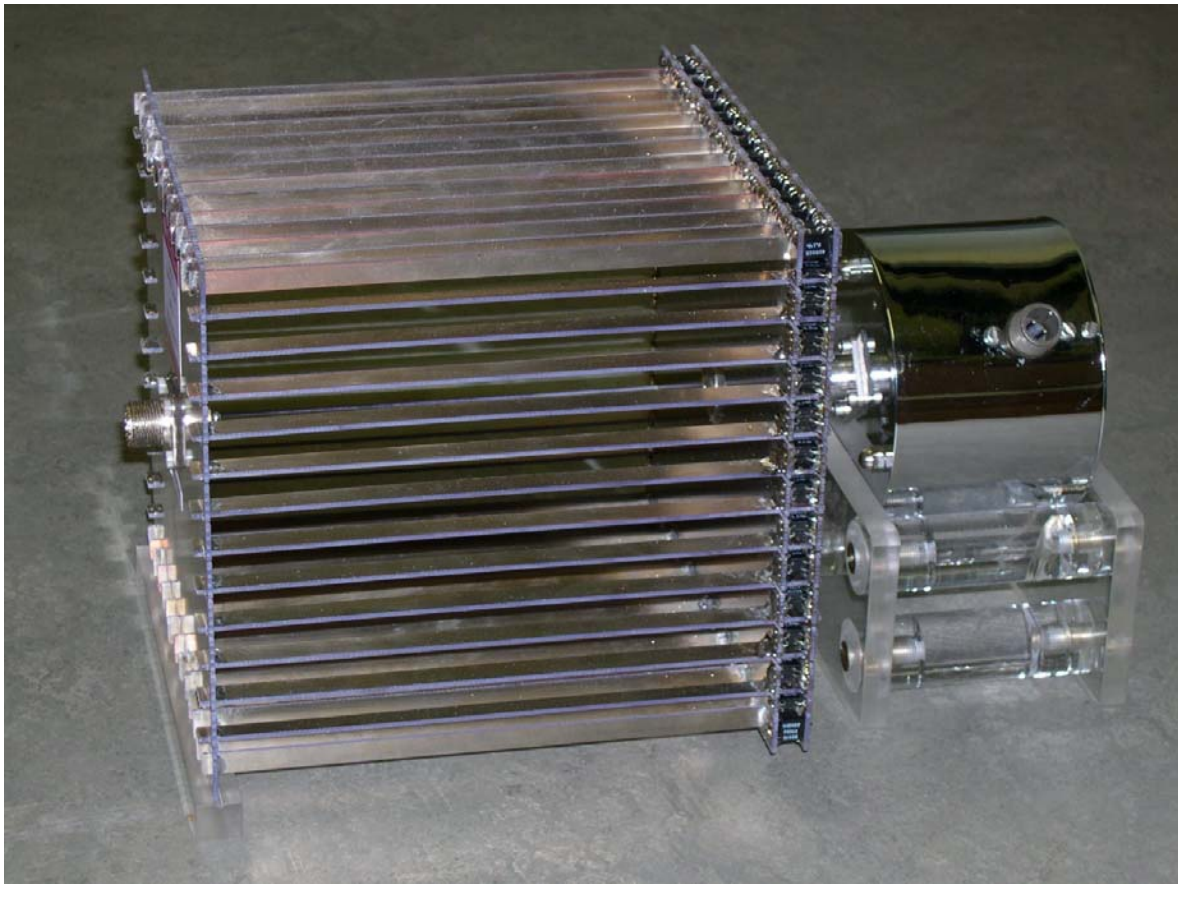

Figure 2 Physical layout of the 5A travelling standard

4. Measurement Conditions

- Upon receiving the package, check input and output resistances of the two thermal converters. Check also that there is a high resistance (>100 MΩ) between the input and the output. In making these preliminary measurements, make sure not to exceed the nominal current of the thermal converters and 100 V between the heater and the thermocouple. In case of any failure, inform the pilot laboratory immediately.
- The ac-dc transfer difference is to be measured for the “Lo” position of the travelling standard, i.e. with both its input and output earthed. The connection to earth must remain at all times to protect the thermocouple.
- Care should be taken not to apply current above nominal, which may destroy the travelling standards.
- Recommended ambient conditions are temperature (23±1)°C and relative humidity (50±5)%.
- At least 30 minutes should be allowed for stabilisation after the fist application of current.
- The measurement frequency should be within 1 % of its nominal value. The frequency and its uncertainty must be reported.
- Sufficient delay time should be used between successive applications of alternating and direct current. Note that the thermal converter used in the 5A travelling standard has a time constant of approximately 4 seconds.

5. Measuring Scheme

The ac-dc difference of each travelling standard should be measured at its nominal current and the following frequencies:

Mandatary: 10 Hz, 55 Hz, 1 kHz, 10 kHz
Optional: 20 kHz, 50 kHz, 100 kHz.

6. Measurement Uncertainty

A detailed uncertainty analysis and an uncertainty budget in accordance with the ISO Guide to the Expression of Uncertainty in Measurement should be reported.

To have a more comparable uncertainty evaluation a list of principal uncertainty contributions is given, but the uncertainty contributions will depend on the measuring methods used.

- reference standard(s);
- step-up procedure;
- measuring set-up;
- level dependence, e.g. due to dc-effects;
- connectors;
- temperature;
- measurement frequency;
- reproducibility;

7. Report of the Comparison

Each participant is asked to submit a report within one month after completing the measurements. The report should contain at least the following:

- Detailed description of the measurement setup and the reference standard;
- Definition of the measurand;
- Detailed description of the measurement procedure;
- A statement of traceability, if the national standard is not considered to be a primary standard
- The measurement results;
- The ambient conditions of the measurement: the temperature and the humidity with limits of variation
- A complete uncertainty budget in accordance with the principles of the ISO Guide to the Expression of Uncertainty in Measurement.

The participants are also asked to report a summary of the measurement results, Appendix 1. Please also send the report and the summary by e-mail.

The pilot laboratory will inform a participating laboratory if there is a large deviation between the results of the laboratory and the preliminary reference values. No other information on the results will be communicated before the completion of the circulation.

8. Transportation and Customs

- Transportation is at each laboratory's own responsibility and cost. Due to the time constraints please use a recognised courier service e.g. UPS or DHL for the transport of the travelling standard. Do not use a forwarding agent that does not guarantee an adequate delivery time, inclusive of the time for customs procedure
- The case will be transported with an ATA Carnet for customs clearance. Please take special care to ensure that the carnet always stays with the package.
- On receipt of the case, unpack the devices carefully and check for any damage. The list of contents of the packing case should also be checked. Also check carefully that the carnet has been stamped on entry into your country.
- Before sending the case out, check the packing list and ensure everything is enclosed. Ensure that the carnet is packed outside the case for easy access by Customs and ensure that the carnet is stamped by Customs on exit from your country.

9. Circulation of the Travelling Standards

The time schedule is shown in Table 1. As the comparison must to be finished within a reasonable period of time, only six weeks are allowed for each participant, including the time of transportation.

Table 1
Schedule for the CCEM-K12 Key Comparison of Ac-dc Current Transfer

Dates	Laboratory
to Mar 2005	***NMIA***
05 Apr 2005 - 16 May 2005	NRC
17 May 2005 - 27 Jun 2005	INTI
28 Jun 2005 - 08 Aug 2005	***NIST***
09 Aug 2005 - 19 Sep 2005	PTB
20 Sep 2005 - 31 Oct 2005	BEV
01 Nov 2005 - 12 Dec 2005	***JV***
13 Dec 2005 - 23 Jan 2006	SP
24 Jan 2006 - 06 Mar 2006	NPL
07 Mar 2006 - 17 Apr 2006	***NMIA***
18 Apr 2006 - 29 May 2006	VNIIM
30 May 2006 - 10 Jul 2006	SPRING
11 Jul 2006 - 21 Aug 2006	***NMIA***

* Bold letters indicate the pilot laboratory and support group

If unforeseen circumstances prevent a laboratory from carrying out its measurements within the agreed time period, it should send the travelling standard without delay to the laboratory next in line. If time permits, the laboratory will be able to carry out measurements at a later time.

10. Organisation

The pilot laboratory for the comparison is the National Measurement Institute, Australia (NMIA). The support group consists of Mr Joe Kinard, National Institute of Standards and Technology, USA (NIST) and Dr Harald Slinde, Justervesenet, Norway (JV).

The travelling standards will be dispatched from NMIA around April 2004 and will return after the completion of each loop. The number of loops will depend on the number of participants.

Please inform the pilot laboratory of the arrival of the package by e-mail or fax. Please inform the pilot laboratory again of the details when sending the package to the next participant, and also inform the next participant by e-mail or fax. A relevant fax form is enclosed in Appendix 4. Prepare the transport to the next participant so the travelling standard can be sent immediately after the measurements are completed.

Each participating laboratory covers the costs of the measurement, transportation and customs clearance as well as for any damage that may occur within its country. The pilot laboratory covers the overall costs for the organisation of the comparison. The pilot laboratory has no insurance for any loss or damage of the travelling standard.

11. Comparison Coordinator

Any questions related to the Comparison should be directed the Comparison Coordinator:

Dr Ilya Budovsky

National Measurement Institute
PO Box 264
Lindfield NSW 2070
Australia

phone: (+61 2) 8467 3541
fax: (+61 2) 8467 3783
email: ilya.budovsky@nmi.gov.au

Appendix 1. Summary of Results

CCEM Key International Comparison of AC-DC Current Transfer Standards CCEM-K12

Please also send this information by e-mail.

Institute:

Date of measurements:

Remarks:

Measurement Results:

Current	Measured ac-dc current difference / 10^{-6} at frequency						
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
10 mA							
5A							

Expanded Uncertainty:

Current	Expanded Uncertainty / 10^{-6} at frequency						
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
10 mA							
5A							

Measurement Frequency:

Current	Nominal Frequency						
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
Meas. Frequency							
Expanded Uncertainty							

Environmental parameters:

	Min	Max	Remarks
Ambient temperature (ºC)			
Relative humidity (%)			

Appendix 2. Summary of Uncertainty Budget

CCEM Key International Comparison of AC-DC Current Transfer Standards CCEM-K12

Please also send this information by e-mail.

Institute:

Date:

Remarks:

Measurement Current : 10 mA

Contribution of:	Standard Uncertainty / 10^{-6} at frequency							Type A or B	Distri-bution
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz		

Combined unc (*k*=1):							
Expanded unc:							

Measurement Current : 5 A

Contribution of:	Standard Uncertainty / 10^{-6} at frequency							Type A or B	Distri-bution
	10 Hz	55 Hz	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz		

Combined unc (*k*=1):							
Expanded unc:							

Appendix 3. Packing List

CCEM Key International Comparison of AC-DC Current Transfer Standards CCEM-K12

1. Single Junction Thermal Converter, NMIA Serial No 1001 – 2003
2. Single Junction Thermal Converter, NMIA Serial No 251 – 2003
3. Current Shunt, NMIA Serial No S10
4. Thermal Converter Output Cable
5. Supports (2)
6. This Protocol

Appendix 4 Forms for Notifying Receipt and Shipment of Artefact

CCEM Key International Comparison of AC-DC Current Transfer Standards CCEM-K12

ARTEFACTS RECEIVED

To:…*(sender and coordinator)*….

The package was received at …….*(name of laboratory)*…. on …*(date)*..

The condition when it was received was *in good physical and working order

*damaged – *(explain)*

____
(name of participant)

ARTEFACTS SHIPPED

To: *(recipient and coordinator)*

The package was shipped through ….*(shipper)*….. on …*(date)*.. The shippers agent in the recipient country is …………*(agent name and contact details)*……………………..

Shipping Details:

Expected date of arrival at destination country:…………..

Shipped: door-to-door / port –to – port

Air Way Bill No. (house): ………………….

If available: Master Air Way Bill No:
Flight details:

____
(Name of Participant)