APMP reference no. APMP.EM-K9

APMP International Comparison of High Voltage AC-DC Transfer Standards

Final Report

Yih-Cheng Wei, Hsin-Da Yeh

Center for Measurement Standards (CMS), ITRI
Chinese Taipei

APMP International Comparison of High Voltage AC-DC Transfer Standards

1. Introduction

This comparison has offered the same range and frequencies as CIPM key comparison CCEM-K9 with the view of providing the National Metrology Institutes (NMI) of the APMP member economies with an opportunity to link the values of their standards for ac-dc transfer difference to the international reference values. Center for Measurement Standards (CMS)/ITRI, Chinese Taipei, was assigned as the pilot laboratory for this program.

2. Definition of the Measurand

AC-DC transfer difference is defined as

$$\delta = \frac{V_{\mathrm{ac}} - V_{\mathrm{dc}}}{V_{\mathrm{dc}}}$$

where

V_{ac} is an rms ac voltage, and

V_{dc} is a dc voltage, which produces the same mean output response, when reversed, as the rms ac voltage.

AC-DC difference is expressed in microvolt per volt (μV/V), and a positive sign means that more ac voltage than dc voltage is required for the same output response.

3. The Travelling Standard

The travelling standard is a CMS (Chinese Taipei) made single junction thermal voltage converter (SJTC), part number 011, with a Fluke 792A-7002 1000 V Range Resistor, serial number 6840001. The nominal parameters are:

Rated input voltage: 1000 V
Resistance of 792A-7002: 200 kΩ
Single Junction Thermal Element:
Rated current: 5 mA
Heater resistance: 90 Ω
Couple resistance: 8 Ω
Output voltage: ~ 7 mV
Insulation: 100 VDC

The SJTC of the travelling standard was destroyed near to the end of the comparison during the measurements in PTB. PTB replaced the SJTC with a 400-Ω PMJTC of IPHT/PTB manufacture.

4. Test Points

The ac-dc difference of the travelling standard should be measured with 500 V and 1000 V applied at the following frequencies: 1 kHz, 10 kHz, 20 kHz, 50 kHz and 100 kHz.

5. Reports

Each participant was asked to submit a report within one month after completing the measurements. All reports have been received and contain at least the following:

5.1 Detailed descriptions of uncertainty budget, following the principles of the ISO Guide to the Expression of Uncertainty in Measurement, including individual uncertainty components, standard uncertainties and degrees of freedom.
5.2 The mean value of the results, their standard deviation and the number of measurements.
5.3 Detailed descriptions of the measurement procedure

6. Participants and Schedule

The list of the participants and time schedule is shown in Table 1. Each participant had a time slot of two months, including measurement and transportation.

Table 1 Participants of APMP.EM-K9

Economy	NMI	Period of Measurement	Responsible Person	Traceability	Voltage Level of Traceability
Chinese Taipei	CMS	6-7/2000	Yih-Cheng Wei	PTB	1 V - 3 V
Hong Kong	SCL	8-11/2000	Y.K.Yan	NPL, UK	0.5 V - 1000 V
Malaysia	SIRIM	12/2000-1/2001	Abdul Rashid Bin Zainal Abidin	NMIA	600 V, 1000 V
Australia	NMIA	2-5/2001	Ilya Budovsky	NMIA	1 V - 3 V
Chinese Taipei	CMS	6-7/2001	Yih-Cheng Wei	PTB	1 V - 3 V
South Africa	NMISA (CSIR)	8-9/2001	Moses L Temba, Flippie Prinsloo	PTB	1 V - 3 V
India	NPLI (NPL)	10-11/2001	V. K. Rustagi, Anil Kumar Govil	NPLI (NPL)	1 V - 3 V
Thailand	NIMT	12/2001-3/2002	Ajchara Charoensook, Chalit Kumtawee	PTB	500 V, 1000 V
Vietnam	VMI	4-5/2002	Nguyen Anh Son	NMIA	1 V - 3 V
Singapore	NMC	8-9/2002	Liu Lingxiang, Jing Tao	NPL, UK	500 V, 1000 V
Japan	NMIJ (AIST)	10-11/2002	Hiroyuki Fujiki	NMIJ (AIST)	5 V
Germany	PTB	12/2002-1/2003	Manfred Klonz	PTB	1 V - 3 V
New Zealand	MSL	2-11/2003	Murray D Early	NMIA	200 V
Chinese Taipei	CMS	12/2003-1/2004	Yih-Cheng Wei, Hsin-Da Yeh	PTB	1 V - 3 V

7. Measurement results

The measuring methods used in different NMIs have been described in more or less detail in their reports. They use an automatic system to compare the travelling standards against their reference standards. In general the AC-DC measurement consists of an input sequence DC+, AC, DC-, AC, etc…. Each time, either the output voltages of both thermal converters are directly measured (dual-channel method), or one of them only and the difference between them (“differential” method). The number of measurements differ from one institute to another.

The summaries of measurement results are listed in Table 2 and Table 3.

PTB_1: Results are measured after a 400 Ω PMJTC replaced the destroyed SJTC in PTB.

Table 2(a) Measured AC-DC difference δ and its expanded uncertainty (95 %) U in μV/V at 500 V measurement

NMI	1 kHz		10 kHz		20 kHz		50 kHz		100 kHz	
	δ	U	δ	U	δ	U	δ	U	δ	U
CMS (averaged)	-4.2	20	-12.5	20	-29.4	20	-120	34	-417	40
SCL	1	16	-15	18	-28	23	-124	48	-421	76
SIRIM	-0.3	14	-10.7	15	-26.1	17	-121.5	26	-418.5	36
NMIA	-0.8	9	-6.3	9	-20.6	10	-110	15	-403	23
NMISA	3.4	30	-3.7	30	-17.7	30	-25.9	30	-32.5	80
NPLI	9.9	16	-4.6	16	-16.1	21	-121	32	-447	51
NIMT	0	24	-5	24	-18	24	-115	24	-420	42
VMI	-1.2	30	-9.4	30	-27	31	-117	65	-433	72
NMC	-3	14	-10	12	-28	16	-125	24	-418	42
NMIJ	0.9	11	-7.6	12	-22	13	-110	19	-401	36
PTB	-2.1	8	-9.5	8	-25	8	-117	10	-415	22
PTB_1	0.4	8	-0.9	8	-1.7	8	2.7	10	29.7	22
*	**-2.1**		**-9.5**		**-25**		**-117**		**-415**	
MSL	2	18	2	18	0	18	6	22	43	28
*	**-0.5**		**-6.6**		**-23.3**		**-113.7**		**-401.7**	

***** values adjusted to the PTB result with SJTC

The MSL's values are adjusted by adding the difference of the PTB's values between the SJTC and the new PMJTC to the MSL's value with the new PMJTC as the following equation:

$$\delta_{\mathrm{MSL}}^{\mathrm{SJTC}} = \delta_{\mathrm{MSL}}^{\mathrm{PMJTC}} + \left(\delta_{\mathrm{PTB}}^{\mathrm{SJTC}} - \delta_{\mathrm{PTB}}^{\mathrm{PMJTC}}\right)$$

Table 2(b) Measured AC-DC difference δ and its expanded uncertainty (95 %) U in μV/V at 500 V measurement by CMS

NMI	1 kHz		10 kHz		20 kHz		50 kHz		100 kHz		Period of Measurement
	δ	U	δ	U	δ	U	δ	U	δ	U	
CMS	-4	20	-12	20	-29	20	-121	34	-420	40	6,7/2000
CMS	-7	20	-16	20	-33	20	-125	34	-435	40	6,7/2001
CMS	1	20	-1	20	-3	20	7	34	49	40	12/2003,1/2004
*	**-1.5**		**-9.6**		**-26.3**		**-112.7**		**-395.7**		
CMS (averaged)	-4.2	20	-12.5	20	-29.4	20	-120	34	-417	40	

***** values adjusted to the PTB result with SJTC

Table 3(a) Measured AC-DC difference δ and its expanded uncertainty (95 %) U in μV/V at 1000 V measurement

NMI	1 kHz		10 kHz		20 kHz		50 kHz		100 kHz	
	δ	U	δ	U	δ	U	δ	U	δ	U
CMS (averaged)	-6.4	20	-18.3	20	-40	26	-145	40	-458	48
SCL	0	16	-14	18	-30	30	-	-	-	-
SIRIM	-1.1	15	-8.1	17	-23.5	19	-101	32	-378.6	45
NMIA	-0.9	11	-6.3	14	-21	16	-109	28	-397	41
NMISA	5.6	40	2.9	40	-11	40	-11.1	40	-8.1	100
NPLI	-1.95	21	-11.3	21	-34.3	26	-149	42	-485	71
NIMT	1	24	-9	24	-26	28	-115	42	-413	81
VMI	-	-	-	-	-	-	-	-	-	-
NMC	-0.7	11	-12	13	-34	24	-127	34	-418	62
NMIJ	0	12	-8.5	12	-23	13	-108	20	-391	39
PTB	-1.5	8	-10.5	8	-25	8	-119	10	-420	30
PTB_1	0.6	8	-2.5	8	-2.0	8	1.8	10	28.2	30
*	**-1.5**		**-10.5**		**-25**		**-119**		**-420**	
MSL	-2	20	-4	20	-6	20	1	24	43	30
*	**-4.1**		**-12**		**-29**		**-119.8**		**-405.2**	

* values adjusted to the PTB result with SJTC

Table 3(b) Measured AC-DC difference δ and its expanded uncertainty (95 %) U in μV/V at 1000 V measurement by CMS

NMI	1 kHz		10 kHz		20 kHz		50 kHz		100 kHz		Period of Measurement
	δ	U	δ	U	δ	U	δ	U	δ	U	
CMS	-8	20	-19	20	-40	26	-147	40	-461	48	6,7/2000
CMS	-12	20	-22	20	-45	26	-150	40	-472	48	6,7/2001
CMS	3	20	-6	20	-12	26	-18	40	7	48	12/2003,1/2004
*	**0.9**		**-14**		**-35**		**-138.8**		**-441.2**		
CMS (averaged)	-6.4	20	-18.3	20	-40	26	-145	40	-458	48	

* values adjusted to the PTB result with SJTC

8. Determination of the Reference Values

The reference values for the APMP.EM-K9 are based on the results of two participants, NMIA (Australia) and PTB (Germany). Both laboratories have an independent realization of primary standards for ac-dc difference [1][2] and also participated in CCEM-K9 (2000-2002) [3].

For each test point, the APMP.EM-K9 reference value $\delta_{\mathrm{REF-APMP}}$ and its standard uncertainty $u_{\mathrm{REF-APMP}}$ have been calculated from the results of these two laboratories given by [4]:

$$\delta_{\mathrm{REF-APMP}} = u^2_{\mathrm{REF-APMP}} \sum \delta_{\mathrm{LAB_i}} / u^2_{\mathrm{LAB_i}}$$

where $$u^2_{\mathrm{REF-APMP}} = \left(\sum 1/u^2_{\mathrm{LAB_i}}\right)^{-1}$$

The reference values for APMP.EM-K9 with their expanded uncertainty at 95% confidence interval, $U_{\mathrm{REF-APMP}}$, are shown as Table 4.

Table 4 APMP reference values $\delta_{\mathrm{REF-APMP}}$ and its expanded uncertainty (95 %) $U_{\mathrm{REF-APMP}}$ in μV/V

Voltage	1 kHz		10 kHz		20 kHz		50 kHz		100 kHz	
	δ	U	δ	U	δ	U	δ	U	δ	U
500 V	-1.5	6.0	-8.1	6.0	-23.3	6.3	-115	8.4	-409	16
1000 V	-1.3	6.5	-9.5	7.0	-24.2	7.2	-118	9.5	-412	25

The deviation of each laboratory's results from the APMP.EM-K9 reference value, $D_{\mathrm{LAB-APMP}}$, and its expanded uncertainty, $U_{\mathrm{REF-APMP}}$, are listed in Table 5 and Table 6. The correlation with the reference value for the reference laboratories has been taken into account by using the formula

$$u^2_{\mathrm{LAB-APMP}} = u^2_{\mathrm{LAB}} - u^2_{\mathrm{REF-APMP}}$$

For the remaining laboratories,

$$u^2_{\mathrm{LAB-APMP}} = u^2_{\mathrm{LAB}} + u^2_{\mathrm{REF-APMP}}$$

where u_{LAB} is the uncertainty reported by each laboratory.

Table 5 Deviation $D_{\mathrm{LAB-APMP}}$ from APMP reference value and its expanded uncertainty (95 %) $U_{\mathrm{LAB-APMP}}$ of 500 V measurement in μV/V

NMI	1 kHz		10 kHz		20 kHz		50 kHz		100 kHz	
	D	U	D	U	D	U	D	U	D	U
CMS	-2.7	21	-4.4	21	-6.1	21	-5.2	35	-7.7	43
SCL	2.5	17	-6.9	19	-4.7	24	-9.2	49	-11.7	78
SIRIM	1.2	15	-2.6	16	-2.8	18	-6.7	27	-9.2	39
NMIA	0.7	6.7	1.8	6.7	2.7	7.8	4.9	13	6.3	17
NMISA	4.9	31	4.4	31	5.6	31	88.9	31	377	82
NPLI	11.4	17	3.5	17	7.2	22	-6.2	33	-37.7	54
NIMT	1.5	25	3.1	25	5.3	25	-0.2	26	-10.7	45
VMI	0.3	31	-1.3	31	-3.7	32	-2.2	66	-23.7	74
NMC	-1.5	15	-1.9	14	-4.7	17	-10.2	26	-8.7	45
NMIJ	2.4	12	0.5	13	1.3	14	4.9	21	8.3	39
PTB	-0.6	5.3	-1.4	5.3	-1.7	5.0	-2.2	5.6	-5.7	15
MSL	1.0	19	1.5	19	0.0	19	1.1	24	7.6	32

Table 6 Deviation $D_{\text{LAB-APMP}}$ from APMP reference value and its expanded uncertainty (95 %) $U_{\text{LAB-APMP}}$ of 1000 V measurement in μV/V

NMI	1 kHz		10 kHz		20 kHz		50 kHz		100 kHz	
	D	*U*	*D*	*U*	*D*	*U*	*D*	*U*	*D*	*U*
CMS	-5.1	21	-8.8	21	-15.8	27	-27.1	41	-46.0	54
SCL	1.3	17	-4.5	19	-5.8	31	-	-	-	-
SIRIM	0.2	16	1.4	18	0.7	20	16.9	33	33.4	51
NMIA	0.4	8.9	3.2	12	3.2	14	8.9	26	15.0	33
NMISA	6.9	41	12.4	41	13.2	41	107	41	404	103
NPLI	-0.7	22	-1.8	22	-10.1	27	-31.1	43	-73.0	75
NIMT	2.3	25	0.5	25	-1.8	29	2.9	43	-1.0	85
NMC	0.6	13	-2.5	15	-9.8	25	-9.1	35	-6.0	67
NMIJ	1.3	13	1.0	14	1.2	15	9.9	22	21.0	46
PTB	-0.2	4.7	-1.0	4.0	-0.8	3.6	-1.1	3.4	-8.0	18
MSL	-2.8	21	-2.5	21	-4.8	21	-1.9	26	6.8	39

9. Linking to the CCEM-K9

The results of APMP.EM-K9 can be linked to CCEM-K9 [3]. Both NMIA and PTB took part in both comparisons. Using their results, the difference between the APMP.EM-K9 reference value $\delta_{\text{REF-APMP}}$ and the CCEM-K9 reference value $\delta_{\text{REF-CCEM}}$ can be calculated from:

$$\delta_{\text{REF-APMP}} - \delta_{\text{REF-CCEM}} = \sum w_{\text{LAB}} (D_{\text{LAB-CCEM}} - D_{\text{LAB-APMP}})$$

where $D_{\text{LAB-CCEM}}$ are the deviation from the CCEM reference value of linking laboratories reported in CCEM-K9, shown with corresponding expanded uncertainty in Table 7 and Table 8.

Table 7 Deviation $D_{\text{LAB-CCEM}}$ from CCEM-K9 reference value and its expanded uncertainty (95%) $U_{\text{LAB-CCEM}}$ in μV/V at 500 V measurement

NMI	1 kHz		10 kHz		20 kHz		50 kHz		100 kHz	
	D	*U*	*D*	*U*	*D*	*U*	*D*	*U*	*D*	*U*
PTB	-2.3	7.5	-0.6	7.5	-1.2	7.3	-1.6	9.1	-0.6	20.6
NMIA	1.2	8.8	1.7	8.7	3.0	9.6	7.2	14.5	17.5	21.8

Table 8 Deviation $D_{\mathrm{LAB-CCEM}}$ from CCEM-K9 reference value and its expanded uncertainty (95%) $U_{\mathrm{LAB-CCEM}}$ in μV/V at 1000 V measurement

NMI	1 kHz		10 kHz		20 kHz		50 kHz		100 kHz	
	D	*U*	*D*	*U*	*D*	*U*	*D*	*U*	*D*	*U*
PTB	-0.7	7.4	-1.5	7.2	-2.0	7.1	-2.0	8.7	-3.5	28.3
NMIA	0.8	10.7	2.7	13.7	3.0	15.7	4.9	27.5	12.3	39.8

The weight w_{LAB} is calculated from

$$w_{\mathrm{LAB}} = (1/(t^2{}_{\mathrm{LAB-CCEM}} + t^2{}_{\mathrm{LAB-APMP}} + 2r^2{}_{\mathrm{LAB}})) / \sum 1/(t^2{}_{\mathrm{LAB-CCEM}} + t^2{}_{\mathrm{LAB-APMP}} + 2r^2{}_{\mathrm{LAB}})$$

The $t_{\mathrm{LAB-CCEM}}$ is the transfer uncertainty in the CCEM comparison, calculated from BNM-LNE results of travelling standards S2 and S4, listed in Table 4a and 4b of the "CCEM-K9 comparison of AC-DC high voltage transfer standards" report. $t_{\mathrm{LAB-APMP}}$ is the transfer uncertainty in the APMP comparison, calculated from CMS results. r_{LAB} is the uncertainty associated with the imperfect reproducibility of the laboratory in the period spanning its two measurements in the CCEM and APMP comparisons. Values of r_{LAB} are assumed to be from 1 μV/V to 4 μV/V at frequencies from 1 kHz to 100 kHz for both voltage ranges and for the two linking laboratories. The correction values of $\delta_{\mathrm{REF-APMP}} - \delta_{\mathrm{REF-CCEM}}$ are shown in Table 9 with its expanded uncertainty, $U_{\mathrm{APMP-CCEM}}$. The uncertainties of $u_{\mathrm{APMP-CCEM}}$ have been calculated from

$$\frac{1}{u^2{}_{\mathrm{APMP-CCEM}}} = \sum \frac{1}{t^2{}_{\mathrm{LAB-CCEM}} + t^2{}_{\mathrm{LAB-APMP}} + 2r^2{}_{\mathrm{LAB}}}$$

Table 9 Correction $\delta_{\mathrm{REF-APMP}} - \delta_{\mathrm{REF-CCEM}}$ and its expanded uncertainty (95%) $U_{\mathrm{APMP-CCEM}}$ **in μV/V**

Voltage	1 kHz		10 kHz		20 kHz		50 kHz		100 kHz	
	δ	*U*	δ	*U*	δ	*U*	δ	*U*	δ	*U*
500 V	-0.6	4	0.4	5	0.4	6	1.5	7	8.2	17
1000 V	0.0	5	-0.5	4	-0.7	6	-2.4	7	0.9	14

For the participants of APMP.EM-K9, the deviation of each laboratory's results from the CCEM-K9 reference values, $D_{\mathrm{LAB-CCEM}}$, and its expanded uncertainty, $U_{\mathrm{LAB-CCEM}}$, are listed in Table 10, Table 11 and graphically in Figure 1 to Figure 10.

$$D_{\mathrm{LAB-CCEM}} = D_{\mathrm{LAB-APMP}} - (\delta_{\mathrm{REF-APMP}} - \delta_{\mathrm{REF-CCEM}})$$

and

$$u^2{}_{\mathrm{LAB-CCEM}} = u^2{}_{\mathrm{LAB-APMP}} + u^2{}_{\mathrm{APMP-CCEM}}$$

Table 10 Deviation $D_{\text{LAB–CCEM}}$ from CCEM-K9 reference value and its expanded uncertainty (95%) $U_{\text{LAB–CCEM}}$ in μV/V at 500 V measurement

NMI	1 kHz		10 kHz		20 kHz		50 kHz		100 kHz	
	D	*U*	*D*	*U*	*D*	*U*	*D*	*U*	*D*	*U*
CMS	-2.0	21	-4.8	21	-6.5	22	-6.6	36	-15.9	46
SCL	3.2	18	-7.3	19	-5.1	25	-10.6	49	-19.9	79
SIRIM	1.9	16	-3.0	17	-3.2	19	-8.1	28	-17.4	42
NMIA	1.4	7.8	1.4	7.8	2.3	10	3.4	15	-1.9	23
NMISA	5.6	31	4.0	31	5.2	31	87.5	32	369	83
NPLI	12.1	18	3.1	18	6.8	23	-7.6	34	-45.9	56
NIMT	2.2	25	2.7	25	4.9	26	-1.6	27	-18.9	48
VMI	1.0	31	-1.7	31	-4.1	32	-3.6	66	-31.9	75
NMC	-0.8	16	-2.3	14	-5.1	18	-11.6	27	-16.9	48
NMIJ	3.1	13	0.1	13	0.9	16	3.4	22	0.1	43
PTB	0.1	6.7	-1.8	6.7	-2.1	7.8	-3.6	10	-13.9	22
MSL	1.7	19	1.1	19	-0.4	20	-0.3	25	-0.6	36

Table 11 Deviation $D_{\text{LAB–CCEM}}$ from CCEM-K9 reference value and its expanded uncertainty (95%) $U_{\text{LAB–CCEM}}$ in μV/V at 1000 V measurement

NMI	1 kHz		10 kHz		20 kHz		50 kHz		100 kHz	
	D	*U*	*D*	*U*	*D*	*U*	*D*	*U*	*D*	*U*
CMS	-5.1	22	-8.4	22	-15.1	28	-24.7	42	-46.9	55
SCL	1.3	18	-4.1	20	-5.1	31				
SIRIM	0.2	17	1.8	19	1.4	21	19.3	34	32.5	53
NMIA	0.4	10	3.6	13	3.9	16	11.3	27	14.1	36
NMISA	6.9	41	12.8	41	13.9	41	109	42	403	104
NPLI	-0.6	22	-1.4	22	-9.4	28	-28.7	44	-73.9	76
NIMT	2.3	25	0.9	25	-1.1	30	5.3	44	-1.9	86
NMC	0.6	14	-2.1	15	-9.1	26	-6.7	36	-6.9	68
NMIJ	1.3	14	1.4	14	1.9	16	12.3	23	20.1	48
PTB	-0.2	6.6	-0.6	5.6	-0.1	7.4	1.3	7.7	-8.9	22
MSL	-2.8	22	-2.1	22	-4.1	22	0.5	27	5.9	41

10. Conclusion

The APMP international comparison of high voltage AC-DC transfer standards, P1-APMP.EM-K9, started in 2000 and concluded in 2004. The traveling standard has shown good stability before the PMJTC replaced the destroyed SJTC. For the majority of the participating NMIs, the expanded uncertainty of the deviations from the reference value overlaps the reference value, and they have checked their comparison results against their CMC claims. Tables of the degree of equivalence of all participants are given in appendix 1. The results from the participants are reported as above and have been linked to the CCEM-K9 Key comparison.

References

[1] I. Budovsky and B D Inglis, "High-Frequency AC-DC Differences of NML Single-Junction Thermal Voltage Converters," IEEE Transactions on Instrum. Meas., Vol. 50, No. 1, Feb. 2001, pp 101-105.

[2] M. Klonz, "AC-DC transfer difference of the PTB-Multijunction thermal converter in the frequency range from 10 Hz to 100 kHz," IEEE Transactions on Instrum. Meas., Vol. 36, No 2, June 1987, pp 320-329, 1987.

[3] Andre Poletaeff, "CCEM-K9 comparison of AC–DC high voltage standards", Metrologia, 43, Tech. Suppl., 01001, 2006.

[4] I. Budovsky, "APMP International Comparison of AC-DC Transfer Standards at the Lowest Attainable Level of Uncertainty," IEEE Transactions on Instrum. Meas., Vol. 54, No. 2, April. 2005, pp 795-798.

[5] Andre Poletaeff, "EUROMET 557 comparison EUROMET.EM-K9 of AC–DC high voltage standards," Metrologia, 2006, Vol. 43, Tech. Suppl., 01003.

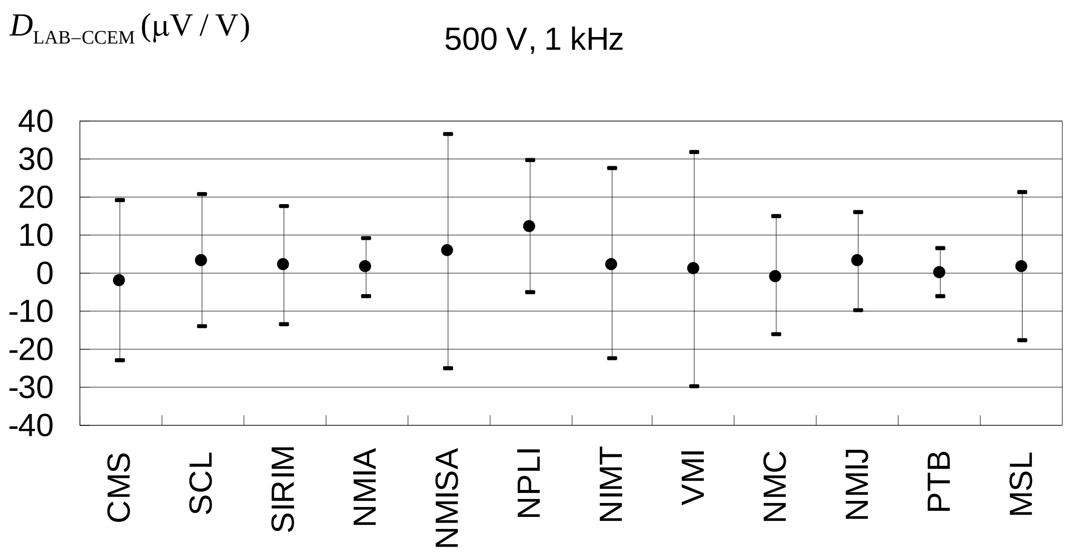

Figure 1 Deviation of 500 V, 1 kHz measurement from CCEM-K9 reference value $D_{LAB-CCEM}$ and expanded uncertainty (95%) $U_{LAB-CCEM}$ in μV/V

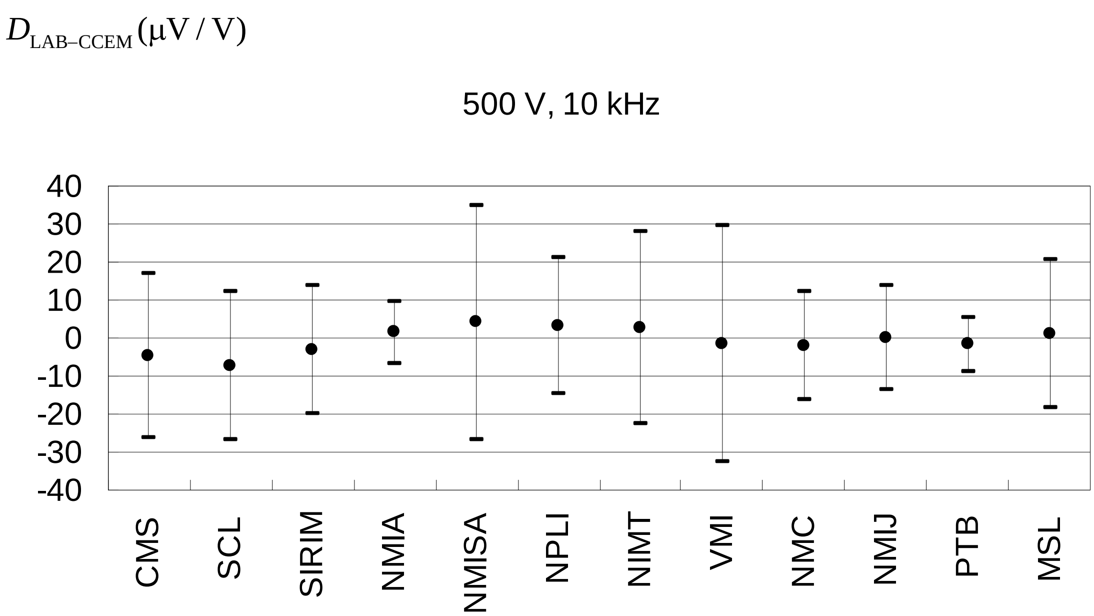

Figure 2 Deviation of 500 V, 10 kHz measurement from CCEM-K9 reference value $D_{LAB-CCEM}$ and expanded uncertainty (95%) $U_{LAB-CCEM}$ in μV/V

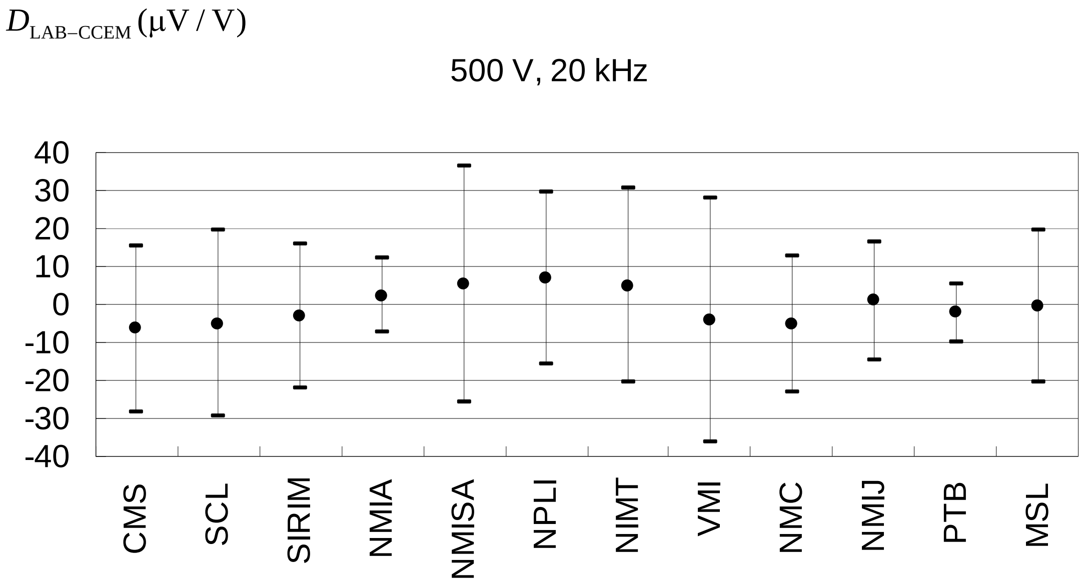

Figure 3 Deviation of 500 V, 20 kHz measurement from CCEM-K9 reference value $D_{LAB-CCEM}$ and expanded uncertainty (95%) $U_{LAB-CCEM}$ in μV/V

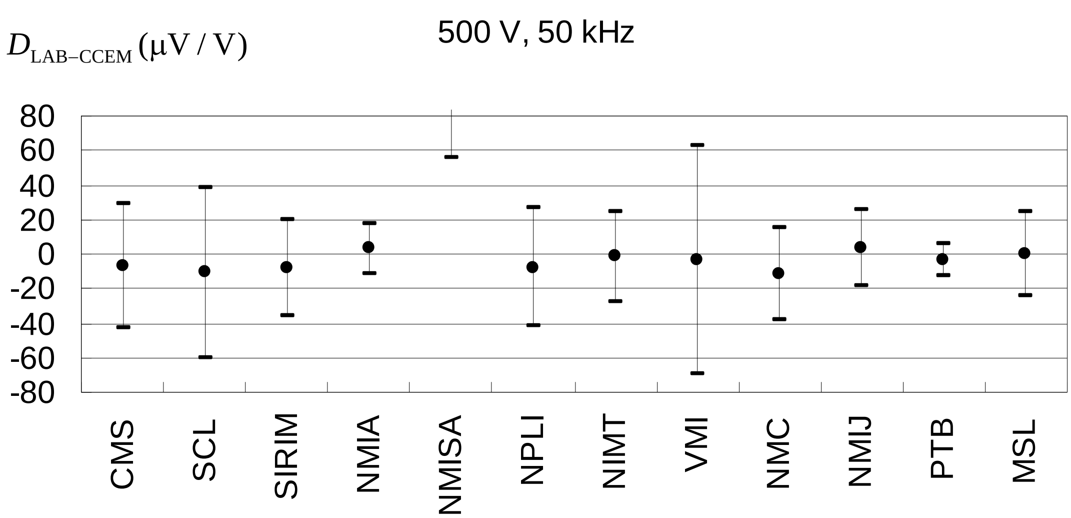

Figure 4 Deviation of 500 V, 50 kHz measurement from CCEM-K9 reference value $D_{LAB-CCEM}$ and expanded uncertainty (95%) $U_{LAB-CCEM}$ in μV/V

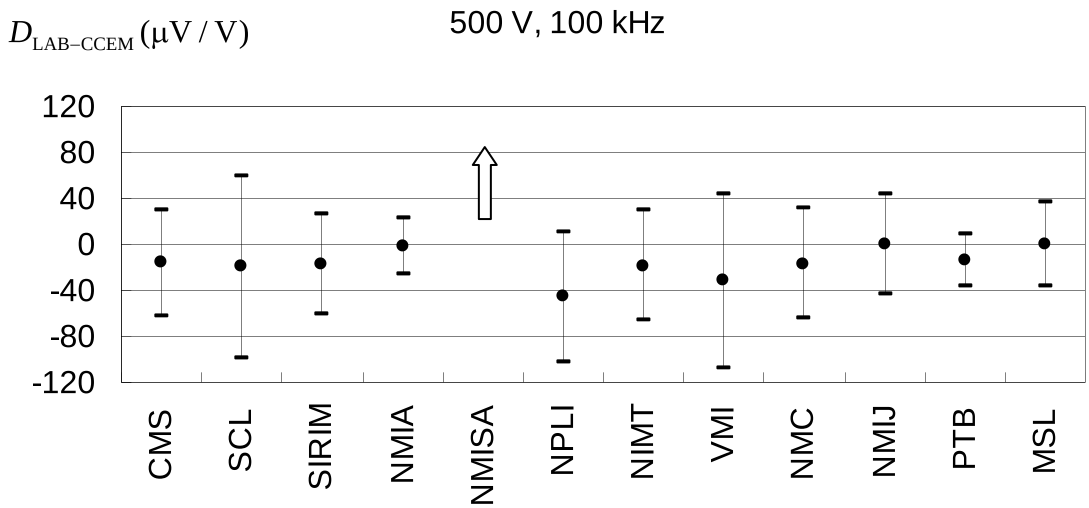

Figure 5 Deviation of 500 V, 100 kHz measurement from CCEM-K9 reference value $D_{LAB-CCEM}$ and expanded uncertainty (95%) $U_{LAB-CCEM}$ in μV/V

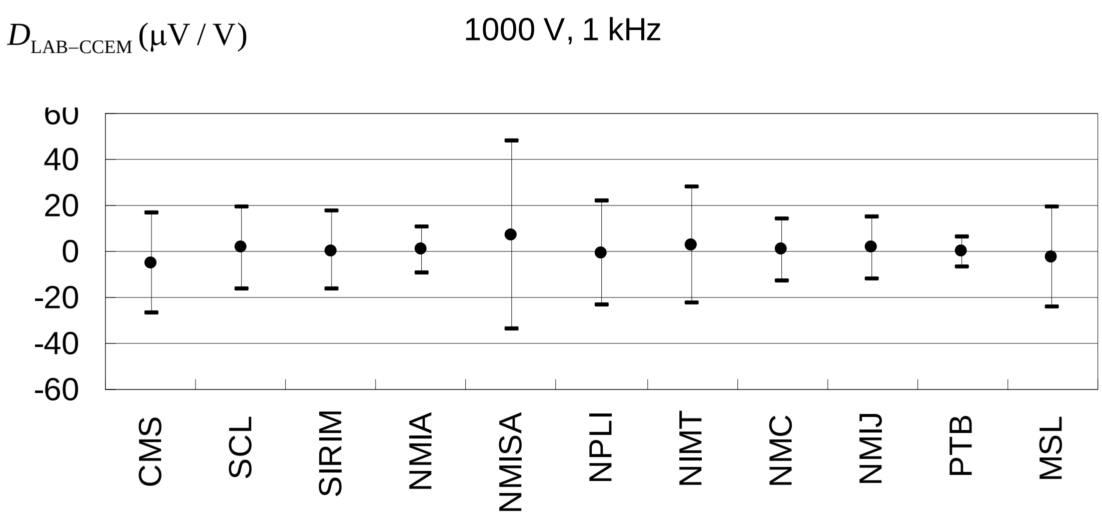

Figure 6 Deviation of 1000 V, 1 kHz measurement from CCEM-K9 reference value $D_{LAB-CCEM}$ and expanded uncertainty (95%) $U_{LAB-CCEM}$ in μV/V

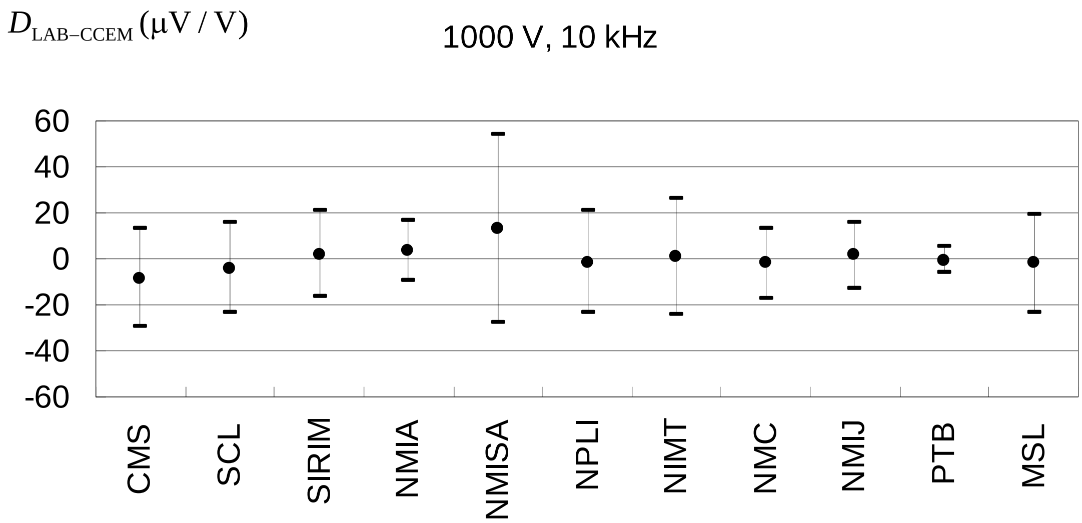

Figure 7 Deviation of 1000 V, 10 kHz measurement from CCEM-K9 reference value $D_{\text{LAB−CCEM}}$ and expanded uncertainty (95%) $U_{\text{LAB−CCEM}}$ in μV/V

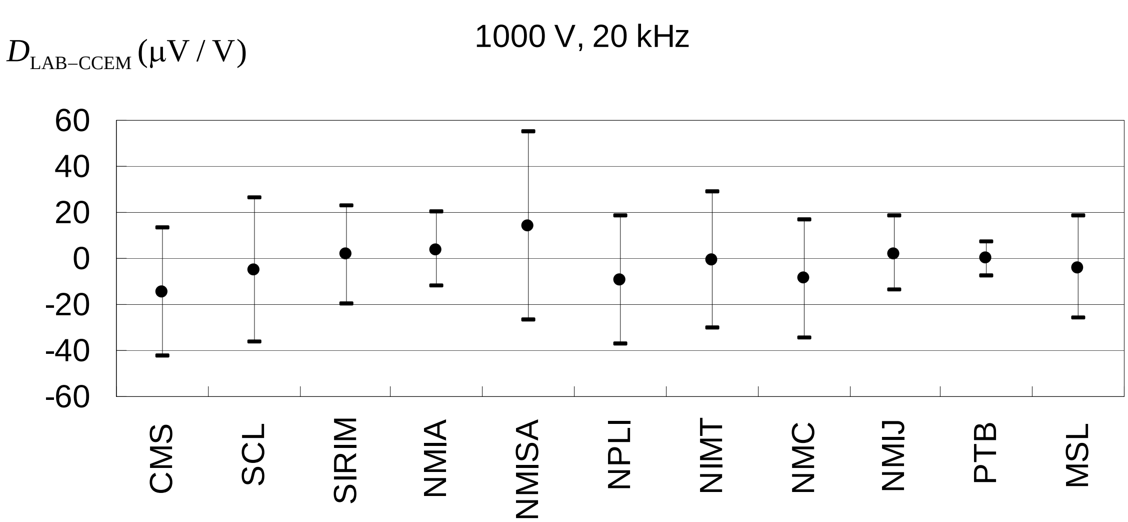

Figure 8 Deviation of 1000 V, 20 kHz measurement from CCEM-K9 reference value $D_{\text{LAB−CCEM}}$ and expanded uncertainty (95%) $U_{\text{LAB−CCEM}}$ in μV/V

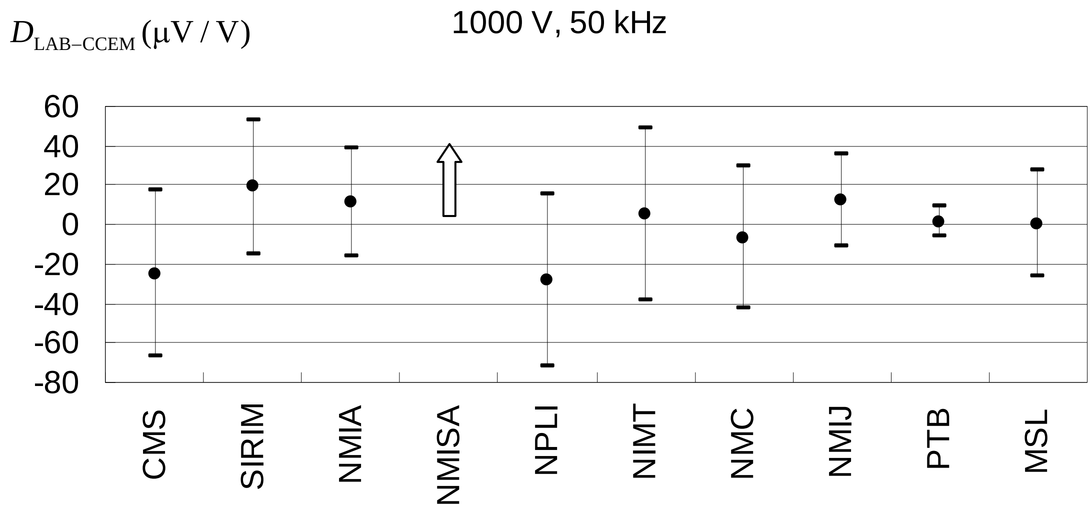

Figure 9 Deviation of 1000 V, 50 kHz measurement from CCEM-K9 reference value $D_{\text{LAB-CCEM}}$ and expanded uncertainty (95%) $U_{\text{LAB-CCEM}}$ in μV/V

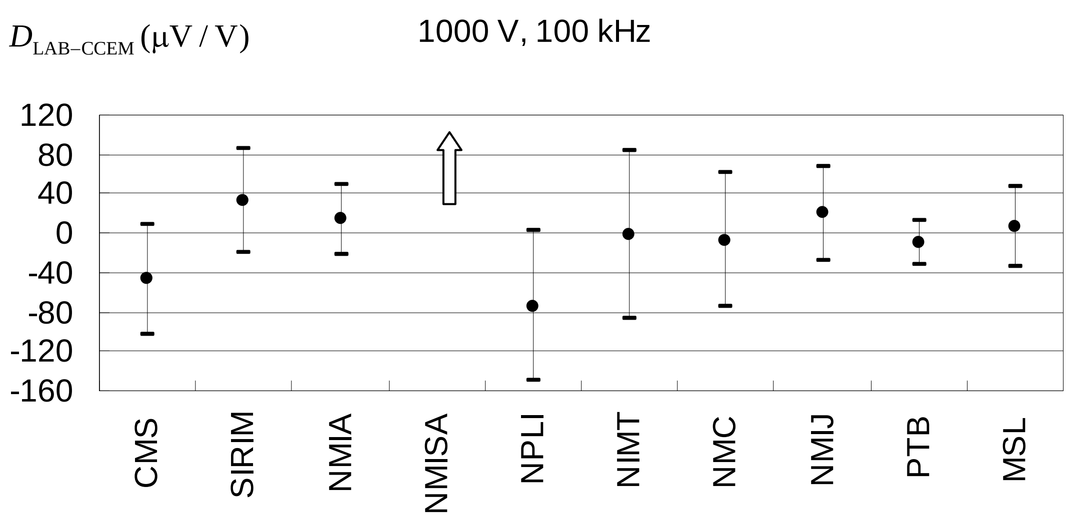

Figure 10 Deviation of 1000 V, 100 kHz measurement from CCEM-K9 reference value $D_{\text{LAB-CCEM}}$ and expanded uncertainty (95%) $U_{\text{LAB-CCEM}}$ in μV/V

Appendix 1 Degree of equivalence between pairs of laboratories

The degree of equivalence between any pair of mutually independent laboratories i and j is given by [5]:

$$D_{\mathrm{i,j}} = d_{\mathrm{i}} - d_{\mathrm{j}}$$

and

$$U^2(D_{\mathrm{i,j}}) = U^2(d_{\mathrm{i}}) + U^2(d_{\mathrm{j}})$$

where d_{i} and d_{j} are the measurement results of laboratories i and j, $U(d_{\mathrm{i}})$ and $U(d_{\mathrm{j}})$ are the expanded uncertainties of these values.

When laboratory i is traceable to laboratory j, $U(D_{\mathrm{i,j}})$ will be given by [5]:

$$U^2(D_{\mathrm{i,j}}) = \left|U^2(d_{\mathrm{i}}) - U^2(d_{\mathrm{j}})\right|$$

Correlations between two laboratories that are traceable to the same third laboratory have been ignored. Tables 12 to 21 show the degrees of equivalence between all the pairs of participating laboratories.

Table 12 Degree of equivalence $D_{\mathrm{i,j}}$ and $U(D_{\mathrm{i,j}})$ at 500 V, 1 kHz in μV/V

	CMS		SCL		SIRIM		NMIA		NMISA		NPLI		NIMT		VMI		NMC		NMIJ		PTB		MSL	
	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}
CMS			-5.2	26	-3.9	24	-3.4	22	-7.6	36	-14.1	26	-4.2	31	-3	36	-1.2	24	-5.1	23	-2.1	18	-3.7	27
SCL	5.2	26			1.3	21	1.8	18	-2.4	34	-8.9	23	1	29	2.2	34	4	21	0.1	19	3.1	18	1.5	24
SIRIM	3.9	24	-1.3	21			0.5	11	-3.7	33	-10.2	21	-0.3	28	0.9	33	2.7	20	-1.2	18	1.8	16	0.2	23
NMIA	3.4	22	-1.8	18	-0.5	11			-4.2	31	-10.7	18	-0.8	22	0.4	29	2.2	16	-1.7	14	1.3	12	-0.3	16
NMISA	7.6	36	2.4	34	3.7	33	4.2	31			-6.5	34	3.4	38	4.6	42	6.4	33	2.5	32	5.5	29	3.9	35
NPLI	14.1	26	8.9	23	10.2	21	10.7	18	6.5	34			9.9	29	11.1	34	12.9	21	9	19	12	18	10.4	24
NIMT	4.2	31	-1	29	0.3	28	0.8	22	-3.4	38	-9.9	29			1.2	38	3	28	-0.9	26	2.1	25	0.5	30
VMI	3	36	-2.2	34	-0.9	33	-0.4	29	-4.6	42	-11.1	34	-1.2	38			1.8	33	-2.1	32	0.9	31	-0.7	35
NMC	1.2	24	-4	21	-2.7	20	-2.2	16	-6.4	33	-12.9	21	-3	28	-1.8	33			-3.9	18	-0.9	16	-2.5	23
NMIJ	5.1	23	-0.1	19	1.2	18	1.7	14	-2.5	32	-9	19	0.9	26	2.1	32	3.9	18			3	14	1.4	21
PTB	2.1	18	-3.1	18	-1.8	16	-1.3	12	-5.5	29	-12	18	-2.1	25	-0.9	31	0.9	16	-3	14			-1.6	20
MSL	3.7	27	-1.5	24	-0.2	23	0.3	16	-3.9	35	-10.4	24	-0.5	30	0.7	35	2.5	23	-1.4	21	1.6	20		

Table 13 Degree of equivalence $D_{i,j}$ and $U(D_{i,j})$ at 500 V, 10 kHz in μV/V

	CMS		SCL		SIRIM		NMIA		NMISA		NPLI		NIMT		VMI		NMC		NMIJ		PTB		MSL	
	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}
CMS			2.5	27	-1.8	25	-6.2	22	-8.8	36	-7.9	26	-7.5	31	-3.1	36	-2.5	23	-4.9	23	-3	18	-5.9	27
SCL	-2.5	27			-4.3	23	-8.7	20	-11.3	35	-10.4	24	-10	30	-5.6	35	-5	22	-7.4	21	-5.5	20	-8.4	25
SIRIM	1.8	25	4.3	23			-4.4	12	-7	34	-6.1	22	-5.7	28	-1.3	34	-0.7	19	-3.1	19	-1.2	17	-4.1	23
NMIA	6.2	22	8.7	20	4.4	12			-2.6	31	-1.7	18	-1.3	22	3.1	29	3.7	15	1.3	14	3.2	12	0.3	16
NMISA	8.8	36	11.3	35	7	34	2.6	31			0.9	34	1.3	38	5.7	42	6.3	32	3.9	32	5.8	29	2.9	35
NPLI	7.9	26	10.4	24	6.1	22	1.7	18	-0.9	34			0.4	29	4.8	34	5.4	20	3	20	4.9	18	2	24
NIMT	7.5	31	10	30	5.7	28	1.3	22	-1.3	38	-0.4	29			4.4	38	5	27	2.6	27	4.5	25	1.6	30
VMI	3.1	36	5.6	35	1.3	34	-3.1	29	-5.7	42	-4.8	34	-4.4	38			0.6	32	-1.8	32	0.1	31	-2.8	35
NMC	2.5	23	5	22	0.7	19	-3.7	15	-6.3	32	-5.4	20	-5	27	-0.6	32			-2.4	16	-0.5	14	-3.4	22
NMIJ	4.9	23	7.4	21	3.1	19	-1.3	14	-3.9	32	-3	20	-2.6	27	1.8	32	2.4	16			1.9	14	-1	21
PTB	3	18	5.5	20	1.2	17	-3.2	12	-5.8	29	-4.9	18	-4.5	25	-0.1	31	0.5	14	-1.9	14			-2.9	20
MSL	5.9	27	8.4	25	4.1	23	-0.3	16	-2.9	35	-2	24	-1.6	30	2.8	35	3.4	22	1	21	2.9	20		

Table 14 Degree of equivalence $D_{i,j}$ and $U(D_{i,j})$ at 500 V, 20 kHz in μV/V

	CMS		SCL		SIRIM		NMIA		NMISA		NPLI		NIMT		VMI		NMC		NMIJ		PTB		MSL	
	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}
CMS			-1.4	30	-3.3	26	-8.8	22	-11.7	36	-13.3	29	-11.4	31	-2.4	37	-1.4	25	-7.4	24	-4.4	18	-6.1	27
SCL	1.4	30			-1.9	29	-7.4	25	-10.3	38	-11.9	31	-10	33	-1	39	0	28	-6	26	-3	24	-4.7	29
SIRIM	3.3	26	1.9	29			-5.5	14	-8.4	34	-10	27	-8.1	29	0.9	35	1.9	23	-4.1	21	-1.1	19	-2.8	25
NMIA	8.8	22	7.4	25	5.5	14			-2.9	32	-4.5	23	-2.6	22	6.4	29	7.4	19	1.4	16	4.4	13	2.7	15
NMISA	11.7	36	10.3	38	8.4	34	2.9	32			-1.6	37	0.3	38	9.3	43	10.3	34	4.3	33	7.3	29	5.6	35
NPLI	13.3	29	11.9	31	10	27	4.5	23	1.6	37			1.9	32	10.9	37	11.9	26	5.9	25	8.9	22	7.2	28
NIMT	11.4	31	10	33	8.1	29	2.6	22	-0.3	38	-1.9	32			9	39	10	29	4	27	7	25	5.3	30
VMI	2.4	37	1	39	-0.9	35	-6.4	29	-9.3	43	-10.9	37	-9	39			1	35	-5	34	-2	32	-3.7	36
NMC	1.4	25	0	28	-1.9	23	-7.4	19	-10.3	34	-11.9	26	-10	29	-1	35			-6	20	-3	18	-4.7	24
NMIJ	7.4	24	6	26	4.1	21	-1.4	16	-4.3	33	-5.9	25	-4	27	5	34	6	20			3	15	1.3	22
PTB	4.4	18	3	24	1.1	19	-4.4	13	-7.3	29	-8.9	22	-7	25	2	32	3	18	-3	15			-1.7	20
MSL	6.1	27	4.7	29	2.8	25	-2.7	15	-5.6	35	-7.2	28	-5.3	30	3.7	36	4.7	24	-1.3	22	1.7	20		

Table 15 Degree of equivalence $D_{i,j}$ and $U(D_{i,j})$ at 500 V, 50 kHz in μV/V

	CMS		SCL		SIRIM		NMIA		NMISA		NPLI		NIMT		VMI		NMC		NMIJ		PTB		MSL	
	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}
CMS			4	59	1.5	43	-10	37	-94.1	45	1	47	-5	42	-3	73	5	42	-10	39	-3	32	-6.3	40
SCL	-4	59			-2.5	55	-14	50	-98.1	57	-3	58	-9	54	-7	81	1	54	-14	52	-7	49	-10.3	53
SIRIM	-1.5	43	2.5	55			-11.5	21	-95.6	40	-0.5	41	-6.5	35	-4.5	70	3.5	35	-11.5	32	-4.5	28	-7.8	34
NMIA	10	37	14	50	11.5	21			-84.1	34	11	35	5	19	7	63	15	28	0	24	7	18	3.7	16
NMISA	94.1	45	98.1	57	95.6	40	84.1	34			95.1	44	89.1	38	91.1	72	99.1	38	84.1	36	91.1	28	87.8	37
NPLI	-1	47	3	58	0.5	41	-11	35	-95.1	44			-6	40	-4	72	4	40	-11	37	-4	34	-7.3	39
NIMT	5	42	9	54	6.5	35	-5	19	-89.1	38	6	40			2	69	10	34	-5	31	2	26	-1.3	33
VMI	3	73	7	81	4.5	70	-7	63	-91.1	72	4	72	-2	69			8	69	-7	68	0	66	-3.3	69
NMC	-5	42	-1	54	-3.5	35	-15	28	-99.1	38	-4	40	-10	34	-8	69			-15	31	-8	26	-11.3	33
NMIJ	10	39	14	52	11.5	32	0	24	-84.1	36	11	37	5	31	7	68	15	31			7	21	3.7	29
PTB	3	32	7	49	4.5	28	-7	18	-91.1	28	4	34	-2	26	0	66	8	26	-7	21			-3.3	24
MSL	6.3	40	10.3	53	7.8	34	-3.7	16	-87.8	37	7.3	39	1.3	33	3.3	69	11.3	33	-3.7	29	3.3	24		

Table 16 Degree of equivalence $D_{i,j}$ and $U(D_{i,j})$ at 500 V, 100 kHz in μV/V

	CMS		SCL		SIRIM		NMIA		NMISA		NPLI		NIMT		VMI		NMC		NMIJ		PTB		MSL	
	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}
CMS			4	86	1.5	54	-14	46	-385	89	30	65	3	58	16	82	1	58	-16	54	-2	33	-15.3	49
SCL	-4	86			-2.5	84	-18	79	-389	110	26	92	-1	87	12	105	-3	87	-20	84	-6	79	-19.3	81
SIRIM	-1.5	54	2.5	84			-15.5	28	-386	88	28.5	62	1.5	55	14.5	80	-0.5	55	-17.5	51	-3.5	42	-16.8	46
NMIA	14	46	18	79	15.5	28			-371	83	44	56	17	35	30	68	15	48	-2	43	12	32	-1.3	16
NMISA	384.5	89	389	110	386	88	371	83			415	95	387.5	90	401	108	386	90	369	88	383	77	369.2	85
NPLI	-30	65	-26	92	-28.5	62	-44	56	-415	95			-27	66	-14	88	-29	66	-46	62	-32	56	-45.3	58
NIMT	-3	58	1	87	-1.5	55	-17	35	-388	90	27	66			13	83	-2	59	-19	55	-5	47	-18.3	50
VMI	-16	82	-12	105	-14.5	80	-30	68	-401	108	14	88	-13	83			-15	83	-32	80	-18	75	-31.3	77
NMC	-1	58	3	87	0.5	55	-15	48	-386	90	29	66	2	59	15	83			-17	55	-3	47	-16.3	50
NMIJ	16	54	20	84	17.5	51	2	43	-369	88	46	62	19	55	32	80	17	55			14	42	0.7	46
PTB	2	33	6	79	3.5	42	-12	32	-383	77	32	56	5	47	18	75	3	47	-14	42			-13.3	36
MSL	15.3	49	19.3	81	16.8	46	1.3	16	-369	85	45.3	58	18.3	50	31.3	77	16.3	50	-0.7	46	13.3	36		

Table 17 Degree of equivalence $D_{i,j}$ and $U(D_{i,j})$ at 1000 V, 1 kHz in μV/V

	CMS		SCL		SIRIM		NMIA		NMISA		NPLI		NIMT		NMC		NMIJ		PTB		MSL	
	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}
CMS			-6.4	26	-5.3	25	-5.5	23	-12	45	-4.45	29	-7.4	31	-5.7	23	-6.4	23	-4.9	18	-2.3	28
SCL	6.4	26			1.1	22	0.9	19	-5.6	43	1.95	26	-1	29	0.7	19	0	20	1.5	18	4.1	26
SIRIM	5.3	25	-1.1	22			-0.2	10	-6.7	43	0.85	26	-2.1	28	-0.4	19	-1.1	19	0.4	17	3	25
NMIA	5.5	23	-0.9	19	0.2	10			-6.5	41	1.05	24	-1.9	21	-0.2	16	-0.9	16	0.6	14	3.2	17
NMISA	12	45	5.6	43	6.7	43	6.5	41			7.55	45	4.6	47	6.3	41	5.6	42	7.1	39	9.7	45
NPLI	4.45	29	-1.95	26	-0.85	26	-1.05	24	-7.55	45			-2.95	32	-1.25	24	-1.95	24	-0.45	22	2.15	29
NIMT	7.4	31	1	29	2.1	28	1.9	21	-4.6	47	2.95	32			1.7	26	1	27	2.5	25	5.1	31
NMC	5.7	23	-0.7	19	0.4	19	0.2	16	-6.3	41	1.25	24	-1.7	26			-0.7	16	0.8	14	3.4	23
NMIJ	6.4	23	0	20	1.1	19	0.9	16	-5.6	42	1.95	24	-1	27	0.7	16			1.5	14	4.1	23
PTB	4.9	18	-1.5	18	-0.4	17	-0.6	14	-7.1	39	0.45	22	-2.5	25	-0.8	14	-1.5	14			2.6	22
MSL	2.3	28	-4.1	26	-3	25	-3.2	17	-9.7	45	-2.15	29	-5.1	31	-3.4	23	-4.1	23	-2.6	22		

Table 18 Degree of equivalence $D_{i,j}$ and $U(D_{i,j})$ at 1000 V, 10 kHz in μV/V

	CMS		SCL		SIRIM		NMIA		NMISA		NPLI		NIMT		NMC		NMIJ		PTB		MSL	
	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}
CMS			-4.3	27	-10.2	26	-12	24	-21.2	45	-7	29	-9.3	31	-6.3	24	-9.8	23	-7.8	18	-6.3	28
SCL	4.3	27			-5.9	25	-7.7	23	-16.9	44	-2.7	28	-5	30	-2	22	-5.5	22	-3.5	20	-2	27
SIRIM	10.2	26	5.9	25			-1.8	10	-11	43	3.2	27	0.9	29	3.9	21	0.4	21	2.4	19	3.9	26
NMIA	12	24	7.7	23	1.8	10			-9.2	42	5	25	2.7	19	5.7	19	2.2	18	4.2	16	5.7	14
NMISA	21.2	45	16.9	44	11	43	9.2	42			14.2	45	11.9	47	14.9	42	11.4	42	13.4	39	14.9	45
NPLI	7	29	2.7	28	-3.2	27	-5	25	-14.2	45			-2.3	32	0.7	25	-2.8	24	-0.8	22	0.7	29
NIMT	9.3	31	5	30	-0.9	29	-2.7	19	-11.9	47	2.3	32			3	27	-0.5	27	1.5	25	3	31
NMC	6.3	24	2	22	-3.9	21	-5.7	19	-14.9	42	-0.7	25	-3	27			-3.5	18	-1.5	15	0	24
NMIJ	9.8	23	5.5	22	-0.4	21	-2.2	18	-11.4	42	2.8	24	0.5	27	3.5	18			2	14	3.5	23
PTB	7.8	18	3.5	20	-2.4	19	-4.2	16	-13.4	39	0.8	22	-1.5	25	1.5	15	-2	14			1.5	22
MSL	6.3	28	2	27	-3.9	26	-5.7	14	-14.9	45	-0.7	29	-3	31	0	24	-3.5	23	-1.5	22		

Table 19 Degree of equivalence $D_{i,j}$ and $U(D_{i,j})$ at 1000 V, 20 kHz in μV/V

	CMS		SCL		SIRIM		NMIA		NMISA		NPLI		NIMT		NMC		NMIJ		PTB		MSL	
	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}
CMS			-10	40	-16.5	32	-19	31	-29	48	-5.7	37	-14	38	-6	35	-17	29	-15	25	-11	33
SCL	10	40			-6.5	36	-9	34	-19	50	4.3	40	-4	41	4	38	-7	33	-5	31	-1	36
SIRIM	16.5	32	6.5	36			-2.5	10	-12.5	44	10.8	32	2.5	34	10.5	31	-0.5	23	1.5	21	5.5	28
NMIA	19	31	9	34	2.5	10			-10	43	13.3	31	5	23	13	29	2	21	4	18	8	12
NMISA	29	48	19	50	12.5	44	10	43			23.3	48	15	49	23	47	12	42	14	39	18	45
NPLI	5.7	37	-4.3	40	-10.8	32	-13.3	31	-23.3	48			-8.3	38	-0.3	35	-11.3	29	-9.3	27	-5.3	33
NIMT	14	38	4	41	-2.5	34	-5	23	-15	49	8.3	38			8	37	-3	31	-1	29	3	34
NMC	6	35	-4	38	-10.5	31	-13	29	-23	47	0.3	35	-8	37			-11	27	-9	25	-5	31
NMIJ	17	29	7	33	0.5	23	-2	21	-12	42	11.3	29	3	31	11	27			2	15	6	24
PTB	15	25	5	31	-1.5	21	-4	18	-14	39	9.3	27	1	29	9	25	-2	15			4	22
MSL	11	33	1	36	-5.5	28	-8	12	-18	45	5.3	33	-3	34	5	31	-6	24	-4	22		

Table 20 Degree of equivalence $D_{i,j}$ and $U(D_{i,j})$ at 1000 V, 50 kHz in μV/V

	CMS		SCL		SIRIM		NMIA		NMISA		NPLI		NIMT		NMC		NMIJ		PTB		MSL	
	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}
CMS					-44	51	-36	49	-134	57	4	58	-30	58	-18	52	-37	45	-26	39	-25.2	47
SCL																						
SIRIM	44	51					8	15	-89.9	51	48	53	14	53	26	47	7	38	18	34	18.8	40
NMIA	36	49			-8	15			-97.9	49	40	50	6	31	18	44	-1	34	10	30	10.8	14
NMISA	133.9	57			89.9	51	97.9	49			138	58	104	58	116	52	96.9	45	108	39	108.7	47
NPLI	-4	58			-48	53	-40	50	-138	58			-34	59	-22	54	-41	47	-30	43	-29.2	48
NIMT	30	58			-14	53	-6	31	-104	58	34	59			12	54	-7	47	4	43	4.8	48
NMC	18	52			-26	47	-18	44	-116	52	22	54	-12	54			-19	39	-8	35	-7.2	42
NMIJ	37	45			-7	38	1	34	-96.9	45	41	47	7	47	19	39			11	22	11.8	31
PTB	26	39			-18	34	-10	30	-108	39	30	43	-4	43	8	35	-11	22			0.8	26
MSL	25.2	47			-18.8	40	-10.8	14	-109	47	29.2	48	-4.8	48	7.2	42	-11.8	31	-0.8	26		

Table 21 Degree of equivalence $D_{i,j}$ and $U(D_{i,j})$ at 1000 V, 100 kHz in μV/V

	CMS		SCL		SIRIM		NMIA		NMISA		NPLI		NIMT		NMC		NMIJ		PTB		MSL	
	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}
CMS					-79.4	66	-61	63	-450	111	27	86	-45	94	-40	78	-67	62	-38	37	-52.8	57
SCL																						
SIRIM	79.4	66					18.4	19	-371	110	106	84	34.4	93	39.4	77	12.4	60	41.4	54	26.6	54
NMIA	61	63			-18.4	19			-389	108	88	82	16	70	21	74	-6	57	23	51	8.2	28
NMISA	449.9	111			370.5	110	388.9	108			476.9	123	404.9	129	409.9	118	382.9	107	411.9	95	397.1	104
NPLI	-27	86			-106	84	-88	82	-477	123			-72	108	-67	94	-94	81	-65	77	-79.8	77
NIMT	45	94			-34.4	93	-16	70	-405	129	72	108			5	102	-22	90	7	86	-7.8	86
NMC	40	78			-39.4	77	-21	74	-410	118	67	94	-5	102			-27	73	2	69	-12.8	69
NMIJ	67	62			-12.4	60	6	57	-383	107	94	81	22	90	27	73			29	49	14.2	49
PTB	38	37			-41.4	54	-23	51	-412	95	65	77	-7	86	-2	69	-29	49			-14.8	42
MSL	52.8	57			-26.6	54	-8.2	28	-397	104	79.8	77	7.8	86	12.8	69	-14.2	49	14.8	42		

Appendix 2 Deviation *D* of NMIA and PTB from APMP and CCEM reference values and their differences $D_{NMIA} – D_{PTB}$

Table 22(a) Deviation *D* from APMP and CCEM reference values and its expanded uncertainties (95 %) *U* of 500 V measurement in μV/V respectively

NMI	1 kHz		10 kHz		20 kHz		50 kHz		100 kHz	
	D	*U*	*D*	*U*	*D*	*U*	*D*	*U*	*D*	*U*
NMIA (APMP)	0.7	6.7	1.8	6.7	2.7	7.8	4.9	13	6.3	17
NMIA (CCEM)	1.2	8.8	1.7	8.7	3.0	9.6	7.2	14.5	17.5	21.8
PTB (APMP)	-0.6	5.3	-1.4	5.3	-1.7	5.0	-2.2	5.6	-5.7	15
PTB (CCEM)	-2.3	7.5	-0.6	7.5	-1.2	7.3	-1.6	9.1	-0.6	20.6

Table 22(b) The differences $D_{NMIA} – D_{PTB}$ for CCEM and APMP of 500 V measurement in μV/V

NMI	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
	D	*D*	*D*	*D*	*D*
$D_{NMIA} – D_{PTB}$ **(APMP)**	1.3	3.2	4.4	7.1	12.0
$D_{NMIA} – D_{PTB}$ **(CCEM)**	3.5	2.3	4.2	8.8	18.1

Table 23(a) Deviation *D* from APMP and CCEM reference values and its expanded uncertainties (95 %) *U* of 1000 V measurement in μV/V respectively

NMI	1 kHz		10 kHz		20 kHz		50 kHz		100 kHz	
	D	*U*	*D*	*U*	*D*	*U*	*D*	*U*	*D*	*U*
NMIA (APMP)	0.4	8.9	3.2	12	3.2	14	8.9	26	15.0	33
NMIA (CCEM)	0.8	10.7	2.7	13.7	3.0	15.7	4.9	27.5	12.3	39.8
PTB (APMP)	-0.2	4.7	-1.0	4.0	-0.8	3.6	-1.1	3.4	-8.0	18
PTB (CCEM)	-0.7	7.4	-1.5	7.2	-2.0	7.1	-2.0	8.7	-3.5	28.3

Table 23(b) The differences $D_{NMIA} – D_{PTB}$ for CCEM and APMP of 1000 V measurement in μV/V

NMI	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
	D	*D*	*D*	*D*	*D*

$D_{NMIA} - D_{PTB}$ (APMP)	0.6	4.2	4.0	10.0	23.0
$D_{NMIA} - D_{PTB}$ (CCEM)	1.5	4.2	5.0	6.9	15.8

Appendix 3 APMP International Comparison Protocol of High Voltage AC-DC Transfer Standard

1. Scope

This comparison offers the same range and frequencies as BIPM Key Comparison CCEM-K9, 500 V and 1000 V, frequency from 1 kHz to 100 kHz. The comparison is providing the National Metrology Institutes (NMIs) of the APMP member economies with an opportunity to link the values of their standards for ac-dc transfer difference to the international reference values.

2. Definition of the AC-DC transfer difference

Ac-dc transfer difference δ of a thermal converter is defined as:

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

where: V_{ac} is the rms value of the applied ac voltage, and
V_{dc} is the mean value of the direct and reversed dc voltages, which produce the same output voltage of the converter as V_{ac}.

3. The Travelling Standard

The travelling standard is a CMS made single-junction thermal element, serial number 011, with a 200 kΩ range resistor, Fluke 792A-7002. The parameters of the thermal element are rated current 5 mA, heater resistance 90 Ω and output voltage 7 mV. To determine the travelling standard at high voltage should connect the output terminal of the resistor to the input connector of the thermal element and apply the AC or DC voltages from the INPUT connector of the range resistor.

4. Measurement Conditions

4.1 The voltage is defined at the mid-point of the Tee-piece.
4.2 The input and output of the Travelling Standard should always be earthed to protect the insulation between the heater and the thermocouple.
4.3 The participants are asked to use their best measurement procedure.

5. Test Points

The ac-dc difference of the travelling standard should be measured at

Voltage: 500 V and 1000 V

Frequency: 1 kHz, 10 kHz, 20 kHz, 50 kHz and 100 kHz

6. Report

Each participant is asked to submit a report, e-mail or mail, within two month after completing the measurements. The report should contain at least the following:

6.1 Detailed description of the measurement setup including a drawing that can be used, if necessary, in the final report of the Comparison;
6.2 Detailed description of the measurement procedure;
6.3 Complete uncertainty budget in accordance with the principles of the ISO Guide to the Expression of Uncertainty in Measurement.

Appendix 4 Uncertainty budgets

1. Uncertainty budget for CMS (Chinese Taipei)

Uncertainty budget of the 500 V AC-DC voltage transfer difference

Influence quantity	Type	Standard uncertainty in 10E-6 at frequencies					
		u	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
1. Reference standard		$\boldsymbol{u_s}$	9.1	9.1	9.1	16.1	19.2
- primary standard	B	u_p	1.5	1.5	1.5	2	2.5
- Voltage step-up	B	u_{up}	9	9	9	16	19
2. Difference measurement		$\boldsymbol{u_d}$	2.1	2.1	2.1	3.1	4.1
-Ambient temperature	B	u_t	0.2	0.2	0.2	0.2	0.2
-System(DVMs,T-connector, Set-up)	B	u_e	2	2	2	3	4
-standard deviation of measurement	A	u_a	0.5	0.5	0.5	0.8	1
Standard measurement uncertainty		$\boldsymbol{u_x}$	9.4	9.4	9.4	16.4	19.6
Expanded uncertainty for confidence level of 95 %		$\boldsymbol{U}$	20	20	20	34	40

$$u_s^2 = u_p^2 + u_{up}^2, u_d^2 = u_t^2 + u_e^2 + u_a^2; u_x^2 = u_s^2 + u_d^2$$

Uncertainty budget of the 1000 V AC-DC voltage transfer difference

Influence quantity	Type	Standard uncertainty in 10E-6 at frequencies					
		u	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
1. Reference standard		u_s	9.1	9.1	12.1	19.1	23.1
- primary standard	B	u_p	1.5	1.5	1.5	2	2.5
- Voltage step-up	B	u_{up}	9	9	12	19	23
2. Difference measurement		u_d	2.1	2.1	2.1	3.2	4.2
-Ambient temperature	B	u_t	0.2	0.2	0.2	0.2	0.2
-System(DVMs,T-connector, Set-up)	B	u_e	2	2	2	3	4
-standard deviation of measurement	A	u_a	0.7	0.7	0.7	1	1.2
Standard measurement uncertainty		u_x	9.4	9.4	12.3	19.4	23.5
Expanded uncertainty for confidence level of 95 %		U	20	20	26	40	48

$$u_s^2 = u_p^2 + u_{up}^2, u_d^2 = u_t^2 + u_e^2 + u_a^2; u_x^2 = u_s^2 + u_d^2$$

2. Uncertainty budget for SCL (Hong Kong)

Uncertainty in the measured values of ac-dc voltage difference

of the combination of Fluke 792A-7002 1000 V Range Resistor and CMS 5 mA Thermal Converter

Test Voltage (V)	Test Freq. (Hz)	Ks (10^{-6}/nV)	Kx (10^{-6}/nV)	Standard Uncertainty Contributions					Combined Standard Uncertainty u(Sx) (±μV/V)	Expanded Uncertainty at 95% C.L. U (±μV/V)	Coverage Factor k
				Type B				Type A			
				u(Ss) (μV/V)	u(Mr) (nV)	U(Nr) (nV)	u(β) (μV/V)	u(random) (μV/V)			
500	1k	0.10	0.24	5.5	5.8	5.8	5.8	0.6	8.1	15.9	1.96
	10k	0.10	0.24	6.5	5.8	5.8	5.8	0.5	8.8	17.3	1.96
	20k	0.10	0.24	10.0	5.8	5.8	5.8	0.4	11.7	22.8	1.96
	50k	0.10	0.24	17.0	5.8	5.8	17.3	0.6	24.3	47.7	1.96
	100k	0.10	0.24	31.0	5.8	5.8	23.1	1.2	38.7	75.9	1.96
1000	1k	0.11	0.08	5.5	5.8	5.8	5.8	0.4	8.0	15.7	1.96
	10k	0.11	0.08	7.0	5.8	5.8	5.8	0.6	9.1	17.9	1.96
	20k	0.11	0.08	13.5	5.8	5.8	5.8	0.5	14.7	28.8	1.96

$$u^2(Sx) = u^2(Ss) + Ks^2u^2(Mr) + Kx^2u^2(Nr) + u^2(\beta) + u^2(random)$$

3. Uncertainty budget for SIRIM (Malaysia)

APMP International Comparison of AC-DC Transfer Standards at High Voltages

Measurement Uncertainty Evaluation

Method: ISO GUM

Measurement at 500 V

Sources of Uncertainty	**1 kHz**	**10 kHz**	**20 kHz**	**50 kHz**	**100 kHz**
600 V Standard (μV/V)	6.5	7	8	12.6	17.6
Repeatability of measurement (μV/V)	0.77	0.83	0.8	1.28	1.75
Tee-piece (μV/V)	0.58	0.58	0.58	0.58	0.58
u(μV/V)	6.57	7.07	8.06	12.68	17.70
Effective DOF	52	52	52	51	51
k	2	2	2	2	2
$U_{95\%}$ (μV/V)	**14**	**15**	**17**	**26**	**36**

Measurement at 1000 V

Sources of Uncertainty	**1 kHz**	**10 kHz**	**20 kHz**	**50 kHz**	**100 kHz**
1000 V Standard (μV/V)	7.1	8.1	9.2	15.7	22.2
Repeatability of measurement (μV/V)	1.0	1.6	1.8	2.7	3.0
Tee-piece (μV/V)	0.58	0.58	0.58	0.58	0.58
u(μV/V)	7.19	8.28	9.39	15.94	22.41
Effective DOF	53	54	54	53	52
k	2	2	2	2	2
$U_{95\%}$ (μV/V)	**15**	**17**	**19**	**32**	**45**

4. Uncertainty budget for NMIA (Australia)

4.1 Uncertainty of NMIA Reference Standards

Table 1

Influence Quantity	*u*	Standard Measurement Uncertainties in μV/V				
		1 kHz	**10 kHz**	**20 kHz**	**50 kHz**	**100 kHz**
6 V						
Reference Uncertainty (4V)	$u(\delta_{REF})$	1.00	1.24	1.33	2.18	2.85
Random Uncertainty	$u(\delta_{RND})$	0.04	0.11	0.08	0.28	0.37
Connectors	$u(\delta_{conn})$	0.14	0.28	0.35	0.57	0.71
Voltage Coefficient	$u(\delta_{VC})$	0.57	0.57	0.57	0.57	0.71
Measurement Setup	$u(\delta_{d})$	0.71	0.71	0.71	0.71	1.41
Standard Uncertainty at	**6 V**	**1.36**	**1.57**	**1.65**	**2.44**	**3.35**
10 V						
Reference Uncertainty	$u(\delta_{REF})$	1.36	1.57	1.65	2.44	3.35
Random Uncertainty (1)	$u(\delta_{RND1})$	0.13	0.18	0.16	0.12	0.27
Random Uncertainty (2)	$u(\delta_{RND2})$	0.30	0.30	0.30	0.30	0.30
Connectors	$u(\delta_{conn})$	0.14	0.28	0.35	0.57	0.71
Voltage Coefficient	$u(\delta_{VC})$	0.57	0.57	0.57	0.57	0.71
Measurement Setup	$u(\delta_{d})$	0.71	0.71	0.71	0.71	1.41
Standard Uncertainty at	**10 V**	**1.67**	**1.86**	**1.94**	**2.69**	**3.80**
12 V						
Reference Uncertainty	$u(\delta_{REF})$	1.67	1.86	1.94	2.69	3.80
Random Uncertainty	$u(\delta_{RND})$	0.11	0.22	0.07	0.09	0.29
Connectors	$u(\delta_{conn})$	0.14	0.28	0.35	0.57	0.71
Voltage Coefficient	$u(\delta_{VC})$	0.57	0.57	0.57	0.57	0.71
Measurement Setup	$u(\delta_{d})$	0.71	0.71	0.71	0.71	1.41
Standard Uncertainty at	**12 V**	**1.91**	**2.10**	**2.17**	**2.89**	**4.18**
20 V						
Reference Uncertainty	$u(\delta_{REF})$	1.91	2.10	2.17	2.89	4.18
Random Uncertainty (1)	$u(\delta_{RND1})$	0.11	0.11	0.09	0.16	0.23
Random Uncertainty (2)	$u(\delta_{RND2})$	0.10	0.10	0.10	0.10	0.10
Connectors	$u(\delta_{conn})$	0.14	0.28	0.35	0.57	0.71
Voltage Coefficient	$u(\delta_{VC})$	0.57	0.57	0.57	0.57	0.71
Measurement Setup	$u(\delta_{d})$	0.71	0.71	0.71	0.71	1.41
Standard Uncertainty at	**20 V**	**2.12**	**2.31**	**2.38**	**3.09**	**4.53**

Influence Quantity	u	Standard Measurement Uncertainties in μV/V				
		1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
30 V						
Reference Uncertainty	$u(\delta_{REF})$	2.12	2.31	2.38	3.09	4.53
Random Uncertainty (1)	$u(\delta_{RND1})$	0.34	0.16	0.12	0.21	0.55
Random Uncertainty (2)	$u(\delta_{RND2})$	0.40	0.40	0.40	0.40	0.40
Connectors	$u(\delta_{conn})$	0.14	0.28	0.35	0.57	0.71
Voltage Coefficient	$u(\delta_{VC})$	0.57	0.57	0.57	0.57	0.71
Measurement Setup	$u(\delta_{d})$	0.71	0.71	0.71	0.71	1.41
Standard Uncertainty at	**30 V**	**2.37**	**2.54**	**2.61**	**3.30**	**4.90**
40 V						
Reference Uncertainty	$u(\delta_{REF})$	2.37	2.54	2.61	3.30	4.90
Random Uncertainty	$u(\delta_{RND})$	0.11	0.17	0.19	0.18	0.15
Connectors	$u(\delta_{conn})$	0.14	0.28	0.35	0.57	0.71
Voltage Coefficient	$u(\delta_{VC})$	0.85	0.85	0.85	1.41	2.12
Measurement Setup	$u(\delta_{d})$	0.71	0.71	0.71	0.71	1.41
Standard Uncertainty at	**40 V**	**2.62**	**2.78**	**2.86**	**3.71**	**5.57**
60 V						
Reference Uncertainty	$u(\delta_{REF})$	2.62	2.78	2.86	3.71	5.57
Random Uncertainty (1)	$u(\delta_{RND1})$	0.11	0.17	0.19	0.46	0.45
Random Uncertainty (2)	$u(\delta_{RND2})$	0.10	0.10	0.10	0.10	0.10
Connectors	$u(\delta_{conn})$	0.14	0.28	0.35	0.57	0.71
Voltage Coefficient	$u(\delta_{VC})$	0.85	0.85	0.85	1.41	2.12
Measurement Setup	$u(\delta_{d})$	0.71	0.71	0.71	0.71	1.41
Standard Uncertainty at	**60 V**	**2.85**	**3.02**	**3.09**	**4.10**	**6.18**
100 V						
Reference Uncertainty	$u(\delta_{REF})$	2.85	3.02	3.09	4.10	6.18
Random Uncertainty (1)	$u(\delta_{RND1})$	0.11	0.09	0.07	0.13	0.11
Random Uncertainty (2)	$u(\delta_{RND2})$	0.40	0.40	0.40	0.40	0.40
Connectors	$u(\delta_{conn})$	0.14	0.28	0.35	0.57	0.71
Voltage Coefficient	$u(\delta_{VC})$	0.85	0.85	0.85	1.41	2.12
Measurement Setup	$u(\delta_{d})$	0.71	0.71	0.71	0.71	1.41
Standard Uncertainty at	**100 V**	**3.09**	**3.25**	**3.33**	**4.45**	**6.74**

Table 1 (continued)

Influence Quantity	u	Standard Measurement Uncertainties in μV/V				
		1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
120 V						
Reference Uncertainty	$u(\delta_{REF})$	3.09	3.25	3.33	4.45	6.74
Random Uncertainty	$u(\delta_{RND})$	0.35	0.20	0.45	0.30	0.20
Connectors	$u(\delta_{conn})$	0.14	0.28	0.35	0.57	0.71
Voltage Coefficient	$u(\delta_{VC})$	0.85	0.85	0.85	1.41	2.12
Measurement Setup	$u(\delta_{d})$	0.71	0.71	0.71	0.71	1.41
Standard Uncertainty at	**120 V**	**3.30**	**3.45**	**3.55**	**4.76**	**7.24**
200 V						
Reference Uncertainty	$u(\delta_{REF})$	3.30	3.45	3.55	4.76	7.24
Random Uncertainty (1)	$u(\delta_{RND1})$	0.25	0.05	0.05	0.16	0.21
Random Uncertainty (2)	$u(\delta_{RND2})$	0.10	0.10	0.10	0.10	0.10
Connectors	$u(\delta_{conn})$	0.14	0.28	0.35	0.57	0.71
Voltage Coefficient	$u(\delta_{VC})$	0.85	0.85	0.85	1.41	2.12
Measurement Setup	$u(\delta_{d})$	0.71	0.71	0.71	0.71	1.41
Standard Uncertainty at	**200 V**	**3.49**	**3.64**	**3.74**	**5.05**	**7.71**
300 V						
Reference Uncertainty	$u(\delta_{REF})$	3.49	3.64	3.74	5.05	7.71
Random Uncertainty (1)	$u(\delta_{RND1})$	0.30	0.20	0.25	0.10	0.15
Random Uncertainty (2)	$u(\delta_{RND2})$	0.50	0.50	0.50	0.50	0.50
Connectors	$u(\delta_{conn})$	0.14	0.28	0.35	0.57	0.71
Voltage Coefficient	$u(\delta_{VC})$	0.85	0.85	0.85	1.41	2.12
Measurement Setup	$u(\delta_{d})$	0.71	0.71	0.71	0.71	1.41
Standard Uncertainty at	**300 V**	**3.71**	**3.85**	**3.96**	**5.35**	**8.17**
400 V						
Reference Uncertainty	$u(\delta_{REF})$	3.71	3.85	3.96	5.35	8.17
Random Uncertainty	$u(\delta_{RND})$	0.05	0.50	0.15	0.10	0.10
Connectors	$u(\delta_{conn})$	0.14	0.28	0.35	0.57	0.71
Voltage Coefficient	$u(\delta_{VC})$	0.85	0.85	1.41	2.83	4.24
Measurement Setup	$u(\delta_{d})$	1.41	1.41	1.41	2.12	2.83
Standard Uncertainty at	**400 V**	**4.07**	**4.23**	**4.45**	**6.44**	**9.66**

Table 1 (continued)

Influence Quantity	*u*	Standard Measurement Uncertainties in μV/V				
		1 kHz	**10 kHz**	**20 kHz**	**50 kHz**	**100 kHz**
500 V						
Reference Uncertainty	$u(\delta_{REF})$	4.07	4.23	4.45	6.44	9.66
Random Uncertainty (1)	$u(\delta_{RND1})$	0.05	0.45	0.20	0.35	0.75
Random Uncertainty (2)	$u(\delta_{RND2})$	0.10	0.10	0.10	0.10	0.10
Connectors	$u(\delta_{conn})$	0.14	0.28	0.35	0.57	0.71
Voltage Coefficient	$u(\delta_{VC})$	0.85	0.85	1.41	2.83	4.24
Measurement Setup	$u(\delta_{d})$	1.41	1.41	1.41	2.12	2.83
Standard Uncertainty at	**500 V**	**4.39**	**4.57**	**4.90**	**7.38**	**10.97**
600 V						
Reference Uncertainty	$u(\delta_{REF})$	4.39	4.57	4.90	7.38	10.97
Random Uncertainty	$u(\delta_{RND})$	0.25	0.20	0.25	0.15	0.10
Connectors	$u(\delta_{conn})$	0.14	0.28	0.35	0.57	0.71
Voltage Coefficient	$u(\delta_{VC})$	0.85	2.12	2.83	4.95	7.07
Measurement Setup	$u(\delta_{d})$	1.41	1.41	1.41	2.12	2.83
Standard Uncertainty at	**600 V**	**4.70**	**5.24**	**5.84**	**9.15**	**13.37**
800 V						
Reference Uncertainty	$u(\delta_{REF})$	4.70	5.24	5.84	9.15	13.37
Random Uncertainty	$u(\delta_{RND})$	0.10	0.10	0.20	0.25	0.07
Connectors	$u(\delta_{conn})$	0.14	0.28	0.35	0.57	0.71
Voltage Coefficient	$u(\delta_{VC})$	0.85	2.12	2.83	4.95	7.07
Measurement Setup	$u(\delta_{d})$	1.41	1.41	1.41	2.12	2.83
Standard Uncertainty at	**800 V**	**4.98**	**5.84**	**6.66**	**10.64**	**15.41**
1000 V						
Reference Uncertainty	$u(\delta_{REF})$	4.98	5.84	6.66	10.64	15.41
Random Uncertainty	$u(\delta_{RND})$	0.20	0.05	0.10	0.70	0.55
Connectors	$u(\delta_{conn})$	0.14	0.28	0.35	0.57	0.71
Voltage Coefficient	$u(\delta_{VC})$	1.41	3.54	4.24	8.49	11.31
Measurement Setup	$u(\delta_{d})$	1.41	1.41	1.41	2.83	5.66
Standard Uncertainty at	**1000 V**	**5.38**	**6.98**	**8.03**	**13.93**	**19.95**

4.2 Uncertainty of APMP.EM-K9 Measurements

Table 2

Influence Quantity	*u*	Standard Measurement Uncertainties in µV/V				
		1 kHz	**10 kHz**	**20 kHz**	**50 kHz**	**100 kHz**
500 V						
Reference Uncertainty	$u(\delta_{REF})$	4.4	4.6	4.9	7.4	11.0
Random Uncertainty	$u(\delta_{RND})$	0.1	0.1	0.1	0.1	0.1
IUT Drift	$u(\delta_{IUT})$	0.6	0.6	1.2	1.2	3.5
Temperature/Humidity	$u(\delta_{T-RH})$	0.2	0.2	0.2	0.5	0.7
Measurement Setup	$u(\delta_d)$	0.2	0.2	0.2	0.3	0.3
Standard Uncertainty at	**500 V**	**4.4**	**4.6**	**5.0**	**7.5**	**11.5**
95% Uncertainty at	**500 V**	**9**	**9**	**10**	**15**	**23**
1000 V						
Reference Uncertainty	$u(\delta_{REF})$	5.4	7.0	8.0	13.9	20.0
Random Uncertainty	$u(\delta_{RND})$	0.1	0.1	0.1	0.1	0.1
IUT Drift	$u(\delta_{IUT})$	0.6	0.6	1.2	1.2	3.5
Temperature/Humidity	$u(\delta_{T-RH})$	0.2	0.3	0.5	1.5	2.5
Measurement Setup	$u(\delta_d)$	0.2	0.2	0.2	0.3	0.5
Standard Uncertainty at	**1000 V**	**5.4**	**7.0**	**8.1**	**14.1**	**20.4**
95% Uncertainty at	**1000 V**	**11**	**14**	**16**	**28**	**41**

5. Uncertainty budget for NMISA (South Africa)

5.1 Although it was the average of 12 individual measurements, the mean result for each day and at each frequency was taken as a single observation of the ac-dc difference. The scatter of the mean results for the six sets of measurements over the 19 days on which the measurements were performed was then taken an a measure of their type A evaluated uncertainty.

Type A and type B evaluation uncertainties were analysed and are as follows:

5.1.1 Type A evaluation for the 500 V at 1 kHz

The estimated standard deviation is given by

$$s(x_i) = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \overline{x})^2}$$

The estimated standard deviation of the mean is given by

$$s(\overline{x}) = \frac{s(x_i)}{\sqrt{n}}$$

In the case at hand (n = 6), the type A evaluation yielded the following results (μV/V)

$\overline{x}$ = 3,4

s(x) = 0,76

$s(\overline{x})$ = 0,31

$$U_A = s(\overline{x}) = \frac{s(x_i)}{\sqrt{n}} = \frac{0{,}76}{\sqrt{6}} = 0{,}31$$

Type B evaluation for the 500 V at 1 kHz:

Table I

Symbol	Source of Uncertainty	Uncertainty (μV/V) (k = 2)	Probability Distribution	Divisor	$U_i(U_x)$ (μV/V) (k = 1)
δ_S	Certified systematic Uncertainty of Ref	25,0	Normal	2	12,5
D_S	Ageing of reference	4,0	Rectangular	$\sqrt{3}$	2,31
δ_A	Transfer difference Measurements	0,4	Rectangular	$\sqrt{3}$	0,23
δ_M	Measurements set-up	0,6	Rectangular	$\sqrt{3}$	0,35
δ_C	Connectors and T	1,0	Rectangular	$\sqrt{3}$	0,58
δ_E	Effect of ambient Temperature	1,0	Triangular	$\sqrt{6}$	0,41
δ_{Rs}	Resolution of DVM(s)	1,0	Rectangular	$\sqrt{3}$	0,58
δ_{Rx}	Resolution of DVM(x)	1,0	Rectangular	$\sqrt{3}$	0,58
δ_{SU}	Voltage step-up each step	2,2	Rectangular	$\sqrt{3}$	1,27
δ_U	Other sources	2,0	Rectangular	$\sqrt{3}$	1,15

Assuming no correlation the total type B uncertainty at 1 kHz is

$$U_B = \sqrt{\delta_S{}^2 + D_S{}^2 + \delta_A{}^2 + \delta^2{}_M + \delta^2{}_C + \delta^2{}_{RS} + \delta^2{}_{RX} + \delta^2{}_{ST} + \delta^2{}_U}$$

$$U_B = \sqrt{12{,}5^2 + 2{,}31^2 + 0{,}23^2 + 0{,}35^2 + 0{,}58^2 + 0{,}41^2 + 0{,}58^2 + 0{,}58^2 + 1{,}27^2 + 1{,}15^2}$$

$$U_B = 12{,}55$$

5.1.2 Combined (type A plus Type B) standard uncertainty evaluation for the 200 V at 1 kHz

$$U_C = \sqrt{U_A{}^2 + U_B{}^2}$$

$$U_C = \sqrt{0{,}3^2 + 12{,}55^2}$$

$$U_C = 12{,}55$$

5.2 Analysis at other frequencies at 500 V and 1000 V

5.2.1 The same procedure as for the 500 V at 1 kHz was used.

5.2.2 The estimated standard uncertainty (type A evaluation) together with the certified uncertainties of the reference standard (type B evaluation) at these frequencies is listed in the tables below. The other type B evaluated uncertainties at the other frequency points are the same as those listed in table I.

5.3 Results

The ac-dc difference in μV/V for the CMS 5mA/90Ω TVC + 792A-7002 ranger resistor

INPUT VOLTAGE	FREQUENCY	MEASURED FREQUENCY (kHz)	AC-DC DIFFERENCE	COMBINED UNCERTAINTY (±μV/V)
500 V	1 kHz	0,999 97	+ 3,4	30,0
500 V	10 kHz	9,999 8	- 3,7	30,0
500 V	20 kHz	19,999 6	- 17,7	30,0
500 V	50 kHz	49,999 2	- 25,9	30,0
500 V	100 kHz	99,994	- 32,5	80,0
1 000 V	1 kHz	0,999 97	+ 5,6	40,0
1 000 V	10 kHz	9,999 8	+ 2,9	40,0
1 000 V	20 kHz	19,999 6	- 11,0	40,0
1 000 V	50 kHz	49,999 2	- 11,1	40,0
1 000 V	100 kHz	99, 994	- 8,1	100,0

6. Uncertainty budget for NPLI (India)

Results of comparison at 500 V

Frequency (kHz)	1	10	20	50	100
No. of measurements	15	15	15	15	15
Ac/dc transfer error (μV/V)	+ 10.5	- 5.5	- 18.4	- 131	- 481
Standard deviation	± 4.3	± 4.2	± 4.1	± 4.1	± 5.7

Uncertainty Budget:

Uncertainty budget of the ac-dc voltage transfer difference measurement in NPL, India Standard measurement uncertainty in μV/V at different frequencies								
Influence quantity	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz	Degrees of freedom	Type A or B	Shape of distribution
Measurement data	1.1	1.1	1.1	1.1	1.5	14	A	Normal
Reference Standard	7.5	7.5	10	15	25	Infinity	A	Normal
Measurement set up	1	1	2	2	2	Infinity	B	Rectangular
Connector & Tee	1	1	2	5	5	Infinity	B	Rectangular
Value of Exponent	2	2	2	2	2	Infinity	B	Rectangular
Combined standard uncertainty (u_δ)	8	8	10.6	16.1	25.7			
Expanded uncertainty for 95% confidence level (U)	± 16	± 16	± 21	± 32	± 51			

Results of comparison at 1000V

Frequency (kHz)	1	10	20	50	100
No. of measurements	15	15	15	15	15
Ac/dc transfer error (μV/V)	- 2.3	+ 2.8	- 38.3	- 165	- 534
Standard deviation	± 2.2	± 2.3	± 1.7	± 3.0	± 4.6

Uncertainty Budget:

Uncertainty budget of the ac-dc voltage transfer difference measurement in NPL, India Standard measurement uncertainty in μV/V at different frequencies								
Influence quantity	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz	Degrees of freedom	Type A or B	Shape of distribution
Measurement data	0.6	0.6	0.4	0.8	1.2	14	A	Normal
Reference Standard	10	10	12.5	20	35	Infinity	A	Normal
Measurement set up	1	1	2	2	2	Infinity	B	Rectangular
Connector & Tee	1	1	2	5	5	Infinity	B	Rectangular
Value of Exponent	2	2	2	2	2	Infinity	B	Rectangular
Combined standard uncertainty (u_δ)	10.3	10.3	12.8	20.8	35.5			
Expanded uncertainty for 95% confidence level (U)	± 21	± 21	± 26	± 42	± 71			

7. Uncertainty budget for NIMT (Thailand)

Uncertainty Budget for TVC APMP 500V HV

	Repeatability of meas		Calibration of Standard		Drift of Standard		Calibration of Sens		Drift in Temp drift		Drift in Hum drift		Linearity of Ac-dc	
Unit	1*10^-6		1*10^-6		1*10^-6		1*10^-6		1*10^-6		1*10^-6		1*10^-6	
Dist.	Normal		Normal		Rect		Normal		Rect		Rect		Rect	
Divisor	1		2		$\sqrt{3}$		1		$\sqrt{3}$		$\sqrt{3}$		$\sqrt{3}$	
Ci	1		1		1		1		1		1		1	
Vi	9		∞		∞		∞		∞		∞		∞	
Freq (Hz)	Value	Ur	Value	Us	Value	Ud	Value	Usen	Value	Ut	Value	Ut	Value	Uunc
1k	0.272	0.27	20	10	10	5.8	1	1	1	0.6	1	0.58	1	0.58
10k	0.335	0.34	20	10	10	5.8	1	1	1	0.58	1	0.58	1	0.58
20k	0.1	0.09	20	10	10	5.8	1	1	1	0.58	1	0.58	1	0.58
50k	0.2	0.20	20	10	10	5.8	1	1	1	0.58	1	0.58	1	0.58
100k	0.4	0.39	40	20	10	5.8	1	1	1	0.58	1	0.58	1	0.58

	Error of Connector		Distort and Noise		EMI and RFI		Unknown Error.		Drift in Freq setting		Resolution of DMM		Zero Stab of dmm					
Unit	1*10^-6		1*10^-6		1*10^-6		1*10^-6		1*10^-6		1*10^-6		1*10^-6					
Dist.	Normal		Rect		Rect		Rect		Normal		Rect		Rect					
Divisor	1		$\sqrt{3}$		$\sqrt{3}$		$\sqrt{3}$		1		$\sqrt{3}$		$\sqrt{3}$					
Ci	1		1		1		1		1		1		1					
Vi	∞		∞		∞		∞		∞		∞		∞					
Freq (Hz)																		U
	Value	Ucon	Value	Udis	Value	Uemi	Value	Uunk	Value	Ufr	Value	Uunc	Value	Ustb	Uc	veff	k	1*10
1k	1	1	1	0.6	1	0.6	0	0.0	1	1	1	0.58	2	1.15	11.8	3.2E+07	2.000	23
10k	1	1	1	0.6	1	0.6	0	0.0	1	1	1	0.58	2	1.15	11.8	1.4E+07	2.000	23
20k	1	1	1	0.6	1	0.6	0	0.0	1	1	1	0.58	2	1.15	11.8	2.7E+09	2.000	23
50k	1	1	1	0.6	1	0.6	0	0.0	1	1	1	0.58	2	1.15	11.8	1.1E+08	2.000	23
100k	1	1	1	0.6	1	0.6	0	0.0	1	1	1	0.58	2	1.15	21.0	7.5E+07	2.000	41

Uncertainty Budget for TVC APMP 1000V HV

	Repeatability of meas		Calibration of Standard		Drift of Standard		Calibration of Sensitivity		Drift in Temp drift		Drift in Hum drift		Linearity of Ac-dc		Error of Connector		Distort and Noise		EMI and RFI		Unknown Error.		Drift in Freq setting		Resolution of DMM		Zero Stab of dmm					
Unit	1*10^-6		1*10^-6		1*10^-6		1*10^-6		1*10^-6		1*10^-6		1*10^-6		1*10^-6		1*10^-6		1*10^-6		1*10^-6		1*10^-6		1*10^-6		1*10^-6					
Dist.	Normal		Normal		Rect		Normal		Rect		Rect		Rect		Normal		Rect		Rect		Rect		Normal		Rect		Rect					
Divisor	1		2		$\sqrt{3}$		1		$\sqrt{3}$		$\sqrt{3}$		$\sqrt{3}$		1		$\sqrt{3}$		$\sqrt{3}$		$\sqrt{3}$		1		$\sqrt{3}$		$\sqrt{3}$					
Ci	1		1		1		1		1		1		1		1		1		1		1		1		1		1					
Vi	9		∞		∞		∞		∞		∞		∞		∞		∞		∞		∞		∞		∞		∞					
Freq (Hz)																																U
	Value	Ur	Value	Us	Value	Ud	Value	Usen	Value	Ut	Value	Ut	Value	Uunc	Value	Ucon	Value	Udis	Value	Uemi	Value	Uunk	Value	Ufr	Value	Uunc	Value	Ustb	Uc	veff	k	1*10
1k	0.188	0.19	20	10	10	5.8	1	1	1	0.58	1	0.58	1	0.58	1	1	1	0.6	1	0.6	0	0.0	1	1	1	0.58	2	1.15	11.8	1.4E+08	2.00	23
10k	0.156	0.16	20	10	10	5.8	1	1	1	0.58	1	0.58	1	0.58	1	1	1	0.6	1	0.6	0	0.0	1	1	1	0.58	2	1.15	11.8	3E+08	2.00	23
20k	0.2	0.20	25	12.5	10	5.8	1	1	1	0.58	1	0.58	1	0.58	1	1	1	0.6	1	0.6	0	0.0	1	1	1	0.58	2	1.15	14.0	2.2E+08	2.000	28
50k	0.184	0.18	40	20	10	5.8	1	1	1	0.58	1	0.58	1	0.58	1	1	1	0.6	1	0.6	0	0.0	1	1	1	0.58	2	1.15	21.0	1.5E+09	2.000	41
100k	0.1	0.10	80	40	10	5.8	1	1	1	0.58	1	0.58	1	0.58	1	1	1	0.6	1	0.6	0	0.0	1	1	1	0.58	2	1.15	40.5	2.4E+11	2.00	81

8. Uncertainty budget for VMI (Vietnam)

Results:

Table 1

Ac-dc Voltage Transfer Differences (μV/V)

Ref Voltage Range (V)	Iut Voltage Range (V)	Voltage Applied (V)	Frequency (kHz)					
			1	10	20	50	100	
1000	1000	500	-1.2	-9.4	-27	-117	-433	

Table 2

Uncertainty (μV/V)

Ref Voltage Range (V)	Iut Voltage Range (V)	Voltage Applied (V)	Frequency (kHz)					
			1	10	20	50	100	
1000	1000	500	30	30	31	65	72	

Table 3

Components of Uncertainty

Component		Applied	Type	Distribution	ν	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
Reference 792A (s/n: 7808003) (1)	$u(\delta_{Ref})$	500V	B	Normal	30	15.0	15.0	15.0	32.0	35.0
Connectors	$U(\delta_{conn})$		B	Normal	10	0.2	0.2	0.2	0.2	0.2
~~Drift in Ref 792A /year~~ (2)	~~$u(\delta_{RefDrift})$~~		~~B~~	~~Rectangular~~		-	-	-	-	-
ESDM	$u(\delta_{A})$		A	Normal	4	0.6	0.7	0.6	0.5	0.9
Temperature/Humidity	$u(\delta_{T,H})$		B	Normal	20	1	1	1	4	6
Sensitivity Calculation	$u(\delta_{n})$		B	Normal	25	0.1	0.1	0.1	0.1	0.1
Frequence Setting	$u(\delta_{f})$		B	Normal	20	0.5	0.5	0.5	1.0	2.0
IUT Stability	$u(\delta_{IUT\ Stab})$		B	Normal	10	2	2	3	3	5
Rounding off values	$u(\delta_{round\ val})$		A	Rectangular	1000	0.6	0.6	0.6	0.6	0.6
Rounding off uncertainty	$u(\delta_{round\ unc})$		A	Rectangular	1000	0.6	0.6	0.6	0.6	0.6

(1)：From Manual of Fluke 792A.

(2)：We couldn't estimated drift in Fluke 792A because we have received it May, 2001.

9. Uncertainty budget for NMC (Singapore)

<u>Results of Comparison</u>

AC-DC Difference for 500 V

Frequency	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
Mean (μV/V)	**-3**	**-10**	**-28**	**-125**	**-418**
Standard deviation (μV/V)	3.1	1.5	2.5	1.8	1.5
Number of measurements	14	14	14	14	14

Measurement Uncertainty for 500 V

Frequency	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
Type A standard uncertainty (μV/V)	**0.8**	**0.4**	**0.7**	**0.5**	**0.4**
· Standard deviation (μV/V)	3.1	1.5	2.5	1.8	1.5
Type B standard uncertainty (μV/V)	**6.9**	**6.0**	**7.9**	**11.7**	**21**
· Reference standard (μV/V)	6.5	5.5	7.5	11.5	21
· System set-up (μV/V)	2.3	2.3	2.4	2.4	2.4
Combined standard uncertainty (μV/V)	**6.9**	**6.0**	**7.9**	**12**	**21**
Degree of freedom	13	13	13	13	13

AC-DC Difference for 1 kV

Frequency	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
Mean (μV/V)	**-0.7**	**-12**	**-34**	**-127**	**-418**
Standard deviation (μV/V)	2.2	2.0	1.4	2.0	3.4
Number of measurements	15	15	15	15	15

Measurement Uncertainty for 1 kV

Frequency	1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
Type A standard uncertainty (μV/V)	**0.6**	**0.5**	**0.4**	**0.5**	**0.9**
· Standard deviation (μV/V)	2.2	2.0	1.4	2.0	3.4
Type B standard uncertainty (μV/V)	**5.5**	**6.4**	**11.7**	**16.7**	**31**
· Reference standard (μV/V)	5	6	11.5	16.5	31
· System set-up (μV/V)	2.3	2.3	2.4	2.4	2.4
Combined standard uncertainty (μV/V)	**5.5**	**6.4**	**12**	**17**	**31**
Degree of freedom	14	14	14	14	14

10. Uncertainty budget for NMIJ (Japan)

Table I. AC-dc transfer difference of the travelling standard calibrated by the primary standards of NMIJ.

Calibration date	AC-DC-transfer difference δ in 10^{-6} at the frequencies						
	voltage		1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
Nov .02	500V	δ	0.9	-7.6	-22	-110	-401
		sd	0.73	0.71	0.70	0.71	0.86
	number of measurements		48	48	48	48	48

Calibration date	AC-DC-transfer difference δ in 10^{-6} at the frequencies						
	voltage		1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
Nov .02	1000V	δ	0.0	-8.5	-23	-108	-391
		sd	0.46	0.87	0.61	0.96	0.93
	number of measurements		48	48	48	48	48

Uncertainty budget of the ac-dc voltage transfer difference measurement													
influence quantity	Type	***u***	voltage	Standard measurement uncertainty u in 10^{-6} at frequencies									
				1 kHz	degree	10 kHz	degree	20 kHz	degree	50 kHz	degree	100 kHz	degree
reference standard		***u* (δs)**		**4.3**		**4.5**		**4.9**		**7.9**		**13.3**	
voltage setup up to 400 V	B	*u* (δset)		**3.0**		**3.1**		**3.5**		**5.6**		**6.9**	
comparison of 400 V TC to 1000 V TC		*u* (δc)		**1.3**		**1.4**		**1.4**		**2.3**		**6.4**	
Std dev. of comparison	A	*u* (δa)		0.9	47	1.0	47	0.9	47	1.0	47	1.0	47
TC output circuit system	B	*u* (δT)		0.1	23	0.1	23	0.3	23	0.5	23	1.3	23
level dependence	B	*u* (δl)		0.7	47	0.7	47	0.7	47	1.7	47	6.0	47
Disagreement among other TCVs	B	*u* (δD)		0.1	47	0.2	47	0.2	47	0.3	47	0.5	47
Reproducibility	A	*u* (δR)		0.2	47	0.3	47	0.3	47	0.4	47	0.4	47
drift	B	*u* (δdr)		0.2	47	0.2	47	0.2		0.3		0.3	
measuring sequence	B	*u* (δm)		0.7	47	0.7	47	0.7		1		1.3	
different measurement		***u* (δd)**	500 V	**1.2**		**1.2**		**1.4**		**1.6**		**4.6**	
			1000V	**1.3**		**1.4**		**1.5**		**2.1**		**6.0**	
standard deviation	A	*u* (δa)	500V	0.7	47	0.7	47	0.7	47	0.7	47	0.9	47
			1000V	0.5	47	0.9	47	0.6	47	1.0	47	0.9	47
resolution of DVM	B	*u* (δr)	500V	0.1	47	0.1	47	0.1	47	0.1	47	0.1	47
			1000V	0.0	47	0.0	47	0.0	47	0.0	47	0.0	47
TC output circuit system	B	*u* (δT)	500V	0.1	23	0.1	23	0.1	23	0.3	23	2.0	23
			1000V	0.7	23	0.2	23	0.2	23	0.7	23	2.3	23
level dependence	B	*u* (δl)	500V	0.3	47	0.3	47	0.3	47	0.7	47	2.0	47
			1000V	0.7	47	0.7	47	0.7	47	1.0	47	4.0	47
Disagreement between another TCVs	B	*u* (δD)	500V	0.3	47	0.3	47	0.3	47	0.3	47	0.3	47
			1000V	0.3		0.3	47	0.3	47	0.3	47	0.3	47
Reproducibility	A	*u* (δR)	500V	0.1	47	0.2	47	0.2	47	0.3	47	1.3	47
			1000V	0.1	47	0.1	47	0.2	47	0.2	47	0.3	47
drift	B	*u* (δdr)	500V	0.2	47	0.2	47	0.2	47	0.3	47	0.3	47
			1000V	0.2	47	0.2	47	0.2	47	0.3	47	1.0	47
measuring sequence	B	*u* (δm)	500V	0.7	47	0.7	47	1.0	47	1.0	47	1.3	47
			1000V	0.7	47	0.7	47	1.0	47	1.0	47	1.3	47
Grounding	B	*u* (δg)	500V	0.3	47	0.3	47	0.3	47	0.3	47	3.0	47
			1000V	0.3	47	0.3	47	0.3	47	1.0	47	3.3	47
Standard measurement uncertainty		***u* (δx)**	500V	**5.5**		**5.7**		**6.3**		**9.5**		**18**	
			1000V	**5.6**		**5.9**		**6.4**		**10.0**		**19**	
expanded uncertainty for confidence level of 95%		**U**	500V	**10.9**		**11.3**		**13**		**19**		**36**	
			1000V	**11.3**		**12**		**13**		**20**		**39**	

Remarks: *u*(δx) = *u*(δs) + *u*(δd) u^2(δd) = u^2(δa) + u^2(δr) + …… + u^2(δg)

11. Uncertainty budget for PTB (Germany)

Uncertainty budget of the ac-dc voltage transfer standards in PTB

influence quantity	u	standard measurement uncertaintyies u in 10^{-6} at the frequencies				
		1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
MJTC at 5-V-level						
Thomson effect at dc	$u(\delta_{TH})$	0,01	0,01	0,01	0,01	0,01
reactive components and loss factor of the heater	$u(\delta_{L,G,C})$	0,00	0,02	0,02	0,05	0,13
skineffect	$u(\delta_{SKIN})$	0,00	0,00	0,00	0,00	0,03
low frequency effect	$u(\delta_{LF})$	0,00	0,00	0,00	0,00	0,00
connector and T	$u(\delta_{Connect})$	0,00	0,10	0,10	0,30	0,50
measurements between different converters	$u(\delta_{d})$	0,10	0,10	0,10	0,10	0,50
standard uncertainty 5-V	$\boldsymbol{u(\delta_{S\ 5\text{-}V})}$	**0,1**	**0,1**	**0,1**	**0,3**	**0,7**
Step-up procedure						
10-V-level						
standard uncertainty 5 V	$u(\delta_{S\ 5\ V})$	0,1	0,1	0,1	0,3	0,7
comparison measurements	$u(\delta_{d})$	0,1	0,1	0,1	0,1	0,5
resistor voltage coefficient	$u(\delta_{U\text{voltage coefficient}})$	0,4	0,4	0,4	0,4	1,0
standard uncertainty 10 V	$\boldsymbol{u(\delta_{S\ 10\ V})}$	**0,4**	**0,4**	**0,4**	**0,5**	**1,3**
20-V-level						
standard uncertainty 10 V	$u(\delta_{S\ 10\ V})$	0,4	0,4	0,4	0,5	1,3
comparison measurements	$u(\delta_{d})$	0,1	0,1	0,1	0,1	0,5
resistor voltage coefficient	$u(\delta_{U\text{voltage coefficient}})$	0,4	0,4	0,4	0,4	1,0
standard uncertainty 20 V	$\boldsymbol{u(\delta_{S\ 20\ V})}$	**0,6**	**0,6**	**0,6**	**0,7**	**1,7**
100-V-level						
standard uncertainty 20 V	$u(\delta_{S\ 20\ V})$	0,6	0,6	0,6	0,7	1,7
comparison measurements	$u(\delta_{d})$	0,1	0,1	0,1	0,1	0,5
resistor/converter combination	$u(\delta_{U\text{standards}})$	1,9	1,9	1,9	1,9	1,9
resistor voltage coefficient	$u(\delta_{U\text{voltage coefficient}})$	1,0	1,0	1,0	1,0	1,0
standard uncertainty 100 V	$\boldsymbol{u(\delta_{S\ 100\ V})}$	**2,2**	**2,2**	**2,2**	**2,3**	**2,8**
200-V-level						
standard uncertainty 100 V	$u(\delta_{S\ 100\ V})$	2,2	2,2	2,2	2,3	2,8
comparison measurements	$u(\delta_{d})$	0,1	0,1	0,1	0,1	0,5
resistor/converter combination	$u(\delta_{U\text{standards}})$	1,2	1,2	1,2	1,2	2,8
resistor voltage coefficient	$u(\delta_{U\text{volt. coefficient}})$	1,5	1,5	1,5	1,6	4,1
with high voltage amplifiers	$u(\delta_{U\text{amplifiers}})$	2,3	2,3	2,9	3,5	9,0
standard uncertainty 200 V	$\boldsymbol{u(\delta_{S\ 200\ V})}$	**3,7**	**3,7**	**4,1**	**4,6**	**11**

influence quantity	*u*	standard measurement uncertaintyies *u* in 10^{-6} at the frequencies				
		1 kHz	10 kHz	20 kHz	50 kHz	100 kHz
500-V-level						
standard uncertainty 100 V	$u(\delta_{S\ 100\ V})$	2,2	2,2	2,2	2,3	2,8
comparison measurements	$u(\delta_{d})$	0,1	0,1	0,1	0,1	0,5
resistor/converter combination	$u(\delta_{U\text{standards}})$	0,5	0,5	0,5	1	4,5
resistor voltage coefficient	$u(\delta_{U\text{volt. coefficient}})$	0,6	0,6	0,8	0,4	2,3
high voltage amplifiers	$u(\delta_{U\text{amplifiers}})$	0,7	0,7	0,7	2,1	8,1
standard uncertainty 500 V	$\boldsymbol{u(\delta_{S\ 500\ V})}$	**2,5**	**2,5**	**2,5**	**3,3**	**10**
600-V-level						
standard uncertainty 500 V	$u(\delta_{S\ 500\ V})$	2,5	2,5	2,5	3,3	10
comparison measurements	$u(\delta_{d})$	0,1	0,1	0,1	0,1	0,5
resistor/converter combination	$u(\delta_{U\text{standards}})$	0,5	0,5	0,5	1	4,5
resistor voltage coefficient	$u(\delta_{U\text{volt. coefficient}})$	0,6	0,6	0,8	0,4	2,3
high voltage amplifiers	$u(\delta_{U\text{amplifiers}})$	0,9	0,9	0,8	2,1	8,8
standard uncertainty 600 V	$\boldsymbol{u(\delta_{S\ 600\ V})}$	**2,7**	**2,7**	**2,8**	**4,0**	**14**
1000-V-level						
standard uncertainty 500 V	$u(\delta_{S\ 500\ V})$	2,5	2,5	2,5	3,3	10,0
comparison measurements	$u(\delta_{d})$	0,1	0,1	0,1	0,1	0,5
resistor/converter combination	$u(\delta_{U\text{standards}})$	0,5	0,5	0,5	1	4,5
resistor voltage coefficient	$u(\delta_{U\text{volt. coefficient}})$	0,4	0,4	0,9	0,3	5,5
high voltage amplifiers	$u(\delta_{U\text{amplifiers}})$	1,0	1,0	1,0	3,2	4,7
standard uncertainty 1000 V	$\boldsymbol{u(\delta_{S\ 1000\ V})}$	**2,7**	**2,7**	**2,9**	**4,7**	**13**

As at 100 kHz the standard measurement uncertainty at 600 V is larger than at 1000 V, the larger value is taken for the uncertainty at 1000 V.

All uncertainties are calculated as a mean of more than 40 measurements. Therefore the degrees of freedom can be taken as large enough to use k=2 for the calculation of the expanded measurement uncertainty at a confidence level of 95 %.

12. Uncertainty budget for MSL (New Zealand)

Results

The RMS voltage applied to the converter was 500 V and 1000 V for the range of frequencies given in the following table.

Voltage (V)	Frequency (kHz)	Ac-dc Transfer Difference (μV/V)	Expanded Uncertainty (μV/V)	Coverage Factor
500	1	+2	18	2.0
500	10	+2	18	2.0
500	20	+0	18	2.0
500	50	+6	22	2.0
500	100	+43	28	2.0
1000	1	-2	20	2.0
1000	10	-4	20	2.0
1000	20	-6	20	2.0
1000	50	+1	24	2.0
1000	100	+43	30	2.0

Uncertainties

The expanded uncertainties given in the Results section are at a 95% level of confidence. They are calculated by combining type A and type B uncertainty components using the Welch-Satterthwaite formula (see the "Guide to the Expression of Uncertainty in Measurement (ISO, 1st edition, 1993) for and explanation of terms).

The following Tables list the significant uncertainties together with their assigned degrees of freedom for each measured point.

(a) 500 V

Table of Uncertainty Components						
Description	**Standard Uncertainty (μV/V)**					**Comment**
	Frequency (kHz)					
	1	**10**	**20**	**50**	**100**	
Reference standard	7.0	7.0	7.0	9.0	12.5	NML Cablibration of 792A at 200 V (ν = 200)
Stability of reference	2.2	2.8	1.9	3.7	3.7	Comparison with other instrument (ν = 8)
Build-up from 200 V to 500 V	3.4	3.4	3.3	3.3	4.2	Use heating method (ν = 7)
Type A, non-linear drift, and meeting definition	0.6	0.5	0.5	0.5	0.7	Evaluate during measurement process (ν = 100)
Measurement setup	4.0	4.0	3.7	3.7	3.2	Changes due to variation in equipment (ν = 13)
Grounding	0.5	0.5	2.0	3.0	3.0	Different grounding points (ν = 5)
Combined standard uncertainty	9.1	9.2	9.0	11.3	14.4	
Effective degrees of freedom	130	128	139	161	227	
Expanded uncertainty	**18**	**18**	**18**	**22**	**28**	

(b) 1000 V

Table of Uncertainty Components						
Description	**Standard Uncertainty (μV/V)**					**Comment**
	Frequency (kHz)					
	1	**10**	**20**	**50**	**100**	
Reference standard	7.0	7.0	7.0	9.0	12.5	NML Cablibration of 792A at 200 V (ν = 200)
Stability of reference	2.2	2.8	1.9	3.7	3.7	Comparison with other instrument (ν = 8)
Build-up from 200 V to 500 V	6.2	6.2	6.1	6.2	6.7	Use heating method (ν = 11)
Type A, non-linear drift, and meeting definition	0.3	0.3	0.3	0.3	0.4	Evaluate during measurement process (ν = 100)
Measurement setup	1.5	1.5	1.5	1.5	1.5	Changes due to variation in equipment (ν = 13)
Grounding	0.5	0.5	2.0	3.0	3.0	Different grounding points (ν = 5)
Combined standard uncertainty	9.7	9.9	9.8	12.0	15.0	
Effective degrees of freedom	33	34	34	62	120	
Expanded uncertainty	**20**	**20**	**20**	**24**	**30**	

All uncertainties are estimated by combining the uncertainties of the calibration process (including those of the reference standards) with those associated with the short-term behaviour of the instrument.