Final report of key comparison EURAMET.EM-K11 ac-dc voltage transfer difference at low voltages

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1 Introduction

The Mutual Recognition Arrangement (MRA) state, that the metrological equivalence of national measurement standards will be determined by a set of key comparisons chosen and organised by the Consultative Committees of the CIPM working closely together with the Regional Metrology Organisations (RMO).

A regional key comparison EURAMET.EM-K11 “ac-dc voltage transfer difference at low voltages” has been conducted between National Metrology Institutes (NMI). Most of the participating NMIs are members of EURAMET but three NMIs from AFRIMETS, APMP and COOMET are also participating. The aim of the comparison is to determine the Degree of Equivalence (DoE) between the participating NMIs and will be linked to the participants of the CIPM key comparison CCEM-K11 “ac-dc voltage transfer difference at low voltages” conducted 2001-2005.

2 Participants and organisation

The comparison was organised in accordance with the EUROMET Guidelines on Conducting Comparisons (valid at the time of the start of the comparison). SP Technical Research Institute of Sweden has been the pilot laboratory with a support group from Physikalisch-Technischen Bundesanstalt (PTB) and Dutch Metrology Institute (VSL). The technical protocol of the comparison was prepared by the pilot laboratory and the final version was agreed in cooperation with the support group. It agrees to a large extent with the technical protocol of the CCEM-K11. After the finalization of the CCEM-K11 another travelling standard was characterized to be used in this comparison. The comparison was organized with one travelling standard circulated in seven consecutive loops with one to seven participants. The stability of the travelling standard was monitored by measurements of the pilot laboratory between each loop. In case of failure the VSL had offered to supply a back-up standard of the same type.

Twenty one NMIs participated in the comparison and they are listed in Table 1.

SP, PTB and VSL have also participated in the CCEM-K11 and will be the linking laboratories.

Table 1 Participants listed in chronological order of the time schedule.

Acronym	NMI	Country	Contact persons
SP	Technical Research Institute of Sweden	Sweden	K.-E. Rydler V. Tarasso
JV	Justervesenet, National Standards Laboratory	Norway	H. Slinde K. Lind
INRIM[1]	Istituto Nazionale per la Ricerca Metrologica	Italy	U. Pogliano
PTB	Physikalisch-Technischen Bundesanstalt	Germany	M. Klonz T. Funck
VSL[2]	Dutch Metrology Institute	The Netherlands	E. Dierikx J. Dessens
BEV	Bundesamt für Eich- und Vermessungswesen	Austria	M. Garcocz
OMH	Országos Mérésügyi Hivatal National Office of Measures	Hungary	T. Németh
INETI	Instituto Nacional de Engenharia, Tecnologia e Inovação	Portugal	R. de Mello Freitas
CEM	Centro Espanol de Metrologia	Spain	S. Ramiro
GUM	Central Office of Measures	Poland	J. Ratajczak
MIRS/SIQ	Slovenian Institute of Quality and Metrology	Slovenia	Z. Svetic
MIKES	Centre for Metrology and Accreditation	Finland	T. Mansten
DANIAmet-DPLE	Trescal A/S[3]	Denmark	T. Lippert
LNE	Laboratoire National de Métrologie et d'Essais	France	A. Poletaeff
METAS	Swiss Federal Office of Metrology	Switzerland	A. Mortara
UME	TÜBİTAK UME-Ulusal Metrolji Enstitusu	Turkey	M. Arifovic
NMISA[4]	National Metrology Laboratory	South Africa	L. Marais
CMI	Czech Metrology Institute	Czech republic	V. Zachovalova
EIM	Hellenic Institute of Metrology	Greece	M. Holiastou
NPLI	National Physical Laboratory	India	V. K. Rustagi
VNIIM	D.I. Mendeleyev Institute for Metrology	Russia	G. P. Telitchenko

[1] IEN at the time of measurement
[2] NMI-VSL at the time of measurement
[3] AREPA at the time of measurement
[4] CSIR-NML at the time of measurement

The Federal Public Service Economy - Metrology Division (SMD), Belgium, withdraw their participation before doing any measurements due to shortage of staff.

3 Travelling standard and measuring instruction

The travelling standard was a Fluke 792A ac-dc transfer standard, serial number 5495 003, which has amplified low voltage ranges 220 mV and 22 mV. At the rated input voltage the output voltage is approximately 2 V. The input connector of the standard is a type N female extended with a stainless steel connector saver, N male to N female. The output connectors are 4 mm binding posts, female. A battery pack with connecting cable was included, as the travelling standard had to be operated on battery during measurement.

The task was to measure the ac-dc voltage transfer difference of the travelling standard at the voltages 100 mV and 10 mV and at the frequencies 1 kHz, 20 kHz, 100 kHz and 1 MHz and at the temperature 23°C and relative humidity 45 %.

The ac-dc voltage transfer difference δ of the travelling standard is defined as:

$$\delta = (V_{ac} - V_{dc}) / V_{dc} \qquad (1)$$

where

V_{ac} is the rms value of the ac input voltage

V_{dc} is the dc input voltage, which when reversed produces the same mean output voltage of the transfer standard as V_{ac}.

The reference plane of the measured ac-dc voltage transfer difference was to be reported and should preferably be at the centre of a type N-Tee connector with type N male output connectors. The temperature and relative humidity coefficients of the travelling standard were given and the measuring values should be corrected to a nominal temperature of 23°C and relative humidity of 45%, Table 2. The following information was given in the technical protocol to define the temperature and relative humidity coefficient:

The correction $\Delta\delta_T$ of the ac-dc transfer difference due to temperature dependence of the travelling standard is:

$$\Delta\delta_T = \alpha_T \Delta T \qquad (2)$$

where

α_T is the temperature coefficient, values and uncertainties given in table below.

ΔT is the correction for the deviation of the temperature from the reference value 23°C during the measurement (ΔT = 23 – temperature during measurement)

The correction $\Delta\delta_{RH}$ of the ac-dc transfer difference due to humidity dependence of the travelling standard is:

$$\Delta\delta_{RH} = \alpha_{RH} \Delta RH \qquad (3)$$

where

α_{RH} is the relative humidity coefficient, values and uncertainties given in table below.

ΔRH is the correction for the deviation of the relative humidity from the reference value 45% during the measurement (ΔRH = 45 – RH during measurement)

Table 2 The temperature and relative humidity coefficients, at 23°C and 45% RH, of the ac-dc transfer difference of the travelling standard with their expanded uncertainties

Range	Frequency	Temperature coefficient 10^{-6}/K	Expanded uncertainty 10^{-6}/K	Relative humidity coefficient 10^{-6}/%	Expanded uncertainty 10^{-6}/%
220 mV	1 kHz	0,4	1	0	0,02
	20 kHz	0,4	1	0	0,05
	100 kHz	0,6	1	0,1	0,1
	1 MHz	10	4	1,3	0,5
22 mV	1 kHz	1,2	2	0	0,02
	20 kHz	1,2	2	0	0,05
	100 kHz	1,3	2	0,1	0,1
	1 MHz	17	8	0,9	0,5

The ac-dc voltage transfer difference of the travelling standard also has a dependence on the power supply voltage. Hence, the voltage of the battery pack was to be measured a few times during the comparison, before and after recharging. The uncertainty due to the power supply voltage was estimated to be insignificant compared to other contributions if the battery pack included in the travelling standard was used only. If not insignificant the pilot laboratory will add an uncertainty contribution. As one of the uncertainty contributions is due to loading it was also pointed out in the technical protocol that the equivalent input resistance of a Fluke 792A is frequency dependent.

The travelling standard had been evaluated and found to be very stable both regarding the long-term drift and the influence due to transportation.

4 Methods of measurement

Table 3 Reference standards and measurements methods used by the participants and source of traceability.

NMI	Reference standard and measurement method at 100 mV	Source of traceability at 100 mV	Reference standard and measurement method at 10 mV	Source of traceability at 10 mV
SP	µPot step-down	In-house	µPot step-down	In-house
JV	µPot step-down	In-house	µPot step-down, RVD and attenuator	In-house
INRIM	Direct comparison SJTC	In-house	SJTC+RVD	In-house
PTB	Direct comparison PMJTC	In-house	µPot step-down	In-house
VSL	µPot step-down	In-house	µPot step-down	In-house
BEV	Direct comparison PMJTC	PTB	PMJTC+RVD	In-house
OMH	µPot step-down	In-house	µPot step-down	In-house
INETI	Indirect comparison with PMJTC via Fluke 792A	PTB	PMJTC+RVD	PTB, SP
CEM	Direct comparison PMJTC	PTB	PMJTC+RVD	In-house
GUM	Direct comparison Fluke 792A	Fluke	Direct comparison Fluke 792A	Fluke
MIRS/SIQ	Direct comparison Fluke 5790A	SP	Direct comparison Fluke 5790A	SP
MIKES	Direct comparison PMJTC	PTB	PMJTC+RVD	PTB, SP
DANIAmet-DPLE	µPot step-down	In-house	µPot step-down	In-house
LNE	Direct comparison Fluke 792A calibrated by RVD	In-house	Direct comparison Fluke 792A calibrated by RVD	In-house
METAS	µPot step-down	In-house	µPot step-down	In-house
UME	Direct comparison PMJTC	PTB	µPot step-down	In-house
NMISA	Direct measurement µPot	NIST	Direct measurement µPot	NIST
CMI	Direct comparison PMJTC	PTB	µPot step-down	In-house
EIM	Direct comparison PMJTC	PTB	Direct measurement µPot	PTB
NPLI	µPot step-down	In-house	µPot step-down	In-house
VNIIM	Divider, type?	In-house	Divider, type?	In-house

5 Measurements of the pilot laboratory and influence parameters

During the course of the comparison the stability of the travelling standard has been monitored by the pilot laboratory. The drift of the travelling standard relative the standards of the pilot laboratory is estimated by a linear least square fit. The stability of the travelling standard has been very good with a maximum yearly drift of <5 µV/V at 1 MHz, Table 4. But the short term stability of the 10 mV range of the travelling standard was not quite as good as for the travelling standard used in the CCEM-K11.

The temperature and relative humidity coefficients of the travelling standard were characterized before the comparison started and were given in the technical protocol. The power supply voltage coefficients of the travelling standard were also characterized before the comparison. The influence of the power supply voltage was estimated to be insignificant, but the participants were asked to report minimum and maximum power supply voltages during their measuring period. If the influence is not insignificant corrections of the participants reported values to a reference voltage will be made by the pilot laboratory.

6 Measurement results

The results of the NMIs were reported for each measuring point as measured ac-dc transfer difference δ_i and expanded uncertainty U_i. The expanded uncertainty is obtained as the standard uncertainty of the measurand multiplied by a coverage factor k_i. All but two of the NMIs reported the effective degrees of freedom ν_{eff} of the standard uncertainty of the results.

6.1 Corrections

6.1.1 Correction due to power supply voltage

All participants have reported minimum and maximum power supply voltages during their measuring period. All laboratories but two had a mean value of the total power supply voltage within ±10 mV of the mean value of SP (22,260 V). For the two labs with larger deviations it seems obvious that there is a mistake in one of the four reported values, e.g. the min value of the positive battery voltage is similar to other participants but the maximum value deviates oddly. Hence, for these two labs the deviating value was replaced by the mean of the measured value by the lab before and after. Then these two labs also got a deviation of the mean value within ±10 mV. With this small voltage deviation the influence of the power supply voltage on the measured ac-dc transfer difference is insignificant.

6.1.2 Correction due to drift

The drift of the travelling standard is estimated for each measuring point by linear least square fit to the seven corrected ac-dc transfer differences of the pilot laboratory. The annual drift is given together with the standard deviation of the residuals s_r in Table 4. The ac-dc transfer difference of the travelling standard is predicted for the mean measuring dates t_i of the NMIs based on the regression coefficients. The standard uncertainty u_{iP} of the predicted vales is determined as:

$$u_{iP}^2 = s_r^2\left[1+\frac{1}{n}+\frac{(t_i-\overline{t})^2}{\sum(t_i-\overline{t})^2}\right] \quad (4)$$

where n is seven and $\overline{t}$ is the mean date of the comparison.

Then the drift of the travelling standard is eliminated from the results by subtracting the predicted ac-dc transfer difference δ_{iP} from the reported ac-dc transfer difference δ_i of the NMIs, Table 11 to Table 18. The drift compensated ac-dc transfer difference δ_{id} of NMI i is:

$$\delta_{id} = \delta_i - \delta_{iP} \quad (5)$$

with a standard uncertainty u_{id} given by:

$$u_{id}^2 = u_i^2 + u_{iP}^2 \quad (6)$$

Table 4 The estimated annual drift of the travelling standard and the standard deviation of the residuals from the linear fit given in µV/V.

Voltage	1 kHz		20 kHz		100 kHz		1 MHz	
	Drift/y	s_r	Drift/y	s_r	Drift/y	s_r	Drift/y	s_r
100 mV	0,44	0,31	0,21	0,57	0,43	0,62	1,4	4,2
10 mV	0,3	4,4	-0,4	2,8	0,7	2,2	-4,2	8,7

Before calculating the reference value for each measuring point the seven results of the pilot laboratory are combined to one result. The new δ_{id} for SP is determined by averaging:

$$\delta_{id} = \frac{1}{7}\sum_{k=1}^{7}\delta_{kd} \quad (7)$$

with a pooled standard uncertainty u_{id} given by:

$$u_{id}^2 = \frac{1}{7}\sum_{k=1}^{7}u_{kd}^2 \quad (8)$$

6.1.3 Reference value

The comparison reference value (CRV) is determined as the weighted mean of NMIs with mutually independent results and reliable uncertainty budgets. In this comparison some NMIs have an independent realisation at the reference voltage level (1 V – 3 V) and an in-house step-down procedure. Other NMIs are traceable to another NMI at the reference voltage level and a realisation at the lower voltage levels by an in-house step-down procedure. Also some NMIs have standards at 100 mV and 10 mV that are directly traceable or strongly correlated to another NMI.

In this comparison the results of NMIs are also reckoned as independent if the value of the standard used at 100 mV or 10 mV is determined in-house by at least two steps, even if starting from a standard traceable to another NMI. Based on the experience of the CCEM-K11 the mutual correlation of the results of these NMIs will be low.

However, a few of the NMIs fulfilling these criteria have results that deviate substantially from the majority. The normalized error (E_n-value) is used as a test to determine eventual outliers. The E_n-value is determined based on a weighted mean of the results of the NMIs with independent realisations but excluding the result of the tested NMI. Results with a normalized error ≥1,5 is determined as outlier and not included in the determination of the CRV. The NMIs included in the CRV are given for each measuring point in Table 5.

Hence, the comparison reference value δ_R for each of the eight measuring points is calculated as the weighted mean of δ_{id} of the participating NMIs with independent realisations and E_n-values <1,5. That is:

$$\delta_R = \sum_{i=1}^{n} w_i \delta_{id} \tag{9}$$

where the weights w_i are determined as:

$$w_i = \frac{\dfrac{1}{u_{id}^2}}{\sum_{i=1}^{n} \dfrac{1}{u_{id}^2}} \tag{10}$$

Although the CRV is based the results of the NMIs with independent realisations there are mutual correlation due the corrections applied for relative humidity, temperature and drift. Only the correlation due to drift correction is considered significant. The standard uncertainty of the KCRV u_R is given by:

$$u_R^2 = u_{R'}^2 \left(1 + 2u_{R'}^2 \sum_{j=1}^{n-1} \sum_{k>j}^{n} \frac{r_{jk}}{u_{jd} u_{kd}} \right) \tag{11}$$

where $u_{R'}$ is the standard uncertainty of the KCRV determined as if all results are mutually independent:

$$\frac{1}{u_{R'}^2} = \sum_{i=1}^{n} \frac{1}{u_{id}^2} \tag{12}$$

and r_{jk} is the correlation coefficient for the results of NMI_j and NMI_k due to mutual correlation of drift. The correlation coefficient is determined as:

$$r_{jk} = \frac{u_j u_k}{u_{jd} u_{kd}} \tag{13}$$

where u_{jd} and u_{kd} are the standard uncertainties u_{id} of NMI_j and NMI_k given by equation (6) or (8) and u_j and u_k are the standard uncertainties associated with the correction of drift. The standard uncertainty associated with correlation due to correction of the drift u_{jdrift} is:

$$u_{\mathrm{jdrift}} = \Delta t_{\mathrm{j}} u(\alpha_{\mathrm{drift}}) \qquad (14)$$

where Δt_j is the deviation of the date of measurement of NMI_j from the mean date of the comparison and $u(\alpha_{drift})$ is the standard uncertainty of the drift rate of the travelling standard. The maximum absolute values of correlation coefficients due to correction of drift are given in Table 6.

A summary of the CRVs and the expanded uncertainties is given in Table 7.

Table 5 The NMIs with independent realisations and En-values <1,5 who’s results were used to determine the CRV for the different measuring points.

Voltage	NMIs include in CRV at frequency			
	1 kHz	20 kHz	100 kHz	1 MHz
100 mV	SP JV INRIM PTB VSL OMH DPLE LNE METAS NPLI VNIIM	SP JV INRIM PTB VSL OMH DPLE LNE METAS NPLI	SP JV INRIM PTB VSL OMH DPLE LNE METAS NPLI	SP JV INRIM PTB VSL OMH DPLE METAS
10 mV	SP JV INRIM PTB VSL BEV OMH CEM DPLE LNE METAS UME CMI NPLI VNIIM	SP JV INRIM PTB VSL BEV OMH CEM DPLE LNE METAS UME CMI NPLI VNIIM	SP JV INRIM PTB VSL BEV OMH CEM DPLE LNE METAS UME CMI NPLI VNIIM	SP JV INRIM PTB VSL BEV OMH CEM DPLE METAS UME CMI NPLI VNIIM

Table 6 The maximum absolute value of correlation coefficients due to correction of drift.

Voltage	Max correlation coefficient at frequency			
	1 kHz	20 kHz	100 kHz	1 MHz
100 mV	0,02	0,03	0,02	0,05
10 mV	0,38	0,19	0,05	0,12

Table 7 The CRV δ_R and the expanded uncertainties U_R in µV/V

Voltage	1 kHz		20 kHz		100 kHz		1 MHz	
	δ_R	U_R	δ_R	U_R	δ_R	U_R	δ_R	U_R
100 mV	-2,6	2,0	-2,3	2,5	-5,5	3,6	-8	17
10 mV	-7	7	1	6	-4	8	8	22

6.1.4 Consistency of the results

A chi-squared test has been applied to carry out an overall consistency check of the results obtained. For each measurement point the observed chi-squared value χ_{obs}^2 has been determined as:

$$\chi_{obs}^2 = \sum_{i=1}^{N} \frac{(\delta_{id} - \delta_R)^2}{u_{id}^2} \qquad (15)$$

The degrees of freedom ν = N-1.
The consistency check is considered as failing if $\Pr\{\chi^2(\nu) > \chi_{obs}^2\} < 5\%$ where Pr denotes “probability of”.

Table 8 The result of chi-square test.

	1 kHz	20 kHz	100 kHz	1 MHz
100 mV				
χ_{obs}^2	15,40	12,17	17,15	6,76
ν	10	9	9	7
Pr	12%	20%	5%	45%
10 mV				
χ_{obs}^2	10,80	17,72	13,71	16,84
ν	14	14	14	13
Pr	70%	22%	47%	21%

The consistency check does not fail in any of the measuring points, although one is on the border. Hence the results in Table 7 can be accepted as the CRV.

6.1.5 Degree of equivalence with reference value

For the NMIs included in the determination of the CRV the degree of equivalence D_{iE} of a NMIs result with the CRV is calculated as:

$$D_{iE} = \delta_{id} - \delta_R \qquad (16)$$

with a standard uncertainty u_{iDE} given by:

$$u_{iDE}^2 = u_{id}^2 - u_{R'}^2 \left(1 - 2u_{R'}^2 \sum_{j=1}^{n-1} \sum_{k>j}^{n} \frac{r_{jk}}{u_{jd} u_{kd}} \right) \qquad (17)$$

For the NMIs not included in the determination of the CRV the degree of equivalence D_{iE} of a NMIs result with the CRV is calculated as:

$$D_{iE} = \delta_{id} - \delta_{R} \tag{18}$$

with a standard uncertainty u_{iDE} given by:

$$u_{iDE}^2 = u_{id}^2 + u_{R}^2 \tag{19}$$

The expanded uncertainty U_{iE} is calculated as:

$$U_{iE} = k_{iDE} u_{iDE} \tag{20}$$

The coverage factor $k_{iDE} = 2$ is used. The degrees of equivalence D_{iE} and associated expanded uncertainties U_{iE} are given in Table 19 and Table 20.

6.1.6 Degree of equivalence between pairs of NMIs

The degree of equivalence D_{ij} between pairs of NMIs result is calculated as:

$$D_{ij} = \delta_{id} - \delta_{jd} \tag{21}$$

with a standard uncertainty u_{ijD} given by:

$$u_{ijD}^2 = u_{id}^2 + u_{jd}^2 - 2 u_{id} u_{jd} r_{ij} \tag{22}$$

The expanded uncertainty U_{ij} is calculated as:

$$U_{ij} = k_{ijD} u_{ijD} \tag{23}$$

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

6.1.7 Tables and graphs of reported results

In Table 9 and Table 10 the values reported by the participants are given. All but one NMI have measured all eight measuring points. The measured values are shown in Figure 1 to Figure 10.

Table 9 Reported values of the participants δ_i and expanded uncertainties U_i

100 mV		1 kHz		20 kHz		100 kHz		1 MHz	
		δ_i	U_i	δ_i	U_i	δ_i	U_i	δ_i	U_i
NMI	Date	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V
SP	jul-05	7,8	3,6	-6,4	4,2	19,3	6,6	24	37
JV	aug-05	7	14	-7	15	22	28	57	104
INRIM	okt-05	-3,7	9,6	-15,7	9,4	1	12	-13	60
PTB	nov-05	6	4	-7	6	20	8	43	36
SP	dec-05	8,5	3,6	-7,7	4,2	19,4	6,6	31	37
VSL	jan-06	5,6	7	-7,8	8	14,8	10	25	40
BEV	feb-06	8,8	12	-6,8	13	17,7	17	18,3	60
OMH	mar-06	8,1	7,5	-6,7	8,9	15	17,5	3	150
INETI	apr-06	16	41	-1	48	27	61	10	80
CEM	maj-06	10	10	-15	10	9	30	0	80
MIRS/SIQ	jul-06	11	30	-6	30	13	50	-9	400
SP	aug-06	8,5	3,6	-6,9	4,2	18,9	6,6	26	37
MIKES	sep-06	8,1	4,7	-6,9	5,5	17,9	6,2	16,3	32
DPLE	okt-06	-2	8	-16	8	6	13	-10	48
LNE	nov-06	9,4	7	-6,5	8	16,1	14		
METAS	dec-06	-4,3	13	-19,1	9	4,7	14	-8,5	63
UME	feb-07	8	13	-2	14	12	16	25	40
NMISA	mar-07	13,8	17,5	-0,5	17,9	30,7	34,9	242,1	186,9
SP	maj-07	9,2	3,6	-7,1	4,2	19,2	6,6	34	37
CMI	jun-07	9,3	19	-3,5	21	16,7	29	-7,9	80
EIM	jul-07	8,7	3,9	-4,1	3,6	16	4,6	9	20
SP	aug-07	9,3	3,6	-6,4	4,2	19,8	6,6	31	37
NPLI	okt-07	-0,5	11,1	-8,6	11,4	1,6	12,9	155,1	35,7
SP	nov-07	8,8	3,6	-7	4,2	19,5	6,6	24	37
VNIIM	feb-08	8,7	10	11,4	13	87,8	33	279	118
SP	apr-08	9,1	3,6	-6	4,2	21,1	6,6	32	37

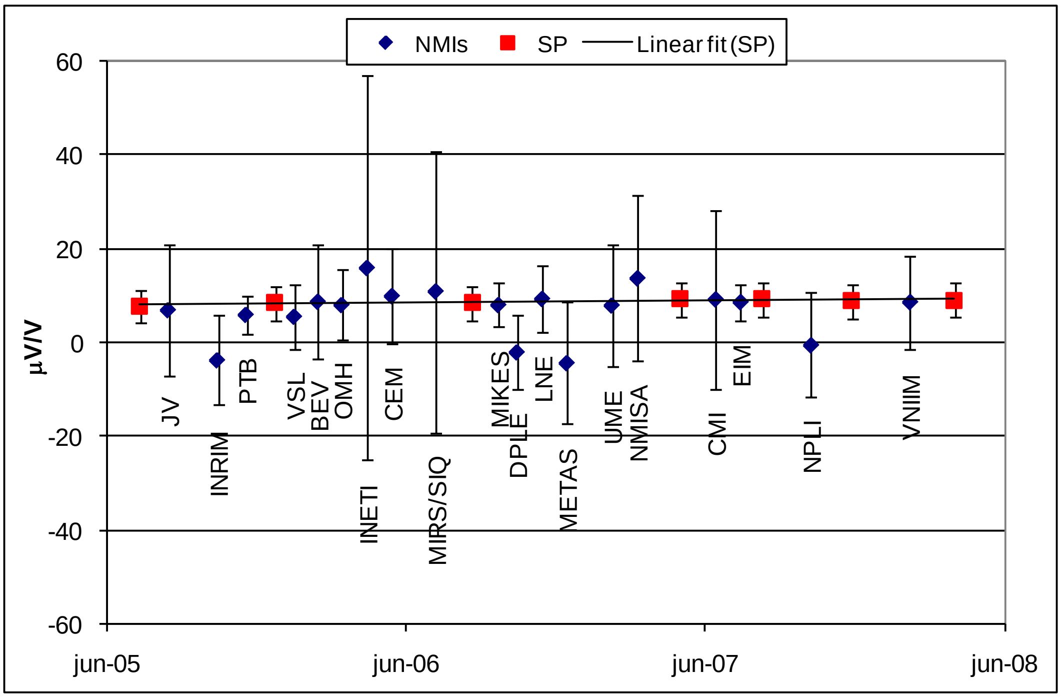

Figure 1 Reported values δ_i, 100 mV, 1 kHz, and stability of travelling standard

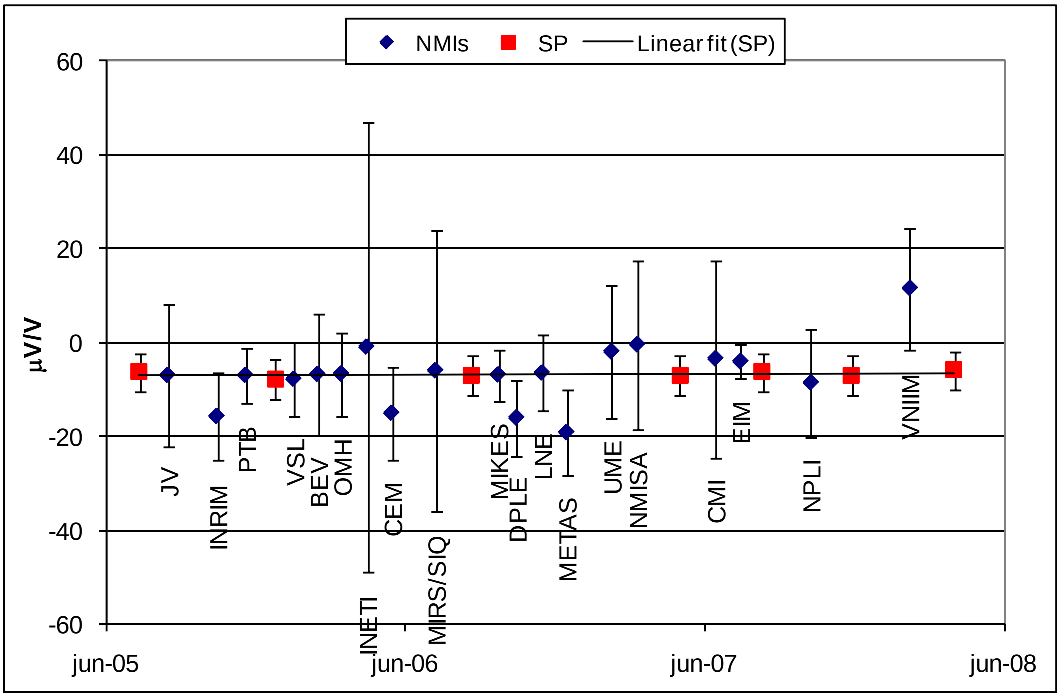

Figure 2 Reported values δ_i, 100 mV, 20 kHz, and stability of travelling standard

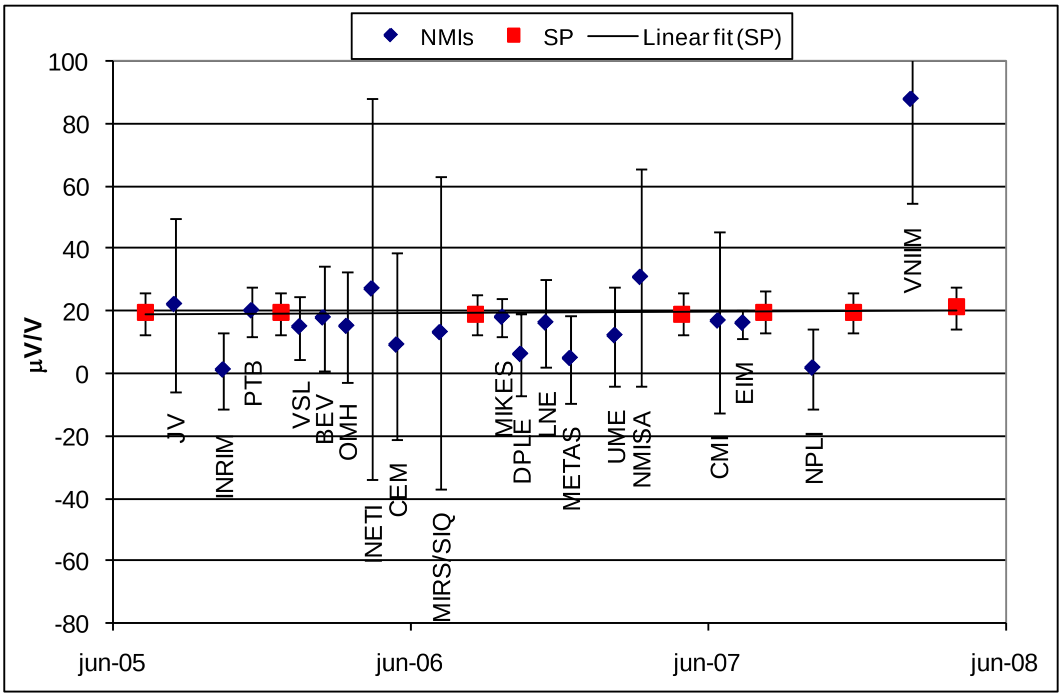

Figure 3 Reported values δ_i, 100 mV, 100 kHz, and stability of travelling standard

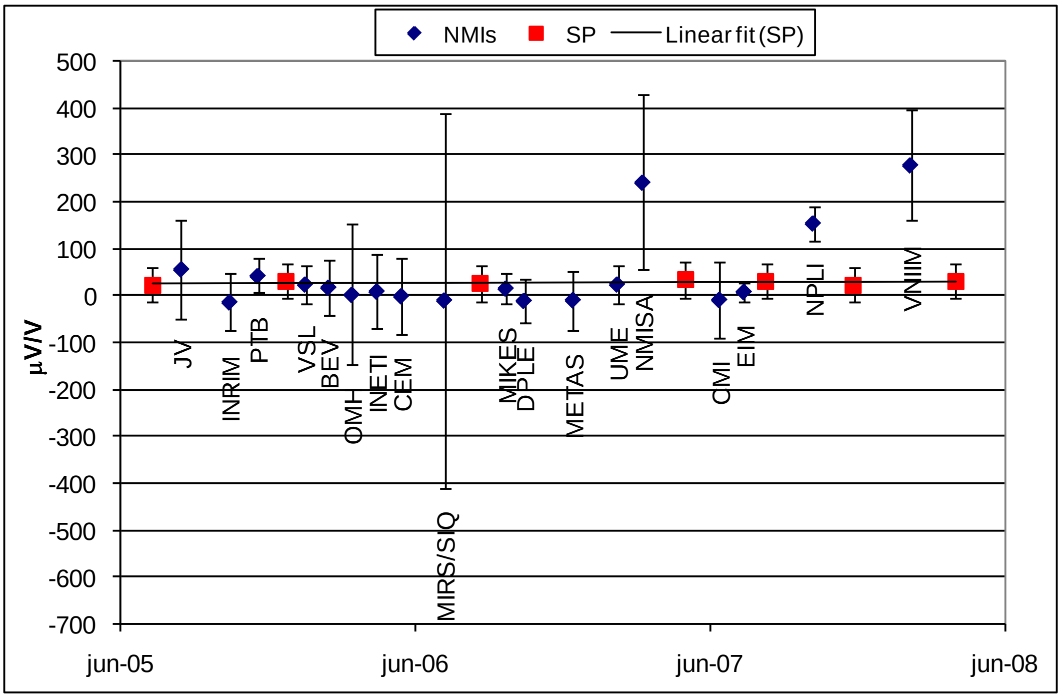

Figure 4 Reported values δ_i, 100 mV, 1MHz, and stability of travelling standard

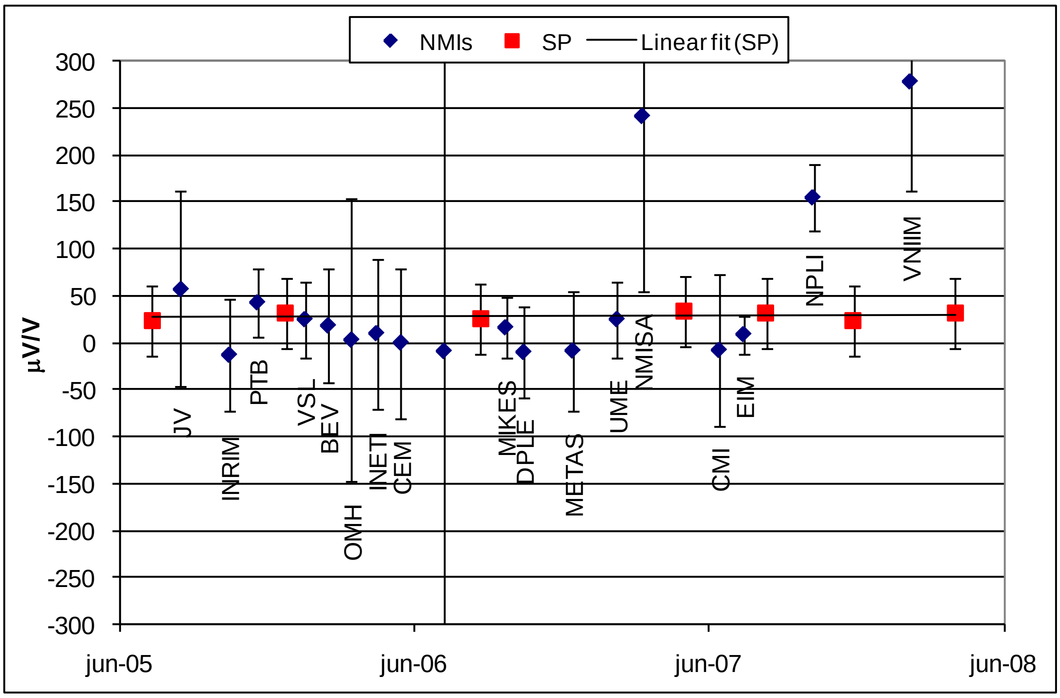

Figure 5 Reported values δ_i, 100 mV, 1MHz, at lager scale, and stability of travelling standard

Table 10 Reported values of the participants δ_i and expanded uncertainties U_i									
10 mV		1 kHz		20 kHz		100 kHz		1 MHz	
		δ_i	U_i	δ_i	U_i	δ_i	U_i	δ_i	U_i
NMI	Date	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V
SP	jul-05	6	15	-10	15	-19	19	-147	60
JV	aug-05	13	22	5	25	5	68	-95	258
INRIM	okt-05	-9	14	-24	15	-45	37	-245	120
PTB	nov-05	-10	13	-8	13	-11	20	-119	49
SP	dec-05	11	15	-12	15	-20	19	-144	60
VSL	jan-06	3,5	30	-12,3	30	-26	35	-184	100
BEV	feb-06	14	31	-6	32	-16	39	-154	127
OMH	mar-06	9,1	15,7	-9,3	17,2	-22	27,7	-277	220
INETI	apr-06	10	56	-12	56	-23	65	-27	275
CEM	maj-06	3	40	-10	40	-15	60	-104	150
MIRS/SIQ	jul-06	8	70	-18	70	-23	120	-76	750
SP	aug-06	14	15	-9	15	-17	19	-139	60
MIKES	sep-06	21,7	23,2	1,6	23,6	-13,6	35	-146	122
DPLE	okt-06	-8	41	-32	41	-45	62	-234	193
LNE	nov-06	10,5	10	-0,1	16	-17,8	21		
METAS	dec-06	-21,2	32	-48,8	31	-56,4	52	-259,7	105
UME	feb-07	14	47	0	47	-32	54	-160	109
NMISA	mar-07	2,3	57,5	10,3	56,4	-10,4	136,1	-688,7	753,3
SP	maj-07	9	15	-14	15	-20	19	-161	60
CMI	jun-07	10,7	54	-5,5	59	-11,2	80	-70,6	231
EIM	jul-07	13	85	-10	80	27	86	15	172
SP	aug-07	15	15	-12	15	-17	19	-139	60
NPLI	okt-07	1,3	14,4	-15	14,9	-34,3	15,6	-114,5	33,8
SP	nov-07	4	15	-15	15	-21	19	-155	60
VNIIM	feb-08	10,8	19	12,9	22	50	64	-60,4	161
SP	apr-08	11	15	-8	15	-15	19	-158	60

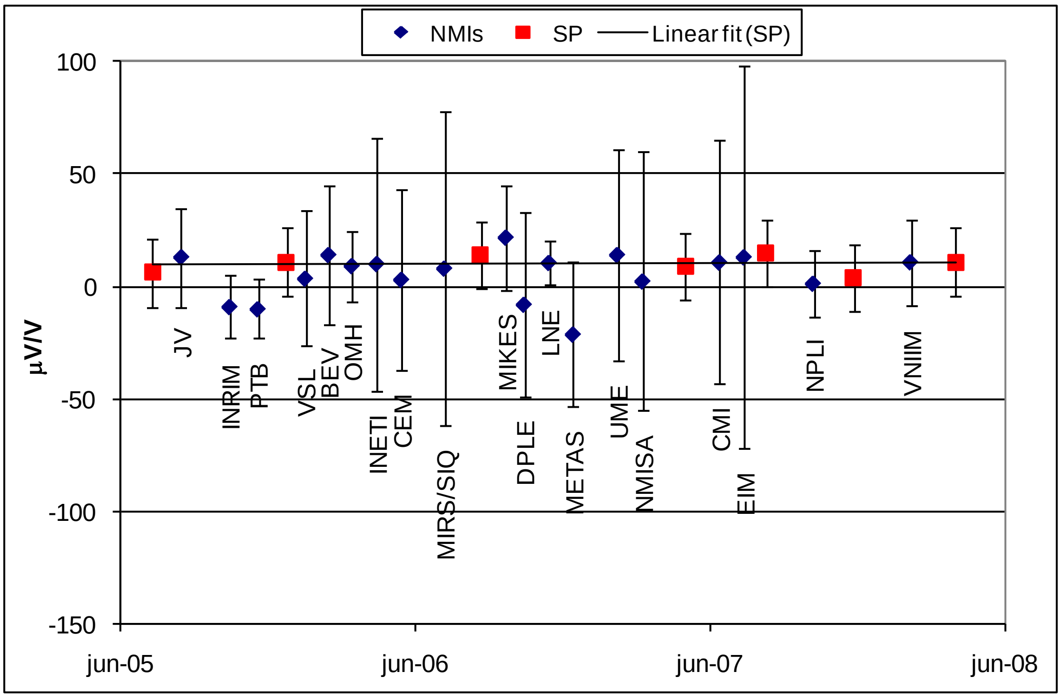

Figure 6 Reported values δ_i, 10 mV, 1 kHz, and stability of travelling standard

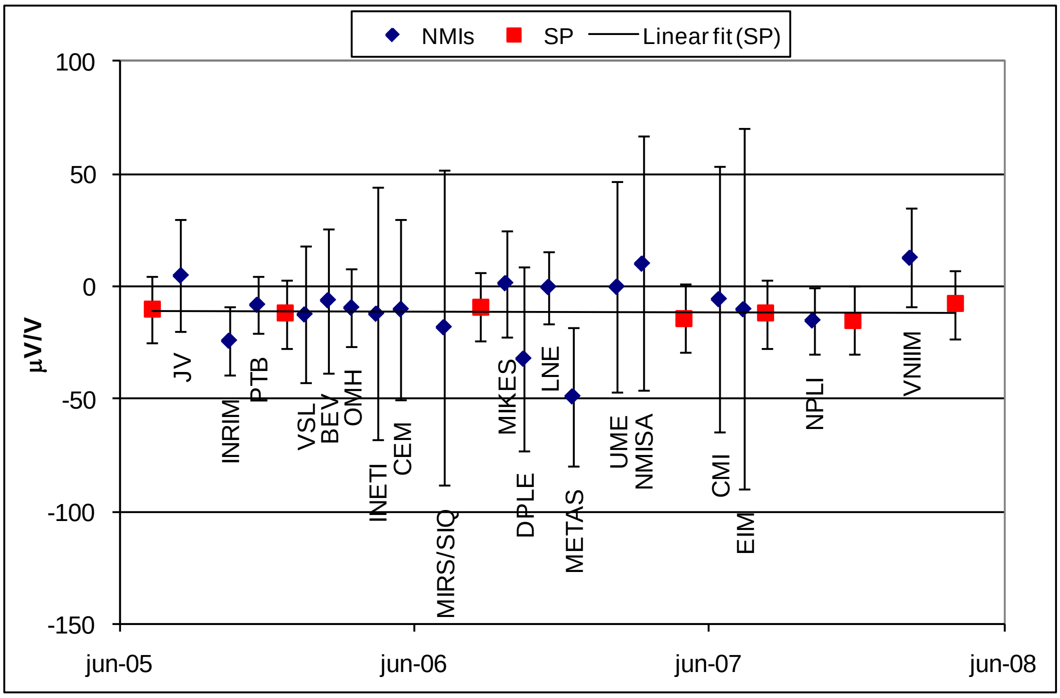

Figure 7 Reported values δ_i, 10 mV, 20 kHz, and stability of travelling standard

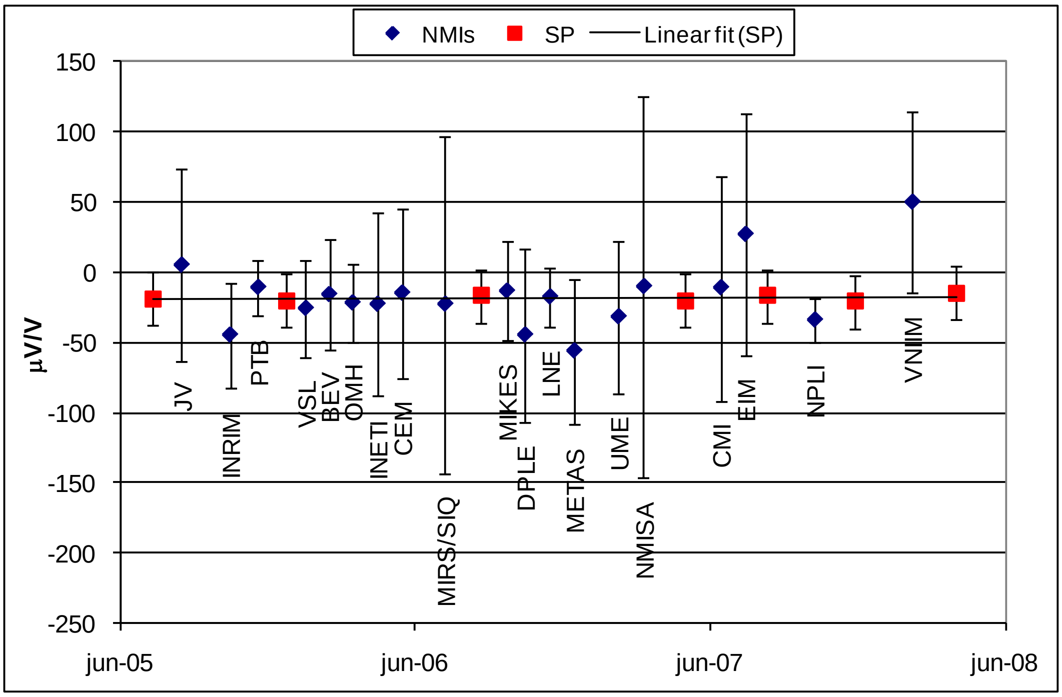

Figure 8 Reported values δ_i, 10 mV, 100 kHz, and stability of travelling standard

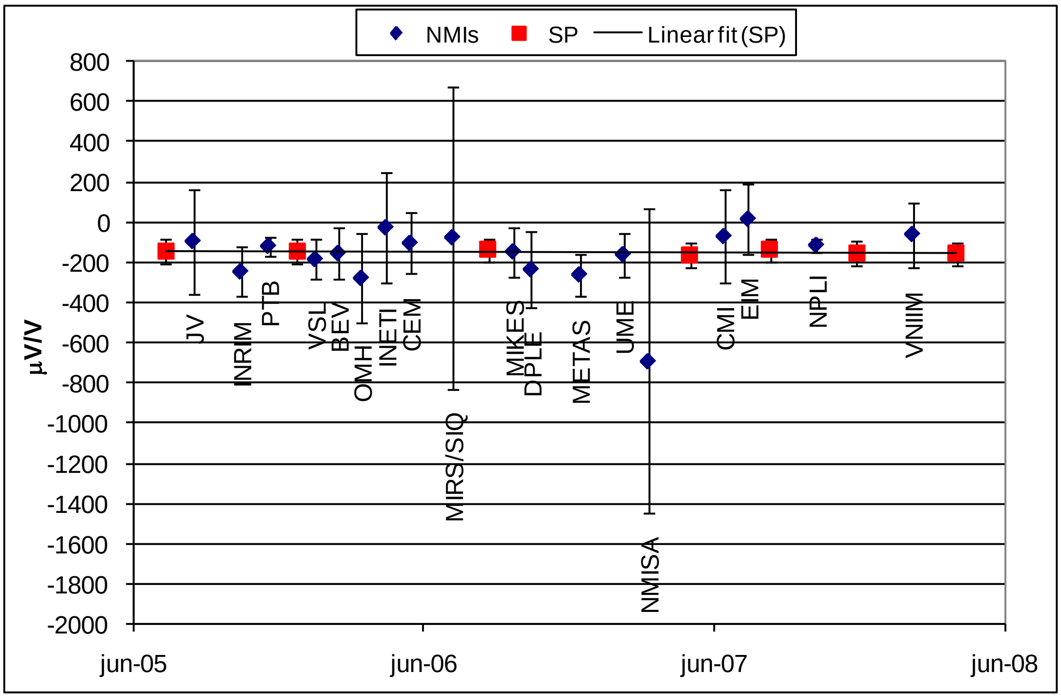

Figure 9 Reported values δ_{ic}, 10 mV, 1 MHz, and stability of travelling standard

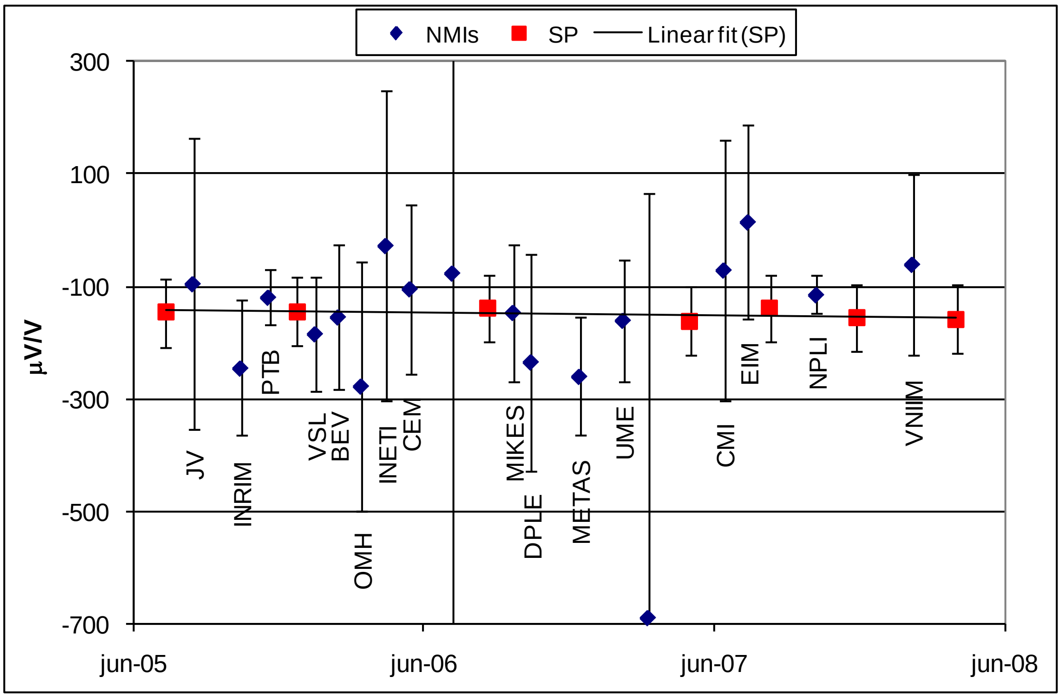

Figure 10 Reported values δ_i, 10 mV, 1 MHz, at lager scale, and stability of travelling standard

6.1.8 Tables of results after correction for drift

Table 11 Reported values corrected for drift of the travelling standard (δ_{id}), 100 mV, 1 kHz

		δ_i	U_i	δ_P	u_P	δ_{id}	U_{id}
NMI	Date	μV/V	μV/V	μV/V	μV/V	μV/V	μV/V
SP	jul-05	7,8	3,6	8,2	0,4	-0,4	3,7
JV	aug-05	7,0	14,0	8,2	0,4	-1,2	14,0
INRIM	okt-05	-3,7	9,6	8,3	0,4	-12,0	9,6
PTB	nov-05	6,0	4,0	8,3	0,4	-2,3	4,1
SP	dec-05	8,7	3,6	8,3	0,4	0,4	3,7
VSL	jan-06	5,6	7,0	8,4	0,4	-2,8	7,0
BEV	feb-06	8,8	12,0	8,4	0,4	0,4	12,0
OMH	mar-06	8,1	7,5	8,4	0,4	-0,3	7,5
INETI	apr-06	16,0	41,0	8,5	0,4	7,5	41,0
CEM	maj-06	10,0	10,0	8,5	0,4	1,5	10,0
MIRS/SIQ	jul-06	11,0	30,0	8,6	0,4	2,4	30,0
SP	aug-06	8,5	3,6	8,6	0,4	-0,1	3,7
MIKES	sep-06	8,1	4,7	8,6	0,4	-0,5	4,8
DPLE	okt-06	-2,0	8,0	8,7	0,4	-10,7	8,0
LNE	nov-06	9,4	7,0	8,7	0,3	0,7	7,0
METAS	dec-06	-4,3	13,0	8,7	0,3	-13,0	13,0
UME	feb-07	8,0	13,0	8,8	0,3	-0,8	13,0
NMISA	mar-07	13,8	17,5	8,8	0,3	5,0	17,5
SP	maj-07	9,2	3,6	8,9	0,4	0,3	3,7
CMI	jun-07	9,3	19,0	8,9	0,4	0,4	19,0
EIM	jul-07	8,7	3,9	9,0	0,4	-0,3	4,0
SP	aug-07	9,2	3,6	9,0	0,4	0,2	3,7
NPLI	okt-07	-0,5	11,1	9,0	0,4	-9,5	11,1
SP	nov-07	8,8	3,6	9,1	0,4	-0,3	3,7
VNIIM	feb-08	8,7	10,0	9,2	0,4	-0,5	10,0
SP	apr-08	9,1	3,6	9,2	0,4	-0,1	3,7

Table 12 Reported values corrected for drift of the travelling standard (δ_{id}), 100 mV, 20 kHz

		δ_i	U_i	δ_P	u_P	δ_{id}	U_{id}
NMI	Date	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V
SP	jul-05	-6,5	4,2	-7,1	0,6	0,6	4,4
JV	aug-05	-7,0	15,0	-7,1	0,6	0,1	15,0
INRIM	okt-05	-15,7	9,4	-7,0	0,6	-8,7	9,5
PTB	nov-05	-7,0	6,0	-7,0	0,6	0,0	6,1
SP	dec-05	-7,5	4,2	-7,0	0,6	-0,5	4,4
VSL	jan-06	-7,8	8,0	-7,0	0,6	-0,8	8,1
BEV	feb-06	-6,8	13,0	-7,0	0,6	0,2	13,0
OMH	mar-06	-6,7	8,9	-6,9	0,6	0,2	9,0
INETI	apr-06	-1,0	48,0	-6,9	0,6	5,9	48,0
CEM	maj-06	-15,0	10,0	-6,9	0,6	-8,1	10,1
MIRS/SIQ	jul-06	-6,0	30,0	-6,9	0,5	0,9	30,0
SP	aug-06	-6,9	4,2	-6,9	0,5	0,0	4,3
MIKES	sep-06	-6,9	5,5	-6,8	0,5	-0,1	5,6
DPLE	okt-06	-16,0	8,0	-6,8	0,5	-9,2	8,1
LNE	nov-06	-6,5	8,0	-6,8	0,5	0,3	8,1
METAS	dec-06	-19,1	9,0	-6,8	0,5	-12,3	9,1
UME	feb-07	-2,0	14,0	-6,8	0,5	4,8	14,0
NMISA	mar-07	-0,5	17,9	-6,7	0,5	6,2	17,9
SP	maj-07	-7,1	4,2	-6,7	0,5	-0,4	4,3
CMI	jun-07	-3,5	21,0	-6,7	0,5	3,2	21,0
EIM	jul-07	-4,1	3,6	-6,7	0,5	2,6	3,8
SP	aug-07	-6,4	4,2	-6,7	0,5	0,3	4,3
NPLI	okt-07	-8,6	11,4	-6,6	0,6	-2,0	11,5
SP	nov-07	-7,0	4,2	-6,6	0,6	-0,4	4,3
VNIIM	feb-08	11,4	13,0	-6,6	0,6	18,0	13,1
SP	apr-08	-6,0	4,2	-6,5	0,6	0,5	4,4

Table 13 Reported values corrected for drift of the travelling standard (δ_{id}), 100 mV, 100 kHz							
		δ_i	U_i	δ_P	u_P	δ_{id}	U_{id}
NMI	Date	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V
SP	jul-05	20,1	5,8	19,7	2,0	0,4	7,0
JV	aug-05	22,0	28,0	19,7	1,9	2,3	28,3
INRIM	okt-05	1,0	12,0	19,8	1,9	-18,8	12,6
PTB	nov-05	20,0	8,0	19,8	1,9	0,2	8,8
SP	dec-05	21,2	5,8	19,9	1,8	1,3	6,9
VSL	jan-06	14,8	10,0	19,9	1,8	-5,1	10,6
BEV	feb-06	17,7	17,0	19,9	1,8	-2,2	17,4
OMH	mar-06	15,0	17,5	20,0	1,8	-5,0	17,9
INETI	apr-06	27,0	61,0	20,0	1,8	7,0	61,1
CEM	maj-06	9,0	30,0	20,0	1,8	-11,0	30,2
MIRS/SIQ	jul-06	13,0	50,0	20,1	1,7	-7,1	50,1
SP	aug-06	18,4	5,8	20,2	1,7	-1,8	6,8
MIKES	sep-06	17,9	6,2	20,2	1,7	-2,3	7,1
DPLE	okt-06	6,0	13,0	20,2	1,7	-14,2	13,4
LNE	nov-06	16,1	14,0	20,3	1,7	-4,2	14,4
METAS	dec-06	4,7	14,0	20,3	1,7	-15,6	14,4
UME	feb-07	12,0	16,0	20,4	1,7	-8,4	16,4
NMISA	mar-07	30,7	34,9	20,4	1,7	10,3	35,1
SP	maj-07	20,2	5,8	20,5	1,7	-0,3	6,7
CMI	jun-07	16,7	29,0	20,5	1,7	-3,8	29,2
EIM	jul-07	16,0	4,6	20,6	1,7	-4,6	5,8
SP	aug-07	18,6	5,8	20,6	1,8	-2,0	6,8
NPLI	okt-07	1,6	12,9	20,7	1,8	-19,1	13,4
SP	nov-07	21,0	5,8	20,7	1,8	0,3	6,8
VNIIM	feb-08	87,8	33,0	20,8	1,8	67,0	33,2
SP	apr-08	22,8	5,8	20,9	1,9	1,9	6,9

Table 14 Reported values corrected for drift of the travelling standard (δ_{id}), 100 mV, 1 MHz

		δ_i	U_i	δ_P	u_P	δ_{id}	U_{id}
NMI	Date	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V
SP	jul-05	33,0	37,0	35,2	22,0	-2,2	57,5
JV	aug-05	57,0	104,0	35,4	21,6	21,6	112,6
INRIM	okt-05	-13,0	60,0	35,7	21,1	-48,7	73,4
PTB	nov-05	43,0	36,0	35,9	20,8	7,1	55,1
SP	dec-05	55,0	37,0	36,1	20,6	18,9	55,3
VSL	jan-06	25,0	40,0	36,2	20,4	-11,2	57,1
BEV	feb-06	18,3	60,0	36,3	20,2	-18,0	72,3
OMH	mar-06	3,0	150,0	36,5	20,0	-33,5	155,3
INETI	apr-06	10,0	80,0	36,6	19,9	-26,6	89,3
CEM	maj-06	0,0	80,0	36,8	19,7	-36,8	89,2
MIRS/SIQ	jul-06	-9,0	400,0	37,1	19,5	-46,1	401,9
SP	aug-06	19,0	37,0	37,3	19,3	-18,3	53,5
MIKES	sep-06	16,3	32,0	37,4	19,2	-21,1	50,1
DPLE	okt-06	-10,0	48,0	37,5	19,2	-47,5	61,5
LNE	nov-06						
METAS	dec-06	-8,5	63,0	37,9	19,1	-46,4	73,7
UME	feb-07	25,0	40,0	38,1	19,1	-13,1	55,3
NMISA	mar-07	242,1	186,9	38,3	19,2	203,8	190,8
SP	maj-07	46,0	37,0	38,5	19,2	7,5	53,4
CMI	jun-07	-7,9	80,0	38,8	19,4	-46,7	88,9
EIM	jul-07	9,0	20,0	38,9	19,5	-29,9	43,7
SP	aug-07	14,0	37,0	39,0	19,6	-25,0	53,8
NPLI	okt-07	155,1	35,7	39,3	19,8	115,8	53,4
SP	nov-07	45,0	37,0	39,6	20,1	5,4	54,7
VNIIM	feb-08	279,0	118,0	39,9	20,6	239,1	125,0
SP	apr-08	54,0	37,0	40,2	21,0	13,8	56,0

Table 15 Reported values corrected for drift of the travelling standard (δ_{id}), 10 mV, 1 kHz							
		δ_i	U_i	δ_P	u_P	δ_{id}	U_{id}
NMI	Date	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V
SP	jul-05	6,0	15,0	9,5	5,4	-3,5	18,4
JV	aug-05	13,0	22,0	9,6	5,3	3,4	24,4
INRIM	okt-05	-9,0	14,0	9,6	5,2	-18,6	17,4
PTB	nov-05	-10,0	13,0	9,6	5,1	-19,6	16,5
SP	dec-05	11,0	15,0	9,7	5,0	1,3	18,1
VSL	jan-06	3,5	30,0	9,7	5,0	-6,2	31,6
BEV	feb-06	14,0	31,0	9,7	4,9	4,3	32,5
OMH	mar-06	9,1	15,7	9,7	4,9	-0,6	18,5
INETI	apr-06	10,0	56,0	9,8	4,8	0,2	56,8
CEM	maj-06	3,0	40,0	9,8	4,8	-6,8	41,1
MIRS/SIQ	jul-06	8,0	70,0	9,8	4,8	-1,8	70,6
SP	aug-06	14,0	15,0	9,9	4,7	4,1	17,7
MIKES	sep-06	21,7	23,2	9,9	4,7	11,8	25,0
DPLE	okt-06	-8,0	41,0	9,9	4,7	-17,9	42,1
LNE	nov-06	10,5	10,0	9,9	4,7	0,6	13,7
METAS	dec-06	-21,2	32,0	10,0	4,7	-31,2	33,3
UME	feb-07	14,0	47,0	10,0	4,7	4,0	47,9
NMISA	mar-07	2,3	57,5	10,0	4,7	-7,7	58,3
SP	maj-07	9,0	15,0	10,1	4,7	-1,1	17,7
CMI	jun-07	10,7	54,0	10,1	4,7	0,6	54,8
EIM	jul-07	13,0	85,0	10,2	4,8	2,8	85,5
SP	aug-07	15,0	15,0	10,2	4,8	4,8	17,8
NPLI	okt-07	1,3	14,4	10,2	4,8	-8,9	17,4
SP	nov-07	4,0	15,0	10,3	4,9	-6,3	17,9
VNIIM	feb-08	10,8	19,0	10,3	5,0	0,5	21,5
SP	apr-08	11,0	15,0	10,4	5,1	0,6	18,2

Table 16 Reported values corrected for drift of the travelling standard (δ_{id}), 10 mV, 20 kHz							
		δ_i	U_i	δ_P	u_P	δ_{id}	U_{id}
NMI	Date	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V
SP	jul-05	-10,0	15,0	-10,8	3,4	0,8	16,5
JV	aug-05	5,0	25,0	-10,8	3,4	15,8	25,9
INRIM	okt-05	-24,0	15,0	-10,9	3,3	-13,1	16,4
PTB	nov-05	-8,0	13,0	-11,0	3,2	3,0	14,5
SP	dec-05	-12,0	15,0	-11,0	3,2	-1,0	16,3
VSL	jan-06	-12,3	30,0	-11,0	3,2	-1,3	30,7
BEV	feb-06	-6,0	32,0	-11,1	3,1	5,1	32,6
OMH	mar-06	-9,3	17,2	-11,1	3,1	1,8	18,3
INETI	apr-06	-12,0	56,0	-11,1	3,1	-0,9	56,3
CEM	maj-06	-10,0	40,0	-11,2	3,1	1,2	40,5
MIRS/SIQ	jul-06	-18,0	70,0	-11,2	3,0	-6,8	70,3
SP	aug-06	-9,0	15,0	-11,3	3,0	2,3	16,2
MIKES	sep-06	1,6	23,6	-11,3	3,0	12,9	24,3
DPLE	okt-06	-32,0	41,0	-11,3	3,0	-20,7	41,4
LNE	nov-06	-0,1	16,0	-11,4	3,0	11,3	17,1
METAS	dec-06	-48,8	31,0	-11,4	3,0	-37,4	31,6
UME	feb-07	0,0	47,0	-11,5	3,0	11,5	47,4
NMISA	mar-07	10,3	56,4	-11,5	3,0	21,8	56,7
SP	maj-07	-14,0	15,0	-11,6	3,0	-2,4	16,1
CMI	jun-07	-5,5	59,0	-11,6	3,0	6,1	59,3
EIM	jul-07	-10,0	80,0	-11,6	3,0	1,6	80,2
SP	aug-07	-12,0	15,0	-11,7	3,0	-0,3	16,2
NPLI	okt-07	-15,0	14,9	-11,7	3,1	-3,3	16,1
SP	nov-07	-15,0	15,0	-11,8	3,1	-3,2	16,3
VNIIM	feb-08	12,9	22,0	-11,9	3,2	24,8	22,9
SP	apr-08	-8,0	15,0	-11,9	3,3	3,9	16,4

Table 17 Reported values corrected for drift of the travelling standard (δ_{id}), 10 mV, 100 kHz							
		δ_i	U_i	δ_P	u_P	δ_{id}	U_{id}
NMI	Date	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V
SP	jul-05	-19,0	19,0	-19,5	2,7	0,5	19,8
JV	aug-05	5,0	68,0	-19,4	2,7	24,4	68,2
INRIM	okt-05	-45,0	37,0	-19,3	2,6	-25,7	37,4
PTB	nov-05	-11,0	20,0	-19,2	2,6	8,2	20,7
SP	dec-05	-20,0	19,0	-19,1	2,6	-0,9	19,7
VSL	jan-06	-26,0	35,0	-19,1	2,5	-6,9	35,4
BEV	feb-06	-16,0	39,0	-19,1	2,5	3,1	39,3
OMH	mar-06	-22,0	27,7	-19,0	2,5	-3,0	28,1
INETI	apr-06	-23,0	65,0	-18,9	2,5	-4,1	65,2
CEM	maj-06	-15,0	60,0	-18,9	2,5	3,9	60,2
MIRS/SIQ	jul-06	-23,0	120,0	-18,8	2,4	-4,2	120,1
SP	aug-06	-17,0	19,0	-18,7	2,4	1,7	19,6
MIKES	sep-06	-13,6	35,0	-18,6	2,4	5,0	35,3
DPLE	okt-06	-45,0	62,0	-18,6	2,4	-26,4	62,2
LNE	nov-06	-17,8	21,0	-18,5	2,4	0,7	21,5
METAS	dec-06	-56,4	52,0	-18,5	2,4	-37,9	52,2
UME	feb-07	-32,0	54,0	-18,4	2,4	-13,6	54,2
NMISA	mar-07	-10,4	136,1	-18,3	2,4	7,9	136,2
SP	maj-07	-20,0	19,0	-18,2	2,4	-1,8	19,6
CMI	jun-07	-11,2	80,0	-18,1	2,4	6,9	80,1
EIM	jul-07	27,0	86,0	-18,1	2,4	45,1	86,1
SP	aug-07	-17,0	19,0	-18,0	2,4	1,0	19,6
NPLI	okt-07	-34,3	15,6	-17,9	2,5	-16,4	16,4
SP	nov-07	-21,0	19,0	-17,8	2,5	-3,2	19,7
VNIIM	feb-08	50,0	64,0	-17,7	2,6	67,7	64,2
SP	apr-08	-15,0	19,0	-17,6	2,6	2,6	19,7

Table 18 Reported values corrected for drift of the travelling standard (δ_{id}), 10 mV, 1 MHz

		δ_i	U_i	δ_P	u_P	δ_{id}	U_{id}
NMI	Date	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V
SP	jul-05	-147	60	-142,6	10,7	-4	64
JV	aug-05	-95	258	-143,0	10,5	48	259
INRIM	okt-05	-245	120	-143,7	10,3	-101	122
PTB	nov-05	-119	49	-144,1	10,1	25	53
SP	dec-05	-144	60	-144,5	10,0	1	63
VSL	jan-06	-184	100	-144,8	9,9	-39	102
BEV	feb-06	-154	127	-145,1	9,8	-9	129
OMH	mar-06	-277	220	-145,5	9,7	-132	221
INETI	apr-06	-27	275	-145,8	9,7	119	276
CEM	maj-06	-104	150	-146,2	9,6	42	151
MIRS/SIQ	jul-06	-76	750	-146,8	9,5	71	750
SP	aug-06	-139	60	-147,3	9,4	8	63
MIKES	sep-06	-146	122	-147,7	9,4	2	123
DPLE	okt-06	-234	193	-148,0	9,3	-86	194
LNE	nov-06						
METAS	dec-06	-260	105	-148,7	9,3	-111	107
UME	feb-07	-160	109	-149,3	9,3	-11	111
NMISA	mar-07	-689	753	-149,7	9,3	-539	754
SP	maj-07	-161	60	-150,3	9,4	-11	63
CMI	jun-07	-71	231	-150,8	9,4	80	232
EIM	jul-07	15	172	-151,1	9,5	166	173
SP	aug-07	-139	60	-151,4	9,5	12	63
NPLI	okt-07	-115	34	-152,1	9,7	38	39
SP	nov-07	-155	60	-152,7	9,8	-2	63
VNIIM	feb-08	-60	161	-153,5	10,0	93	162
SP	apr-08	-158	60	-154,1	10,2	-4	63

6.1.9 Tables and graphs of degree of equivalence with the CRV

The degree of equivalence with the CRV and the expanded uncertainty for each NMI and measuring point are presented in Table 19 – Table 20 and Figure 11 – Figure 19. The degree of equivalence between pairs of NMIs will be included.

Table 19 Degree of equivalence with the CRV with corresponding expanded uncertainty (k=2) in µV/V, 100 mV.

D_{iE}	Difference NMI-CRV							
U_{iE}	Expanded uncertainty of D_{iE}							
Level	100 mV							
	1 kHz		20 kHz		100 kHz		1 MHz	
NMI	D_{iE}	U_{iE}	D_{iE}	U_{iE}	D_{iE}	U_{iE}	D_{iE}	U_{iE}
SP	2,6	3,1	2,3	3,7	5,5	5,8	8	33
JV	1,5	13,9	2,4	14,9	8,5	27,8	38	103
INRIM	-9,3	9,4	-6,3	9,2	-12,6	11,6	-32	58
PTB	0,4	3,5	2,3	5,7	6,4	7,4	24	32
VSL	-0,1	6,7	1,5	7,8	1,1	9,5	6	37
BEV	3,1	12,2	2,5	13,3	4,0	17,4	-1	63
OMH	2,3	7,3	2,6	8,7	1,3	17,2	-17	149
INETI	10,2	41,1	8,2	48,1	13,2	61,1	-10	82
CEM	4,1	10,2	-5,8	10,4	-4,8	30,2	-20	82
MIRS/SIQ	5,1	30,1	3,2	30,1	-0,9	50,1	-29	400
MIKES	2,1	5,2	2,3	6,2	3,9	7,3	-4	37
DPLE	-8,0	7,8	-6,9	7,8	-8,0	12,6	-30	45
LNE	3,3	6,7	2,6	7,8	2,1	13,6		
METAS	-10,4	12,9	-10,0	8,8	-9,4	13,6	-29	61
UME	1,8	13,2	7,1	14,3	-2,1	16,5	4	44
NMISA	7,6	17,6	8,6	18,1	16,5	35,1	221	188
CMI	3,0	19,1	5,5	21,2	2,4	29,3	-29	82
EIM	2,3	4,4	4,9	4,6	1,7	6,0	-12	28
NPLI	-7,0	10,9	0,3	11,2	-12,8	12,5	133	41
VNIIM	2,1	9,8	20,3	13,3	73,2	33,2	257	120

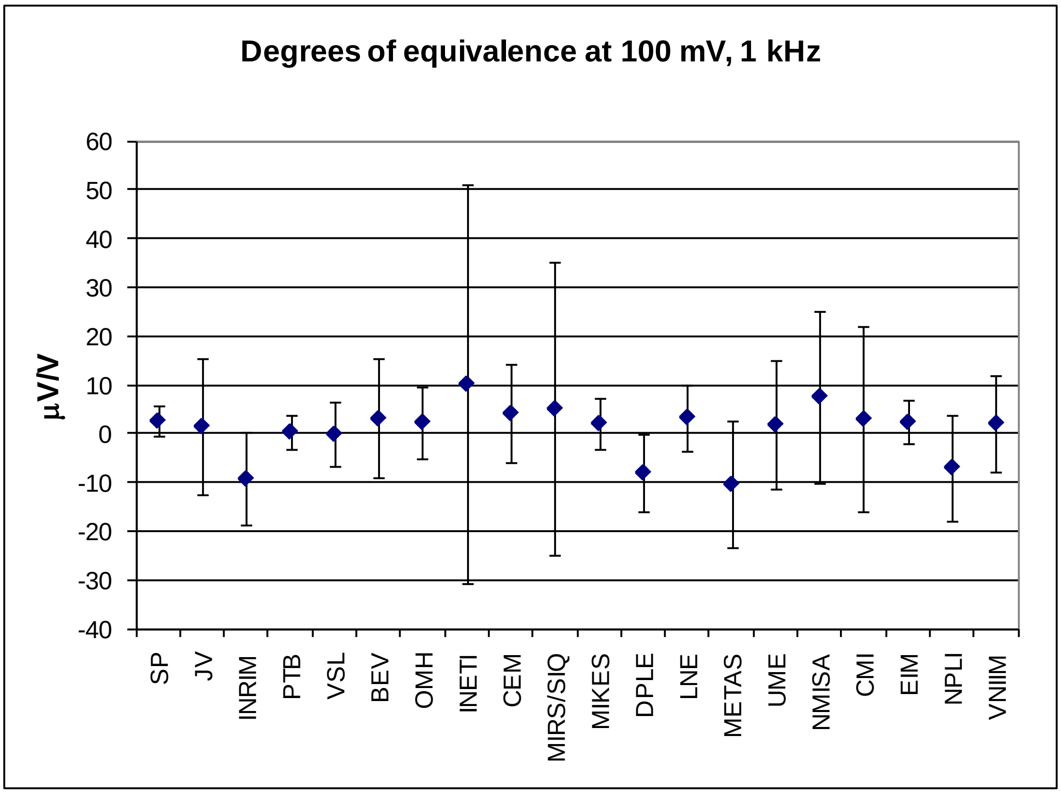

Figure 11 Degree of equivalence with the CRV at 100 mV, 1 kHz with corresponding expanded uncertainties (k=2).

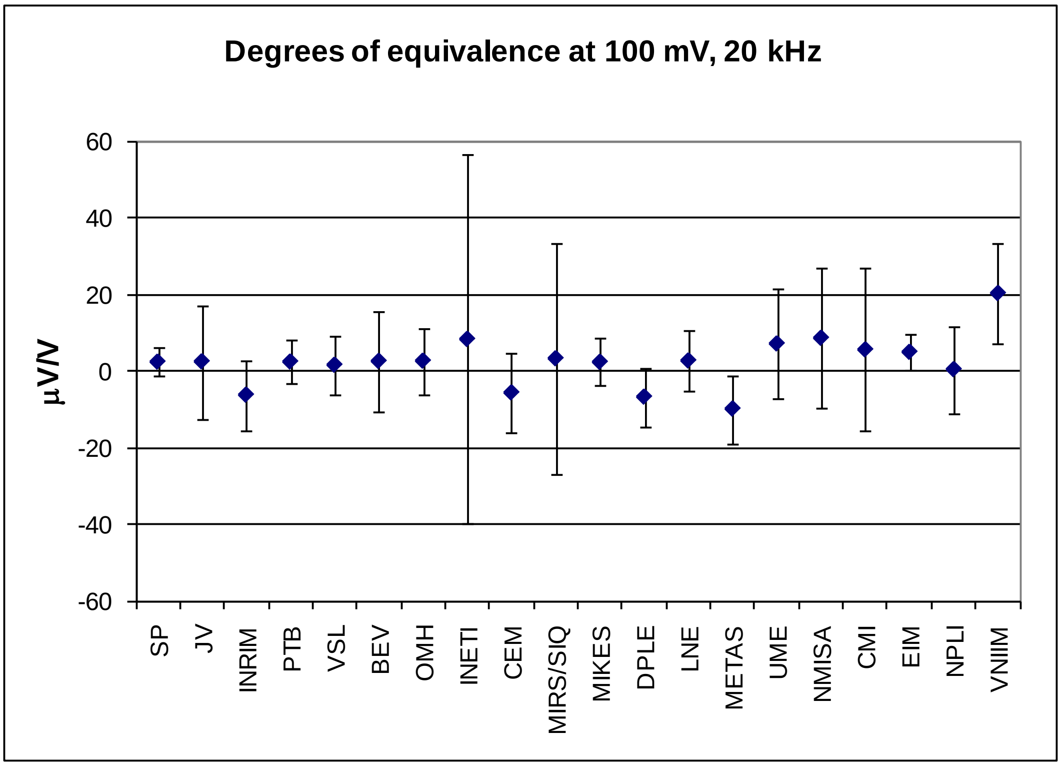

Figure 12 Degree of equivalence with the CRV at 100 mV, 20 kHz with corresponding expanded uncertainties (k=2).

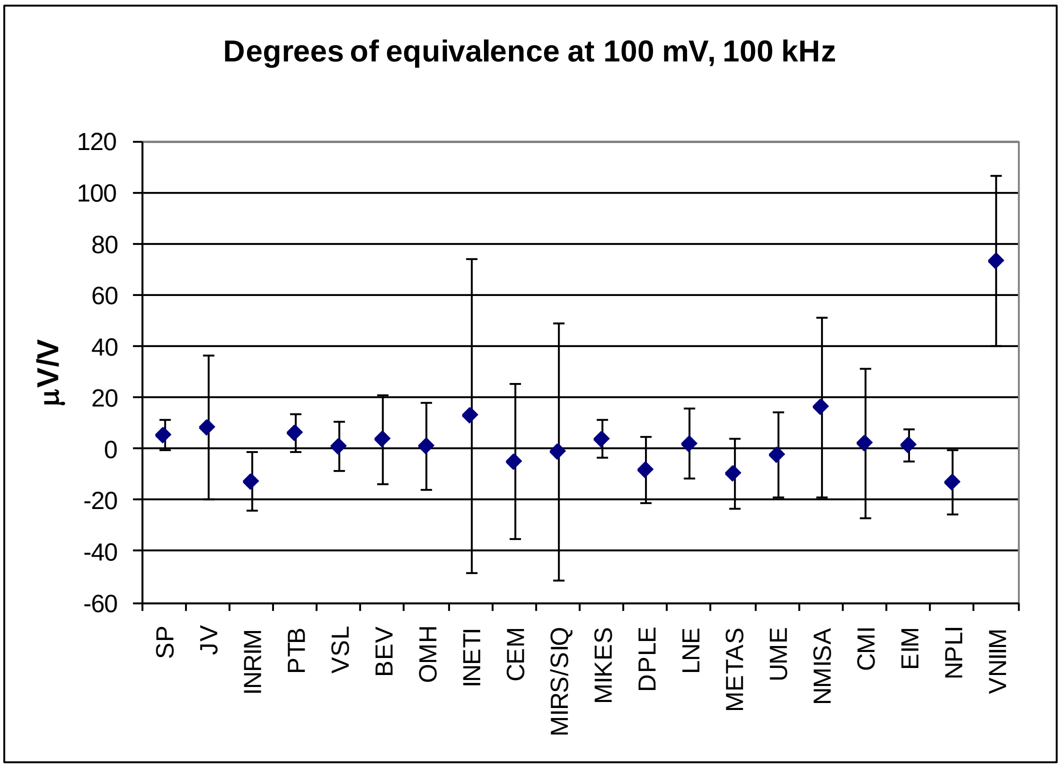

Figure 13 Degree of equivalence with the CRV at 100 mV, 100 kHz with corresponding expanded uncertainties (k=2).

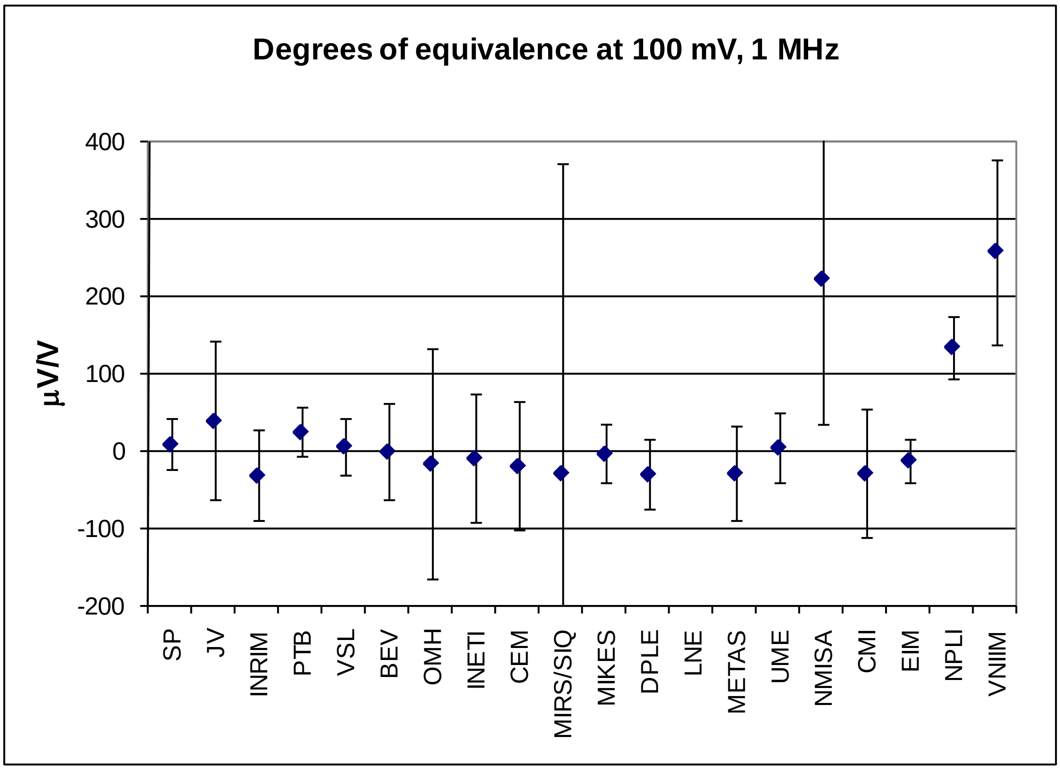

Figure 14 Degree of equivalence with the CRV at 100 mV, 1 MHz with corresponding expanded uncertainties (k=2).

Table 20 Degree of equivalence with the CRV with corresponding expanded uncertainties (k=2) in µV/V, 10 mV.								
D_{iE}	Difference NMI-CRV							
U_{iE}	Expanded standard uncertainty of D_{iE}							
Level	10 mV							
	1 kHz		20 kHz		100 kHz		1 MHz	
NMI	D_{iE}	U_{iE}	D_{iE}	U_{iE}	D_{iE}	U_{iE}	D_{iE}	U_{iE}
SP	7	17	-1	15	4	18	-8	59
JV	10	23	15	25	29	68	40	258
INRIM	-12	16	-14	15	-22	37	-109	120
PTB	-13	15	2	13	12	19	17	48
VSL	0	31	-2	30	-3	34	-47	100
BEV	11	32	4	32	7	39	-17	127
OMH	6	17	1	17	1	27	-140	220
INETI	7	57	-2	57	0	66	111	277
CEM	0	41	0	40	8	60	34	150
MIRS/SIQ	5	71	-8	71	0	120	63	751
MIKES	18	26	12	25	9	36	-6	125
DPLE	-11	42	-22	41	-22	62	-94	193
LNE	7	12	10	16	5	20		
METAS	-25	33	-38	31	-34	52	-119	104
UME	10	47	11	47	-9	54	-19	108
NMISA	-1	59	21	57	12	136	-547	754
CMI	7	55	5	60	11	81	72	233
EIM	9	86	1	80	49	86	158	174
NPLI	-2	16	-4	15	-12	14	30	32
VNIIM	7	20	24	22	72	64	85	161

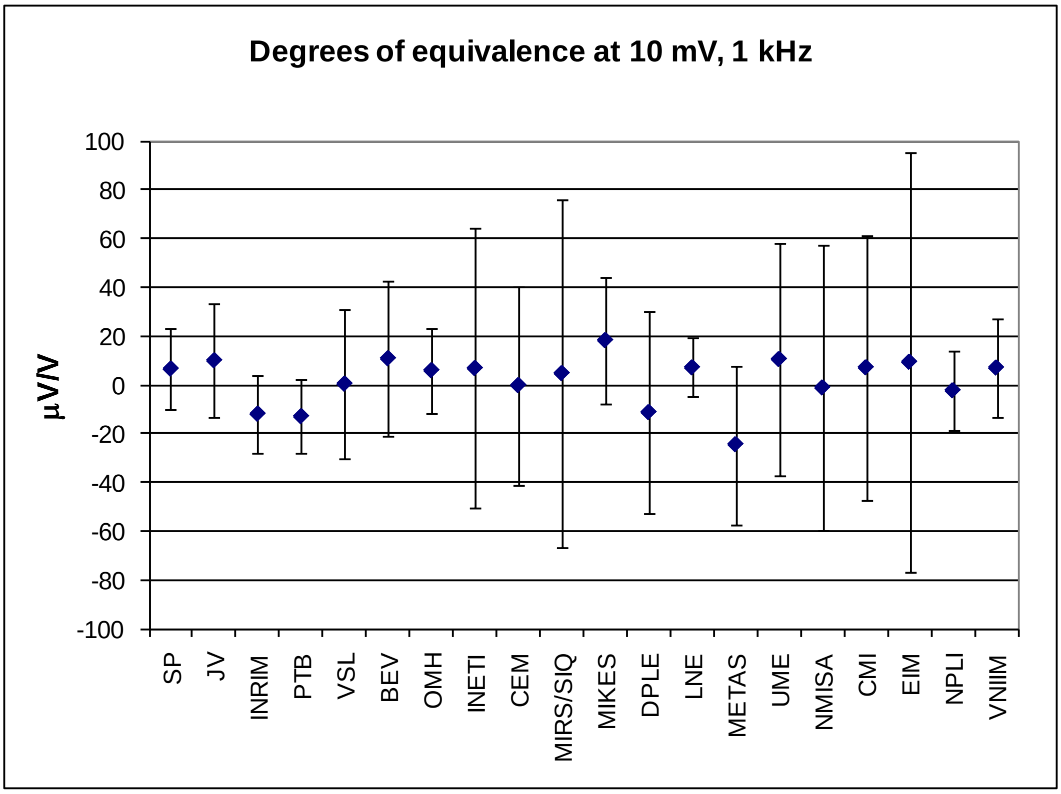

Figure 15 Degree of equivalence with the CRV at 10 mV, 1 kHz with corresponding expanded uncertainties (k=2).

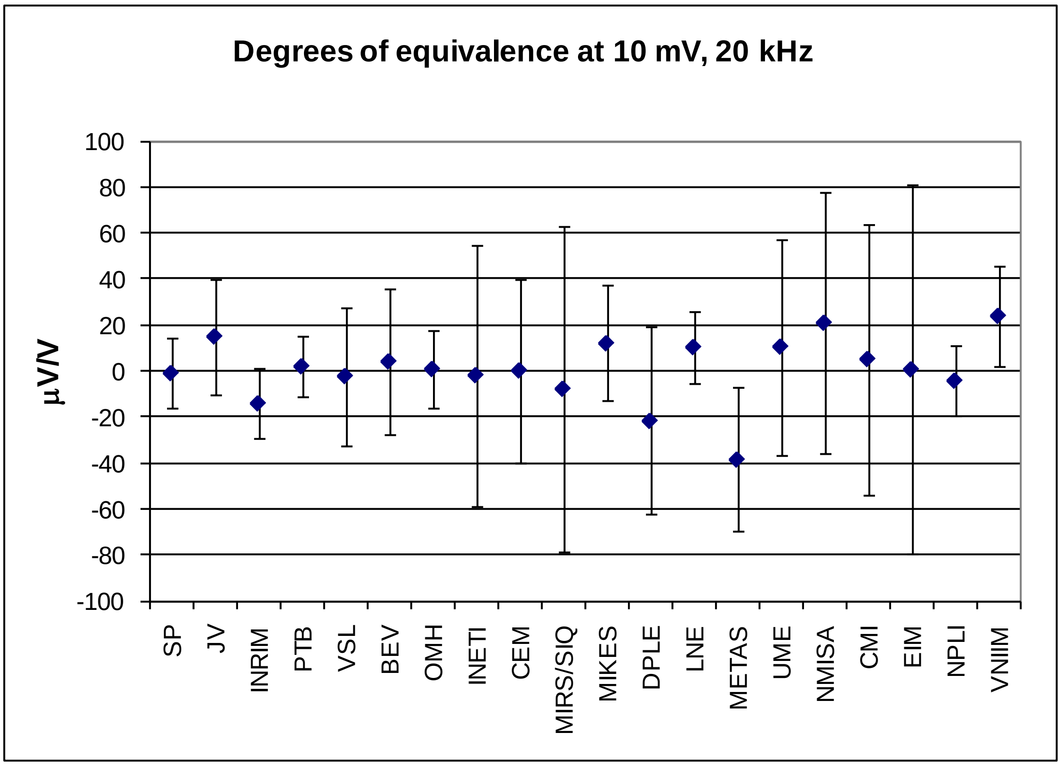

Figure 16 Degree of equivalence with the CRV at 10 mV, 20 kHz with corresponding expanded uncertainties (k=2).

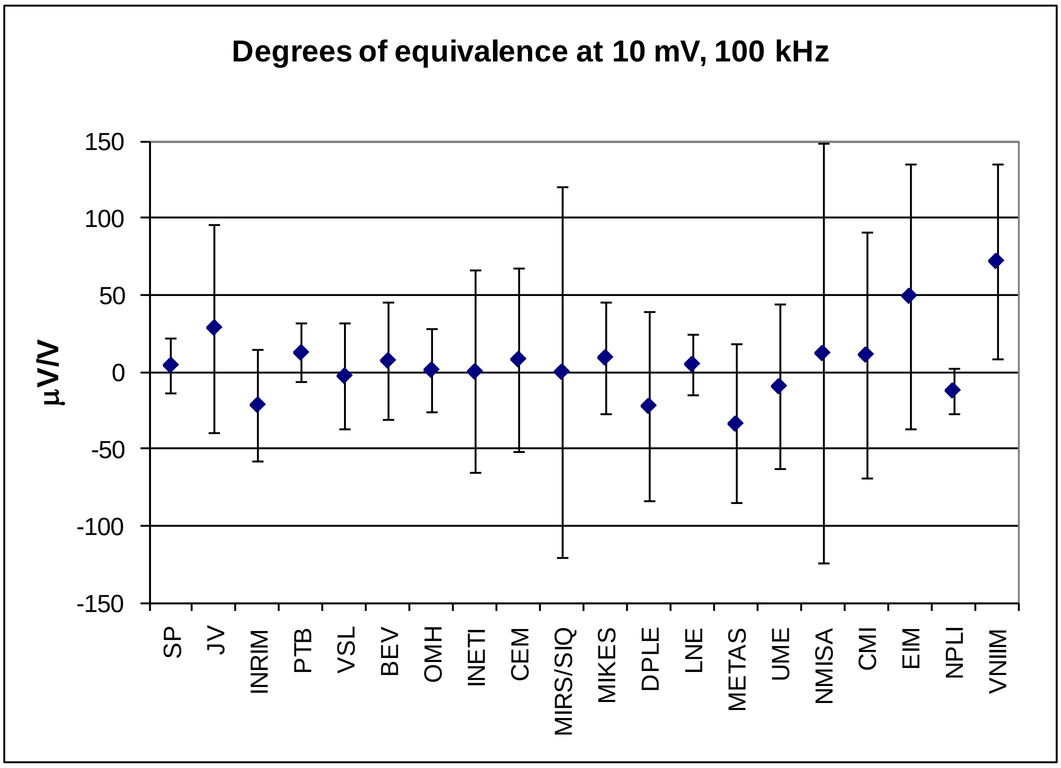

Figure 17 Degree of equivalence with the CRV at 10 mV, 100 kHz with corresponding expanded uncertainties (k=2).

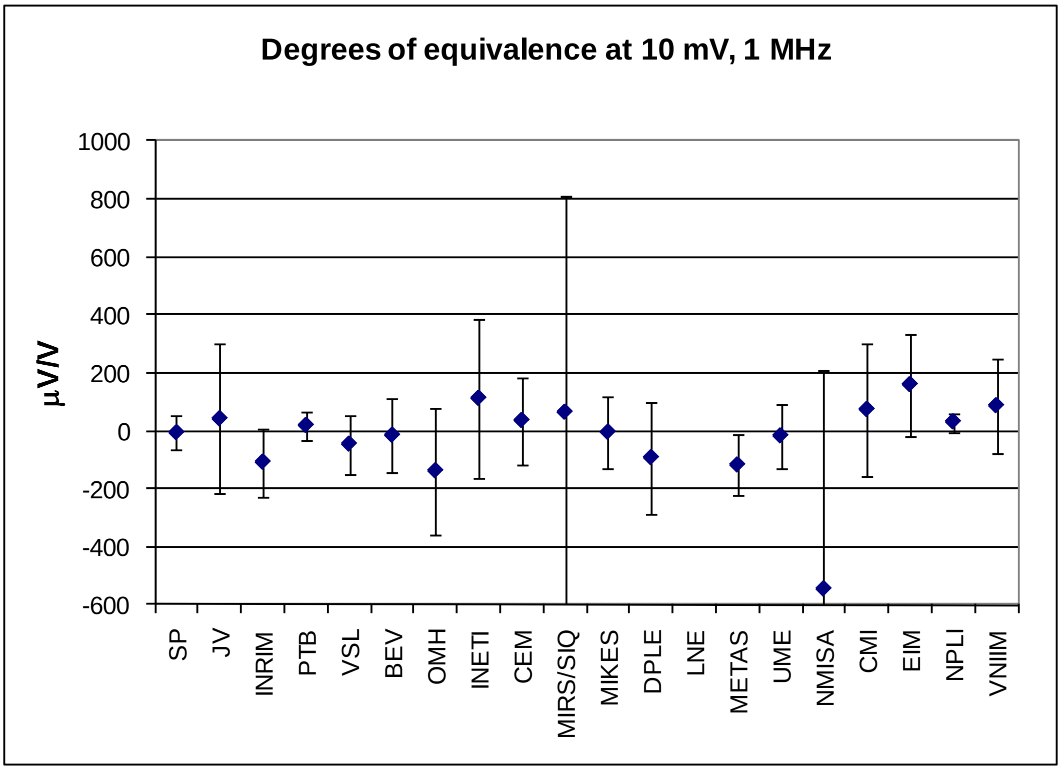

Figure 18 Degree of equivalence with the CRV at 10 mV, 1 MHz with corresponding expanded uncertainties (k=2).

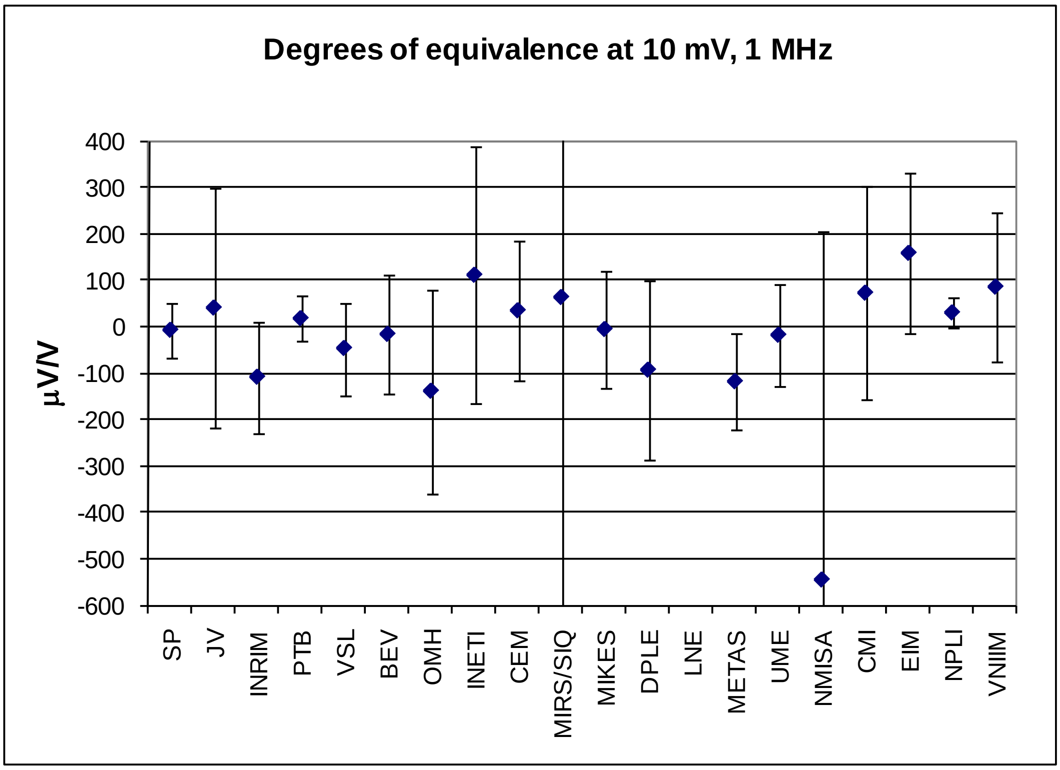

Figure 19 Degree of equivalence with the CRV at 10 mV, 1 MHz with corresponding expanded uncertainties (k=2) at larger scale.

6.1.10 Linking to the Key Comparison CCEM-K11

The results of the participants in the EURAMET.EM-K11, not participating in the CCEM-K11, have been evaluated against the CCEM key comparison reference value (KCRV) in the following way:

The degrees of equivalence for NMI i had it participated in CCEM-K11, D_{iC}, is determined as:

$$D_{\mathrm{iC}} = D_{\mathrm{iE}} - \Delta \tag{24}$$

where

D_{iE} is the degrees of equivalence with the CRV for NMI i participating in EURAMET.EM-K11 only

Δ is the correction for the difference between the CRV and the KCRV

The correction between the CRV and the KCRV as measured by the linking NMIs, Δ_{iLink}, is used to estimate the correction, Δ, because:

$$\Delta_{\mathrm{iLink}} = D_{\mathrm{iLinkC}} - D_{\mathrm{iLinkE}} \tag{25}$$

where

D_{iLinkC} is the degree of equivalence with the KCRV for linking NMI i participating in CCEM-K11

D_{iLinkE} is the degree of equivalence with the CRV for linking NMI i participating in EURAMET.EM-K11

The correction, Δ, is calculated as the weighted mean of the linking NMIs estimates:

$$\Delta = \frac{\sum_{\mathrm{iLink}} \frac{\Delta_{\mathrm{iLink}}}{u^2_{\Delta\mathrm{iLink}}}}{\sum_{\mathrm{iLink}} \frac{1}{u^2_{\Delta\mathrm{iLink}}}} \tag{26}$$

Where the standard uncertainty $u_{\Delta\mathrm{iLink}}$ is given by:

$$u^2_{\Delta\mathrm{iLink}} = u^2_{\mathrm{DiLinkC}} + u^2_{\mathrm{DiLinkE}} \tag{27}$$

The standard uncertainty of the estimated correction, u_{Δ}, is calculated as the uncertainty of the weighted mean:

$$u^2_{\Delta} = \frac{1}{\sum_{\mathrm{iLink}} \frac{1}{u^2_{\Delta\mathrm{iLink}}}} \tag{28}$$

The standard uncertainty of the degree of equivalence with KCRV for NMI i had it participated in the CCEM-K11, u_{DiC}, is calculated as:

$$u_{\mathrm{DiC}}^2 = u_{\mathrm{DiE}}^2 + u_{\Delta}^2 \quad (29)$$

Finally the expanded uncertainty U_{DiC} is equal to:

$$U_{\mathrm{DiC}} = k_{\mathrm{iDC}} u_{\mathrm{iDC}} \quad (30)$$

6.1.11 Calculation of corrections for linking to CCEM-K11

Three NMIs, SP, PTB and VSL, participated in both comparisons and act as linking laboratories. The corrections, Δ, between the CRV and the KCRV with standard uncertainties u_{Δ} are calculated according to (26) and (28), see Table 23, based on the results of the linking laboratories, Tables 21 and 22.

Table 21 The degree of equivalence and expanded uncertainty with the KCRV, D_{iLinkC} and U_{iLinkC}, and the CRV, D_{iLinkE} and U_{iLinkE}, of the linking NMIs at 100 mV and the correction with expanded uncertainty between the CRV and the KCRV as measured by the linking NMIs, Δ_{iLink} and U_{iLink}, in µV/V.

100 mV	1 kHz		20 kHz		100 kHz		1 MHz	
	D_{iLinkC}	U_{iLinkC}	D_{iLinkC}	U_{iLinkC}	D_{iLinkC}	U_{iLinkC}	D_{iLinkC}	U_{iLinkC}
SP	0,5	6,5	0,3	6,5	-1,6	12,8	7	63
PTB	0,3	2,5	-0,3	4,3	-1,5	6	-28	50
VSL	-1,7	7,9	0,9	11,8	-0,6	14,7	-1	101
	D_{iLinkE}	U_{iLinkE}	D_{iLinkE}	U_{iLinkE}	D_{iLinkE}	U_{iLinkE}	D_{iLinkE}	U_{iLinkE}
SP	2,6	3,1	2,3	3,7	5,5	5,8	8	33
PTB	0,4	3,5	2,3	5,7	6,4	7,4	24	32
VSL	-0,1	6,7	1,5	7,8	1,1	9,5	6	37
	Δ_{iLink}	$U_{\Delta\mathrm{iLink}}$	Δ_{iLink}	$U_{\Delta\mathrm{iLink}}$	Δ_{iLink}	$U_{\Delta\mathrm{iLink}}$	Δ_{iLink}	$U_{\Delta\mathrm{iLink}}$
SP	-2,1	7,2	-2,0	7,5	-7,1	14,1	-1	71
PTB	-0,1	4,3	-2,6	7,1	-7,9	9,5	-52	59
VSL	-1,6	10,4	-0,6	14,1	-1,7	17,5	-7	108

Table 22 The degree of equivalence and expanded uncertainty with the KCRV, D_{iLinkC} and U_{iLinkC}, and the CRV, D_{iLinkE} and U_{iLinkE}, of the linking NMIs at 10 mV and the correction with expanded uncertainty between the CRV and the KCRV as measured by the linking NMIs, Δ_{iLink} and U_{iLink}, in µV/V.

10 mV	1 kHz		20 kHz		100 kHz		1 MHz	
	D_{iLinkC}	U_{iLinkC}	D_{iLinkC}	U_{iLinkC}	D_{iLinkC}	U_{iLinkC}	D_{iLinkC}	U_{iLinkC}
SP	-2	20	-1	21	-3	30	-24	94
PTB	-6	40	-13	41	-9	43	-44	100
VSL	-9	39	-7	39	-5	48	26	298
	D_{iLinkE}	U_{iLinkE}	D_{iLinkE}	U_{iLinkE}	D_{iLinkE}	U_{iLinkE}	D_{iLinkE}	U_{iLinkE}
SP	7	17	-1	15	4	18	-8	59
PTB	-13	15	2	13	12	19	17	48
VSL	0	31	-2	30	-3	34	-47	100
	Δ_{iLink}	$U_{\Delta\mathrm{iLink}}$	Δ_{iLink}	$U_{\Delta\mathrm{iLink}}$	Δ_{iLink}	$U_{\Delta\mathrm{iLink}}$	Δ_{iLink}	$U_{\Delta\mathrm{iLink}}$
SP	-9	26	0	26	-7	35	-16	111
PTB	7	43	-15	43	-21	47	-61	111
VSL	-9	50	-5	49	-2	59	73	314

Table 23 The corrections, Δ, between the CRV and the KCRV with standard uncertainties u_Δ in μV/V.

Voltage	1 kHz		20 kHz		100 kHz		1 MHz	
	Δ	u_Δ	Δ	u_Δ	Δ	u_Δ	Δ	u_Δ
100 mV	-0,7	1,7	-2,1	2,4	-6,6	3,6	-27	21
10 mV	-5	10	-4	10	-10	13	-32	38

6.1.12 Consistency of the corrections

A chi-squared test has been applied to carry out an overall consistency check of the corrections obtained. For each measurement point the observed chi-squared value χ_{obs}^2 has been determined as:

$$\chi_{obs}^2 = \sum_{i=1}^{3} \frac{(\Delta_{iLink} - \Delta)^2}{u_{\Delta iLink}^2} \tag{31}$$

The degrees of freedom ν = 2.
The consistency check is considered as failing if $\Pr\{\chi^2(\nu) > \chi_{obs}^2\} < 5\%$ where Pr denotes "probability of".

Table 24 The result of chi-square test.

	1 kHz	20 kHz	100 kHz	1 MHz
100 mV				
χ_{obs}^2	0,26	0,07	0,39	1,38
ν	2	2	2	2
Pr	88%	97%	82%	50%
10 mV				
χ_{obs}^2	0,43	0,36	0,32	0,80
ν	2	2	2	2
Pr	81%	84%	85%	67%

The consistency check does not fail in any of the measuring points. Hence the results in Table 23 can be accepted as corrections.

6.1.13 Tables and graphs of degree of equivalence with the KCRV of the CCEM-K11

The results of the participants in the EURAMET.EM-K11, not participating in the CCEM-K11, are evaluated against the CCEM key comparison reference value (KCRV) and presented in Table 25 and 26 and Figure 20 to 27. The results of the participants in the CCEM-K11 are also shown for comparison (rather than evaluating the degree of equivalence between all pairs of NMIs).

Table 25 Degree of equivalence with the KCRV with corresponding expanded uncertainty (k=2) in µV/V, 100 mV.								
D_{iC}	Difference NMI-KCRV							
U_{iC}	Expanded uncertainty of D_{iC}							
Level	100 mV							
	1 kHz		20 kHz		100 kHz		1 MHz	
NMI	D_{iC}	U_{iC}	D_{iC}	U_{iC}	D_{iC}	U_{iC}	D_{iC}	U_{iC}
PTB	0,3	2,5	-0,3	4,3	-1,5	6,0	-28	50
NPL	-5,1	8,9	-3,2	8,7	-2,6	12,7	-18	67
VSL	-1,7	7,9	0,9	11,8	-0,6	14,7	-1	101
NMIA	-0,1	5,7	2,9	6,7	-1,1	15,8	13	77
INTI	-0,1	9,9	0,9	9,8	-0,2	20,8	-30	62
NRC	0,7	4,8	-0,2	5,6	3,5	6,6	13	32
SPRING	-3,3	18,0	-4,2	23,9	-5,8	26,9	-6	88
NIM	3,7	13,9	-3,2	15,8	8,1	29,9	72	99
SP	0,5	6,5	0,3	6,5	-1,6	12,8	7	63
NIST	-0,9	12,3	-2,8	12,7	2,7	23,1	1	77
JV	0,8	14,3	0,3	15,6	1,9	28,7	11	111
INRIM	-10,0	10,0	-8,4	10,4	-19,2	13,7	-59	71
BEV	2,4	12,7	0,4	14,1	-2,6	18,9	-29	76
OMH	1,6	8,0	0,5	9,9	-5,3	18,7	-44	155
INETI	9,5	41,2	6,1	48,3	6,6	61,5	-37	92
CEM	3,4	10,8	-7,9	11,4	-11,4	31,1	-47	92
MIRS/SIQ	4,4	30,3	1,1	30,5	-7,5	50,7	-56	403
MIKES	1,4	6,2	0,2	7,8	-2,7	10,2	-31	56
DPLE	-8,7	8,5	-9,0	9,1	-14,6	14,5	-58	62
LNE	2,6	7,5	0,5	9,1	-4,5	15,4		
METAS	-11,1	13,3	-12,1	10,0	-16,0	15,4	-57	74
UME	1,1	13,6	5,0	15,1	-8,7	18,0	-23	61
NMISA	6,9	18,0	6,5	18,7	9,9	35,8	194	193
CMI	2,3	19,4	3,4	21,7	-4,2	30,1	-57	92
EIM	1,6	5,6	2,8	6,6	-4,9	9,4	-40	50
NPLI	-7,7	11,5	-1,8	12,2	-19,4	14,4	106	58
VNIIM	1,4	10,4	18,2	14,1	66,6	34,0	229	127

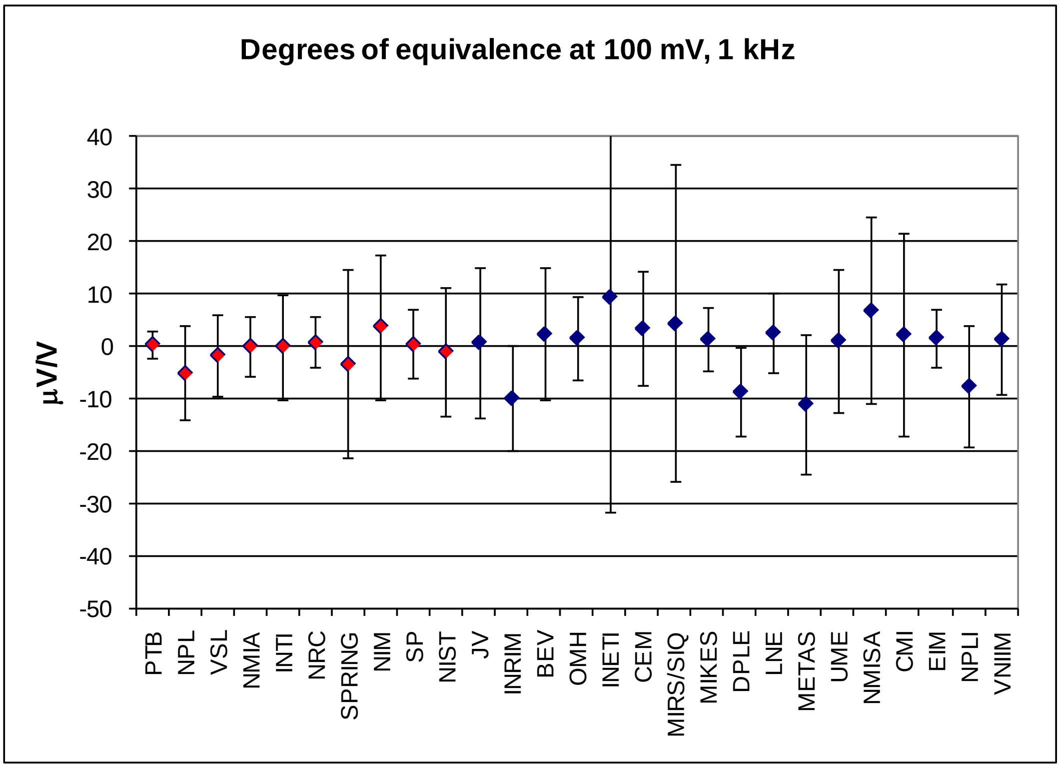

Figure 20 Degree of equivalence with the KCRV at 100 mV, 1 kHz with corresponding expanded uncertainties (k=2).

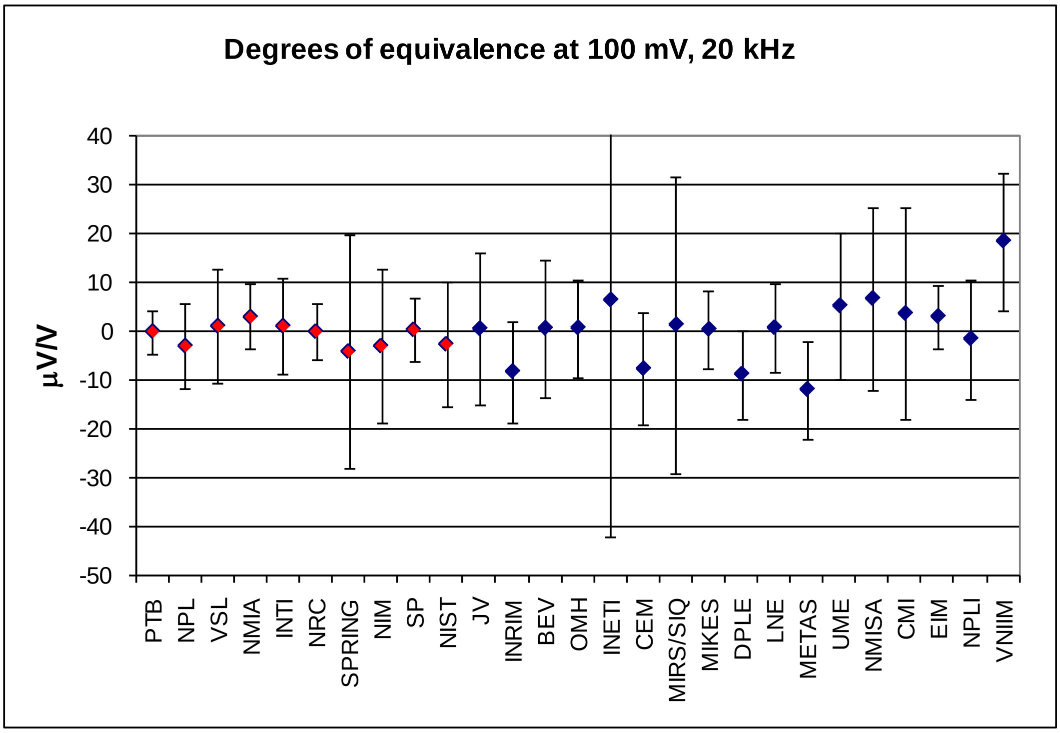

Figure 21 Degree of equivalence with the KCRV at 100 mV, 20 kHz with corresponding expanded uncertainties (k=2).

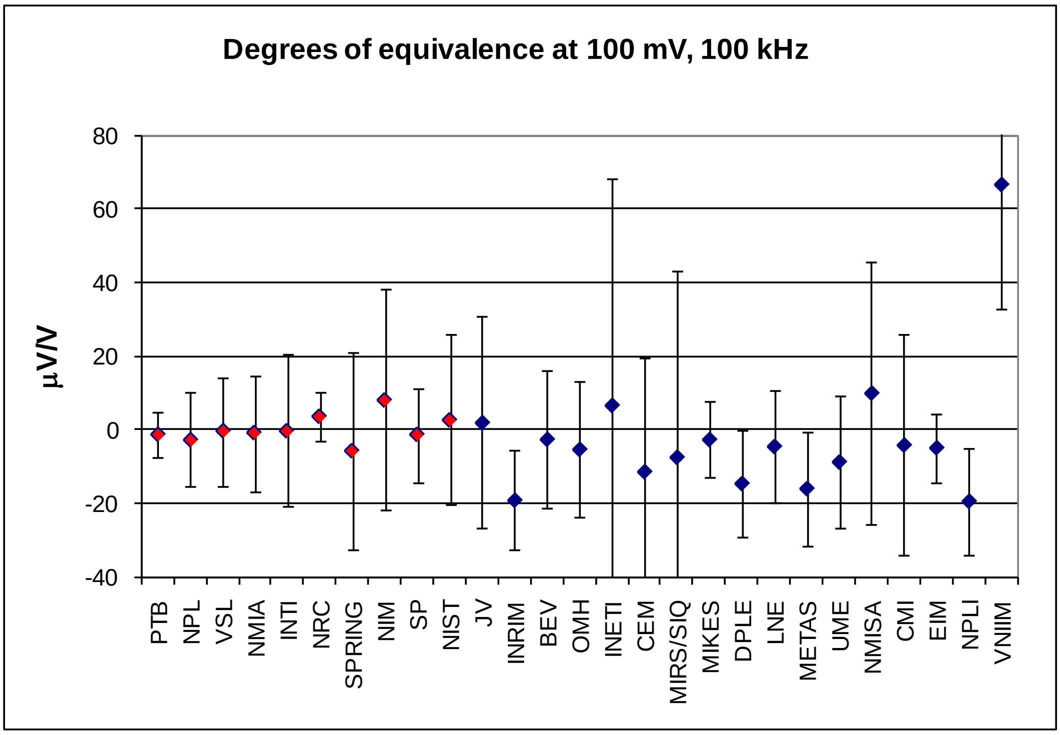

Figure 22 Degree of equivalence with the KCRV at 100 mV, 100 kHz with corresponding expanded uncertainties (k=2).

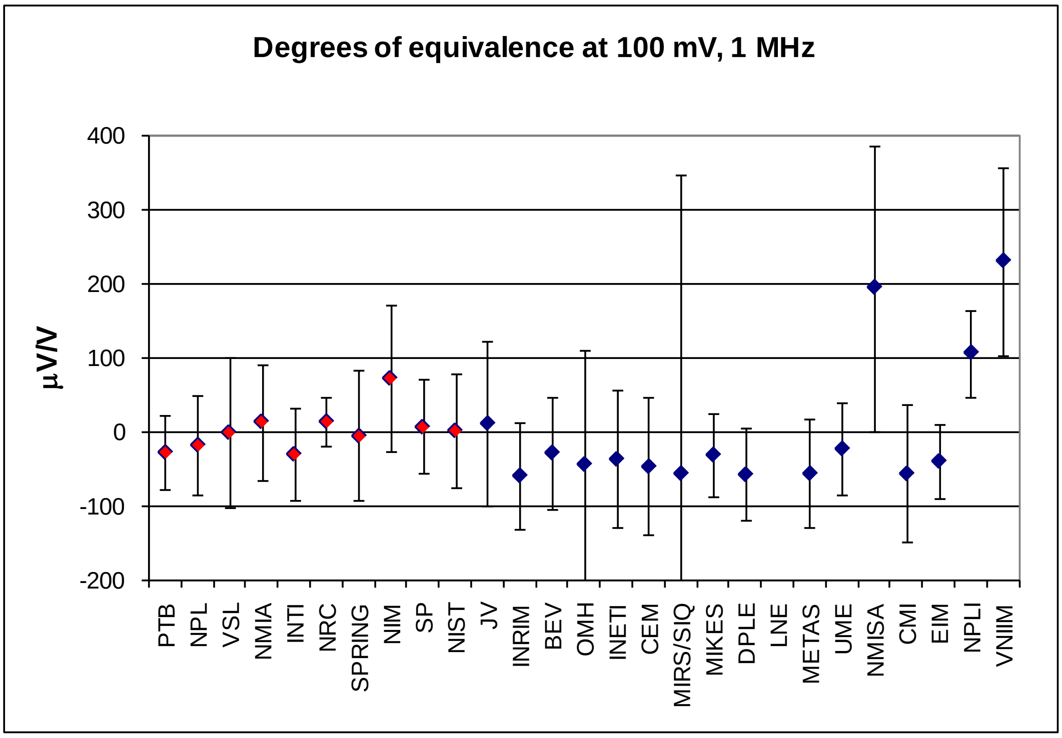

Figure 23 Degree of equivalence with the KCRV at 100 mV, 1 MHz with corresponding expanded uncertainties (k=2).

Table 26 Degree of equivalence with the KCRV with corresponding expanded uncertainty (k=2) in µV/V, 10 mV.								
D_{iC}	Difference NMI-KCRV							
U_{iC}	Expanded uncertainty of D_{iC}							
Level	10 mV							
	1 kHz		20 kHz		100 kHz		1 MHz	
NMI	D_{iC}	U_{iC}	D_{iC}	U_{iC}	D_{iC}	U_{iC}	D_{iC}	U_{iC}
PTB	-6	40	-13	41	-9	43	-44	100
NPL	-4	29	-4	29	4	40	-46	281
VSL	-9	39	-7	39	-5	48	26	298
NMIA	0	11	2	14	7	39	3	102
INTI	13	25	11	28	13	44	-29	105
NRC	8	35	2	31	7	59	42	84
SPRING	-1	33	-2	36	-9	42	-42	369
NIM	-41	78	-28	78	1	95	138	184
SP	-2	20	-1	21	-3	30	-24	94
NIST	6	38	25	40	-3	53	19	151
JV	5	31	11	32	19	73	8	269
INRIM	-17	26	-18	25	-32	45	-141	142
BEV	6	38	0	38	-3	46	-49	148
OMH	1	26	-3	26	-9	37	-172	233
INETI	2	61	-6	60	-10	71	79	287
CEM	-5	45	-4	45	-2	65	2	168
MIRS/SIQ	0	74	-12	73	-10	123	31	754
MIKES	13	33	8	32	-1	45	-38	147
DPLE	-16	46	-26	46	-32	67	-126	207
LNE	2	23	6	26	-5	33		
METAS	-30	38	-42	37	-44	58	-151	129
UME	5	51	7	51	-19	60	-51	132
NMISA	-6	62	17	60	2	139	-579	758
CMI	2	59	1	63	1	85	40	245
EIM	4	88	-3	83	39	90	126	190
NPLI	-7	26	-8	25	-22	30	-2	83
VNIIM	2	29	20	30	62	69	53	178

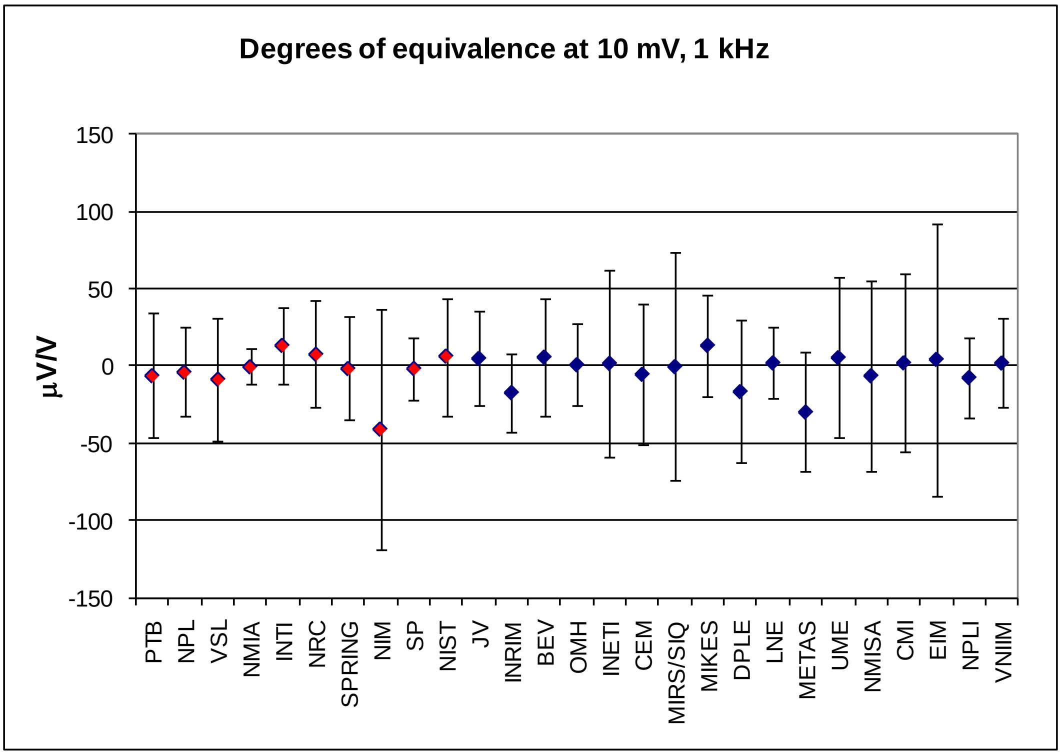

Figure 24 Degree of equivalence with the KCRV at 10 mV, 1 kHz with corresponding expanded uncertainties (k=2).

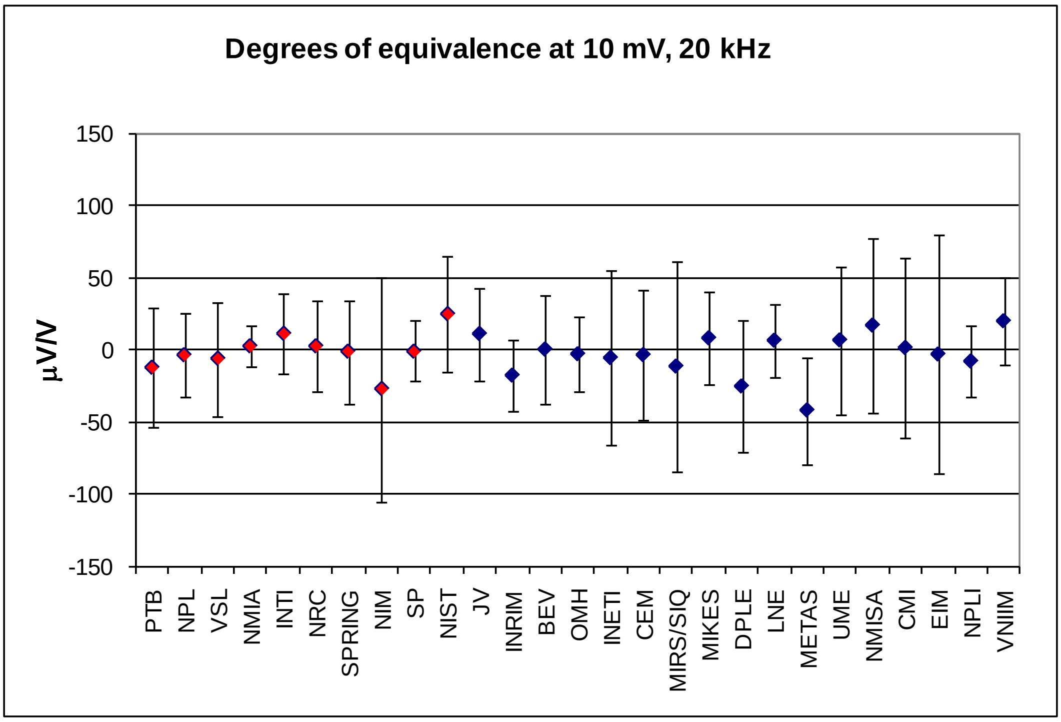

Figure 25 Degree of equivalence with the KCRV at 10 mV, 20 kHz with corresponding expanded uncertainties (k=2).

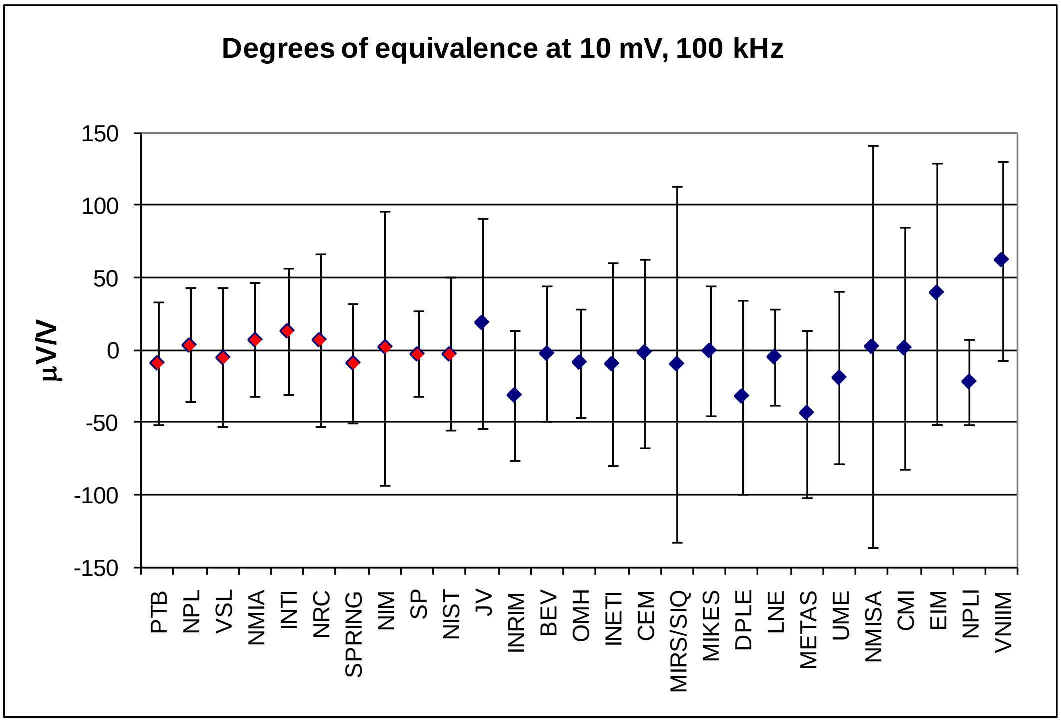

Figure 26 Degree of equivalence with the KCRV at 10 mV, 100 kHz with corresponding expanded uncertainties (k=2).

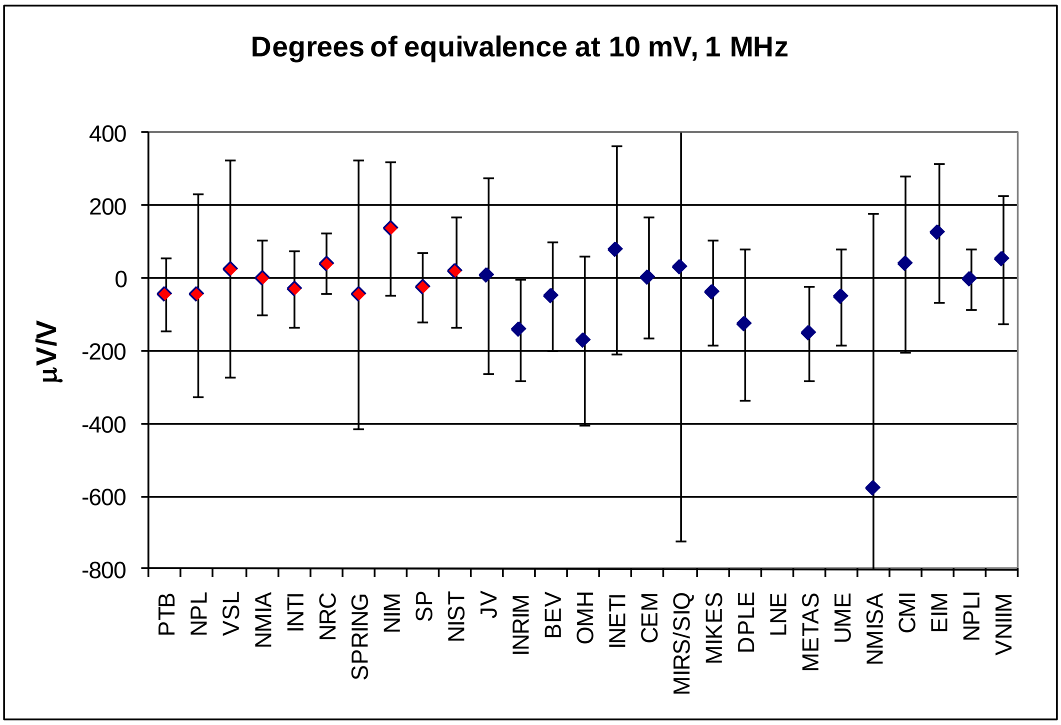

Figure 27 Degree of equivalence with the KCRV at 10 mV, 1 MHz with corresponding expanded uncertainties (k=2).

7 Withdrawals and corrective actions

The Federal Public Service Economy - Metrology Division (SMD), Belgium, withdraw their participation before their scheduled measurement period due to shortage of staff.

Central Office of Measures in Poland (GUM) has withdrawn their participation after distribution of the draft A report. GUM also indicated that they wish to participate in a bilateral comparison in the future.

Trescal A/S (DANIAmet-DPLE), Denmark, has sent comments on a suspected error in their measurements, included as appendix 3.

Swiss Federal Office of Metrology (METAS), Switzerland, has sent a description of their corrective actions taken, included as appendix 3.

8 Summary and conclusion

The circulation of the travelling standard in the regional key comparison EURAMET.EM-K11 of ac-dc voltage transfer difference at low voltages began in Aug 2005 and was completed in Feb 2008. Out of the 22 participants two have withdrawn.

The ac-dc transfer differences of the travelling standard have been measured at 100 mV and 10 mV and at the frequencies 1 kHz, 20 kHz, 100 kHz and 1 MHz. The agreement between all participants is very good at low frequencies. At high frequencies the agreement between the majority of the participants is also very good.

9 Acknowledgement

The authors wish to thank all participants and especially the support group Erik Dierikx, VSL, Torsten Funck and Manfred Klonz, PTB, for their valuable assistance during the comparison.

10 References

[1] K.-E. Rydler and V. Tarasso "Final report on key comparisons CCEM-K11 and CCEM-K11.1 (ac-dc voltage transfer difference at low voltages)," *Metrologia*, 2007, **44**, *Tech. Suppl.*, 01008

Table 1 Degrees of equivalence 100 mV, 1 kHz

100 mV, 1 kHz			CRV		SP		JV		INRIM		PTB		VSL		BEV		OMH		INETI		CEM		MIRS/SIQ	
			δ_R	U_R	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}
			-2,6	2,0	0,0	3,7	-1,1	14,0	-11,9	9,6	-2,2	4,1	-2,7	7,0	0,5	12,0	-0,3	7,5	7,6	41,0	1,5	10,0	2,5	30,0
	δ_{id}	U_{id}	$\boldsymbol{D_{iE}}$	$\boldsymbol{U_{iE}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$
SP	0,0	3,7	2,6	3,1			1,1	14,5	11,9	10,3	2,2	5,5	2,7	7,9	-0,5	12,6	0,3	8,4	-7,6	41,2	-1,5	10,7	-2,5	30,2
JV	-1,1	14,0	1,5	13,9	-1,1	14,5			10,8	17,0	1,1	14,6	1,6	15,7	-1,6	18,5	-0,8	15,9	-8,7	43,3	-2,7	17,2	-3,6	33,1
INRIM	-11,9	9,6	-9,3	9,4	-11,9	10,3	-10,8	17,0			-9,7	10,4	-9,2	11,9	-12,4	15,4	-11,6	12,2	-19,5	42,1	-13,4	13,9	-14,4	31,5
PTB	-2,2	4,1	0,4	3,5	-2,2	5,5	-1,1	14,6	9,7	10,4			0,5	8,1	-2,7	12,7	-2,0	8,6	-9,8	41,2	-3,8	10,8	-4,7	30,3
VSL	-2,7	7,0	-0,1	6,7	-2,7	7,9	-1,6	15,7	9,2	11,9	-0,5	8,1			-3,2	13,9	-2,4	10,3	-10,3	41,6	-4,3	12,2	-5,2	30,8
BEV	0,5	12,0	3,1	12,2	0,5	12,6	1,6	18,5	12,4	15,4	2,7	12,7	3,2	13,9			0,7	14,2	-7,1	42,7	-1,1	15,7	-2,0	32,3
OMH	-0,3	7,5	2,3	7,3	-0,3	8,4	0,8	15,9	11,6	12,2	2,0	8,6	2,4	10,3	-0,7	14,2			-7,9	41,7	-1,8	12,5	-2,8	30,9
INETI	7,6	41,0	10,2	41,1	7,6	41,2	8,7	43,3	19,5	42,1	9,8	41,2	10,3	41,6	7,1	42,7	7,9	41,7			6,0	42,2	5,1	50,8
CEM	1,5	10,0	4,1	10,2	1,5	10,7	2,7	17,2	13,4	13,9	3,8	10,8	4,3	12,2	1,1	15,7	1,8	12,5	-6,0	42,2			-0,9	31,6
MIRS/SIQ	2,5	30,0	5,1	30,1	2,5	30,2	3,6	33,1	14,4	31,5	4,7	30,3	5,2	30,8	2,0	32,3	2,8	30,9	-5,1	50,8	0,9	31,6		

Table 2 Degrees of equivalence 100 mV, 1 kHz

100 mV, 1 kHz			MIKES		DPLE		LNE		METAS		UME		NMISA		CMI		EIM		NPLI		VNIIM	
			δ_R	U_R	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}
			-0,5	4,7	-10,6	8,0	0,7	7,0	-13,0	13,0	-0,8	13,0	-10,4	17,5	0,4	19,0	-0,3	4,0	-9,6	11,1	-0,5	10,0
	δ_{id}	U_{id}	$\boldsymbol{D_{iE}}$	$\boldsymbol{U_{iE}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$
SP	0,0	3,7	0,5	6,0	10,6	8,8	-0,7	7,9	13,0	13,5	0,8	13,5	10,4	17,9	-0,4	19,4	0,3	5,4	9,6	11,7	0,5	10,7
JV	-1,1	14,0	-0,6	14,8	9,5	16,2	-1,9	15,7	11,9	19,1	-0,4	19,1	9,3	22,4	-1,5	23,6	-0,9	14,6	8,4	17,9	-0,6	17,2
INRIM	-11,9	9,6	-11,4	10,7	-1,3	12,5	-12,6	11,9	1,1	16,2	-11,1	16,2	-1,5	20,0	-12,3	21,3	-11,6	10,4	-2,3	14,7	-11,4	13,9
PTB	-2,2	4,1	-1,7	6,2	8,4	9,0	-3,0	8,1	10,8	13,6	-1,5	13,6	8,2	18,0	-2,6	19,4	-2,0	5,7	7,3	11,8	-1,7	10,8
VSL	-2,7	7,0	-2,2	8,5	7,9	10,7	-3,4	9,9	10,3	14,8	-1,9	14,8	7,7	18,9	-3,1	20,3	-2,4	8,1	6,9	13,2	-2,2	12,2
BEV	0,5	12,0	1,0	12,9	11,1	14,5	-0,3	13,9	13,5	17,7	1,2	17,7	10,9	21,2	0,1	22,5	0,7	12,7	10,0	16,4	1,0	15,7
OMH	-0,3	7,5	0,2	8,9	10,4	11,0	-1,0	10,3	12,7	15,0	0,5	15,0	10,1	19,1	-0,7	20,4	0,0	8,5	9,3	13,4	0,2	12,5
INETI	7,6	41,0	8,1	41,3	18,2	41,8	6,9	41,6	20,6	43,0	8,4	43,0	18,0	44,6	7,2	45,2	7,8	41,2	17,1	42,5	8,1	42,2
CEM	1,5	10,0	2,1	11,1	12,2	12,8	0,8	12,2	14,6	16,4	2,3	16,4	12,0	20,2	1,2	21,5	1,8	10,8	11,1	15,0	2,1	14,2
MIRS/SIQ	2,5	30,0	3,0	30,4	13,1	31,1	1,8	30,8	15,5	32,7	3,3	32,7	-2,5	34,7	2,1	35,5	2,7	30,3	12,0	32,0	3,0	31,6

Table 3 Degrees of equivalence 100 mV, 1 kHz

100 mV, 1 kHz			CRV		SP		JV		INRIM		PTB		VSL		BEV		OMH		INETI		CEM		MIRS/SIQ	
			δ_R	U_R	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}
			-2,6	2,0	0,0	3,7	-1,1	14,0	-11,9	9,6	-2,2	4,1	-2,7	7,0	0,5	12,0	-0,3	7,5	7,6	41,0	1,5	10,0	2,5	30,0
	δ_{id}	U_{id}	D_{iE}	U_{iE}	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}
MIKES	-0,5	4,7	2,1	5,2	-0,5	6,0	0,6	14,8	11,4	10,7	1,7	6,2	2,2	8,5	-1,0	12,9	-0,2	8,9	-8,1	41,3	-2,1	11,1	-3,0	30,4
DPLE	-10,6	8,0	-8,0	7,8	-10,6	8,8	-9,5	16,2	1,3	12,5	-8,4	9,0	-7,9	10,7	-11,1	14,5	-10,4	11,0	-18,2	41,8	-12,2	12,8	-13,1	31,1
LNE	0,7	7,0	3,3	6,7	0,7	7,9	1,9	15,7	12,6	11,9	3,0	8,1	3,4	9,9	0,3	13,9	1,0	10,3	-6,9	41,6	-0,8	12,2	-1,8	30,8
METAS	-13,0	13,0	-10,4	12,9	-13,0	13,5	-11,9	19,1	-1,1	16,2	-10,8	13,6	-10,3	14,8	-13,5	17,7	-12,7	15,0	-20,6	43,0	-14,6	16,4	-15,5	32,7
UME	-0,8	13,0	1,8	13,2	-0,8	13,5	0,4	19,1	11,1	16,2	1,5	13,6	1,9	14,8	-1,2	17,7	-0,5	15,0	-8,4	43,0	-2,3	16,4	-3,3	32,7
NMISA	5,0	17,5	7,6	17,6	5,0	17,9	6,1	22,4	16,9	20,0	7,2	18,0	7,7	18,9	4,5	21,2	5,3	19,1	-2,6	44,6	3,4	20,2	2,5	34,7
CMI	0,4	19,0	3,0	19,1	0,4	19,4	1,5	23,6	12,3	21,3	2,6	19,4	3,1	20,3	-0,1	22,5	0,7	20,4	-7,2	45,2	-1,2	21,5	-2,1	35,5
EIM	-0,3	4,0	2,3	4,4	-0,3	5,4	0,9	14,6	11,6	10,4	2,0	5,7	2,4	8,1	-0,7	12,7	0,0	8,5	-7,8	41,2	-1,8	10,8	-2,7	30,3
NPLI	-9,6	11,1	-7,0	10,9	-9,6	11,7	-8,4	17,9	2,3	14,7	-7,3	11,8	-6,9	13,2	-10,0	16,4	-9,3	13,4	-17,1	42,5	-11,1	15,0	-12,0	32,0
VNIIM	-0,5	10,0	2,1	9,8	-0,5	10,7	0,6	17,2	11,4	13,9	1,7	10,8	2,2	12,2	-1,0	15,7	-0,2	12,5	-8,1	42,2	-2,1	14,2	-3,0	31,6

Table 4 Degrees of equivalence 100 mV, 1 kHz

100 mV, 1 kHz			MIKES		DPLE		LNE		METAS		UME		NMISA		CMI		EIM		NPLI		VNIIM	
			δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}
			-0,5	4,7	-10,6	8,0	0,7	7,0	-13,0	13,0	-0,8	13,0	-10,4	17,5	0,4	19,0	-0,3	4,0	-9,6	11,1	-0,5	10,0
	δ_{id}	U_{id}	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}
MIKES	-0,5	4,7			10,1	9,3	-1,2	8,5	12,5	13,9	0,3	13,9	-5,5	18,1	-0,9	19,6	-0,2	6,2	9,1	12,1	0,0	11,1
DPLE	-10,6	8,0	-10,1	9,3			-11,4	10,7	2,4	15,3	-9,9	15,3	-15,6	19,3	-11,0	20,6	-10,4	8,9	-1,1	13,7	-10,1	12,8
LNE	0,7	7,0	1,2	8,5	11,4	10,7			13,7	14,8	1,5	14,8	-4,3	18,9	0,4	20,3	1,0	8,1	10,3	13,2	1,2	12,2
METAS	-13,0	13,0	-12,5	13,9	-2,4	15,3	-13,7	14,8			-12,2	18,4	-18,0	21,8	-13,4	23,0	-12,7	13,6	-3,4	17,1	-12,5	16,4
UME	-0,8	13,0	-0,3	13,9	9,9	15,3	-1,5	14,8	12,2	18,4			-5,8	21,8	-1,1	23,0	-0,5	13,6	8,8	17,1	-0,3	16,4
NMISA	5,0	17,5	5,5	18,1	15,6	19,3	4,3	18,9	18,0	21,8	5,8	21,8			4,6	25,8	5,3	18,0	14,6	20,7	5,5	20,2
CMI	0,4	19,0	0,9	19,6	11,0	20,6	-0,4	20,3	13,4	23,0	1,1	23,0	-4,6	25,8			0,6	19,4	9,9	22,0	0,9	21,5
EIM	-0,3	4,0	0,2	6,2	10,4	8,9	-1,0	8,1	12,7	13,6	0,5	13,6	-5,3	18,0	-0,6	19,4			9,3	11,8	0,2	10,8
NPLI	-9,6	11,1	-9,1	12,1	1,1	13,7	-10,3	13,2	3,4	17,1	-8,8	17,1	-14,6	20,7	-9,9	22,0	-9,3	11,8			-9,1	15,0
VNIIM	-0,5	10,0	0,0	11,1	10,1	12,8	-1,2	12,2	12,5	16,4	0,3	16,4	-5,5	20,2	-0,9	21,5	-0,2	10,8	9,1	15,0		

Table 5 Degrees of equivalence 100 mV, 20 kHz

100 mV, 20 kHz			CRV		SP		JV		INRIM		PTB		VSL		BEV		OMH		INETI		CEM		MIRS/SIQ	
			δ_R	U_R	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}
			-2,3	2,5	0,0	4,4	0,1	15,1	-8,6	9,5	0,0	6,1	-0,8	8,1	0,2	13,1	0,3	9,0	5,9	48,0	-8,1	10,1	0,9	30,0
	δ_{id}	U_{id}	$\boldsymbol{D_{iE}}$	$\boldsymbol{U_{iE}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$
SP	0,0	4,4	2,3	3,6			-0,1	15,7	8,6	10,5	0,0	7,6	0,8	9,2	-0,2	13,8	-0,3	10,0	-5,9	48,2	8,1	11,0	-0,9	30,3
JV	0,1	15,1	2,4	14,9	0,1	15,7			8,7	17,8	0,1	16,3	0,9	17,1	-0,1	19,9	-0,2	17,5	-5,9	50,3	8,2	18,1	-0,8	33,6
INRIM	-8,6	9,5	-6,3	9,2	-8,6	10,5	-8,7	17,8			-8,7	11,3	-7,8	12,5	-8,8	16,2	-8,9	13,1	-14,6	48,9	-0,6	13,8	-9,5	31,5
PTB	0,0	6,1	2,3	5,6	0,0	7,6	-0,1	16,3	8,7	11,3			0,8	10,2	-0,1	14,4	-0,2	10,9	-5,9	48,4	8,1	11,8	-0,9	30,6
VSL	-0,8	8,1	1,5	7,7	-0,8	9,2	-0,9	17,1	7,8	12,5	-0,8	10,2			-1,0	15,4	-1,1	12,1	-6,7	48,7	7,3	12,9	-1,7	31,1
BEV	0,2	13,1	2,5	13,3	0,2	13,8	0,1	19,9	8,8	16,2	0,1	14,4	1,0	15,4			-0,1	15,9	-5,8	49,8	8,3	16,5	-0,7	32,7
OMH	0,3	9,0	2,6	8,6	0,3	10,0	0,2	17,5	8,9	13,1	0,2	10,9	1,1	12,1	0,1	15,9			-5,7	48,9	8,3	13,5	-0,6	31,3
INETI	5,9	48,0	8,2	48,1	5,9	48,2	5,9	50,3	14,6	48,9	5,9	48,4	6,7	48,7	5,8	49,8	5,7	48,9			14,0	49,1	5,0	56,6
CEM	-8,1	10,1	-5,8	10,4	-8,1	11,0	-8,2	18,1	0,6	13,8	-8,1	11,8	-7,3	12,9	-8,3	16,5	-8,3	13,5	-14,0	49,1			-9,0	31,7
MIRS/SIQ	0,9	30,0	3,2	30,1	0,9	30,3	0,8	33,6	9,5	31,5	0,9	30,6	1,7	31,1	0,7	32,7	0,6	31,3	-5,0	56,6	9,0	31,7		

Table 6 Degrees of equivalence 100 mV, 20 kHz

100 mV, 20 kHz			MIKES		DPLE		LNE		METAS		UME		NMISA		CMI		EIM		NPLI		VNIIM	
			δ_R	U_R	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}
			0,0	5,6	-9,2	8,1	0,3	8,1	-12,3	9,1	4,8	14,1	-18,3	17,9	3,2	21,0	2,6	3,8	-2,0	11,5	18,0	13,1
	δ_{id}	U_{id}	$\boldsymbol{D_{iE}}$	$\boldsymbol{U_{iE}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$
SP	0,0	4,4	0,0	7,1	9,2	9,2	-0,3	9,2	12,3	10,1	-4,8	14,7	18,3	18,5	-3,2	21,5	-2,6	5,8	2,0	12,3	-18,0	13,8
JV	0,1	15,1	0,1	16,1	9,2	17,1	-0,2	17,1	12,4	17,6	-4,7	20,6	18,4	23,4	-3,1	25,9	-2,5	15,5	2,1	18,9	-17,9	19,9
INRIM	-8,6	9,5	-8,6	11,0	0,5	12,5	-9,0	12,5	3,6	13,1	-13,4	17,0	9,6	20,3	-11,8	23,1	-11,2	10,2	-6,7	14,9	-26,6	16,2
PTB	0,0	6,1	0,1	8,3	9,2	10,2	-0,3	10,2	12,3	11,0	-4,7	15,3	18,3	19,0	-3,2	21,9	-2,5	7,2	2,0	13,0	-17,9	14,4
VSL	-0,8	8,1	-0,8	9,9	8,4	11,5	-1,1	11,5	11,5	12,2	-5,6	16,2	17,5	19,7	-4,0	22,5	-3,4	9,0	1,2	14,0	-18,8	15,4
BEV	0,2	13,1	0,2	14,2	9,3	15,4	-0,1	15,4	12,5	15,9	-4,6	19,2	18,5	22,2	-3,0	24,8	-2,4	13,6	2,2	17,4	-17,8	18,5
OMH	0,3	9,0	0,3	10,6	9,4	12,1	-0,1	12,1	12,6	12,8	-4,5	16,7	18,5	20,1	-2,9	22,9	-2,3	9,8	2,2	14,6	-17,7	15,9
INETI	5,9	48,0	6,0	48,3	15,1	48,7	5,6	48,7	18,2	48,9	1,2	50,0	24,2	51,3	2,7	52,4	3,4	48,2	7,9	49,4	-12,0	49,8
CEM	-8,1	10,1	-8,0	11,5	1,1	12,9	-8,4	12,9	4,2	13,6	-12,8	17,3	10,2	20,6	-11,3	23,3	-10,7	10,8	-6,1	15,3	-26,0	16,5
MIRS/SIQ	0,9	30,0	0,9	30,5	10,1	31,1	0,6	31,1	13,2	31,4	-3,9	33,2	-5,4	35,0	-2,3	36,7	-1,7	30,3	2,9	32,1	-17,1	32,7

Table 7 Degrees of equivalence 100 mV, 20 kHz

			CRV		SP		JV		INRIM		PTB		VSL		BEV		OMH		INETI		CEM		MIRS/SIQ	
100 mV, 20 kHz			δ_R	U_R	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}
			-2,3	2,5	0,0	4,4	0,1	15,1	-8,6	9,5	0,0	6,1	-0,8	8,1	0,2	13,1	0,3	9,0	5,9	48,0	-8,1	10,1	0,9	30,0
	δ_{id}	U_{id}	D_{iE}	U_{iE}	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}
MIKES	0,0	5,6	2,3	6,2	0,0	7,1	-0,1	16,1	8,6	11,0	-0,1	8,3	0,8	9,9	-0,2	14,2	-0,3	10,6	-6,0	48,3	8,0	11,5	-0,9	30,5
DPLE	-9,2	8,1	-6,9	7,7	-9,2	9,2	-9,2	17,1	-0,5	12,5	-9,2	10,2	-8,4	11,5	-9,3	15,4	-9,4	12,1	-15,1	48,7	-1,1	12,9	-10,1	31,1
LNE	0,3	8,1	2,6	7,7	0,3	9,2	0,2	17,1	9,0	12,5	0,3	10,2	1,1	11,5	0,1	15,4	0,1	12,1	-5,6	48,7	8,4	12,9	-0,6	31,1
METAS	-12,3	9,1	-10,0	8,7	-12,3	10,1	-12,4	17,6	-3,6	13,1	-12,3	11,0	-11,5	12,2	-12,5	15,9	-12,6	12,8	-18,2	48,9	-4,2	13,6	-13,2	31,4
UME	4,8	14,1	7,1	14,3	4,8	14,7	4,7	20,6	13,4	17,0	4,7	15,3	5,6	16,2	4,6	19,2	4,5	16,7	-1,2	50,0	12,8	17,3	3,9	33,2
NMISA	6,3	17,9	8,6	18,1	6,3	18,5	6,2	23,4	14,9	20,3	6,2	19,0	7,1	19,7	6,1	22,2	6,0	20,1	0,3	51,3	14,3	20,6	5,4	35,0
CMI	3,2	21,0	5,5	21,2	3,2	21,5	3,1	25,9	11,8	23,1	3,2	21,9	4,0	22,5	3,0	24,8	2,9	22,9	-2,7	52,4	11,3	23,3	2,3	36,7
EIM	2,6	3,8	4,9	4,6	2,6	5,8	2,5	15,5	11,2	10,2	2,5	7,2	3,4	9,0	2,4	13,6	2,3	9,8	-3,4	48,2	10,7	10,8	1,7	30,3
NPLI	-2,0	11,5	0,3	11,2	-2,0	12,3	-2,1	18,9	6,7	14,9	-2,0	13,0	-1,2	14,0	-2,2	17,4	-2,2	14,6	-7,9	49,4	6,1	15,3	-2,9	32,1
VNIIM	18,0	13,1	20,3	13,3	18,0	13,8	17,9	19,9	26,6	16,2	17,9	14,4	18,8	15,4	17,8	18,5	17,7	15,9	12,0	49,8	26,0	16,5	17,1	32,7

Table 8 Degrees of equivalence 100 mV, 20 kHz

			MIKES		DPLE		LNE		METAS		UME		NMISA		CMI		EIM		NPLI		VNIIM	
100 mV, 20 kHz			δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}
	δ_{id}	U_{id}	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}
MIKES	0,0	5,6			9,1	9,9	-0,4	9,9	12,2	10,7	-4,8	15,1	-6,3	18,8	-3,2	21,8	-2,6	6,8	1,9	12,8	-18,0	14,2
DPLE	-9,2	8,1	-9,1	9,9			-9,5	11,4	3,1	12,2	-13,9	16,2	-15,4	19,7	-12,4	22,5	-11,7	8,9	-7,2	14,0	-27,1	15,4
LNE	0,3	8,1	0,4	9,9	9,5	11,4			12,6	12,2	-4,5	16,2	-5,9	19,7	-2,9	22,5	-2,3	8,9	2,3	14,0	-17,6	15,4
METAS	-12,3	9,1	-12,2	10,7	-3,1	12,2	-12,6	12,2			-17,1	16,7	-18,5	20,1	-15,5	22,9	-14,9	9,8	-10,3	14,6	-30,3	15,9
UME	4,8	14,1	4,8	15,1	13,9	16,2	4,5	16,2	17,1	16,7			-1,5	22,8	1,6	25,3	2,2	14,6	6,7	18,1	-13,2	19,2
NMISA	6,3	17,9	6,3	18,8	15,4	19,7	5,9	19,7	18,5	20,1	1,5	22,8			3,1	27,6	3,7	18,3	8,2	21,3	-11,7	22,2
CMI	3,2	21,0	3,2	21,8	12,4	22,5	2,9	22,5	15,5	22,9	-1,6	25,3	-3,1	27,6			0,6	21,4	5,2	24,0	-14,8	24,8
EIM	2,6	3,8	2,6	6,8	11,7	8,9	2,3	8,9	14,9	9,8	-2,2	14,6	-3,7	18,3	-0,6	21,4			4,6	12,1	-15,4	13,6
NPLI	-2,0	11,5	-1,9	12,8	7,2	14,0	-2,3	14,0	10,3	14,6	-6,7	18,1	-8,2	21,3	-5,2	24,0	-4,6	12,1			-19,9	17,4
VNIIM	18,0	13,1	18,0	14,2	27,1	15,4	17,6	15,4	30,3	15,9	13,2	19,2	11,7	22,2	14,8	24,8	15,4	13,6	19,9	17,4		

Table 9 Degrees of equivalence 100 mV, 100 kHz

			CRV		SP		JV		INRIM		PTB		VSL		BEV		OMH		INETI		CEM		MIRS/SIQ	
100 mV, 100 kHz			δ_R	U_R	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}
			-5,5	3,6	0,0	6,7	3,0	28,0	-18,1	12,1	0,9	8,1	-4,4	10,1	-1,5	17,1	-4,2	17,6	7,7	61,0	-10,3	30,0	-6,4	50,0
	δ_{id}	U_{id}	D_{iE}	U_{iE}	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}
SP	0,0	6,7	5,5	5,7			-3,0	28,8	18,1	13,8	-0,9	10,6	4,4	12,1	1,5	18,3	4,2	18,8	-7,7	61,4	10,3	30,8	6,4	50,5
JV	3,0	28,0	8,5	27,8	3,0	28,8			21,1	30,5	2,1	29,2	7,4	29,8	4,5	32,8	7,2	33,1	-4,7	67,2	13,3	41,1	9,4	57,3
INRIM	-18,1	12,1	-12,6	11,5	-18,1	13,8	-21,1	30,5			-19,0	14,6	-13,7	15,8	-16,6	20,9	-13,8	21,3	-25,8	62,2	-7,7	32,4	-11,7	51,5
PTB	0,9	8,1	6,4	7,3	0,9	10,6	-2,1	29,2	19,0	14,6			5,3	13,0	2,4	18,9	5,1	19,3	-6,8	61,6	11,2	31,1	7,3	50,7
VSL	-4,4	10,1	1,1	9,4	-4,4	12,1	-7,4	29,8	13,7	15,8	-5,3	13,0			-2,9	19,8	-0,1	20,3	-12,1	61,8	5,9	31,7	2,0	51,0
BEV	-1,5	17,1	4,0	17,4	-1,5	18,3	-4,5	32,8	16,6	20,9	-2,4	18,9	2,9	19,8			2,7	24,5	-9,2	63,4	8,8	34,5	4,9	52,8
OMH	-4,2	17,6	1,3	17,2	-4,2	18,8	-7,2	33,1	13,8	21,3	-5,1	19,3	0,1	20,3	-2,7	24,5			-12,0	63,5	6,1	34,8	2,1	53,0
INETI	7,7	61,0	13,2	61,1	7,7	61,4	4,7	67,2	25,8	62,2	6,8	61,6	12,1	61,8	9,2	63,4	12,0	63,5			18,0	68,0	14,1	78,9
CEM	-10,3	30,0	-4,8	30,2	-10,3	30,8	-13,3	41,1	7,7	32,4	-11,2	31,1	-5,9	31,7	-8,8	34,5	-6,1	34,8	-18,0	68,0			-3,9	58,3
MIRS/SIQ	-6,4	50,0	-0,9	50,1	-6,4	50,5	-9,4	57,3	11,7	51,5	-7,3	50,7	-2,0	51,0	-4,9	52,8	-2,1	53,0	-14,1	78,9	3,9	58,3		

Table 10 Degrees of equivalence 100 mV, 100 kHz

			MIKES		DPLE		LNE		METAS		UME		NMISA		CMI		EIM		NPLI		VNIIM	
100 mV, 100 kHz			δ_R	U_R	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}
	δ_{id}	U_{id}	D_{iE}	U_{iE}	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}
SP	0,0	6,7	1,6	9,3	13,5	14,7	3,4	15,6	14,9	15,6	7,6	17,4	-11,0	35,6	3,1	29,8	3,8	8,3	18,3	14,6	-67,7	33,7
JV	3,0	28,0	4,6	28,7	16,5	30,9	6,4	31,4	17,9	31,4	10,6	32,3	-8,0	44,8	6,1	40,4	6,8	28,4	21,3	30,9	-64,7	43,3
INRIM	-18,1	12,1	-16,5	13,7	-4,6	17,8	-14,6	18,5	-3,2	18,5	-10,4	20,1	-29,1	37,0	-15,0	31,4	-14,2	13,0	0,3	17,7	-85,8	35,2
PTB	0,9	8,1	2,5	10,3	14,4	15,4	4,3	16,2	15,8	16,2	8,5	18,0	-10,1	35,9	4,0	30,1	4,7	9,4	19,2	15,3	-66,8	34,0
VSL	-4,4	10,1	-2,8	11,9	9,1	16,5	-0,9	17,3	10,5	17,3	3,3	19,0	-15,4	36,4	-1,3	30,7	-0,6	11,2	13,9	16,4	-72,1	34,5
BEV	-1,5	17,1	0,1	18,2	12,0	21,5	1,9	22,1	13,4	22,1	6,1	23,4	-12,5	38,9	1,6	33,7	2,3	17,7	16,8	21,4	-69,2	37,2
OMH	-4,2	17,6	-2,7	18,7	9,3	21,9	-0,8	22,5	10,6	22,5	3,4	23,8	-15,3	39,1	-1,2	33,9	-0,4	18,2	14,1	21,8	-72,0	37,4
INETI	7,7	61,0	9,3	61,3	21,2	62,4	11,2	62,6	22,6	62,6	15,4	63,1	-3,3	70,3	10,8	67,6	11,5	61,2	26,0	62,4	-60,0	69,4
CEM	-10,3	30,0	-8,7	30,7	3,2	32,8	-6,9	33,2	4,6	33,2	-2,7	34,1	-21,3	46,1	-7,2	41,8	-6,5	30,4	8,0	32,7	-78,1	44,6
MIRS/SIQ	-6,4	50,0	-4,8	50,4	7,1	51,7	-2,9	52,0	8,5	52,0	1,3	52,5	-17,4	61,0	-3,3	57,8	-2,6	50,2	11,9	51,7	-74,1	59,9

Table 11 Degrees of equivalence 100 mV, 100 kHz

100 mV, 100 kHz			CRV		SP		JV		INRIM		PTB		VSL		BEV		OMH		INETI		CEM		MIRS/SIQ	
			δ_R	U_R	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}
			-5,5	3,6	0,0	6,7	3,0	28,0	-18,1	12,1	0,9	8,1	-4,4	10,1	-1,5	17,1	-4,2	17,6	7,7	61,0	-10,3	30,0	-6,4	50,0
	δ_{id}	U_{id}	$\boldsymbol{D_{iE}}$	$\boldsymbol{U_{iE}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$
MIKES	-1,6	6,3	3,9	7,3	-1,6	9,3	-4,6	28,7	16,5	13,7	-2,5	10,3	2,8	11,9	-0,1	18,2	2,7	18,7	-9,3	61,3	8,7	30,7	4,8	50,4
DPLE	-13,5	13,1	-8,0	12,6	-13,5	14,7	-16,5	30,9	4,6	17,8	-14,4	15,4	-9,1	16,5	-12,0	21,5	-9,3	21,9	-21,2	62,4	-3,2	32,8	-7,1	51,7
LNE	-3,4	14,1	2,1	13,6	-3,4	15,6	-6,4	31,4	14,6	18,5	-4,3	16,2	0,9	17,3	-1,9	22,1	0,8	22,5	-11,2	62,6	6,9	33,2	2,9	52,0
METAS	-14,9	14,1	-9,4	13,6	-14,9	15,6	-17,9	31,4	3,2	18,5	-15,8	16,2	-10,5	17,3	-13,4	22,1	-10,6	22,5	-22,6	62,6	-4,6	33,2	-8,5	52,0
UME	-7,6	16,1	-2,1	16,5	-7,6	17,4	-10,6	32,3	10,4	20,1	-8,5	18,0	-3,3	19,0	-6,1	23,4	-3,4	23,8	-15,4	63,1	2,7	34,1	-1,3	52,5
NMISA	11,0	34,9	16,5	35,1	11,0	35,6	8,0	44,8	29,1	37,0	10,1	35,9	15,4	36,4	12,5	38,9	15,3	39,1	3,3	70,3	21,3	46,1	17,4	61,0
CMI	-3,1	29,0	2,4	29,3	-3,1	29,8	-6,1	40,4	15,0	31,4	-4,0	30,1	1,3	30,7	-1,6	33,7	1,2	33,9	-10,8	67,6	7,2	41,8	3,3	57,8
EIM	-3,8	4,8	1,7	6,0	-3,8	8,3	-6,8	28,4	14,2	13,0	-4,7	9,4	0,6	11,2	-2,3	17,7	0,4	18,2	-11,5	61,2	6,5	30,4	2,6	50,2
NPLI	-18,3	13,0	-12,8	12,5	-18,3	14,6	-21,3	30,9	-0,3	17,7	-19,2	15,3	-13,9	16,4	-16,8	21,4	-14,1	21,8	-26,0	62,4	-8,0	32,7	-11,9	51,7
VNIIM	67,7	33,0	73,2	33,2	67,7	33,7	64,7	43,3	85,8	35,2	66,8	34,0	72,1	34,5	69,2	37,2	72,0	37,4	60,0	69,4	78,1	44,6	74,1	59,9

Table 12 Degrees of equivalence 100 mV, 100 kHz

100 mV, 100 kHz			MIKES		DPLE		LNE		METAS		UME		NMISA		CMI		EIM		NPLI		VNIIM	
			δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}
	δ_{id}	U_{id}	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$
MIKES	-1,6	6,3			11,9	14,5	1,9	15,4	13,3	15,4	6,1	17,3	-12,6	35,5	1,5	29,7	2,2	8,0	16,7	14,4	-69,3	33,6
DPLE	-13,5	13,1	-11,9	14,5			-10,1	19,2	1,4	19,2	-5,9	20,7	-24,5	37,3	-10,4	31,8	-9,7	13,9	4,8	18,4	-81,2	35,5
LNE	-3,4	14,1	-1,9	15,4	10,1	19,2			11,4	19,9	4,2	21,3	-14,5	37,7	-0,4	32,3	0,4	14,9	14,9	19,1	-71,2	35,9
METAS	-14,9	14,1	-13,3	15,4	-1,4	19,2	-11,4	19,9			-7,2	21,3	-25,9	37,7	-11,8	32,3	-11,0	14,9	3,5	19,1	-82,6	35,9
UME	-7,6	16,1	-6,1	17,3	5,9	20,7	-4,2	21,3	7,2	21,3			-18,7	38,4	-4,6	33,2	-3,8	16,8	10,7	20,6	-75,4	36,7
NMISA	11,0	34,9	12,6	35,5	24,5	37,3	14,5	37,7	25,9	37,7	18,7	38,4			14,1	45,4	14,8	35,3	29,3	37,3	-56,7	48,1
CMI	-3,1	29,0	-1,5	29,7	10,4	31,8	0,4	32,3	11,8	32,3	4,6	33,2	-14,1	45,4			0,7	29,4	15,2	31,8	-70,8	44,0
EIM	-3,8	4,8	-2,2	8,0	9,7	13,9	-0,4	14,9	11,0	14,9	3,8	16,8	-14,8	35,3	-0,7	29,4			14,5	13,8	-71,6	33,4
NPLI	-18,3	13,0	-16,7	14,4	-4,8	18,4	-14,9	19,1	-3,5	19,1	-10,7	20,6	-29,3	37,3	-15,2	31,8	-14,5	13,8			-86,1	35,5
VNIIM	67,7	33,0	69,3	33,6	81,2	35,5	71,2	35,9	82,6	35,9	75,4	36,7	56,7	48,1	70,8	44,0	71,6	33,4	86,1	35,5		

Table 13 Degrees of equivalence 100 mV, 1 MHz

			CRV		SP		JV		INRIM		PTB		VSL		BEV		OMH		INETI		CEM		MIRS/SIQ	
100 mV, 1 MHz			δ_R	U_R	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}
	δ_{id}	U_{id}	D_{iE}	U_{iE}	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}
SP	0	38	8	34			-30	111	40	72	-16	53	2	56	9	72	25	155	18	89	28	89	37	402
JV	30	105	38	103	30	111			70	121	14	111	33	112	39	121	55	183	48	132	58	132	67	414
INRIM	-40	61	-32	58	-40	72	-70	121			-56	71	-38	73	-31	86	-15	162	-22	101	-12	101	-3	405
PTB	16	37	24	33	16	53	-14	111	56	71			18	56	25	71	40	155	34	89	44	89	53	402
VSL	-2	41	6	37	-2	56	-33	112	38	73	-18	56			7	73	22	156	15	90	25	90	35	402
BEV	-9	61	-1	63	-9	72	-39	121	31	86	-25	71	-7	73			15	162	9	101	19	101	28	405
OMH	-25	150	-17	149	-25	155	-55	183	15	162	-40	155	-22	156	-15	162			-7	171	3	171	12	427
INETI	-18	81	-10	82	-18	89	-48	132	22	101	-34	89	-15	90	-9	101	7	171			10	114	19	408
CEM	-28	81	-20	82	-28	89	-58	132	12	101	-44	89	-25	90	-19	101	-3	171	-10	114			9	408
MIRS/SIQ	-37	400	-29	400	-37	402	-67	414	3	405	-53	402	-35	402	-28	405	-12	427	-19	408	-9	408		

Table 14 Degrees of equivalence 100 mV, 1 MHz

			MIKES		DPLE		LNE		METAS		UME		NMISA		CMI		EIM		NPLI		VNIIM	
100 mV, 1 MHz			δ_R	U_R	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}
			-12	33	-39	49			-37	64	-4	41	213	187	-37	81	-21	22	125	37	249	118
	δ_{id}	U_{id}	D_{iE}	U_{iE}	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}
SP	0	38	12	51	39	62			37	74	4	56	-213	191	37	89	21	44	-125	53	-249	124
JV	30	105	42	110	69	115			67	122	34	112	-183	214	67	132	51	107	-95	111	-219	158
INRIM	-40	61	-28	69	-2	78			-3	88	-36	73	-253	197	-3	101	-20	65	-165	71	-289	133
PTB	16	37	28	50	54	61			53	74	20	55	-197	191	53	89	36	43	-109	52	-233	124
VSL	-2	41	10	53	36	64			35	76	1	58	-216	192	35	90	18	47	-128	55	-251	125
BEV	-9	61	3	69	29	78			28	88	-5	73	-222	197	28	101	11	65	-135	71	-258	133
OMH	-25	150	-13	154	14	158			13	163	-21	156	-238	240	13	171	-4	152	-150	155	-273	191
INETI	-18	81	-6	87	21	94			19	103	-14	90	-231	204	20	114	3	83	-143	89	-267	143
CEM	-28	81	-16	87	11	94			9	103	-24	90	-241	204	9	114	-7	83	-153	89	-277	143
MIRS/SIQ	-37	400	-25	401	1	403			0	405	-33	402	-250	442	0	408	-17	401	-162	402	-286	417

Table 15 Degrees of equivalence 100 mV, 1 MHz

100 mV, 1 MHz			CRV		SP		JV		INRIM		PTB		VSL		BEV		OMH		INETI		CEM		MIRS/SIQ	
			δ_R	U_R	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}
			-8	17	0	38	30	105	-40	61	16	37	-2	41	-9	61	-25	150	-18	81	-28	81	-37	400
	δ_{id}	U_{id}	$\boldsymbol{D_{iE}}$	$\boldsymbol{U_{iE}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$
MIKES	-12	33	-4	37	-12	51	-42	110	28	69	-28	50	-10	53	-3	69	13	154	6	87	16	87	25	401
DPLE	-39	49	-30	46	-39	62	-69	115	2	78	-54	61	-36	64	-29	78	-14	158	-21	94	-11	94	-1	403
LNE																								
METAS	-37	64	-29	61	-37	74	-67	122	3	88	-53	74	-35	76	-28	88	-13	163	-19	103	-9	103	0	405
UME	-4	41	4	44	-4	56	-34	112	36	73	-20	55	-1	58	5	73	21	156	14	90	24	90	33	402
NMISA	213	187	221	188	213	191	183	214	253	197	197	191	216	192	222	197	238	240	231	204	241	204	250	442
CMI	-37	81	-29	82	-37	89	-67	132	3	101	-53	89	-35	90	-28	101	-13	171	-20	114	-9	114	0	408
EIM	-21	22	-12	28	-21	44	-51	107	20	65	-36	43	-18	47	-11	65	4	152	-3	83	7	83	17	401
NPLI	125	37	133	41	125	53	95	111	165	71	109	52	128	55	135	71	150	155	143	89	153	89	162	402
VNIIM	249	118	257	120	249	124	219	158	289	133	233	124	251	125	258	133	273	191	267	143	277	143	286	417

Table 16 Degrees of equivalence 100 mV, 1 MHz

100 mV, 1 MHz			MIKES		DPLE		LNE		METAS		UME		NMISA		CMI		EIM		NPLI		VNIIM	
			δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}
			-12	33	-39	49			-37	64	-4	41	213	187	-37	81	-21	22	125	37	249	118
	δ_{id}	U_{id}	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$
MIKES	-12	33			26	59			25	72	-8	53	-225	190	25	87	8	40	-137	50	-261	123
DPLE	-39	49	-26	59					-1	80	-35	64	-252	193	-1	94	-18	54	-164	61	-287	128
LNE																						
METAS	-37	64	-25	72	1	80					-33	76	-250	198	0	103	-17	67	-162	74	-286	134
UME	-4	41	8	53	35	64			33	76			-217	192	33	90	17	47	-129	55	-253	125
NMISA	213	187	225	190	252	193			250	198	217	192			250	204	234	188	88	191	-36	221
CMI	-37	81	-25	87	1	94			0	103	-33	90	-250	204			-17	83	-163	89	-286	143
EIM	-21	22	-8	40	18	54			17	67	-17	47	-234	188	17	83			-146	43	-269	120
NPLI	125	37	137	50	164	61			162	74	129	55	-88	191	163	89	146	43			-123	124
VNIIM	249	118	261	123	287	128			286	134	253	125	36	221	286	143	269	120	123	124		

Table 17 Degrees of equivalence 10 mV, 1 kHz

10 mV, 1 kHz			CRV		SP		JV		INRIM		PTB		VSL		BEV		OMH		INETI		CEM		MIRS/SIQ	
			δ_R	U_R	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}
			-7	7	0	18	3	24	-19	17	-20	17	-6	32	4	33	-1	18	0	57	-7	41	-2	71
	δ_{id}	U_{id}	$\boldsymbol{D_{iE}}$	$\boldsymbol{U_{iE}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$
SP	0	18	7	17			-3	30	19	25	20	24	6	36	-4	37	1	26	0	60	7	45	2	73
JV	3	24	10	23	3	30			22	30	23	29	10	40	-1	41	4	31	3	62	10	48	5	75
INRIM	-19	17	-12	16	-19	25	-22	30			1	24	-12	36	-23	37	-18	25	-19	59	-12	45	-17	73
PTB	-20	17	-13	15	-20	24	-23	29	-1	24			-13	36	-24	36	-19	25	-20	59	-13	44	-18	73
VSL	-6	32	0	31	-6	36	-10	40	12	36	13	36			-10	45	-6	37	-6	65	1	52	-4	77
BEV	4	33	11	32	4	37	1	41	23	37	24	36	10	45			5	37	4	65	11	52	6	78
OMH	-1	18	6	17	-1	26	-4	31	18	25	19	25	6	37	-5	37			-1	60	6	45	1	73
INETI	0	57	7	57	0	60	-3	62	19	59	20	59	6	65	-4	65	1	60			7	70	2	91
CEM	-7	41	0	41	-7	45	-10	48	12	45	13	44	-1	52	-11	52	-6	45	-7	70			-5	82
MIRS/SIQ	-2	71	5	71	-2	73	-5	75	17	73	18	73	4	77	-6	78	-1	73	-2	91	5	82		

Table 18 Degrees of equivalence 10 mV, 1 kHz

10 mV, 1 kHz			MIKES		DPLE		LNE		METAS		UME		NMISA		CMI		EIM		NPLI		VNIIM	
			δ_R	U_R	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}
			12	25	-18	42	1	14	-31	33	4	48	-50	58	1	55	3	86	-9	17	0	21
	δ_{id}	U_{id}	$\boldsymbol{D_{iE}}$	$\boldsymbol{U_{iE}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$
SP	0	18	-12	31	18	46	-1	23	31	38	-4	51	50	61	-1	58	-3	87	9	25	0	28
JV	3	24	-8	35	21	49	3	28	35	41	-1	54	54	63	3	60	1	89	12	30	3	33
INRIM	-19	17	-30	30	-1	46	-19	22	13	38	-23	51	32	61	-19	58	-21	87	-10	25	-19	28
PTB	-20	17	-31	30	-2	45	-20	21	12	37	-24	51	31	61	-20	57	-22	87	-11	24	-20	27
VSL	-6	32	-18	40	12	53	-7	34	25	46	-10	57	44	66	-7	63	-9	91	3	36	-7	38
BEV	4	33	-8	41	22	53	4	35	35	47	0	58	55	67	4	64	1	92	13	37	4	39
OMH	-1	18	-12	31	17	46	-1	23	31	38	-5	51	50	61	-1	58	-3	88	8	25	-1	28
INETI	0	57	-12	62	18	71	0	58	31	66	-4	74	50	81	0	79	-3	103	9	59	0	61
CEM	-7	41	-19	48	11	59	-7	43	24	53	-11	63	43	71	-7	69	-10	95	2	45	-7	46
MIRS/SIQ	-2	71	-14	75	16	82	-2	72	29	78	-6	85	6	92	-2	89	-5	111	7	73	-2	74

Table 19 Degrees of equivalence 10 mV, 1 kHz

10 mV, 1 kHz			CRV		SP		JV		INRIM		PTB		VSL		BEV		OMH		INETI		CEM		MIRS/SIQ	
			δ_R	U_R	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}
			-7	7	0	18	3	24	-19	17	-20	17	-6	32	4	33	-1	18	0	57	-7	41	-2	71
	δ_{id}	U_{id}	D_{iE}	U_{iE}	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}
MIKES	12	25	18	26	12	31	8	35	30	30	31	30	18	40	8	41	12	31	12	62	19	48	14	75
DPLE	-18	42	-11	42	-18	46	-21	49	1	46	2	45	-12	53	-22	53	-17	46	-18	71	-11	59	-16	82
LNE	1	14	7	12	1	23	-3	28	19	22	20	21	7	34	-4	35	1	23	0	58	7	43	2	72
METAS	-31	33	-25	33	-31	38	-35	41	-13	38	-12	37	-25	46	-35	47	-31	38	-31	66	-24	53	-29	78
UME	4	48	10	47	4	51	1	54	23	51	24	51	10	57	0	58	5	51	4	74	11	63	6	85
NMISA	-8	58	-1	59	-8	61	-11	63	11	61	12	61	-2	66	-12	67	-7	61	-8	81	-1	71	-6	92
CMI	1	55	7	54	1	58	-3	60	19	58	20	57	7	63	-4	64	1	58	0	79	7	69	2	89
EIM	3	86	9	86	3	87	-1	89	21	87	22	87	9	91	-1	92	3	88	3	103	10	95	5	111
NPLI	-9	17	-2	16	-9	25	-12	30	10	25	11	24	-3	36	-13	37	-8	25	-9	59	-2	45	-7	73
VNIIM	0	21	7	20	0	28	-3	33	19	28	20	27	7	38	-4	39	1	28	0	61	7	46	2	74

Table 20 Degrees of equivalence 10 mV, 1 kHz

10 mV, 1 kHz			MIKES		DPLE		LNE		METAS		UME		NMISA		CMI		EIM		NPLI		VNIIM	
			δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}
			12	25	-18	42	1	14	-31	33	4	48	-8	58	1	55	3	86	-9	17	0	21
	δ_{id}	U_{id}	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}
MIKES	12	25			30	49	11	29	43	42	8	54	20	63	11	60	9	89	21	30	11	33
DPLE	-18	42	-30	49			-18	44	13	54	-22	64	-10	72	-18	69	-21	95	-9	45	-18	47
LNE	1	14	-11	29	18	44			32	36	-3	50	8	60	0	57	-2	87	9	22	0	25
METAS	-31	33	-43	42	-13	54	-32	36			-35	58	-23	67	-32	64	-34	92	-22	38	-32	40
UME	4	48	-8	54	22	64	3	50	35	58			12	75	3	73	1	98	13	51	4	53
NMISA	-8	58	-20	63	10	72	-8	60	23	67	-12	75			-8	80	-11	103	1	61	-8	62
CMI	1	55	-11	60	18	69	0	57	32	64	-3	73	8	80			-2	102	10	58	0	59
EIM	3	86	-9	89	21	95	2	87	34	92	-1	98	11	103	2	102			12	87	2	88
NPLI	-9	17	-21	30	9	45	-9	22	22	38	-13	51	-1	61	-10	58	-12	87			-9	28
VNIIM	0	21	-11	33	18	47	0	25	32	40	-4	53	8	62	0	59	-2	88	9	28		

Table 21 Degrees of equivalence 10 mV, 20 kHz

10 mV, 20 kHz			CRV		SP		JV		INRIM		PTB		VSL		BEV		OMH		INETI		CEM		MIRS/SIQ	
			δ_R	U_R	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}
			1	6	0	16	16	26	-13	16	3	15	-1	31	5	33	2	18	-1	56	1	40	-7	70
	δ_{id}	U_{id}	$\boldsymbol{D_{iE}}$	$\boldsymbol{U_{iE}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$
SP	0	16	-1	15			-16	31	13	23	-3	22	1	35	-5	36	-2	24	1	59	-1	44	7	72
JV	16	26	15	25	16	31			29	31	13	30	17	40	11	42	14	32	17	62	15	48	23	75
INRIM	-13	16	-14	15	-13	23	-29	31			-16	22	-12	35	-18	36	-15	25	-12	59	-14	44	-6	72
PTB	3	15	2	13	3	22	-13	30	16	22			4	34	-2	36	1	23	4	58	2	43	10	72
VSL	-1	31	-2	30	-1	35	-17	40	12	35	-4	34			-6	45	-3	36	0	64	-2	51	6	77
BEV	5	33	4	32	5	36	-11	42	18	36	2	36	6	45			3	37	6	65	4	52	12	77
OMH	2	18	1	19	2	24	-14	32	15	25	-1	23	3	36	-3	37			3	59	1	44	9	73
INETI	-1	56	-2	56	-1	59	-17	62	12	59	-4	58	0	64	-6	65	-3	59			-2	69	6	90
CEM	1	40	0	40	1	44	-15	48	14	44	-2	43	2	51	-4	52	-1	44	2	69			8	81
MIRS/SIQ	-7	70	-8	71	-7	72	-23	75	6	72	-10	72	-6	77	-12	77	-9	73	-6	90	-8	81		

Table 22 Degrees of equivalence 10 mV, 20 kHz

10 mV, 20 kHz			MIKES		DPLE		LNE		METAS		UME		NMISA		CMI		EIM		NPLI		VNIIM	
			δ_R	U_R	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}
			13	24	-21	41	11	17	-37	32	11	47	-13	57	6	59	2	80	-3	16	25	23
	δ_{id}	U_{id}	$\boldsymbol{D_{iE}}$	$\boldsymbol{U_{iE}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$
SP	0	16	-13	29	21	45	-11	24	37	36	-11	50	13	59	-6	61	-2	82	3	23	-25	28
JV	16	26	3	36	37	49	5	31	53	41	4	54	28	62	10	65	14	84	19	31	-9	35
INRIM	-13	16	-26	29	8	45	-24	24	24	36	-25	50	-1	59	-19	62	-15	82	-10	23	-38	28
PTB	3	15	-10	28	24	44	-8	22	40	35	-9	50	15	59	-3	61	1	82	6	22	-22	27
VSL	-1	31	-14	39	19	52	-13	35	36	44	-13	56	11	64	-7	67	-3	86	2	35	-26	38
BEV	5	33	-8	41	26	53	-6	37	42	45	-6	58	18	65	-1	68	3	87	8	36	-20	40
OMH	2	18	-11	30	22	45	-9	25	39	36	-10	51	14	60	-4	62	0	82	5	24	-23	29
INETI	-1	56	-14	61	20	70	-12	59	37	65	-12	74	12	80	-7	82	-3	98	2	59	-26	61
CEM	1	40	-12	47	22	58	-10	44	39	51	-10	62	14	70	-5	72	0	90	4	44	-24	47
MIRS/SIQ	-7	70	-20	74	14	82	-18	72	31	77	-18	85	-29	90	-13	92	-8	107	-4	72	-32	74

Table 23 Degrees of equivalence 10 mV, 20 kHz

10 mV, 20 kHz			CRV		SP		JV		INRIM		PTB		VSL		BEV		OMH		INETI		CEM		MIRS/SIQ	
			δ_R	U_R	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}
			1	6	0	16	16	26	-13	16	3	15	-1	31	5	33	2	18	-1	56	1	40	-7	70
	δ_{id}	U_{id}	$\boldsymbol{D_{iE}}$	$\boldsymbol{U_{iE}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$
MIKES	13	24	12	25	13	29	-3	36	26	29	10	28	14	39	8	41	11	30	14	61	12	47	20	74
DPLE	-21	41	-22	41	-21	45	-37	49	-8	45	-24	44	-19	52	-26	53	-22	45	-20	70	-22	58	-14	82
LNE	11	17	10	16	11	24	-5	31	24	24	8	22	13	35	6	37	9	25	12	59	10	44	18	72
METAS	-37	32	-38	31	-37	36	-53	41	-24	36	-40	35	-36	44	-42	45	-39	36	-37	65	-39	51	-31	77
UME	11	47	11	47	11	50	-4	54	25	50	9	50	13	56	6	58	10	51	12	74	10	62	18	85
NMISA	22	57	21	57	22	59	6	62	35	59	19	59	23	64	17	65	20	60	23	80	21	70	29	90
CMI	6	59	5	59	6	61	-10	65	19	62	3	61	7	67	1	68	4	62	7	82	5	72	13	92
EIM	2	80	1	80	2	82	-14	84	15	82	-1	82	3	86	-3	87	0	82	3	98	0	90	8	107
NPLI	-3	16	-4	15	-3	23	-19	31	10	23	-6	22	-2	35	-8	36	-5	24	-2	59	-4	44	4	72
VNIIM	25	23	24	22	25	28	9	35	38	28	22	27	26	38	20	40	23	29	26	61	24	47	32	74

Table 24 Degrees of equivalence 10 mV, 20 kHz

10 mV, 20 kHz			MIKES		DPLE		LNE		METAS		UME		NMISA		CMI		EIM		NPLI		VNIIM	
			δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}
			13	24	-21	41	11	17	-37	32	11	47	22	57	6	59	2	80	-3	16	25	23
	δ_{id}	U_{id}	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$
MIKES	13	24			34	48	2	30	50	40	1	53	-9	62	7	64	11	84	16	29	-12	33
DPLE	-21	41	-34	48			-32	45	17	52	-32	63	-42	70	-27	72	-22	90	-17	44	-45	47
LNE	11	17	-2	30	32	45			49	36	0	50	-11	59	5	62	10	82	15	23	-14	29
METAS	-37	32	-50	40	-17	52	-49	36			-49	57	-59	65	-44	67	-39	86	-34	35	-62	39
UME	11	47	-1	53	32	63	0	50	49	57			-10	74	5	76	10	93	15	50	-13	53
NMISA	22	57	9	62	42	70	11	59	59	65	10	74			16	82	20	98	25	59	-3	61
CMI	6	59	-7	64	27	72	-5	62	44	67	-5	76	-16	82			4	100	9	61	-19	64
EIM	2	80	-11	84	22	90	-10	82	39	86	-10	93	-20	98	-4	100			5	82	-23	83
NPLI	-3	16	-16	29	17	44	-15	23	34	35	-15	50	-25	59	-9	61	-5	82			-28	28
VNIIM	25	23	12	33	45	47	14	29	62	39	13	53	3	61	19	64	23	83	28	28		

Table 25 Degrees of equivalence 10 mV, 100 kHz

10 mV, 100 kHz			CRV		SP		JV		INRIM		PTB		VSL		BEV		OMH		INETI		CEM		MIRS/SIQ	
			δ_R	U_R	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}
			-4	8	0	20	24	68	-26	37	8	21	-7	35	3	39	-3	28	-4	65	4	60	-4	120
	δ_{id}	U_{id}	$\boldsymbol{D_{iE}}$	$\boldsymbol{U_{iE}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$
SP	0	20	4	18			-24	71	26	42	-8	29	7	40	-3	44	3	34	4	68	-4	63	4	122
JV	24	68	29	68	24	71			50	78	16	71	31	77	21	79	27	74	28	94	21	91	29	138
INRIM	-26	37	-22	37	-26	42	-50	78			-34	43	-19	51	-29	54	-23	47	-22	75	-30	71	-22	126
PTB	8	21	12	19	8	29	-16	71	34	43			15	41	5	44	11	35	12	68	4	64	12	122
VSL	-7	35	-3	34	-7	40	-31	77	19	51	-15	41			-10	53	-4	45	-3	74	-11	70	-3	125
BEV	3	39	7	39	3	44	-21	79	29	54	-5	44	10	53			6	48	7	76	-1	72	7	126
OMH	-3	28	1	27	-3	34	-27	74	23	47	-11	35	4	45	-6	48			1	71	-7	66	1	123
INETI	-4	65	0	66	-4	68	-28	94	22	75	-12	68	3	74	-7	76	-1	71			-8	89	0	137
CEM	4	60	8	60	4	63	-21	91	30	71	-4	64	11	70	1	72	7	66	8	89			8	134
MIRS/SIQ	-4	120	0	120	-4	122	-29	138	22	126	-12	122	3	125	-7	126	-1	123	0	137	-8	134		

Table 26 Degrees of equivalence 10 mV, 100 kHz

10 mV, 100 kHz			MIKES		DPLE		LNE		METAS		UME		NMISA		CMI		EIM		NPLI		VNIIM	
			δ_R	U_R	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}
			5	35	-26	62	1	22	-38	52	-14	54	8	136	7	80	45	86	-16	16	68	64
	δ_{id}	U_{id}	$\boldsymbol{D_{iE}}$	$\boldsymbol{U_{iE}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$
SP	0	20	-5	40	26	65	-1	29	38	56	14	58	-8	138	-7	83	-45	88	16	26	-68	67
JV	24	68	19	77	51	92	24	72	62	86	38	87	16	152	17	105	-21	110	41	70	-43	94
INRIM	-26	37	-31	51	1	73	-26	43	12	64	-12	66	-34	141	-33	88	-71	94	-9	41	-93	74
PTB	8	21	3	41	35	66	7	30	46	56	22	58	0	138	1	83	-37	89	25	26	-59	67
VSL	-7	35	-12	50	20	72	-8	41	31	63	7	65	-15	141	-14	88	-52	93	9	39	-75	73
BEV	3	39	-2	53	29	74	2	45	41	65	17	67	-5	142	-4	89	-42	95	19	43	-65	75
OMH	-3	28	-8	45	23	68	-4	35	35	59	11	61	-11	139	-10	85	-48	91	13	33	-71	70
INETI	-4	65	-9	74	22	90	-5	69	34	84	10	85	-12	151	-11	103	-49	108	12	67	-72	91
CEM	4	60	-1	70	30	87	3	64	42	80	18	81	-4	149	-3	100	-41	105	20	62	-64	88
MIRS/SIQ	-4	120	-9	125	22	135	-5	122	34	131	9	132	-12	182	-11	144	-49	148	12	121	-72	136

Table 27 Degrees of equivalence 10 mV, 100 kHz

10 mV, 100 kHz			CRV		SP		JV		INRIM		PTB		VSL		BEV		OMH		INETI		CEM		MIRS/SIQ	
			δ_R	U_R	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}
			-4	8	0	20	24	68	-26	37	8	21	-7	35	3	39	-3	28	-4	65	4	60	-4	120
	δ_{id}	U_{id}	D_{iE}	U_{iE}	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}
MIKES	5	35	9	36	5	40	-19	77	31	51	-3	41	12	50	2	53	8	45	9	74	1	70	9	125
DPLE	-26	62	-22	62	-26	65	-51	92	-1	73	-35	66	-20	72	-29	74	-23	68	-22	90	-30	87	-22	135
LNE	1	22	5	20	1	29	-24	72	26	43	-7	30	8	41	-2	45	4	35	5	69	-3	64	5	122
METAS	-38	52	-34	52	-38	56	-62	86	-12	64	-46	56	-31	63	-41	65	-35	59	-34	84	-42	80	-34	131
UME	-14	54	-9	54	-14	58	-38	87	12	66	-22	58	-7	65	-17	67	-11	61	-10	85	-18	81	-9	132
NMISA	8	136	12	136	8	138	-16	152	34	141	0	138	15	141	5	142	11	139	12	151	4	149	12	182
CMI	7	80	11	80	7	83	-17	105	33	88	-1	83	14	88	4	89	10	85	11	103	3	100	11	144
EIM	45	86	49	86	45	88	21	110	71	94	37	89	52	93	42	95	48	91	49	108	41	105	49	148
NPLI	-16	16	-12	14	-16	26	-41	70	9	41	-25	26	-9	39	-19	43	-13	33	-12	67	-20	62	-12	121
VNIIM	68	64	72	64	68	67	43	94	93	74	59	67	75	73	65	75	71	70	72	91	64	88	72	136

Table 28 Degrees of equivalence 10 mV, 100 kHz

10 mV, 100 kHz			MIKES		DPLE		LNE		METAS		UME		NMISA		CMI		EIM		NPLI		VNIIM	
			δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}
			5	35	-26	62	1	22	-38	52	-14	54	8	136	7	80	45	86	-16	16	68	64
	δ_{id}	U_{id}	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}
MIKES	5	35			31	72	4	41	43	63	19	65	-3	141	-2	88	-40	93	21	39	-63	73
DPLE	-26	62	-31	72			-27	66	12	81	-13	82	-34	150	-33	101	-71	106	-10	64	-94	89
LNE	1	22	-4	41	27	66			39	56	14	58	-7	138	-6	83	-44	89	17	27	-67	68
METAS	-38	52	-43	63	-12	81	-39	56			-24	75	-46	146	-45	96	-83	101	-22	55	-106	83
UME	-14	54	-19	65	13	82	-14	58	24	75			-22	147	-21	97	-59	102	3	57	-81	84
NMISA	8	136	3	141	34	150	7	138	46	146	22	147			1	158	-37	161	24	137	-60	151
CMI	7	80	2	88	33	101	6	83	45	96	21	97	-1	158			-38	118	23	82	-61	103
EIM	45	86	40	93	71	106	44	89	83	101	59	102	37	161	38	118			61	88	-23	107
NPLI	-16	16	-21	39	10	64	-17	27	22	55	-3	57	-24	137	-23	82	-61	88			-84	66
VNIIM	68	64	63	73	94	89	67	68	106	83	81	84	60	151	61	103	23	107	84	66		

Table 29 Degrees of equivalence 10 mV, 1 MHz

10 mV, 1 MHz			CRV		SP		JV		INRIM		PTB		VSL		BEV		OMH		INETI		CEM		MIRS/SIQ	
			δ_R	U_R	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}
			8	22	0	63	48	259	-101	122	25	53	-39	102	-9	129	-132	221	119	276	42	151	71	750
	δ_{id}	U_{id}	D_{iE}	U_{iE}	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}
SP	0	63	-8	59			-48	266	101	137	-25	82	39	120	9	143	132	230	-119	283	-42	164	-71	753
JV	48	259	40	258	48	266			149	286	23	264	87	278	57	289	180	340	-71	378	6	300	-23	794
INRIM	-101	122	-109	120	-101	137	-149	286			-126	133	-62	159	-92	177	30	252	-220	301	-143	194	-172	760
PTB	25	53	17	48	25	82	-23	264	126	133			64	115	34	139	157	227	-94	281	-17	160	-46	752
VSL	-39	102	-47	100	-39	120	-87	278	62	159	-64	115			-30	164	92	243	-158	294	-81	182	-110	757
BEV	-9	129	-17	127	-9	143	-57	289	92	177	-34	139	30	164			123	256	-128	304	-51	198	-80	761
OMH	-132	221	-140	220	-132	230	-180	340	-30	252	-157	227	-92	243	-123	256			-250	353	-174	268	-202	782
INETI	119	276	111	277	119	283	71	378	220	301	94	281	158	294	128	304	250	353			77	314	48	799
CEM	42	151	34	150	42	164	-6	300	143	194	17	160	81	182	51	198	174	268	-77	314			-29	765
MIRS/SIQ	71	750	63	751	71	753	23	794	172	760	46	752	110	757	80	761	202	782	-48	799	29	765		

Table 30 Degrees of equivalence 10 mV, 1 MHz

10 mV, 1 MHz			MIKES		DPLE		LNE		METAS		UME		NMISA		CMI		EIM		NPLI		VNIIM	
			δ_R	U_R	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}
			2	123	-86	194			-111	107	-11	111	-539	754	80	232	166	173	38	39	93	162
	δ_{id}	U_{id}	D_{iE}	U_{iE}	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}
SP	0	63	-2	139	86	204			111	124	11	127	539	756	-80	240	-166	184	-38	74	-93	174
JV	48	259	46	287	134	323			159	280	59	281	587	797	-32	347	-118	311	10	262	-45	306
INRIM	-101	122	-103	173	-15	229			10	162	-91	164	438	763	-181	262	-267	212	-139	128	-194	203
PTB	25	53	23	134	111	201			136	119	36	123	564	755	-55	238	-141	181	-12	66	-68	171
VSL	-39	102	-41	160	47	219			72	148	-28	150	500	760	-119	253	-205	201	-77	109	-132	192
BEV	-9	129	-11	178	77	233			102	167	2	170	530	764	-89	265	-175	216	-46	134	-102	207
OMH	-132	221	-133	253	-45	294			-20	245	-121	247	408	785	-212	320	-298	281	-169	224	-225	274
INETI	119	276	117	302	205	337			230	296	130	297	658	802	39	360	-47	325	81	278	26	320
CEM	42	151	40	195	128	246			153	185	53	187	581	769	-38	277	-124	230	5	156	-51	222
MIRS/SIQ	71	750	69	760	157	775			182	758	82	758	610	1063	-9	785	-95	770	33	751	-22	768

Table 31 Degrees of equivalence 10 mV, 1 MHz

10 mV, 1 MHz			CRV		SP		JV		INRIM		PTB		VSL		BEV		OMH		INETI		CEM		MIRS/SIQ	
			δ_{R}	U_{R}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}
			8	22	0	63	48	259	-101	122	25	53	-39	102	-9	129	-132	221	119	276	42	151	71	750
	δ_{id}	U_{id}	**D_{iE}**	**U_{iE}**	**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}**
MIKES	2	123	-6	125	2	139	-46	287	103	173	-23	134	41	160	11	178	133	253	-117	302	-40	195	-69	760
DPLE	-86	194	-94	193	-86	204	-134	323	15	229	-111	201	-47	219	-77	233	45	294	-205	337	-128	246	-157	775
LNE																								
METAS	-111	107	-119	104	-111	124	-159	280	-10	162	-136	119	-72	148	-102	167	20	245	-230	296	-153	185	-182	758
UME	-11	111	-19	108	-11	127	-59	281	91	164	-36	123	28	150	-2	170	121	247	-130	297	-53	187	-82	758
NMISA	-539	754	-547	754	-539	756	-587	797	-438	763	-564	755	-500	760	-530	764	-408	785	-658	802	-581	769	-610	1063
CMI	80	232	72	231	80	240	32	347	181	262	55	238	119	253	89	265	212	320	-39	360	38	277	9	785
EIM	166	173	158	174	166	184	118	311	267	212	141	181	205	201	175	216	298	281	47	325	124	230	95	770
NPLI	38	39	30	32	38	74	-10	262	139	128	12	66	77	109	46	134	169	224	-81	278	-5	156	-33	751
VNIIM	93	162	85	161	93	174	45	306	194	203	68	171	132	192	102	207	225	274	-26	320	51	222	22	768

Table 32 Degrees of equivalence 10 mV, 1 MHz

10 mV, 1 MHz			MIKES		DPLE		LNE		METAS		UME		NMISA		CMI		EIM		NPLI		VNIIM	
			δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}	δ_{jd}	U_{jd}
			2	123	-86	194			-111	107	-11	111	-539	754	80	232	166	173	38	39	93	162
	δ_{id}	U_{id}	**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}**
MIKES	2	123			88	230			113	163	12	166	541	764	-78	263	-164	213	-36	129	-91	204
DPLE	-86	194	-88	230					25	221	-75	223	453	778	-166	302	-252	260	-124	198	-179	253
LNE																						
METAS	-111	107	-113	163	-25	221					-100	154	428	761	-191	255	-277	203	-149	114	-204	194
UME	-11	111	-12	166	75	223			100	154			528	762	-91	257	-177	205	-48	117	-104	196
NMISA	-539	754	-541	764	-453	778			-428	761	-528	762			-619	788	-705	773	-577	755	-632	771
CMI	80	232	78	263	166	302			191	255	91	257	619	788			-86	289	43	235	-13	283
EIM	166	173	164	213	252	260			277	203	177	205	705	773	86	289			129	177	73	237
NPLI	38	39	36	129	124	198			149	114	48	117	577	755	-43	235	-129	177			-56	167
VNIIM	93	162	91	204	179	253			204	194	104	196	632	771	13	283	-73	237	56	167		

Appendix 2: Uncertainty budgets EURAMET.EM-K11 Draft B Report

SP, Sweden

JV, Norway

INRIM, Italy

PTB, Germany

VSL, The Netherlands

BEV, Austria

OMH, Hungary

INETI, Portugal

CEM, Spain

MIRS/SIQ, Slovenia

MIKES, Finland

DANIAmet-DPLE, Denmark

LNE, France

METAS, Switzerland (unsigned copy of original report)

UME, Turkey

NMISA, South Africa

CMI, Czech Republic

EIM, Greece

NPLI, India

VNIIM, Russia

Report on key comparison EURAMET.EM-K11

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Contents

Report on key comparison EURAMET.EM-K11 “Ac-dc voltage transfer difference at low voltages”

1 Introduction

As the pilot laboratory SP has monitored the stability of the travelling standard. The ac-dc difference of the travelling standard has been determined by comparison with the ac-dc transfer standards of SP at seven occasions from July 2005 to April 2008. The travelling standard was a Fluke 792A thermal transfer standard (TTS), serial number 5495 003, with amplified low voltage ranges 700 mV, 220 mV and 22 mV.

2 Ac-dc voltage transfer standards of SP

The ac-dc transfer difference at the reference voltage level is maintained by a group of multijunction thermal converters (MJTC) and high-frequency thermal voltage converters (HF-TVC). At the reference voltage level 2 V the realisation of ac-dc transfer difference at 1 kHz is made by the Fast Reversed DC method (FRDC) and at higher frequencies up to 1 MHz traceability is achieved by comparisons to PTB. The ac-dc transfer difference in the range 1 V to 200 mV is determined by a planar multijunction thermal converter (PMJTC), which has been calibrated by comparison with a MJTC at 1 V. From the 200 mV level to 10 mV the ac-dc transfer difference of a TTS is determined by a step-down procedure using micro potentiometers (uPot), [1] [2].

The ac-dc voltage transfer difference δ is defined as:

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

where

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

Differences are expressed in microvolt per volt (μV/V) and a positive sign signifies that more ac than dc voltage is required for the same output response.

3 Measuring system

The comparison of the PMJTC and F792 is made by an automated measuring system, Fig. 1, [3]. In the measuring system the inputs of the PMJTC and F792 are connected in parallel using type N T-connector with male output connectors. The ac-dc transfer difference of the F792 under test is measured with the centre of the T-connector as the reference plane.

The comparison of the uPot and F792 is also made by the same automated measuring system, slightly modified, Fig. 2. In the measuring system the uPot is connected directly to the input of the F792 type N-connector. Due to the step-down procedure the measured ac-dc transfer difference at voltages <200 mV of the F792 under test will also have the centre of a type N T-connector with male output connectors as the reference plane.

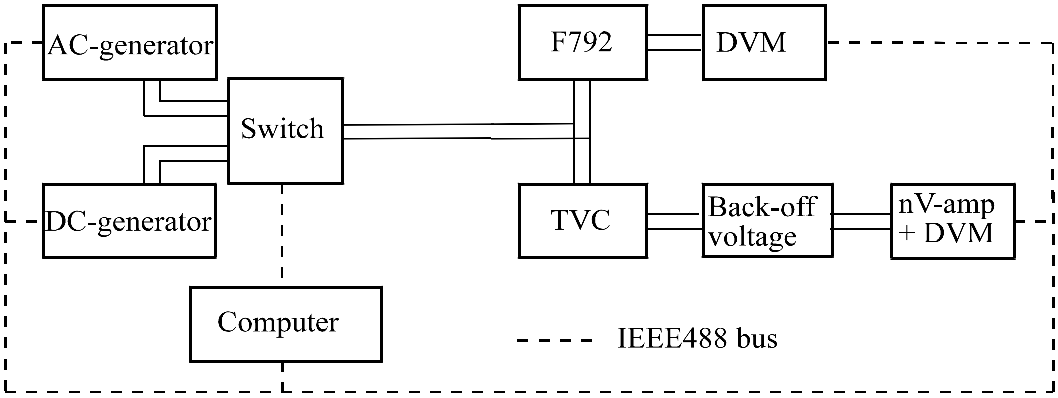

Fig. 1. Automated measuring system for comparison of Fluke 792A and PMJTC.

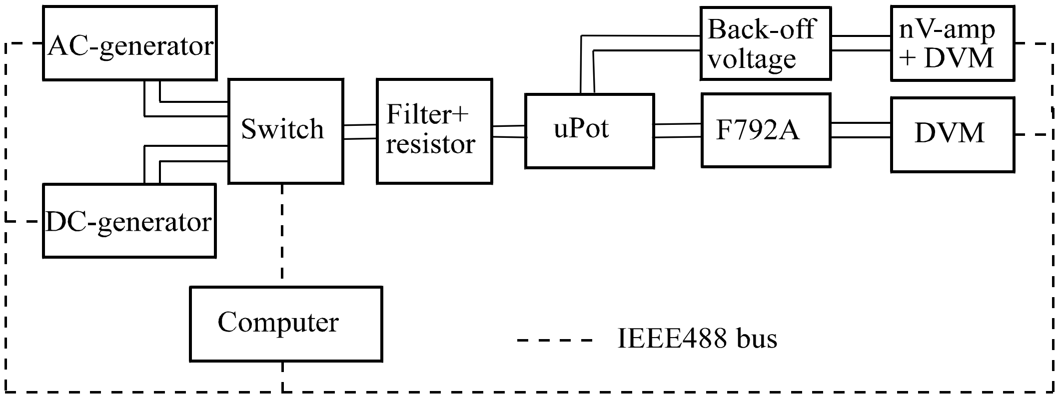

Fig. 2. Automated measuring system for comparison of micropotentiometer and Fluke 792A.

The measuring voltages are generated by an ac-voltage generator and a dc-voltage generator. The ac- and dc-voltages are applied by a switch with a switching time less than 1 ms. The switch is connected to the T-connector (or filter + resistor) via a coaxial choke, not shown in the figures. The measurement starts by determining the scale factors of the ac-dc transfer standards. At each frequency the RMS-value of the ac-voltage is then adjusted to within $1 \cdot 10^{-4}$ of the dc-voltage. Ac- and dc-voltage is applied consecutively and the differences between the output voltage of the PMJTC (or uPot) and the back-off voltage is amplified with nV-amplifier and measured by digital voltmeter. The output voltage of the F792 is measured directly by a DVM. The ac-dc transfer difference is determined by computation. In this comparison each measured value is the sum of the mean of seven ac(1 kHz)-dc transfer difference values and the mean of two ac-ac(1 kHz) transfer difference values.

Before the measurements starts the ac-dc transfer standards are warmed-up for more than 20 minutes. A stabilisation time related to the time constant of the ac-dc transfer standards is allowed after each switching. The stabilisation time 30 s is allowed for PMJTC, time constant 2 s, and 20 s for uPots, time constant 1,5 s. Errors in the measured values due to drift in the output voltages and the back-off voltages are minimised by using a symmetric measuring sequence: DC^{+}, AC, DC^{-}. Errors in the measured values due to instability of the input voltages are minimised by simultaneous triggering of the DVMs. The DVMs are connected to the IEEE 488-bus via opto interfaces.

4 Measuring conditions

The ac-dc difference of the travelling standard is measured at a voltage of 100 mV and 10 mV and frequencies 1 kHz, 20 kHz 100 kHz and 1 MHz. The ac-voltage was of practically sine wave form and the frequencies were nominal within $\pm 50 \cdot 10^{-6}$. The ambient temperature was $23{,}0 \pm 1{,}5\,^{o}C$ and the relative humidity 45±15 %. In the step-down with the MJTC and PMJTC involved the input low and the output low were connected to the centre of the T-connector which was the common ground point. The output of the MJTC and PMJTC had a large capacitive load. In the µPot step-down the common ground point was the connector between the µPot and TTS. The thermo-couple output low of the µPot was connected to the common ground point. The output low of the TTS is internally connected to the TTS input low. Care has been taken to keep the ambient space free from disturbing electromagnetic fields and draught and to avoid fast air pressure changes in the laboratory.

5 Measurements on the travelling standard

The ac-dc transfer difference of the travelling standard has been measured by comparison with the standards of SP at seven occasions. At the three first and the last comparison a complete step-down was made, which also calibrates the µPots (with the load of the travelling standard). The three intermediate comparisons have been made by direct calibration with uPots. At each occasion the measurements were repeated during three days to obtain three independent values. A summary of the results is given in table 1 and 2. The measured values have been corrected to the reference temperature 23˚C and relative humidity (RH) 45% using the temperature and RH coefficients and equations given in the technical protocol. Before the technical protocol was prepared the travelling standard was characterised in a similar way as the travelling standard used in the CCEM-K11 [4].

Table 1. Measured ac-dc transfer difference and expanded uncertainty of the travelling standard at 100 mV, 23˚C and 45% RH.

Mean date	Measured ac-dc transfer differences in µV/V at the frequency			
	1 kHz	20 kHz	100 kHz	1 MHz
2005-07-11	7,8	-6,4	19,3	24
2005-12-24	8,5	-7,7	19,4	31
2006-08-22	8,5	-6,9	18,9	26
2007-05-03	9,2	-7,1	19,2	34
2007-08-12	9,3	-6,4	19,8	31
2007-11-29	8,8	-7,0	19,5	24
2008-04-03	9,1	-6,0	21,1	32
Mean	8,7	-6,8	19,6	29
Exp. unc.	3,6	4,2	6,6	37

Table 2. Measured ac-dc transfer difference and expanded uncertainty of the travelling standard at 10 mV, 23˚C and 45% RH.

Mean date	Measured ac-dc transfer differences in µV/V at the frequency			
	1 kHz	20 kHz	100 kHz	1 MHz
2005-07-11	6	-10	-19	-147
2005-12-24	11	-12	-20	-144
2006-08-22	14	-9	-17	-139
2007-05-03	9	-14	-20	-161
2007-08-12	15	-12	-17	-139
2007-11-29	4	-15	-21	-155
2008-04-03	11	-8	-15	-158
Mean	10	-11	-19	-149
Exp. unc.	15	15	19	60

6 Uncertainty analysis of the voltage step-down procedure

The ac-dc transfer differences of the thermal transfer standard (TTS) with amplified mV-ranges are determined by a step-down procedure from the reference voltage level maintained by a group of multijunction thermal converters (MJTC) and high-frequency thermal voltage converters (HF-TVC). At the reference voltage level 2 V the realisation of ac-dc transfer difference at 1 kHz is made by the Fast Reversed DC method (FRDC) and at higher frequencies traceability is achieved by comparisons to PTB. The ac-dc transfer difference of the TTS at the 200 mV level is determined by comparison with planar multijunction thermal converters (PMJTC), which is calibrated by comparison with the MJTC. From the 200 mV level to 10 mV the ac-dc transfer difference of the TTS is determined by a step-down procedure using micro potentiometers (uPot). The ac-dc transfer difference of the TTS is in the step-down procedure determined at the current ambient temperature and relative humidity. The ac-dc transfer difference of the TTS is then corrected for the error due to the temperature coefficient and relative humidity coefficient of the TTS and the deviation from the nominal temperature and relative humidity. The model equations for the measurements of the different steps in the voltage step-down procedure are described below:

1. Comparison of PMJTC to MJTC

The measured ac-dc transfer difference δ_T of the test PMJTC at the voltage 1 V is determined as:

$$\delta_T = \delta_A + \delta_B + \delta_C + \delta_S + \delta_{LD} \qquad \text{(A1)}$$

where

- δ_A indicated ac-dc transfer difference between the standard MJTC and the test PMJTC
- δ_B correction for the error in the indicated ac-dc transfer difference due to the measurement set-up, except T-connector
- δ_C correction for the error in the indicated ac-dc transfer difference due to the T-connector
- δ_S ac-dc transfer difference of the standard MJTC
- δ_{LD} correction for the error in the ac-dc transfer difference of the standard MJTC due to level dependence

The variance of the measured ac-dc transfer difference $u^2(\delta_T)$ is

$$u^2(\delta_T) = u^2(\delta_A) + u^2(\delta_B) + u^2(\delta_C) + u^2(\delta_S) + u^2(\delta_{LD}) \qquad \text{(A2)}$$

2. Comparison of TTS to PMJTC

The measured ac-dc transfer difference δ_T of the test TTS at the voltage 0,2 V is determined as:

$$\delta_T = \delta_A + \delta_B + \delta_C + \delta_S + \delta_{LD} \qquad \text{(A3)}$$

where

- δ_A indicated ac-dc transfer difference between the standard PMJTC and the test TTS
- δ_B correction for the error in the indicated ac-dc transfer difference due to the measurement set-up, except T-connector
- δ_C correction for the error in the indicated ac-dc transfer difference due to the T-connector
- δ_S Ac-dc transfer difference of the standard PMJTC

δ_{LD} correction for the error in the ac-dc transfer difference of the standard PMJTC due to level dependence

The variance of the measured ac-dc transfer difference $u^2(\delta_T)$ is

$$u^2(\delta_T) = u^2(\delta_A) + u^2(\delta_B) + u^2(\delta_C) + u^2(\delta_S) + u^2(\delta_{LD}) \quad \text{(A4)}$$

3. Comparison of TTS at level V_1 to TTS at level V_2 via micropotentiometer, $V_2 < V_1$

The measured ac-dc transfer difference δ_T of the test TTS at the voltage level V_2 at current temperature and relative humidity is determined as:

$$\delta_T = \delta_{A1} + \delta_{B1} + \delta_{A2} + \delta_{B2} + \delta_S + \delta_{LD} + \delta_L \quad \text{(A5)}$$

where

δ_{A1} indicated ac-dc transfer difference between the standard TTS and the test uPot at level V_1

δ_{B1} correction for the error in the indicated ac-dc transfer difference due to the measurement set-up, uncorrelated to measurement 2

δ_{A2} indicated ac-dc transfer difference between the standard uPot and the test TTS at level V_2

δ_{B2} correction for the error in the indicated ac-dc transfer difference due to the measurement set-up, uncorrelated to measurement 1

δ_S ac-dc transfer difference of the standard TTS at level V_1

δ_{LD} correction for the error in the ac-dc transfer difference of the standard uPot due to level dependence

δ_L correction for the error in the ac-dc transfer difference of the standard uPot due to changes in loading

The variance of the measured ac-dc transfer difference $u^2(\delta_T)$ is

$$u^2(\delta_T) = u^2(\delta_{A1}) + u^2(\delta_{B1}) + u^2(\delta_{A2}) + u^2(\delta_{B2}) + u^2(\delta_S) + u^2(\delta_{LD}) + u^2(\delta_L) \quad \text{(A6)}$$

4. Correction of error due to temperature and relative humidity coefficient of TTS and T-connector reference plane

The measured ac-dc transfer difference δ_{yV} of the TTS at nominal temperature and relative humidity and at the centre of the T-connector is determined as:

$$\delta_{yV} = \delta_T + \delta_{TC} + \delta_{RH} + \delta_C \quad \text{(A7)}$$

where

δ_T measured ac-dc transfer difference the TTS at current ambient temperature

δ_{TC} correction for the error in the ac-dc transfer difference of the TTS due to the temperature coefficient

δ_{RH} correction for the error in the ac-dc transfer difference of the TTS due to the relative humitity coefficient

δ_C correction for the error in the ac-dc transfer difference of the TTS at the reference plane in the centre of the T-connector due to changes in the input capacitance of the TTS

The variance of the measured ac-dc transfer difference $u^2(\delta_{yV})$ is

$$u^2(\delta_{yV}) = u^2(\delta_T) + u^2(\delta_{TC}) + u^2(\delta_{RH}) + u^2(\delta_C) \quad \text{(A8)}$$

5. Uncertainty budget

Quantity	u	Standard uncertainties in μV/V at frequency			
		1 kHz	20 kHz	100 kHz	1 MHz
From 2 V to 1 V					
1:1 comparison					
Ac-dc difference MJTC 2 V	$u(\delta_S)$	0,5	0,7	1,6	6,0
Level dependence 2 V to 1 V	$u(\delta_{LD})$	0,1	0,1	0,1	0,1
Measurement set-up	$u(\delta_B)$	0,1	0,1	0,4	4
Indicated ac-dc difference	$u(\delta_A)$	0,2	0,2	0,3	1,0
T-connector	$u(\delta_C)$	0	0,1	0,3	2
Ac-dc diff PMJTC 1 V	$u(\delta_T)$	0,56	0,75	1,71	7,55
Standard uncertainty PMJTC 1 V	$\mathbf{u(\delta_{1V})}$	**0,6**	**0,8**	**1,8**	**7,6**
From 1 V to 0,2 V					
1:1 comparison					
Ac-dc diff PMJTC 1 V	$u(\delta_S)$	0,6	0,8	1,8	7,6
Level dependence 1 V to 0,2 V	$u(\delta_{LD})$	0,3	0,3	0,3	0,3
Measurement set-up	$u(\delta_B)$	0,5	0,5	0,7	3
Indicated ac-dc difference	$u(\delta_A)$	0,3	0,5	0,7	3
T-connector	$u(\delta_C)$	0	0,1	0,3	2
Temperature coefficient TTS	$u(\delta_{TC})$	0,3	0,3	0,4	4
RH coefficient TTS	$u(\delta_{RH})$	0,1	0,3	0,8	8
Ac-dc difference TTS 0,2 V	$u(\delta_T)$	0,94	1,19	2,28	12,64
Standard uncertainty 0,2 V	$\mathbf{u(\delta_{0,2V})}$	**1,0**	**1,2**	**2,3**	**12,7**
From 0,2 V to 0,1 V					
1:1 comparison					
Ac-dc difference TTS 0,2 V *	$u(\delta_S)$	0,89	1,11	2,10	8,94
Measurement set-up	$u(\delta_{B1})$	0,4	0,4	0,6	3
Indicated ac-dc difference	$u(\delta_{A1})$	0,3	0,5	0,7	3
Ac-dc difference uPot 0,2 V	$u(\delta_{T1})$	1,02	1,28	2,29	9,89
1:1 comparison					
Ac-dc difference uPot 0,2 V	$u(\delta_{S1})$	1,02	1,28	2,29	9,89
Level dependence 0,2 V to 0,1 V	$u(\delta_{LD})$	1	1	1	1
Loading of uPot	$u(\delta_L)$	0,3	0,6	1,2	12
Measurement set-up	$u(\delta_{B2})$	0,9	0,9	1,2	3,5
Indicated ac-dc difference	$u(\delta_{A2})$	0,3	0,5	0,7	3
Temperature coefficient TTS	$u(\delta_{TC})$	0,3	0,3	0,4	4
RH coefficient TTS	$u(\delta_{RH})$	0,1	0,3	0,8	8
T-connector reference plane	$u(\delta_C)$	0	0	0	0
Ac-dc difference TTS 0,1 V	$u(\delta_{T2})$	1,77	2,06	3,23	18,55
Standard uncertainty 0,1 V	$\mathbf{u(\delta_{0,1V})}$	**1,8**	**2,1**	**3,3**	**18,6**

* The uncertainty due to the temperature and relative humidity coefficient of the TTS and the T-connector reference plane is not forwarded to the next step.

Quantity	u	Standard uncertainties in µV/V at frequency			
		1 kHz	20 kHz	100 kHz	1 MHz
From 100 mV to 50 mV					
1:1 comparison					
Ac-dc difference TTS 100 mV *	$u(\delta_S)$	1,74	2,02	3,10	16,25
Measurement set-up	$u(\delta_{B1})$	0,5	0,5	0,7	3,5
Indicated ac-dc difference	$u(\delta_{A1})$	0,3	0,5	0,7	3
Ac-dc difference uPot 100 mV	$u(\delta_{T1})$	1,84	2,14	3,26	16,89
1:1 comparison					
Ac-dc difference uPot 100 mV	$u(\delta_{S1})$	1,84	2,14	3,26	16,89
Level dependence 100 mV to 50 mV	$u(\delta_{LD})$	1	1	1	1
Loading of uPot	$u(\delta_L)$	0,1	0,3	0,6	3
Measurement set-up	$u(\delta_{B2})$	1,1	1,1	1,5	3,5
Indicated ac-dc difference	$u(\delta_{A2})$	1	1	1,2	3
Temperature coefficient TTS	$u(\delta_{TC})$	0,3	0,3	0,4	4
RH coefficient TTS	$u(\delta_{RH})$	0,1	0,3	0,8	8
T-connector reference plane	$u(\delta_C)$	0	0	0	0
Ac-dc difference TTS 50 mV	$u(\delta_{T2})$	2,59	2,84	4,06	19,91
Standard uncertainty 50 mV	$\mathbf{u(\delta_{50mV})}$	**2,6**	**2,9**	**4,1**	**20,0**
From 50 mV to 20 mV					
1:1 comparison					
Ac-dc difference TTS 50 mV *	$u(\delta_S)$	2,57	2,81	3,96	17,79
Measurement set-up	$u(\delta_{B1})$	0,8	0,8	1	3,5
Indicated ac-dc difference	$u(\delta_{A1})$	1	1	1,2	3
Ac-dc difference uPot 50 mV	$u(\delta_{T1})$	2,87	3,08	4,25	18,38
1:1 comparison					
Ac-dc difference uPot 50 mV	$u(\delta_{S1})$	2,87	3,08	4,25	18,38
Level dependence 50 mV to 20 mV	$u(\delta_{LD})$	1	1	1	1
Loading of uPot	$u(\delta_L)$	0,1	0,3	0,6	6
Measurement set-up	$u(\delta_{B2})$	2,2	2,2	3	8
Indicated ac-dc difference	$u(\delta_{A2})$	2	2	2,5	4
Temperature coefficient TTS	$u(\delta_{TC})$	0,7	0,7	0,7	6
RH coefficient TTS	$u(\delta_{RH})$	0,1	0,3	0,8	6
T-connector reference plane	$u(\delta_C)$	0	0	0,1	3
Ac-dc difference TTS 20 mV	$u(\delta_{T2})$	4,31	4,47	5,99	23,15
Standard uncertainty 20 mV	$\mathbf{u(\delta_{20mV})}$	**4,4**	**4,5**	**6,0**	**23,2**

* The uncertainty due to the temperature and relative humidity coefficient of the TTS and the T-connector reference plane is not forwarded to the next step.

Quantity	u	Standard uncertainties in µV/V at frequency			
		1 kHz	20 kHz	100 kHz	1 MHz
From 20 mV to 10 mV					
1:1 comparison					
Ac-dc difference TTS 20 mV *	$u(\delta_S)$	4,25	4,41	5,89	21,33
Measurement set-up	$u(\delta_{B1})$	1,8	1,8	2,2	8
Indicated ac-dc difference	$u(\delta_{A1})$	2	2	2,5	4
Ac-dc difference uPot 20 mV	$u(\delta_{T1})$	5,03	5,17	6,77	23,13
1:1 comparison					
Ac-dc difference uPot 20 mV	$u(\delta_{S1})$	5,03	5,17	6,77	23,13
Level dependence 20 mV to 10 mV	$u(\delta_{LD})$	2	2	2	2
Loading of uPot	$u(\delta_L)$	0	0	0	4
Measurement set-up	$u(\delta_{B2})$	3,7	3,7	5	16
Indicated ac-dc difference	$u(\delta_{A2})$	3	3	3	4
Temperature coefficient TTS	$u(\delta_{TC})$	0,7	0,7	0,7	6
RH coefficient TTS	$u(\delta_{RH})$	0,1	0,3	0,8	6
T-connector reference plane	$u(\delta_C)$	0	0	0,1	3
Ac-dc difference TTS 10 mV	$u(\delta_{T2})$	7,25	7,35	9,22	30,13
Standard uncertainty 10 mV	**$u(\delta_{10mV})$**	**7,3**	**7,4**	**9,3**	**30,2**

* The uncertainty due to the temperature and relative humidity coefficient of the TTS and the T-connector reference plane is not forwarded to the next step.

6. Summary

Expanded uncertainty and degrees of freedom of the travelling standard at 100 mV and 10 mV

		1 kHz	**20 kHz**	**100 kHz**	**1 MHz**
Expanded uncertainty 100 mV	**U = 2u**	**3,6**	**4,2**	**6,6**	**37**
Expanded uncertainty 10 mV	**U = 2u**	**15**	**15**	**19**	**60**
Degrees of freedom 100 mV		**>80**	**>80**	**>80**	**>80**
Degrees of freedom 10 mV		**>35**	**>35**	**>35**	**>35**

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Euromet.EM-K11

AC-DC voltage transfer differences at low voltages

Report from Justervesenets participation

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Introduction

The purpose of this comparison was to verify the agreement between European national measurement institutes in the field of low voltage AC-DC transfer (10 and 100 mV) in the frequency range from 1 kHz to 1 MHz.

The most common problem in this measurement range is to account correctly for the loading of the unit under test on the reference standard and the level dependence of the reference standards. The input impedance of the unit under test has to be measured and corrected for, to obtain the lowest uncertainties.

The relative AC-DC transfer difference δ is defined as:

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

where: V_{ac} is the rms value of the applied AC-voltage
V_{dc} is the mean value of the positive and negative DC-voltage which produce the same output voltage of the converter as V_{ac}

Set-up and measurement procedure

The methods used were the same as described by Oldham[1], Filipski[2] and Rydler[3].

The Fluke 792A Thermal Transfer Standard (TTS) was calibrated using three different standards for both voltage levels: using micropotentiometers[4] (MPOTs) with single junction thermal converters (sjtc's), using planar multi junction thermal converters[5] (pmjtc's) with dividers[3] and using pmjtc's[5] with commercial high frequency coaxial attenuators[1].

When the MPOTs were used, the TTS was connected in series with the MPOT. The outputs from the MPOT and the TTS were measured with nV-meters in the digital bridge configuration[6]. To be able to use the voltage source at it's most stable range, the input voltage to the MPOTs were scaled down with a coaxially mounted film resistor mounted in series, when measurements were performed at the 10 mV level.

When the resistive dividers and attenuators were used, the dividers were connected in parallel with pmjtc's. The TTS was then connected to the output from the dividers. The outputs were again measured with nV-meters in the digital bridge configuration[6].

The digital bridge works as described below.

First, the scale factors or sensitivities of the two channels are established from a series of measurements made with 1kHz ACV at levels +0.5% and -0.5% away from the nominal level to be used. A set of 13 measurements is made, and a curve-fitting algorithm applied to compensate for temperature drift and offset in the detectors. The scale factors are used to convert the data collected during the AC-DC transfer run into input voltage units.

Next, for each frequency, the ACV-supply is adjusted to within $\pm 25 \cdot 10^{-6}$ of the DCV-supply as indicated by the standard thermal converter. The AC-DC difference is then determined from a series of 13 measurements made at uniform time intervals, the drive to the transfer devices being switched by a relay box. This is to keep the temperature of the converters as constant as possible. For each reading the two digital voltmeters are triggered simultaneously by the computer. The 13 pair of readings are first converted to input units using the scale factors. The algebraic difference of these new values is then calculated. The curve fitting process[1] is then applied to this set of differences and the difference in AC-DC difference between the two converters calculated. The set of 13 pair of readings give several degrees of freedom in the determination of the difference in the AC-DC difference, and a standard deviation in the difference is calculated. The absolute difference of the test converter is calculated from the measured difference and the known absolute difference of the standard.

A set of 13 measurements as described above is defined as "one run" in this report. Several runs can be made for each measurement of scale factors, since the voltage is applied constantly to the converters between and during each run.

The input impedances of the TTS were measured with a precision RCL-meter.

Traceability and calibration of the standards used

The values of the reference standards for δ at 10 mV and 100 mV were obtained in three different ways:

1. Step-down from ~1 V to ~10 mV, using MPOTs. At ~1V the standards used are traceable to PTB (pmjtcs). The step-down was performed with a commercial set of Ballantine 1251/1351 MPOTs used in combination with JVs own Fluke 792A TTS. The principles for the step-down have been described by several authors elsewhere[2,3]. Some level dependencies in the current AC-DC differences of the sjtcs in the MPOTs have been found using a fast reversed DC-source and from comparison with pmjtcs. The values of the AC-DC differences in the MPOTs have been corrected for this effect. Possible level dependencies in the AC-DC differences of the annular resistors are taken into account in the uncertainty budget. Comparisons between pairs of MPOTs with different ranges are always performed at the highest possible voltage, given by the MPOT with the smaller voltage range. The input impedances of the JV TTS used have been measured both with a commercial RCL-meter and the “insertion method” described by Oldham[1].
2. From the calibration of the pmjtcs and the resistive dividers. The pmjtcs are traceable to PTB and the resistive dividers to SP.
3. From the calibration of the pmjtcs and the assumption that the AC-DC differences of the commercial attenuators (Hewlett Packard model 8491A) dividers are negligible in the DC to 1 MHz range. The pmjtcs are traceable to PTB.

The estimated uncertainties of the standards and the step-down procedure to 10 mV are given in table 1. These values are for method 1 above and are used as the uncertainties for the standards for δ in the measurements on the audit TTS. A schematic of the step-down is given in figure 1.

Influence quantity	Standard uncertainties in µV/V at the frequencies (in Hz)			
	1 000	20 000	100 000	1 000 000
0.2V level				
Uncertainty of standard at 1-2V (from CCEM-K6a)	0.5	0.5	1.0	5.0
Uncertainty of comparator measurements	2.8	3.0	3.5	4.1
pmjtc level dependence unc., 100% to 20% of range	0.3	0.3	0.3	0.3
Standard uncertainty 0.2V with TTS	**2.9**	**3.1**	**3.6**	**6.5**
0.2V level				
Uncertainty of standard at 0.2V	2.9	3.1	3.6	6.5
Uncertainty of comparator measurements	2.8	3.0	3.5	4.1
MPOT(sjtc) level dependence unc.	0.0	0.0	0.0	0.0
Uncertainty of loading correction	0.0	1.0	2.0	20.0
Standard uncertainty 0.2V with MPOT	**4.0**	**4.4**	**5.4**	**21.4**
0.1V level				
Uncertainty of standard at 0.2V	4.0	4.4	5.4	21.4
Uncertainty of comparator measurements	2.8	3.0	3.5	4.1
MPOT level dep.unc., 10 mA TCC	1.3	1.3	1.3	1.3
Level dep.unc. 22ohm disc resistor	2.0	2.0	4.0	8.0
Uncertainty of loading correction	0.0	1.0	2.0	20.0
Standard uncertainty 0.1V	**5.5**	**5.9**	**7.9**	**30.7**
0.1V level				
Uncertainty of standard at 0.1V	5.5	5.9	7.9	30.7
Uncertainty of comparator measurements	2.8	3.0	3.5	4.1
MPOT(sjtc) level dependence unc.	0.0	0.0	0.0	0.0
Uncertainty of loading correction	0.0	1.0	2.0	20.0
Standard uncertainty 0.1V with MPOT	**6.2**	**6.7**	**8.9**	**36.9**
0.05V level				
Uncertainty of standard at 0.1V	6.2	6.7	8.9	36.9
Uncertainty of comparator measurements	2.8	3.0	3.5	4.1
MPOT level dep.unc., 5 mA TCC	0.6	0.6	0.6	0.6
Level dep.unc. 22ohm disc resistor	1.5	1.5	3.0	6.0
Uncertainty of loading correction	0.0	1.0	2.0	20.0
Standard uncertainty 0.05V	**7.0**	**7.6**	**10.2**	**42.6**
0.05V level				
Uncertainty of standard at 0.05V	7.0	7.6	10.2	42.6
Uncertainty of comparator measurements	2.8	3.0	3.5	4.1
MPOT level dependence unc.	0.0	0.0	0.0	0.0
Uncertainty of loading correction	0.0	0.1	0.5	5.0
Standard uncertainty 0.05V with MPOT	**7.5**	**8.2**	**10.8**	**43.1**
0.025V level				
Uncertainty of standard at 0.05V	7.5	8.2	10.8	43.1
Uncertainty of comparator measurements	2.8	3.0	3.5	4.1
MPOT level dep.unc., 15 mA TCC	1.0	1.0	1.0	1.0
Level dep.unc. 3ohm disc resistor	2.5	2.5	5.0	10.0
Uncertainty of loading correction	0.0	0.1	0.5	5.0
Standard uncertainty 0.025V	**8.5**	**9.1**	**12.4**	**44.7**
0.025V level				
Uncertainty of standard at 0.025V	8.5	9.1	12.4	44.7
Uncertainty of comparator measurements	2.8	3.0	3.5	4.1
MPOT level dependence unc.	0.0	0.0	0.0	0.0
Uncertainty of loading correction	0.0	0.5	1.0	7.0
Standard uncertainty 0.025V with MPOT	**8.9**	**9.6**	**12.9**	**45.4**
0.013V level				
Uncertainty of standard at 0.025V	8.9	9.6	12.9	45.4
Uncertainty of comparator measurements	2.8	3.0	3.5	4.1
MPOT level dep.unc., 10 mA TCC	1.3	1.3	1.3	1.3
Level dep.unc. 3ohm disc resistor	2.0	2.0	4.0	8.0
Uncertainty of loading correction	0.0	0.5	1.0	7.0
Standard uncertainty 0.013V	**9.7**	**10.3**	**14.1**	**46.8**
0.013V level				
Uncertainty of standard at 0.013V	9.7	10.3	14.1	46.8
Uncertainty of comparator measurements	2.8	3.0	3.5	4.1
MPOT level dependence unc.	0.0	0.0	0.0	0.0
Uncertainty of loading correction	0.0	0.5	0.5	2.0
Standard uncertainty 0.013V with MPOT	**10.1**	**10.8**	**14.5**	**47.1**
0.010V level				
Uncertainty of standard at 0.013V	10.1	10.8	14.5	47.1
MPOT level dep.unc., 25 mA TCC	0.9	0.9	0.9	0.9
Level dep.unc. 0.5ohm disc resistor	2.0	2.0	4.0	8.0
Standard uncertainty 0.010V	**10.3**	**11.0**	**15.1**	**47.8**

Table 1 **Estimated uncertainties in the AC-DC transfer standards and the step-down to 10 mV for k=1.**

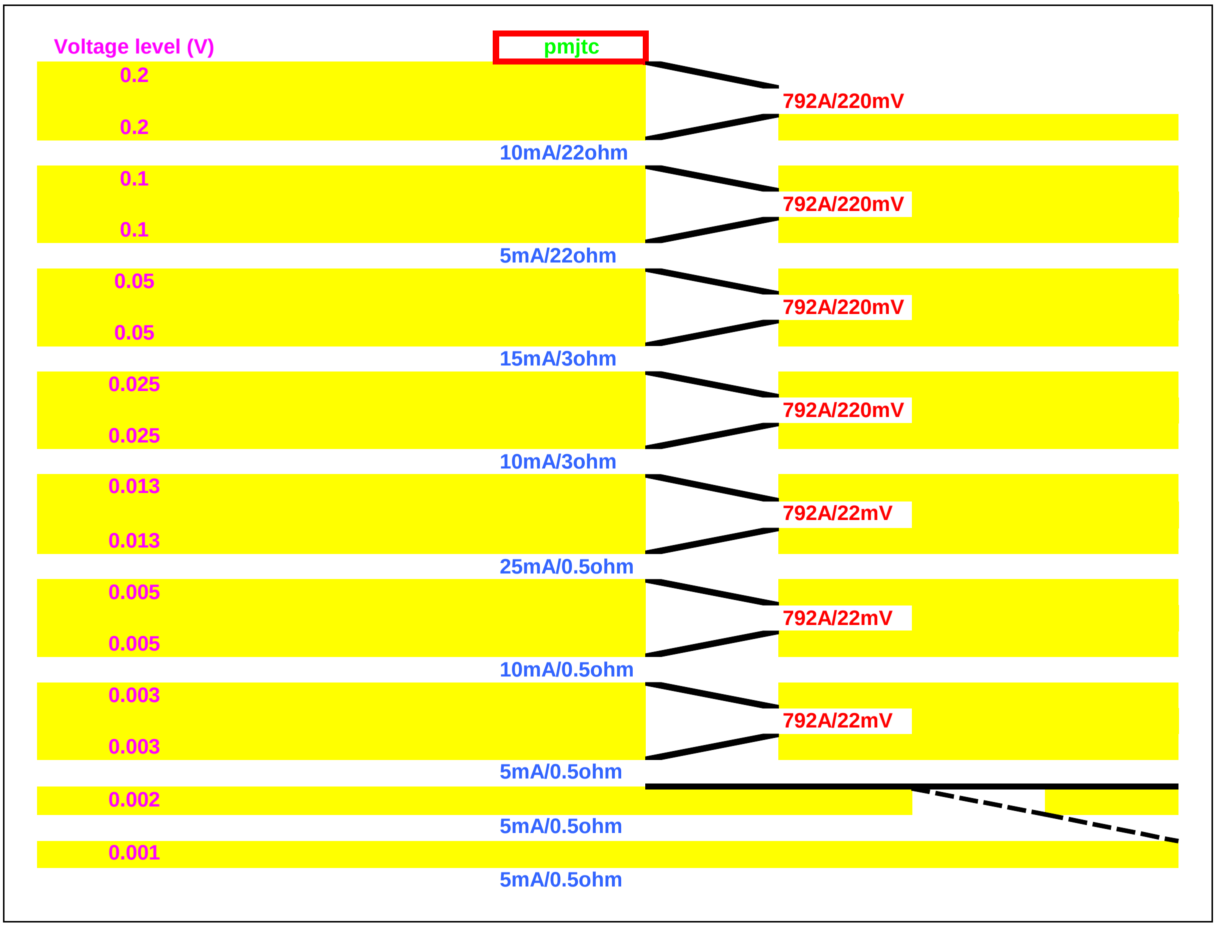

Figure 1 **Schematic of the step-down procedure with micropotentiometers (method 1).**

Results and uncertainties

The measured AC-DC differences and the corresponding uncertainties of the audit TTS are given in table 2.

The estimated uncertainties of the standards at 10 and 100 mV were given in table 1 in the previous chapter.

The uncertainty budget for the measurement on the audit TTS are given in table 3 below. The number of effective degrees of freedom is high because each “run” (see “Set-up and measurements”) has seven degrees of freedom and several runs were performed for each frequency and voltage combination.

The values of the influence parameters are given in appendix 1, which is also the filled-in summary report.

Appendix 2 is a summary of the uncertainty budget, as requested in the technical protocol.

	10 mV		100 mV	
	δabs	u (k=1)	δabs	u (k=1)
1 kHz	13	11	7.4	6.8
20 kHz	5	12	-7.3	7.5
100 kHz	5	34	22	14
1 MHz	-95	129	57	52

Table 2 Measured AC-DC differences of the audit TTS from at 10 mV and 100 mV. All AC-DC differences and uncertainties are in μV/V.

Influence quantity	Standard uncert.at frequency (in Hz)					Probability distrib. / method	Sensitivity	Uncertainty at frequency (in Hz)				Degrees of
Xi	u(xi)	u(xi)	u(xi)	u(xi)	Units	of evaluation	coefficient	ui(δ)	ui(δ)	ui(δ)	ui(δ)	Freedom
	1 000	20 000	100 000	1 000 000	--	--	ci	1 000	20 000	100 000	1 000 000	
0.1V level												
Uncertainty of standard at 0.1V	6.2	6.7	8.9	36.9	μV/V	Gaussian / B	1	6.2	6.7	8.9	36.9	Infinite
Uncertainty of comparator measurements	2.8	3.0	3.5	4.1	μV/V	Gaussian / B	1	2.8	3.0	3.5	4.1	Infinite
Uncertainty of loading correction	0.0	1.0	2.0	20.0	μV/V	Gaussian / B	1	0.0	1.0	2.0	20.0	Infinite
Uncertainty due to incorrect ref.plane	0.0	0.0	10.0	30.0	μV/V	Square / B	1	0.0	0.0	10.0	30.0	Infinite
Std.dev. of mean	0.4	0.7	0.6	0.5	μV/V	Gaussian / A	1	0.4	0.7	0.6	0.5	> 100
Standard uncertainty 0.1V					μV/V			**6.8**	**7.5**	**14**	**52**	**>1*10^{5}**
Expanded uncertainty 0.1V, k=2					μV/V			**14**	**15**	**28**	**103**	
Influence quantity	Standard uncert.at frequency (in Hz)					Probability distrib. / method	Sensitivity	Uncertainty at frequency (in Hz)				Degrees of
Xi	u(xi)	u(xi)	u(xi)	u(xi)	Units	of evaluation	coefficient	ui(δ)	ui(δ)	ui(δ)	ui(δ)	Freedom
	1 000	20 000	100 000	1 000 000	--	--	ci	1 000	20 000	100 000	1 000 000	
0.010V level												
Uncertainty of standard at 0.010V	10.3	11.0	15.1	47.8	μV/V	Gaussian / B	1	10.3	11.0	15.1	47.8	Infinite
Uncertainty of comparator measurements	2.8	3.0	3.5	4.1	μV/V	Gaussian / B	1	2.8	3.0	3.5	4.1	Infinite
Uncertainty of loading correction	0.0	0.5	0.5	2.0	μV/V	Gaussian / B	1	0.0	0.5	0.5	2.0	Infinite
Uncertainty due to incorrect ref.plane	0.0	0.0	30.0	120.0	μV/V	Square / B	1	0.0	0.0	30.0	120.0	Infinite
Std.dev. of mean	2.3	4.6	4.1	5.8	μV/V	Gaussian / A	1	2.3	4.6	4.1	5.8	> 100
Standard uncertainty 0.01V					μV/V			**11**	**12**	**34**	**129**	**>1*10^{5}**
Uncertainty 0.01V, k=2					μV/V			**22**	**25**	**68**	**259**	

Table 3 Uncertainty budget for the measured AC-DC differences at 10 and 100 mV.

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Appendix 1. Summary of results

Key comparison CCEM-K11 “ac-dc voltage transfer difference at low voltages”

Institute: **Justervesenet, National standards laboratory**

Date of measurements: **01.08.2005 – 30.08.2005**

Remarks:

Measuring result:

Voltage	Range	Measured ac-dc voltage difference / 10^{-6} at frequency			
		1 kHz	20 kHz	100 kHz	1 MHz
100 mV	220 mV	7	-7	22	57
10 mV	22 mV	13	5	5	-95

Expanded uncertainty:

Voltage	Range	Expanded uncertainty / 10^{-6} at frequency			
		1 kHz	20 kHz	100 kHz	1 MHz
100 mV	220 mV	14	15	28	104
10 mV	22 mV	22	25	68	258

Measuring frequency:

	Nominal frequency			
	1 kHz	20 kHz	100 kHz	1 MHz
Measuring frequency	1 000 Hz	20 000 Hz	99 999 Hz	999 991 Hz
Expanded uncertainty	<1 Hz	<1 Hz	< 1 Hz	<1 Hz

Influence parameters:

	Min	Max	Remarks
Ambient temperature / ºC	22.3	22.7	Reported results corrected to 23ºC
Relative humidity / %	37.7	41.9	Reported results corrected to 45%RH
Power supply voltage / V – Positive	11.092	11.101	
Power supply voltage / V – Negative	-11.163	-11.155	

Appendix 2. Summary of uncertainty budget

Key comparison CCEM-K11 “ac-dc voltage transfer difference at low voltages”

Institute: **Justervesenet**

Date: **01.08.2005 – 30.08.2005**

Remarks:

Measuring voltage: 100 mV

Contribution of:	Std. unc. f: 1 kHz	Std. unc. f: 20 kHz	Std. unc. f: 100 kHz	Std. unc. f: 1 MHz	Type A or B	Distri-bution
Standards	6.2	6.7	8.9	36.9	B	Gauss.
Comparator meas. (includes temp, humid., etc.)	2.8	3.0	3.5	4.1	B	Gauss.
Loading correction	0.0	1.0	2.0	20.0	B	Gauss.
Incorrect ref.plane	0.0	0.0	10.0	30.0	B	Square
Std.dev.mean	0.4	0.7	0.6	0.5	A	Gauss.

Standard unc (k=1):	6.8	7.5	14	52
Expanded unc:	14	15	28	104

Measuring voltage: 10 mV

Contribution of:	Std. unc. f: 1 kHz	Std. unc. f: 20 kHz	Std. unc. f: 100 kHz	Std. unc. f: 1 MHz	Type A or B	Distri-bution
Standards	10.3	11.0	15.1	47.8	B	Gauss.
Comparator meas. (includes temp, humid., etc.)	2.8	3.0	3.5	4.1	B	Gauss.
Loading correction	0.0	0.5	0.5	2.0	B	Gauss.
Incorrect ref.plane	0.0	0.0	30.0	120.0	B	Square
Std.dev.mean	2.3	4.6	4.1	5.8	A	Gauss.

Standard unc (k=1):	11	12	34	129
Expanded unc:	22	24	68	258

Istituto Nazionale di Ricerca Metrologica (I.N.RI.M)

U. POGLIANO, G. C. BOSCO

International comparison EUROMET.EM-K11
Report of the measurements at I.N.RI.M.

Torino, 23th February 2006

The Responsible for the Measurements
At I.N.RI.M.

(Ing. Umberto Pogliano)

1. GENERAL INFORMATION

This report describes the method and the results of the measurements performed at I.N.RI.M. from the 3rd of October to the 26th of October 2005 as part of the international comparison EUROMET.EM-K11.

The tested device has been a:

Multirange thermal transfer standard

Manufacturer:	Fluke
Model:	792A
Serial number:	5495 003
Nominal voltage:	Measured in the ranges 220 mV and 22 mV

The measured parameter is the ac-dc transfer difference δ defined as:

$$\delta = \frac{U_{ac} - U_{dc}}{U_{dc}} \tag{1}$$

where:

U_{ac} is the rms value of the ac input voltage

U_{dc} is the dc input voltage which when reversed produces the same mean output voltage of the transfer standard as U_{ac}.

2. DESCRIPTION OF THE MEASURING METHOD

2.1. Evaluation of the ac-dc transfer difference of the travelling standard

The ac-dc transfer difference of the travelling standard has been evaluated in the following ways.

Voltage of 100 mV

The input of multirange thermal transfer standard (the travelling standard) has been connected in parallel by means of a T-connector with a calibrated single-junction thermal converter of the I.N.RI.M. working standard having a nominal voltage of 250 mV. Ac and dc voltages in the proper sequence have been applied and the variations of respectively the output voltage of multirange thermal transfer standard and the output electromotive force of the single-junction thermal converter have been measured using the method described in detail in the following paragraph.

Voltage of 10 mV

A calibrated resistive voltage divider with a nominal ratio $\boldsymbol{r}$ = 0.1 and the multirange ac-dc transfer standard have been connected in cascade in one side of a T-connector. In the other side is connected a calibrated single-junction thermal converter of the I.N.RI.M. working standards, having a nominal voltage of 0.1 V. As in the previous point ac and dc voltages in the proper sequence have been applied and the variations of the outputs have been measured.

The ac-dc transfer difference of the ac-dc transfer standard $\delta_{tr\text{-}st}$ is related to that at the input of the cascade connection δ_{in}, which is measured by the usual measurement methods, by the following relation:

$$\delta_{tr-st} = \frac{r_{ac}}{r_{dc}} \cdot \delta_{in} + \frac{r_{ac} - r_{dc}}{r_{dc}} \cong \delta_{in} + \frac{r_{ac} - r_{dc}}{r_{dc}} \tag{2}$$

where $\boldsymbol{r_{ac}}$ and $\boldsymbol{r_{dc}}$ are respectively the ratio in ac and in dc.

2.2. Measurement system

The measurement system used for the comparisons is described in [1]. This system can be used in a wide range of comparisons from 1 mV to 1000 V.

The system includes two sub-systems automatically driven by a computer.

The supplying system

The basic circuit of the supplying system is drawn in Fig. 1. After a proper configuration, it produces the suitable voltages to the inputs of the converters. These signals are available on a voltage node where the output and the sense terminals of an ac calibrator or those of a dc calibrator, selected by a switch, are connected.

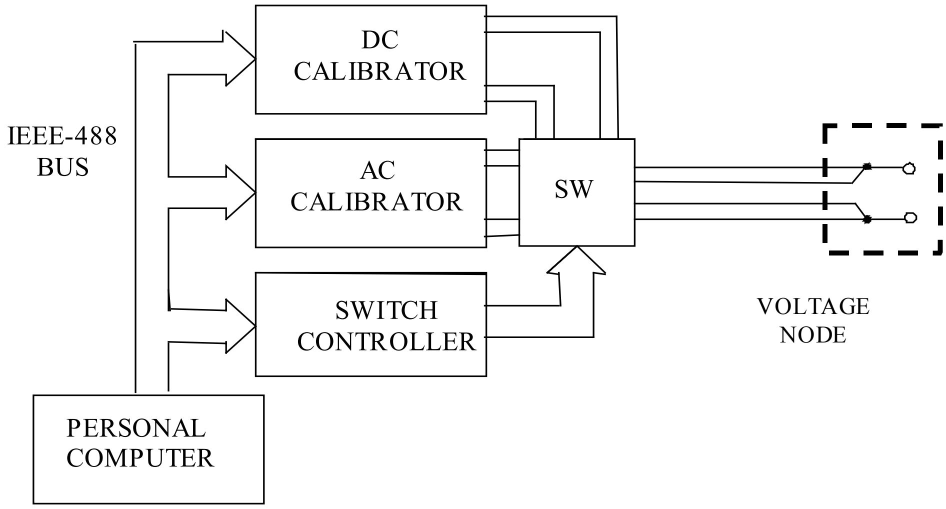

Fig. 1 *Basic circuit of the voltage generating system.*

The system utilises the dc calibrator Datron mod. 4000 and the ac calibrator Datron mod. 4200. The output of the dc calibrator can supply voltages with both polarities. The ac and the dc calibrator can be controlled either from the front panel or by a computer through the IEEE-488 bus.

The switching system is made up of a switch unit and a control unit. To reduce the capacitive load, the switch unit is directly plugged into the output connector of the ac calibrator. Each sense of both calibrators can be shorted to its output or connected to the voltage node by means of two position relays. The control unit of the switch includes a general purpose IEEE-488 interface and two specially designed cards and can be controlled either manually or by a computer.

The voltage signal from the switched calibrators is applied by means of a 50 Ω coaxial cable (RG-58) and a high frequency choke, built by winding 16 turns of cable around a core of amorphous magnetic material. For supplying to the instruments under measurement voltages lower than 0.5 V to a resistive voltage divider is utilised. The connection scheme from the calibrator to the amplifier and the T-connector (a Suhner connector with both symmetric sides made with N-female) is represented in Fig. 2.

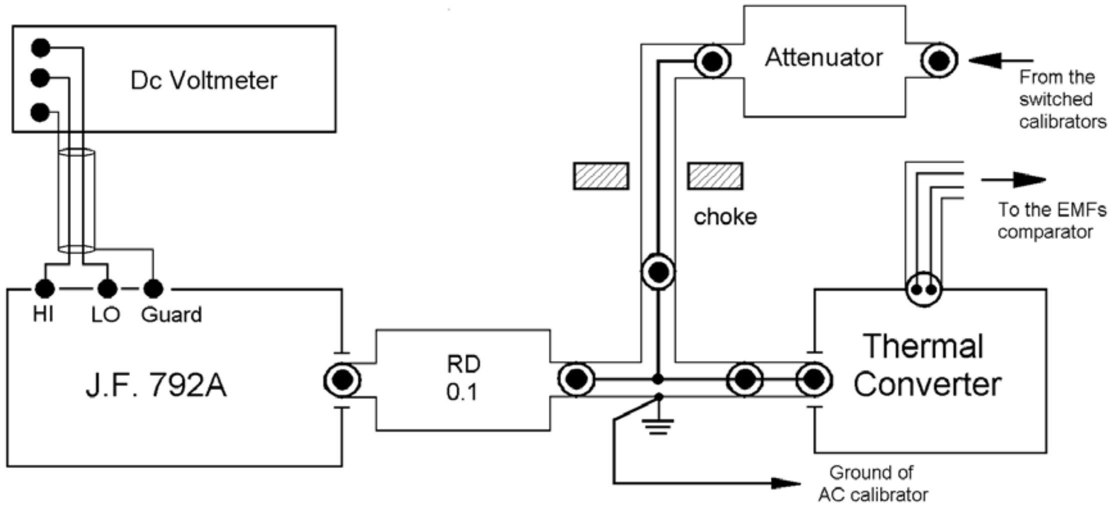

Fig. 2 *Scheme of the connection of the standards for 10 mV measurement. In case of 100 V measurements the resistive divider is not used.*

The acquisition of the outputs

For acquiring the voltage at the output of the a dc voltmeter Agilent mod. 3458A is used. Its inputs and guard connectors are connected as shown in Fig. 2.

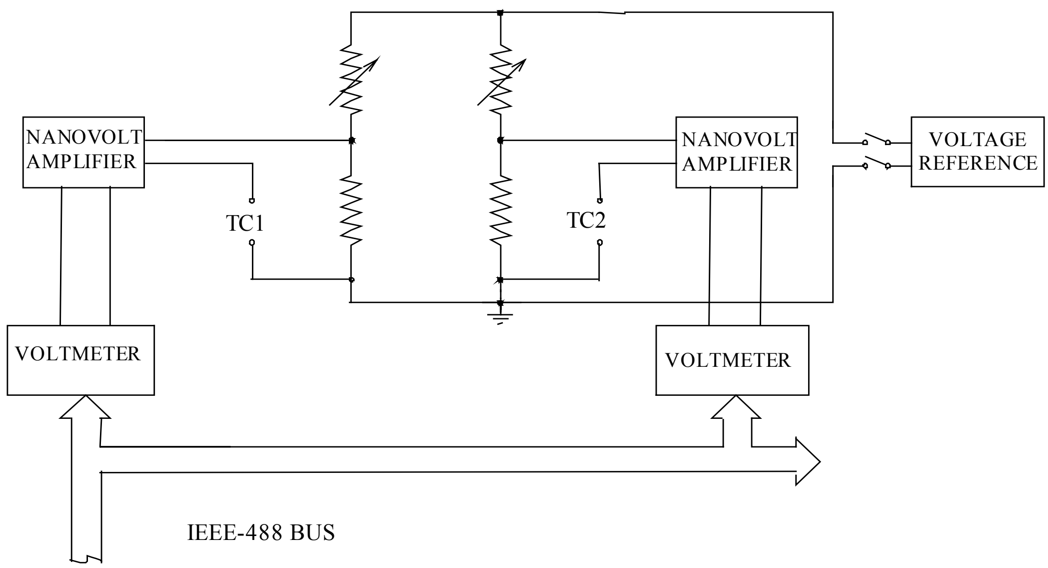

Fig. 3 *Basic circuit of the EMFs comparator.*

The electromotive force variation of the single junction thermal converter is instead measured by means of one arm of the electromotive force comparator of the system. The basic circuit of this comparator is represented in Fig. 3. Two resistors, R_1 and R_2 (10 Ω), are inserted in suitable plugs. These plugs and other terminals requiring low thermal electromotive forces are mounted, for a more uniform temperature distribution, on a thick plate of copper, electrically insulated with washers of beryllium oxide. The resistors are connected together at one end and act as the outputs of two Lindek potentiometers, which can be adjusted against the two electromotive forces of the converters under comparison.

The two potentiometers are supplied by a voltage reference made of a series of four high capacity mercury batteries, and controlled by two resistance boxes with a maximum value of 111.111 kΩ and a resolution of 0.1 Ω. External influences in the low voltage section are reduced by means of an appropriate screening and thermal insulation. In fact the batteries and the variable resistors are enclosed in metallic boxes connected to the ground potential for electrostatic protection. Furthermore the rotary switches of the variable resistors are operated from outside the box with thermal insulating shafts.

In each channel of the electromotive-force comparator the difference between the electromotive force of the converter and the voltage from the Lindek potentiometer is amplified by a low-noise amplifier (EM mod. 14). This amplifier has a highly linear gain (non-linearity less than 1 part in 10^6) that can be manually settled in decimal ranges from 10 to 10^6. The instrument is battery supplied and has been used in a floating configuration. To avoid electromagnetic interference low pass filters are connected between the output of the Lindek potentiometer and the input of the amplifier. The detailed scheme of the low voltage section is represented in Fig. 5.

The analog outputs of the amplifiers are read and transferred to the computer by two digital voltmeters (Hewlett Packard mod 3478A) operating under the IEEE-488 bus control.

The measurement procedure

The software was developed using Quick Basic. The procedure for voltage thermal converter comparison has the following steps:

After the connection of the instruments and the manual adjustment of the variable resistances to bring the nanovolt amplifiers near the balance condition, all the procedure is controlled by the computer.

- The nominal voltage is applied to the converters for a predetermined heating time, necessary to reach the condition of thermal equilibrium.
- A preliminary sensitivity check is made: a series of positive and negative increments of the calibrator output (at the level of nearly 0.1% of the nominal voltage) is programmed and the converter sensitivities are evaluated as the ratio of the mean value of the voltage and of the electromotive force variations at the outputs of the converters and the corresponding input voltage variations.

Then, for every frequency, some steps are repeated.

- The ac calibrator is adjusted so that the electromotive force at the output of one of the thermal converters is close to the mean value of those measured with the dc calibrator in the direct and reverse polarity. This step was proved to be necessary because of the great difference, especially at higher frequency, between the voltage indicated on the ac calibrator and the actual voltage at the voltage node.
- A series of successive ac, dc+, ac, dc-, ac, dc+, ... voltages are applied to the input of the converters, in regular periods. In correspondence to each period, after the switching and a suitable settling time, the nanovolt amplifier outputs are read and the values are recorded.
- For every frequency, the transfer difference of the converter under test related to that of the standard is computed from the data and from the previously measured sensitivity of the converters.
- A report on the measurement with all the relevant statistical data is released to the printer.

3: THE REFERENCE STANDARD

3.1. The basic standard

The basic standard at I.N.RI.M. is based on 3D multijunction thermal converters of PTB model. The mean value of their transfer difference has been assumed as zero, without corrections, within the range from 40 Hz to 10 kHz [2], [3].

For higher frequencies, up to 1 MHz, a special thermal converter built with a 1 kΩ anti-inductive film resistor in series with an UHF 5 mA single junction thermal converter is used [4]. For this converter, the knowledge of the geometrical dimensions had allowed us to evaluate the correction due to the reactive and to the skin effects. The thermoelectric effect of this single junction converter has been evaluated at the voltage of 3 V and at the frequency of 1 kHz by direct comparison to the multijunction thermal converters.

3.2. The working standard

For voltages equal or higher than 100 mV a single junction converters are used. The extension of the traceability to these converters is accomplished by a step-down procedure, described in [5].

Step-down of thermal converters

By means of this procedure, starting from the basic standard, the assignment of the ac-dc transfer difference to each converter is achieved by a sequence of comparisons. The converters are organised in groups of descending nominal value, then the converters of a group for which the transfer differences are already known are compared with the converters of the group having the lower nominal value.

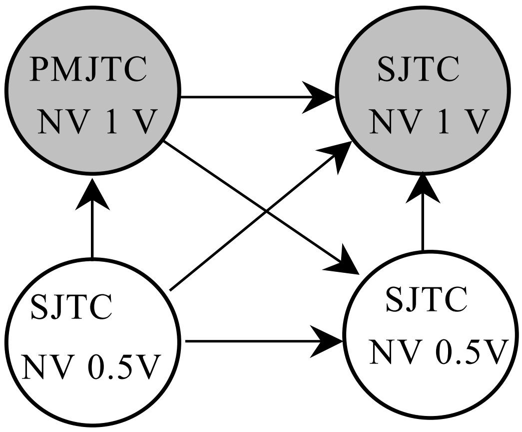

Fig.4 *Example of the measurement in the step-down procedure at 0.5 V. Four standards of different nominal voltage (two already calibrated in the previous step) are compared at 0.5 V*

In each step a redundant set of measurements allows to reduce the uncertainty by the application of a least squares adjustment. To connect two contiguous steps additional assumptions about the variation of the transfer difference of the converters at two different voltage levels have been introduced:

<u>*From 3 V to 1 V*</u> the transition between the two voltage has been made by means the 3D multijunction thermal converters, assuming that their ac-dc transfer difference does not change with the applied voltage.

<u>*From 1 V to 0.5 V*</u> the assumption is that at intermediate frequency (1 kHz) the mean ac-dc transfer difference standard of a planar multijuction thermal converter of the 1 V of group does not change, while at other frequencies the mean of the variations of all the thermal converters (multijuction and single-junction is assumed not to change the frequency characteristics as a function of the applied voltage).

<u>*From 0.5 V to 0.25 V*</u> is the same as the previous step.

<u>*From 0.25 V to 100 mV*</u> the ac-dc transfer difference variation has been measured. For this purpose, a especially made additional coaxial resistor has been built. The connection of the additional resistor and the thermal converter has been measured in comparison with a planar multijuction thermal converter.

The value and the uncertainty of the working standard at 100 mV and a detailed budget are given in chapter 8.

Calibration of the resistive divider

The effect of the insertion of the resistive divider $\delta_r = \frac{r_{ac} - r_{dc}}{r_{dc}}$ is calibrated by supplying 1 V. The resistive divider is connected between the T-connector and the input of the multirange thermal transfer standard already calibrated at 100 mV. The other output of the T-connector is connected to a calibrated thermal converter.

In order to evaluate the effect of the insertion in the measurement condition (multirange thermal transfer standard in the 22 mV range, input voltage at the resistive voltage divider 100 mV), differential correction for the voltage effect and load effect has been computed.

The first effect has been evaluated by measuring the variation of the ac-dc transfer difference in the same range of the transfer standard, by applying different voltages at the input of the resistive divider (eg. 1 V and 0.707 V) and extrapolating for the variation between 1 V and 0.1 V (the effect is assumed to be proportional to the input power).

The second effect has been evaluated by a mathematical model from the variation of the input admittance of the thermal transfer standard and the output impedance of the resistive divider, measured up to 1 MHz by a high frequency impedance bridge.

Also for the calibration of the resistive divider a detailed uncertainty budget is given in chapter 8.

4. THE AMBIENT CONDITIONS AND VALUES OF OTHER INFLUENCE PARAMETERS

The measurements have been performed in a shielded room at the temperature near to of 23 °C. The automatic control keeps the temperature generally of the room within ± 0.1 °C and inside the room there is also a humidity control.

The values of these parameters recorded, during the period of the measurements on the travelling standard, are:

	Min	Max
Ambient temperature / ºC	22.4	22.8
Relative humidity / %	41	51
Pos. power supply voltage / V	+11.097	+11.103
Neg. power supply voltage / V	-11.160	-11.165

From the data of humidity recorded during the measurement the means and the standard deviation have been computed.

<u>*Temperature*</u>

mean value: 22.7° C

standard deviation: 0.10 °C

<u>*Humidity*</u>

mean value: 45%

standard deviation: 3.1%

6. THE RESULTS OF THE MEASUREMENTS

The travelling standard was compared, for at least 5 times, with a specific thermal converter of the working standard directly at 100 mV and with the resistive divider applied for 10 mV and in each a group of 4 measurement were taken. For each group of measurement the converters were disconnected and reconnected to the T-connector.

Each measurement at a specified frequency comprised four repetitions of the sequence: ac, dc+ ac, dc-, ac. Each measurement point took 40 s: after the switching the system waited for a settling time of 20 s and then, every 0.5 s, the two voltmeters sampled the outputs of the low-noise amplifiers, whose time constants were set to 1 s. The value of the ac-dc transfer difference was evaluated in each sequence and the mean and the standard deviation were computed for each group of 4 repetitions.

Table 4 *Comparison between the device under test and a I.N.RI.M. working standard at a voltage of 100mV (ac-dc transfer difference in parts in 10^6).*

Input voltage	Working standard	Divider		1kHz	20 kHz	100 kHz	1 MHz
100 mV	025B-387		mean value	11.8	-15.1	-46.8	-192.6
			standard deviation	0.4	0.6	0.5	1.0
			No. Meas.	5	5	5	5
100 mV	025B-387	0.1 ratio SP-	mean value	15.1	-2.9	-35.1	-116.9
			standard deviation	0.5	1.2	2.6	4.8
			No. Meas.	5	5	5	5

The results of the measurements have been corrected by applying the temperature and relative humidity coefficients, at 23°C and 45% RH, of the ac-dc transfer difference of the travelling standard with their expanded uncertainties are given in the measurement protocol and shown in the table 5.

Table 5 *Temperature and relative humidity coefficients, at 23°C and 45% RH, of the ac-dc transfer difference of the travelling standard with their expanded uncertainties (in parts in 10^6).*

Range	Frequency	Temperature coefficient 10^{-6}/K	Expanded uncertainty 10^{-6}/K	Relative humidity coefficient 10^{-6}/%	Expanded uncertainty 10^{-6}/%
220 mV	1 kHz	0,4	1	0	0,02
	20 kHz	0,4	1	0	0,05
	100 kHz	0,6	1	0,1	0,1
	1 MHz	10	4	1,3	0,5
22 mV	1 kHz	1,2	2	0	0,02
	20 kHz	1,2	2	0	0,05
	100 kHz	1,3	2	0,1	0,1
	1 MHz	17	8	0,9	0,5

After applying all the corrections the transfer differences assigned to the device under test are given in Table 6. They are derived from the assigned values of the working standards, the measurement data given in Table 4 and the corrections given in Table 5.

Table 6 *Ac-dc transfer differences of the device under test (parts in 10^6).*

Voltage	Range	1 kHz	20 kHz	100 kHz	1 MHz
100 mV	**220 mV**	**-3.7**	**-15.7**	**1**	**-13**
10 mV	**22 mV**	**-9**	**-24**	**-45**	**-245**

The total uncertainties of the results and the given in table 7.

Table 7 *Assigned uncertainties at k=1(**u**) of the ac-dc transfer differences and the rounded degrees of freedom (**ν**) and expanded uncertainty (**U**).*

Voltage	Range		1 kHz	20 kHz	100 kHz	1 MHz
100 mV	**220 mV**	***u***	**3.9**	**3.8**	**5.5**	**25**
		ν	**6**	**6**	**9**	**7**
		U	**9.6**	**9.4**	**12**	**60**
10 mV	**22 mV**	***u***	**6.1**	**6.4**	**15**	**49**
		ν	**8**	**8**	**6**	**6**
		U	**14**	**15**	**37**	**120**

A detailed budget of the uncertainty is given in the next chapter.

7. DETAILED UNCERTAINTY BUDGET

Uncertainty of the working standard at 100 mV

Table 8 *Uncertainty budget of the working standard*
(the standard deviations are in parts in 10^6)

Uncertainty Component	Type / ν	1 kHz	20 kHz	100 kHz	1 MHz
Basic standard at 3 V	***u***	**0.40**	**0.7**	**1.7**	**8**
	ν	**142**	**25**	**13**	**49**
• Step-down 3 V-1 V	B / 3	0.28	0.30	0.32	0.95
• Comparison at 1 V	A / 3	0.37	0.32	0.57	2.12
Standards at 1 V	***u***	**0.6**	**0.8**	**1.8**	**8.3**
	ν	**16**	**30**	**16**	**53**
• Step-down 1 V-0.5 V	B / 4	1.0	0.8	0.8	6.1
• Comparison at 0.5 V	A / 3	0.42	0.42	1.3	4.7
Standards at 0.5 V	***u***	**1.2**	**1.2**	**2.4**	**11**
	ν	**9.0**	**17**	**19**	**28**
• Step-down 0.5 V-0.25 V	B / 4	2.0	1.5	1.7	5.6
• Comparison at 0.25 V	A / 3	0.21	0.6	1.3	5.3
Standards at 0.25 V	***u***	**2.4**	**2.0**	**3.2**	**14**
	ν	**7.4**	**12**	**22**	**32**
• Step-down 100 mV	B / 2	2.9	2.9	3.6	5.9
Calibration of coaxial thermal converter at 100 mV	***u***	**3.7**	**3.5**	**4.8**	**15**
	ν	**5.0**	**4.2**	**6.1**	**29**
Additional uncertainty for connection of the multirange transfer standard	B / 3	1.2	1.4	2.3	20
Calibration of the multirange coaxial thermal converter at 100 mV	***u***	**3.9**	**3.8**	**5.4**	**25**
	ν	**5.9**	**5.5**	**8.3**	**7.1**

Notes:

- The uncertainty of the basic standard is computed is assumed here as a starting point and is described in the internal procedure PT-ME-07-T-01. The uncertainties are supported by the results of the international comparison CCEM-K5 [5].
- The measurement uncertainties in each step is derived from the least square adjustment and the standard deviation of the links is evaluated by the relation:

$$s = \sqrt{\frac{\sum_{j=1}^{n}\left(\delta_{m,\ j} - \delta_{adj,\ j}\right)^2}{\nu \cdot (\nu - 1)}} \tag{5}$$

where:

δ_m are the measured values, δ_{adj} are the estimated values, ***n*** is the number of measurement links between the converters and ν is the number of degrees of freedom. (in the example in Fig. 4 ***n***=6 and ν=3).

- For the step-down from 3 V to 0.25 V, the 3D or the planar multijuction thermal converters have been employed. The uncertainty of the correction due to the different voltages applied has been evaluated in a series of tests on some converters (possibly with different input resistance). The converters are compared in couples and measuring, without disconnection, the difference between the variations of the ac-dc transfer differences at the two voltages. To take account for the partial correlation, at each frequency, the maximum variation detected has been taken as the possible voltage effect. The degree of freedom has been assumed to be the number of standards involved in the test.

The accuracy of the voltage effect determination in the single junctions used in the step from 250 mV to 100 mV has been evaluated from the variation measured. Also in this case the degrees of freedom has been assumed to be the number of the converters tested in the transition from 250 mV to 100 mV.

- The additional component has been estimated from the difference between direct and indirect measurement of a multirange thermal converter when compared with coaxial thermal converters (this difference is negligible when the device under test is instead another coaxial thermal converter). Presumably this is a systematic error due to ground loop in the measurement system or to a different frequency band of the two devices, but it has not been completely explained yet.

The calculation of the partial and total is made by quadratic composition of the standard deviation and using the Welch-Satterthwaite formula for the determination of the effective degrees of freedom.

Uncertainty of the calibration of the resistive ratio to operate down to 10 mV

Table 9 *Uncertainty budget of the resistive ratio at 10 mV (the standard deviations are in parts in 10*^{6}*)*

Uncertainty component	Type / ν	1 kHz	20 kHz	100 kHz	1 MHz
Standards at 1 V	***u***	**0.6**	**0.8**	**1.8**	**8.3**
See table 8	***ν***	**16**	**30**	**16**	**53**
Calibration of the multirange thermal converter at 100 mV	***u***	**3.9**	**3.8**	**5.4**	**25**
See table 8	***ν***	**5.9**	**5.5**	**8.3**	**7.1**
Comparison uncertainty at 1V	A / 4	0.4	0.6	0.5	1.0
Voltage effect	B / 2	1.2	1.4	5.6	6.1
Evaluation of the load effect	B / ∞	0.0	0.0	0.1	6.3
Additional uncertainty due to the connection.	B / 3	4.4	4.7	12.6	40.0
Ac-dc difference of the ratio	***u***	**6.1**	**6.3**	**15**	**49**
	ν	**8.2**	**7.8**	**5.5**	**6.2**

Notes:

- The measurement uncertainties for 1 V measurements is derived from ***n*** independent measurements with disconnection and re-connection of the T from the transfer standards. The standard deviation and ν are evaluated as:

$$s = \sqrt{\frac{\sum_{j=1}^{n} \left(\delta_j - \delta_{mean}\right)^2}{(n-1)}} \qquad \upsilon = n - 1 \qquad (6)$$

- The uncertainty of the voltage effects has been derived by the difference between 3 different evaluations by changing the thermal converter and using different types of extrapolation.
- The uncertainty of the load effect has been derived theoretically from the difference between the results computed with different model of the circuit.
- The additional uncertainty due to the connection of the resistive divider has been evaluated from the differences in the results obtained by using different connectors at the input of the divider.

Uncertainty of the measurement at 100 mV

Table 10 *Uncertainty budget of the measurement at 100 mV (the standard deviations are in parts in 10^6)*

Uncertainty component	Type / ν	1 kHz	20 kHz	100 kHz	1 MHz
Working standard at 100 mV	***u***	**3.9**	**3.8**	**5.4**	**25**
See table 8	ν_f	**5.9**	**5.5**	**8.3**	**7.1**
Standard deviation of the measurements	A / 4	0.2	0.5	1.0	1.6
Correction for the temperature	B / ∞	0.09	0.09	0.10	0.80
Correction for humidity	B / ∞	0.00	0.00	0.20	2.6
Calibration of the multirange thermal converter at 100 mV	***u***	**3.9**	**3.8**	**5.5**	**25**
Rounded degrees of freedom	ν	**6**	**6**	**9**	**7**

Table 11 *Uncertainty budget of the measurement at 10 mV (the standard deviations are in parts in 10^6)*

Uncertainty component	Type / ν	1 kHz	20 kHz	100 kHz	1 MHz
Ac-dc difference of the ratio	***u***	**4.4**	**5.0**	**12**	**49**
See table 9	ν	**9.1**	**10.9**	**7.1**	**6.2**
Standard deviation of the measurements at 100 mV	A / 4	0.5	1.2	2.6	4.8
Correction for the temperature	B / ∞	0.19	0.19	0.20	1.41
Correction for humidity	B / ∞	0.00	0.00	0.20	1.80
Calibration of the multirange coaxial thermal converter at 10 mV	***u***	**6.1**	**6.4**	**15**	**49**
Rounded degrees of freedom	ν	**8**	**8**	**6**	**6**

Notes:

- The uncertainties for the correction in temperature and humidity have been derived by using the coefficient supplied (the expanded uncertainty is considered with (k=1.96).

  In both cases the uncertainty is derived by:

$$u = \sqrt{\left[(Q - Q_{ref}) \cdot u_{par}\right]^2 + \left[s_Q \cdot par\right]^2} \qquad (7)$$

where:
$\boldsymbol{Q}$ is the mean value of the quantity (temperature or humidity), $\boldsymbol{Q_{ref}}$ the reference (23°C and 45%) $\boldsymbol{s_Q}$ is the standard deviation of the quantity, ***par*** is the value of the correction parameter and $\boldsymbol{u_{par}}$ is the uncertainty of the correction parameter.

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Key comparison EUROMET.EM-K11
ac-dc voltage transfer difference at low voltages

Report
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Content

1. Introduction

The CIPM key comparison CCEM-K11 “ac-dc voltage transfer difference at low voltages” started in 2001 and the circulation of the travelling standard has now been finalised. It is time to restart the EUROMET project 464 that now also has the KCDB appendix B identifier EUROMET.EM-K11 with the Swedish National Testing and Research Institute (SP) as the pilot laboratory and with the Physikalisch-Technische Bundesanstalt (PTB) and the Nederlands Meetinstituut (NMi) as advisors to the pilot laboratory.

This comparison is needed because of the growing importance of new measuring instruments introduced with the ability to measure or generate ac voltage with small uncertainties in the mV-range. This is the first European comparison for the ac-dc voltage transfer difference in the mV-range. The aim of the comparison is to achieve an agreement at 1 kHz within an expanded uncertainty of $10 \cdot 10^{-6}$ and $50 \cdot 10^{-6}$ at 100 mV and 10 mV respectively. At higher frequencies up to 1 MHz the uncertainties can be ten times larger.

The comparison will be accomplished in accordance with the EUROMET Guidelines on Conducting Comparisons.

2. Definition of the ac-dc voltage transfer difference

The ac-dc voltage transfer difference δ of a transfer standard is defined as:

$\delta = (V_{ac} - V_{dc}) / V_{dc}$

where

V_{ac} is the rms value of the ac input voltage

V_{dc} is the dc input voltage which when reversed produces the same mean output voltage of the transfer standard as V_{ac}.

3. The travelling standard

The travelling standard is a Fluke 792A thermal transfer standard, serial number 5495 003, which has amplified low voltage ranges 700 mV, 220 mV and 22 mV. At the rated input voltage the output voltage is approximately 2 V. The input connector of the standard is a type N female (The stainless steel connector saver should always be connected to the input of the Fluke 792A). The output connectors are 4 mm binding posts, female. A battery pack with connecting cable is included, as the travelling standard has to be operated on battery during measurement. **Note** that the 700 mV range is not working properly.

The temperature and relative humidity coefficients of the travelling standard are given below and corrections are applied for both the measurement results and the uncertainty budget. The ac-dc voltage transfer difference of the travelling standard has a dependence on the power supply voltage. The stability of the supply voltage is important. Therefore an electronic power supply built in PTB has been used. It has exactly the same output voltage as the Fluke battery pack.

Table I: Temperature and relative humidity coefficients, at 23°C and 45% RH, of the ac-dc transfer difference of the travelling standard with their expanded uncertainties.

Range	Frequency	Temperature coefficient 10^{-6}/K	Expanded uncertainty 10^{-6}/K	Relative humidity coefficient 10^{-6}/%	Expanded uncertainty 10^{-6}/%
220 mV	1 kHz	0,4	1	0	0,02
	20 kHz	0,4	1	0	0,05
	100 kHz	0,6	1	0,1	0,1
	1 MHz	10	4	1,3	0,5
22 mV	1 kHz	1,2	2	0	0,02
	20 kHz	1,2	2	0	0,05
	100 kHz	1,3	2	0,1	0,1
	1 MHz	17	8	0,9	0,5

The travelling standard has been evaluated and found to be very stable both regarding the long-term drift and the influence due to transportation.

4. Measuring conditions

PTB followed their usual measurement procedure to their best measurement capabilities.

- The **ac-dc voltage transfer difference** at **23°C, 45 % RH** has been reported.
- The **reference plane** of the measured ac-dc voltage transfer difference has been at the centre of a type N-Tee connector with type N male output connectors for the 100 mV measurements and the direct connection of a micropotentiometer with a male N-connector.
- The **ambient conditions** during the measurements are:
  temperature (22,8 to 23,4)°C and relative humidity (45±10)% for the 100 mV measurements and for the 10 mV measurements (29,9 to 23,0) °C and relative humidity (32 to 40)%.
- The low of the input connector and the guard and the ground terminals of the transfer standard were connected to common ground in order to maintain a defined calibration condition. The ground terminal and the guard terminal are connected directly. The output low and the input low are internally connected in the Fluke 792A.
- The instrument was always turned on during the whole time of the measurements in PTB
- The **measuring frequency** has been within 1 % of the nominal frequency. The frequency and its uncertainty are reported.
- An electronic power supply built in PTB has been used. It has exactly the same output voltage as the Fluke battery pack.

5. Measuring scheme

The ac-dc voltage transfer difference of the travelling standard has been measured at the voltages 100 mV and 10 mV and at the frequencies 1 kHz, 20 kHz, 100 kHz and 1 MHz.

6. Description of the measuring method

Measuring instruments for AC voltages and ac-dc voltage transfer standards like the Fluke 792 A down to 100 mV are calibrated by AC-DC voltage transfer with planar multijunction thermal converters (PMJTCs). Below 100 mV µpots have to be used. At the 100-mV level µpots are calibrated against the calibrated instrument or ac-dc transfer standard.

The input impedance of low voltage AC-DC transfer devices like the popular Thermal AC/DC Transfer Standard Fluke 792A loads the output of a µpot [1]. To calculate the ac-dc voltage transfer difference of the µpot, it is necessary to measure the input impedance of the 792A and to apply corrections. With 10-Ω-µpots generating 100 mV, usually corrections of 67 µV/V have to be applied at 1 MHz. Recently new amplifiers have been designed with high input impedances (> 1 MΩ || <6 pF at 1 MHz) to decrease the necessary load corrections [2].

With the known ac-dc transfer differences of the µpot lower voltages in the 100-mV-range down to 20 mV are calibrated only by assuming voltage independent ac-dc transfer differences and voltage independent input impedance of the transfer device in its voltage range. But this assumption results in some contribution in the uncertainty budget.

Another solution is to reduce the output impedance of the µpot by a factor of 100. In this case an increase of the current in the thermal converter of the µpot is necessary with the same factor. The idea came up during the calibration of ac-dc current transfer standards for the CCEM Key Comparison K12. New high current shunts for currents up to 10 A (0.1 Ω) designed by the NMI of Norway Justervesenet (JV) were used for a new current step-up and showed very flat frequency response up to 1 MHz. With such shunts of 0.1 Ω to 0.2 Ω used in the µpot the load corrections for 150-kΩ-input impedance amplifiers of the Fluke 792A are reduced to less than 1 µV/V. Now the input impedance of the amplifier has to be known only approximately. On the other hand such measurements validate the assumption of a voltage independent input impedance of the Fluke 792A. The current in the new µpot is measured with a 1-A thermal current converter (1-A shunt and a 10-mA-PMJTC). Measurements at 1 MHz and 1 A were only possible with the design of a new transconductance amplifier.

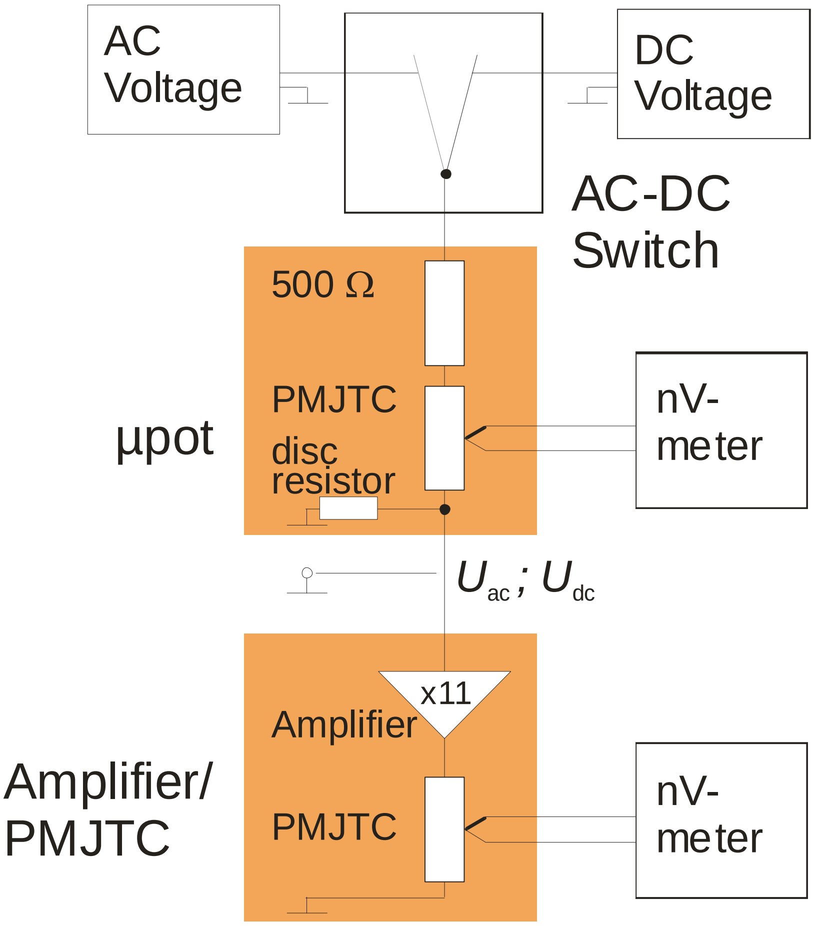

Fig. 1. Measurement set-up for AC-DC mV-transfer with common 10-mA µpots. With discrete µpots a transconductance amplifier as a current source is used and the 500-Ω resistor in the µpot is not needed.

7. Design of the discrete micropotentiometers

The output resistor and the thermal converter are connected in series using a low capacitance tee-connector [3] shown in Fig. 2. The JV-shunts are made up from many SMD resistors in through-hole technology [4]. This technology results in a quite flat frequency response up to 1 MHz (Fig. 3). To achieve well defined stray capacitances, potential driven guarding [5] was applied to the PMJTC and the nanovoltmeter reading its output voltage.

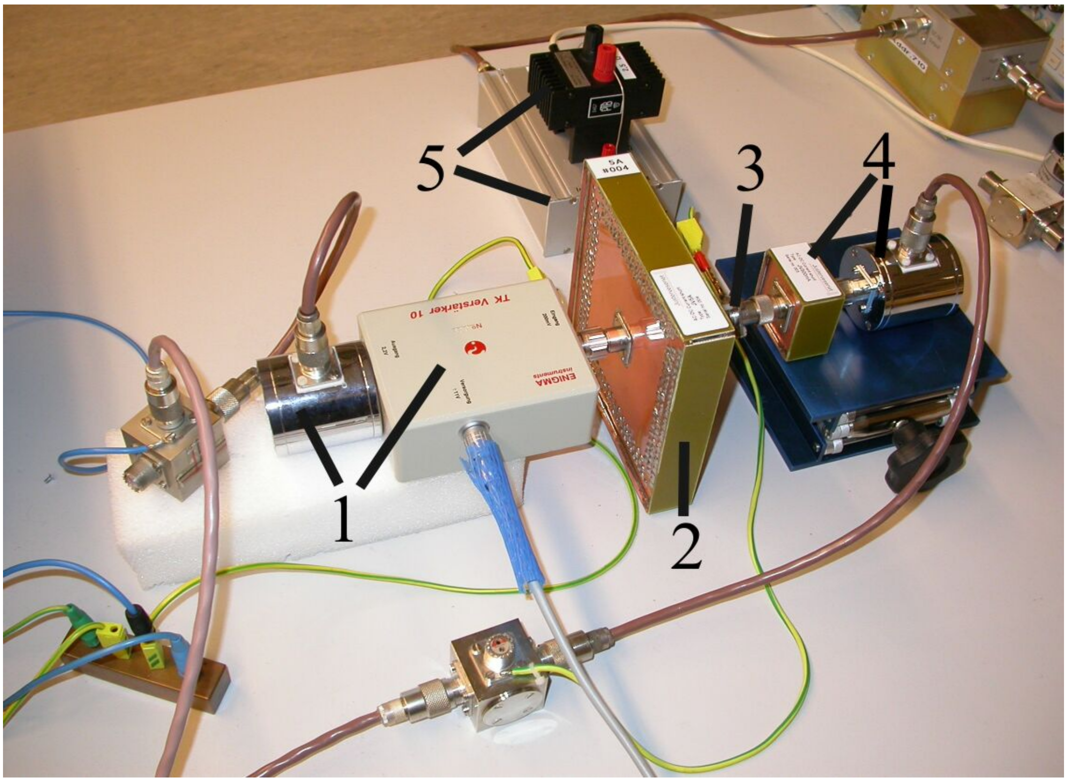

Fig. 2: PMJTC with amplifier (1), discrete µpot with 0.2-Ω-shunt (2), current Tee-connector (3), 1-A-shunt and PMJTC (4), 1 A/1 MHz transconductance amplifier with external shunt (5).

8. Transconductance amplifier

Commercially available voltage calibrators, which are normally used for AC-DC transfer, can deliver only currents up to 50 mA up to 1 MHz. High current amplifiers or transconductance amplifiers up to 100 A are limited in the frequency to about 100 kHz. Therefore a transconductance amplifier had to be designed to deliver currents of 1 A at frequencies from DC to 1 MHz [5].

9. Measurement results

Measurements are performed using the 6.9-Ω/10-mA-µpot and the 0.2-Ω/500-mA-µpot. Both µpots showed within narrow limits the same results for the 100-mV-range of the Fluke 792A down to 20 mV. These results validate the assumption of the voltage independence of the ac-dc transfer differences of both µpots and of the input impedances of the 792A and validate moreover the correct measurement of the input impedance of the 792A and the calculation of the corrections. Fig. 3 shows the ac-dc transfer differences of the two 100-mV-µpots.

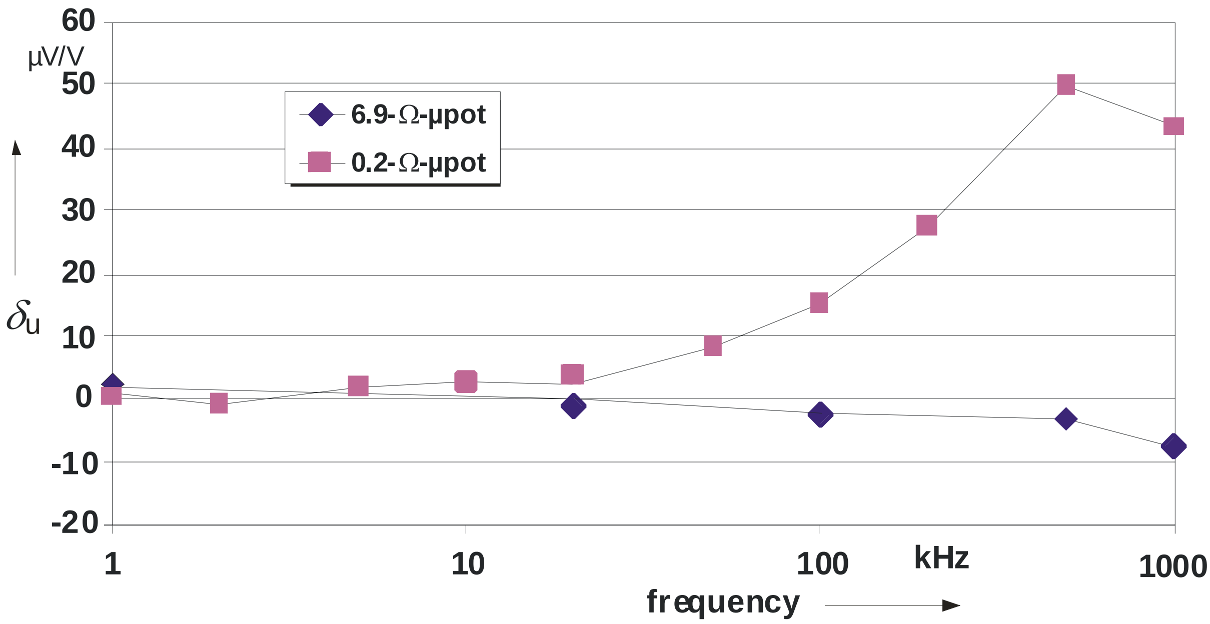

Fig. 3 Ac-dc voltage transfer difference δ of the 6.9-Ω-µpot and the 0.2-Ω-µpot at 100 mV.

Table I shows the calibration results. No correction is applied for the temperature coefficient and the differences due to the relative humidity because the 100 mV measurements are made at an average of (23±0,5) °C and (45±5) % relative humidity and the 10 mV measurements are made at (23±0,1) °C and (36±4) % relative humidity. The starting voltage for the 10 mV measurement is the calibrated 100-mV value. This has to be corrected by -9 % re. humidity and then the 10 mV has to be corrected by +9 % to 45 %. As the coefficients for the 100 mV and the 10 mV are quite the same, no correction has been made. But in the uncertainty budget some contributions from the temperature and humidity coefficient have been introduced.

Table I: Calibration results: ac-dc voltage transfer difference:

Voltage	Range	Measured ac-dc voltage difference in µV/V at frequency			
		1 kHz	20 kHz	100 kHz	1 MHz
100 mV	220 mV	**+6**	**-7**	**+20**	**+43**
10 mV	22 mV	**-10**	**-8**	**-11**	**-119**

Expanded uncertainty (k=2):

Voltage	Range	Expanded uncertainty in µV/V at frequency			
		1 kHz	20 kHz	100 kHz	1 MHz
100 mV	220 mV	**4**	**6**	**8**	**36**
10 mV	22 mV	**12**	**14**	**20**	**42**

10. Uncertainty analysis

The model function for the evaluation of the measurement is given below and the uncertainty budget in table II.

$$\delta_{XLV} = \delta_{S1\,V} + \delta_A + \delta_C \; \delta_{con} + \delta_{divid} + \delta_{cali} + \delta_{f792} + \delta_{temp} + \delta_{humii}$$

$$+ \delta_{in\,ímp} + \delta_A + \delta_C + \delta_{Lev} + \delta_{f792} + \delta_{temp} + \delta_{humi} + \delta_{corr}$$

with

δ_{XLV} AC-DC voltage transfer difference of the Fluke 792A
at 100 mV: first line only
at 10 mV: add second line twice

For the calibration of the Fluke 792 A at 100 mV against PMJTC:

δ_{S1V} AC-DC voltage transfer difference of PTB-PMJTC at 1 V [6]
δ_A Contribution from the type A standard deviation of the mean of 12 measurements
δ_C Systematic difference contribution of the calibration set-up
δ_{con} AC-DC voltage transfer difference due to the different T-connectors especially at high frequencies and electromagnetic influences from outside
δ_{divid} AC-DC voltage transfer difference with different dividers in front of the T-connectors
δ_{cali} AC-DC voltage transfer difference with different calibrators and calibration set-ups in the step-down
δ_{f792} AC-DC voltage transfer difference due to the frequency correction of Fluke 792A
δ_{temp} AC-DC voltage transfer difference due to the contribution of the temperature coefficient of the ac-dc voltage transfer difference of the 792A. The temperature was controlled between 22,8 °C and 23,4 °C.
δ_{humi} AC-DC voltage transfer difference due to the contribution of the humidity coefficient of the ac-dc voltage transfer difference of the 792A. It was only possible to control the humidity between 40 % and 50 %.

For the calibration of the 0.2-Ω-µpot at 100 mV against the Fluke 792A and the calibration of the Fluke 792A at 10 mV:

$\delta_{in\,ímp}$ load correction due to the input impedance of 792A at 100 mV
$\delta_{A\,µpot}$ Contribution from the type A standard deviation of the mean of 12 measurements
$\delta_{C\,µpot}$ Systematic difference contribution of the calibration set-up
δ_{Lev} Level effect of the ac-dc current converter in the µpot
δ_{temp} AC-DC Voltage Transfer Difference due to the temperature coefficient of the ac-dc voltage transfer difference of the 792 A. The temperature was controlled between 29,9 °C and 23,0 °C.
δ_{humi} AC-DC Voltage Transfer Difference the humidity coefficient of the ac-dc voltage transfer difference of the 792 A. The humidity was controlled between 32 % and 40 %. This has to be corrected to 45 % and a correction term δ_{corr} has to be added.

Table II: Uncertainty budget for the calibration of the Fluke 792A at 100 mV and 10 mV.

Influencing quantity	Standard measurement uncertainty *u* in µV/V at the frequencies			
	1 kHz	20 kHz	100 kHz	1 MHz
$u\ (\delta_{S\ 1V})$	0.2	0.2	1.2	2.4
$u\ (\delta_{A})$	1.2	1.7	2.7	3.0
$u\ (\delta_{C})$	0.2	0.2	0.2	0.2
$u\ (\delta_{connector})$	0.3	0.3	0.3	1.1
$u\ (\delta_{divers\ PMTC})$	0.5	0.5	0.7	0.9
$u\ (\delta_{divers\ divider})$	0.8	2.0	1.7	8.7
$u\ (\delta_{divers\ calibrator})$	0.2	0.8	1.2	13.3
$u\ (\delta_{f\ 792})$	0.1	0.1	0.1	0.1
$u\ (\delta_{temperature})$	0.2	0.2	0.2	3.5
$u\ (\delta_{humidity})$	0.0	0.0	0.3	5.0
$u\ (\delta_{792A100\ mV})$	2.0	3.0	4.0	18
$U\ (\delta_{792A100\ mV})(k=2)$	**4**	**6**	**8**	**36**
$u\ (\delta_{input\ impedance})$	0.3	0.3	0.3	1.1
$u\ (\delta_{A\ \mu pot\ 100\ mV})$	1.0	1.0	1.0	1.0
$u\ (\delta_{C\ set\text{-}up})$	0.2	0.2	0.2	0.2
$u\ (\delta_{Lev})$	0.5	0.6	0.6	1.4
$u\ (\delta_{f792\ 100\ mV})$	0.3	0.3	0.3	0.3
$u\ (\delta_{temperature\ 100\ mV})$	0.1	0.1	0.1	1.0
$u\ (\delta_{humidity\ 100\ mV})$	0.0	0.0	0.2	3.0
$u\ (\delta_{correct\ to\ 45\ \%})$	0.0	0.0	0.5	2.3
$u\ (\delta_{A\ 10\ mV})$	6.0	6.0	9.0	11
$u\ (\delta_{C\ 10\ mV})$	0.2	0.2	0.2	0.2
$u\ (\delta_{f\ 792\ 10\ mV})$	0.1	0.1	0.1	0.1
$u\ (\delta_{temperature\ 10\ mV})$	0.1	0.1	0.1	1.0
$u\ (\delta_{humidity\ 10\ mV})$	0.0	0.0	0.2	2.0
$u\ (\delta_{correct\ to\ 45\ \%})$	0.0	0.0	0.5	2.3
$u\ (\delta_{792A\ 10\ mV})$	6.0	7	10	21
$U\ (\delta_{792A\ 10\ mV})\ (k=2)$	**13**	**13**	**20**	**49**

12. References

[1] M. Klonz, G. Schliestedt, T. Funck, M. Stojanovic, and B. Stojanovic, "Millivolt calibrations using micropotentiometers with new disc resistors and planar MJTCs aided by new millivolt amplifiers," *IEEE Trans. Instrum. Meas*., vol. 54, pp. 787-790, April 2005.

[2] M. Stojanovic, M. Klonz, B. Stojanovic, "High performance mV-amplifier for the planar multijunction thermal converter," *IEEE Trans. Instrum. Meas.,* vol. 52, pp. 341-344, April 2003.

[3] L. Scarioni, M. Klonz and T. Funck, "Quartz planar multijunction thermal converter as a new ac-dc current transfer standard up to 1 MHz," *IEEE Trans. Instrum. Meas*., vol. 54, pp. 799-802, April 2005.

[4] K. Lind, T. Sørsdal, and H. Slinde, "High performance AC-DC Current shunts from inexpensive components," *this issue*

[5] T. Funck and M. Klonz, "Improved ac-dc current transfer step-up with new current shunts and potential driven guarding," *this issue*.

[6] L. Scarioni, M. Klonz and T. Funck, "Quartz planar multijunction thermal converter as a new ac-dc voltage transfer standard up to 100 MHz," in this issue

Appendix 1. Summary of results

Key comparison EUROMET.EM-K11 “ac-dc voltage transfer difference at low voltages”

Please send this information by e-mail also.

Acronym of institute: Physikalisch-Technische Bundesanstalt (PTB)

Date of measurements: November 1, 2005 to December 6, 2005

Measuring result:

Voltage	Range	Measured ac-dc voltage difference in µV/V at frequency			
		1 kHz	20 kHz	100 kHz	1 MHz
100 mV	220 mV	**+6**	**-7**	**+20**	**+43**
10 mV	22 mV	**-10**	**-8**	**-11**	**-119**

Expanded uncertainty:

Voltage	Range	Expanded uncertainty in µV/V at frequency			
		1 kHz	20 kHz	100 kHz	1 MHz
100 mV	220 mV	**4**	**6**	**8**	**36**
10 mV	22 mV	**13**	**13**	**20**	**49**

Measuring frequency:

	Nominal frequency				Remarks
	1 kHz	20 kHz	100 kHz	1 MHz	
Measuring frequency	999,97 Hz	19,999 kHz	99,996 kHz	999,97 kHz	100 mV
Measuring frequency	999,97 Hz	19,999 kHz	99,997 kHz	999,97 kHz	10 mV
Expanded uncertainty	$1\bullet10^{-3}$	$1\bullet10^{-3}$	$1\bullet10^{-3}$	$1\bullet10^{-3}$	

Influence parameters:

	Min	Max	Remarks
Ambient temperature / ºC	22,8	23,4	**100 mV with PMJTC**
Relative humidity / %	40	50	**100 mV with PMJTC**
Ambient temperature / ºC	22,9	23,0	**10 mV with µpots**
Relative humidity / %	32	40	**10 mV with µpots**
Pos. power supply voltage / V	+11,098	+11,106	Electronic power supply
Neg. power supply voltage / V	-11,154	-11,168	Electronic power supply

Appendix 2. Summary of uncertainty budget

Key comparison EUROMET.EM-K11 "ac-dc voltage transfer difference at low voltages"

Please send this information by e-mail also.

Acronym of institute: Physikalisch-Technische Bundesanstalt (PTB)

Date of measurements: November1, 2005 to December 6, 2005

Measuring voltage: 100 mV

Contribution of:	Std. unc. f: 1 kHz	Std. unc. f: 20 kHz	Std. unc. f: 100 kHz	Std. unc. f: 1 MHz	Type A or B	Distri-bution
$u\ (\delta_{S\ 1V})$	0.2	0.2	1.2	2.4	B	gaussian
$u\ (\delta_{A})$	1.2	1.7	2.7	3.0	A	gaussian
$u\ (\delta_{C})$	0.2	0.2	0.2	0.2	B	rectangular
$u\ (\delta_{connector})$	0.3	0.3	0.3	1.1	B	rectangular
$u\ (\delta_{divers\ PMTC})$	0.5	0.5	0.7	0.9	B	rectangular
$u\ (\delta_{divers\ divider})$	0.8	2.0	1.7	8.7	B	rectangular
$u\ (\delta_{divers\ calibrator})$	0.2	0.8	1.2	13.3	B	rectangular
$u\ (\delta_{f\ 792})$	0.1	0.1	0.1	0.1	B	rectangular
$u\ (\delta_{temperature})$	0.2	0.2	0.2	3.5	B	rectangular
$u\ (\delta_{humidity})$	0.0	0.0	0.3	5.0	B	rectangular
$u\ (\delta_{792A100\ mV})$	1.6	2.8	3.7	18		
$\boldsymbol{U(\delta_{792A100mV})(k=2)}$	**4**	**6**	**8**	**36**		
$\boldsymbol{\nu_{eff}}$	129	306	139	34978		

Measuring voltage: 10 mV

Contribution of:	Std. unc. f: 1 kHz	Std. unc. f: 20 kHz	Std. unc. f: 100 kHz	Std. unc. f: 1 MHz	Type A or B	Distribution
$u\ (\delta_{792A100\ mV})$	1.6	2.8	3.7	17.5	B	gaussian
$u\ (\delta_{input\ impedance})$	0.3	0.3	0.3	1.1	B	rectangular
$u\ (\delta_{A\ \mu pot\ 100\ mV})$	1.0	1.0	1.0	1.0	B	gaussian
$u\ (\delta_{C\ set\text{-}up})$	0.2	0.2	0.2	0.2	B	rectangular
$u\ (\delta_{Lev})$	0.5	0.6	0.6	1.4	B	rectangular
$u\ (\delta_{f792\ 100\ mV})$	0.3	0.3	0.3	0.3	B	rectangular
$u\ (\delta_{temperature\ 100\ mV})$	0.1	0.1	0.1	1.0	B	rectangular
$u\ (\delta_{humidity\ 100\ mV})$	0.0	0.0	0.2	3.0	B	rectangular
$u\ (\delta_{correct\ to\ 45\ \%\ r.F.})$	0.0	0.0	0.5	2.3	B	rectangular
$u\ (\delta_{A\ 10\ mV})$	6.0	6.0	9.0	11	A	gaussian
$u\ (\delta_{C\ 10\ mV})$	0.2	0.2	0.2	0.2	B	rectangular
$u\ (\delta_{f\ 792\ 10\ mV})$	0.1	0.1	0.1	0.1	B	rectangular
$u\ (\delta_{temperature\ 10\ mV})$	0.1	0.1	0.1	1.0	B	rectangular
$u\ (\delta_{humidity\ 10\ mV})$	0.0	0.0	0.2	2.0	B	rectangular
$u\ (\delta_{correct\ to\ 45\ \%\ r.F.})$	0.0	0.0	0.5	2.3	B	rectangular
$u\ (\delta_{792A\ 10\ mV})$	6.3	6.8	9.9	21		
$U(\delta_{792A\ 10\ mV})\ (k=2)$	**13**	**14**	**20**	**43**		
ν_{eff}	99	126	112	1131		

Euromet.EM-K11 Key comparison

AC-DC VOLTAGE TRANSFER DIFFERENCE AT LOW VOLTAGES

NMi VSL Results

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Report name	:	IKR-Euromet.EM-K11
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NMi Van Swinden Laboratorium

Department Electricity, Radiation and Length

Delft, The Netherlands

Summary

At this moment the worldwide CCEM-K11, a CIPM key comparison is finalised (draft A version), so the previously organised mV-comparison, known as the Euromet 464 project has been restarted.
This report presents the results of the regional Euromet.EM-K11 Key comparison, which is the replacement of the suspended Euromet 464 project.
The project concerns AC-DC voltage transfer devices used at low voltages and has been carried out at the NMi Van Swinden Laboratorium in January 2006.
The pilot laboratory is the Swedish National Testing and Research Institute (SP), supported by the Physikalisch-Technische Bundesanstalt (PTB) and the Nederlands Meetinstituut (NMi VSL).

Table of contents

1 Introduction

In 1997 the Euromet project No. 464, a comparison of low voltage ac-dc transfer standards, was initiated by the group of Euromet ac-dc experts. Just after starting this project in 2000 the CCEM decided to organize a worldwide similar comparison, known as CCEM-K11. As a result of this development the ac-dc expert group decided to suspend the just started regional Euromet project until the worldwide comparison was finalized.
The CCEM-K11 comparison has now reached its final stage, so the Euromet ac-dc group restarted the suspended comparison as the Euromet.EM-K11 comparison.

Instruments suitable for measuring or generating very accurate alternating signals at low voltages are nowadays more common within the National Measurements Institutes of the European community. Mutual recognition of these reference standards is not only stimulated by CIPM but also by the Regional Metrology Organisations, RMO.
For this purpose the restarted key-comparison, known as Euromet.EM-K11 is organised. The pilot laboratory and the co-ordinator of this comparison, the Swedish National Testing and Research Institute (SP), again provided the travelling standard.
This is another Fluke 792A then used in the previous comparisons, but it will be carried out on the same levels, which will be 100 mV and 10 mV at frequencies of 1 kHz, 20 kHz, 100 kHz and 1 MHz.
The aim of uncertainties at 1 kHz is 10 µV/V at 100 mV and 50 µV/V at 10 mV. At the 1 MHz frequency a ten times higher uncertainty will be allowed.
The travelling standard is thoroughly characterized by the pilot laboratory before it was sent to the different participants. They investigated the effects of change in temperature and humidity and the output voltage of the supply voltage unit on the ac-dc error. Also drift of the travelling standard during the comparison loop will be registered. All these preparations will contribute to realize a good agreement between the results of measurements at national levels.
For measuring the output voltage of the supply unit during the measurements a special loading device is provided. The national measurement institute of the Netherlands, NMi will be supporting the activities of SP and will deliver another Fluke 792A if in the unlikely event that the travelling standard has a breakdown.

The results mentioned in this report represent the activities executed by the Department Electricity, Radiation and Length as part of the NMi Van Swinden Laboratorium (NMi VSL), the national standards laboratory of the Netherlands and will be accomplished in accordance with the Euromet Guidelines on Conducting Comparisons.

2 Intercomparison at VSL

2.1 The travelling standard

The travelling standard for this Euromet key comparison is a Fluke 792A transfer standard. This standard is based on the thermal principle and its output voltage of approximately 2 V is proportional to the input voltage. The two most sensitive ranges of this instrument, 220 mV and 22 mV have to be calibrated by all the participants on the 100 mV and 10 mV-level with the lowest uncertainty possible. At this low voltage levels the input voltage is amplified before it is fed to the thermal element of the transfer standard. During the measurements the standard has to be operated with the companion battery pack.
The measurements at both ranges have to be carried out at the frequencies 1 kHz, 20 kHz, 100 kHz and 1 MHz. The Fluke 792A is considerably sensitive for voltage level and temperature variations at the higher frequencies and in certain extend for the relative humidity. This is the reason why these parameters have to be measured exactly and corrections have to be made. Also the output voltage of the supply battery can influence the measurement result, so a dummy load (included with the travelling standard) should be connected to the battery output and the voltage must be recorded. For this parameter the pilot-laboratory only will correct the results, if necessary.
The input resistance of the travelling standard varies at higher frequencies, which has to be taken in account at the measurement set-up and the uncertainty budget.

Details of the travelling standard:

Type	:	Fluke 792A
Serial number	:	5495003
Dummy load	:	self-made by SP; impedance equal to input Fluke 792A
Temperature coefficient	:	provided by SP
Relative humidity	:	provided by SP

Note: 700 mV-range is not working properly, but is not used in this comparison.

<u>Table 1. Temperature & relative humidity coefficients of the travelling standard.</u>

Range: 220 mV	Temp. coeff.	Exp. unc.	Rel.Hum. coeff.	Exp. unc.
Freq (kHz)	(µV/V)/K	(µV/V)/K	(µV/V)/%	(µV/V)/%
1	**0.4**	1	**0**	0.02
20	**0.4**	1	**0**	0.05
100	**0.6**	1	**0.1**	0.1
1000	**10**	4	**1.3**	0.5

Range: 22 mV	Temp. coeff.	Exp. unc.	Rel.Hum. coeff.	Exp. unc.
Freq (kHz)	(µV/V)/K	(µV/V)/K	(µV/V)/%	(µV/V)/%
1	**1.2**	2	**0**	0.02
20	**1.2**	2	**0**	0.05
100	**1.3**	2	**0.1**	0.1
1000	**17**	8	**0.9**	0.5

For more detailed information see the technical protocol of this comparison.

2.2 The VSL standards for low voltages

To 100 kHz the VSL primary AV-DV transfer standards for this low voltage ranges are derived from our set of three-dimensional Multi Junction Thermal Converters (MJTC's) and our new Planar Multi Junction Thermal Converters (PMJTC's). Both converter types are manufactured at the Physikalisch-Technische Bundesanstalt (PTB). The 3D MJTC's are mounted in a cylindrical metal housing developed by VSL and the AV-DV behaviour is characterized for the contribution of the element and the housing [450..454, 406, 407, 458]. For frequencies above 100 kHz we switch over to our own developed calculable HF-S converter as primary standard [459].

Until now the low voltage primary AV-DV transfer standards of VSL exist of a self-built resistor divider in combination with conventional thermal converters. The standards are characterized for their voltage dependence, so it can be used at lower voltages than it was calibrated for [404]. With this combination we calibrated our working standard Fluke 792A_005. This standard will be used as check for systematic errors in this comparison. Also our new PMJTC's are now used to characterize the Fluke 792A_005 at the 200 mV and 100 mV-range.

For calibrating the travelling standard we make use of both of our new micropotentiometer sets, one set is the Holt 12 type and the other one is the Ballantine 1351 set.
The standard type Holt 12 has an output voltage range from 2 mV to 200 mV and consists of a thermal element of 5 mA in combination with a number of disk-resistors. It has a high input voltage (10 V) and continuous availability of all ranges, so no change of resistors is necessary. In this way noise and thermal effect are limited [410, 411].
The other micropotentiometer set, the Ballantine 1351 consists of several disk resistors which have to be connected to converters with each a different current range. The disk resistors have values of 22 ohm and 4,7 ohm, the current ranges are 5 mA and 10 mA. All the ranges from 200 mV down to 10 mV are possible with combinations of the mentioned values.
The traceability here of the 200 mV range to national standards at lower frequencies is realized with our Fluke 792A_005 to the 3D-MJTC's (<=100 kHz) and at the higher frequencies (>= 200 kHz) with our Fluke A55 commercial set to the VSL HF-S calculable converter.

2.3 Measurement method

The measurements have been performed at our operating systems which are available for AV-DV measurement to 1 MHz (OS 4 and OS 2). Both systems have build-in facilities to obtain settings for compensation of several parameters, see also chapter 3. The travelling standard, in this comparison called the SP_Fluke 792A, is measured against the VSL reference AV-DV standard Holt 12 on operating sytem 4 and against the Ballantine 1351 set on system 2. The measurements determine the AV-DV error of the DUT by measuring the difference between the REF and the DUT and correcting for the error of the reference, all realised by the use of a step-down procedure.

The AV-DV transfer difference is determined by:

$$\delta = \frac{\boldsymbol{U}_{av} - \boldsymbol{U}_{dvavg}}{\boldsymbol{U}_{dvavg}} \qquad (1)$$

Where:

δ	AV-DV difference (-)
U_{av}	RMS value of the supplied alternating voltage (V)
U_{dvavg}	average of a positive and a negative supplied direct voltage to produce the same output voltage as the voltage U_{av} (V)

Calibration of the DUT with the Holt 12 micropotentiometer.

First the SP_Fluke 792A (DUT) is calibrated on the 200 mV-level against the VSL Planar Multi Junction Converter, PMJTC-2 (REF). The reference value was determined on the 1 V-level with a combination of our 3D MJTC 6, our HFS3 calculable converter and some PTB-values of the PMJTC2 itself. For voltage dependence of the PMJTC-2 an uncertainty contribution is added to the uncertainty calculation for the 200 mV-level. An input resistor divider (: 3) is used to solve the problem of the 50 ohm output resistance of the source (Fluke 5720A) at voltages below 220 mV. Figure 1 shows the set-up of this measurement.

Figure 1. PMJTC-2 against SP_792A at 220 mV-range

All the measurements with Holt 12 micropotentiometer and the VSL Fluke 792A_005 against the travelling standard (SP_03) are carried out on exactly (within 1*10E-04) the input voltages. By doing this we eliminated the influence of the voltage dependence of the travelling standard as well as for the VSL Fluke 792A.
To check if there are systematic errors in the measurements with the PMJTC-2, an extra measurement with the VSL 792A_005 is carried out on the 200 mV-level. The Fluke 792A_005 is directly traceable to our 3D MJTC-7 at the range of 220 mV. From this point on the micropotentiometer Holt 12 reference takes over to realize the step-down procedure. The Holt 12 is calibrated at 200 mV and without disconnecting used on the 100 mV-level to calibrate the SP_Fluke 792A. This procedure repeats itself until the 10 mV-level is reached. The advantage of using this micropotentiometer is that it has a very low input voltage dependence and temperature dependence. Hence it can be calibrated at full range and further be used at half range and no additional temperature corrections have to be made.
At the 100 mV level we controlled the contributions of the setup uncertainties by checking the obtained results of the travelling standard via the Holt 12 with results of this range obtained through the measurements with our Fluke 792A_005 and the VSL PMJC-2 (see fig. 3).
In the end the results of the 10 mV range are verified with our Fluke 792A 10 mV range. All the information is used to make a good estimation of several uncertainty contributions.

Figure 2. Holt 12 against SP_792A at 220 mV-range

Figure 2 shows the set-up of the measurements between the Holt 12 en de SP_Fluke 792A. A special N-male to N-male is used to connect the central ground.
Also the low output of the thermal element of the micropotentiometer is connected to the central ground.

Temperature and relative humidity were constantly monitored during the measurements. The sensor was placed under the carrying handle of the Fluke 792A. Some gradient errors have to be taken in account at the calculations of the uncertainties caused by measuring point because there were differences of temperature and humidity between the measuring point and other places (for instance at TEE).

The different resistors of the micropotentiometer Holt 12 are all mounted in one fixed housing, together with the thermal element and the input resistor. At the 100 mV-level and the 10 mV-level we checked the Holt 12 measurements on systematic errors by calibrating the SP_Fluke 792A with the VSL_Fluke 792A.

Another point of concern is the change in range switching of the SP_Fluke 792A. Due to the change of input impedance between the 220mV range and the 22mV range of the instrument there will occur a systematic error at frequencies above 100 kHz. To overcome this problem we first calibrated the SP_Fluke 792A at 20 mV on the 220mV range, followed by a calibration of the VSL_Fluke 792A on 20 mV on the 22 mV range. At least a measurement between the VSL_Fluke 792A and the SP_Fluke 792A, both at 20 mV-level on the 22mV range, was realized. A disadvantage of this method is a loss in resolution, but it will give a good impression of the errors caused by the impedance change.

Figure 3 shows the total chain of the step-down procedure of the measurements with the Holt 12 micropotentiometer. Because of temperature and relative humidity dependence both parameters are measured during the measurements. In every step the AV-DV differences for the DUT are corrected for temperature and relative humidity variations.
Each result of the DUT can be corrected to 23.0 degrees and 45 % RH or only corrections based on the difference in temperature between two measurements can be made. We used both options, because on one hand we want to have the right corrections for the Holt 12 directly, not only a transfer value. On the other hand we want to make corrections which are as small as possible, for better uncertainties.

In the beginning all the measurements are carried out with an input voltage large enough to generate a nominal output voltage of 7 mV on the Holt 12 transfer standard. However, due to the voltage dependence of Fluke 792A we adjusted the input voltage to the exact value (within 100 ppm), so corrections for voltage dependence are no longer of interest and can be omitted.

Step-down procedure

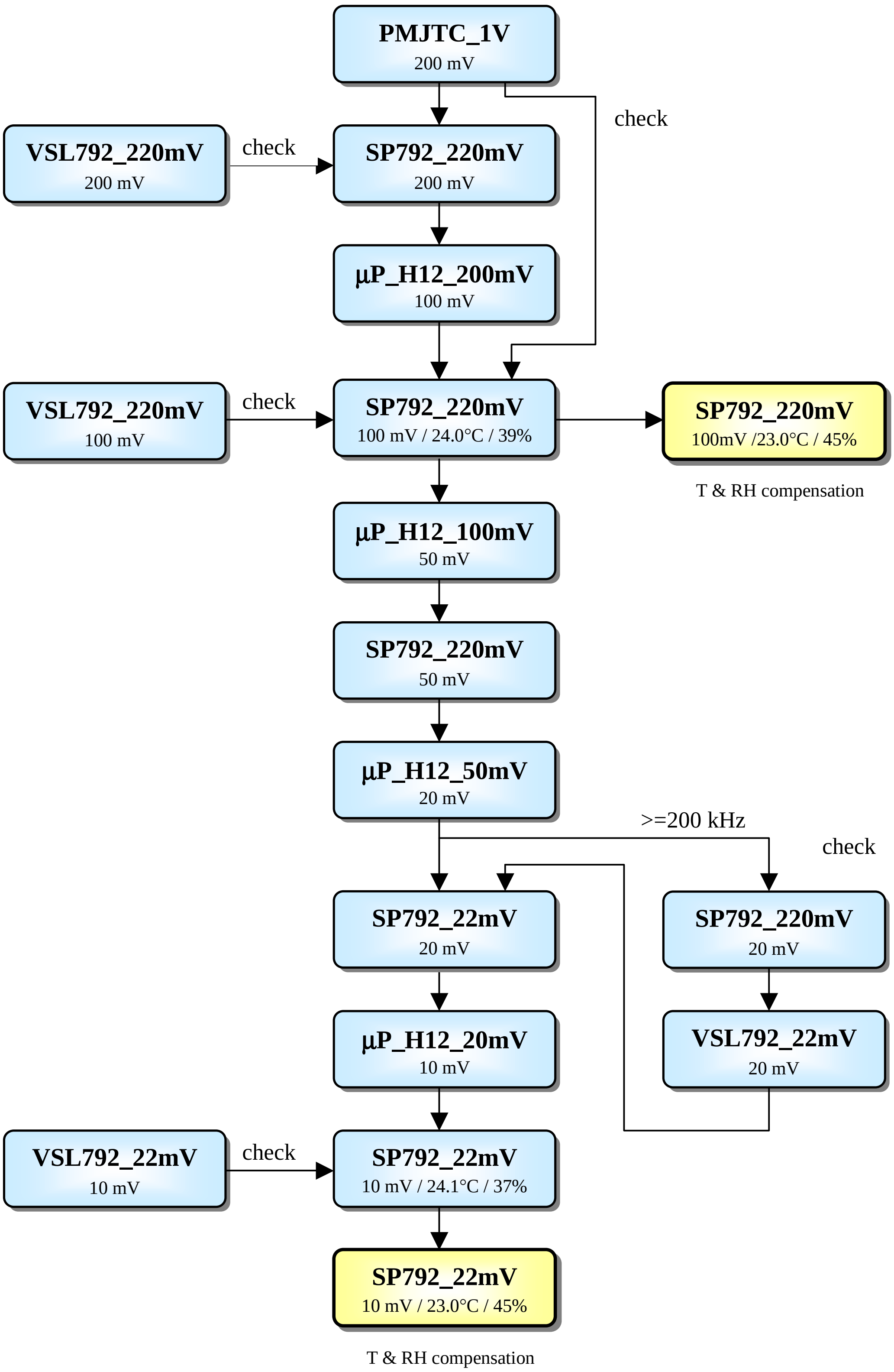

Figure 3. Step-down procedure of the low voltage AV-DV measurements via Holt 12.

Calibration of the DUT with the Ballantine 1351.

The measurements done with Ballantine 1351 micropotentiometer set are realized on our operating system that is normally used for HF-calibrations, known as OS2. Again a stepdown procedure (fig. 5) is used to measure the ranges of the travelling standard from 200 mV down to 10 mV.
Different sources and setups give different contributions to the total uncertainty, so we can base our estimations for the setup uncertainties on more information.
First the SP_Fluke 792A (DUT) is calibrated on the 200 mV-level against the VSL HF1A converter., The reference value of this converter was determined with the VSL Fl792A_005. Checks of this results are realized with the VSL Fl792A_005 at the 700 mV-range and on the 1 V-level with the VSL FLA55-WB, which on its turn is traceable to the VSL HF-S calculable converter.
From the 200 mV-level of the SP Fluke 792A the micropotentiometer Ballantine 1351 takes over to realize the step-down procedure. The Ballantine 1351 is calibrated at 200 mV and without disconnecting used on the 100 mV-level to calibrate the SP_Fluke 792A. This procedure repeats itself until the 10 mV-level is reached. Mostly the same as described by the Holt 12 measurements.
In the end the results of the 10 mV range are verified with the results which we obtained via the Holt 12 set. All the information is used to made a good estimation of several uncertainty contributions.

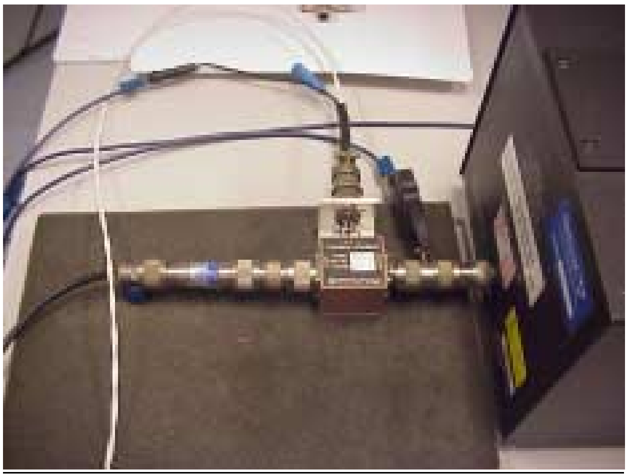

Figure 4. Ballantine 1351 against SP_792A at 220 mV-range

Figure 4 shows the set-up of the measurements between the Ballantine 1351 en de SP_Fluke 792A. A special N-male to N-male is used to connect the central ground. Also the low output of the thermal element of the micropotentiometer is connected to the central ground.

Temperature and relative humidity were constantly monitored during the measurements. Figure 5 shows the total chain of the step-down procedure of the measurements with the Ballantine 1351 micropotentiometer. In every step the AV-DV differences for the DUT are corrected for temperature and relative humidity variations.

Step-down procedure

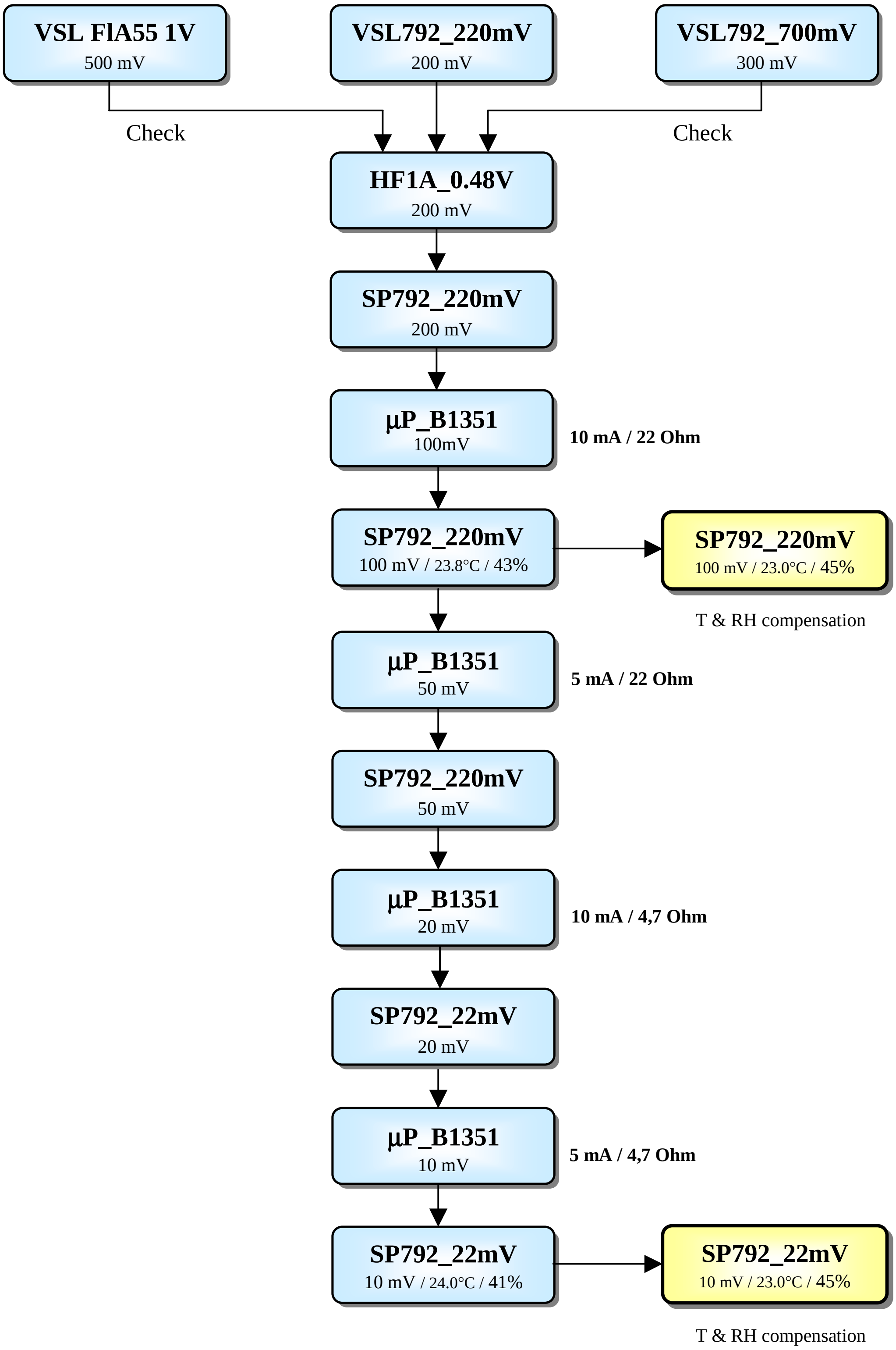

Figure 5. Step-down procedure of the low voltage AV-DV measurements via Ballantine 1351.

3 Measurement set-up

The measurements were carried out on both of the VSL operating systems for determination of the AV-DV differences of transfer standards. One of the systems for this comparison is operating system number 4 (OS 4). This is the system which is mostly used for low frequencies. Figure 6 gives a good overview of this system.
The second system (OS2) is the one mostly used for high frequency calibrations. It is not showed in detail because it is basically the same as the one described below.

The measurement set-up consists of an alternating voltage source (Fluke 5720A) and a direct voltage source (Fluke 5720A). Both sources are floating and internally guarded to give the system the possibility of grounding at one point. The alternating or direct voltage is in turn connected to the micropotentiometer (Holt 12) by an AV-DV switch. This action is controlled via IEEE interfacing of the computer.

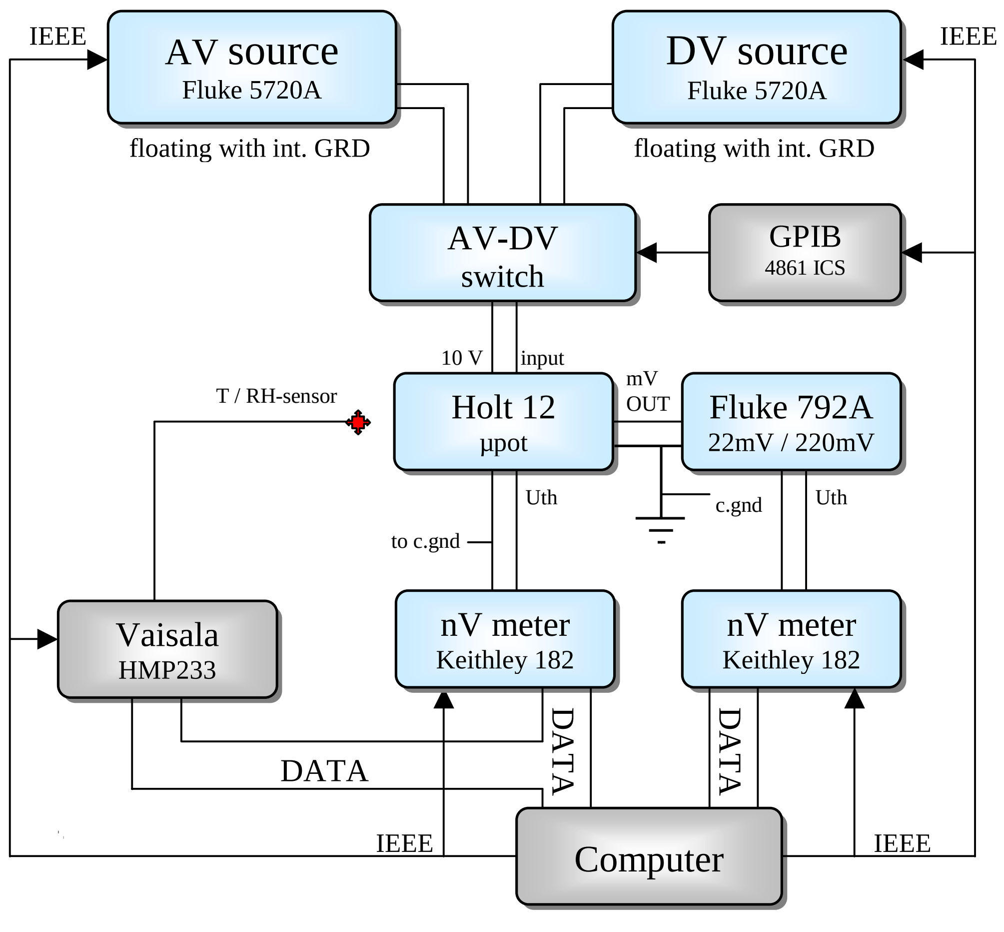

Figure 6. Measurement set-up realised on VSL operating system OS 4.

The Holt 12 generates output voltages from 2 mV to 200 mV at an input voltage of 10 V. The comparison of the rms values of the alternating and direct voltage is controlled by the thermal element of the micropotentiometer. The divided output voltage (mV OUT) of the micropotentiometer is measured by the SP_Fluke 792A on the 22 mV and the 220 mV range. The outputs of the thermal element of both transfer standards (Uth) are simultaneously read with two nV-meters. Because of the importance of the temperature and relative humidity these parameters are continuously monitored during the measurement. The data of all the meters is collected by the computer and transferred to AV-DV differences.

The central point of grounding is chosen on the place where the low output of mV OUT is connected to the low of the SP_Fluke 792A input. This input low of the Fluke 792A is internally connected to the low of the output Uth. The low of output Uth of the Holt 12 standard is floating, so this point is connected to the central ground. Also all the guards of the connecting cables are on one side tied with the central grounding point.

Before the actual measurement starts, determination of the sensitivity of both standard will take place. Together with this parameter and a DV-characterization, which delivers a DV-average point, the AV adjustment at a certain frequency is started. After this action a sequence of DV+, AV(freq1), DV-, AV(freq1), DV+,…. is supplied to the input of the standards. The length of the sequence depends on the chosen number of cycles (normally 5). The AV-DV differences will be calculated from the differences in Uth of the standards between the average of supplied DV+ / DV- and AV(freq1).
Next step is the AV-adjustment of the next frequency (freq2) and supplying a new sequence with this frequency.

The used step-down method (see chapter 2.3) causes that first the Fluke 792A is the reference for calibrating the Holt 12 at a certain level and next the Holt 12 is the reference for calibrating the Fluke 792A at a lower level. A great advantage of this system is the low voltage dependence of the Holt 12 and that disconnecting of the standards between the two measurements is not necessary. This will result in more consistency of the measurements.

At lower voltage levels also measurements are made to the reference point 1 kHz instead of the DV-average point. Moreover an extra measurement with a high cycle number is taken to determine the AV-DV difference of 1 kHz to DV. The advantage of this procedure is that the output of the converters are more stable, which results in lower standard deviations.

4 Measurement results

4.1 Environmental conditions

The measurements were performed under the following conditions:

Ambient temperature : (23.9 ± 1.0) °C

Relative humidity : (40 ± 10) %

The temperature and relative humidity were monitored during the measurements with a sensor, which was placed near the standards. The results are corrected for both the measured parameter variations. The measurements have been carried out in January 2006.

4.2 Power supply voltage

The output voltage of the Fluke 792A Power pack was measured before and after the measurements with the special power pack testing box, provided by SP. From all the measurements we made we calculate the average value of the voltage decrease for this particular power pack.
From results with our own power pack we also know that there is a warming up phenomenon. After loading and activating the power pack an increase of the output voltage of 100 µV in the first 20 minutes will appear before the output voltage starts decreasing. This is the reason why we don't start the measurement within 30 minutes after activating the power pack.
We made no correction for the possible influence of this supply voltage variation. If necessary it will be done by the pilot laboratory.

4.3 Measuring frequency

The aim for the accuracy of the supplied input signal was the frequency has to be within 1% of nominal. An HP 3458A in frequency measurement mode was used to check this. The results and the expanded uncertainties of these measurements are reported in the Summery of results (appendix 1) of this report.

4.4 References & Transfer measurement results

The results of the transfer measurements of the used reference standards and the travelling standard Fluke 792A are shown in the next tables. Table 2 represents the values and uncertainties of the reference standards. The planar converter PMJTC2 is measured against our 3D-MJTC6 (<=100 kHz) and our calculable HF-standard HF-S3 (1 MHz). The corrections used for the PMJTC2 are a combination of these results and some known values from the PTB-certificate.
The reference PMJTC2 is the startpoint of the stepdown procedure of the travelling standard and the micropotentiometer set Holt12.

The VSL Fluke 792A_005 is at 200 mV measured against the 3D-MJTC7, which on higher frequencies is traceable to the HF-S3 calculable converter of VSL. The VSL Fluke 792A_005 is used for the measurements with the Ballantine micropotentiometer set and the controlling measurements at the Holt 12 stepdown.

Table 2. AV-DV values and their uncertainties of the used references

	PMJTC2	Unc.(*k*=2)	**Fl92A_005**	Unc.(*k*=2)
Range:	1 V		220 mV	
Date:	01-Jan-06		01-Sept-04	
Ref:	MJTC6&HF-S3&PTB		MJTC7&(HF-S3)	
Freq (kHz)	(µV/V)	(µV/V)	(µV/V)	(µV/V)
1	**0.0**	1.7	**3**	7
20	**2.2**	2.0	**-9**	7
100	**7.5**	3.0	**9**	9
1000	**42**	21	**-46**	26

The step-down procedure consists of a lot of measurements; to give a reasonable overview we limited the data in this report to the 100 mV and 10 mV-level. The next tables show the measurements of Holt 12 at 200 mV with the SP_Fluke792A as reference, directly followed by a measurement of the 100 mV range of the SP_792A with the Holt 12 as reference. Used temperature and relative humidity coefficients of the output voltage of the Fluke 792A are mentioned in chapter 2.1.
De next formule is used for correction of the AV-DV transfer difference with these parameters:

$$\delta_{REF(T2/RH2)} = \delta_{REF(T1/RH1)} + (T2 - T1) * \alpha_T + (RH2 - RH1) * \alpha_{RH}$$

where

$\delta_{REF(T2/RH2)}$	AV-DV transfer difference at desired temperature and relative humidity
$\delta_{REF(T1/RH1)}$	AV-DV transfer difference at measured temperature and relative humidity
(T2 –T1)	difference between desired and measured temperature
α_T	temperature coefficient of the travelling standard (see table 1, page 5)
(RH2 – RH1)	difference between desired and measured relative humidity
α_{RH}	relative humidity coefficient of the travelling standard (see table 1, page 5)

The *measured* temperature / rel. humidity is the value at which the reference is calibrated, if it is used in a measurement at other temperature or relative humidity it has to be corrected to the *desired* one.

The measurements were carried out at different temperature and humidity. The average value (column 2 table 3) of both measurements is the desired one. Because the measured value of the temperature and humidity of the reference was the same as the average no compensation was needed this time. The reference value of the SP Fluke 792A was determined at exactly 200 mV and the measurement with the Holt 12 also, therefore no voltage dependence correction was not needed here.

Table 3. AV-DV differences of Holt 12 at 200 mV-level

	H12_SP03 (avg)		SP792_220m	**H12_200mV**
Input:	200.00 mV	std.dev.	200 mV	200 mV
Freq (kHz)	(µV/V)	(µV/V)	(µV/V)	(µV/V)
1	18.9	0.8	5.7	**-13.2**
20	3.3	0.8	-9.0	**-12.3**
100	15.7	0.9	13.2	**-2.5**
1000	105.0	0.9	1.8	**-103.2**

Temp:	24.0 °C	24.0 °C
Rel.Hum.:	39.1 %	39.1 %
Accu:		
before +:	11.097 V	
before -:	-11.160 V	
after +:	11.096 V	
after -:	-11.159 V	

Table 4. AV-DV differences of SP_Fluke 792A at 100 mV-level

	H12_SP03 (avg)		H12_200mV	SP792_220m	**SP792_220m**
Input:	100.00 mV	std.dev.	200 mV	100 mV	100 mV
Freq (kHz)	(µV/V)	(µV/V)	(µV/V)	(µV/V)	(µV/V)
1	19.2	1.5	-13.2	6.0	**5.6**
20	4.9	1.7	-12.3	-7.4	**-7.8**
100	17.2	1.9	-2.5	14.7	**14.8**
1000	129.6	1.6	-103.2	26.4	**25.2**

Temp:	24.0 °C	24.0	**23.0**
Rel.Hum.:	38.6 %	38.6	**45.0**
Accu:			
before +:	11.096 V		
before -:	-11.159 V		
after +:	11.095 V		
after -:	-11.158 V		

The last column of table 3 gives the result of the 200 mV-micropotentiometer of Holt 12. This result is compensated so we have a real standard value now instead of a transfer value. This correction value of the Holt 12_ 200mV is compared with results gathered in 2002, only differences of 0 to 7 ppm were found.
The last column of table 4 represents the end result of the step-down procedure to the 100 mV-level. The SP Fluke 792A is on the 220 mV range calibrated at the 100 mV-level on exact 100 mV. This value is temperature and humidity corrected to 23 °C and 45 %. No voltage compensation was necessary.

The next tables show the measurements of Holt 12 at 20 mV with the SP_Fluke792A as reference, directly followed by a measurement of the 10 mV range of the SP_792A with the Holt 12 as reference. The reference SP Fluke 792A at the 20 mV-level was calibrated via two ways to see the influence changing of input impedance (see fig. 3). Only differences of about 10 ppm between the two ways were found, so VSL choose for the result with the lowest uncertainty. The other way (via VSL Fl792A) was used as check measurement.

Table 5. AV-DV differences of Holt 12 at 20 mV-level

	H12_SP03 (avg)		SP792_22m	**H12_20mV**
Input:	20.000 mV	std.dev.	20 mV	20 mV
Freq (kHz)	(µV/V)	(µV/V)	(µV/V)	(µV/V)
1	27.0	4.0	0.7	**-26.3**
20	-21.1	4.0	-12.7	**8.4**
100	-131.0	4.0	-27.8	**103.2**
1000	-1203.7	4.0	-219.6	**984.1**

Temp:	24.1 °C	24.1 °C
Rel.Hum.:	38.2 %	38.2 %
Accu:		
before +:	11.095 V	
before -:	-11.159 V	
after +:	11.094 V	
after -:	-11.158 V	

The results for the Holt 12 standard at the 20 mV-level are calculated with the compensated reference values at 24.1 °C and 38.2 %. The average values of both measurements. This result can thus also be used as real standard value instead of transfer value only. This Holt 12 value is the reference value for the determination of the SP_Fluke 792A at the 10 mV-level, the last step in this comparison.

Table 6. AV-DV differences of SP_Fluke 792A at 10 mV-level

	H12_SP03 (avg)		H12_20mV	SP792_22m	**SP792_22m**
Input:	10.000 mV	std.dev.	20 mV	10 mV	10 mV
Freq (kHz)	(µV/V)	(µV/V)	(µV/V)	(µV/V)	(µV/V)
1	31.1	6.6	-26.3	4.8	**3.5**
20	-19.4	6.7	8.4	-11.0	**-12.3**
100	-128.5	6.7	103.2	-25.3	**-26.0**
1000	-1156.0	6.7	984.1	-171.9	**-183.5**
Temp:	24.1 °C			24.1	**23.0**
Rel.Hum.:	37.1 %			37.1	**45.0**
Accu:					
before +:	11.094 V				
before -:	-11.158 V				
after +:	11.093 V				
after -:	-11.157 V				

For calibrations at the 10 mV-level (table 6), both corrections for temperature as well as for relative humidity have to be made. The difference between the values of the reference Holt 12_20mV measured now compared to results from 2002 at 10 mV is larger than at the 100 mV level. This is the reason why we have taken this in account in the uncertainty calculations later on (see appendices).

All the measurements done with the step-down method are realised the same way as the two ranges mentioned above. In the last result tables we summarize the values of the Euromet K11 comparison. Both methods shows good conformity, because of the lowest uncertainty is reached by the measurements with the Holt 12 micropotentiometer procedure, this will represent our end result. The results of the measurements with the Ballantine 1351 set gives a good view about the contributions of uncertainty caused by changing of setup (different sources, software, guarding) and references.

Table 7. Total overview AV-DV differences of SP_Fluke 792A at 100mV-level

	SP792_220m		SP792_220m	
	ref=H12_200mV	$U_{EXP(k=2)}$	ref=B1351_200mV	$U_{EXP(k=2)}$
Input:	**100 mV**		100 mV	
Freq (kHz)	**(µV/V)**	(µV/V)	(µV/V)	(µV/V)
1	**5.6**	6.8	9.5	15.2
20	**-7.8**	7.5	-10.7	15.0
100	**14.8**	9.9	14.0	22.3
1000	**25.2**	38.8	24.2	52.2
Temp:	23.0 °C		23.0 °C	
Rel.Hum.:	45.0 %		45.0 %	

The results in above table (column 2) represent the values of the AV-DV difference of the SP_Fluke 792A at the 100 mV level in the 220mV range. The uncertainties (column 3) are the calculated values corresponding to these values, the composition of this uncertainty budget is added to this report, see appendix 3.
In the summary of the results of this comparison (appendix 1) the expanded uncertainties are rounded to the nearest higher uncertainty in row. Column 4 represents the values as carried out by the Ballantine set, which gives a good impression of the estimated contribution of the systematic errors.
Check measurements with our Fluke 792A_005 at 200 mV & 100 mV level on the 220mV-range were very satisfying if we take the uncertainties in account.

Table 8. Total overview AV-DV differences of SP_Fluke 792A at 10mV-level

	SP792_22m		SP792_22m	
	ref=H12_20mV	$U_{EXP(k=2)}$	ref=H12_20mV	$U_{EXP(k=2)}$
Input:	**10 mV**		10 mV	
Freq (kHz)	**(µV/V)**	(µV/V)	(µV/V)	(µV/V)
1	**3.5**	27.8	6.6	42.7
20	**-12.3**	28.6	-11.7	40.3
100	**-26.0**	32.6	-36.8	49.5
1000	**-183.5**	91.7	-209.4	94.8
Temp:	23.0 °C		23.0 °C	
Rel.Hum.:	45.0 %		45.0 %	

The measurement results at the 10 mV-level are summarized in table 8. Here also the results of the two different step-down procedures are in good agreement with each other.
Results with the VSL 792A_005 at the 10 mV-level on the 22 mV-range, which were used as control measurements, show us that the comparison was successful and useful.

In the next chapter we show how all the uncertainties contributions are included in the calculations of the expanded uncertainty.

5 Uncertainty calculations

The uncertainty budgets mentioned in this report are based on the reference publication EA-4/ 02 Expression of the Uncertainty of Measurement in Calibration which is in agreement with the recommendations of the Guide to the Expression of Uncertainty in Measurement.
The different contributions to the uncertainty budget are schematic summarized in figure 7.

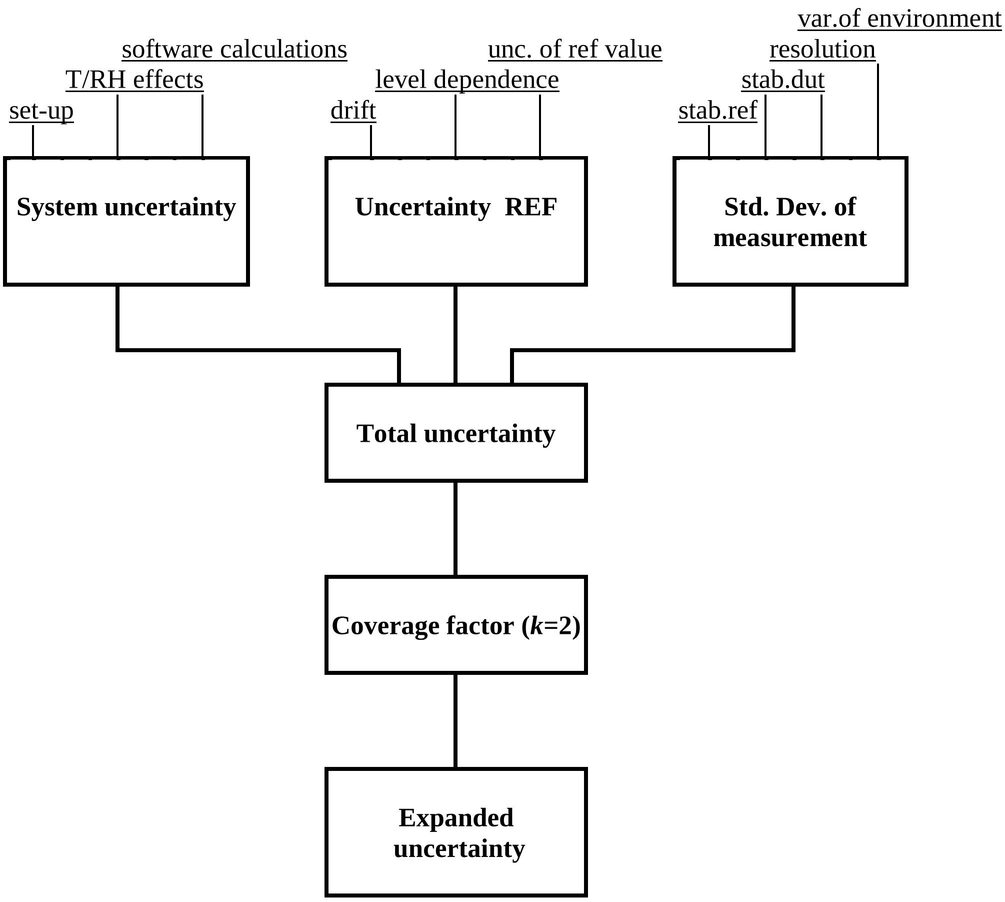

Figure 7. Expression of the contributions to the expanded uncertainty budget of AV-DV measurements at low voltages.

Normally the set-up contribution of the measurement system contains the estimated errors caused by used cables, connectors, grounding, loading, environmental conditions and reproducibility. If one of the included contributions forms a substantial part it will be mentioned separately. For this comparison we took out the contributions of the reproducibility, connectors, temperature and relative humidity. The loading effect was only separated from the setup uncertainty if there was range-switching of the Fluke 792A. The temperature and humidity for the Fluke 792A was a source of uncertainty, therefore we added this contribution to the existing equation. The drift of the standards is estimated to zero, so it will be omitted from the uncertainty tables (appendix 3).

For determination of the AV-DV difference of the device under test counts now the following equation:

$$\delta_{DUT} = \delta_{REF} + d_{level} + d_{drift} + d_{temp} + d_{RH} + (\delta_{m,REF} - \delta_{m,DUT})\cdot d_S + d_{set\text{-}up} + d_{repr} + d_{conn} + d_{load}$$

δ_{REF}	AV-DV difference of the reference
d_{level}	voltage level of the AV-DV difference
d_{drift}	long term drift of the reference
d_{temp}	temperature dependence of AV-DV difference
d_{RH}	relative humidity dependence of AV-DV difference
d_S	determination of the sensitivity (relative)
$d_{set\text{-}up}$	set-up of the measurement
d_{repr}	reproducibility of the measurement
d_{conn}	influence of used connectors
d_{load}	influence of input impedance of the Fluke 792A

Due to the chosen step-down method the AV-DV difference of the reference will constantly change from Holt 12 to SP_Fluke 792A.

Description of the different contributions:

- The uncertainty in voltage level of the AV-DV difference for the Fluke 792A consist of the remaining difference between input voltage of calibration and followed measurement. For the Holt 12 the level changes from full range to half range.
- The long-term drift was estimated to zero for both standards because of the very short time between calibration and using the value in the measurement.
- The contributions of the temperature and humidity dependence only counts for the Fluke 792A. The pilot lab provides coefficients and uncertainty. Also the uncertainty in measuring the temperature and humidity is taken in account here. No corrections for the Holt 12 temperature are taken.
- The uncertainty in the determination of the sensitivity is supposed to be always less than 1%. This contribution is mainly determined by the magnitude of the AV-DV difference.
- Set-up contribution is the summarized influence of the remaining uncertainty caused by used cables, grounding and environmental conditions; it is estimated by acquired experience with this kind of measurements.
- The reproducibility of the measurement was determined by a second measurement on a later point of time.
- Influence caused by changing the connectors was based on measurements done earlier on the 200 mV-level, for lower voltages we increased the values by estimating. When the connectors were not changed during two following measurements the value was stated on zero.
- Loading effect by range switching can also causes some change in AV-DV difference.

For the determination of the AV-DV difference and the corresponding uncertainty in the 100mV and 10mV range at 1 kHz we realized following tables based on the EA-4/ 02 publication.
All other frequencies are mentioned in appendix 3, include at the end of this report.

Table 11. AV-DV difference with uncertainty of SP_Fluke 792A on 100mV-level at 1 kHz.

Quantity	Estimate	Sensitivity coefficient	Probability distribution	Standard uncertainty	Uncertainty contribution
δ_{REF}	-13.2	1	normal	2.4	2.4
d_{level}	0	1	rectangular	0.0	0.0
δm,REF - δm,DUT	19.2	1	normal	1.5	1.5
d_S	1	19.2	rectangular	0.01	0.1
d_{temp}	-0.38	1	rectangular	1.07	0.6
d_{RH}	0.00	1	rectangular	0.13	0.1
d_{set-up}	0	1	rectangular	3.0	1.7
d_{repr}	0	1	rectangular	1.0	0.6
d_{conn}	0	1	rectangular	0.0	0.0
δ_{DUT}	**5.6**			U_{TOTAL}	3.4
				$U_{EXP(k=2)}$	**6.8**

Table 12. AV-DV difference with uncertainty of SP_Fluke 792A on 10mV-level at 1 kHz.

Quantity	Estimate	Sensitivity coefficient	Probability distribution	Standard uncertainty	Uncertainty contribution
δ_{REF}	-26.3	1	normal	11.0	11.0
d_{level}	0	1	rectangular	0.0	0.0
δm,REF - δm,DUT	31.1	1	normal	6.2	6.2
d_S	1	31.1	rectangular	0.01	0.2
d_{temp}	-1.32	1	rectangular	2.56	1.5
d_{RH}	0.00	1	rectangular	0.16	0.1
d_{set-up}	0	1	rectangular	7.0	4.0
d_{repr}	0	1	rectangular	7.0	4.0
d_{conn}	0	1	rectangular	0.0	0.0
δ_{DUT}	**3.5**			U_{TOTAL}	13.9
				$U_{EXP(k=2)}$	**27.8**

6 Conclusions

The measurements for the Euromet.EM-K11 key comparison performed at the NMi Van Swinden Laboratorium were quite intensive, but useful. Our equivalence to other National Measurement Institutes worldwide in the field of measuring AC-DC voltage transfer differences at low voltages was already proven with the results of the CPIM key comparison CCEM-K11. This result and further research provided us to upgrade the values and uncertainties of our standards for the low voltage ranges.

Now we can prove our compatibility with a lot of regional National Measurement Institutes within this Euromet comparison. Micropotentiometers are stable enough for service as reference standard at low voltages and are not very sensitivity for temperature, humidity variations and input levels. The agreement between measurements results at different times, setups and with different standards was very good in relation to their related uncertainties.

Before the start of the first comparison at low voltages the uncertainties for calibrations at the level of 100 mV to 10 mV amounted 20 ppm to 2000 ppm. At this moment we were able to lower our uncertainties to 7 ppm at 1 kHz on the 100 mV-level and to 100 ppm at 1 MHz on the 10 mV-level.

7 References

404	LSS-91	New low voltage standards for the range of 20 mV- 200 mV, March 1991 (J.T. Dessens)
406	94/SEL182/CM	AC-DC Voltage transfer at the lowest level of uncertainty, CCE 92-3, (C.J. van Mullem, J.T. Dessens, J.P.M. de Vreede), Sept '94
407	95/SEL/CM01	Addition to AC-DC Voltage transfer at the lowest level of uncertainty, CCE 92-3, (C.J. van Mullem, J.T. Dessens), Sept '95
410	RVD-96-E	Calibration of Resistive Voltage Dividers, April 1996 (C.van Mullem)
411	AC_LV-97	AC Measurements in the millivolt Ranges, December 1997 (S. Campos Hernandez)
419	IKR-CCEM-K11	CCEM-K11 Key comparison: AC-DC Voltage transfer difference at low voltages (J. T. Dessens (author), C.J. van Mullem.), may '02
420	Total report CCEM-K11	CCEM-K11 Key comparison: AC-DC Voltage transfer difference at low voltages incl. unc. and data (J. T. Dessens) august '05
450	VSL-BCR-8609 ET	Intercomparison measurements of thermal ACDC-transfer standards, August 1987 (C. Harmans)
451	PTB –E-29	PTB-Bericht Entwicklung von vielfachthermokonvertern..., March 1987 nr E-29 (M. Klonz).
453	IEEE-93-1	CCE Intercomparison of AC-DC Tranfer Standards (C. Harmans, J. Schmitt, J. Dessens, author: J. de Vreede); IEEE April 1993
454	IEEE-93-2	Intercomparison of NIST, NPL, PTB, and VSL Thermal Voltage Converters from 100 kHz to 1 MHz (J. Kinard, R. Knight, P. Martin, M. Klonz, J. de Vreede, and J. Dessens); IEEE April 1993
458	IEEE-97-1	CCE 92-03; Transfer standards at lowest attainable level of uncertainty (M. Klonz) IEEE April 1997
459	IEEE-97-2	C.J. van Mullem, W.J.G.D. Janssen en J.P.M. de Vreede, Evaluation of the Calculable High Frequency AC/DC Standard, IEEE IM-46, pg. 361-364, 1997.

8 Appendices

Appendix 1. Summary of results

Key comparison EUROMET.EM-K11 "ac-dc voltage transfer difference at low voltages"

Please send this information by e-mail also.

Acronym of institute: NMi VSL

Date of measurements: January 02-31, 2006

Remarks: Results are corrected for temperature and humidity variations during the measurements.
Expanded uncertainty is rounded to the nearest next step.

Measuring result:

Voltage	Range	Measured ac-dc voltage difference / 10^{-6} at frequency			
		1 kHz	20 kHz	100 kHz	1 MHz
100 mV	220 mV	5.6	-7.8	14.8	25
10 mV	22 mV	3.5	-12.3	-26.0	-184

Expanded uncertainty:

Voltage	Range	Expanded uncertainty / 10^{-6} at frequency			
		1 kHz	20 kHz	100 kHz	1 MHz
100 mV	220 mV	7	8	10	40
10 mV	22 mV	30	30	35	100

Measuring frequency:

	Nominal frequency			
	1 kHz	20 kHz	100 kHz	1 MHz
Measuring frequency / kHz	1.0000	20.000	100.00	1000.0
Expanded uncertainty / %	0.05	0.05	0.05	0.05

Influence parameters:

	Min	Max	Remarks
Ambient temperature / ºC	23.8	24.1	Measured under Fl792A handle
Relative humidity / %	31.2	43.4	Measured under Fl792A handle
Pos. power supply voltage / V	11.092	11.102	Please state with mV resolution
Neg. power supply voltage / V	-11.156	-11.164	Please state with mV resolution

Appendix 2. Summary of uncertainty budget

Key comparison EUROMET.EM-K11 “ac-dc voltage transfer difference at low voltages”

Please send this information by e-mail also.

Acronym of institute: NMi VSL

Date: 24 February 2006

Remarks: Uncertainty in µV/V
Rounded expanded uncertainty added
No correction for level dependence of the SP Fluke 792 owing to exact input level
No correction for connectors; not disconnected

Measuring voltage: 100 mV

Contribution of:	Std. unc. f: 1 kHz	Std. unc. f: 20 kHz	Std. unc. f: 100 kHz	Std. unc. f: 1 MHz	Type A or B	Distri-bution
Reference	2.4	2.8	3.8	16.0	B	N
Standard deviation	1.5	1.6	1.9	1.6	A	N
Level dependence	0	0	0	0	B	R
Temperature	1.07	1.07	1.13	6.8	B	R
Rel. humidity	0.13	0.32	0.84	5.80	B	R
Sensitivity	0.20	0.04	0.17	1.3	B	R
Setup	3	3	4	15	B	R
Reproducibility	1	1	1	7	B	R
Connectors	0	0	0	0	B	R

Standard unc (k=1):	3.4	3.8	4.9	19.4
Expanded unc:	6.8	7.5	9.9	38.8
Rounded exp. unc:	7	8	10	40
Eff. deg. of freedom:	> 100	> 100	> 100	> 100

Remarks: Uncertainty in µV/V
Rounded expanded uncertainty added
No correction for level dependence of the SP Fluke 792 owing to exact input level
No correction for connectors; not disconnected

Measuring voltage: 10 mV

Contribution of:	Std. unc. f: 1 kHz	Std. unc. f: 20 kHz	Std. unc. f: 100 kHz	Std. unc. f: 1 MHz	Type A or B	Distri-bution
Reference	11.0	11.3	13.2	40.1	B	N
Standard deviation	6.2	6.3	6.3	6.3	A	N
Level dependence	0	0	0	0	B	R
Temperature	2.56	2.56	2.59	13.90	B	R
Rel. humidity	0.16	0.40	0.99	5.75	B	R
Sensitivity	0.30	0.20	1.30	11.6	B	R
Setup	7	7	10	30	B	R
Reproducibility	7	7	7	10	B	R
Connectors	0	0	0	0	B	R

Standard unc (k=1):	13.9	14.3	16.3	45.8
Expanded unc:	27.8	28.6	32.6	91.7
Rounded exp. unc:	30	30	35	100
Eff. deg. of freedom:	> 100	> 100	> 100	> 100

Appendix 3. Uncertainty budgets of the step-down levels

Uncertainty calculations for the standard SP 792A_220mV_200mV.

Freq (kHz)	U_{REF}	$U(\delta m)$	d_{level}	d_{temp}	d_{RH}	$\delta m(R\text{-}D)$	d_s	$d_{set\text{-}up}$	d_{repr}	d_{conn}	U_{TOTAL}	$U_{EXP(k=2)}$
Distribution	Normal	Normal	Rectang.	Rectang.	Rectang.		Rectang.	Rectang.	Rectang.	Rectang.		
	PMJTC2		1V to 0.2V					200 mV			SP200mV	SP200mV
	(uV/V)	(uV/V)	(uV/V)	(uV/V)	(uV/V)	(uV/V)	(%)	(uV/V)	(uV/V)	(uV/V)	(uV/V)	(uV/V)
1	0.9	1.2	0.5	0.12	0.00	6.2	1	2	0.5	0.2	1.9	**3.8**
20	1.0	1.7	0.5	0.12	0.00	-11.5	1	2	0.5	1.0	2.4	**4.8**
100	1.5	1.5	0.5	0.18	0.20	5.7	1	3	0.5	2.0	3.0	**6.0**
1000	10.3	2.1	0.5	3.0	2.60	-39.6	1	10	7.0	7.0	13.5	**27.0**

U_{REF} : Uncertainty of the reference; $k=1$

$U(\delta m)$: Experimental standard deviation of the measurement (at 1kHz to DV, sqrs of the sum)

d_{level} : Uncertainty caused by change in voltage-level; calibration voltage of reference to calibration voltage of dut; estimated

d_{temp} : The total uncertainty caused by the uncertainty of the temp.coeff. and the uncertainty in the measured temperature

d_{RH} : The total uncertainty caused by the uncertainty of the relative humidity coeff. and the uncertainty in the measured relative humidi

$\delta m(R\text{-}D)$: The measured difference between the reference and the device under test

d_s : The accuracy of linearisation of the workpoint; considered that 1% of the difference between REF and DUT.
will always be enough as uncertainty contribution.

$d_{set\text{-}up}$: set-up of the measurement system; estimated errors caused by used cables, connectors, earthing, environmental conditions
loading errors and offsets. If one of the included contributions forms a substantial part it will be mentioned separately.

d_{repr} : reproducibility of the measurement

d_{conn} : influence of used connectors

U_{TOTAL} : The total uncertainty, calculated as root of the sum of the squares

$U_{EXP(k=2)}$: The expanded uncertainty, calculated as twice the total uncertainty

"d" stands for contributions which are not measured during the measurement itself. Because these contributions are rectangular , they are transfered to normal distributions by:

$$u_{norm} = \frac{u_{rect}}{\sqrt{3}}$$

Uncertainty calculations for the standard Holt 12_200mV.

Freq (kHz)	U_{REF}	$U(\delta m)$	d_{level}	d_{temp}	d_{RH}	$\delta m(R\text{-}D)$	d_s	$d_{set\text{-}up}$	d_{repr}	d_{conn}	U_{TOTAL}	$U_{EXP(k=2)}$
Distribution	Normal	Normal	Rectang.	Rectang.	Rectang.		Rectang.	Rectang.	Rectang.	Rectang.		
	SP200mV		< 1*10E-04					200 mV			H12_200m	H12_200m
	(uV/V)	(uV/V)	(uV/V)	(uV/V)	(uV/V)	(uV/V)	(%)	(uV/V)	(uV/V)	(uV/V)	(uV/V)	(uV/V)
1	1.9	0.7	0	0.12	0.00	18.5	1	2	0.5	0.2	2.4	**4.7**
20	2.4	0.8	0	0.12	0.00	2.9	1	2	0.5	1.0	2.8	**5.7**
100	3.0	1.0	0	0.18	0.21	15.0	1	3	0.5	2.0	3.8	**7.6**
1000	13.5	0.8	0	3.00	2.63	104.0	1	10	7.0	7.0	16.0	**31.9**

Uncertainty calculations for the standard SP 792A_220mV_100mV.

Freq (kHz)	U_{REF}	$U(\delta m)$	d_{level}	d_{temp}	d_{RH}	$\delta m(R\text{-}D)$	d_s	$d_{set\text{-}up}$	d_{repr}	d_{conn}	U_{TOTAL}	$U_{EXP(k=2)}$
Distribution	Normal	Normal	Rectang.	Rectang.	Rectang.		Rectang.	Rectang.	Rectang.	Rectang.		
	H12_200m		< 1*10E-04					100 mV			SP100mV	SP100mV
	(uV/V)	(uV/V)	(uV/V)	(uV/V)	(uV/V)	(uV/V)	(%)	(uV/V)	(uV/V)	(uV/V)	(uV/V)	(uV/V)
1	2.4	1.5	0	1.07	0.13	19.5	1	3	1.0	0	3.4	**6.8**
20	2.8	1.6	0	1.07	0.32	4.2	1	3	1.0	0	3.8	**7.5**
100	3.8	1.9	0	1.13	0.84	16.6	1	4	1.0	0	4.9	**9.9**
1000	16.0	1.6	0	6.8	5.80	127.8	1	15	7.0	0	19.4	**38.8**

Uncertainty calculations for the standard Holt 12_100mV.

Freq (kHz)	U_{REF}	$U(\delta m)$	d_{level}	d_{temp}	d_{RH}	$\delta m(R\text{-}D)$	d_s	$d_{set\text{-}up}$	d_{repr}	d_{conn}	U_{TOTAL}	$U_{EXP(k=2)}$
Distribution	Normal	Normal	Rectang.	Rectang.	Rectang.		Rectang.	Rectang.	Rectang.	Rectang.		
	SP100mV		< 1*10E-04					100 mV			H12_100m	H12_100m
	(uV/V)	(uV/V)	(uV/V)	(uV/V)	(uV/V)	(uV/V)	(%)	(uV/V)	(uV/V)	(uV/V)	(uV/V)	(uV/V)
1	3.4	1.1	0	0.22	0.03	23.6	1	3	1.0	0.2	4.0	**8.0**
20	3.8	1.4	0	0.22	0.07	3.6	1	3	1.0	1.0	4.4	**8.9**
100	4.9	1.4	0	0.28	0.35	4.1	1	4	1.0	2.0	5.8	**11.6**
1000	19.4	1.1	0	3.40	3.33	-173.8	1	15	7.0	7.0	22.2	**44.4**

Uncertainty calculations for the standard SP 792A_220mV_50mV.

Freq (kHz)	U_{REF}	$U(\delta m)$	d_{level}	d_{temp}	d_{RH}	$\delta m(R\text{-}D)$	d_s	$d_{set\text{-}up}$	d_{repr}	d_{conn}	U_{TOTAL}	$U_{EXP(k=2)}$
Distribution	Normal	Normal	Rectang.	Rectang.	Rectang.		Rectang.	Rectang.	Rectang.	Rectang.		
	H12_100m		< 1*10E-04					50 mV			SP50mV	SP50mV
	(uV/V)	(uV/V)	(uV/V)	(uV/V)	(uV/V)	(uV/V)	(%)	(uV/V)	(uV/V)	(uV/V)	(uV/V)	(uV/V)
1	4.0	1.5	0	0.12	0.00	21.6	1	4	1.0	0	4.9	**9.8**
20	4.4	1.6	0	0.12	0.00	3.7	1	4	1.0	0	5.3	**10.6**
100	5.8	1.9	0	0.18	0.20	2.9	1	5	1.0	0	6.8	**13.6**
1000	22.2	1.6	0	3.0	2.60	-152.4	1	20	7.0	0	25.5	**51.1**

Uncertainty calculations for the standard Holt 12_50mV.

Freq (kHz)	U_{REF}	$U(\delta m)$	d_{level}	d_{temp}	d_{RH}	$\delta m(R\text{-}D)$	d_s	$d_{set\text{-}up}$	d_{repr}	d_{conn}	U_{TOTAL}	$U_{EXP(k=2)}$
Distribution	Normal	Normal	Rectang.	Rectang.	Rectang.		Rectang.	Rectang.	Rectang.	Rectang.		
	SP50mV		< 1*10E-04					50 mV			H12_50m	H12_50m
	(uV/V)	(uV/V)	(uV/V)	(uV/V)	(uV/V)	(uV/V)	(%)	(uV/V)	(uV/V)	(uV/V)	(uV/V)	(uV/V)
1	4.9	2.0	0	0.17	0.04	28.4	1	4	1.0	0.2	5.8	**11.6**
20	5.3	2.3	0	0.17	0.10	4.9	1	4	1.0	1.0	6.3	**12.5**
100	6.8	2.7	0	0.23	0.41	-17.0	1	5	1.0	2.0	7.9	**15.9**
1000	25.5	2.0	0	3.20	3.63	-475.9	1	20	7.0	7.0	28.9	**57.9**

Uncertainty calculations for the standard SP 792A_22mV_20mV.

Freq (kHz)	U_{REF}	$U(\delta m)$	d_{level}	d_{temp}	d_{RH}	$\delta m(R\text{-}D)$	d_s	$d_{set\text{-}up}$	d_{repr}	d_{conn}	d_{load}	U_{TOTAL}	$U_{EXP(k=2)}$
Distribution	Normal	Normal	Rectang.	Rectang.	Rectang.		Rectang.	Rectang.	Rectang.	Rectang.	Rectang.		
	H12_50m		< 1*10E-04					20 mV				SP20mV22m	SP20mV22m
	(uV/V)	(uV/V)	(uV/V)	(uV/V)	(uV/V)	(uV/V)	(%)	(uV/V)	(uV/V)	(uV/V)	(uV/V)	(uV/V)	(uV/V)
1	5.8	5.8	0	0.36	0.00	22.8	1	5	5.0	0.2	0.5	9.2	**18.4**
20	6.3	6.0	0	0.36	0.00	-0.4	1	5	5.0	1.0	1.0	9.6	**19.2**
100	7.9	6.0	0	0.39	0.20	-58.5	1	7	5.0	2.0	2.0	11.3	**22.5**
1000	28.9	6.6	0	5.10	1.80	-746.6	1	25	7.0	7.0	20.0	35.8	**71.6**

d_{load} : uncertainty contribution caused by change of input range from 220mV to 22mV; loading effect on miropotentiometer.

Uncertainty calculations for the standard Holt 12_20mV

Freq (kHz)	U_{REF}	$U(\delta m)$	d_{level}	d_{temp}	d_{RH}	$\delta m(R\text{-}D)$	d_s	$d_{set\text{-}up}$	d_{repr}	d_{conn}	U_{TOTAL}	$U_{EXP(k=2)}$
Distribution	Normal	Normal	Rectang.	Rectang.	Rectang.		Rectang.	Rectang.	Rectang.	Rectang.		
	SP20mV22m		< 1*10E-04					20 mV			H12_20mV	H12_20mV
	(uV/V)	(uV/V)	(uV/V)	(uV/V)	(uV/V)	(uV/V)	(%)	(uV/V)	(uV/V)	(uV/V)	(uV/V)	(uV/V)
1	9.2	4.4	0	0.66	0.04	28.0	1	5	5.0	0.2	11.0	**22.0**
20	9.6	4.4	0	0.66	0.09	-19.9	1	5	5.0	1.0	11.3	**22.7**
100	11.3	4.4	0	0.69	0.38	-129.6	1	7	5.0	2.0	13.2	**26.3**
1000	35.8	4.4	0	6.30	2.73	-1205.0	1	25	7.0	7.0	40.1	**80.2**

Uncertainty calculations for the standard SP 792A_22mV_10mV.

Freq (kHz)	U_{REF}	$U(\delta m)$	d_{level}	d_{temp}	d_{RH}	$\delta m(R\text{-}D)$	d_s	$d_{set\text{-}up}$	d_{repr}	d_{conn}	U_{TOTAL}	$U_{EXP(k=2)}$
Distribution	Normal	Normal	Rectang.	Rectang.	Rectang.		Rectang.	Rectang.	Rectang.	Rectang.		
	H12_20mV		< 1*10E-04					10 mV			SP 10mV	SP 10mV
	(uV/V)	(uV/V)	(uV/V)	(uV/V)	(uV/V)	(uV/V)	(%)	(uV/V)	(uV/V)	(uV/V)	(uV/V)	(uV/V)
1	11.0	6.2	0	2.56	0.16	30.4	1	7	7.0	0.0	13.9	**27.8**
20	11.3	6.3	0	2.56	0.40	-19.7	1	7	7.0	0.0	14.3	**28.6**
100	13.2	6.3	0	2.59	0.99	-129.3	1	10	7.0	0.0	16.3	**32.6**
1000	40.1	6.3	0	13.90	5.75	-1158.6	1	30	10.0	0.0	45.8	**91.7**

U_{REF}	:	Uncertainty of the reference; $k=1$
$U(\delta m)$	:	Experimental standard deviation of the measurement (at 1kHz to DV, sqrs of the sum)
d_{level}	:	Uncertainty caused by change in voltage-level; calibration voltage of reference to calibration voltage of dut; estimated
d_{temp}	:	The total uncertainty caused by the uncertainty of the temp.coeff. and the uncertainty in the measured temperature
d_{RH}	:	The total uncertainty caused by the uncertainty of the relative humidity coeff. and the uncertainty in the measured relative humidit
δm(R-D)	:	The measured difference between the reference and the device under test
d_s	:	The accuracy of linearisation of the workpoint; considered that 1% of the difference between REF and DUT.
		will always be enough as uncertainty contribution.
$d_{set\text{-}up}$	:	set-up of the measurement system; estimated errors caused by used cables, connectors, earthing, environmental conditions
		loading errors and offsets. If one of the included contributions forms a substantial part it will be mentioned separately.
d_{repr}	:	reproducibility of the measurement
d_{conn}	:	influence of used connectors; no influence when used as transfer standard, stay's connected during measurement.
U_{TOTAL}	:	The total uncertainty, calculated as root of the sum of the squares
$U_{EXP(k=2)}$	:	The expanded uncertainty, calculated as twice the total uncertainty

"d" stands for contributions which are not measured during the measurement itself. Because these contributions are rectangular , they are transfered to normal distributions by:

$$u_{norm} = \frac{u_{rect}}{\sqrt{3}}$$

EUROMET EM - K11

AC-DC Voltage Transfer Difference at Low Voltages

BEV – Report

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A-1160 Vienna
AUSTRIA

By: M. Garcocz

Date: 10. April 2006

Measurements performed in February 2006

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Definition of the measurand

The ac-dc voltage transfer difference is defined as

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

where V_{ac} is an rms ac voltage, and V_{dc} is a dc voltage which, when reversed, produces the same mean output response as the rms ac voltage.
Differences are expressed in microvolts per volts (μV/V) and a positive sign signifies that more ac than dc voltage was required for the same output response.

Travelling standard

The travelling standard is a Fluke 792A thermal transfer standard with an accompanied power pack. The serial number for both units is 5495 003.

BEV standards

Traceability: For AC-DC voltage transfer difference at the level of 1 volts BEV is directly traceable to PTB, Germany.
For higher and lower voltage levels BEV performs its own step-up and step-down procedures.

100 mV:
A Planar Multijunction Thermal Converter (PMJTC) ("PTC14", 90 Ohms, manufactured at IPHT, Jena, Germany) has directly been used to determine the ac-dc voltage transfer difference of the travelling standard at 100 mV.

10 mV:
A PMJTC ("PTC14") and a Resistive Voltage Divider ("RDD5", ratio 10:1, manufactured at BEV) have been used to determine the ac-dc voltage transfer difference of the travelling standard at 10 mV.

Measurement setup

A type "N" Tee connector has been used to connect the travelling standard with the standards of BEV. It has type "N-male" connectors on all sides and was directly connected with the central measurement earth via a short cable.
The nanovoltmeters were separated from ground- connections of power supply and GPIB-connectors and grounded via the shieldings of their input - cables.
The Ground and Guard terminals of the F 792A were connected to measurement earth, the stainless steel input- connector remained always at the input and only the travelling power pack was used with the power line disconnected during the measurements.

At both voltage levels a resistor in series with the input to the Tee connector was put in to achieve a voltage level of approx. 1.5 volts for the calibrators.

Instruments used:

Calibrators:	Fluke 5700 S.N. 6280303
	Datron 4808 S.N. 42982
Nanovoltmeters:	Keithley 182 for PMJTC and F 792A
GPIB-isolators:	I/O-Tech 488F
Transferswitch:	BEV < 5ms, 1000 V, AC/DC and polarity switch
Software:	BEV, MS-Visual Basic

Ambient conditions :

Room temperature: 23°C ± 0.8°C

Relative Humidity: 50 % ± 10 %

Measurement procedure

The measurements have been performed automatically, controlled by a PC with a home-made software. All relevant parameters, including the sensitivity of the converter, was put into the starting sheet before the measurements.

As a preparation for the ac-dc measurements the input impedance of the travelling standard was measured and corrections for the used resistive voltage dividers calculated.

Warm-up time: more than 30 min with nominal voltage.

Fitting of the ac voltage to the mean of dc voltage of both polarities for equal output response of the TC (better than 20 µA/A).

The measurement sequence was AC1 - DC plus - DC minus - AC2. A minimum of 40 independent evaluations of the transfer difference for each compared voltage / frequency point has been performed.

After completing the measurements the software calculates mean value and standard- deviation. All single readings are stored in a text file for later corrections, if necessary.

Measurement results

The ac-dc voltage transfer difference for the travelling standard in µV/V is:

	1 kHz	20 kHz	100 kHz	1 MHz
100 mV	+ 8.8	- 6.8	+ 17.7	+ 18.3
10 mV	+ 14	- 6	- 16	- 154

Measurement uncertainty

The expanded measurement uncertainty in µV/V is:

	1 kHz	20 kHz	100 kHz	1 MHz
100 mV	12	13	17	60
10 mV	31	32	39	127

Uncertainty budget for the comparison at 100 mV [µV/]:

frequency	PMJTC 14 norm ∞	std-dev norm 40	dc-eff. rect. ∞	setup rect. ∞	tee rect. ∞	repeat rect. ∞	temp. rect. ∞	humidity rect. ∞	792 100 mV norm	eff. deg. of freedom	expanded uncertainty [µV/V]
1 kHz	1,7	4	2	3,3	0,2	1,5	0,7	0,1	6,0	206	12
20 kHz	2,5	4	2	3,3	0,2	1,5	0,7	0,3	6,3	248	13
100 kHZ	3	4	2	5,6	1	2,2	0,9	1,5	8,3	749	17
1 MHz	18,5	4	2	10,3	3	8,2	9,6	15,6	29,7	156940	60

Uncertainty budget for the comparison at 10 mV [µV/]:

frequency	PMJTC 14 norm ∞	RDD5 norm ∞	std-dev norm 40	dc-eff. rect. ∞	setup rect. ∞	tee rect. ∞	repeat rect. ∞	temp. rect. ∞	humidity rect. ∞	load-eff. rect. ∞	792 10 mV norm	eff. deg. of freedom	expanded uncertainty [µV/V]
1 kHz	1,7	8,6	10	2	6,5	0,2	2	1,8	0,1	0,2	15,2	206	31
20 kHz	2,5	9,0	10	2	6,5	0,2	3	1,8	0,3	0,3	15,7	237	32
100 kHZ	3	12,7	10	2	8,0	1	4	1,9	1,5	1,1	19,0	508	39
1 MHz	18,5	49,5	10	2	11,8	3	20	20,0	11,6	6,4	63,4	63036	127

Temperature / Humidity - Corrections

The measured values for the ac-dc voltage transfer difference have been corrected following the technical protocol.

measurement values	temp/humidity- coefficients (protocol)	corrections

100 mV

	measurement values	protocol	ΔT	ΔRH
temp	22,8	23	0,2	
humidity	50	45		-5

	δ 792A [µV/V] value	tempCoeff [µV/V//K] value	tempCoeff uncert	rel.humCoeff [µV/V//%] value	rel.humCoeff uncert	Δδ(T) [µV/V] value	Δδ(T) uncert	Δδ(RH) [µV/V] value	Δδ(RH) uncert	**corrected ac-dc-diff. 100 mV [µV/V]**
1 kHz	8,7	0,4	1	0	0,02	0,08	0,2	0	0,1	**8,8**
20 kHz	-6,9	0,4	1	0	0,05	0,08	0,2	0	0,25	**-6,8**
100 kHZ	18,1	0,6	1	0,1	0,1	0,12	0,2	-0,5	0,5	**17,7**
1 MHz	22,8	10	4	1,3	0,5	2	0,8	-6,5	2,5	**18,3**

10 mV

	measurement values	protocol	ΔT	ΔRH
temp	22,9	23	0,1	
humidity	50	45		-5

	δ 792A [µV/V] value	tempCoeff [µV/V//K] value	tempCoeff uncert	rel.humCoeff [µV/V//%] value	rel.humCoeff uncert	Δδ(T) [µV/V] value	Δδ(T) uncert	Δδ(RH) [µV/V] value	Δδ(RH) uncert	**10 mV [µV/V]**
1 kHz	14	1,2	2	0	0,02	0,12	0,2	0	0,1	**14**
20 kHz	-6	1,2	2	0	0,05	0,12	0,2	0	0,25	**-6**
100 kHZ	-16	1,3	2	0,1	0,1	0,13	0,2	-0,5	0,5	**-16**
1 MHz	-151	17	8	0,9	0,5	1,7	0,8	-4,5	2,5	**-154**

Note: the uncertainties of the corrections were combined with the uncertainties for temperature and relative humidity during the measurements and appear as one value for each quantity in the uncertainty budget.

Other Influence Parameters

Frequency: The frequency of the output voltage of both used calibrators was measured with and without load (standard: HP 53131 S.N.3736A24005). The deviations from the nominal frequencies were smaller than 10^-5 and negligible for the uncertainty budget.
Power Pack: The voltage of the power pack of the travelling standard has been measured in both polarities during the comparison using the provided dummy-load.

positive Voltage:	Max: + 11.104 V	Min: + 11.091 V
negative voltage:	Max: - 11.166 V	Min: - 11.155 V

Stepdown Procedure

Before measuring the ac-dc transfer differences the divider's in- and output impedance and the input impedance of the Fluke 792A (BEV) as well as the input impedance of the travelling standard have been evaluated using a LCR bridge (Agilent 4284, S.N. 2940J11720). The corrections for loading the divider with the used F 792A were calculated.
Then a stepdown- procedure was performed by calibrating a resistive divider "RDD5" with the ratio 10:1. This has been done in the following way:

1) The BEV Fluke 792A (S.N.: 8928001) was calibrated at the level of 150 mV directly against a PMJTC ("PTC 3", 90 ohms).

δ792BEV(150mV) = δPTC3 - δ(PTC3-792)

uncertainty budget for Step 1: calibration of F 792A (BEV) with PTC3 at 150 mV:

frequency	PMJTC 3 norm ∞	std-dev norm 40	dc-eff. rect. ∞	set-up rect. ∞	tee rect. ∞	repeat rect. ∞	temperature rect. ∞	humidity rect. ∞	792 150mV k = 1 norm	effective degrees of freedom
1 kHz	2,5	3	2	3,3	0,2	1	2	1	6,0	626
20 kHz	3,2	3	2	3,3	0,2	1	2	1	6,3	772
100 kHZ	3,6	3	2	5,6	1	1	3	3	8,8	2908
1 MHz	20	3	2	10,3	3	6	15	20	34,5	681551

2) The resistive divider was connected to the input of the 792A and a PMJTC with nominal 1.5 volts ("PTC 48, 190 ohms) was used to evaluate the ac-dc transfer difference of the divider. Corrections for the used PMJTC, the 792A at 150 mV and the loading effect due to the input impedance of the 792A in parallel to the output of the divider have been applied.

δRDD5 = δ792(150mV) - δ(PTC48) + δ(PTC48 - (792+RDD5)) - load-corr.(792BEV)

uncertainty budget for Step 2: calibration of RDD5 with 792A (BEV) and PTC48:

frequency	PMJTC 48 norm ∞	792 150mV norm ∞	std-dev norm 40	dc-effects rect. ∞	set-up rect. ∞	tee-conn rect. ∞	repeat rect. ∞	temperature rect. ∞	humidity rect. ∞	load-corr rect. ∞	RDD 5 k = 1 norm	effective degrees of freedom
1 kHz	2,5	6,0	3	2	3,3	0,2	1,5	2	1	0,2	8,6	2593
20 kHz	3,2	6,3	3	2	3,3	0,2	1,5	2	1	0,3	9,0	3192
100 kHZ	3,6	8,8	3	2	5,6	1	2,2	3	3	1,1	12,7	12402
1 MHz	20	34,5	3	2	10,3	3	8,2	15	20	6,4	49,5	2894152

3) This evaluated ac-dc- transfer difference for the RDD5 was used to calibrate the travelling standard at the level of 10 mV by using the PTC14 at the level of 100 mV and the RDD5 connected to the input of the travelling standard.

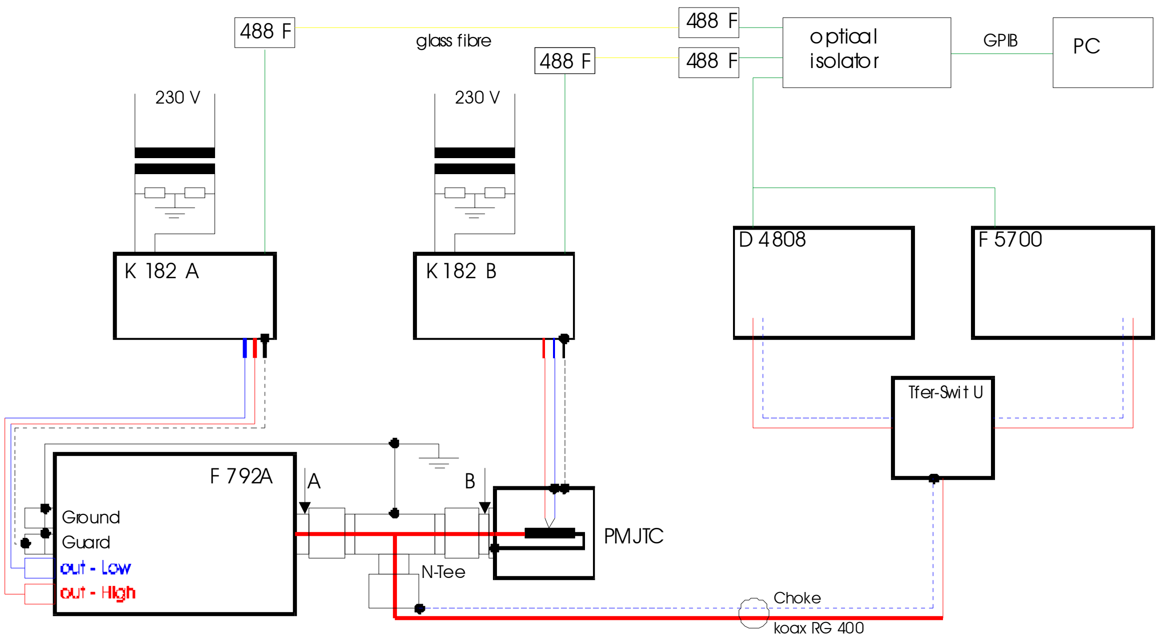
$\delta 792SP(10mV) = \delta PTC14 - \delta(PTC14-(792+RDD5)) + \delta RDD5 + \text{load-corr}(792SP)$

uncertainty budget for Step 3: calibration of F 792A (SP) with PTC14 + RDD5 at a level of 10 mV:

frequency	PMJTC 14	RDD5	std-dev	dc-eff.	setup	tee	repeat	temp.	humidity	load-eff.	792 10mV	effective
	norm	norm	norm	rect.	rect.	rect.	rect.	rect.	rect.	rect.	k = 1	degrees of
	∞	∞	40	∞	∞	∞	∞	∞	∞	∞	norm	freedom
1 kHz	1,7	8,6	10	2	6,5	0,2	2	1,0	0,1	0,2	15,1	202
20 kHz	2,5	9,0	10	2	6,5	0,2	3	1,0	0,3	0,3	15,6	233
100 kHZ	3	12,7	10	2	8,0	1	4	1,0	0,6	1,1	18,9	496
1 MHz	18,5	49,5	10	2	11,8	3	20	4,0	2,8	6,4	59,2	48058

Measurement Circuit

BEV - AC/DC voltage calibration Fluke 792



A...insert Resistive Divider for Low Voltages
B...insert series resistor for High Voltages

EM K-11 comparison

AC-DC VOLTAGE TRANSFER DIFFERENCE AT LOW VOLTAGES

Report on the measurements by the National Office of Measures, Hungary

Measuring procedure

AC/DC transfer difference measurement of the travelling standard:

The AC/DC transfer difference determination of the transfer standard against the Hungarian national standards for 100 mV and 10 mV were carried out at 1 kHz, 20 kHz, 100 kHz and 1000 kHz frequencies.

The standards to be compared were used in a two channel automatic measuring system for thermal voltage converter comparison. During the substitution process instead of achieving a perfect balance the system uses DC or reference frequency (1 kHz) input value giving nearly balanced thermal output voltage for both converters simultaneously. Correction are made in the input voltage in dependence of the measured ΔE thermal voltage unbalance on the basis of the

$$E_{out}+\Delta E_{out}=k(V_{in}+\Delta V_{in})^n$$

theoretical function. The n exponent for each converter was determined before the actual measurement in a separate measuring phase using known input voltage step.

At the first step a PMJTC calibrated in PTB was used as reference converter at 221 mV. The following measurements were carried out by using a micropotentiometer with 3 different resistors. 3.3 , 10.5 and 33 ohm. The voltage ranges were 63…220, 22..63 and 6.3…22 mV.

Place of measurement: National Office of Measures
Division for Reference Measurements II
Section of Electrical and Temperature Measurements

Measuring conditions:

1. Connection of the standards

The converters were connected to the corresponding arm of a special T (N male/female).

2. Environment parameters

Ambient temperature:	23 ±2°C
Relative humidity:	40±10%

Measurement setup for the AC/DC transfer difference measurement

The setup for the first step for comparison is shown on Fig. 1.

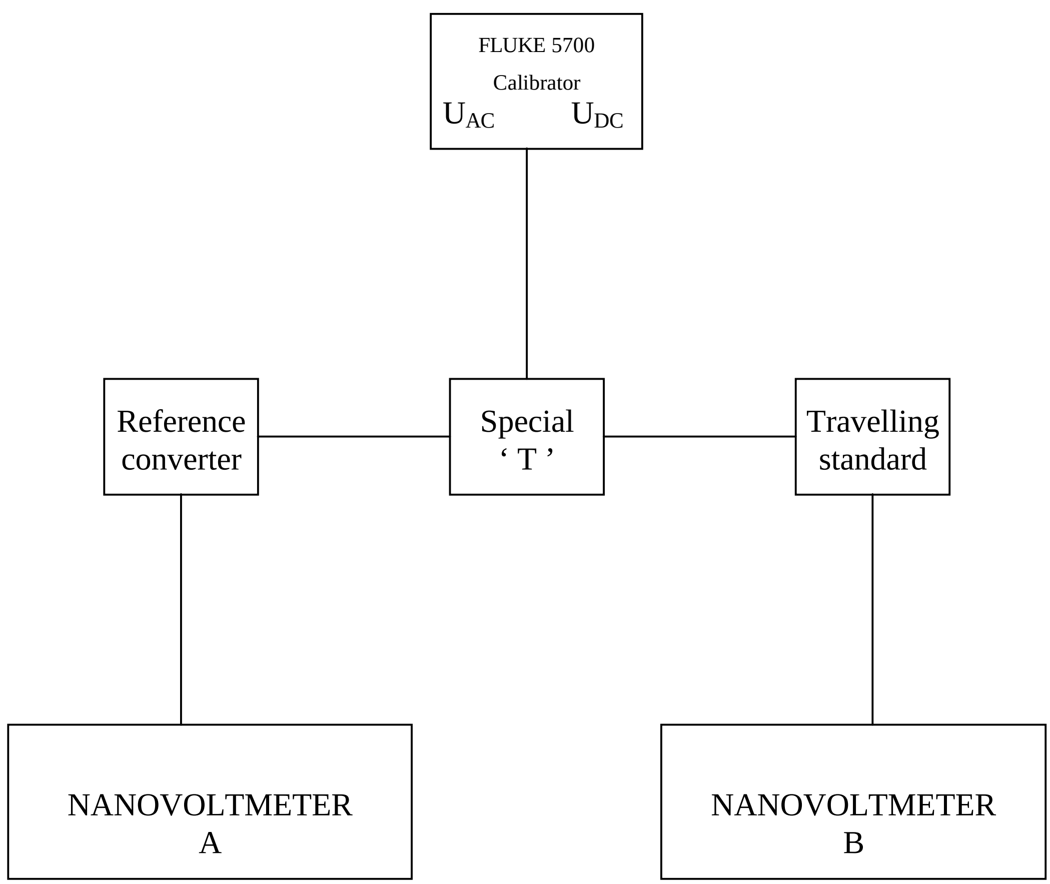


Figure 1.

The setup for the following steps for comparison is shown on Fig. 2.

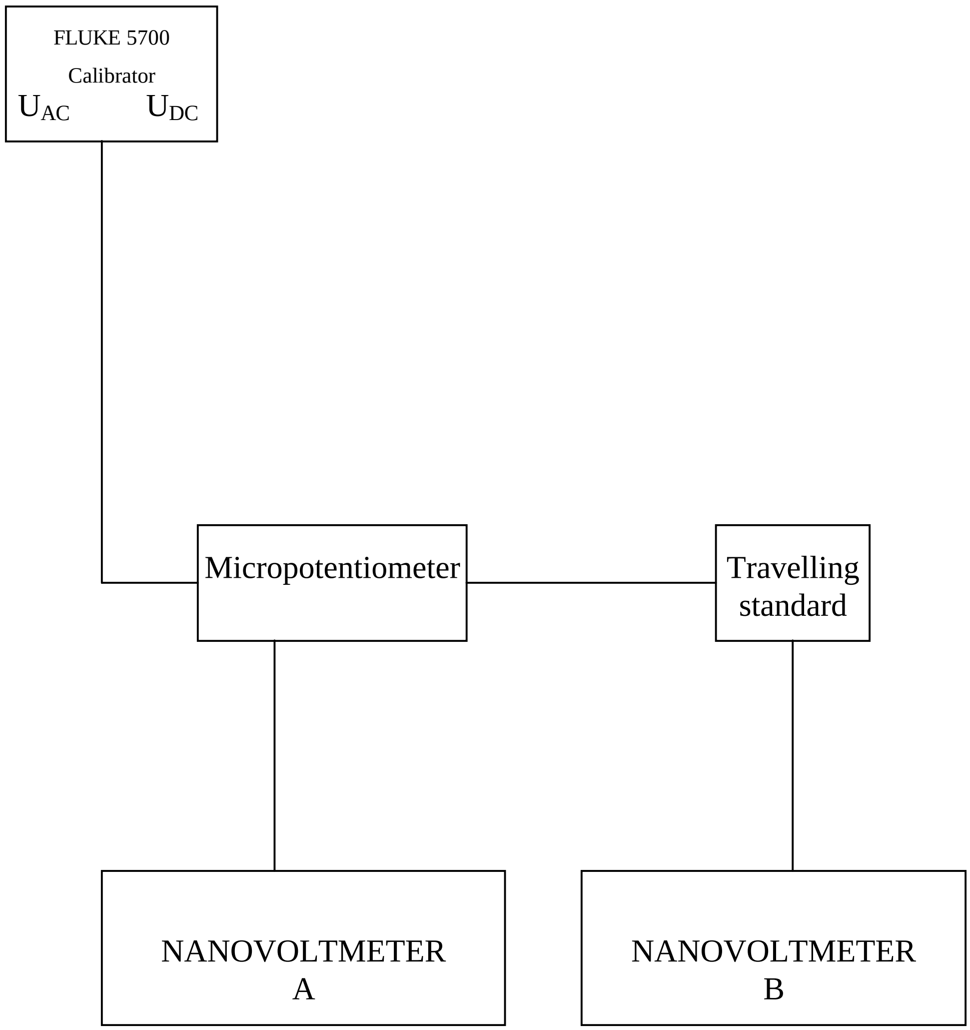


Figure 2.

The same setup was used to measure the n exponent of the converter thermal voltage-input voltage function.

The setup for the measurement of the loading effect is shown on the Figure 3. An 11 ohm flat smd resistor was built into a high frequency relay controlled by a computer. The transformer has ensured the very low driving impedance and the working range at high signal level of the calibrator. The DC output voltage of the travelling standard was measured while the relay was switched on and off. The loading effect was calculated from the difference of the two measured voltage values in the case of each frequency and each signal level.

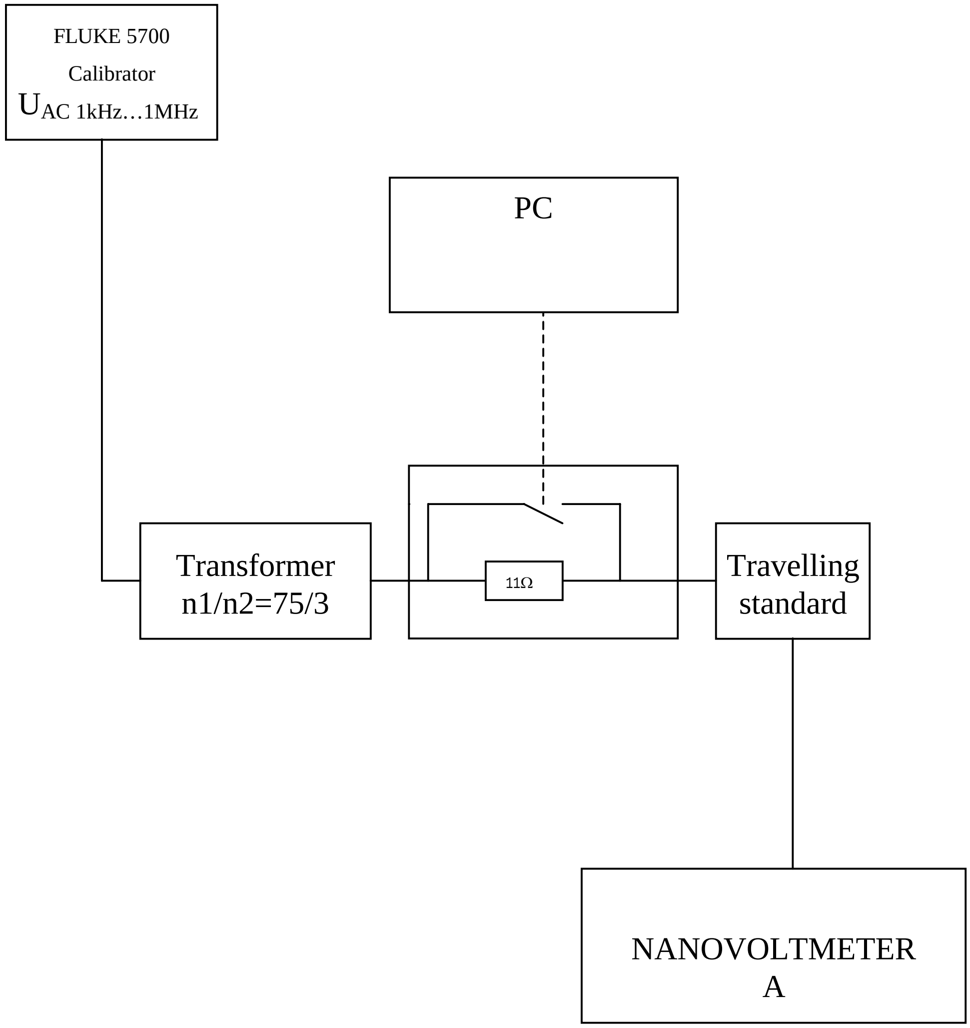


Figure 3.

As a result of the measurements the loading effect is independent of the signal level but it is different in the two measurement ranges. The 33 ohm micropotentiometer was calibrated at 221mV with the travelling standard then the travelling standard was calibrated with the micropotentiometer at 100 and 63 mV signal levels which are belong to the same range. So there was not need any correction because during all the calibrations also the same loading effect existed. As the loading effect was different in the two measuring ranges of the travelling standard it was necessary to make some correction using the 10.5 ohm micropotentiometer when the range was changed from 220 mV to 22 mV. This correction was 31ppm at 1MHz and less then 1ppm at lower frequencies. The calibration of the 3.3 ohm micropotentiometer and the measurements with it were carried out in the same measuring range so there was not necessary to make any loading correction.

Reference standard

Type: PTB/IPHT Thin-Film Multijunction Thermal Converter

Manufacturer: IPHT Jena

Serial number: 35 PTB/IPHT 2003

Reference number:2.12-06000520 (PTB calibration certificate)

Budapest, 03. May 2006

Tibor Németh

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Uncertainty budget

	1kHz	20kHz	100kHz	1000kHz	type	Distribution
Calibration of the travelling standard with PMJTC at 221mV						
Measurement uncertainties	2	2	3	4	A	Gaussian
Assembly ,cables,connectors	1	2	5	50	B	Rectangular
Level dependency	1	1	1	1	B	Rectangular
Temperature	0.4	0.4	0.6	9.8	B	Rectangular
Relative humidity	0	0	0.3	4.5	B	Rectangular
Resulting standard uncertainty	2.48	3.03	5.96	51.32		
Calibration of 33ohm micropotentiometer at 221mV						
Measurement uncertainties	1	1	2	3	A	Gaussian
Assembly ,cables, connectors	1	2	5	50	B	Rectangular
Temperature	0.68	0.68	1.02	17	B	Rectangular
Relative humidity	0	0	0.3	4.5	B	Rectangular
Combined uncertainty	2.94	3.82	8.10	73.84		
Calibration of the travelling standard with 33ohm micropot. at 100mV						
Measurement uncertainties	1	1	2	3	A	Gaussian
No assembly ;cables, connectors	0	0	0	0	B	Rectangular
Level dependency	2	2	2	2	B	Rectangular
Temperature	0.4	0.4	0.6	9.8	B	Rectangular
Relative humidity	0	0	0.3	4.5	B	Rectangular
Combined uncertainty	**3.71**	**4.45**	**8.61**	**74.71**		
Expanded uncertainty k=2	7.4	8.9	17.2	149.4		
Calibration of the travelling standard with 33ohm micropot. at 63mV						
Measurement uncertainties	2	2	3	4	A	Gaussian
No assembly ;cables, connectors	0	0	0	0	B	Rectangular
Level dependency	3	3	3	3	B	Rectangular
Temperature	0.4	0.4	0.6	9.8	B	Rectangular
Relative humidity	0	0	0.3	4.5	B	Rectangular
Combined uncertainty	4.67	5.27	9.17	74.79		
Calibration of 10.5ohm mikropotentiometer at 63mV-on						
Measurement uncertainties	1	1	2	3	A	Gaussian
Assembly ,cables, connectors	1	2	5	50	B	Rectangular
Temperature	0.68	0.68	1.02	17	B	Rectangular
Relative humidity	0	0	0.3	4.5	B	Rectangular
Combined uncertainty	4.92	5.76	10.69	91.72		
Calibration of the travelling standard with 10.5ohm micropotenciometer at 22mV						
Measurement uncertainties	2	2	3	4	A	Gaussian
No assembly ;cables, connectors	0	0	0	0	B	Rectangular
Level dependency	3	3	3	3	B	Rectangular
Loading effect correction measurement	1	1	1	4	A	Gaussian
Temperature	1.2	1.2	1.3	16.7	B	Rectangular

Relative humidity	0	0	0.3	3.1	B	Rectangular
Combined uncertainty	6.29	6.97	11.62	93.50		
Calibration of 3.3ohm micropotentiometer at 22mV-on						
Measurement uncertainties	1	1	2	3	A	Gaussian
Assembly ,cables, connectors	1	2	5	50	B	Rectangular
Level dependency	3	3	3	3	B	Rectangular
Temperature	1.2	1.2	1.3	16.7	B	Rectangular
Relative humidity	0	0	0.3	3.1	B	Rectangular
Combined uncertainty	7.21	8.00	13.22	107.48		
Calibration of the travelling standard with 10.5ohm micropotenciometer at 10mV						
Measurement uncertainties	2	2	3	4	A	Gaussian
No assembly ;cables, connectors	0	0	0	0	B	Rectangular
Level dependency	2	2	2	2	B	Rectangular
Temperature	1.2	1.2	1.3	16.7	B	Rectangular
Relative humidity	0	0	0.3	3.1	B	Rectangular
Combined uncertainty	**7.84**	**8.57**	**13.77**	**109**		
Expanded uncertainty k=2	15.7	17.1	27.5	217.8		

Summary of results

Key comparison EUROMET.EM-K11 “ac-dc voltage transfer difference at low voltages”

Acronym of institute:OMH

Date of measurements:2006.03

Remarks:

Measuring result:

Voltage	Range	Measured ac-dc voltage difference / 10^{-6} at frequency			
		1 kHz	20 kHz	100 kHz	1 MHz
100 mV	220 mV	**8.1**	**-6.7**	**15**	**3**
10 mV	22 mV	**9.1**	**-9.3**	**-22**	**-277**

Expanded uncertainty (k=2):

Voltage	Range	Expanded uncertainty / 10^{-6} at frequency			
		1 kHz	20 kHz	100 kHz	1 MHz
100 mV	220 mV	7.5	8.9	17.5	150
10 mV	22 mV	15.7	17.2	27.7	220

Measuring frequency:

	Nominal frequency			
	1 kHz	20 kHz	100 kHz	1 MHz
Measuring frequency	1.000011	20.00022	100.0011	1.000011
Expanded uncertainty	1ppm	1ppm	1ppm	1ppm

Influence parameters:

	Min	Max	Remarks
Ambient temperature / ºC	22.33	24.7	
Relative humidity / %	39	49	
Pos. power supply voltage / V	11.091	11.104	
Neg. power supply voltage / V	11.156	11.167	

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Regional Key Comparison EUROMET.EM-K11

"AC-DC Voltage Transfer Difference at Low Voltages"

(EUROMET Project 464)

Participation of INETI - PORTUGAL

Report by ***Rui de Mello Freitas, INETI-LME***

1. Circulating AC-DC transfer standard

The thermal transfer standard used for this comparison was a FLUKE 792A AC-DC Thermal Voltage Transfer Standard (s/n 5495003) provided by SP, which was measured at the voltages of 100 mV and 10 mV, according to the instructions received from the pilot-laboratory.

2. Conditions for the measurements

The measuring procedures used were in agreement with the instructions provided with the device.

We measured the standard at 1 kHz, 20 kHz, 100 kHz and 1 MHz, aiming at our lowest uncertainty level and corresponding to the goal of the EM-K11 comparison.

3. Measurements

The AC-DC voltage transfer difference ∂ of the travelling standard, defined as

$$\partial = (U_{ac} - U_{dc}) / U_{dc}$$

where U_{ac} is the *rms* value of the AC input voltage and U_{dc} is the DC input voltage which when reversed produces the same mean output voltage of the transfer standard as U_{ac}, was measured at the voltages and frequencies stated in *Table 1.*

SP FLUKE 792A s/n 5495003

Voltage (mV)	Frequency (kHz)
100 - 10	1 - 20 - 100 -1000

TABLE 1 - Test values

4. Measuring Methods

The travelling standard was compared with INETI's reference set of standards for ac-dc voltage transfer measurement at mV ranges.

The INETI’s primary standards for ac-dc voltage transfer consists of a set of three multijunction thermalconverters (PTB 3D-type) rated at 3 V. From the 3 V level, and using a «build-down» technique, we go down to the 100 mV level through 4 steps. This is done using different planar multijunction thermalconverters (PTB planar-type) and INETI’s FLUKE 792A which is measured at 100 mV @ 220mV range (*Figure 1*).

We compared the travelling standard directly with INETI’s FLUKE 792A, at the 100 mV level.

During all the measurements, we followed our usual and tested measurement procedure, using INETI's ac-dc semi-automatic differential comparator, which is shown schematically in *Figure 2*. Both the input and output circuits are earthed.

With this comparator and after half an hour "warm-up", the AC-DC differences of the travelling standard were measured, taking 12 measurements for each test voltage at each value of frequency. Each measurement cycle followed the usual sequence of applying DC^{+}, AC, DC^{-}, AC, DC^{+},… The measurements were done in a fully automated way for each voltage value, using as reference plane the middle of a N “tee” connector. We made three series of measurements and complementary measurements following different configurations of our own standards to control the results.

For the 10 mV level, we used recently received calibrated RVD’s (100:1) from SP, which allowed us to compare the travelling standard at 10 mV with a 1 V planar multijunction thermalconverter (*Figure 3*).

The measurements were always performed in a temperature and humidity controlled room (23±1°C; 45±10% RH). This room is not specially shielded against RF interference. We measured the test frequency during one series of measurements, to monitor the deviations from the nominal values and the frequency stability of the AC Source.

Before and after each measurement series, we measured the output of the SP FLUKE battery pack with the supplied dummy load. We also measured INETI FLUKE battery pack with the same load with identical results.

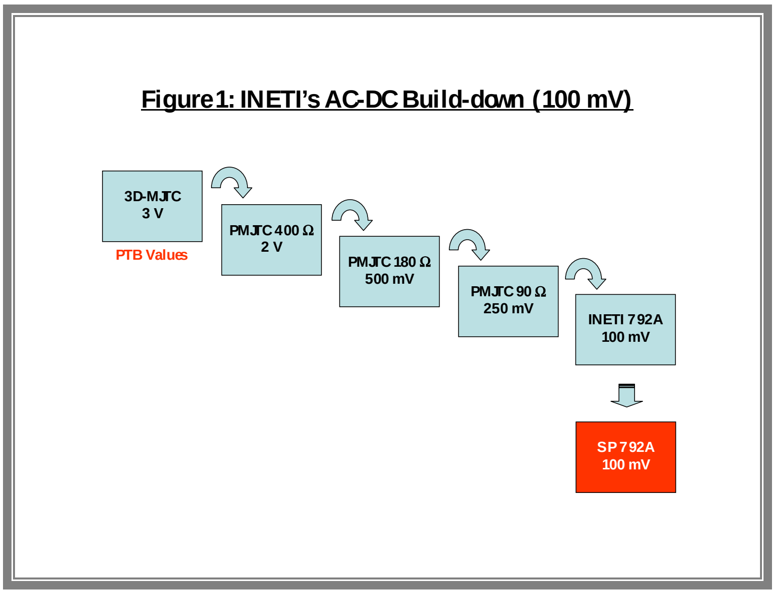
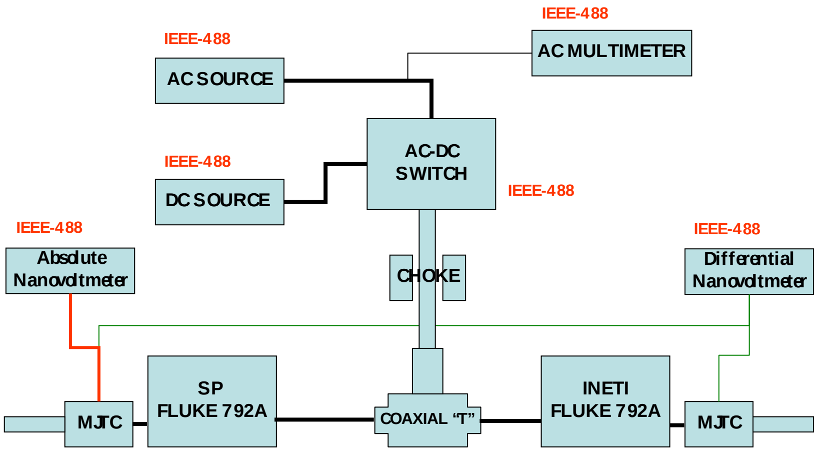


Figure1: INETI's AC-DC Build-down (100 mV)
3D-MJTC
3 V
PTB Values
PMJTC 400 Ω
2 V
PMJTC 180 Ω
500 mV
PMJTC 90 Ω
250 mV
INETI 792A
100 mV
SP 792A
100 mV

Figure 2: INETI's AC-DC Comparator



Fel! Objekt kan inte skapas genom redigering av fältkoder.

5. Results of the Measurements

The results of the series of measurements provided by the several comparisons between the travelling standard and our reference standards are condensed in *Table 2* . The ac-dc differences are in μV/V.

	1 kHz	20 kHz	100 kHz	1 MHz
100 mV	**16**	**-1**	**27**	**10**
10 mV	**10**	**-12**	**-23**	**-27**

TABLE 2 - Measured values (μV/V)

6. Uncertainties

The measurements were carried out at our lowest uncertainty level. INETI's uncertainties (in μV/V) at 100 mV and 10 mV are shown in *Table 3*. INETI has not recognized CMC's on mV ranges yet.

For the uncertainty budget, we followed the ISO Guide to the Expression of Uncertainty in Measurement (*Appendix 3)*. The rectangular Type B uncertainties are stated as *a* on *Appendix 3* and *a/√3* on *Appendix 2*.

INETI	1 kHz	20 kHz	100 kHz	1 MHz
100 mV	**41**	**48**	**61**	**80**
10 mV	**56**	**56**	**65**	**275**

TABLE 3 – Uncertainties (μV/V)

Lisbon, 06.05.31.

KEY COMPARISON EUROMET.EM-K11
AC/DC TRANSFER DIFFERENCE AT LOW VOLTAGES.

MEASUREMENT REPORT

Participant: **Centro Español de Metrología. CEM. SPAIN**

Performed by: **Susana Ramiro.**

May 2006

KEY COMPARISON EUROMET.EM-K11

MEASUREMENT REPORT BY CEM, SPAIN.

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1. Abstract.

According to the instructions for participants of the EUROMET.EM-K11 Comparison, CEM has been carrying out measurements on May 2006. A Fluke 792A (n/s 5495 003), was used as travelling standard.

The measurements have been carried out at 100 mV and 10 mV and at the frequencies of 1 kHz, 20 kHz, 100 kHz and 1 MHz.

2. Method and instrumentation.

The measurement system, a two-channel method, is shown schematically in fig. 1. The system is fully automated by IEEE-488, with an ac/dc automatic switch. The method is based on **PTB-Planar Multijunction** Thermal Converter and **resistive voltage dividers** from **SP**.

The SP - resistive voltage divider with ratio 10/1 is calibrated in a step down procedure obtaining the traceability from PTB – PMJTC.

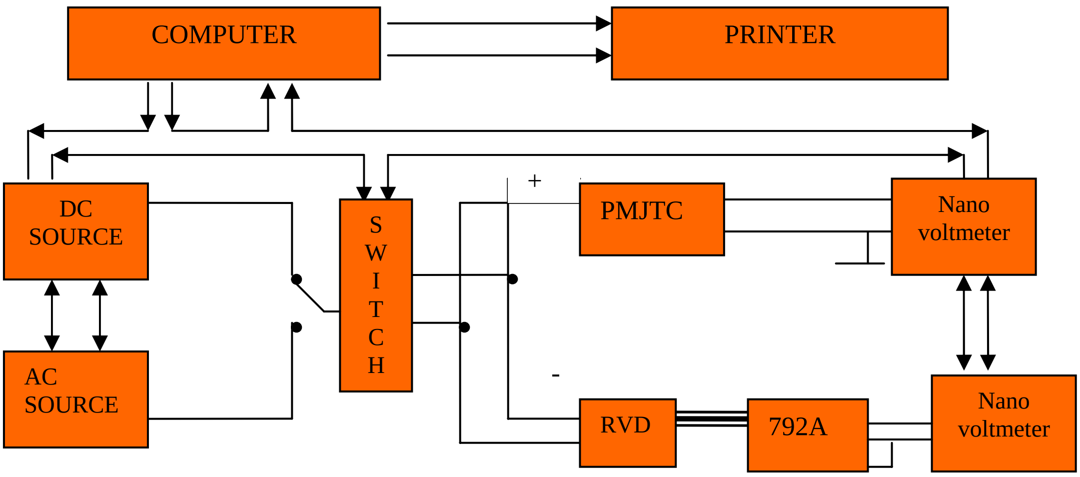

Fig. 1. ac/dc transfer system. CEM

The basic diagram shows two high precision power sources from Fluke (AC and DC), an ac low output impedance source, Fluke 5200A, and a dc 5700A source. The AC/DC automatic switch is based on vacuum relays, which uses a four-terminal operation at low level voltage. Operation and release times are less than 10 ms. The switch is controlled by interface IEEE-488. The reference plane is the central plane of the enclosed T-connector, with two type N male connectors. A coaxial choke is used at the input of the T connector.

The AC/DC voltage transfer difference was determined by comparison against the CEM standard AC/DC voltage transfer equipment. The AC/DC voltage transfer difference δ is defined as the relative difference between the alternating voltage U_{ac} and the direct voltage U_{dc} which when reversed produces the same mean output voltage of the standard as U_{ac}:

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

The comparator-detector has got two high precision nanovoltmeters, Keithley 182, in order to measure the absolute output voltage of the two converters. The two voltmeters are triggered simultaneously by the computer, so that the results correspond to signal obtained over the same time intervals for both devices.

A twisted and shielded cable, Guideline low thermal copper cable, is used for the connection to the comparator system. The input and output of the Thermal Voltage Converter have to be earthed, in order to protect the insulation between heater and thermocouples. The low of the input connector and the guard and ground terminals of the 792 transfer standard have been connected to common ground.

The measurement proceeds in the usual way of applying: DC+, AC, DC-, AC, DC+, etc. Each sequence allows measurements of the AC/DC difference as: $\delta_T - \delta_S = \frac{ac_S}{dc_S} * \frac{dc_T}{ac_T} - 1$, with n = 12 measurements for each point to produce the mean value, it means that each measurement sequence uses 12 cycles. Every sequence is run two times on separate days.

Measurements have been performed at an ambient temperature of 23 ± 1ºC and a relative humidity between 40 % and 55 %. All measurements have been performed in an electromagnetically shielded room. The measuring frequency has been within 1 % of the nominal frequency.

4. Uncertainty of measurement.

An analysis of the uncertainties of measurement for the CEM-standards has been performed in accordance with the ISO Guide to the Expression of Uncertainty in Measurement.

The model function for the evaluation of the measurement is given below and the uncertainty budget in Appendix 2.

At **100 mV** the ac-dc transfer difference of the Fluke 792A standards is given as:

$$\delta_{792} = \delta_{PMJTC} + \delta_{m}$$

with

δ_{PMJTC}: The transfer difference of the Standard

δ_{m}**:** Measured difference

So, the square of the standard uncertainty, u(δ_{792}),

$$u^2(\delta_{792}) = u^2(\delta_{PMJTC}) + u^2(\delta_{m})$$

The difference δ_m measured is

$$\delta_m = \delta_{con} + \delta_{fr} + \delta_C + \delta_A + \delta_T + \delta_{hum} + \delta_{repr} + \delta_{level}$$

with

δ_{con}**:** AC-DC difference due to adapters and connectors.
δ_{fr} **:** AC-DC difference due to measuring frequency.
δ_C**:** AC-DC difference contribution of the measuring set-up.
δ_A**:** Contribution of the type A standard deviation.
δ_T**:** AC-DC difference due to the contribution of the temperature coefficient of the 792A.
δ_{hum}**:** AC-DC difference due to the contribution of the humidity coefficient of the 792A.
δ_{repr}**:** AC-DC difference due to reproducibility using different calibrators, dividers, and calibration set-ups.
δ_{level}**: L**evel dependence of the ac-dc difference of the reference standard .

$$u^2(\delta_m) = u^2(\delta_{con}) + u^2(\delta_{fr}) + u^2(\delta_C) + u^2(\delta_A) + u^2(\delta_T) + u^2(\delta_{hum}) + u^2(\delta_{repr}) + u^2(\delta_{level})$$

At **10 mV** the ac-dc transfer difference of the Fluke 792A standards is given as:

$$\delta_{792} = \delta_{PMJTC} + \delta_{m} + \delta_{RVD}$$

with

δ_{PMJTC}: The transfer difference of the Standard

δ_m**:** Measured difference

δ_{RVD}**:** The transfer difference of the RVD

So, the square of the standard uncertainty, u(δ_{792}),

$$u^2(\delta_{792}) = u^2(\delta_{PMJTC}) + u^2(\delta_m) + u^2(\delta_{RVD})$$

The difference δ_{RVD} is:

$$\delta_{RVD} = \delta_{con} + \delta_{PMJTC} + \delta_{fr} + \delta_C + \delta_A + \delta_T + \delta_{hum} + \delta_{Zin} + \delta_{792(100\ mV)}$$

with

δ_{Zin}**:** Load correction due to the input impedance of 792A.

The input impedances of the 792A were measured using an RLC bridge HP 4284A. We include in this component the contribution of the impedance measurement deviation and the contribution by the assumption of equal impedances within one range of measurement.

$$u^2(\delta_{RVD}) = u^2(\delta_{con}) + u^2(\delta_{PMJTC}) + u^2(\delta_{fr}) + u^2(\delta_C) + u^2(\delta_A) + u^2(\delta_T) + u^2(\delta_{hum}) + u^2(\delta_{Zin}) + u^2(\delta_{792100mV})$$

We enclose, at Appendix 2, an uncertainty budget with the reason of the deviation, type of distribution and standard deviations in 10^{-6} at measurement frequencies. We provide a list of type A and type B contributions. It also provides an overall uncertainty with the root squares of all contributions.

At the end we represent a combined value. All uncertainties are given at 1σ. The degrees of freedom ν, for the uncertainty contribution of the 12 measurements is 11 (type A evaluation). The uncertainties obtained from a type B evaluation, dominate in the final combined standard uncertainty, and they can be treated as exactly known, so, we can consider $\nu_i \rightarrow \infty$, and the number of effective degrees of freedom of our results, $\nu_{eff} \rightarrow \infty$, too ($\nu_{eff}$ >25000).

5. Results of the measurements.

The measurements were performed using the procedure and set-up described in the previous sections.

The final measurement value of the ac-dc voltage transfer difference is given in appendix 1, for each frequency measured at rated voltage.

Appendix 1. Summary of results

Key comparison EUROMET.EM-K11 "ac-dc voltage transfer difference at low voltages"

Acronym of institute: **CEM**

Date of measurements: **May 2006**

Remarks: The ac-dc transfer differences have been corrected due to temperature and humidity dependence

Measuring result:

Voltage	Range	Measured ac-dc voltage difference / 10^{-6} at frequency			
		1 kHz	20 kHz	100 kHz	1 MHz
100 mV	220 mV	**10**	**-15**	**9**	**0**
10 mV	22 mV	**3**	**-10**	**-15**	**-104**

Expanded uncertainty:

Voltage	Range	Expanded uncertainty / 10^{-6} at frequency			
		1 kHz	20 kHz	100 kHz	1 MHz
100 mV	220 mV	**10**	**10**	**30**	**80**
10 mV	22 mV	**40**	**40**	**60**	**150**

Measuring frequency:

	Nominal frequency			
	1 kHz	20 kHz	100 kHz	1 MHz
Measuring frequency	**1,000 00**	**20,026 8**	**100,037**	**1,000 4**
Expanded uncertainty	**1,000 00**	**20,026 8**	**100,037**	**1,000 4**

Influence parameters:

	Min	Max
Ambient temperature / ºC	**23,2**	**23,8**
Relative humidity / %	**40,3**	**51,7**
Pos. power supply voltage / V	**11,091**	**11,098**
Neg. power supply voltage / V	**11,156**	**11,162**

Appendix 2. Summary of uncertainty budget

Key comparison EUROMET.EM-K11 "ac-dc voltage transfer difference at low voltages"

Please send this information by e-mail also.

Acronym of institute: **CEM**

Date: **May 2006**

Remarks:

Measuring voltage: **100 mV**

Contribution of:	Std. unc. f: 1 kHz	Std. unc. f: 20 kHz	Std. unc. f: 100 kHz	Std. unc. f: 1 MHz	Type A or B	Distri-bution
reference standard, $u(\delta_{MJTC})$	0,5	0,6	1,2	12	B	normal
Standard deviation, $u(\delta_A)$	5	5	5	6	A	normal
measuring set-up, $u(\delta_C)$	1	1	5	15	B	Rectan
level dependence, $u(\delta_{level})$	5	5	5	5	B	Rectan
Connectors, $u(\delta_{con})$	1	1	5	15	B	Rectan
Temperature, $u(\delta_T)$	0,5	0,5	0,5	2	B	Rectan
relative humidity, $u(\delta_{hum})$	0,01	0,025	0,05	0,25	B	Rectan
measuring frequency, $u(\delta_{fr})$	1	1	1	1	B	Rectan
Reproducibility, $u(\delta_{repr})$	2	2	12	30	B	Rectan

Standard unc (k=1):	**8**	**8**	**16**	**40**
Expanded unc:	**16**	**16**	**32**	**80**
Eff. deg. of freedom:	∞	∞	∞	∞

Measuring voltage: **10 mV**

Contribution of:	Std. unc. f: 1 kHz	Std. unc. f: 20 kHz	Std. unc. f: 100 kHz	Std. unc. f: 1 MHz	Type A or B	Distri-bution
$u(\delta_{PMJTC})$	0,5	0,6	1,2	12	B	normal
$u(\delta_{con})$	1	1	5	15	B	rectan
$u(\delta_{fr})$	1	1	1	1	B	rectan
$u(\delta_{C})$	2	2	10	25	B	rectan
$u(\delta_{A})$	7	9	7	7	A	normal
$u(\delta_{T})$	1	1	1	4	B	rectan
$u(\delta_{hum})$	0,01	0,025	0,05	0,25	B	rectan
$u(\delta_{repr})$	2	2	15	40	B	rectan
$u(\delta_{level})$	5	5	5	5	B	rectan
$u(\delta_{PMJTC})$	0,5	0,6	1,2	12	B	rectan
$u(\delta_{Zin(RVD)})$	5	5	5	15	B	rectan
$u(\delta_{fr(RVD)})$	1	1	1	1	B	rectan
$u(\delta_{C(RVD)})$	10	10	20	30	B	rectan
$u(\delta_{A\ (RVD)})$	8	8	8	8	A	normal
$u(\delta_{T(RVD)})$	0,5	0,5	0,5	2	B	rectan
$u(\delta_{con(RVD)})$	5	5	10	25	B	rectan
$u(\delta_{792(100\ mV)})$	8	8	16	39	B	normal

Standard unc (k=1):	**19**	**20**	**36**	**79**
Expanded unc (k=2):	**38**	**40**	**72**	**158**
Eff. deg. of freedom:	∞	∞	∞	∞

EUROMET.EM - K11: AC-DC voltage transfer difference at low voltages

Contents

Prepared by:	Boštjan Voljč	2006-07-01	____________
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Approved by:	Zoran Svetik	2006-07-01	____________

1 Introduction

In July 2006 our laboratory participated in the comparison EUROMET.EM – K11: AC-DC voltage transfer at low voltages. The measurements were done between the 3. - 14. July 2006.

2 Traceability

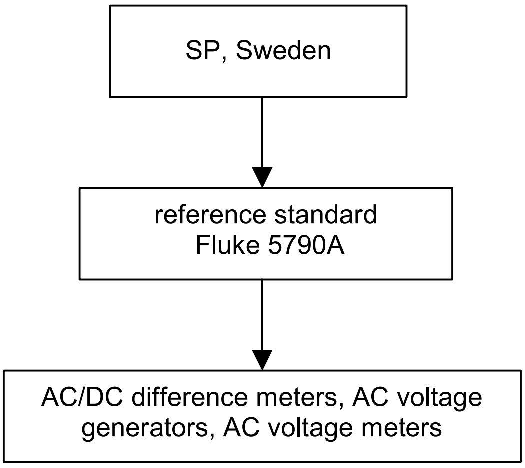

Figure 2.1: Traceability

3 Standards used for the comparison

Standards and other equipment, used to perform the comparison:

- reference standard Fluke 5790A,
- multifunction calibrator Fluke 5720A,
- digital multimeter HP 3458A,
- original N extenders,
- N-type T-piece SUHNER,
- 2 x adapter N-male to N-male POMONA 3842,
- BNC to banana plug,
- 25 cm BNC cable,
- BNC to N-male adapter POMONA 3288,
- N-female to N-female adapter SUHNER,
- 3 x low thermal cable POMONA 1756-24
- Fluke banana to banana cable to connect HP 3458A.

4 Measurement

4.1 Ambient conditions

Temperature: 23 °C +/- 2 °C

Humidity: 50 % +/- 20 %

4.2 Connections

In the calibration only one source (multifunction calibrator Fluke 5720A) was used for generating the DC+, DC- and AC voltage. For switching between the voltages internal switch of the calibrator was used.

Reference standard Fluke 5790A and transfer standard under comparison Fluke 792A were connected to the source over symmetrical N-type T-piece (SUHNER). On each side of the T-piece and adapter N-male to N-male (POMONA 3842) was used. On both standards the N-type extender was used (standards were calibrated with these extenders).

The source was connected to the T-piece through the following connections: BNC to banana adapter, 25 cm BNC cable, BNC to N-male adapter (POMONA 3288) and N-female to N-female adapter (SUHNER).

The source was set to INTERNAL GUARD and reference standard Fluke 5790A to EXTERNAL GUARD. GROUNDS and GUARDS were connected as seen in Figure 4.1. All GUARDS are connected in one point (GUARD on source Fluke 5720A). All shields of the cables were connected to GROUND on source Fluke 5720A. GROUND and GUARD on source were connected together.

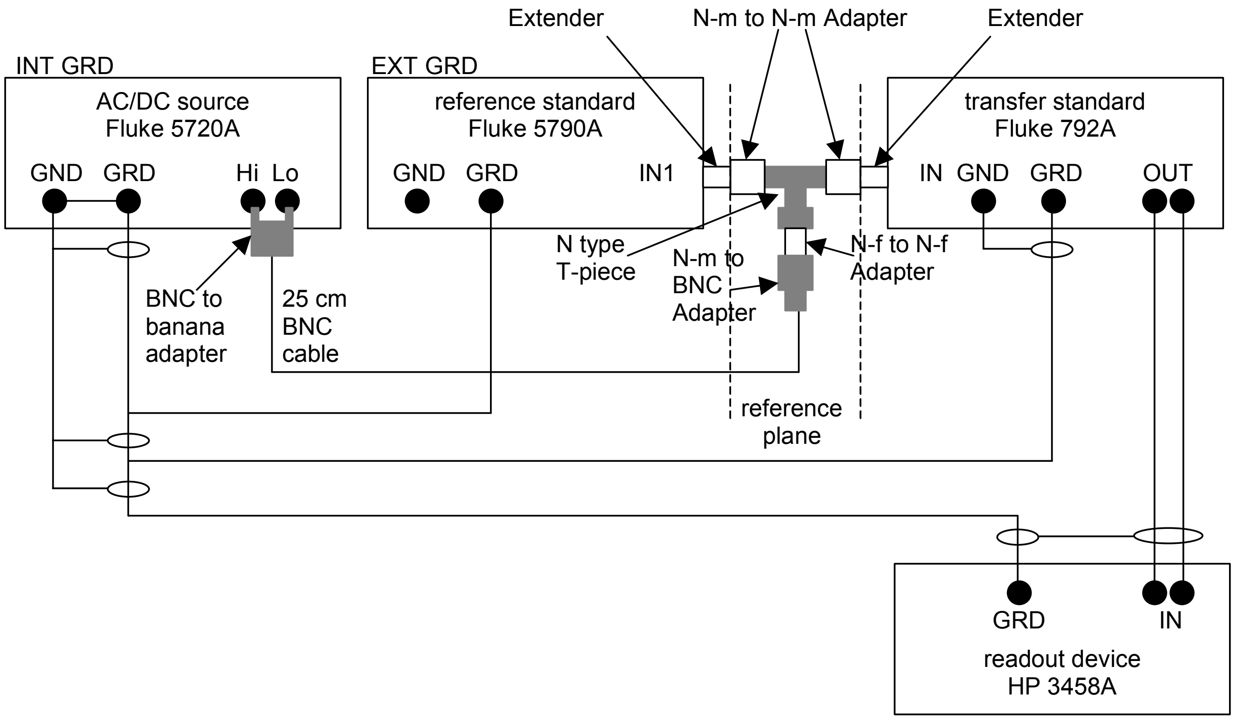

Figure 4.1: Measurement setup

4.3 Measurement principle

4.3.1 Determination of output/input sensitivity

Sensitivity coefficient S was determined for each measured AC voltage by varying DC input voltage for the same percentage in plus and minus direction and dividing the difference between two thermal output readings by the difference between two applied input voltages.

For determination of sensitivity coefficient, seven reading in sequence DC + ΔU, DC - ΔU, DC + ΔU, DC - ΔU, DC + ΔU, DC - ΔU, DC + ΔU, yielding six voltage differences at input and output with three balanced pairs (with opposite slopes) of sensitivity coefficient, effectively canceling out drift effects (the effect of drift shall be opposite for DC + ΔU and DC - ΔU measurement pairs) under the assumption that drift is linear.

4.3.2 Measurement of AC/DC voltage difference

DC1+, AC2, DC3-, AC4, DC5+, AC6, DC7-, AC8, DC9+, AC10, DC11-, AC12, DC13+ sequence of voltage modes has been adopted with total of 13 measurement points for each voltage measured. From each DC+, AC, DC- and DC-, AC, DC+ (triplet) subsequence, an AC/DC difference is calculated.

Six measured values are obtained in this way and the actual AC/DC difference is calculated as their mean, while the standard deviation is used to calculate the uncertainty contribution by type A evaluation.

An overview of measurement sequences for sensitivity determination and for determination of AC/DC difference is shown in the following table:

meas. step	time of step	input voltage (sens. deter.)	input voltage (AC/DC)	input voltage (AC/AC)	output voltage (measured)	measurement result
1	t_1	DC + ΔU	DC1+	AC1 (f_r)	U_{th1}	
2	t_2		AC2	AC2 (f_x)	U_{th2}	U_{AC2} from steps(1, 2, 3.)
3	t_3	DC - ΔU	DC3-	AC3 (f_r)	U_{th3}	
4	t_4		AC4	AC4 (f_x)	U_{th4}	U_{AC4} from steps (3, 4, 5)
5	t_5	DC + ΔU	DC5+	AC5 (f_r)	U_{th5}	
etc.	etc.	etc.	etc.	etc.	etc.	
11	t_{11}	DC - ΔU	DC11-	AC11 (f_r)	U_{th11}	
12	t_{12}		AC12	AC12 (f_x)	U_{th12}	U_{AC12} from steps (11, 12, 13)
13	t_{13}	DC + ΔU	DC13+	AC13 (f_r)	U_{th13}	
Measurement result for single voltage/frequency point:						mean (U_{AC}), s (U_{AC})

Table 4-1: AC/DC difference determination sequences

4.3.3 Determination of AC/DC difference

The AC/DC difference is obtained by the following equation:

$$\delta_X = \frac{1}{U_{DC}} \cdot \left(\frac{\Delta U_{THS}}{S_S} - \frac{\Delta U_{THX}}{S_X} \right) + \delta_S$$

where

δ_X correction for AC/DC difference of TVC under calibration,

U_{DC} average voltage of U_{DC+} and U_{DC-},

ΔU_{THS} thermal voltage difference between DC and AC input on reference standard TVC,

ΔU_{THX} thermal voltage difference between DC and AC input on TVC under calibration,

S_S sensitivity coefficient of reference standard TVC,

S_X sensitivity coefficient of the TVC under calibration,

δ_S AC/DC transfer correction of reference standard TVC from its calibration certificate.

5 Uncertainties

5.1 Mathematical model of measurement

The AC/DC difference of the unit under calibration, δ_X, is obtained from average value of more AC/DC differences that are calculated with equation:

Eq. 5.1: $$\delta_X = \delta_{AVG} + \delta_S + u_{LTS} + u_{LINT} + u_{RESS} + u_{RESX} + u_{REP} + u_{GEN} + u_{OTH}$$

where:

δ_{AVG} average value of measured AC/DC difference,

δ_S correction coefficient of the reference transfer standard from its certificate,

u_{LTS} long term stability of reference transfer standard,

u_{LINT} uncertainty of linear interpolation of correction coefficient of the reference transfer standard,

u_{RESS} resolution of the reference transfer standard,

u_{RESX} resolution of the unit under test (or its readout device),

u_{REP} reproducibility of the measurement,

u_{GEN} stability of DC or AC source used,

u_{OTH} other influences not evaluated individually,

- distance from reference point in respect to the distance used in calibration of the reference transfer standard;
- evaluation of nonlinear drift of converters,
- uncertainty of sensitivity of both TVC.

Average value of measured AC/DC difference (δ_{AVG})

The average value of the measured AC/DC difference is calculated from six triplets out of 13 points sequence of measurement.

The standard deviation of the average value of AC/DC difference is calculated as:

$$u_A = \sqrt{\frac{\sum_{i=1}^{n}(\delta_i - \delta_{AVG})^2}{n \cdot (n-1)}}$$ - normal distribution.

Correction coefficient of the reference transfer standard from its certificate (δ_S)

Value of the correction coefficient and its uncertainty is taken from the calibration certificate of the reference transfer standard. Uncertainty has a normal probability distribution with coverage factor k = 2.

Long term stability of the reference transfer standard (u_{LTS})

The long term stability was evaluated from the previous calibration certificates of AC/DC transfer standard and also from the calibration certificates of other AC/DC transfer standards that have been calibrated with reference transfer standard Fluke 5790A. It has been overestimated to the one fourth (1/4) of the relative specification of the reference transfer standard.

Uncertainty of linear interpolation of correction coefficients of the reference transfer standard (u_{LINT})

This is the uncertainty of linear interpolation of correction coefficient of the reference transfer standard for frequency or voltage points for which correction coefficients were not obtained by calibration.

Where two voltages on the same range were calibrated the correction coefficients for other voltages within the range are calculated with linear interpolation. The uncertainty of linear interpolation is overestimated to one half (1/2) of the AC/DC difference between two measured points from which the linear interpolation has been calculated.

In case that AC/DC difference has been measured at only one voltage on range (ranges below 220 mV) the linear interpolation could not be calculated. In that case the correction at measured voltage is taken for any voltage on that range. The uncertainty is higher and is determined from the difference between measured points on higher ranges since the instrument exhibit similar frequency and voltage dependence on higher ranges as can be seen from the calibration certificate.

The uncertainty contribution has rectangular probability distribution.

Resolution of the reference transfer standard (u_{RESS})

The quantity corresponding to the least significant digit of the reference transfer standard display equals the finite resolution of the display. The correction is estimated to be zero with limits ± half the resolution (half the magnitude of the least significant digit).

Eq. 5.2 $$u\_r = \frac{Us_{RESOLUTION}}{2}$$

Resolution of the unit under test (its readout device) (u_{RESX})

The quantity corresponding to the least significant digit of the readout device equals the finite resolution of the display. The correction is estimated to be zero with limits ± half the resolution (half the magnitude of the least significant digit).

Eq. 5.3 $$u\_r = \frac{Ux_{RESOLUTION}}{2}$$

Reproducibility of the measurement (u_{REP})

This uncertainty contribution is determined by repeating the measurement several times. During the measurement repetitions the measurement setup has been taken apart and back together and cables and connectors have been replaced with the ones of the same type. The difference between the minimum and maximum measured value has been extended at least by safety factor of 100 % and taken in account as uncertainty contribution of the reproducibility.

Stability of DC and AC source (u_{GEN})

For AC/DC difference measurements the absolute values of DC and AC voltages do not need to be known very accurately as long as source exhibit sufficient stability and resolution in setting of the output voltage as all measurements are performed relatively.

Because the measurement is completed relatively fast (less than 10 minutes for one measuring point) one tenth (1/10) of the 24 hour stability uncertainty is taken in account for uncertainty due to the stability of the source.

Other influences not evaluated individually (u_{OTH})

- **Uncertainty of drift d**

Drift contributes to uncertainty partially with its non-linear component and with non-accurate timing of the measurement sequence. Our measurements have shown that it is practically negligible for small AC/DC differences and becomes significant with larger (several hundreds of ppm). Uncertainty of timing measurement is independent of measurement setup and is estimated to be approximately 1 s.

- **Uncertainty of sensitivity S**

The influence of uncertainty of sensitivity determination is also very small and was evaluated by calculating standard deviation from measurements taken to determine drift.

- **Uncertainty of linearity of the system including readout units**

This has been estimated to be 3 ppm for smaller AC/DC differences (less than 1000 ppm) and 6 ppm for very large AC/DC differences (several thousand ppm).

- **Distance from reference point in respect to the distance used in calibration of the standard TVC**

This part was only estimated.

6 Results with uncertainty calculation

6.1 100 mV @ 1 kHz

Measurement conditions:

	START	STOP	Uncertainty
Temperature	22,9 °C	23,1 °C	
Humidity	49,5 %	50,1 %	
DCV +	11,1002 V	11,0999 V	0,1mV
DCV-	-11,1641 V	-11,1639 V	0,1 mV
Frequency	0,999985 kHz		0,003 Hz

Mathematical model of measurement:

	result	
δ_{AVG}	2,8 ppm	
st.dev.	0,9 ppm	(based on 6 measurement results)

Quantity *Xi*	Estimate *xi*	Standard uncertainty *u(xi)*	Probability distribution	Div.	Sensitivity coefficient *ci*		Uncertainty contribution *ui(y)*	Effective degr. of freedom *vi*	Uncertainty contribution
δ_{AVG}	2,8 ppm	0,9 ppm	normal	1	1	-	0,90 ppm	5	0,90
δ_S	8,0 ppm	8,5 ppm	normal	2	1	-	8,50 ppm	1E+99	17,00
u_{LTS}	0 ppm	4,9 ppm	normal	2	1	-	4,88 ppm	1E+99	9,75
u_{LINT}	0 ppm	0,0 ppm	normal	2	1	-	0,00 ppm	1E+99	0,00
u_{RESS}	0 ppm	0,3 ppm	rectangula	1,73	1	-	0,29 ppm	1E+99	0,50
u_{RESX}	0 ppm	0,0 ppm	rectangula	1,73	1	-	0,02 ppm	1E+99	0,03
u_{REP}	0 ppm	5,0 ppm	normal	2	1	-	5,00 ppm	1E+99	10,00
u_{GEN}	0 ppm	1,6 ppm	normal	2	1	-	1,60 ppm	1E+99	3,20
u_{OTH}	0 ppm	7,5 ppm	normal	2	1	-	7,50 ppm	1E+99	15,00
δ_X	10,8 ppm						13,4 ppm	248891	
		Expanded uncertainty of measurement:					26,9 ppm		

Table 6.1: Calculation example for 100 mV @ 1 kHz

6.2 100 mV @ 20 kHz

Measurement conditions:

	START	STOP	Uncertainty
Temperature	22,9 °C	23,1 °C	
Humidity	49,5 %	50,1 %	
DCV +	11,1002 V	11,0999 V	0,1 mV
DCV-	-11,1641 V	-11,1639 V	0,1 mV
Frequency	9,99985 kHz		0,03 Hz

Mathematical model of measurement:

	result	
δ_{AVG}	-10,9 ppm	
st.dev.	0,8 ppm	(based on 6 measurement results)

Quantity *Xi*	Estimate *xi*	Standard uncertainty *u(xi)*	Probability distribution	Div.	Sensitivity coefficient *ci*		Uncertainty contribution *ui(y)*	Effective degr. of freedom *vi*	Uncertainty contribution
δ_{AVG}	-10,9 ppm	0,8 ppm	normal	1	1	-	0,80 ppm	5	0,80
δ_S	5,0 ppm	8,5 ppm	normal	2	1	-	8,50 ppm	1E+99	17,00
u_{LTS}	0 ppm	4,9 ppm	normal	2	1	-	4,88 ppm	1E+99	9,75
u_{LINT}	0 ppm	0,0 ppm	normal	2	1	-	0,00 ppm	1E+99	0,00
u_{RESS}	0 ppm	0,3 ppm	rectangula	1,73	1	-	0,29 ppm	1E+99	0,50
u_{RESX}	0 ppm	0,0 ppm	rectangula	1,73	1	-	0,02 ppm	1E+99	0,03
u_{REP}	0 ppm	5,0 ppm	normal	2	1	-	5,00 ppm	1E+99	10,00
u_{GEN}	0 ppm	1,5 ppm	normal	2	1	-	1,50 ppm	1E+99	3,00
u_{OTH}	0 ppm	7,5 ppm	normal	2	1	-	7,50 ppm	1E+99	15,00
δ_X	-5,9 ppm						13,4 ppm	4E+05	
		Expanded uncertainty of measurement:					26,9 ppm		

Table 6.2: Calculation example for 100 mV @ 20 kHz

6.3 100 mV @ 100 kHz

Measurement conditions:

	START	STOP	Uncertainty
Temperature	22,9 °C	23,1 °C	
Humidity	49,5 %	50,1 %	
DCV +	11,1002 V	11,0999 V	0,1 mV
DCV-	-11,1641 V	-11,1639 V	0,1 mV
Frequency	99,9985 kHz		0,3 Hz

Mathematical model of measurement:

	result	
δ_{AVG}	6,3 ppm	
st.dev.	0,9 ppm	(based on 6 measurement results)

Quantity *Xi*	Estimate *xi*	Standard uncertainty *u(xi)*	Probability distributio n	Div.	Sensitivity coefficient *ci*		Uncertainty contribution *ui(y)*	Effective degr. of freedom *vi*	Uncertainty contribution
δ_{AVG}	6,3 ppm	0,9 ppm	normal	1	1	-	0,90 ppm	5	0,90
δ_S	7,0 ppm	13,0 ppm	normal	2	1	-	13,00 ppm	1E+99	26,00
u_{LTS}	0 ppm	9,6 ppm	normal	2	1	-	9,63 ppm	1E+99	19,25
u_{LINT}	0 ppm	0,0 ppm	normal	2	1	-	0,00 ppm	1E+99	0,00
u_{RESS}	0 ppm	0,3 ppm	rectangula	1,73	1	-	0,29 ppm	1E+99	0,50
u_{RESX}	0 ppm	0,0 ppm	rectangula	1,73	1	-	0,02 ppm	1E+99	0,03
u_{REP}	0 ppm	10,0 ppm	normal	2	1	-	10,00 ppm	1E+99	20,00
u_{GEN}	0 ppm	1,5 ppm	normal	2	1	-	1,50 ppm	1E+99	3,00
u_{OTH}	0 ppm	7,5 ppm	normal	2	1	-	7,50 ppm	1E+99	15,00
δ_X	13,3 ppm						20,5 ppm	1E+06	
		Expanded uncertainty of measurement:					41,0 ppm		

Table 6.3: Calculation example for 100 mV @ 20 kHz

6.4 100 mV @ 1 MHz

Measurement conditions:

	START	STOP	Uncertainty
Temperature	22,9 °C	23,1 °C	
Humidity	49,5 %	50,1 %	
DCV +	11,1002 V	11,0999 V	0,1 mV
DCV-	-11,1641 V	-11,1639 V	0,1 mV
Frequency	0,999985 M Hz		3 Hz

Mathematical model of measurement:

	result	
δ_{AVG}	54,5 ppm	
st.dev.	1,9 ppm	(based on 6 measurement results)

Quantity *Xi*	Estimate *xi*	Standard uncertainty *u(xi)*	Probability distribution	Div.	Sensitivity coefficient *ci*		Uncertainty contribution *ui(y)*	Effective degr. of freedom *vi*	Uncertainty contribution
δ_{AVG}	54,5 ppm	1,9 ppm	normal	1	1	-	1,90 ppm	5	1,90
δ_{S}	-64,0 ppm	120,0 ppm	normal	2	1	-	120,00 ppm	1E+99	240,00
u_{LTS}	0 ppm	126,3 ppm	normal	2	1	-	126,25 ppm	1E+99	252,50
u_{LINT}	0 ppm	0,0 ppm	normal	2	1	-	0,00 ppm	1E+99	0,00
u_{RESS}	0 ppm	0,3 ppm	rectangula	1,73	1	-	0,29 ppm	1E+99	0,50
u_{RESX}	0 ppm	0,0 ppm	rectangula	1,73	1	-	0,02 ppm	1E+99	0,03
u_{REP}	0 ppm	25,0 ppm	normal	2	1	-	25,00 ppm	1E+99	50,00
u_{GEN}	0 ppm	20,0 ppm	normal	2	1	-	20,00 ppm	1E+99	40,00
u_{OTH}	0 ppm	10,0 ppm	normal	2	1	-	10,00 ppm	1E+99	20,00
δ_{X}	-9,5 ppm						177,4 ppm	4E+08	
		Expanded uncertainty of measurement:					354,8 ppm		

Table 6.4: Calculation example for 100 mV @ 20 kHz

6.5 10 mV @ 1 kHz

Measurement conditions:

	START	STOP	Uncertainty
Temperature	23,1 °C	23,0 °C	
Humidity	50,1 %	50,6 %	
DCV +	11,0999 V	11,0997 V	0,1 mV
DCV-	-11,1639 V	-11,1635 V	0,1 mV
Frequency	0,999985 kHz		0,003 Hz

Mathematical model of measurement:

	result	
δ_{AVG}	47,6 ppm	
st.dev.	8,9 ppm	(based on 6 measurement results)

Quantity *Xi*	Estimate *xi*	Standard uncertainty *u(xi)*	Probability distribution	Div.	Sensitivity coefficient *ci*		Uncertainty contribution *ui(y)*	Effective degr. of freedom *vi*	Uncertainty contribution
δ_{AVG}	47,6 ppm	8,9 ppm	normal	1	1	-	8,90 ppm	5	8,90
δ_{S}	-40,0 ppm	15,0 ppm	normal	2	1	-	15,00 ppm	1E+99	30,00
u_{LTS}	0 ppm	20,8 ppm	normal	2	1	-	20,75 ppm	1E+99	41,50
u_{LINT}	0 ppm	5,0 ppm	normal	2	1	-	5,00 ppm	1E+99	10,00
u_{RESS}	0 ppm	2,9 ppm	rectangula	1,73	1	-	2,89 ppm	1E+99	5,00
u_{RESX}	0 ppm	0,0 ppm	rectangula	1,73	1	-	0,02 ppm	1E+99	0,03
u_{REP}	0 ppm	15,0 ppm	normal	2	1	-	15,00 ppm	1E+99	30,00
u_{GEN}	0 ppm	10,0 ppm	normal	2	1	-	10,00 ppm	1E+99	20,00
u_{OTH}	0 ppm	7,5 ppm	normal	2	1	-	7,50 ppm	1E+99	15,00
δ_{X}	7,6 ppm						33,9 ppm	1053	
		Expanded uncertainty of measurement:					67,8 ppm		

Table 6.5: Calculation example for 10 mV @ 1 kHz

6.6 10 mV @ 20 kHz

Measurement conditions:

	START	STOP	Uncertainty
Temperature	23,1 °C	23,0 °C	
Humidity	50,1 %	50,6 %	
DCV +	11,0999 V	11,0997 V	0,1 mV
DCV-	-11,1639 V	-11,1635 V	0,1 mV
Frequency	9,99985 kHz		0,03 Hz

Mathematical model of measurement:

	result	
δ_{AVG}	59,0 ppm	
st.dev.	10,2 ppm	(based on 6 measurement results)

Quantity *Xi*	Estimate *xi*	Standard uncertainty *u(xi)*	Probability distribution	Div.	Sensitivity coefficient *ci*		Uncertainty contribution *ui(y)*	Effective degr. of freedom *vi*	Uncertainty contribution
δ_{AVG}	59,0 ppm	10,2 ppm	normal	1	1	-	10,20 ppm	5	10,20
δ_{S}	-41,0 ppm	15,0 ppm	normal	2	1	-	15,00 ppm	1E+99	30,00
u_{LTS}	0 ppm	20,8 ppm	normal	2	1	-	20,75 ppm	1E+99	41,50
u_{LINT}	0 ppm	5,0 ppm	normal	2	1	-	5,00 ppm	1E+99	10,00
u_{RESS}	0 ppm	2,9 ppm	rectangula	1,73	1	-	2,89 ppm	1E+99	5,00
u_{RESX}	0 ppm	0,0 ppm	rectangula	1,73	1	-	0,02 ppm	1E+99	0,03
u_{REP}	0 ppm	15,0 ppm	normal	2	1	-	15,00 ppm	1E+99	30,00
u_{GEN}	0 ppm	10,0 ppm	normal	2	1	-	10,00 ppm	1E+99	20,00
u_{OTH}	0 ppm	7,5 ppm	normal	2	1	-	7,50 ppm	1E+99	15,00
δ_{X}	18,0 ppm						34,3 ppm	6E+02	
		Expanded uncertainty of measurement:					68,5 ppm		

Table 6.6: Calculation example for 10 mV @ 20 kHz

6.7 10 mV @ 100 kHz

Measurement conditions:

	START	STOP	Uncertainty
Temperature	23,1 °C	23,0 °C	
Humidity	50,1 %	50,6 %	
DCV +	11,0999 V	11,0997 V	0,1 mV
DCV-	-11,1639 V	-11,1635 V	0,1 mV
Frequency	99,9985 kHz		0,3 Hz

Mathematical model of measurement:

	result	
δ_{AVG}	6,5 ppm	
st.dev.	10,2 ppm	(based on 6 measurement results)

Quantity *Xi*	Estimate *xi*	Standard uncertainty *u(xi)*	Probability distribution	Div.	Sensitivity coefficient *ci*		Uncertainty contribution *ui(y)*	Effective degr. of freedom *vi*	Uncertainty contribution
δ_{AVG}	6,5 ppm	10,2 ppm	normal	1	1	-	10,20 ppm	5	10,20
δ_{S}	-29,0 ppm	22,5 ppm	normal	2	1	-	22,50 ppm	1E+99	45,00
u_{LTS}	0 ppm	38,4 ppm	normal	2	1	-	38,38 ppm	1E+99	76,75
u_{LINT}	0 ppm	5,0 ppm	normal	2	1	-	5,00 ppm	1E+99	10,00
u_{RESS}	0 ppm	2,9 ppm	rectangular	1,73	1	-	2,89 ppm	1E+99	5,00
u_{RESX}	0 ppm	0,0 ppm	rectangular	1,73	1	-	0,02 ppm	1E+99	0,03
u_{REP}	0 ppm	30,0 ppm	normal	2	1	-	30,00 ppm	1E+99	60,00
u_{GEN}	0 ppm	15,0 ppm	normal	2	1	-	15,00 ppm	1E+99	30,00
u_{OTH}	0 ppm	7,5 ppm	normal	2	1	-	7,50 ppm	1E+99	15,00
δ_{X}	-22,5 ppm						57,4 ppm	5E+03	
		Expanded uncertainty of measurement:					114,8 ppm		

Table 6.7: Calculation example for 10 mV @ 100 kHz

6.8 10 mV @ 1 MHz

Measurement conditions:

	START	STOP	Uncertainty
Temperature	23,1 °C	23,0 °C	
Humidity	50,1 %	50,6 %	
DCV +	11,0999 V	11,0997 V	0,1 mV
DCV-	-11,1639 V	-11,1635 V	0,1 mV
Frequency	0,999985 MHz		3 Hz

Mathematical model of measurement:

	result	
δ_{AVG}	-76,1 ppm	
st.dev.	10,6 ppm	(based on 6 measurement results)

Quantity *Xi*	Estimate *xi*	Standard uncertainty *u(xi)*	Probability distribution	Div.	Sensitivity coefficient *ci*		Uncertainty contribution *ui(y)*	Effective degr. of freedom *vi*	Uncertainty contribution
δ_{AVG}	-76,1 ppm	10,6 ppm	normal	1	1	-	10,60 ppm	5	10,60
δ_S	0,0 ppm	175,0 ppm	normal	2	1	-	175,00 ppm	1E+99	350,00
u_{LTS}	0 ppm	287,5 ppm	normal	2	1	-	287,50 ppm	1E+99	575,00
u_{LINT}	0 ppm	100,0 ppm	normal	2	1	-	100,00 ppm	1E+99	200,00
u_{RESS}	0 ppm	2,9 ppm	rectangular	1,73	1	-	2,89 ppm	1E+99	5,00
u_{RESX}	0 ppm	0,0 ppm	rectangular	1,73	1	-	0,02 ppm	1E+99	0,03
u_{REP}	0 ppm	50,0 ppm	normal	2	1	-	50,00 ppm	1E+99	100,00
u_{GEN}	0 ppm	75,0 ppm	normal	2	1	-	75,00 ppm	1E+99	150,00
u_{OTH}	0 ppm	10,0 ppm	normal	2	1	-	10,00 ppm	1E+99	20,00
δ_X	-76,1 ppm						362,8 ppm	7E+06	
		Expanded uncertainty of measurement:					725,6 ppm		

Table 6.8: Calculation example for 10 mV @ 1 MHz

6.9 Measurement results – summary

U [mV]	*f* [kHz]	*AC/DC diff* [ppm]	*uncertainty* [ppm]
10	1	8	70
10	20	-18	70
10	100	-23	120
10	1000	-76	750
100	1	11	30
100	20	-6	30
100	100	13	50
100	1000	-9	400

KALIBROINTITODISTUS

KALIBRERINGSBEVIS

CERTIFICATE OF CALIBRATION

Nro nr • no.	M-07E085
Tilaaja Uppdragsgivare • Customer	SP Technical Research Institute of Sweden Measurement Technology P.O. Box 857 SE-501 15 Borås Sweden
Kalibroitu laite Kalibrerat instrument • Calibrated Instrument	Thermal transfer standard
Valmistaja Tillverkare • Manufactured by	Fluke
Tyyppi Typ • Model	792A
Sarjanumero Serienummer • Serial number	5495003
Kalibrointipäivä Kalibreringsdatum • Date of calibration	28.9.2006 (TaMa)
Päiväys Datum • Date	15.11.2007
Allekirjoitukset Underskrifter • Signatures	Tapio Mansten, Senior Research Scientist Antti Manninen, Senior Research Scientist
Sivu Sida • Page	1/6
Liitteitä Bilagor • Appendices	19

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1. BACKGROUND

MIKES is the National Metrology Institute (NMI) in Finland and serves as the National Standards Laboratory (NSL) in the field of electricity. One of the quantities maintained is AC voltage. MIKES uses one PMJTC (planar multi-junction thermal converter) sn 21, manufactured by IPHT and assembled and housed by PTB as a reference standard for basic level (1.5 V) acdc difference of voltage. The PMJTC sn 21 has traceability of its acdc difference to PTB, see App. C1.

MIKES traces ac voltages below 100 mV by using a PMJTC and two resistive voltage dividers (SP RVD 10/1, S/N 98004 and SP RVD 100/1, S/N 98006) calibrated by SP (Certificates of Calibration and 98F12514/08.06.1998), see App. C2.

This document is the EUROMET.EM-K11 Certificate of Calibration for the travelling standard Fluke 792A. The measurements were done in September 2006. The actual measurement dates are imbedded into the names of measurement files.

2. ACDC VOLTAGE COMPARISON SETUP OF MIKES

The dc voltages are produced by Datron 4708 DC generator and the ac voltages by Fluke 5700A generator. An ACDC relay constructed by MIKES applies these voltages alternatively to a T connector. The measurement circuit is grounded from this connector. See Fig. 1.

The output voltages of the devices to be compared are measured by two HP 34420A nV meters.

Before the calibration the levels in the measurement sequence file at each measurement frequency for the ac calibrator are adjusted so that the output voltages of ac and dc generators at the T connector match each other reasonably well under the applied load. Models for the output voltages of both devices as a function of input voltage are established by varying the input DC voltage (both positive and negative values) within ± 2% limits around the nominal measurement voltage. Second order regression model with the input voltages and their squares as independent variables is applied for the thermal output voltages of PMJTCs. Linear regression model with the input voltages as independent variable is applied for the output voltages of linear devices like Fluke 792A. The model for Fluke 792 is the average of positive and negative regression.

In actual measurements these models are used to solve estimations of input voltages from measured thermal voltages (the Seebeck coefficient which determines the thermal voltages at certain input power depends on the ambient temperature and thus these estimated values may differ from applied voltages, but the models treat both ac and dc voltages in the same way and so the estimates are mutually compatible). The solved estimations of input voltages are used to calculate the acdc differences of the compared devices.

After a proper warmup period (some hours) with the nominal voltage applied the measurement was done in the following sequence:

1 DC+
1 AC => AC vs. DC+(1),DC-(1)
1 DC-
1 AC => AC vs. DC-(1),DC+(2)
......
2 DC+
2 AC => AC vs. DC+(2),DC-(2)
2 DC-
2 AC
......

which was repeated several times at each of the frequencies given. Each output voltage pair of the sequence was averaged from 16 individual measurement pairs after an appropriate delay from each turn of the acdc relay. The measuring algorithm also produces standard deviations (SD) of the mean of the

16 measurements for each channel. They are saved to a file together with the averages, and propagate further into the uncertainty calculations.

The ambient temperature during the measurements was 22.8 °C ± 0.2 °C and relative humidity was 41 % ± 1%.

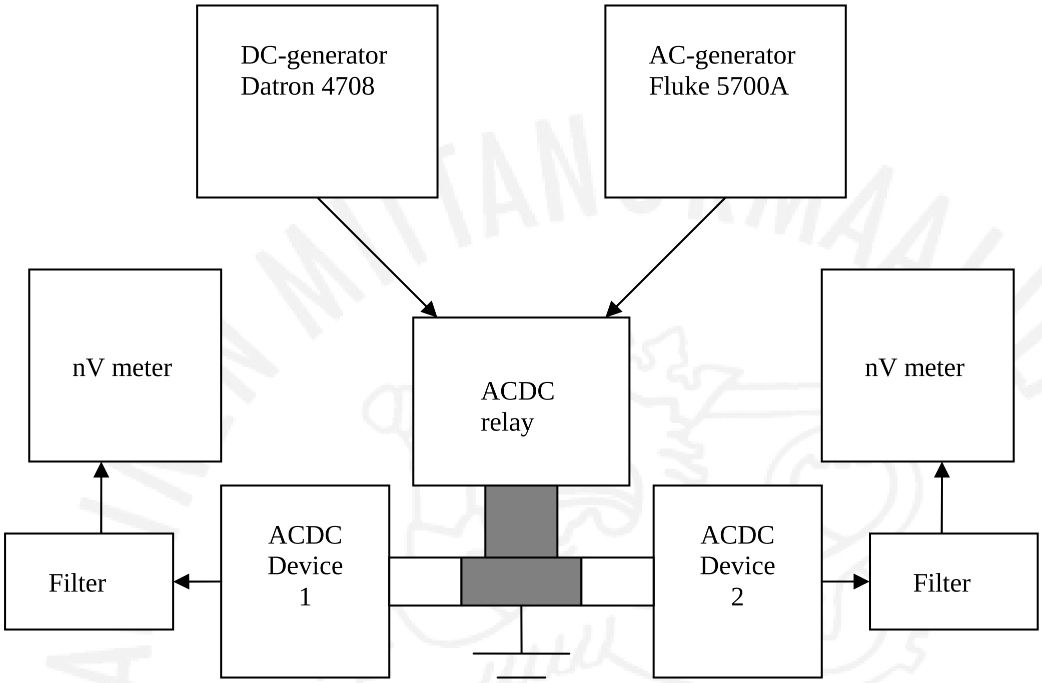


Fig. 1: Measurement setup

3. CALCULATIONS

The apparent acdc differences seen by PMJTC and Fluke 792A were calculated by first solving the input voltages uin_ac, uin_dc from thermal voltages by using the models measured with DC variation, and then applying Eq. (1):

$$acdc\_difference = -\frac{u_{in\_ac} - u_{in\_dc}}{u_{in\_dc}} \quad (1)$$

where u_{in_ac} is the input voltage calculated from the measured thermal voltage for ac by using the model, and u_{in_dc} is the average of the two input voltages calculated by using the model for DC+ and DC- thermal voltages. These apparent acdc differences are calculated for both devices with the acdc difference of the two calibrators included. The difference of the acdc differences of the two thermal converters is obtained at each frequency by substracting their acdc differences from each other and thus cancelling the level difference between the ac and dc generators. The acdc differences are calculated for each ac measurement point that lies between either a DC+ and a DC- or a DC- and a DC+ measurements. With repetitions of the above sequency we get acdc results, which are partially interdependent (most of the dc points have been used twice, but it is acceptable due to the low variance contribution of DC points). See App. F1.

The procedure described produces the difference of the acdc differences of the two converters compared ("A-B"). If the subtrahend ("B") is traceable, the absolute acdc difference of the minuend ("A") is obtained simply by adding the traceable acdc difference of the subtrahend ("B") to the measured difference. See Fig. 2.

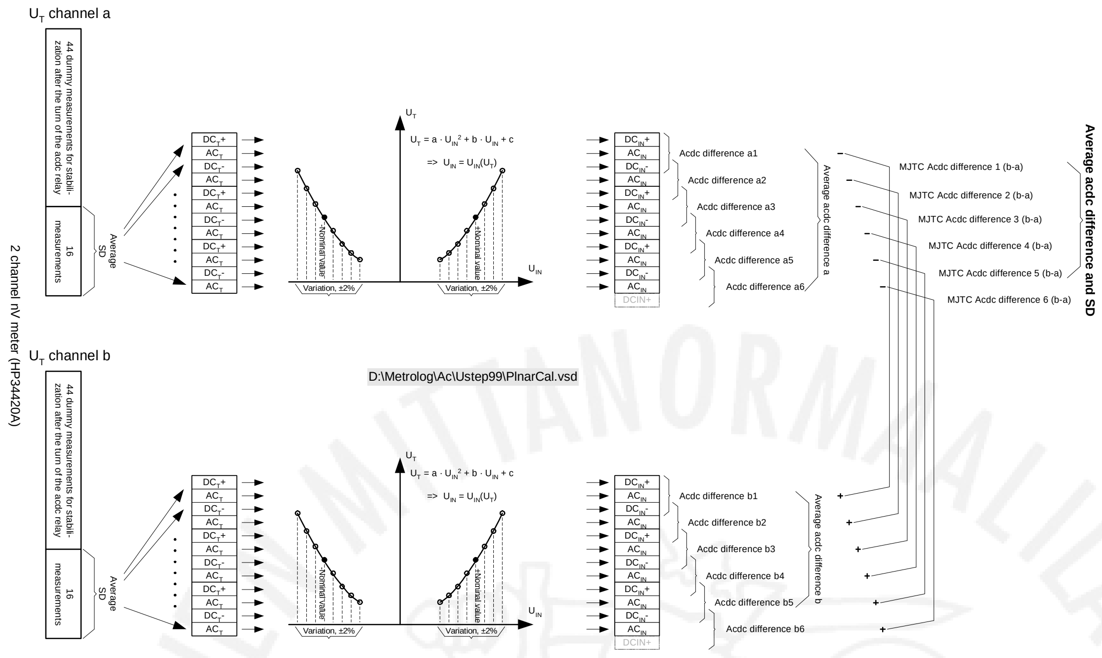


Fig. 2: Measurement procedure

4. MEASUREMENTS

The attenuators used between the relay and "T" allow for a more suitable voltage/impedance range for the generators. The reference plane in each measurement is the middle point of the common feeding N-T connector.

4.1 100 mV at 220 mV range

Five measurements were done:

- ACDC measurement, PMJTC 21 and Fluke 792A connected to the T connector which is connected to the ACDC relay output via a 10 dB 50 Ω uncalibrated attenuator, measurement data file PT001909.06, see App. A1
- ACDC measurement, PMJTC 21 and Fluke 792A connected to the T connector which is connected to the ACDC relay output via a 10 dB 50 Ω uncalibrated attenuator, measurement data file PT002009.06, see App. A2
- ACAC measurement (because of 40 Ω load caused by SP attenuator, which overloaded the current compliance of the DC generator), PMJTC 21 connected directly and Fluke 792A connected via SP 1:10 resistive divider to T connector of the ACDC relay output, measurement data file PT002109.06, see App. A3. This result was omitted due to its deviation from the other four results and its higher uncertainty
- ACDC measurement, PMJTC 21 and Fluke 792A connected to the T connector which is connected to the ACDC relay output via a 20 dB 50 Ω uncalibrated attenuator, measurement data file PT002609.06, see App. A4
- ACDC measurement, PMJTC 21 and Fluke 792A connected to the T connector which is connected to the ACDC relay output via a 20 dB 50 Ω uncalibrated attenuator, measurement data file PT002709.06 (duplication of the previous measurement) , see App. A5

4.2 10 mV at 22 mV range

Three measurements were done:

- ACAC measurement, PMJTC directly connected and Fluke 792A connected via SP 1:100 attenuator to the T connector which is connected to the ACDC relay, measurement data file PT002209.06, see App. B1
- ACAC measurement, PMJTC directly connected and Fluke 792A connected via SP 1:10 attenuator to the T connector which is connected to the ACDC relay output via a 20 dB 50 Ω uncalibrated attenuator, measurement data file PT002309.06, see App. B2
- ACDC measurement, PMJTC directly connected and Fluke 792A connected via SP 1:10 attenuator to the T connector which is connected to the ACDC relay output via a 10 dB 50 Ω uncalibrated attenuator, measurement data file PT002509.06, see App. B3

5. RESULTS

5.1 100 mV at 220 mV range

The results, their degrees of freedom and their expanded uncertainties are in Table I. See App. A6 for details and uncertainty budget. See also App. G1 and G2.

Table I: Results from 100 mV measurements

Frequency		1 kHz	20 kHz	100 kHz	1 MHz
Fluke 792 AcDc difference	µV/V	8.1	-6.9	17.9	16.3
Fluke 792 AcDc diff expanded uncertainty, k = 2	µV/V	4.7	5.5	6.2	32
Degrees of freedom		> 1000	> 1000	> 1000	> 1000

5.2 10 mV at 22 mV range

The results, their degrees of freedom and their expanded uncertainties are in Table II. See App. B4 for details and uncertainty budget. See also App. G1 and G2.

Table II: Results from 10 mV measurements

Frequency		1 kHz	20 kHz	100 kHz	1 MHz
Fluke 792 AcDc difference	µV/V	22	2	-14	-146
Fluke 792 AcDc diff expanded uncertainty, k = 2	µV/V	24	24	35	122
Degrees of freedom		> 1000	> 1000	> 1000	> 1000

6. APPENDIXES

A1: PT001909.06
A2: PT002009.06
A3: PT002109.06
A4: PT002609.06
A5: PT002709.06
A6: 100 mV at 220 mV range

B1: PT002209.06
B2: PT002309.06
B3: PT002509.06
B4: 10 mV at 22 mV range

C1: PMJTC 21 traceability
C2: Traceabilities of 1:10 and 1:100 resistive dividers

D1: Devices used

D2: Battery voltages

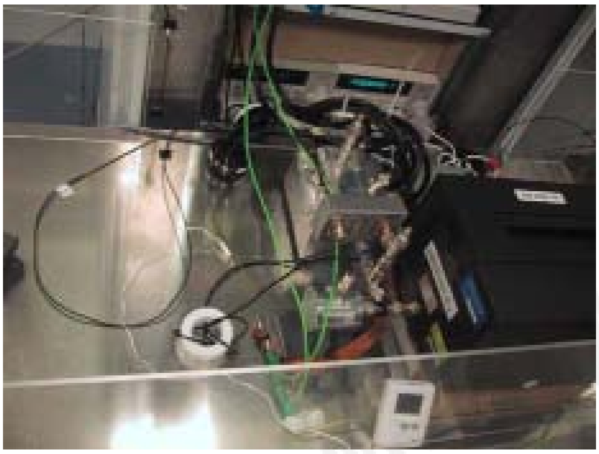
D3: Measurement frequency uncertainty

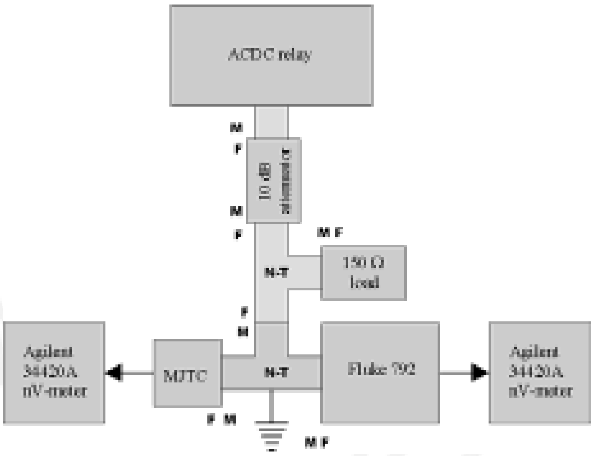
E1: Uncertainty contributions:

F1: Mathematical model of acdc comparison

G1: Summary of results
G2: Summary of uncertainty budget

App. A1: PT001909.06



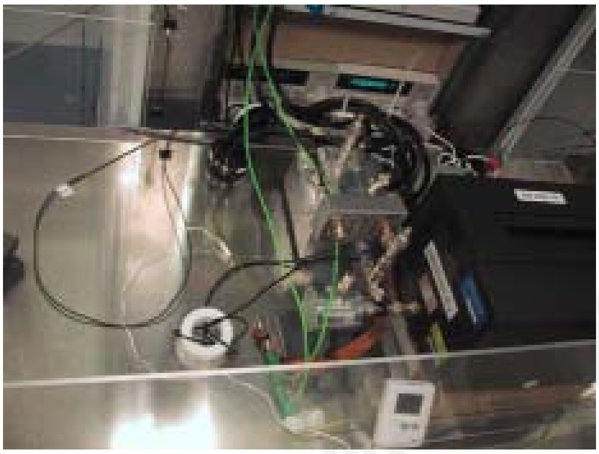


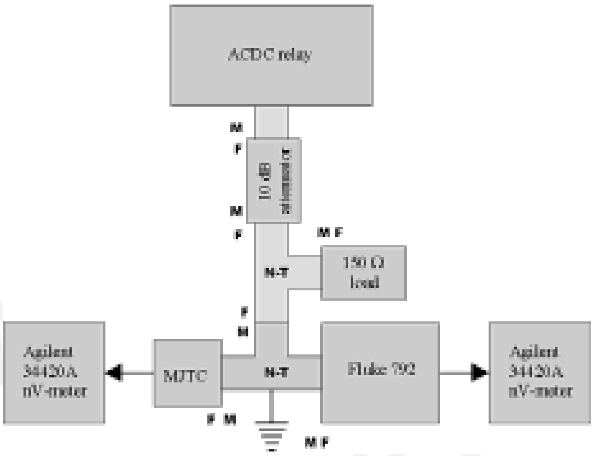
Measurement Pt001909.06
Fluke792 - PTB_MJTC_21

		Ch1		Ch2		F 792-		
		MJTC 21	u	Fluke 792A	u	MJTC 21	u	u
Freq.	Ampl.	AcDc-difference	k = 1	AcDc-difference	k = 1	AcDc-difference	k = 1	k = 1
kHz	V	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V
1	0.100	250.6	2.0	260.3	0.2	9.7	2.73	3.4
1	0.100	174.8	1.7	181.0	0.2	6.2	3.3	3.7
1	0.100	192.6	1.9	204.3	0.4	11.7	1.29	2.3
1	**0.100**					**9.2**		**3.2**
20	0.100	219.5	1.7	210	0.1	-9.5	2	2.6
20	0.100	185.5	1.7	174.4	0.2	-11.1	2.9	3.4
20	0.100	180.0	2	169.6	0.4	-10.4	7.2	7.5
20	**0.100**					**-10.3**		**5.0**
100	0.100	257	1.9	268.4	0.2	11.4	1.8	2.6
100	0.100	248.9	1.7	262.8	0.3	13.9	3.2	3.6
100	0.100	244.5	2	259.1	0.5	14.6	2.1	2.9
100	**0.100**					**13.3**		**3.1**
1000	0.100	19.2	1.7	22.4	0.4	3.2	1.5	2.3
1000	0.100	-127	2	-123.4	0.5	3.6	4	4.5
1000	0.100	-149.5	1.9	-140.7	0.6	8.8	2.1	2.9
1000	**0.100**					**5.2**		**3.4**

Columns 4 and 6 are combined A-type uncertainties from nV meter measurements. Column 8 contains A-type uncertainties from averaging the individual acdc differences for each line. Column 9 is the combined total A-type uncertainty of the measurement.

App. A2: PT002009.06

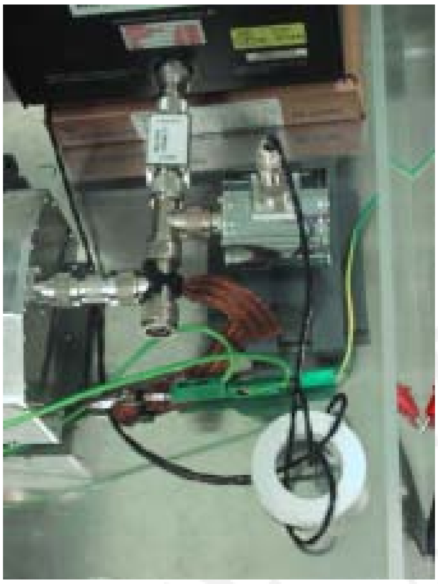


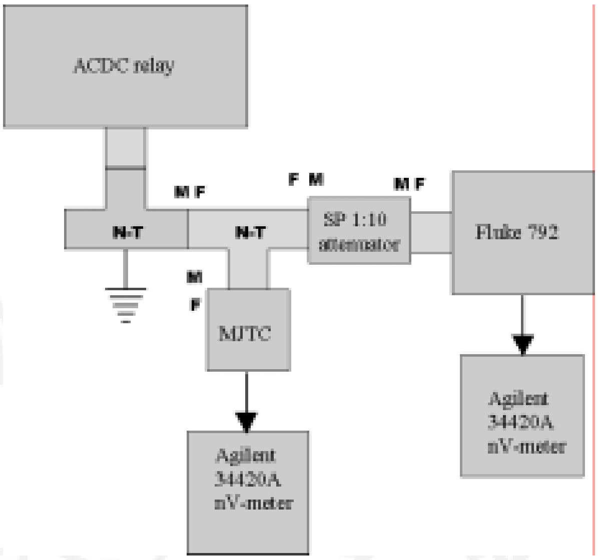


Measurement Pt002009.06
Fluke792 - PTB_MJTC_21

		Ch1		Ch2		F 792-		
		MJTC 21	u	Fluke 792A	u	MJTC 21	u	u
Freq.	Ampl.	AcDc-difference	k = 1	AcDc-difference	k = 1	AcDc-difference	k = 1	k = 1
kHz	V	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V
1	0.100	112.35	1.9	120.94	0.5	8.59	3.75	4.2
1	0.100	129.66	1.9	134.95	0.6	5.29	2.58	3.3
1	0.100	168.7	2.0	180.48	0.5	11.78	3.45	4.0
1	**0.100**					**8.6**		**3.9**
20	0.100	208.8	2.1	205.3	0.5	-3.5	2.93	3.6
20	0.100	86.8	1.9	80.3	0.5	-6.5	2.79	3.4
20	0.100	-27.7	2.0	-33.0	0.6	-5.3	7.61	7.9
20	**0.100**					**-5.1**		**5.4**
100	0.100	8.9	1.9	23.7	0.5	14.8	2.01	2.8
100	0.100	22.3	1.9	37.2	0.4	14.9	2.24	3.0
100	0.100	-76.5	2.2	-60.2	0.7	16.3	2.78	3.6
100	**0.100**					**15.3**		**3.1**
1000	0.100	-251.7	1.9	-246.8	0.6	4.9	1.81	2.7
1000	0.100	-412.5	1.9	-405.8	0.6	6.7	2.11	2.9
1000	0.100	-303.4	2.1	-299.3	0.8	4.1	3.31	4.0
1000	**0.100**					**5.2**		**3.2**

App. A3: PT002109.06



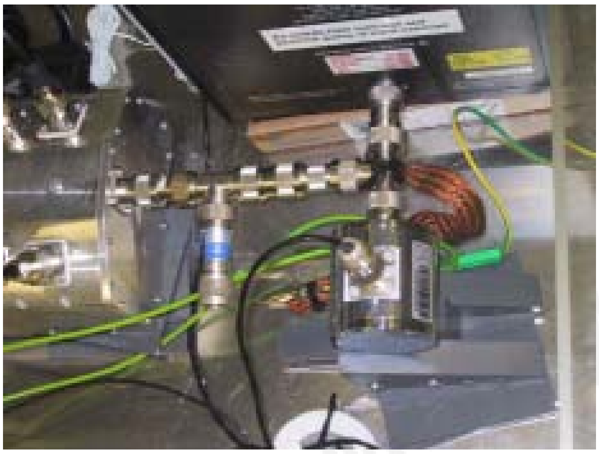


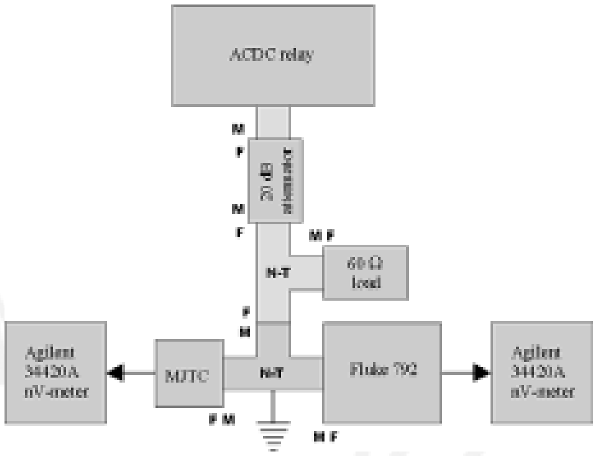
Measurement Pt002109.06
Fluke792 + 10:1 RD - PTB_MJTC_21
AcAc-measurement, reference 1 kHz

		Ch1		Ch2		F 792+10:1 RD		
		MJTC 21	u	Fluke 792A+ 10:1 RD	u	- MJTC 21	u	u
Freq.	Ampl.	AcAc-difference	k = 1	AcAc-difference	k = 1	AcAc-difference	k = 1	k = 1
kHz	V	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V
1	0.100	-0.6	0.05	-0.6	0.03	0	0.27	0.3
1	0.100	-0.1	0.05	0	0.04	0.1	0.2	0.2
1	0.100	0.2	0.05	0.4	0.04	0.2	0.21	0.2
1	0.100	0	0.04	-0.2	0.04	-0.2	0.15	0.2
1	0.100					**0.0**		**0.2**
20	0.100	-28.3	0.12	-38.9	0.08	-10.6	0.24	0.3
20	0.100	-27.3	0.29	-38.7	0.2	-11.4	0.42	0.5
20	0.100	-27.1	0.14	-38	0.1	-10.9	0.64	0.7
20	0.100	-28	0.09	-39	0.06	-11	0.45	0.5
20	0.100					**-11.0**		**0.5**
100	0.100	-15.7	0.13	18.3	0.08	34	0.12	0.2
100	0.100	-15.6	0.11	18.1	0.09	33.7	0.2	0.2
100	0.100	-15.8	0.11	18.1	0.07	33.9	0.31	0.3
100	0.100	-15.9	0.08	18.2	0.06	34.1	0.17	0.2
100	0.100					**33.9**		**0.2**
1000	0.100	215.4	0.13	440.8	0.45	225.4	2.41	2.5
1000	0.100	222.6	0.13	448.7	0.44	226.1	1.89	1.9
1000	0.100	225.1	0.13	449.2	0.5	224.1	2.24	2.3
1000	0.100	228.7	0.12	453.2	0.44	224.5	1.97	2.0
1000	0.100					**225.0**		**2.2**

		F 792+10:1 RD						
		- MJTC 21	u	SP 10:1 Att	u	SP 10:1 Att	F792- MJTC 21	u
Freq.	Ampl.	AcAc-difference	k = 1	AcDc-difference	k = 1	AcAc/AcDc correction	AcDc-difference	k = 1
kHz	V	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V
1	0.100	0.0	0.2	2	10	0	**2.03**	**10.00**
20	0.100	-11.0	0.5	-3	10	2	**-11.98**	**10.01**
100	0.100	33.9	0.2	-30	12.5	2	**5.93**	**12.50**
1000	0.100	225.0	2.2	-204	55	2	**23.02**	**55.04**

App. A4: PT002609.06

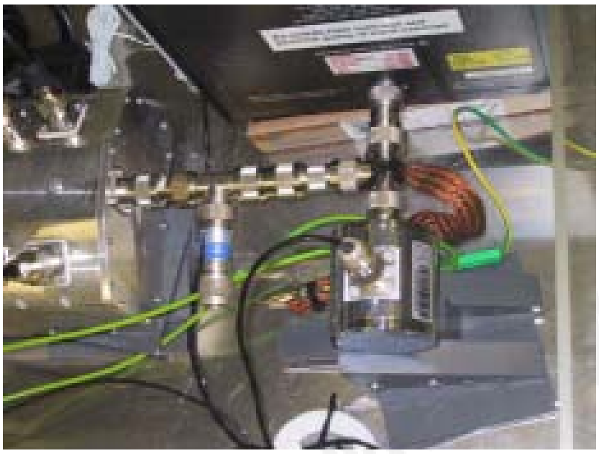


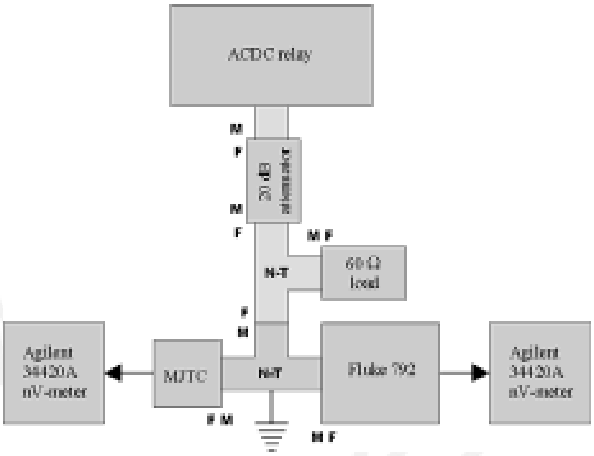


Measurement Pt002609.06
Fluke792 - PTB_MJTC_21

		Ch1		Ch2		F 792-		
		MJTC 21	u	Fluke 792A	u	MJTC 21	u	u
Freq.	Ampl.	AcDc-difference	k = 1	AcDc-difference	k = 1	AcDc-difference	k = 1	k = 1
kHz	V	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V
1	0.100	140.46	1.88	144.14	0.05	3.68	3.76	4.2
1	0.100	134.7	1.82	144.2	0.06	9.50	2.36	3.0
1	0.100	139.69	1.68	146.79	0.05	7.10	4.25	4.6
1	0.100	137.34	1.63	145.5	0.05	8.16	2.95	3.4
1	**0.100**					**7.1**		**3.8**
20	0.100	139.06	2.04	129.32	0.16	-9.74	3.09	3.7
20	0.100	131.84	1.68	128.04	0.08	-3.8	3.86	4.2
20	0.100	132.82	1.80	127.42	0.28	-5.40	2.51	3.1
20	0.100	138.08	1.83	130.63	0.10	-7.45	1.88	2.6
20	**0.100**					**-6.6**		**3.5**
100	0.100	112.43	1.78	128.46	0.06	16.03	2.06	2.7
100	0.100	116.24	1.80	131.12	0.07	14.88	3	3.5
100	0.100	114.01	1.76	126.83	0.06	12.82	0.68	1.9
100	0.100	114.84	1.85	126.85	0.07	12.01	4.35	4.7
100	**0.100**					**13.9**		**3.4**
1000	0.100	-6.19	1.91	6.12	0.27	12.31	1.54	2.5
1000	0.100	66.05	1.83	70.36	0.30	4.31	1.15	2.2
1000	0.100	-12.77	1.80	-7.26	0.24	5.51	2.67	3.2
1000	0.100	38.61	1.67	44.9	0.27	6.29	2.63	3.1
1000	**0.100**					**7.1**		**2.8**

App. A5: PT002709.06





Measurement Pt002709.06
Fluke792 - PTB_MJTC_21

		Ch1		Ch2		F 792-		
		MJTC 21	u	Fluke 792A	u	MJTC 21	u	u
Freq.	Ampl.	AcDc-difference	k = 1	AcDc-difference	k = 1	AcDc-difference	k = 1	k = 1
kHz	V	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V
1	0.100	140.5	1.75	149.3	0.08	8.8	2.2	2.8
1	0.100	138.8	1.72	147.2	0.06	8.4	1.9	2.6
1	0.100	142.9	1.58	147.9	0.06	5	2.4	2.9
1	0.100	137.4	1.52	145.1	0.06	7.70	2.9	3.3
1	**0.100**					**7.5**		**2.9**
20	0.100	138.9	1.88	129.4	0.09	-9.5	3.2	3.7
20	0.100	133.7	1.91	126.8	0.14	-6.9	1.5	2.4
20	0.100	143.1	1.61	128.9	0.10	-14.2	2.7	3.1
20	0.100	136.8	1.42	125.2	0.13	-11.6	2.4	2.8
20	**0.100**					**-10.6**		**3.1**
100	0.100	115.5	2.07	128.3	0.06	12.8	2.9	3.6
100	0.100	116.1	1.58	132	0.08	15.9	2.2	2.7
100	0.100	108.7	1.41	126.6	0.07	17.9	2.7	3.0
100	0.100	109.8	1.60	124.8	0.07	15	2.5	3.0
100	**0.100**					**15.4**		**3.1**
1000	0.100	-154.4	1.87	-145.6	0.24	8.80	3.4	3.9
1000	0.100	-172	1.42	-164.2	0.27	7.8	1.9	2.4
1000	0.100	-231	1.63	-223.8	0.26	7.2	1.9	2.5
1000	0.100	23.1	1.66	31.6	0.28	8.5	3.2	3.6
1000	**0.100**					**8.1**		**3.2**

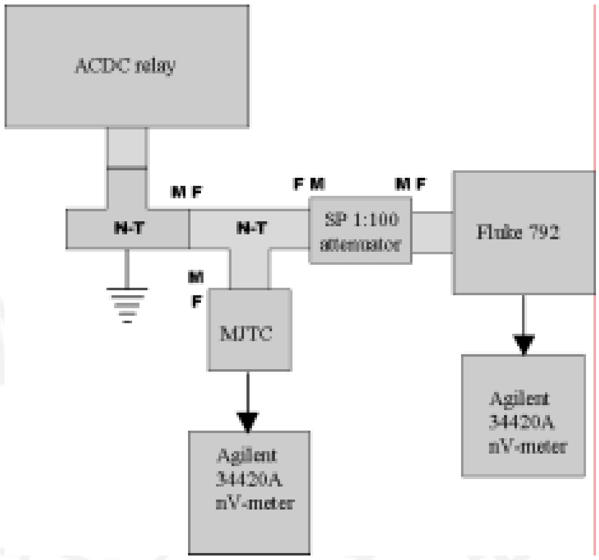
Table A6.1: Results from 100 mV measurements, Apps. A1-A5

			Fluke 792 - MJTC 21	u			u
	Frequency	Ampl.	AcDc-difference	k = 1	comment	AverageAcDc-difference	k = 1
Measurement	Hz	V	µV/V	µV/V		µV/V	µV/V
Pt001909	1000	0.100	9.20	3.20			
Pt002009	1000	0.100	8.55	3.86			
Pt002109	1000	0.100	2.03	10.00	omitted		
Pt002609	1000	0.100	7.11	3.83			
Pt002709	1000	0.100	7.48	2.89		7.97	1.85
Pt001909	20000	0.100	-10.33	4.97			
Pt002009	20000	0.100	-5.10	5.39			
Pt002109	20000	0.100	-11.98	10.01	omitted		
Pt002609	20000	0.100	-6.60	3.46			
Pt002709	20000	0.100	-10.55	3.06		-8.21	2.33
Pt001909	100000	0.100	13.30	3.10			
Pt002009	100000	0.100	15.33	3.15			
Pt002109	100000	0.100	5.93	12.50	omitted		
Pt002609	100000	0.100	13.94	3.38			
Pt002709	100000	0.100	15.40	3.09		14.52	1.66
Pt001909	1000000	0.100	5.20	3.36			
Pt002009	1000000	0.100	5.23	3.25			
Pt002109	1000000	0.100	23.02	55.04	omitted		
Pt002609	1000000	0.100	7.11	2.79			
Pt002709	1000000	0.100	8.07	3.17		6.57	1.72

Table A6.2: Results from 100 mV measurement results, corrections and uncertainties

Frequency	kHz	1	20	100	1000	Ty-pe	Distri-bution
Fluke 792-MJTC 21 AcDc difference	µV/V	7.97	-8.21	14.52	6.57		
F 792-MJTC 21 AcDc diff. uncertainty, k= 1	µV/V	1.85	2.33	1.66	1.72	A	normal
Temperature coefficient Tc	µV/V/°C	0.40	0.40	0.60	10.00		
Tc uncertainty, k = 1	µV/V/°C	0.50	0.50	0.50	2.00		normal
RH coefficient	µV/V/%	0.00	0.00	0.10	1.30		
RH coeff. uncertainty, k = 1	µV/V/%	0.01	0.03	0.05	0.25		normal
Temp dev = -0.25±0.2°C, correction	µV/V	0.10	0.10	0.15	2.50		
Temp correction uncertainty	µV/V	0.16	0.16	0.16	0.64	B	normal
RH dev = - 4%±2%, correction	µV/V	0.00	0.00	0.40	5.20		
RH correction uncertainty	µV/V	0.04	0.11	0.22	1.12	B	normal
F 792-MJTC 21 AcDc difference corrected	µV/V	8.07	-8.11	15.07	14.27		
T-connector asymmetry	µV/V	0.00	0.00	0.00	0.00		
T-connector asymmetry uncertainty, k = 1	µV/V	0.00	0.10	0.40	1.00	B	square
MJTC_21 AcDc difference	µV/V	0.00	1.20	2.80	2.00		
MJTC_21 AcDc difference uncertainty, k = 1	µV/V	1.00	1.00	1.50	15.00	B	normal
MJTC 21 drift after calibration	µV/V	0.00	0.00	0.00	0.00		
MJTC 21 drift after cal., uncertainty, k = 1	µV/V	0.00	0.30	0.60	0.20	B	square
MJTC 21 100mV/1.5V difference	µV/V	0.00	0.00	0.00	0.00		
MJTC 21 100mV/1.5V diff. uncertainty, k = 1	µV/V	1.00	1.00	2.00	4.00	B	square
Fluke 792 AcDc difference	**µV/V**	**8.07**	**-6.91**	**17.87**	**16.27**		
F 792 AcDc diff. unc. combined, k = 1	µV/V	2.33	2.75	3.07	15.67		normal
Fluke 792 AcDc diff. expanded unc., k = 2	**µV/V**	**4.67**	**5.49**	**6.15**	**31.35**		**normal**
Degrees of freedom		>1000	>1000	>1000	>1000		

App. B1: PT002209.06

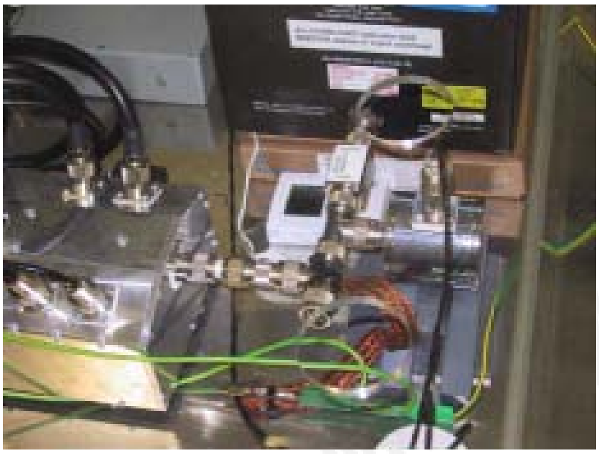


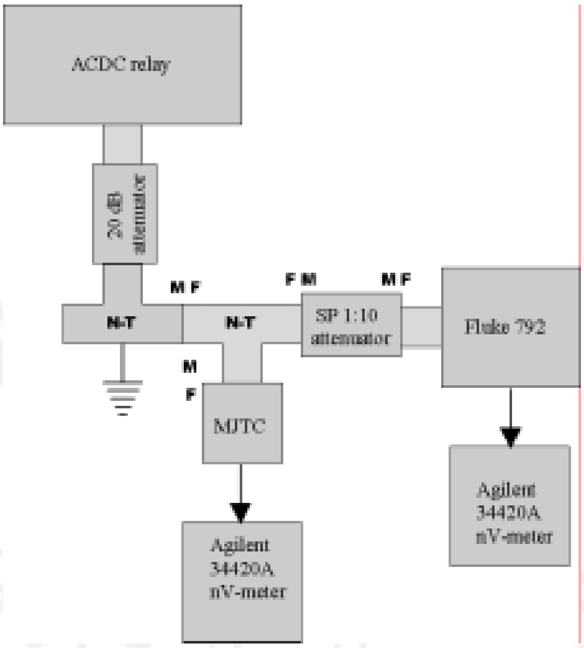
Measurement Pt002209.06
Fluke792 + 100:1 RD - PTB_MJTC_21
AcAc-measurement, reference 1 kHz

		Ch1		Ch2		F 792+100:1 RD		
		MJTC 21	u	Fluke 792A+ 100:1 RD	u	- MJTC 21	u	u
Freq.	Ampl.	AcAc-difference	k = 1	AcAc-difference	k = 1	AcAc-difference	k = 1	k = 1
kHz	V	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V
1	0.0100	0.17	0.05	0.05	0.05	-0.12	0.25	0.26
1	0.0100	-0.20	0.04	-0.42	0.05	-0.22	0.20	0.21
1	0.0100	-0.24	0.05	0.14	0.04	0.38	0.18	0.19
1	0.0100	0.05	0.04	-0.34	0.04	-0.39	0.25	0.26
1	0.0100					**-0.09**		**0.23**
20	0.0100	-6.53	0.34	-14.44	0.26	-7.91	0.69	0.81
20	0.0100	-7.07	0.20	-16.10	0.18	-9.03	0.30	0.40
20	0.0100	-7.94	0.23	-16.60	0.15	-8.66	0.44	0.52
20	0.0100	-7.43	0.06	-16.42	0.05	-8.99	0.24	0.25
20	0.0100					**-8.65**		**0.54**
100	0.0100	5.29	0.10	23.30	0.07	18.01	0.17	0.21
100	0.0100	6.08	0.10	24.05	0.08	17.97	0.21	0.25
100	0.0100	5.53	0.09	23.30	0.08	17.77	0.47	0.49
100	0.0100	5.65	0.11	23.38	0.09	17.73	0.21	0.25
100	0.0100					**17.87**		**0.32**
1000	0.0100	136.24	0.11	242.52	0.49	106.28	2.47	2.52
1000	0.0100	139.02	0.12	247.87	0.43	108.85	2.09	2.14
1000	0.0100	136.39	0.12	244.86	0.42	108.47	3.24	3.27
1000	0.0100	137.35	0.12	244.78	0.42	107.43	3.02	3.05
1000	0.0100					**107.76**		**2.78**

		F 792 100:1 RD				SP 100:1 Att	F 792 100:1 RD	Correc-tion		
		- MJTC 21	u	SP 100:1 Att	SP 100:1 Att	u	- MJTC 21	u	F792-MJTC 21	u
Freq.	Ampl.	AcAc-difference	k = 1	AcDc-difference	AcAc-difference	k = 1	AcAc/AcDc correction	k = 1	AcDc-difference	k = 1
kHz	V	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V
1	0.0100	-0.09	0.23	-1	0	25	20	10	**19.91**	**26.93**
20	0.0100	-8.65	0.54	-14	-13	25	20	10	**-1.65**	**26.93**
100	0.0100	17.87	0.32	-60	-59	30	20	10	**-21.13**	**31.62**
1000	0.0100	107.76	2.78	-299	-298	135	20	10	**-170.24**	**135.40**

App. B2: PT002309.06



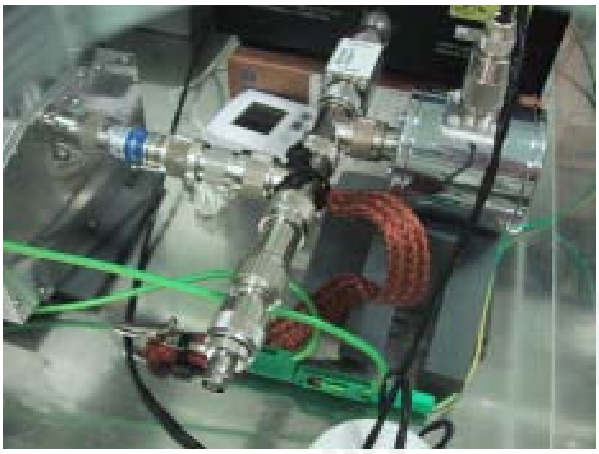


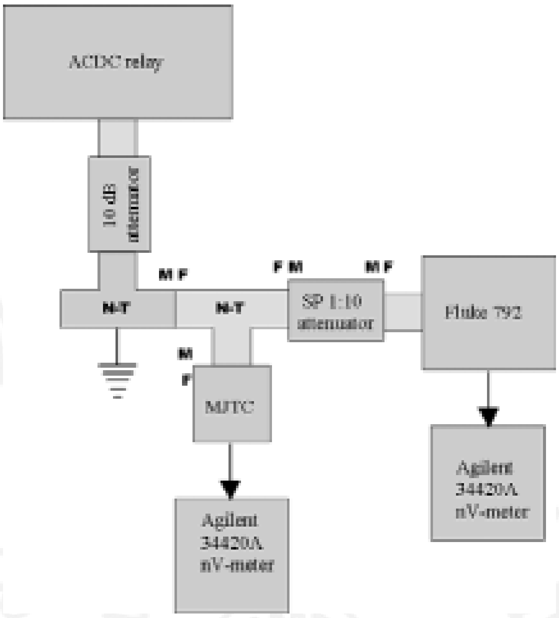
Measurement Pt002309.06
Fluke792 + 10:1 RD - PTB_MJTC_21
AcAc-measurement, reference 1 kHz

		Ch1		Ch2		F 792+10:1 RD		
		MJTC 21	u	Fluke 792A+ 10:1 RD	u	- MJTC 21	u	u
Freq.	Ampl.	AcAc-difference	k = 1	AcAc-difference	k = 1	AcAc-difference	k = 1	k = 1
kHz	V	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V
1	0.0100	-3.59	1.55	0.05	0.05	3.64	3.15	3.51
1	0.0100	-6.00	1.85	0.25	0.05	6.25	2.39	3.02
1	0.0100	-1.17	1.87	-0.16	0.05	1.01	2.34	3.00
1	0.0100	-4.19	1.86	0.39	0.05	4.58	4.68	5.04
1	0.0100					**3.87**		**3.74**
20	0.0100	12.20	2.06	-1.39	0.10	-13.59	5.10	5.50
20	0.0100	16.67	2.04	0.26	0.07	-16.41	3.00	3.63
20	0.0100	13.88	1.93	-0.17	0.06	-14.05	4.52	4.92
20	0.0100	15.43	1.86	0.16	0.18	-15.27	4.98	5.32
20	0.0100					**-14.83**		**4.90**
100	0.0100	-35.64	1.60	-40.39	0.07	-4.75	2.07	2.62
100	0.0100	-34.38	1.75	-38.94	0.06	-4.56	4.05	4.41
100	0.0100	-34.79	1.79	-39.73	0.06	-4.94	5.39	5.68
100	0.0100	-36.13	1.88	-39.55	0.08	-3.42	4.37	4.76
100	0.0100					**-4.42**		**4.51**
1000	0.0100	36.36	1.74	64.56	0.30	28.20	2.47	3.04
1000	0.0100	29.79	1.71	60.27	0.26	30.48	2.27	2.85
1000	0.0100	38.02	1.83	58.38	0.35	20.36	2.11	2.81
1000	0.0100	27.73	2.11	56.69	0.25	28.96	5.76	6.14
1000	0.0100					**27.00**		**3.97**

		F 792 +10:1 RD				SP 10:1 Att	F 792 10:1 RD	Corr		
		- MJTC 21	u	SP 10:1 Att	SP 10:1 Att	u	- MJTC 21	u	F792-MJTC 21	u
Freq.	Ampl.	AcAc-difference	k = 1	AcDc-difference	AcAc-difference	k = 1	AcAc/AcDc correction	k = 1	AcDc-difference	k = 1
kHz	V	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V
1	0.0100	3.87	3.74	2	0	10	20	5	**23.87**	**11.79**
20	0.0100	-14.83	4.90	-3	-5	10	20	5	**0.17**	**12.21**
100	0.0100	-4.42	4.51	-30	-32	12.5	20	5	**-16.42**	**14.20**
1000	0.0100	27.00	3.97	-204	-206	55	20	5	**-159.00**	**55.37**

App. B3: PT002509.06





Measurement Pt002509.06
Fluke792 + 10:1 RD - PTB_MJTC_21

		Ch1		Ch2		F 792 + 10:1 RD		
		MJTC 21	u	Fluke 792A + 10:1 RD	u	- MJTC 21	u	u
Freq.	Ampl.	AcDc-difference	k = 1	AcDc-difference	k = 1	AcDc-difference	k = 1	k = 1
kHz	V	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V
1	0.0100	139.50	1.52	165.97	0.38	26.47	3.84	4.15
1	0.0100	139.91	1.57	149.63	0.34	9.72	4.42	4.70
1	0.0100	141.87	1.62	161.11	0.40	19.24	3.70	4.06
1	0.0100	143.48	1.41	157.53	0.36	14.05	5.79	5.97
1	**0.0100**					**17.37**		**4.78**
20	0.0100	170.74	1.80	174.49	0.38	3.75	4.03	4.43
20	0.0100	170.45	1.63	172.53	0.30	2.08	3.87	4.21
20	0.0100	174.41	1.55	170.56	0.33	-3.85	3.77	4.09
20	0.0100	173.11	1.68	184.18	0.33	11.07	3.74	4.11
20	**0.0100**					**3.26**		**4.21**
100	0.0100	114.78	1.54	127.34	0.38	12.56	3.13	3.51
100	0.0100	117.85	1.61	127.92	0.37	10.07	8.29	8.45
100	0.0100	115.43	1.50	131.75	0.42	16.32	7.52	7.68
100	0.0100	110.03	1.49	123.35	0.31	13.32	2.47	2.90
100	**0.0100**					**13.07**		**6.15**
1000	0.0100	-47.28	1.65	3.70	0.47	50.98	5.07	5.35
1000	0.0100	-24.01	1.51	31.86	0.48	55.87	4.60	4.87
1000	0.0100	0.07	1.47	56.45	0.47	56.38	4.46	4.72
1000	0.0100	6.80	1.54	60.61	0.48	53.81	4.72	4.99
1000	**0.0100**					**54.26**		**4.99**

		F 792 + 10:1 RD					
		- MJTC 21	u	SP 10:1 Att	u	F792- MJTC 21	u
Freq.	Ampl.	AcDc-difference	k = 1	AcDc-difference	k = 1	AcDc-difference	k = 1
kHz	V	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V
1	0.0100	17.37	4.78	2	10	**19.37**	**11.08**
20	0.0100	3.26	4.21	-3	10	**0.26**	**10.85**
100	0.0100	13.07	6.15	-30	12.5	**-16.93**	**13.93**
1000	0.0100	54.26	4.99	-204	55	**-149.74**	**55.23**

Table B4.1: Results from 10 mV measurements, Apps. B1-B3

			Fluke 792 - MJTC 21	u		u
	Frequency	Ampl	AcDc-difference	k = 1	AverageAcDc-difference	k = 1
Measurement	Hz	V	µV/V	µV/V	µV/V	µV/V
Pt002209	1000	0.0100	19.91	26.93		
Pt002309	1000	0.0100	23.87	11.79		
Pt002509	1000	0.0100	19.37	11.08	21.35	11.44
Pt002209	20000	0.0100	-1.65	26.93		
Pt002309	20000	0.0100	0.17	12.21		
Pt002509	20000	0.0100	0.26	10.85	0.07	11.53
Pt002209	100000	0.0100	-21.13	31.62		
Pt002309	100000	0.0100	-16.42	14.20		
Pt002509	100000	0.0100	-16.93	13.93	-17.18	14.06
Pt002209	1000000	0.0100	-170.24	135.40		
Pt002309	1000000	0.0100	-159.00	55.37		
Pt002509	1000000	0.0100	-149.74	55.23	-155.58	55.30

Table A6.2: Results from 10 mV measurement results, corrections and uncertainties

Frequency	kHz	1	20	100	1000	Ty-pe	Distri-bution
Fluke 792-MJTC 21 AcDc difference	µV/V	21.35	0.07	-17.08	-155.58		
F 792-MJTC 21 AcDc diff. uncertainty, k= 1	µV/V	5.55	5.74	6.44	5.73	A	normal
Temperature coefficient Tc	µV/V/°C	1.20	1.20	1.30	17.00		
Tc uncertainty, k = 1	µV/V/°C	1.00	1.00	1.00	4.00		normal
RH coefficient	µV/V/%	0.00	0.00	0.10	0.90		
RH coeff. uncertainty, k = 1	µV/V/%	0.01	0.03	0.05	0.25		normal
Temp dev = -0.25±0.2°C, correction	µV/V	0.30	0.30	0.33	4.25		
Temp correction uncertainty	µV/V	0.32	0.32	0.32	1.28	B	normal
RH dev = - 4±2%, correction	µV/V	0.00	0.00	0.40	3.60		
RH correction uncertainty	µV/V	0.04	0.11	0.22	1.12	B	normal
F 792-MJTC 21 AcDc difference corrected	µV/V	21.65	0.37	-16.36	-147.73		
T-connector asymmetry	µV/V	0.00	0.00	0.00	0.00		
T-connector asymmetry uncertainty, k = 1	µV/V	0.00	0.10	0.40	1.00	B	square
MJTC_21 AcDc difference	µV/V	0.00	1.20	2.80	2.00		
MJTC_21 AcDc difference uncertainty, k = 1	µV/V	1.00	1.00	1.50	15.00	B	normal
MJTC 21 drift after calibration	µV/V	0.00	0.00	0.00	0.00		
MJTC 21 drift after cal., uncertainty, k = 1	µV/V	0.00	0.30	0.60	0.20	B	square
MJTC 21 100mV/1.5V difference	µV/V	0.00	0.00	0.00	0.00		
MJTC 21 100mV/1.5V diff. uncertainty, k = 1	µV/V	1.00	1.00	2.00	4.00	B	square
Resistive 10:1 divider uncertainty (SP), k = 1		10	10	12.5	55	B	normal
Resistive 10:1 divider loading uncert., k = 1		1	2	10	20	B	square
Fluke 792 AcDc difference	**µV/V**	**21.65**	**1.57**	**-13.56**	**-145.73**		
F 792 AcDc diff. unc. combined, k = 1	µV/V	11.57	11.79	17.46	60.85		normal
Fluke 792 AcDc diff. expanded unc., k = 2	**µV/V**	**23.14**	**23.59**	**34.91**	**121.70**		**normal**
Degrees of freedom		>1000	>1000	>1000	>1000		

App. C1: PMJTC 21 traceability

Fig. C1: Planar MJTC 21

Table C1: Calibration results from PTB Certificate of Calibration 4600 PTB 98

	Planar MJTC 21	
Frequency	AcDc difference	u k=2
kHz	µV/V	µV/V
1	**0.0**	**2**
10	-0.2	2
20	**1.2**	**2**
50	2.7	3
100	**2.8**	**3**
200	5.0	5
500	5	10
700	4	20
1000	**2**	**30**

App. C2: Traceabilities of 1:10 and 1:100 resistive dividers

Fig C2. SP resistive dividers

Table C2: Calibration results from SP Certificate of Calibration MTeF507097

	1:10 Resistive AcDc-divider		1:100 Resistive AcDc-divider	
Frequency	AcDc difference	u k=2	AcDc difference	u k=2
kHz	µV/V	µV/V	µV/V	µV/V
1	**2**	**20**	**-1**	**50**
10	-1	20	-10	50
20	**-3**	**20**	**-14**	**50**
50	-14	20	-32	50
100	**-30**	**25**	**-60**	**60**
200	-63	30	-101	80
500	-129	50	-187	110
700	-164	80	-238	170
1000	**-204**	**110**	**-299**	**270**

App. D1: Devices used in the calibration

AC generator: Fluke 5700, sn 6195305
DC generator: Datron 4708, sn 27174-4
nV meters: Agilent 34420A, sn US34000308 and sn MY42001253
ACDC relay: constructed by MIKES, MIKES ACDC_rele_01, sn MIKES003938
Resistive dividers, SP 10/1, sn 98004, SP 100/1, sn 98006
PMJTC: IPHT/PTB 1.5V 190 Ω, sn 21
T-connectors:
- Amphenol 48-50/N-T/M-M-M
- Suhner N-T/F-M-F

App. D2: BATTERY VOLTAGES

The battery voltages during the measurements are given in Table D2

Table D2: Battery voltages during the measurements

Dates are given in local Finnish time

Day	hour	minute	positive voltage	negative voltage	comment
19.09.2006	10	36	+11.094	-11.157	
19.09.2006	12	40	+11.101	-11.163	
20.09.2006	06	45	+11.092	-11.157	"low batt"
20.09.2006	13	53	+11.100	-11.164	
21.09.2006	06	50	+11.092	-11.158	"low batt"
21.09.2006	14	48	+11.102	-11.165	
22.09.2006	06	50	+11.093	-11.156	
22.09.2006	13	37	+11.102	-11.165	
23.09.2006	07	05	+11.091	-11.156	"low batt"
23.09.2006	18	07	+11.102	-11.165	
24.09.2006	13	15	+11.090	-11.156	"low batt"
25.09.2006	14	55	+11.102	-11.166	
26.09.2006	08	42	+11.094	-11.157	
27.09.2006	07	15	+11.093	-11.156	
27.09.2006	15	20	+11.102	-11.165	
28.09.2006	09	40	+11.094	-11.156	

App. D3:Measurement frequency uncertainty

The ac signals were produced by Fluke 5700A calibrator. The measured frequencies were nominal frequencies within ± 50 µHz/Hz uncertainty, see Table D3_1

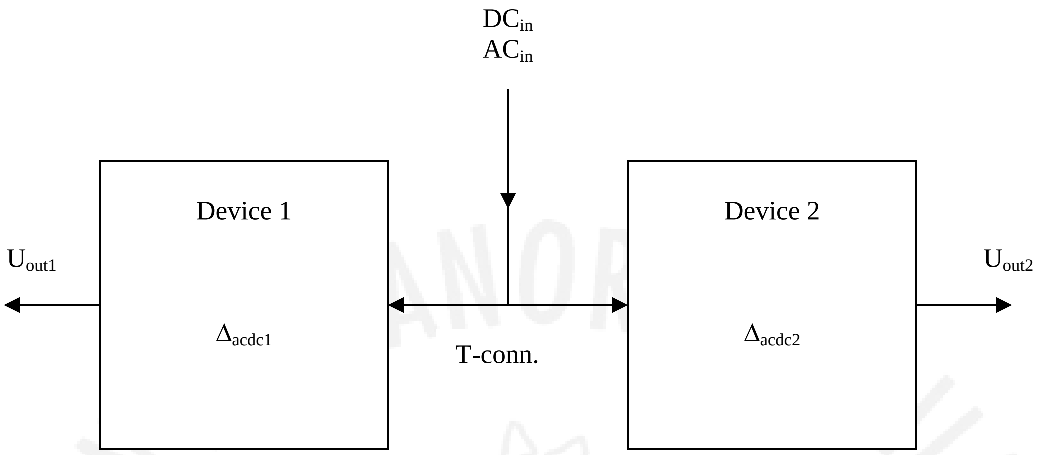
Table D3_1: Frequency deviations of Fluke 5700A calibrator

	Nominal frequency			
	1 kHz	20 kHz	100 kHz	1 MHz
Measurement frequency, kHz	1.0000	20.000	100.00	1000.0
Expanded uncertainty, µHz/Hz	<50	<50	<50	<50

App E1: Uncertainty contributions

	Type	Distribution	Comment
Measurements	A	normal	
Planar MJTC 21 calibration	B	normal	
Planar MJTC 21 drift	B	square	
Planar MJTC 21 100 mV/1.5V acdc difference	B	square	
Calibration uncertainty of resistive dividers	B	normal	
Acac/acdc measurement correction for 1 kHz	B	normal	
Resistive divider loading by Fluke 792	B	square	
T-connector asymmetry	B	square	
Measurement frequency deviation	B	square	insignificant
Ambient temperature deviation from nominal	B	normal	
Ambient RH deviation from nominal	B	normal	

App. F1: Mathematical model of acdc comparison
A. Two devices compared



Input voltages are DC_{in} and AC_{in}. AC_{in} is the RMS value of AC voltage.

The DC behaviour of devices 1 and 2 is known by DC measurements within a dynamic range around the nominal applied voltage (e.g. ±2%).

$$U_{out1}(DC_{in}) = f_1(DC_{in})$$
$$U_{out2}(DC_{in}) = f_2(DC_{in})$$

(typically second order polynomials) (1)

Any DC input voltage within the (±2%) dynamic range can be solved from the respective output voltage, producing input voltage estimations DC_{in1}'', DC_{in2}'' for devices 1 and 2:

$$DC_{in1}'' = f_1^{-1}\left[U_{out1}(DC_{in})\right]$$
$$DC_{in2}'' = f_2^{-1}\left[U_{out2}(DC_{in})\right]$$

(typically solved second order equations) (2)

The AC behaviour of device 1 (reference) is known: If $AC_{in} = (1+\Delta_{acdc1})\cdot DC_{in}$ then $U_{OUT1}(DC_{in}) = U_{out1}(AC_{in})$. The AC difference Δ_{acdc2} of device 2 is unknown: However, if $AC_{in} = (1+\Delta_{acdc2})\cdot DC_{in}$ then $U_{out2}(DC_{in}) = U_{out2}(AC_{in})$.

If voltages DC_{in} (average of DC_{in}^{+} and DC_{in}^{-}) and AC_{in} are applied to the T-connector the respective (thermal) output voltages are:

$U_{out1}(DC_{in}) = f_1(DC_{in})$
$U_{out1}(AC_{in}) = (1+\Delta_{acdc1})^{-1}\cdot f_1(AC_{in})$

$U_{out2}(DC_{in}) = f_2(DC_{in})$
$U_{out2}(AC_{in}) = (1+\Delta_{acdc2})^{-1}\cdot f_2(AC_{in})$

(3)

Estimates for input voltages are then:

$$DC_{in1}'' = f_1^{-1}[U_{out1}(DC_{in})]$$
$$AC_{in1}' = (1+\Delta_{acdc1})\cdot f_1^{-1}[U_{out1}(AC_{in})] \equiv (1+\Delta_{acdc1})\cdot AC_{in1}''$$
$$DC_{in2}'' = f_2^{-1}[U_{out2}(DC_{in})]$$
$$AC_{in2}' = (1+\Delta_{acdc2})\cdot f_2^{-1}[U_{out1}(AC_{in})] \equiv (1+\Delta_{acdc2})\cdot AC_{in2}'' \quad (4)$$

Here DC_{in1}'', DC_{in2}'', AC_{in1}'' and AC_{in2}'' are solved from output voltages by using functions f_1^{-1} and f_2^{-1}.

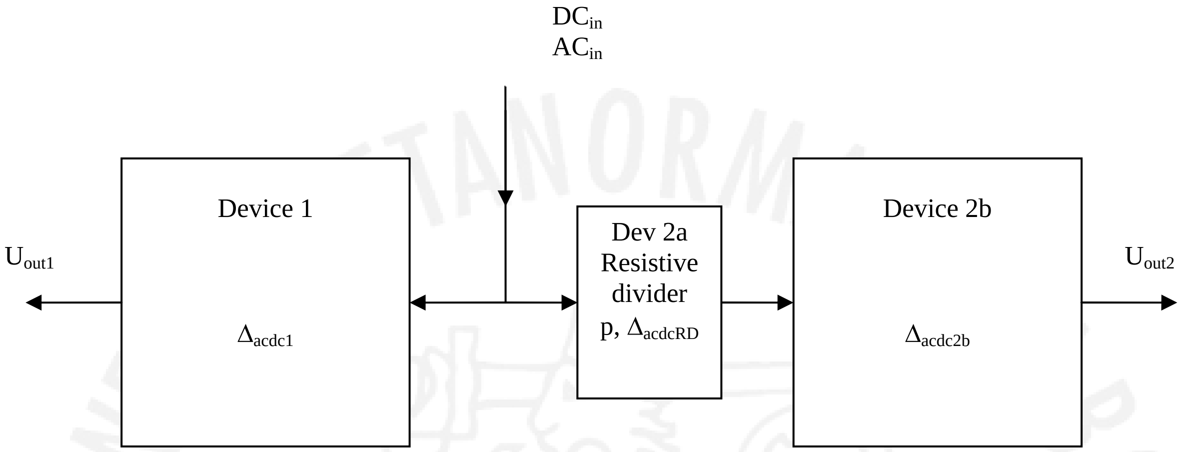
By applying some mathematics we get Eq. 5 for the calculation of acdc differences from the measured thermal voltages:

$$\Delta_{acdc2} \approx -\frac{AC_{in2}''-DC_{in2}''}{DC_{in2}''} - \left(-\frac{AC_{in1}''-DC_{in1}''}{DC_{in1}''}\right) + \Delta_{acdc1} \quad (5)$$

where input estimates $DC_{ini}'' = f_i^{-1}[U_{outi}(DC_{in})]$ and estimates $AC_{ini}'' = f_i^{-1}[U_{outi}(AC_{in})]$ are used. The acdc difference of the ac generator adds itself into the first and second term (apparent acdc differences of devices 1 and 2), but is cancelled in the subtraction. Provided that the acdc differences are not amplitude dependent in the narrow range where Eqs. 2 apply we can use Eq. 5 for any pair AC_{in}, DC_{in} for solving the acdc difference of device 2.

B. Device 2 consists of two parts (e.g. resistive divider and Fluke 792)

If device 2 consists of two parts in series (e.g. a resistive divider followed by Fluke 792A) then the previous result (Eq. 5) applies to the combination of the two.



The calibration certificate (MTeF507097) of SP states on page 2(3):

"Use of adc difference:
acdc difference of the divider output = acdc difference of the divider input + acdc difference of the divider"

The output of the resistive divider for DC is the applied voltage DC_{in} multiplied by p (p<1, e.g. 0.1 or 0.01) and its output for AC is the applied voltage AC_{in} multiplied by $p\cdot(1+\Delta_{ACDCRD})$, where Δ_{ACDCRD} is the ac-dc difference stated in the SP certificate of calibration.

By using Eq. 5 we can calibrate the acdc difference of the two devices 2a, 2b in series.

The resistive divider (typically) attenuates the ac input voltage compared to dc voltage by $1+\Delta_{ACDCRD}$ (typically $\Delta_{ACDCRD} < 0$) for device 2b. This means that the apparent acdc difference of device 2b is too large by the same amount [from the output of device 2 it seems that to achieve the result $U_{out2b}(AC_{in}) = U_{out2b}(DC_{in})$ a larger ac/dc input voltage ratio is needed than without the resistive divider]. Accordingly, the acdc difference of the resistive divider must be added to the calibration result of the devices 2a, 2b in series to obtain the acdc difference of device 2b:

$$\Delta_{acdc2b} \approx -\frac{AC_{in2}''-DC_{in2}''}{DC_{in2}''} - \left(-\frac{AC_{in1}''-DC_{in1}''}{DC_{in1}''}\right) + \Delta_{acdc1} + \Delta_{acdcRD} \qquad (6)$$

where estimates $DC_{ini}'' = f_i^{-1}[U_{outi}(DC_{in})]$ and estimates $AC_{ini}'' = f_i^{-1}[U_{outi}(AC_{in})]$ are used. The acdc difference of the ac generator is included into the first and second term (apparent acdc differences of devices 1 and 2), but is cancelled in the subtraction. Provided that the acdc differences are not amplitude dependent in the narrow range where Eqs. 2 apply we can use Eq. 6 for any pair AC_{in}, DC_{in} for solving the acdc difference of device 2b.

Appendix G1: Summary of results

Key comparison EUROMET.EM-K11 “ac-dc voltage transfer difference at low voltages”

Acronym of institute: MIKES

Date of measurements: Sept 19-Sept 27, 2006

Remarks:

Measuring result:

Voltage	Range	Measured ac-dc voltage difference / 10^{-6} at frequency			
		1 kHz	20 kHz	100 kHz	1 MHz
100 mV	220 mV	8.1	-6.9	17.9	16.3 [1)]
10 mV	22 mV	21.7	1.6	-13.6	-146

[1)] Previously reported as 12.3 due to an error in the used in RH coefficient

Expanded uncertainty (preliminary uncertainties diminished by careful data analysis):

Voltage	Range	Expanded uncertainty / 10^{-6} at frequency			
		1 kHz	20 kHz	100 kHz	1 MHz
100 mV	220 mV	4.7	5.5	6.2	32
10 mV	22 mV	23.2	23.6	35	122

Measuring frequency:

	Nominal frequency			
	1 kHz	20 kHz	100 kHz	1 MHz
Measuring frequency	1.0000	20.000	100.00	1.0000
Expanded uncertainty	<50 µHz/Hz	<50 µHz/Hz	<50 µHz/Hz	<50 µHz/Hz

Influence parameters:

	Min	Max	Remarks
Ambient temperature / ºC	22.7	22.9	correction +0.25°C
Relative humidity / %	40	42	Correction +4%
Pos. power supply voltage / V	11.090	11.102	Please state with mV resolution
Neg. power supply voltage / V	-11.156	-11.166	Please state with mV resolution

Appendix G2: Summary of uncertainty budget

Key comparison EUROMET.EM-K11 “ac-dc voltage transfer difference at low voltages”

Please send this information by e-mail also.

Acronym of institute: MIKES

Date: Nov. 14, 2007

Remarks:

Measuring voltage: 100 mV

Contribution of:		Std. unc. f: 1 kHz	Std. unc. f: 20 kHz	Std. unc. f: 100 kHz	Std. unc. f: 1 MHz	Type A or B	Distri-bution
F 792-MJTC 21 AcDc diff. uncertainty, k= 1	µV/V	1.85	2.33	1.66	1.72	A	normal
Temp correction uncertainty	µV/V	0.16	0.16	0.16	0.64	B	normal
RH correction uncertainty	µV/V	0.04	0.11	0.22	1.12	B	normal
T-connector asymmetry uncertainty, k = 1	µV/V	0.00	0.10	0.40	1.00	B	square
MJTC_21 AcDc difference uncertainty, k = 1	µV/V	1.00	1.00	1.50	15.00	A	normal
MJTC 21 drift after cal., uncertainty, k = 1	µV/V	0.00	0.30	0.60	0.20	B	square
MJTC 21 100mV/1.5V diff. uncertainty, k = 1	µV/V	1.00	1.00	2.00	4.00	B	square

F 792 AcDc diff. standard uncertainty (k=1)	µV/V	2.33	2.75	3.07	15.67
Fluke 792 AcDc diff. expanded unc., k = 2	**µV/V**	**4.67**	**5.49**	**6.15**	**31.35**
Effective degrees of freedom		>1000	>1000	>1000	>1000

Measuring voltage: 10 mV

Contribution of:		Std. unc. f: 1 kHz	Std. unc. f: 20 kHz	Std. unc. f: 100 kHz	Std. unc. f: 1 MHz	Type A or B	Distri-bution
F 792-MJTC 21 AcDc diff. uncertainty, k= 1	µV/V	5.55	5.74	6.44	5.73	A	normal
Temp correction uncertainty	µV/V	0.32	0.32	0.32	1.28	B	normal
RH correction uncertainty	µV/V	0.04	0.11	0.22	1.12	B	normal
T-connector asymmetry uncertainty, k = 1	µV/V	0.00	0.10	0.40	1.00	B	square
MJTC_21 AcDc difference uncertainty, k = 1	µV/V	1.00	1.00	1.50	15.00	B	normal
MJTC 21 drift after cal., uncertainty, k = 1	µV/V	0.00	0.30	0.60	0.20	B	square
MJTC 21 100mV/1.5V diff. uncertainty, k = 1	µV/V	1.00	1.00	2.00	4.00	B	square
Resistive 10:1 divider uncertainty (SP), k = 1		10	10	12.5	55	B	normal
Resistive 10:1 divider loading uncert., k = 1		1	2	10	20	B	square

F 792 AcDc diff. standard uncertainty (k=1)	µV/V	11.57	11.79	17.46	60.85
Fluke 792 AcDc diff. expanded unc., k = 2	**µV/V**	**23.14**	**23.59**	**34.91**	**121.70**
Effective degrees of freedom		>1000	>1000	>1000	>1000

Report

Key comparison EUROMET.EM-K11 “ac-dc voltage transfer difference at low voltages”

Acronym of institute: DANIAmet-DPLE

Date of measurements: 05.10. - 26.10. 2006

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Content

1 Introduction

AREPA Test & Calibration A/S operates the Danish national laboratory for AC-electricity and RF & microwave measurements. Together with DFM (Danish Institute for Fundamental Metrology in Copenhagen) DPLE, Danish Primary Laboratory for Electricity, has been established. Both laboratories are members of DANIAmet, which is a decentralized metrological organization of Danish primary and reference laboratories nominated by the Danish Agency for Development of Trade and Inustry. The acronym DANIAmet is used be each member in order to identify activities covered by the status as primary or reference laboratory. Consequently the acronym for AREPA now is DANIAmet-DPLE.

2 Measuring System

The AC-DC voltage transfer difference δ of a transfer standard is defined as:

$$\delta = \frac{V_{AC} - V_{DC}}{V_{DC}}$$

where:

V_{AC} is the rms value of the input AC voltage.
V_{DC} is the value of the input DC voltage which when reversed produces the same mean output voltage as V_{AC}.

The AC-DC voltage transfer difference of the test object δ_{obj} is calculated as:

$$\delta_{obj} = \frac{E_{AC,ref} - E_{DC,ref}}{n_{ref} E_{DC,ref}} - \frac{E_{AC,obj} - E_{DC,obj}}{n_{obj} E_{DC,obj}} + \delta_{ref}$$

where:

E_{AC} output voltages at AC.
E_{DC} output voltages at DC, averaged for reversed DC.
δ_{ref} AC-DC voltage transfer difference of the reference standard.
n power coefficient determined from the output/input correlation of a thermal transfer standard, given by:

$$E = kV^n$$

By measuring the output voltages for input voltages about 50 - 100 ppm below and above the nominal input voltages, the power coefficient n is determined from:

$$n = \frac{\Delta E}{E} \frac{V}{\Delta V}$$

where ΔE and ΔV are the small changes of output and input values respectively. In this way the value of n was determined to be n = 1 for the travelling standard, which was used for the calculation of δ_{obj} at all voltages and frequencies.

Three multijunction thermal converters, MJTC, of the “3-dim.” PTB type are used at the primary level for voltages between 2 V to 0,5 V. For the first step down towards lower voltage levels a PTB type planar multijunction thermal converter, PMJTC, is calibrated against the primary standards and then used down to 200 mV. The calibration is carried out in a two-channel set-up shown schematically in fig. 1. The reference plane using this set-up is at the centre of the T-adaptor. After this first step home-made μ-pots are used, constructed using single junction thermal converters and a number of SMD resistors soldered in parallel onto a piece of PCB in a star-like configuration at the output connector of the μ-pot. Measurements are carried out in a two-channel set-up as shown in fig. 2.

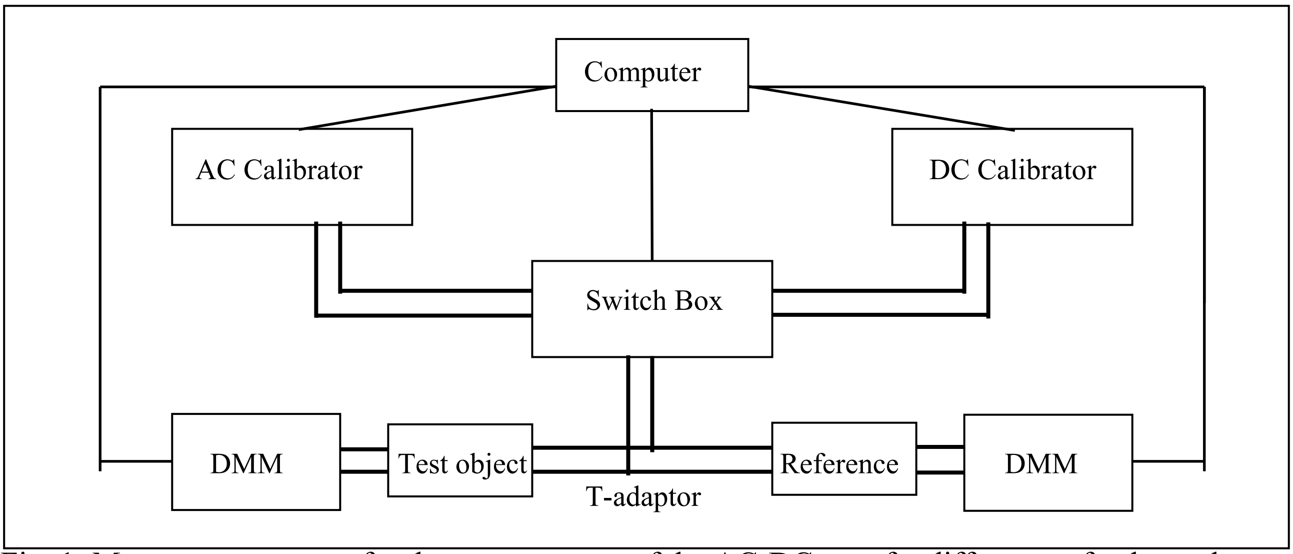

Fig. 1: Measurement set-up for the measurement of the AC-DC transfer difference of a thermal transfer standard.

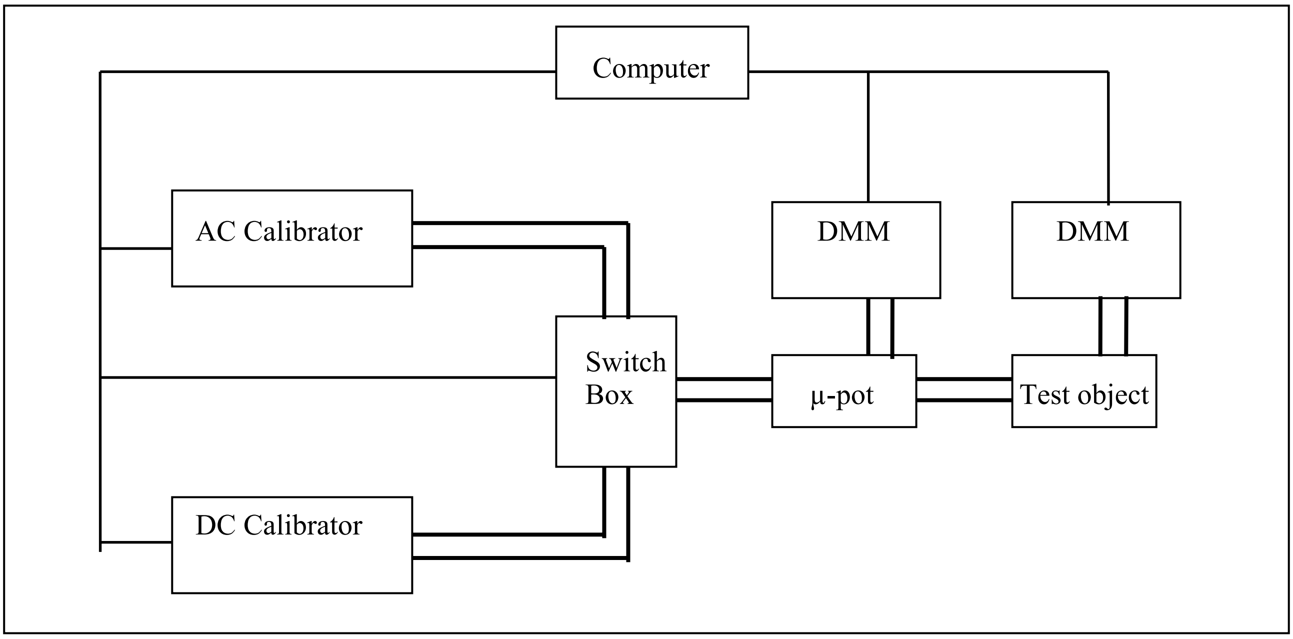

Fig. 2: Step-down set-up using μ-pots.

The measurements of the travelling standard are carried out by first measuring the AC-DC transfer difference at the 200 mV level using the PMJTC as the reference standard. Then the first µ-pot is connected to the travelling standard, which now acts as the known reference, and the AC-DC transfer difference of the µ-pot is measured at 200 mV. The µ-pot is then used to measure the travelling standard at 100 mV. Following this the second µ-pot, to be used down to 50 mV, is measured at 100 mV against the travelling standard. This procedure is repeated with various µ-pots until the 10 mV level is reached. This step-down procedure is depicted in fig. 3, and the main characteristics of the µ-pots are given in table 1.

The main advantage of this procedure is that loading errors are minimized, anticipating a sizeable error mainly when changing from the 200 mV range to the 20 mV range on the travelling standard where a change in the input impedance is to be expected. The reference plane for these measurements is at the input connector of the travelling standard.

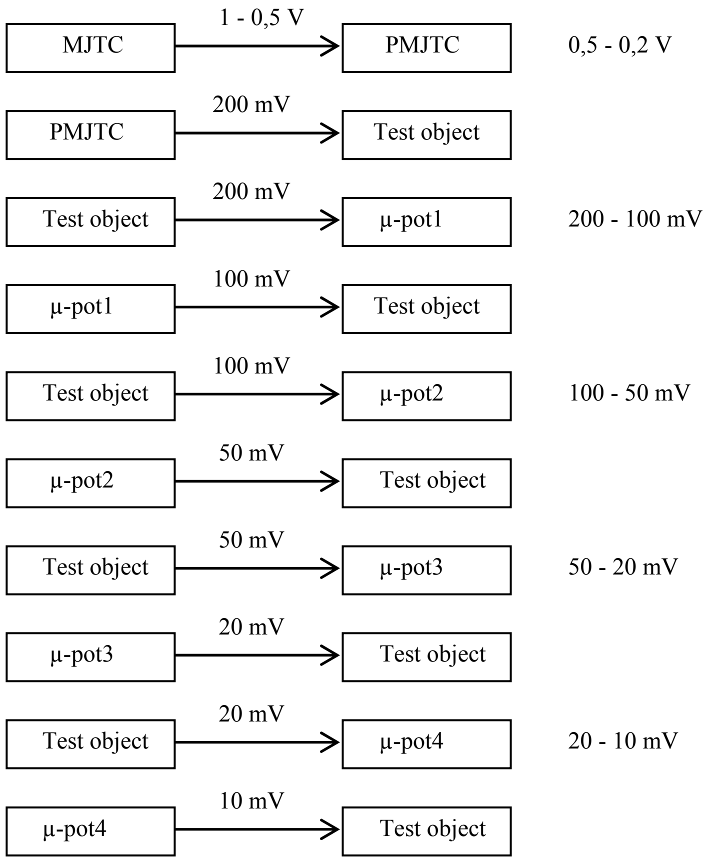

Fig. 3: Step-down procedure.

The AC-DC transfer difference of the travelling standard was measured at 100 mV and 10 mV at the frequencies 1 kHz, 20 kHz, 100 kHz and 1 MHz.

Table 1: Main characteristics of the μ-pots.

	Heater resistance	Output resistance	Power coefficient
μ-pot1 200 mV, 10 mA	25 Ω	20 Ω	1,876, 200 mV 1,959, 100 mV
μ-pot2 100 mV, 10 mA	25 Ω	10 Ω	1,898, 100 mV 1,936, 50 mV
μ-pot3 50 mV, 5 mA	90 Ω	10 Ω	1,743, 50 mV 1,925, 20 mV
μ-pot4 20 mV, 5 mA	90 Ω	4 Ω	1,736, 20 mV 1,885, 10 mV

The equipment used includes the following:

Datron 4000A calibrator used as DC source.
Fluke 5720 A calibrator used as AC source.
Hewlett Packard 34420 Nanovoltmeter used to measure the output voltage of the reference standard.
Keithley 182 Nanovoltmeter used to measure the output voltage of the travelling standard.
An automated AC-DC switchbox.

Travelling standard: Fluke 792 A thermal transfer standard provided by SP (Sweden), sn.: 5495 003

In order to protect the thermal converters and the travelling standard all instruments, except the nV-meters, are connected to earth at the automated switchbox. Also the guard and ground terminals of the travelling standard were connected at all times. All measurements were carried out with the travelling standard battery operated using the travelling battery pack only.

Before any measurement the reference standard and the travelling standard was allowed to warm-up for 15 minutes with DC voltage applied.

After this the AC-DC transfer difference is determined by use of the measuring sequence AC - DC+ - AC - DC– - AC, which is chosen in order to compensate for errors due to drift of the output voltage of transfer standards. After each switching event the thermal transfer standards are allowed to stabilize for 60 seconds before taking five readings five seconds apart of both nV-meters, so that every E_{AC}, E_{DC+} and E_{DC-} is the average five readings.

In order to minimize errors due to the non-linear output/input correlation of the transfer standards, the first sequence is used to adjust the output of the AC calibrator, so that the AC-DC difference measured at the output of the test object is minimized.

At each frequency and voltage the measurement sequence was repeated 12 times, and the arithmetic mean and the corresponding experimental standard deviation was calculated.

3 Measurement Result

The intercomparison was performed in a laboratory with stabilised environmental conditions 23 °C ± 0,5 °C and 45 %RH ± 5 %RH. The minimum and maximum values recorded during the measurements are given in the following table:

Table 2: Minimum and maximum temperature and humidity values.

	Min	Max	Unc.
Ambient temperature / ºC	22,7	23,1	0,3
Relative humidity / %	44,4	47,9	3

The measurements were performed with only weak air streams due to air-conditioning, and the calibrators were placed with the air-cooling pointing away from the set-up.

The measured AC-DC transfer differences of the travelling standard at the required voltages and frequencies are given in the following table:

Table 3: Measurement results.

Voltage	Range	Measured ac-dc voltage difference / 10^{-6} at frequency			
		1 kHz	20 kHz	100 kHz	1 MHz
100 mV	220 mV	–2	–16	6	–10
10 mV	22 mV	–8	–32	–45	–234

In addition the battery pack was monitored as requested in the technical protocol during the measuring period, and the minimum and maximum values are given in the following table:

Table 4: Battery pack control measurements.

	Min	Max
Pos. power supply voltage / V	22,256	22,270
Neg. power supply voltage / V	–22,262	–22,268

4 Uncertainty

The overall uncertainties of the measurement results are estimated in accordance with EA-4/02. It has been distinguished between category A and B uncertainties. The category A uncertainty is stated as the estimated value of the experimental standard deviation. Estimates of the category B uncertainties are based either on experience or on stated specifications of the manufactorers. Here the limits of errors are estimated. In this case a suitable population distribution is assumed and the standard deviation is estimated by multiplying the error estimate with the corresponding factor.

The estimated expanded uncertainties (k = 2) of the measured AC-DC differences of the travelling standard are stated in table 5, whereas table 6 contains the uncertainty budget for the AC-DC transfer difference of the primary standards, and tables 7 - 16 contain the uncertainty budgets for the step-down procedure.

Assuming that all the uncertainty contributions (u_i) are uncorrelated the standard uncertainty u is calculated as:

$$u = \sqrt{\sum u_i^2}$$

The expanded uncertainty U is determined by:

$$U = ku$$

where the coverage factor k for a coverage probability of 95% is found from the effective number of degrees of freedom ν_{eff} and a t-distribution:

$$\nu_{eff} = \frac{u^4}{\sum \frac{u_i^4}{\nu_i}}$$

Table 5: Expanded uncertainty (k = 2).

Voltage	Range	Expanded uncertainty / 10^{-6} at frequency			
		1 kHz	20 kHz	100 kHz	1 MHz
100 mV	220 mV	8	8	13	48
10 mV	22 mV	41	41	62	193

Table 6: Uncertainty budget for AC-DC transfer difference of the primary standards.

Contribution of:	Unc. 1 kHz	Unc. 20 kHz	Unc. 100 kHz	Unc. 1 MHz	Type A or B	Distri-bution	Degrees of freedom
Th.-el. effect, FRDC	0,2	0,2	0,2	0,2	A	Gauss k=1	10
Heater, dielectric loss	0,05	0,05	0,5	10	B	Uniform	∞
Heater, capacitance	0,02	0,02	0,3	5	B	Uniform	∞
Heater, inductance	0,02	0,02	0,3	5	B	Uniform	∞
Leads, dielectric loss	0,05	0,05	0,5	10	B	Uniform	∞
Leads, capacitance	0,02	0,02	0,3	5	B	Uniform	∞
Leads, inductance	0,02	0,02	0,3	5	B	Uniform	∞
Skin effect	0,05	0,05	1,5	15	B	Uniform	∞
Connector	0,1	0,1	0,5	7	B	Uniform	∞
Comp. diff. standards	0,5	0,5	0,5	1	B	Uniform	∞

Standard unc. (k = 1):	0,37	0,37	1,13	13,9
Expanded unc. (k = 2):	0,8	0,8	2,4	28
Eff. Deg. Of freedom:	> 100	> 100	> 1000	> 1000

Table 7: Uncertainty budget for the calibration of a PMJTC against the primary standards (MJTC), 1 V - 0,5 V.

Contribution of:	Unc. 1 kHz	Unc. 20 kHz	Unc. 100 kHz	Unc. 1 MHz	Type A or B	Distri-bution	Degrees of freedom
Reference, MJTC	0,8	0,8	2,4	28	B	Gauss k=2	> 100
Standard deviation	0,2	0,2	0,2	0,2	A	Gauss k=1	11
Power coefficient	0,01	0,01	0,03	0,36	B	Uniform	∞
DMM, linearity	0,3	0,3	0,3	0,3	B	Uniform	∞
DMM, noise & th. volt.	1	1	1	1	B	Uniform	∞
DMM, resolution	0,4	0,4	0,4	0,4	B	Uniform	∞
T-adaptor	0,02	0,02	0,05	5	B	Uniform	∞
Thermoelectric effect	0,2	0,2	0,2	0,2	B	Uniform	∞
Set-up/diff. references	0,5	0,5	0,5	1	B	Uniform	∞

Standard unc. (k = 1):	0,85	0,85	1,42	14,4
Expanded unc. (k = 2):	1,7	1,7	2,9	29
Eff. deg. Of freedom:	> 1000	> 1000	> 1000	> 1000

With the uncertrainty budget in table 7 as a starting point the following tables show the additional uncertainties for each step in the step-down procedure for the measurements of the travelling standard, which means that those contributrions given in table 7 that remain unchanged for each step are not reported again in the following tables. The contribution for the T-adaptor is omitted for all steps involving µ-pots, and the resulting expanded uncertainty for each step is used as the “Reference” contribution in the next step.

The contributions due to the temperature and humidity dependence of the travelling standard are based on the values for the coefficients and corresponding uncertainties, α_T, α_{RH}, $u(\alpha_T)$ and $u(\alpha_{RH})$, given in the technical protocol. The deviations, ΔT and ΔRH, from the nominal values (23°C and 45%RH), and the corresponding uncertainties, u(T) and u(RH), are found from the values reported in table 1, using the largest deviations from nominal in the uncertainty estimates in the tables below.

The uncertainty of each frequency is ± 150 ppm (k = 2), so that the uncertainty contribution due to the frequency dependence may be neglected.

Table 8: Additional uncertainties, step-down procedure, 200 mV
Travelling standard - PMJTC (ref)

Contribution of:	Unc. 1 kHz	Unc. 20 kHz	Unc. 100 kHz	Unc. 1 MHz	Type A or B	Distri-bution	Degrees of freedom
Reference	1,7	1,7	2,9	29	B	Gauss k=2	> 1000
Standard deviation	0,4	0,4	0,4	0,5	A	Gauss k=1	11
Set-up	2	2	3	10	B	Uniform	∞
Repeat./Test. obj.↔ref	2	2	2	5	B	Uniform	∞
Loading	0	0	0	0	B	Uniform	∞
Temperature, $\Delta T \cdot u(\alpha_T)$	0,3	0,3	0,3	1,2	B	Uniform	∞
Temperature, $\alpha_T \cdot u(T)$	0,12	0,12	0,18	3,0	B	Uniform	∞
Humidity, $\Delta RH \cdot u(\alpha_{RH})$	0,06	0,15	0,29	1,45	B	Uniform	∞
Humidity, $\alpha_{RH} \cdot u(RH)$	0	0	0,3	3,9	B	Uniform	∞

Standard unc. (k = 1):	2,0	2,0	2,7	16,2
Expanded unc. (k = 2):	4,0	4,0	5,4	33
Eff. deg. Of freedom:	> 1000	> 1000	> 1000	> 1000

Table 9: Additional uncertainties, step-down procedure, 200 mV
μ-pot1 - travelling standard (ref)

Contribution of:	Unc. 1 kHz	Unc. 20 kHz	Unc. 100 kHz	Unc. 1 MHz	Type A or B	Distri-bution	Degrees of freedom
Reference	4,0	4,0	5,4	33	B	Gauss k=2	> 1000
Standard deviation	0,4	0,4	0,4	0,5	A	Gauss k=1	11
Set-up	2	2	3	10	B	Uniform	∞
Repeat./Test. obj.↔ref	2	2	2	5	B	Uniform	∞
Loading	0	0	0	0	B	Uniform	∞
Temperature, $\Delta T \cdot u(\alpha_T)$	0,3	0,3	0,3	1,2	B	Uniform	∞
Temperature, $\alpha_T \cdot u(T)$	0,12	0,12	0,18	3,0	B	Uniform	∞
Humidity, $\Delta RH \cdot u(\alpha_{RH})$	0,06	0,15	0,29	1,45	B	Uniform	∞
Humidity, $\alpha_{RH} \cdot u(RH)$	0	0	0,3	3,9	B	Uniform	∞

Standard unc. (k = 1):	2,7	2,7	3,5	17,8
Expanded unc. (k = 2):	5,4	5,4	7,0	36
Eff. deg. Of freedom:	> 1000	> 1000	> 1000	> 1000

Table 10: Additional uncertainties, step-down procedure, 100 mV
travelling standard - μ-pot1 (ref)

Contribution of:	Unc. 1 kHz	Unc. 20 kHz	Unc. 100 kHz	Unc. 1 MHz	Type A or B	Distri-bution	Degrees of freedom
Reference	5,4	5,4	7,0	36	B	Gauss k=2	> 1000
Standard deviation	0,8	0,7	0,8	0,9	A	Gauss k=1	11
Set-up	4	4	8	25	B	Uniform	∞
Repeat./Test. obj.↔ref	2	2	4	10	B	Uniform	∞
Loading	0	0	0	0	B	Uniform	∞
Temperature, $\Delta T \cdot u(\alpha_T)$	0,3	0,3	0,3	1,2	B	Uniform	∞
Temperature, $\alpha_T \cdot u(T)$	0,12	0,12	0,18	3,0	B	Uniform	∞
Humidity, $\Delta RH \cdot u(\alpha_{RH})$	0,06	0,15	0,29	1,45	B	Uniform	∞
Humidity, $\alpha_{RH} \cdot u(RH)$	0	0	0,3	3,9	B	Uniform	∞

Standard unc. (k = 1):	3,9	3,9	6,4	23,8
Expanded unc. (k = 2):	7,8	7,8	12,8	48
Eff. deg. Of freedom:	> 1000	> 1000	> 1000	> 1000

Table 11: Additional uncertainties, step-down procedure, 100 mV
μ-pot2 - travelling standard (ref)

Contribution of:	Unc. 1 kHz	Unc. 20 kHz	Unc. 100 kHz	Unc. 1 MHz	Type A or B	Distri-bution	Degrees of freedom
Reference	7,8	7,8	12,8	48	B	Gauss k=2	> 1000
Standard deviation	1,1	0,9	0,8	1,5	A	Gauss k=1	11
Set-up	4	4	8	25	B	Uniform	∞
Repeat./Test. obj.↔ref	2	2	4	10	B	Uniform	∞
Loading	0	0	0	0	B	Uniform	∞
Temperature, $\Delta T \cdot u(\alpha_T)$	0,3	0,3	0,3	1,2	B	Uniform	∞
Temperature, $\alpha_T \cdot u(T)$	0,12	0,12	0,18	3,0	B	Uniform	∞
Humidity, $\Delta RH \cdot u(\alpha_{RH})$	0,06	0,15	0,29	1,45	B	Uniform	∞
Humidity, $\alpha_{RH} \cdot u(RH)$	0	0	0,3	3,9	B	Uniform	∞

Standard unc. (k = 1):	4,9	4,8	8,3	28,7
Expanded unc. (k = 2):	9,7	9,6	16,5	58
Eff. deg. Of freedom:	> 1000	> 1000	> 1000	> 1000

Table 12: Additional uncertainties, step-down procedure, 50 mV
travelling standard - μ-pot2 (ref)

Contribution of:	Unc. 1 kHz	Unc. 20 kHz	Unc. 100 kHz	Unc. 1 MHz	Type A or B	Distri-bution	Degrees of freedom
Reference	9,7	9,6	16,5	58	B	Gauss k=2	> 1000
Standard deviation	1,8	2,1	2,2	2,5	A	Gauss k=1	11
Set-up	7	7	15	50	B	Uniform	∞
Repeat./Test. obj.↔ref	3	3	5	10	B	Uniform	∞
Loading	0	0	0	0	B	Uniform	∞
Temperature, $\Delta T \cdot u(\alpha_T)$	0,3	0,3	0,3	1,2	B	Uniform	∞
Temperature, $\alpha_T \cdot u(T)$	0,12	0,12	0,18	3,0	B	Uniform	∞
Humidity, $\Delta RH \cdot u(\alpha_{RH})$	0,06	0,15	0,29	1,45	B	Uniform	∞
Humidity, $\alpha_{RH} \cdot u(RH)$	0	0	0,3	3,9	B	Uniform	∞

Standard unc. (k = 1):	6,9	6,9	12,6	41,3
Expanded unc. (k = 2):	13,8	13,8	26	83
Eff. deg. Of freedom:	> 1000	> 1000	> 1000	> 1000

Table 13: Additional uncertainties, step-down procedure, 50 mV
μ-pot3 - travelling standard (ref)

Contribution of:	Unc. 1 kHz	Unc. 20 kHz	Unc. 100 kHz	Unc. 1 MHz	Type A or B	Distri-bution	Degrees of freedom
Reference	13,8	13,8	26	83	B	Gauss k=2	> 1000
Standard deviation	2,8	2,4	2,7	3,1	A	Gauss k=1	11
Set-up	7	7	15	50	B	Uniform	∞
Repeat./Test. obj.↔ref	3	3	5	10	B	Uniform	∞
Loading	0	0	0	0	B	Uniform	∞
Temperature, $\Delta T \cdot u(\alpha_T)$	0,3	0,3	0,3	1,2	B	Uniform	∞
Temperature, $\alpha_T \cdot u(T)$	0,12	0,12	0,18	3,0	B	Uniform	∞
Humidity, $\Delta RH \cdot u(\alpha_{RH})$	0,06	0,15	0,29	1,45	B	Uniform	∞
Humidity, $\alpha_{RH} \cdot u(RH)$	0	0	0,3	3,9	B	Uniform	∞

Standard unc. (k = 1):	8,7	8,6	15,8	50,9
Expanded unc. (k = 2):	17,4	17,2	32	102
Eff. deg. Of freedom:	> 1000	> 1000	> 1000	> 1000

Table 14: Additional uncertainties, step-down procedure, 20 mV
travelling standard - μ-pot3 (ref)

Contribution of:	Unc. 1 kHz	Unc. 20 kHz	Unc. 100 kHz	Unc. 1 MHz	Type A or B	Distri-bution	Degrees of freedom
Reference	17,4	17,2	32	102	B	Gauss k=2	> 1000
Standard deviation	3,5	3,6	3,3	4,2	A	Gauss k=1	11
Set-up	15	15	20	75	B	Uniform	∞
Repeat./Test. obj.↔ref	3	3	5	10	B	Uniform	∞
Loading	5	5	15	50	B	Uniform	∞
Temperature, $\Delta T \cdot u(\alpha_T)$	0,6	0,6	0,6	2,4	B	Uniform	∞
Temperature, $\alpha_T \cdot u(T)$	0,36	0,36	0,39	5,1	B	Uniform	∞
Humidity, $\Delta RH \cdot u(\alpha_{RH})$	0,06	0,15	0,29	1,45	B	Uniform	∞
Humidity, $\alpha_{RH} \cdot u(RH)$	0	0	0,3	2,7	B	Uniform	∞

Standard unc. (k = 1):	13,2	13,2	21,9	73,3
Expanded unc. (k = 2):	27	27	44	147
Eff. deg. Of freedom:	> 1000	> 1000	> 1000	> 1000

Table 15: Additional uncertainties, step-down procedure, 50 mV
µ-pot4 - travelling standard (ref)

Contribution of:	Unc. 1 kHz	Unc. 20 kHz	Unc. 100 kHz	Unc. 1 MHz	Type A or B	Distri-bution	Degrees of freedom
Reference	27	27	44	147	B	Gauss k=2	> 1000
Standard deviation	3,1	3,9	3,8	4,1	A	Gauss k=1	11
Set-up	15	15	20	75	B	Uniform	∞
Repeat./Test. obj.↔ref	3	3	5	10	B	Uniform	∞
Loading	0	0	0	0	B	Uniform	∞
Temperature, $\Delta T \cdot u(\alpha_T)$	0,6	0,6	0,6	2,4	B	Uniform	∞
Temperature, $\alpha_T \cdot u(T)$	0,36	0,36	0,39	5,1	B	Uniform	∞
Humidity, $\Delta RH \cdot u(\alpha_{RH})$	0,06	0,15	0,29	1,45	B	Uniform	∞
Humidity, $\alpha_{RH} \cdot u(RH)$	0	0	0,3	2,7	B	Uniform	∞

Standard unc. (k = 1):	16,2	16,4	25,2	85,5
Expanded unc. (k = 2):	33	33	51	171
Eff. deg. Of freedom:	> 1000	> 1000	> 1000	> 1000

Table 16: Additional uncertainties, step-down procedure, 10 mV
travelling standard - µ-pot4 (ref)

Contribution of:	Unc. 1 kHz	Unc. 20 kHz	Unc. 100 kHz	Unc. 1 MHz	Type A or B	Distri-bution	Degrees of freedom
Reference	33	33	51	171	B	Gauss k=2	> 1000
Standard deviation	3,1	3,3	4,3	3,5	A	Gauss k=1	11
Set-up	20	20	30	75	B	Uniform	∞
Repeat./Test. obj.↔ref	3	3	5	10	B	Uniform	∞
Loading	0	0	0	0	B	Uniform	∞
Temperature, $\Delta T \cdot u(\alpha_T)$	0,6	0,6	0,6	2,4	B	Uniform	∞
Temperature, $\alpha_T \cdot u(T)$	0,36	0,36	0,39	5,1	B	Uniform	∞
Humidity, $\Delta RH \cdot u(\alpha_{RH})$	0,06	0,15	0,29	1,45	B	Uniform	∞
Humidity, $\alpha_{RH} \cdot u(RH)$	0	0	0,3	2,7	B	Uniform	∞

Standard unc. (k = 1):	20,3	20,4	31,0	96,1
Expanded unc. (k = 2):	41	41	62	193
Eff. deg. Of freedom:	> 1000	> 1000	> 1000	> 1000

REPORT ON EUROMET COMPARISON EM-K11

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Contents

REPORT ON THE EUROMET COMPARISON EM-K11 ON LOW VOLTAGE AC-DC TRANSFER STANDARDS

1 Introduction

In November 2006, LNE participated in the EUROMET comparison EM-K11 on low voltage AC-DC transfer standards. The travelling standard was a FLUKE 792 A device, serial number 555495 003. It has been compared to a low voltage reference AC-DC transfer standard of LNE.

2 Definition of the mesurand

The quantity to be measured was the AC-DC transfer difference δ of the travelling standard, defined as :

$$\delta = \frac{U_{AC} - U_{DC}}{U_{DC}} \quad (1)$$

where

- U_{AC} is the RMS value of the AC voltage applied at the input of the standard;
- U_{DC}, the direct voltage, which when reversed, produces the same mean output response of the standard as U_{AC}.

These voltages are defined in the reference plane of a type N T-connector used to connect the reference device and the device to be calibrated to the voltage source.

3 Low voltage AC-DC transfer standards of LNE

The low voltage AC-DC transfer standards of LNE are two FLUKE 792 A devices. Their AC-DC transfer differences have been determined by a step down procedure. The voltage level dependence has been taken into account by means of resistive dividers (assumed to have no voltage level dependence). In the first steps of the procedure, the FLUKE 792 A and the resistive dividers were compared to multijunction thermal converters directly calibrated against primary standards of LNE.

The primary standards are planar multijunction chips developed by PTB and manufactured by IPHT. Their nominal voltage is between 1 V and 1.5 V. For frequencies ranging from 10 Hz to 1 kHz, a 90 Ω chip is used. At 1 kHz and above the primary standard is a 180 Ω chip. These chips are mounted in home made housings and can be connected to the reference plane by the means of a type N connector and a short coaxial rigid cable. The AC-DC differences of the chips are assumed to be equal to zero with an uncertainty of 1 µV/V up to 10 kHz, growing up to 2 µV/V at 100 kHz. For frequencies higher than 1 kHz, the AC-DC difference arising from the connection between the chip and the reference plane has been calculated and taken into account. A good agreement between NMIs at voltages ranging from 1 V to 3 V has been shown in a previous comparison (CCEM-K6.a) [1].

4 Measuring system

All the calibrations in the low voltage domain are carried-out by means of an automated measuring system (fig. 1). The inputs of the devices to be compared are connected in parallel using a type N T-connector. Voltmeter V measures directly the output voltage of the reference unit and voltmeter V_d measures a "differential" voltage between the outputs of the resistive dividers loading the outputs of both devices. The ratio of divider R_{d2} is chosen so that its output voltage is not higher than the output voltage of the reference device. The ratio of divider R_{d1} is adjusted in such a way that small variations of the input voltage have no significant influence on voltage V_d. Sequence AC, DC+, DC-, AC, DC+, DC-, AC, DC+, DC-, AC is then applied with a regular time interval and V and V_d voltages are each time measured and recorded. Final values of output voltages measured by voltmeters V and V_d in response to AC, DC+ and DC- input voltages are then computed from this set of data using the least mean square method. In this way, an eventual drift of the system during the time of the measurements, modelised by a 3^{rd} order polynomial , can be eliminated.

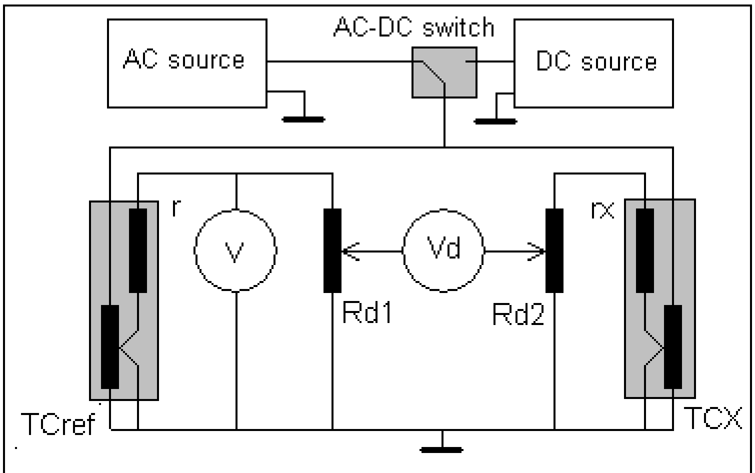

Figure 1 : Scheme of the measuring system

The result of the calibration is given by:

$$Y = d_X - d_{réf} = \frac{1}{n_{ref}} \cdot \left[\frac{2.V_a}{V_{c+} + V_{c-}} - 1 \right] - \frac{1}{n_X} \cdot \left[2. \frac{k.V_a - V_{da}}{k.(V_{c+} + V_{c-}) - (V_{dc+} + V_{dc-})} - 1 \right] \quad (2)$$

where

- V_a (resp. V_{da}) is the voltage, after drift elimination, measured by the voltmeter V (resp. voltmeter V_d) in response to the AC input voltage;
- V_{c+} (resp. V_{dc+}) is the voltage, after drift elimination, measured by the voltmeter V (resp. voltmeter V_d) in response to the DC+ input voltage;
- V_{c-} (resp. V_{dc-}) is the voltage, after drift elimination, measured by the voltmeter V (resp. voltmeter V_d) in response to the DC- input voltage;

- k is the ration of the resistive divider R_{d1};
- n_{ref} (resp. n_X) is a characteristic of the reference device (resp. device under test). n_{ref} and n_X are determined in a preliminary test.

A more detailed description of the measuring system is given in [2].

5 Measuring conditions

During the measurements the temperature was 23 °C ± 0.1 °C and the relative humidity 50 % ± 10 %.

The input low and the output low of both the device under test and the reference device were connected to the external part of the T-connector which was the common ground point.

6 Measurements results

The measured AC-DC transfer difference of the travelling standard and the expanded uncertainty are given in table 1.

	AC-DC transfer difference δ and expanded uncertainty U (k = 2) in µV/V					
	1 kHz		20 kHz		100 kHz	
Voltage	δ	U	δ	U	δ	U
100 mV	9.4	*7*	-6.5	*8*	16.1	*14*
10 mV	10.5	*10*	-0.1	*16*	-17.8	*21*

Table 1 : AC-DC transfer difference and expanded uncertainty of the travelling standard

7 Uncertainty budget

7-1 Measurement uncertainty

- Calculation showed that type B uncertainty arising from uncertainty on voltages measured by voltmeters V and Vd, on values of n_{ref} and n_X and on the value of k (see relation 2) can be neglected. Then, the main components of type B measurement uncertainty are :

- the uncertainty arising from the connector. We have evaluated this uncertainty to be 0.2 µV/V at 1 kHz, 0.3 µV/V at 20 kHz and 0.5 µV/V at 100 kHz ;
- the uncertainty arising from the non-perfect adjustment of the AC voltage. Before each determination of the AC-DC difference, the AC voltage is automatically adjusted as close as possible to the DC voltage. Nevertheless, this adjustment is never perfect and leads to an uncertainty component we estimated to be 0.3 µV/V at 1 kHz and 0.5 µV/V at 20 kHz and 100 kHz ;
- the uncertainty arising from the approximation of the model used. The relation between the output voltage V_{out} and the input voltage V_{in} of a thermal converter ($V_{out} = g.V_{in}^2$) used to establish relation 2 is empirical and then not

perfectly exact. Moreover, relation 2 is just a first order approximation of $Y = d_X - d_{ref}$. Then, this uncertainty component should rise when $|d_x - d_{ref}|$ rises, and we estimated it to be equal to $\left|d_X - d_{ref}\right| / 20$.

- Type A uncertainty on one determination of $d_x - d_{ref}$:

Each determination of $d_X - d_{ref}$ is made using the least mean square method (see paragraph 4). The associated type A uncertainty is equal to the standard deviation calculated from the deviation of the values of the voltages measured by voltmeters V and V_d from the theoretical polynomials.

The final value of $d_x - d_{ref}$ is the mean of 4 determinations. The type A uncertainty on this final value takes into account the type A uncertainty on each determination and the deviation of each determination from the mean.

7-2 Uncertainty on LNE AC-DC transfer standards

The expanded uncertainty of the primary AC-DC transfer standard of LNE (Nominal voltage : 1 V) is given in table 2.

Fréquency (kHz)	*Uncertainty (µV/V)*
1	*2*
20	*2.2*
100	*4.6*

Table 2 : Expanded uncertainty (k = 2) of the primary AC-DC transfer standard of LNE

The expanded uncertainties of low voltage AC-DC transfer standards of LNE have been calculated as indicated in paragraph 7-1. They are given in tables 3a to 3c.

	Range : 0.7 V					
Fréquence (kHz)	Voltage : 0.5 V		Voltage : 0.3 V		Voltage : 0.2 V	
	FL792-1	FL792-2	FL792-1	FL792-2	FL792-1	FL792-2
1	**2.6**	**2.6**	**6.2**	**6.2**	**6**	**5.6**
20	**2.8**	**3**	**6.6**	**7**	**6.2**	**6.2**
100	**5.4**	**5.4**	**12.2**	**12**	**12**	**12.4**

Table 3a : Expanded uncertainty of low voltage AC-DC standards (Range 0.7 V) (µV/V)

	Range 220 mV									
Fréquence (kHz)	Voltage : 200 mV		Voltage : 100 mV		Voltage : 50 mV		Voltage : 30 mV		Voltage : 20 mV	
	FL792-1	FL792-2	FL792-1	FL792-2	FL792-1	FL792-2	FL792-1	FL792-2	FL792-1	FL792-2
1	**6**	**6.2**	**6.8**	**6.6**	**7.4**	**7.2**	**9.2**	**9.2**	**10.4**	**11.2**
20	**6.6**	**6.8**	**7.6**	**7.6**	**8.4**	**8.2**	**10**	**10.2**	**11.4**	**11.2**
100	**12.8**	**12.4**	**13.4**	**13.4**	**14.2**	**14**	**18.6**	**18.8**	**20.8**	**20.8**

Table 3b : Expanded uncertainty of low voltage AC-DC standards (Range 220 mV) (µV/V)

Table 3c : Expanded uncertainty of low voltage AC-DC standards (Range 22 mV) (µV/V)

	Range 22 mV			
Fréquence (kHz)	Voltage : 20 mV		Voltage : 10 mV	
	FL792-1	FL792-2	FL792-1	FL792-2
1	**11.8**	**11.4**	**10**	**9.2**
20	**13.2**	**15.4**	**13**	**15**
100	**21.6**	**22.4**	**19.2**	**19.6**

7-3 Uncertainty of the travelling standard

The standard uncertainty *u* of the travelling standard is given by

$$u = \sqrt{u_{ref}^2 + u_B^2 + u_A^2} \quad (3)$$

where :
u_{ref} is the standard uncertainty of the reference standard
u_B is the type B measurement standard uncertainty
u_A is the type A measurement standard uncertainty

The values of the uncertainty of the travelling standard are shown in tables 4a and 4b. In the last column of these tables, the expanded uncertainty is given with a coverage factor k = 2.

Fréquence (kHz)	Standard uncertainties				Exp. uncert.
	LNE standard	Type B	Type A	Trav. standard	**Trav. standard**
1	3.4	0.7	0.2	3.5	**7**
20	3.8	0.6	0.2	3.9	**8**
100	6.7	0.7	0.3	6.7	**14**

Table 4a : Uncertainty of the travelling standard at 100 mV (µV/V)

Fréquence (kHz)	Standard uncertainties				Exp. uncert.
	LNE standard	Type B	Type A	Trav. standard	**Trav. standard**
1	4.6	0.6	1.5	4.9	**10**
20	7.5	0.6	1.9	7.8	**16**
100	9.8	1.1	2.2	10.1	**21**

Table 4b : Uncertainty of the travelling standard at 10 mV (µV/V)

References

[1] M. Klonz, « CCE Comparison of AC-DC Voltage Transfer Standards at the Lowest Attainable Level of Uncertainty », IEEE Trans. Instr. Meas., Vol. 46, n° 2, pp 342-346, April 1997.

[2] A.POLETAEFF, "Automated comparator for accurate AC-DC difference measurements at the BNM-LCIE", *IEEE Trans. Instr. Meas.,* vol 48, n° 2, pp 412-414, April 1999.

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Object	**Fluke 792A thermal transfer standard S.N. 5495003** *consisting of:* • *Fluke 792A thermal transfer standard S.N.5495003* • *Fluke 792A power pack S.N.5495003*
Order	Determination of the AC/DC voltage transfer difference.
Applicant	**International Comparison EUROMET.EM-K11** „AC-DC Voltage Transfer Difference at Low Voltages“ Pilot Laboratory: SP SE-501 15 Borås
Traceability	The reported measurement values are traceable to national standards and thus to internationally supported realizations of the SI-units.
Date of Calibration	from 08.12.2006 to 23.12.2006

CH-3003 Bern-Wabern, 17 January 2007

For the Measurements	Section Electricity
Dr Alessandro Mortara	Dr Beat Jeckelmann, Head of Section

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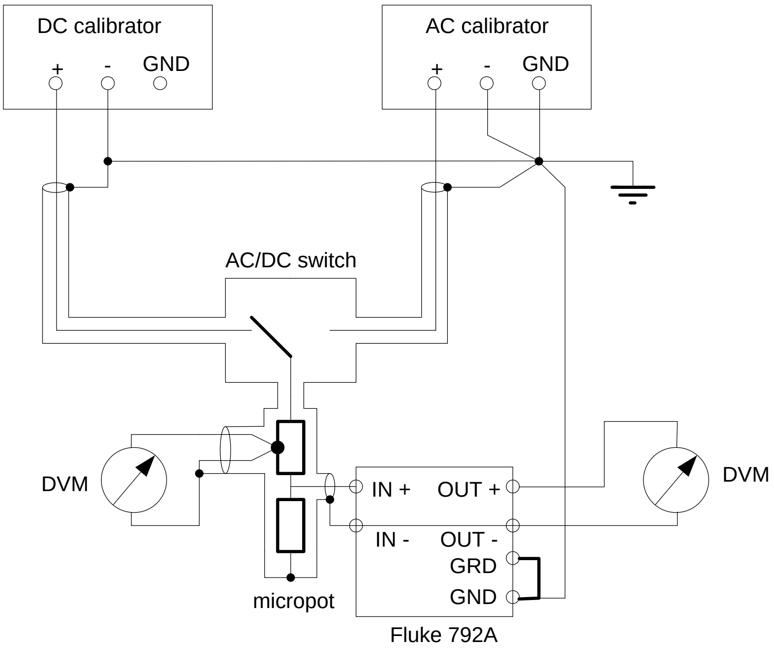

Figure 1: measurement setup

Extent of the Calibration

Determination of the AC/DC voltage transfer difference at 100 mV and at 10 mV input at frequencies of 1 kHz, 20 kHz, 100 kHz and 1 MHz.

Measurement Procedure

The measurement is based on the well-known step-down procedure using micro-potentiometers. The first step is the calibration of the travelling standard with a primary standard (a planar multi-junction thermal converter fabricated by the PTB) at the 200 mV level. Then, and for all of the following steps, an auxiliary transfer standard (micro-potentiometer) is calibrated against the travelling standard at a given voltage level and then used to calibrate the travelling standard at a lower voltage level. It is assumed that neither the AC/DC voltage difference of the micro-potentiometer nor the travelling standard's input impedance change significantly between the two voltage levels. However, this assumption is linked to a specific uncertainty component. In the step number 9 (calibration of the travelling standard at 20 mV), there is the additional assumption that the input loading of the micro-potentiometer by the travelling standard is the same when switching between 220 mV range and 22 mV range. This is justified because the input stage of the Fluke 792A is the same in these two ranges (the lower voltage range cascades an additional amplifying circuit). The results were formed by computing 10 times the difference between AC/DC differences of the UUT and the reference. The DC^+, AC and DC^- values used to compute the AC/DC differences were the result of an average of 10 readings of the DVMs.

Measurement Setup

The measurement setup and grounding scheme is schematically depicted in Figure 1. The micro-potentiometers were fabricated by Ballantine Laboratories and, for steps number 8 and 9, a Ballantine disk resistor was used together with a PTB planar multi-junction thermal converter. The calibrators are a DATRON 4000 A for DC and a DATRON 4200 A for AC. The digital voltmeters are of type Keithley 182.

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Measurement Conditions

step #	Ambient temp. (°C)	Relative humidity (%)	V+ power pack at start (V)	V- power pack at start (V)	V+ power pack at end (V)	V- power pack at end (V)
1	23.2	39.8	11.102	-11.166	11.096	-11.160
2	23.1	39.5	11.104	-11.168	11.096	-11.159
3	23.1	39.8	11.101	-11.164	11.095	-11.159
4	23.1	39.5	11.104	-11.167	11.098	-11.161
5	23.1	39.7	11.102	-11.165	11.094	-11.158
6	23.1	39.5	11.103	-11.166	11.095	-11.158
7	23.1	39.7	11.102	-11.165	11.097	-11.160
8	23.1	39.8	11.102	-11.165	11.095	-11.158
9	23.1	39.4	11.101	-11.165	11.093	-11.156
10	23.2	39.4	11.099	-11.163	11.089	-11.157
11	23.1	39.3	11.145	-11.158	11.139	-11.152

Measuring Frequency

	Nominal frequency			
	1 kHz	20 kHz	100 kHz	1 MHz
Measuring frequency	1.000009 kHz	20.000070 kHz	100.000270 kHz	1.000002 MHz
Expanded uncertainty (ppm)	10	10	10	10

Measurement Results

The ac-dc voltage transfer difference δ of a transfer standard is defined in the key comparison's technical protocol as follows:

$$\delta = (V_{ac} - V_{dc}) / V_{dc}$$

where

V_{ac} is the rms value of the ac input voltage

V_{dc} is the dc input voltage which when reversed produces the same mean output voltage of the transfer standard as V_{ac}.

The following measurement results include the correction for temperature and relative humidity computed using the data from the technical protocol of the comparison.

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Voltage	Range	Measured ac-dc voltage difference / 10^{-6} at frequency			
		1 kHz	20 kHz	100 kHz	1 MHz
100 mV	220 mV	-4.3	-19.1	4.7	-8.5
10 mV	22 mV	-21.2	-48.8	-56.4	-259.7

Uncertainty of Measurement

Voltage	Range	Expanded uncertainty / 10^{-6} at frequency			
		1 kHz	20 kHz	100 kHz	1 MHz
100 mV	220 mV	13	9	14	36
10 mV	22 mV	32	31	52	105

The reported uncertainty of measurement is stated as the combined standard uncertainty multiplied by a coverage factor. The measured value (*y*) and the associated expanded uncertainty (*U*) represent the interval ($y \pm U$) which contains the value of the measured quantity with a probability of approximately 95%. The uncertainty and the coverage factor were estimated following the guidelines of the ISO.

The measurement uncertainty contains contributions originating from the measurement standard, from the calibration method, from the environmental conditions and from the object being calibrated. The long-term characteristic of the object being calibrated is not included.

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Appendix 1: Detailed uncertainty budget

All uncertainties in the following tables are given in ppm.

			1 kHz	20 kHz	100 kHz	1 MHz
primary standard	voltage (V)	0.95				
	standard uncertainty		**1.0**	**1.0**	**2.0**	**4.0**
Step n. 1	voltage (V)	0.2				
	st. dev. of the mean	A, N	1.2	0.4	0.3	2.3
	Utemperature	B, N	0.2	0.2	0.2	2.2
	Uhumidity	B, N	0.1	0.3	0.7	7.0
	UDVM	B, R	1.5	1.5	1.5	1.5
	Uvoltage dependence	B, R	1.0	1.0	2.0	5.0
	Uconnections	B,R	1.0	1.0	2.0	4.0
	Ureproductibi-lity	B,R	1.0	1.0	2.0	3.0
	Standard uncertainty (k=1)		**2.7**	**2.5**	**4.3**	**11.3**
	neff		> 100	> 100	> 100	> 100
	U95		**5.4**	**5.0**	**8.5**	**22.2**

			1 kHz	20 kHz	100 kHz	1 MHz
previous step:	voltage (V)	0.2				
	cumulated uncertainty		**2.7**	**2.5**	**4.3**	**11.3**
Step n. 2	voltage (V)	0.2				
	st. dev. of the mean	A, N	0.6	0.7	0.6	0.5
	Utemperature	B, N	0.1	0.1	0.2	2.0
	Uhumidity	B, N	0.1	0.3	0.7	7.1
	UDVM	B, R	1.5	1.5	1.5	1.5
	Uvoltage dependence	B, R	0.0	0.0	0.0	0.0
	Uconnections	B,R	1.0	1.0	2.0	4.0
	Ureproductibi-lity	B,R	1.0	1.0	2.0	4.0
	Standard uncertainty (k=1)		**3.5**	**3.4**	**5.5**	**14.7**
	neff		> 100	> 100	> 100	> 100
	U95		**6.8**	**6.6**	**10.7**	**28.8**

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			1 kHz	20 kHz	100 kHz	1 MHz
previous step:	voltage (V)	0.2				
	cumulated uncertainty	0	**3.5**	**3.4**	**5.5**	**14.7**
Step n. 3	voltage (V)	0.1				
	st. dev. of the mean	A, N	4.9	2.1	1.7	3.6
	Utemperature	B, N	0.1	0.1	0.1	2.0
	Uhumidity	B, N	0.1	0.3	0.7	7.0
	UDVM	B, R	1.6	1.6	1.6	1.6
	Uvoltage dependence	B, R	1.0	1.0	2.0	4.0
	Uconnections	B,R	1.0	1.0	2.0	4.0
	Ureproductibi-lity	B,R	1.0	1.0	2.0	4.0
	Standard uncertainty (k=1)		**6.4**	**4.6**	**6.9**	**18.2**
	neff		30	> 100	> 100	> 100
	U95		**13.1**	**9.0**	**13.6**	**35.7**

			1 kHz	20 kHz	100 kHz	1 MHz
previous step:	voltage (V)	0.1				
	cumulated uncertainty		**6.4**	**4.6**	**6.9**	**18.2**
Step n. 4	voltage (V)	0.1				
	st. dev. of the mean	A, N	1.9	3.1	1.4	1.5
	Utemperature	B, N	0.1	0.1	0.2	2.1
	Uhumidity	B, N	0.1	0.3	0.7	7.1
	UDVM	B, R	1.6	1.6	1.6	1.6
	Uvoltage dependence	B, R	0.0	0.0	0.0	0.0
	Uconnections	B,R	1.0	1.0	2.0	4.0
	Ureproductibi-lity	B,R	1.0	1.0	2.0	4.0
	Standard uncertainty (k=1)		**7.0**	**5.9**	**7.8**	**20.6**
	neff		42	> 100	> 100	> 100
	U95		**14.2**	**11.8**	**15.3**	**40.3**

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			1 kHz	20 kHz	100 kHz	1 MHz
previous step:	voltage (V)	0.1				
	cumulated uncertainty		**7.0**	**5.9**	**7.8**	**20.6**
Step n. 5	voltage (V)	0.075				
	st. dev. of the mean	A, N	3.9	5.2	2.8	2.8
	Utemperature	B, N	0.1	0.1	0.2	2.1
	Uhumidity	B, N	0.1	0.3	0.7	7.0
	UDVM	B, R	1.7	1.7	1.7	1.7
	Uvoltage dependence	B, R	1.0	1.0	2.0	4.0
	Uconnections	B,R	1.0	1.0	2.0	4.0
	Ureproductibi-lity	B,R	1.0	1.0	2.0	4.0
	Standard uncertainty (k=1)		**8.4**	**8.3**	**9.2**	**23.1**
	neff		61	55	> 100	> 100
	U95		**16.8**	**16.6**	**18.0**	**45.4**

			1 kHz	20 kHz	100 kHz	1 MHz
previous step:	voltage (V)	0.075				
	cumulated uncertainty		**8.4**	**8.3**	**9.2**	**23.1**
Step n. 6	voltage (V)	0.075				
	st. dev. of the mean	A, N	1.2	1.3	1.3	2.2
	Utemperature	B, N	0.1	0.1	0.2	2.0
	Uhumidity	B, N	0.1	0.3	0.7	7.1
	UDVM	B, R	1.7	1.7	1.7	1.7
	Uvoltage dependence	B, R	0.0	0.0	0.0	0.0
	Uconnections	B,R	1.0	1.0	2.0	4.0
	Ureproductibi-lity	B,R	1.0	1.0	2.0	4.0
	Standard uncertainty (k=1)		**8.8**	**8.7**	**9.9**	**25.1**
	neff		73	65	> 100	> 100
	U95		**17.5**	**17.3**	**19.3**	**49.2**

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				1 kHz	20 kHz	100 kHz	1 MHz
previous step:	voltage (V)		0.075				
	cumulated uncertainty			**8.8**	**8.7**	**9.9**	**25.1**
Step n. 7	voltage (V)		0.06				
	st. dev. of the mean		A, N	1.4	2.2	1.5	1.9
	Utemperature		B, N	0.1	0.1	0.1	2.0
	Uhumidity		B, N	0.1	0.3	0.7	7.0
	UDVM		B, R	1.8	1.8	1.8	1.8
	Uvoltage dependence		B, R	1.0	1.0	2.0	4.0
	Uconnections		B,R	1.0	1.0	2.0	4.0
	Ureproductibi-lity		B,R	1.0	1.0	2.0	4.0
	Standard uncertainty (k=1)			**9.2**	**9.3**	**10.7**	**27.2**
	neff			89	84	> 100	> 100
	U95			**18.4**	**18.5**	**21.1**	**53.2**

				1 kHz	20 kHz	100 kHz	1 MHz
previous step:	voltage (V)		0.06				
	cumulated uncertainty			**9.2**	**9.3**	**10.7**	**27.2**
Step n. 8	voltage (V)		0.06				
	st. dev. of the mean		A, N	0.7	0.8	0.9	2.6
	Utemperature		B, N	0.1	0.1	0.1	2.0
	Uhumidity		B, N	0.1	0.3	0.7	7.0
	UDVM		B, R	1.8	1.8	1.8	1.8
	Uvoltage dependence		B, R	0.0	0.0	0.0	0.0
	Uconnections		B,R	1.0	1.0	2.0	4.0
	Ureproductibi-lity		B,R	1.0	1.0	2.0	2.0
	Standard uncertainty (k=1)			**9.5**	**9.6**	**11.3**	**28.6**
	neff			> 100	96	> 100	> 100
	U95			**18.9**	**19.1**	**22.2**	**56.2**

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			1 kHz	20 kHz	100 kHz	1 MHz
previous step:	voltage (V)	0.06				
	cumulated uncertainty		**9.5**	**9.6**	**11.3**	**28.6**
Step n. 9	voltage (V)	0.02				
	st. dev. of the mean	A, N	2.7	2.8	1.4	1.9
	Utemperature	B, N	0.3	0.3	0.3	3.5
	Uhumidity	B, N	0.1	0.3	0.8	5.3
	UDVM	B, R	1.5	1.5	1.5	1.5
	Uvoltage dependence	B, R	10.0	10.0	20.0	40.0
	Uconnections	B,R	2.0	2.0	4.0	8.0
	Ureproductibi-lity	B,R	1.0	1.0	2.0	2.0
	Standard uncertainty (k=1)		**14.3**	**14.4**	**23.5**	**50.3**
	neff		> 100	> 100	> 100	> 100
	U95		**28.2**	**28.3**	**46.1**	**98.7**

			1 kHz	20 kHz	100 kHz	1 MHz
previous step:	voltage (V)	0.02				
	cumulated uncertainty		**14.3**	**14.4**	**23.5**	**50.3**
Step n. 10	voltage (V)	0.02				
	st. dev. of the mean	A, N	2.2	2.2	2.2	2.0
	Utemperature	B, N	0.4	0.4	0.5	3.7
	Uhumidity	B, N	0.1	0.3	0.7	5.2
	UDVM	B, R	1.5	1.5	1.5	1.5
	Uvoltage dependence	B, R	0.0	0.0	0.0	0.0
	Uconnections	B,R	2.0	2.0	4.0	8.0
	Ureproductibi-lity	B,R	1.0	1.0	2.0	4.0
	Standard uncertainty (k=1)		**14.8**	**14.8**	**24.1**	**51.6**
	neff		> 100	> 100	> 100	> 100
	U95		**29.0**	**29.1**	**47.2**	**101.1**

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			1 kHz	20 kHz	100 kHz	1 MHz
previous step:	voltage (V)	0.02				
	cumulated uncertainty		**14.8**	**14.8**	**24.1**	**51.6**
Step n. 11	voltage (V)	0.01				
	st. dev. of the mean	A, N	5.1	2.6	6.6	4.5
	Utemperature	B, N	0.3	0.3	0.3	3.4
	Uhumidity	B, N	0.1	0.3	0.8	5.3
	UDVM	B, R	1.6	1.6	1.6	1.6
	Uvoltage dependence	B, R	1.0	1.0	2.0	4.0
	Uconnections	B,R	2.0	2.0	4.0	8.0
	Ureproductibi-lity	B,R	4.0	4.0	8.0	10.0
	Standard uncertainty (k=1)		**16.4**	**15.8**	**26.7**	**53.9**
	neff		> 100	> 100	> 100	> 100
	U95		**32.2**	**31.1**	**52.3**	**105.6**

Legend:

st. dev. of the mean	standard deviation of the measured AC/DC differences
Utemperature	uncertainty component due to temperature
Uhumidity	uncertainty component due to ambient humidity
UDVM	uncertainty due to DVM resolution
Uvoltage dependence	uncertainty due to the possible AC/DC difference change of the micropotentiometers and input impedance of the UUT at different voltage levels
Uconnections	uncertainty due to the effect of connectors and guarding
Ureproductibi-lity	uncertainty due to reproductibility of the measurements
neff	effective degrees of freedom
U95	uncertanty at 95% confidence according to GUM
A,N	type A, normal distribution
B,N	type B, normal distribution
B,R	type B, rectangular distribution

TÜBİTAK
UME

Report of EUROMET.EM-K11

AC-DC VOLTAGE TRANSFER DIFFERENCE AT LOW VOLTAGES

Voltage Laboratory

Rev. 17.05.2007

1. SCOPE

Key comparison EUROMET.EM-K11 “AC-DC voltage transfer difference at low voltages” (100 mV and 10 mV at frequencies 1 kHz, 20 kHz, 100 kHz and 1 MHz)

2. PERIOD OF MEASUREMENTS

The measurements have been performed at UME in the period of 26.01.2007–22.02.2007.

3. TRAVELING STANDARD

FLUKE 792A Thermal Transfer Standard (S/N: 5495 003), which is capable to measure voltages down to 2mV at frequencies from 10 Hz to 1 MHz.

4. AMBIENT CONDITIONS

The comparison measurements have been performed in UME Voltage Laboratory which has the environmental conditions given below:

Temperature : (23 ± 1) °C

Relative Humidity : (45 ± 10) %

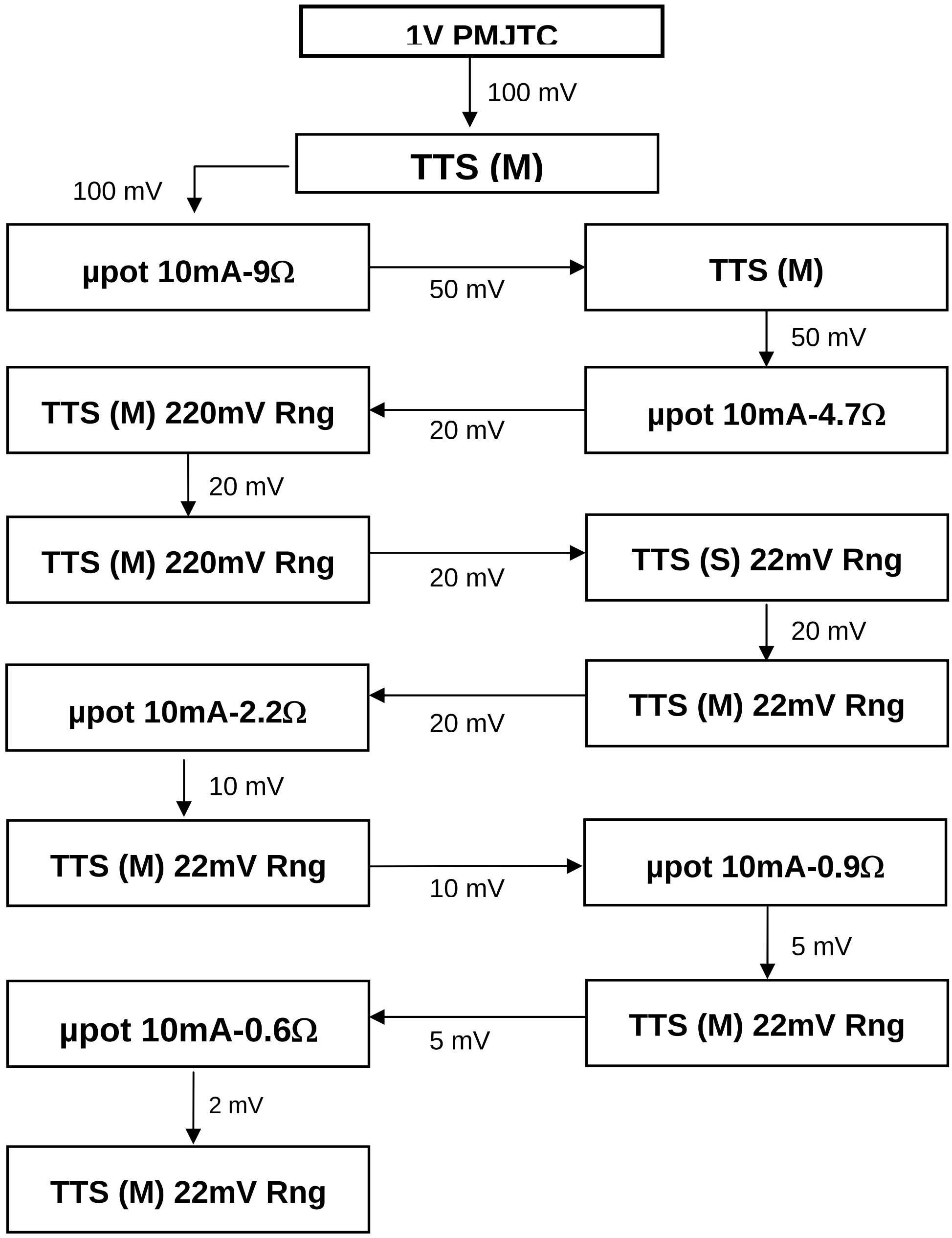
During the comparison measurement, the environmental temperature and relative humidity have been measured by UME temperature-humidity monitoring system.

5. MEASUREMENTS PRECAUTIONS

- The traveling standard has been allowed to stabilise in Laboratory conditions, which is under control for one day after their arrival to Voltage Laboratory of UME.
- The reference plane of the measured ac-dc voltage transfer difference is at the centre of a type N-Tee connector with type N male output connector.
- The low of the input connector and the guard and the ground terminals of the transfer standard were connected to common ground in order to maintain a defined calibration condition. The ground terminal was connected to the guard terminal directly.
- The ground terminal of the Fluke 792A was connected to its guard terminal.
- During the measurements, the traveling standard was supplied by the traveling battery pack. The battery pack was disconnected from the mains during measurements.
- After power on or changing the range, minimum 15 minutes were allowed for stabilisation.

6. AC-DC TRANSFER SYSTEM of UME for LOW VOLTAGES

AC-DC transfer measurement system of UME for low voltages (<100mV) is based on micropotentiometers (µPOT) and Fluke 792A thermal transfer standard (TTS). Micropotentiometers are considered as voltage level independent devices and they are used to calibrate 220mV and 22mV ranges of the TTS in a step-down procedure. First of all, TTS is calibrated at 100mV by using a multi-junction thermal voltage converter (MJTVC), then, TTS is used to calibrate a proper µPOT at 100mV. After wards, the same µPOT is used to calibrate lower voltage of the same TTS range. This procedure is repeated for all other voltage points down to 2mV. Loading effect of the TTS is not considered; instead, second TTS is used to link 220mV and 22mV ranges of the test TTS (Filipski, Rinfet, "Calibration of a Low Voltage AC-DC Transfer Standard", IEEE Trans. Instrum. Meas. Vol. 47 pp. 1067, October 1998). Measurements steps of the step-down procedure are shown in below:



TVC, which is used to calibrate 100 mV voltage of TTS is a 1V planar multi-junction TVC calibrated by PTB as part of a group of several converters in range of 1V-3 V. This group forms primary basis of the step-up and step-down procedures in UME. µPOTs used in calibration are combination of the Ballantine 1251 model thermal housing and 1351 model disk resistors. Values and usable voltage ranges of all combinations available at UME are shown in table:

Resistor \ Housing	5 mA	10 mA	15 mA
0.58 Ω	0.9 mV – 3.5 mV	2 mV – 7.5 mV	2.7 mV – 10 mV
0.92 Ω	1.6 mV – 6 mV	4 mV – 12 mV	5 mV – 18 mV
2.18 Ω	4 mV – 13 mV	8 mV – 28 mV	12 mV – 39 mV
4.70 Ω	8 mV – 30 mV	18 mV – 60 mV	25 mV – 90 mV
6.85 Ω	12 mV – 43 mV	25 mV – 85 mV	40 mV – 130 mV
9.00 Ω	15 mV – 60 mV	35 mV – 120 mV	45 mV – 160 mV
21.00 Ω	40 mV – 140 mV	75 mV – 270 mV	120 mV – 400 mV

7. MEASUREMENT SET-UP of UME

Two different measurement set-ups were used for the measurements of 100 mV and 10 mV. Low voltage limit of the planar MJTVCs (90 Ω heater), which is PTB design, is 100 mV and the planar MJTVC is used to calibrate TTSs at this voltage by direct comparison. Measurement set-up is a two-channel TVC comparator, shown in Figure 1.

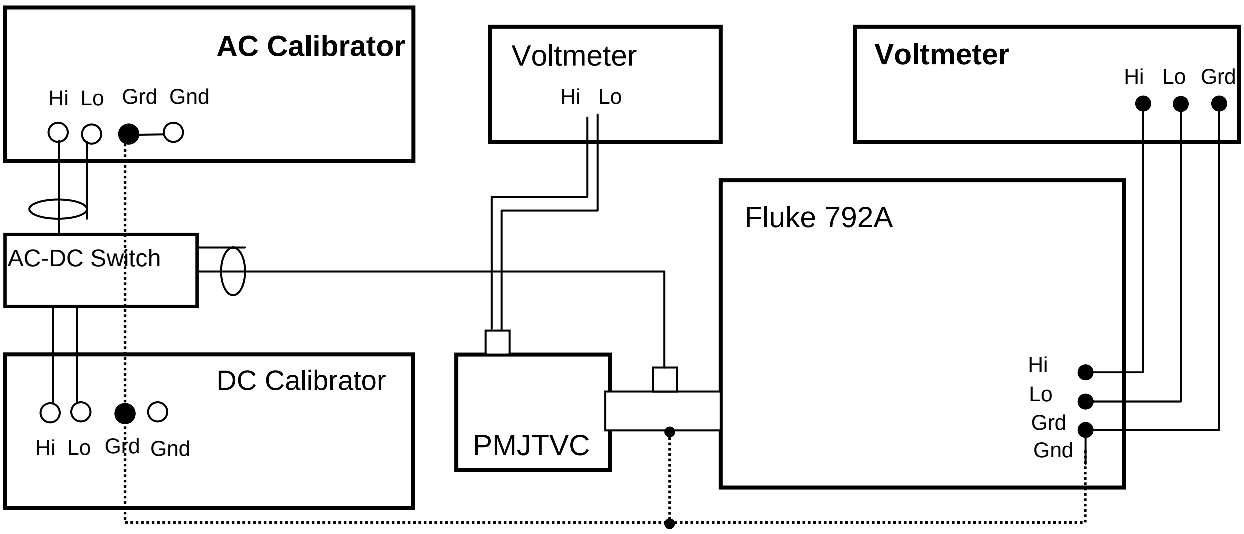


Figure 1. Measurement set-up for 100 mV measurements

For 10 mV, measurement system shown in figure 2 is used. Calibrators are operated in voltage mode; an external resistor is connected between switch and µPOT to drive calibrators in 10V range. Preliminary operation includes determination of the working point at the 792A and voltage to be applied from calibrator and sensitivity of the µPOT and 792A.

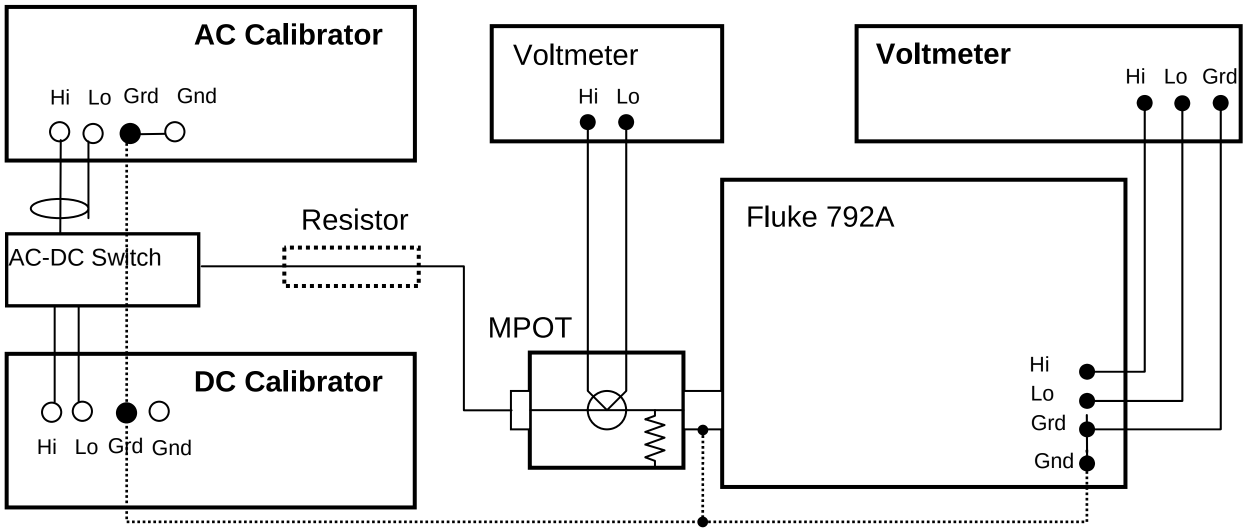


Figure 2. Measurement set-up for 10 mV measurements

8. MEASUREMENT METHOD

For 100 mV measurements, measurement procedure begins with warming up and determination of the sensitivity coefficients of the TVCs at working voltage. Then, ac and dc voltages, adjusted to produce the same (within 50 ppm tolerance) output of MJTVC are applied in dc-, ac, dc+ sequence.

For 10 mV measurements, ac and dc voltages adjusted to produce the same (within 50 ppm tolerance) output of the µPOT are applied to the µPOT input in dc-, ac, dc+ sequence.

AC-DC difference of the test device is calculated by using formula bellow:

$$\delta_t = \delta_s + \frac{V_{dcs} - V_{acs}}{n_s \cdot V_{dcs}} - \frac{V_{dct} - V_{act}}{n_t \cdot V_{dct}}$$

Where, indices “s” and “t” are related to the reference standard and test standard respectively. System is operated by a home-made software via a computer.

9. MEASUREMENT RESULTS

Voltage	Range	Measured ac-dc voltage difference / 10^{-6} at frequency			
		1 kHz	20 kHz	100 kHz	1 MHz
100 mV	220 mV	**8**	**-2**	**12**	**25**
10 mV	22 mV	**14**	**0**	**-32**	**-160**

Measuring frequency:

	Nominal frequency			
	1 kHz	20 kHz	100 kHz	1 MHz
Measuring frequency	999.965 Hz	19.9993 kHz	99.9965 kHz	999.965 MHz
Expanded uncertainty	35 µHz/Hz	35 µHz/Hz	35 µHz/Hz	35 µHz/Hz

Influence parameters:

	Minimum	Maximum
Ambient temperature / ºC	22.23	23.64
Relative humidity / %	35.1	51.8
Pos. power supply voltage / V	11.098	11.104
Neg. power supply voltage / V	-11.162	-11.167

10. UNCERTAINTY BUDGET

Model Function of the measurement at 100 mV is,

$\delta_t = \delta_{diff} + \delta_{ref} + \delta_{con} + \delta_{sys} + \delta_{level}$

where;

δ_t	AC-DC transfer difference of test transfer standard
δ_{diff}	AC-DC transfer difference between test and reference transfer standard
δ_{ref}	AC-DC transfer difference of reference transfer standard
δ_{con}	AC-DC transfer difference due to the connectors and connections
δ_{sys}	AC-DC transfer difference due to the measurement system
δ_{level}	AC-DC transfer difference due to voltage dependence of the thermal converter

UME Uncertainty Budget for 100mV

Contribution of:	Std. unc. f: 1 kHz	Std. unc. f: 20 kHz	Std. unc. f: 100kHz	Std. unc. f: 1 MHz	Type A or B	Distribution
Reference Standard	1.0	1.0	1.5	15.0	Type B	Normal
Standard Deviation	5.0	5.0	5.0	5.0	Type A	Normal
Repeatability	2.0	3.0	4.0	8.0	Type A	Normal
Measurement System	1.2	1.2	2.9	5.8	Type B	Rectangular
Level Dependency	0.6	0.6	1.2	1.2	Type B	Rectangular
Connectors	0.0	0.0	0.6	1.7	Type B	Rectangular

Standard unc (k=1):	5.6	6.1	7.3	18.8
Expanded unc:	**13**	**14**	**16**	**40**
Eff. deg. of freedom:	11	13	21	23

Step-down procedure uncertainty

Model Function is,

$\delta_x = \delta_{diff} + \delta_{ref} + \delta_{sys} + \delta_{con} + \delta_{step} + \delta_{eqp}$.

where;

δ_x	AC-DC transfer difference of test transfer standard
δ_{diff}	AC-DC transfer difference between test and reference transfer standard
δ_{ref}	AC-DC transfer difference of reference transfer standard
δ_{sys}	AC-DC transfer difference due to the measurement system
δ_{step}	AC-DC transfer difference caused by the use of µPOT in step-down
δ_{eqp}	AC-DC transfer difference caused by use of different µPOT&792A in step-down

Uncertainty Budget for 50mV

Contribution of:	Std. unc. f: 1 kHz	Std. unc. f: 20 kHz	Std. unc. f: 100 kHz	Std. unc. f: 1 MHz	Type A or B	Distribution
Reference Standard	6.5	7.0	8.0	20.0	Type B	Normal
Standard Deviation	3.0	2.0	2.0	4.0	Type A	Normal
System	1.2	1.2	2.9	5.8	Type B	Rectangular
Step	2.3	2.3	2.9	5.8	Type B	Rectangular
Equipment	1.7	1.7	2.3	8.7	Type B	Rectangular

Standard unc (k=1):	7.8	7.9	9.5	23.6
Expanded unc:	**17**	**18**	**21**	**52**
Eff. deg. of freedom:	18	15	18	18

Uncertainty Budget for 20mV

Contribution of:	Std. unc. f: 1 kHz	Std. unc. f: 20 kHz	Std. unc. f: 100 kHz	Std. unc. f: 1 MHz	Type A or B	Distribution
Reference Standard	8.5	9.0	10.5	26.0	Type B	Normal
Standard Deviation	5.0	5.0	5.0	5.0	Type A	Normal
System	1.2	1.2	2.9	5.8	Type B	Rectangular
Step	2.3	2.3	2.9	5.8	Type B	Rectangular
Equipment	4.6	4.6	4.6	8.7	Type B	Rectangular

Standard unc (k=1):	11.2	11.6	13.2	29.1
Expanded unc:	**25**	**26**	**29**	**67**
Eff. deg. of freedom:	17	16	15	11

Uncertainty Budget for 20 mV (22 mV Range)

Contribution of:	Std. unc. f: 1 kHz	Std. unc. f: 20 kHz	Std. unc. f: 100 kHz	Std. unc. f: 1 MHz	Type A or B	Distribution
Reference Standard	12.5	13.0	14.5	33.5	Type B	Normal
Standard Deviation	8.0	5.0	8.0	8.0	Type A	Normal
System	1.2	1.2	2.9	5.8	Type B	Rectangular
Step (792A)	5.8	5.8	5.8	8.7	Type B	Rectangular
Equipment	4.6	4.6	4.6	8.7	Type B	Rectangular

Standard unc (k=1):	16.6	15.8	18.4	37.0
Expanded unc:	**36**	**35**	**41**	**85**
Eff. deg. of freedom:	17	13	15	10

Uncertainty Budget for 10mV

Contribution of:	Std. unc. f: 1 kHz	Std. unc. f: 20 kHz	Std. unc. f: 100 kHz	Std. unc. f: 1 MHz	Type A or B	Distribution
Reference Standard	18.0	17.5	20.5	42.5	Type B	Normal
Standard Deviation	9.0	9.0	10.0	11.0	Type A	Normal
System	1.2	1.2	2.9	5.8	Type B	Rectangular
Step	5.8	5.8	5.8	11.6	Type B	Rectangular
Equipment	5.8	5.8	5.8	14.5	Type B	Rectangular

Standard unc (k=1):	21.8	21.4	24.4	48.0
Expanded unc:	**47**	**47**	**54**	**109**
Eff. deg. of freedom:	**14**	**14**	**13**	**11**

Appendix 1. Summary of results

Key comparison EUROMET.EM-K11 "ac-dc voltage transfer difference at low voltages"

Acronym of institute: **UME**

Date of measurements: **26.01.2007–22.02.2007**

Remarks:

Measuring result:

Voltage	Range	Measured ac-dc voltage difference / 10^{-6} at frequency			
		1 kHz	20 kHz	100 kHz	1 MHz
100 mV	220 mV	**8**	**-2**	**12**	**25**
10 mV	22 mV	**14**	**0**	**-32**	**-160**

Expanded uncertainty:

Voltage	Range	Expanded uncertainty / 10^{-6} at frequency			
		1 kHz	20 kHz	100 kHz	1 MHz
100 mV	220 mV	**13**	**14**	**16**	**40**
10 mV	22 mV	**47**	**47**	**54**	**109**

Measuring frequency:

	Nominal frequency			
	1 kHz	20 kHz	100 kHz	1 MHz
Measuring frequency	999.965 Hz	19.9993 kHz	99.9965 kHz	999.965 MHz
Expanded uncertainty	35 µHz/Hz	35 µHz/Hz	35 µHz/Hz	35 µHz/Hz

Influence parameters:

	Min	Max
Ambient temperature / ºC	22.23	23.64
Relative humidity / %	35.1	51.8
Pos. power supply voltage / V	11.098	11.104
Neg. power supply voltage / V	-11.162	-11.167

Appendix 2. Summary of uncertainty budget

Key comparison EUROMET.EM-K11 “ac-dc voltage transfer difference at low voltages”

Acronym of institute: **UME**

Date of measurements: **26.01.2007 – 22.02.2007**

Remarks:

Measuring voltage: **100 mV**

Contribution of:	Std. unc. f: 1 kHz	Std. unc. f: 20 kHz	Std. unc. f: 100kHz	Std. unc. f: 1 MHz	Type A or B	Distribution
Reference Standard	1.0	1.0	1.5	15.0	Type B	Normal
Standard Deviation	5.0	5.0	5.0	5.0	Type A	Normal
Repeatability	2.0	3.0	4.0	8.0	Type A	Normal
Measurement System	1.2	1.2	2.9	5.8	Type B	Rectangular
Level Dependency	0.6	0.6	1.2	1.2	Type B	Rectangular
Connectors	0.0	0.0	0.6	1.7	Type B	Rectangular

Standard unc (k=1):	5.6	6.1	7.3	18.8
Expanded unc:	**13**	**14**	**16**	**40**
Eff. deg. of freedom:	11	13	21	23

Measuring voltage: **10 mV**

Contribution of:	Std. unc. f: 1 kHz	Std. unc. f: 20 kHz	Std. unc. f: 100 kHz	Std. unc. f: 1 MHz	Type A or B	Distribution
Reference Standard	18.0	17.5	20.5	42.5	Type B	Normal
Standard Deviation	9.0	9.0	10.0	11.0	Type A	Normal
System	1.2	1.2	2.9	5.8	Type B	Rectangular
Step	5.8	5.8	5.8	11.6	Type B	Rectangular
Equipment	5.8	5.8	5.8	14.5	Type B	Rectangular

Standard unc (k=1):	21.8	21.4	24.4	48.0
Expanded unc:	**47**	**47**	**54**	**109**
Eff. deg. of freedom:	**14**	**14**	**13**	**11**

NML-07-0088

Report on Measurements performed for the EUROMET.EM-K11 comparison

May 2007

EL Marais

Approval Sheet

Prepared for	CSIR National Metrology Laboratory		
Contract (Project)	NMSEM06 0800 088EM ENMS		
		Signature	**Date**
Prepared by	EL Marais		2007-05-04
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CONTENTS

APPENDIXES

1. INTRODUCTION

The CSIR National Metrology Laboratory (CSIR NML) opted to participate in the EUROMET.EM-K11 AC-DC Difference at Low Voltages comparison [1]. The CSIR NML performed the measurements for this comparison from 5 to 19 March 2007.

This report complements certificate number DCLF\U-1737, and contains additional information on the measurements and the uncertainty analysis.

The CSIR NML became a separate entity known as the National Metrology Institute of South Africa (NMISA) on 1 May 2007. The formation of the NMISA was promulgated by the State President on 26 April 2007 in terms of section 29 of the Measurement Units and Measurement Standards Act, 2006 (Act No. 18 of 2006).

2. TRAVEL ARRANGEMENTS

The travelling standard, a Fluke 792A ac-dc transfer standard, serial number 549 5003, was received from the Turkish national metrology institute (UME) by the CSIR import office on 2 March 2007.

After finalising the measurements, the travelling standard was returned to Sweden. It was delivered to the CSIR export office on 20 March 2007, and was received at SP on 27 March 2007.

3. REFERENCE STANDARD AND EQUIPMENT USED

The reference standard used for the comparison was a Holt model 12 low-voltage thermal voltage converter (LVTVC), serial number 0943500001458 (figure 1). This device was calibrated at the National Institute of Standards and Technology (NIST), USA in 2004 [2].

The Holt Model 12 is a micropotentiometer with an input voltage of 10 V, and 7 outputs of 200 mV, 100 mV, 50 mV, 20 mV, 10 mV, 5 mV, and 2 mV respectively. The NIST certified ac-dc differences of the micropotentiometer were used as the CSIR NML reference values for this comparison.

The comparison was performed using one of the two ac-dc difference measurement setups of the CSIR NML (figure 2). The measurement system consists of the following equipment:

- Fluke 5720A calibrator, serial number 6700201, used as the ac voltage source;
- Wavetek 4808 calibrator, serial number 36398, used as the dc voltage source;
- Keithley 182 nanovoltmeter, serial number 0685931, used to measure the reference standard output;

- Keithley 182 nanovoltmeter, serial number 0685929, used to measure the unit under test output;
- Automated switch to select either of the sources; and
- Computer with measurement software.

Figure 1: Holt model 12 low-voltage thermal transfer standard (LVTVC).

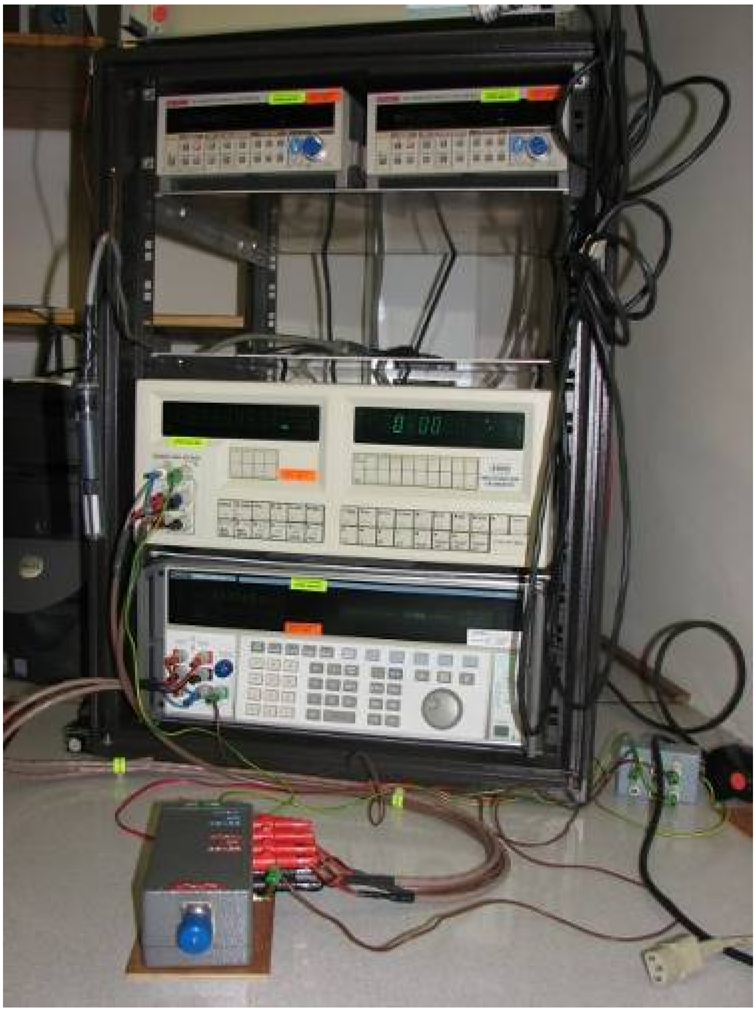

Figure 2: CSIR NML ac-dc difference measurement setup.

4. MEASUREMENT METHOD

Before the start of the comparison measurements, the frequency accuracy of the Fluke 5720A calibrator was determined by generating a 2,5 V signal at each of the comparison frequencies and measuring the output of the calibrator with an Agilent 53151A, serial number MY40006525 frequency counter, referenced to the South African National Standard for time and frequency. The measurements were performed for a high input impedance and a 50 Ohm input impedance. No significant difference in the frequencies was found. The frequency measurement setup is shown in figure 3.

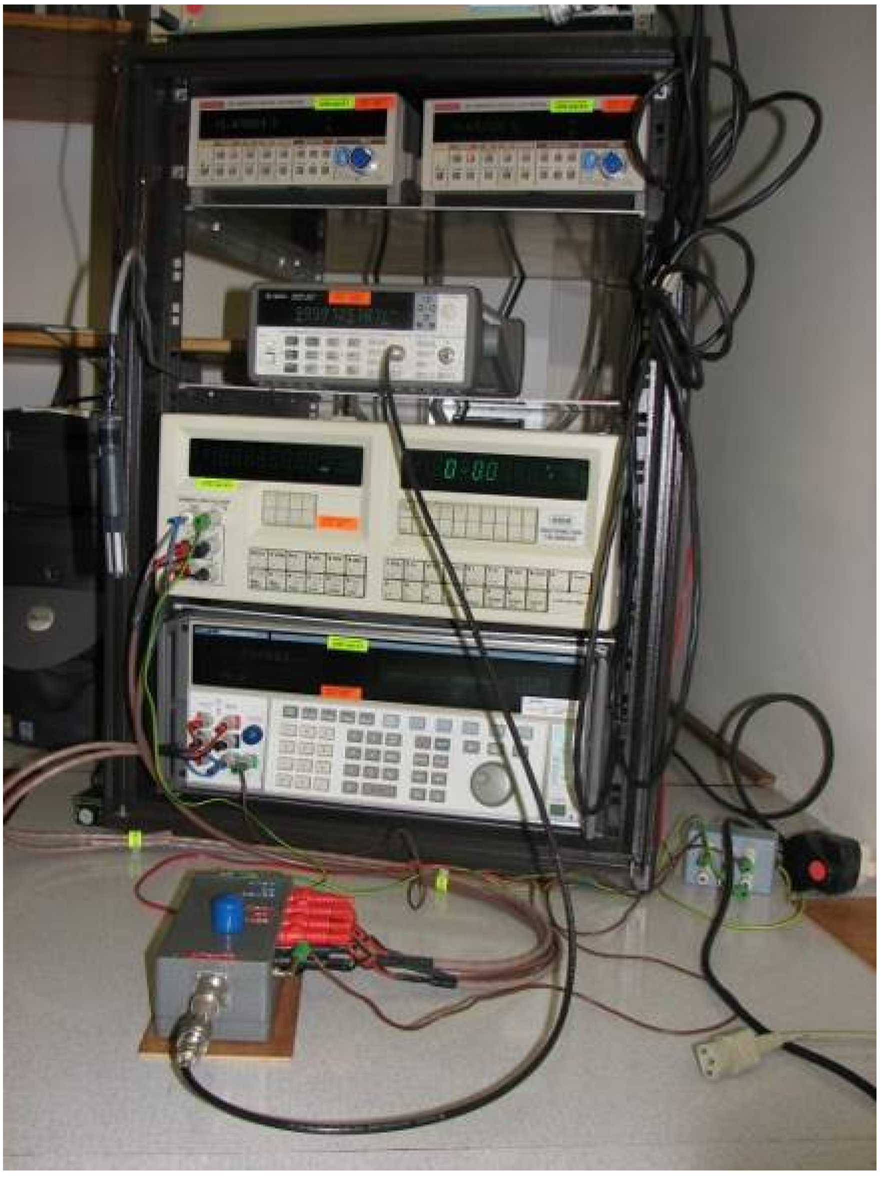

Figure 3: Frequency accuracy measurement setup.

In order to make corrections for the change in the input impedance of the travelling standard, the input impedance of the travelling standard was determined for an input of 10 mV and 100 mV at each of the frequencies of interest. This was done using a low impedance ac source, consisting of a calibrator and a 100:1 resistive voltage divider, and a 50 Ohm load in line with the travelling standard input, as described in [3] (figure 4a, and b).

a. b.

Figure 4: a. Resistive divider detail, and b. Setup to determine input impedance.

To measure the ac-dc difference of the comparison artefact, the LVTVC input was connected to the output of the automated switch. The travelling standard input was connected to either the 10 mV or 100 mV output of the LVTVC. A 10 V ac signal at the frequency of interest was applied to the LVTVC, and the equivalent average dc was found. The LVTVC is operated with a zero ac-dc difference at its Thermal Voltage Converter (TVC) output. The ac-dc difference measurement setup is shown in figure 5.

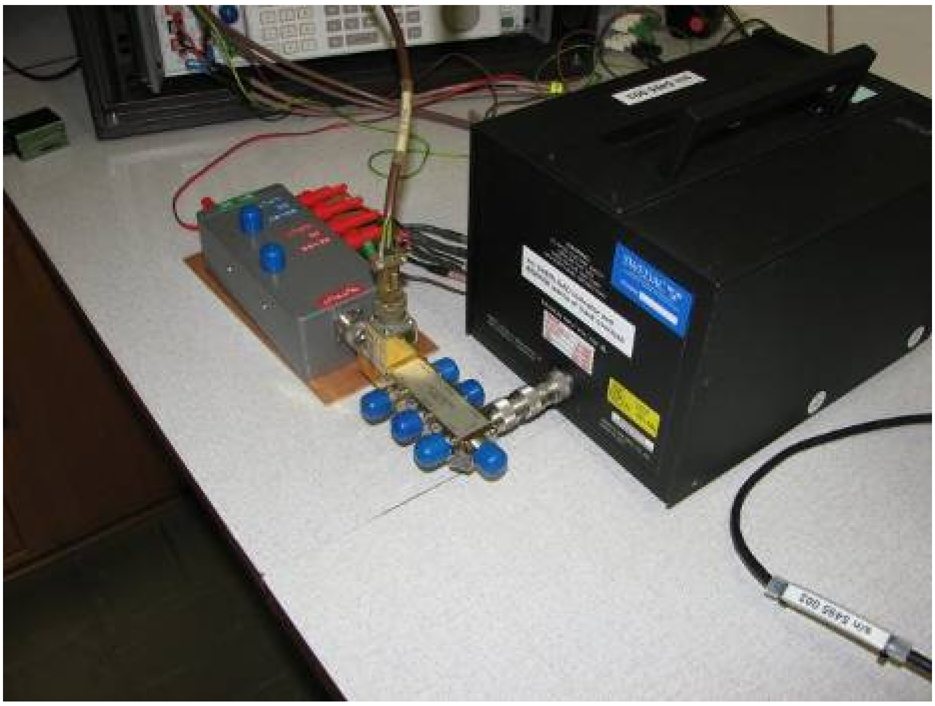

Figure 5: ac-dc difference measurement setup (for 10 mV measurement).

A measurement sequence required about 8 hours to complete. The travelling standard power supply levels were measured at the start and end of each cycle as required in the protocol. The environmental conditions (temperature, humidity and pressure) were measured and recorded throughout the comparison. After each travelling standard measurement, the measurement sequence was repeated using the CSIR NML Fluke model 792A ac-dc transfer standard, as a confidence check on the measurement process.

5. MATHEMATICAL MODEL

The ac-dc voltage transfer difference δ of the travelling standard is defined as:

$$\delta = \frac{V_{ac} - V_{dc}}{V_{dc}} \qquad \text{..........} (1)$$

where

V_{ac} is the root-mean-square (rms) value of the ac input voltage, and
V_{dc} is the average dc input voltage producing the same mean output voltage of the transfer standard as V_{ac}.

The ac-dc difference of the travelling standard is computed by summing a number of ac-dc difference components:

$$\delta_x = \delta_{meas} + \delta_{std} + \delta_{freq} + \delta_{temp} + \delta_{hum} + \varepsilon_{con} \qquad \text{..........} (2)$$

where

δ_x is the ac-dc difference of the travelling standard,
δ_{meas} is the measured ac-dc difference of the travelling standard,
δ_{std} is the certified ac-dc difference of the LVTVC,
δ_{freq} is the calculated frequency correction due to the travelling standard input impedance,
δ_{temp} is the correction due to the temperature deviation from 23 °C,
δ_{hum} is the correction due to the humidity deviation from 45 %RH, and
ε_{con} is the error due to connectors and cables.

6. UNCERTAINTY EVALUATION

Each of the contributors to the uncertainty was evaluated, and the combined standard uncertainty calculated. The effective degrees of freedom were calculated and the coverage factor determined for an approximate 95% level of confidence. The expanded uncertainty was calculated by multiplying the combined standard uncertainty with the coverage factor.

6.1 Uncertainty due to repeated ac-dc difference determinations

The uncertainty due to repeated ac-dc difference measurements of the travelling standard was determined by combining the within run repeatability and between run repeatability of the measurements. The degrees of freedom of this component were taken as one less than the number of repeated measurements. The measured values are shown in paragraph 7.

6.2 Uncertainty due to the certified value of the reference standard

The uncertainty due to the certified value of the reference standard was taken from the calibration certificate of the reference standard. It is treated as a normal distribution at a level of confidence of approximately 95% and with infinite degrees of freedom. The standard uncertainty was obtained by dividing the reported expanded uncertainty by two.

6.3 Uncertainty due to the calculated frequency correction of the travelling standard

The uncertainty for the calculated frequency correction of the travelling standard was found by calculating the worst case limits of the corrections. This was done by varying the component values used in the determination by its specification, and assigning a rectangular distribution for the possible values of the corrections. The calculated values are reported in paragraph 7.

6.4 Uncertainty due to the temperature correction of the travelling standard

The protocol gives the temperature correction and its uncertainty at each comparison frequency. The average, minimum and maximum temperature during the comparison was recorded. The correction was determined by multiplying the difference between the average temperature and the comparison temperature with the provided correction factors. The uncertainty was found by multiplying the uncertainty of the correction factor with the difference between the maximum and minimum recorded temperature, treated as a rectangular distribution. Infinite degrees of freedom were assigned to this component.

6.5 Uncertainty due to the humidity correction of the travelling standard

The protocol gives the humidity correction and its uncertainty at each comparison frequency. The average, minimum and maximum humidity during the comparison was recorded. The correction was determined by multiplying the difference between the average humidity and the comparison humidity with the provided correction factors. The uncertainty was found by multiplying the uncertainty of the correction factor with the difference between the maximum and minimum recorded humidity, treated as a rectangular distribution. Infinite degrees of freedom were assigned to this component.

6.6 Uncertainty due to connectors and cables

The uncertainty due to connectors and cables was deemed to be adequately captured within the variability of repeated ac/dc difference determinations of the travelling standard, as the measurement setup was completely disassembled, and reassembled for each determination. Therefore no additional uncertainty component is calculated for the uncertainty due to connectors and cables, and no correction is applied.

7. RESULTS

7.1 Environmental measurements

The environment in the laboratory, at the point of measurement, was recorded during the comparison. Temperature, humidity and ambient pressure were recorded, and the average, minimum and maximum of each of these are reported in table 7.1.

Table 7.1: Environmental conditions during the comparison.

	Temperature (°C)	Humidity (%RH)	Ambient pressure (mbar)
Average	23,2	49,5	865,33
Maximum	24,1	64,8	872,88
Minimum	22,8	35,1	858,85

The temperature and humidity were recorded using a Rotronic Hygroclip sensor serial number 28012189 and a digital readout unit, and the ambient pressure was recorded using a Druck DPI 142 ambient pressure monitor serial number 1422505057. The environmental parameters were recorded at 5 second intervals, and logged to text files.

7.2 Frequency measurements

The frequency accuracy of the calibrator used to generate the ac voltage signal was evaluated at each of the frequency points used in the comparison. The setup used is shown in figure 3 (see paragraph 4).

At each frequency, a set of 500 measurements were taken, with the counter gate time set to 1 second. The average value of this set of measurements is reported as the frequency of the calibrator. The uncertainty of measurement of the frequency point is determined from the following components: The specification of the time base, the resolution of the counter, and the repeatability of the measurement.

The counter was referenced to the South African national standard for time and frequency, a Hewlett-Packard model 5071A Caesium beam atomic clock. The clock signal is distributed to laboratories requiring accurate frequencies by the Time and Frequency laboratory. In the dc Low Frequency laboratory, a distribution amplifier distributes this signal to the ac-dc Difference laboratory.

The 1 second specification ($5{,}6 \cdot 10^{-11}$) of the Caesium clock is used as the uncertainty contributor for the time base, and is treated as a rectangular distribution with infinite degrees of freedom.

The resolution of the measurement is taken as 1 least significant digit in the indicated frequency, and is treated as a rectangular distribution with infinite degrees of freedom.

The Type A contribution is obtained from the Overlapping Allan deviation, $\sigma_y(\tau)$, of the data set for an integration time of 1 second.

The average frequencies obtained, and their uncertainties are shown below in table 7.2. Please note that the uncertainties shown in the table are standard uncertainties, in units of frequency (Hz).

Table 7.2: Frequency accuracy and uncertainty of the ac calibrator.

Contributor	**1 kHz**	**20 kHz**	**100 kHz**	**1 MHz**
Time base	$1{,}62\cdot10^{-8}$	$3{,}23\cdot10^{-7}$	$1{,}62\cdot10^{-6}$	$1{,}62\cdot10^{-5}$
Resolution	$2{,}89\cdot10^{-8}$	$2{,}89\cdot10^{-6}$	$2{,}89\cdot10^{-6}$	$2{,}89\cdot10^{-5}$
Type A	$1{,}05\cdot10^{-5}$	$1{,}60\cdot10^{-4}$	$5{,}78\cdot10^{-4}$	$2{,}97\cdot10^{-2}$
$u_c(y)$	$1{,}053\cdot10^{-5}$	$1{,}601\cdot10^{-4}$	$5{,}780\cdot10^{-4}$	$2{,}975\cdot10^{-2}$
υ_{eff}	499	499	499	499
$t_{95}(\upsilon)$	1,965	1,965	1,965	1,965
U	$2{,}07\cdot10^{-5}$	$3{,}15\cdot10^{-4}$	$1{,}14\cdot10^{-3}$	$5{,}85\cdot10^{-2}$
Frequency (Hz)	999,972 593 5	19 999,452 11	99 997,260 5	999 972,595
Uncertainty (Hz)	0,000 002 1	0,000 32	0,001 2	0,059

7.2 Travelling standard input impedance

The travelling standard input impedance was evaluated at each voltage level and each of the comparison frequencies using the setup shown in figure 4b (refer to paragraph 4).

A schematic representation of the measurement setup is shown in figure 6.

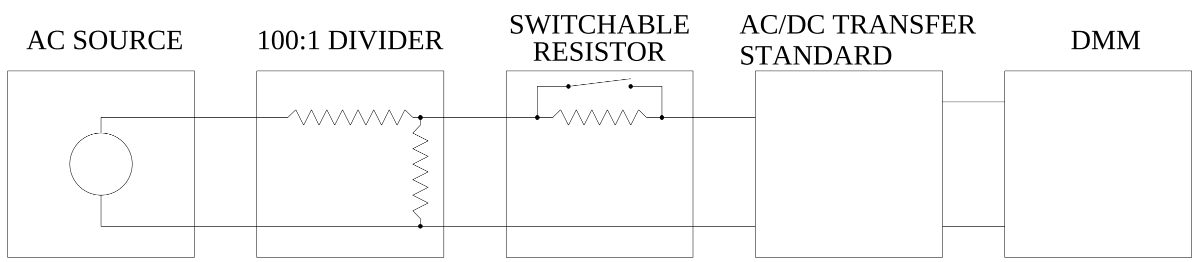

Figure 6: Input impedance measurement setup.

The AC source and the 100:1 resistive divider form a low impedance source (nominal 1 Ohm output impedance). This low impedance source is used to determine the input impedance of the AC/DC transfer standard.

The measurement was performed by applying either a 10 V (for the 100 mV measurement), or a 1 V (for the 10 mV measurement) signal at the frequency of interest to the resistive divider, and then switching the resistor (with a nominal value of 51 Ohm) into the circuit, and observing the change in the ac/dc transfer standard output. The difference in the AC/DC transfer standard output was used to calculate the input impedance of the transfer standard, using equation 3. For an explanation of the symbols used in this equation, refer to figure 7.

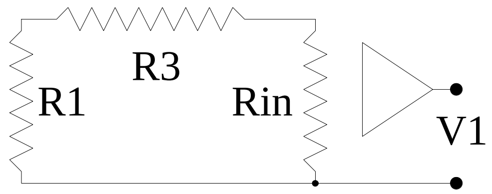

Figure 7: Equivalent circuit for determining AC/DC transfer standard input impedance

$$R_{IN} = \frac{V_1'(R_1 + R_3) - V_1 R_1}{V_1 - V_1'} \quad \text{.........} (3)$$

where
- R_1 is the low impedance source output impedance (1 Ohm);
- R_3 is the switchable resistor (51 Ohm);
- R_{IN} is the input impedance of the AC/DC transfer standard;
- V_1 is the AC/DC transfer standard output with R3 short-circuited; and
- V_1' is the AC/DC transfer standard output with R3 in circuit.

The calculated values of the travelling standard input impedances are reported in table 7.3.

Table 7.3: Travelling standard input impedances.

Frequency (Hz)	**Input impedance (Ohm)**	
	100 mV	**10 mV**
1 000	9 359 225	10 060 654
20 000	4 205 593	4 129 117
100 000	3 627 568	2 581 827
1 000 000	123 138	219 430

The calculated input impedance was subsequently used to calculate the effective source impedance when using the micropot to provide the signal to the travelling standard. The nominal micropot source impedance is 20 Ohm when sourcing 100 mV and 2 Ohm when sourcing 10 mV. The AC/DC transfer standard input impedance reduces the source impedance and the ac signal that appears at the output of the micropot for a zero ac/dc difference at the micropot TVC output is thus lower than the expected value. From this change in output impedance frequency corrections were calculated for each of the output levels and each of the frequencies at which measurements were made. The effective source impedances of the micropot are shown in table 7.4, and the corrections are shown in table 7.5.

The uncertainty of the correction was evaluated by changing the nominal values of R_1 and R_3 in equation 3 by its specification of 5%, and applying a rectangular distribution to the resulting worst case limits. The standard uncertainties are shown in table 7.6.

Table 7.4: Effective micropot output impedances.

Frequency (Hz)	Micropot output impedance (Ohm)	
	100 mV	10 mV
1 000	19,999 957 3	1,999 999 6
20 000	19,999 904 9	1,999 999 0
100 000	19,999 889 7	1,999 998 5
1 000 000	19,996 752 1	1,999 981 8

Table 7.5: Corrections due to travelling standard input impedances.

Frequency (Hz)	Correction (ppm)	
	100 mV	10 mV
1 000	1,9	0,2
20 000	4,5	0,5
100 000	5,3	0,8
1 000 000	160,6	9,1

Table 7.6: Uncertainties of corrections due to travelling standard input impedances.

Frequency (Hz)	Standard uncertainty (ppm)	
	100 mV	10 mV
1 000	0,07	0,01
20 000	0,14	0,02
100 000	0,17	0,02
1 000 000	4,89	0,28

7.4 Travelling standard power supply levels

The protocol states that the power supply levels must be measured before and after each measurement. The measurements were done using the enclosed power supply measuring device, and a HP 3458A digital multimeter, serial number 2823A18742. After connection of the measurement device, the voltage levels were allowed to stabilise before the value was recorded. These measurement results are shown in table 7.7.

Table 7.7: Travelling standard power supply levels.

Date	Before measurement (V)		After measurement (V)	
	V_{pos}	V_{neg}	V_{pos}	V_{neg}
2007-03-06	11,101 2	- 11,165 9	11,098 0	- 11,162 1
2007-03-07	11,100 7	- 11,165 1	11,096 3	- 11,160 1
2007-03-08	11,100 3	- 11,164 8	11,096 2	- 11,159 7
2007-03-09	11,100 3	- 11,164 7	11,095 4	- 11,159 6
2007-03-10	11,100 2	- 11,164 7	11,096 2	- 11,160 3
2007-03-11	11,100 3	- 11,164 7	11,095 1	- 11,159 1
2007-03-12	11,100 0	- 11,164 5	11,096 4	- 11,160 6
2007-03-13	11,100 4	- 11,164 8	11,095 4	- 11,159 5
2007-03-14	11,100 5	- 11,164 8	11,096 3	- 11,160 5
2007-03-15	11,100 5	- 11,164 9	11,095 4	- 11,159 7
2007-03-16	11,100 6	- 11,164 9	11,096 4	- 11,160 7
2007-03-17	11,100 3	- 11,164 8	11,094 3	- 11,158 4
2007-03-18	11,100 0	- 11,164 4	11,095 4	- 11,159 5
2007-03-19	11,099 9	- 11,164 5	11,095 0	- 11,158 6

During the comparison, the maximum level for the positive supply was 11,101 2 V, and the minimum was 11,094 3 V. The maximum level of the negative supply was - 11,158 4 V, and the minimum level was - 11,165 9 V.

7.5 Travelling standard ac-dc differences

7.5.1 100 mV

The ac/dc difference of the travelling standard was measured seven times during the comparison at each of the frequencies. For one of these measurements, the grounding of the travelling standard was not done according to the protocol, and this measurement was discarded. The measured values, corrections and uncertainties are shown in table 7.8. All ac/dc difference values in the table are stated in ppm.

Table 7.8: Measurement result for 100 mV, with ac/dc differences stated in ppm.

Date	**Frequency**			
	1 kHz	**20 kHz**	**100 kHz**	**1 MHz**
2007-03-08	18,7	2	3,9	- 346,7
2007-03-10	17,3	0,5	2,8	- 285,3
2007-03-12	18,3	0	3,5	- 290,5
2007-03-14	20,3	0,5	2,1	- 234,8
2007-03-16	18,9	3,1	2,1	- 242,2
2007-03-18	20,1	0,6	3,5	- 265,2
Averages	18,9	1,1	3,0	- 277,5
Certified ac-dc difference	- 7	- 6	23	367
Frequency correction	1,9	4,5	5,3	160,6
Temperature correction	- 0,1	- 0,1	- 0,1	- 2,2
Humidity correction	0,0	0,0	- 0,5	- 5,9
UUT ac-dc difference	13,8	- 0,5	30,7	242,1
Certified ac-dc difference unc	8,0	7,5	17,5	85,0
Frequency correction unc	0,07	0,14	0,17	4,89
Temperature correction unc	0,21	0,21	0,21	0,83
Humidity correction unc	0,10	0,25	0,49	2,47
Type A unc	3,8	4,8	3,1	41,0
$u_c(y)$	8,9	8,9	17,8	94,5
υ_{eff}	144,3	58,7	5397,4	141,1
$t_{95}(\upsilon)$	1,977	2,002	1,960	1,977
U	17,5	17,9	34,9	186,9

7.5.2 10 mV

The ac/dc difference of the travelling standard was measured seven times during the comparison at each of the frequencies. For one of these measurements the calculated ac/dc differences were significantly different from the other measurements, and this measurement was discarded. The reason for the observed differences is thought to be due to connectors not being thoroughly tightened. In another measurement, both nanovolt meters jumped to its highest range half-way through the measurement. The reason for this is not clear. In another determination the mains cable was left connected to the power supply of the travelling standard. This measurement was also discarded. The measured values, corrections and uncertainties are shown in table 7.9. All ac/dc difference values in the table are stated in ppm.

Table 7.9: Measurement result for 10 mV, with ac/dc differences stated in ppm.

Date	Frequency			
	1 kHz	20 kHz	100 kHz	1 MHz
2007-03-07	3,8	- 17,1	- 163,0	- 1 971,2
2007-03-11			- 163,1	- 2 087,7
2007-03-13	- 4,9	- 24,7	- 167,1	- 2 475,9
2007-03-17	11,5	- 25,9	- 161,8	- 1 783,1
2007-03-19	7,1	- 23,8	- 166,9	- 1 871,4
Averages	4,4	- 22,9	- 164,4	- 2 037,9
Certified ac-dc difference	- 2,0	33,0	154,0	1 348,0
Frequency correction	0,2	0,5	0,8	9,1
Temperature correction	- 0,3	- 0,3	- 0,3	- 3,8
Humidity correction	0,0	0,0	- 0,5	- 4,1
UUT ac-dc difference	2,3	10,3	- 10,4	- 688,7
Certified ac-dc difference unc	25,5	26,0	68,0	168,5
Frequency correction unc	0,01	0,02	0,02	0,28
Temperature correction unc	0,42	0,42	0,42	1,67
Humidity correction unc	0,10	0,25	0,49	2,47
Type A unc	13,3	11,5	14,0	270,3
$u_c(y)$	28,8	28,4	69,4	318,6
υ_{eff}	65,1	111,5	2 421,1	7,7
$t_{95}(\upsilon)$	1,997	1,982	1,961	2,365
U	57,5	56,4	136,1	753,3

8. CONCLUSION

This was the first low voltage ac measurement performed by the laboratory, and it required a lot of effort to establish the measurement. It is hoped that the result of these measurements are comparable with results from the other participants, and that it can be used to improve the measurement capabilities of the laboratory.

9. REFERENCES

[1] Technical Protocol for the Key Comparison EUROMET.EM-K11 AC-DC Voltage Transfer Difference at Low Voltages, version 10, 2005-09-01.

[2] NIST Test report number 817/270131, reference 8600005715, 7 June, 2004.

[3] N. Faulkner, and B. Stott, “Loading Effects of AC/DC Transfer Standards”, presented at the 1997 National Conference of Standards Laboratories.

Appendix I: Copy of certificate DCLF\U-1737

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National Metrology Institute of South Africa

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Fax: +27 12 841 2131
e-mail: info@nmisa.org
http: www.nmisa.org

Private Bag X34
Lynwood Ridge
0040
South Africa

Certificate of Calibration

Calibration of:	AC/DC TRANSFER STANDARD
Manufacturer:	FLUKE
Model number:	792A
Serial number:	549 5003
Calibrated for:	SP Swedish National Testing and Research Institute Measurement Technology, MTe Box 857, SE-501 15 BORÅS, Sweden
Calibration procedure:	NML-DCLF\MC-0270
Period of calibration:	5 to 19 March 2007

1. PROCEDURE

1.1. The ac/dc difference of the AC/DC Transfer Standard was determined by measuring the relative difference between the alternating voltage required for a given output voltage and the average of the direct voltages in both directions for the same output voltage.

1.2. The ac/dc difference is defined as follows:

$$\delta = \left(\frac{V_{ac} - V_{dc}}{V_{dc}} \right)$$

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

1.3. The reported ac/dc difference values of the AC/DC Transfer Standard have been corrected for loading effect of it's input impedance on the Low Voltage Thermal Voltage Converter (micropotentiometer).

Calibrated by (012-841-3013) E.L. Marais (Approved Signatory) Metrologist	Checked by (012-841-4343) A.M. Matlejoane Metrologist	For Chief Executive Officer
Date of issue 3 May 2007	Page 1 of 3	Certificate number DCLF\U-1737

CALIBRATION OF AC/DC TRANSFER STANDARD

1.4. Standard and equipment used:

DESCRIPTION	MODEL	SERIAL NUMBER
Low Voltage Thermal Voltage Converter	12	0943500001458
Multifunction calibrator	5720A	6700201
Multifunction calibrator	4808	36398
Nanovoltmeter	182	0685931
Nanovoltmeter	182	0685929

2. RESULTS

2.1. AC/DC Differences at 10 mV

Frequency	AC/DC Difference (ppm)	Uncertainty (ppm)
1 kHz	2	58
20 kHz	10	57
100 kHz	- 10	140
1 MHz	- 690	760

2.2. AC/DC Differences at 100 mV

Frequency	AC/DC Difference (ppm)	Uncertainty (ppm)
1 kHz	14	18
20 kHz	-1	18
100 kHz	31	35
1 MHz	240	190

Calibrated by (012-841-3013)	Checked by (012-841-4343)	For Chief Executive Officer
E.L. Marais (Approved Signatory) Metrologist	A.M. Matlejoane Metrologist	
Date of issue 3 May 2007	Page 2 of 3	Certificate number DCLF/U-1737

CALIBRATION OF AC/DC TRANSFER STANDARD

3. REMARKS

3.1. The reported uncertainties of measurement were calculated and expressed in accordance with the BIPM, IEC, ISO, IUPAP, OIML document entitled "A Guide to the Expression of Uncertainty in Measurement" (International Organisation for Standardisation, Geneva, Switzerland, 1993).

3.2. The reported expanded uncertainty of measurement is stated as the standard uncertainty of measurement multiplied by a coverage factor of k=2, which for a normal distribution approximates a level of confidence of 95,45%.

3.3. Certain of the NMISA certificates are consistent with the capabilities that are included in appendix C of the MRA (Mutual Recognition Arrangement) drawn up by the CIPM. Under the MRA, all participating institutes recognise the validity of each other's calibration and measurement certificates for the quantities and ranges and measurement uncertainties specified in Appendix C. For details see http://www.bipm.org.

3.4. The calibrations were carried out at an ambient temperature of 23 °C ± 2 °C and a relative humidity of 50 %RH ± 15 %RH.

3.5. The results of the measurement are traceable to the relevant national measuring standards.

---------- End of Certificate ----------

Calibrated by (012-841-3013) E.L. Marais (Approved Signatory) Metrologist	Checked by (012-841-4343) A.M. Matlejoane Metrologist	For Chief Executive Officer
Date of issue 3 May 2007	Page 3 of 3	Certificate number DCLF\U-1737

Appendix II: Summary of results

Key comparison EUROMET.EM-K11 “ac-dc voltage transfer difference at low voltages”

Acronym of institute: CSIR NML (now NMISA)

Date of measurements: 2007-03-05 to 2007-03-19

Remarks: None

Measuring result:

Voltage	Range	Measured ac-dc voltage difference / 10^{-6} at frequency			
		1 kHz	20 kHz	100 kHz	1 MHz
100 mV	220 mV	13,8	- 0,5	30,7	242,1
10 mV	22 mV	2,3	10,3	- 10,4	- 688,7

Expanded uncertainty:

Voltage	Range	Expanded uncertainty / 10^{-6} at frequency			
		1 kHz	20 kHz	100 kHz	1 MHz
100 mV	220 mV	17,5	17,9	34,9	186,9
10 mV	22 mV	57,5	56,4	136,1	753,3

Measuring frequency:

	Nominal frequency / Hz			
	1 kHz	20 kHz	100 kHz	1 MHz
Measuring frequency	999,972 593 5	19 999,452 11	99 997,260 5	999 972,595
Expanded uncertainty	0,000 002 1	0,000 32	0,001 2	0,059

Influence parameters:

	Min	Max	Remarks
Ambient temperature / ºC	22,8	24,1	
Relative humidity / %	35,1	64,8	
Pos. power supply voltage / V	11,094 3	11,101 2	Please state with mV resolution
Neg. power supply voltage / V	- 11,165 9	- 11,158 4	Please state with mV resolution

Appendix III: Summary of uncertainty budget

Key comparison EUROMET.EM-K11 “ac-dc voltage transfer difference at low voltages”

Acronym of institute: CSIR NML (now NMISA)

Date of measurements: 2007-03-05 to 2007-03-19

Remarks: None

Measuring voltage: 100 mV

Contribution of:	**Std. unc. f: 1 kHz**	**Std. unc. f: 20 kHz**	**Std. unc. f: 100 kHz**	**Std. unc. f: 1 MHz**	**Type A or B**	**Distribution**
Reference standard	8,0	7,5	17,5	85,0	B	Normal
Frequency correction	0,07	0,14	0,17	4,89	B	Rectangular
Temperature correction	0,21	0,21	0,21	0,83	B	Rectangular
Humidity correction	0,10	0,25	0,49	2,47	B	Rectangular
Repeatability	3,8	4,8	3,1	41,0	A	

Standard unc (k=1):	8,9	8,9	17,8	94,5
Expanded unc:	17,5	17,9	34,9	186,9
Eff. deg. of freedom:	144,3	58,7	5 397,4	141,1

Measuring voltage: 10 mV

Contribution of:	**Std. unc. f: 1 kHz**	**Std. unc. f: 20 kHz**	**Std. unc. f: 100 kHz**	**Std. unc. f: 1 MHz**	**Type A or B**	**Distribution**
Reference standard	25,5	26,0	68,0	168,5	B	Normal
Frequency correction	0,01	0,02	0,02	0,28	B	Rectangular
Temperature correction	0,42	0,42	0,42	1,67	B	Rectangular
Humidity correction	0,10	0,25	0,49	2,47	B	Rectangular
Repeatability	13,3	11,5	14,0	270,3	A	

Standard unc (k=1):	28,8	28,4	69,4	318,6
Expanded unc:	57,5	56,4	136,2	753,3
Eff. deg. of freedom:	65,1	111,5	2421,1	7,7

Appendix IV: Detailed uncertainty budget for inclusion in the final report

The detailed uncertainty budget below is given for the measurements at 100 mV and 10 mV at 1 kHz. The summary uncertainty budgets provided in appendix III contains the uncertainties for all frequency points.

Uncertainty budget for 100 mV measurement at 1 kHz

Mathematical model: $\delta_x = \delta_{meas} + \delta_{std} + \delta_{freq} + \delta_{temp} + \delta_{hum}$

Symbol	Input quantity	Estimated value of input quantity	Estimated uncertainty Value	Unit	Type	Probability distribution	Standard uncertainty	Degrees of freedom
δ_{meas}	Measurement repeatability	18,9	3,8	ppm	A	-	3,8	5
δ_{std}	Certified value of reference standard	- 7,0	16,0	ppm	B	Normal	8,0	infinite
δ_{freq}	Frequency correction of travelling standard	1,9	0,12	ppm	B	Rectangular	0,07	infinite
δ_{temp}	Temperature correction of travelling standard	- 0,1	0,36	ppm	B	Rectangular	0,21	infinite
δ_{hum}	Humidity correction of travelling standard	0,0	0,17	ppm	B	Rectangular	0,10	infinite
		Combined standard uncertainty, $u_c(y)$					8,9 ppm	
		Effective degrees of freedom, υ_{eff}					144,3	
		Level of Confidence					95%	
		Coverage factor, $t_{95}(\upsilon)$					1,977	
		Expanded uncertainty, U					17,5 ppm	

Uncertainty budget for 10 mV measurement at 1 kHz

Mathematical model: $\delta_x = \delta_{meas} + \delta_{std} + \delta_{freq} + \delta_{temp} + \delta_{hum}$

Symbol	Input quantity	Estimated value of input quantity	Estimated uncertainty Value	Unit	Type	Probability distribution	Standard uncertainty	Degrees of freedom
δ_{meas}	Measurement repeatability	4,4	13,3	ppm	A	-	13,4	3
δ_{std}	Certified value of reference standard	- 2,0	51,0	ppm	B	Normal	25,5	infinite
δ_{freq}	Frequency correction of travelling standard	0,2	0,02	ppm	B	Rectangular	0,01	infinite
δ_{temp}	Temperature correction of travelling standard	- 0,3	0,73	ppm	B	Rectangular	0,42	infinite
δ_{hum}	Humidity correction of travelling standard	0,0	0,17	ppm	B	Rectangular	0,10	infinite
		Combined standard uncertainty, $u_c(y)$					28,8 ppm	
		Effective degrees of freedom, υ_{eff}					65,1	
		Level of Confidence					95%	
		Coverage factor, $t_{95}(\upsilon)$					1,997	
		Expanded uncertainty, U					57,5 ppm	

Key comparison EUROMET.EM-K11 "AC-DC VOLTAGE TRANSFER DIFFERENCE AT LOW VOLTAGES"

EUROMET project 464

Report of CMI

Content

1. Describing of the Measuring Method

1.1. Traceability chart a the reference standard of CMI

The traceability chart for low AC voltages is on Figure No. 1. For AC-DC difference measurements of low voltages down to 100 mV the PMJTCs are used. Below 100 mV the step-down procedure with μpots is applied.

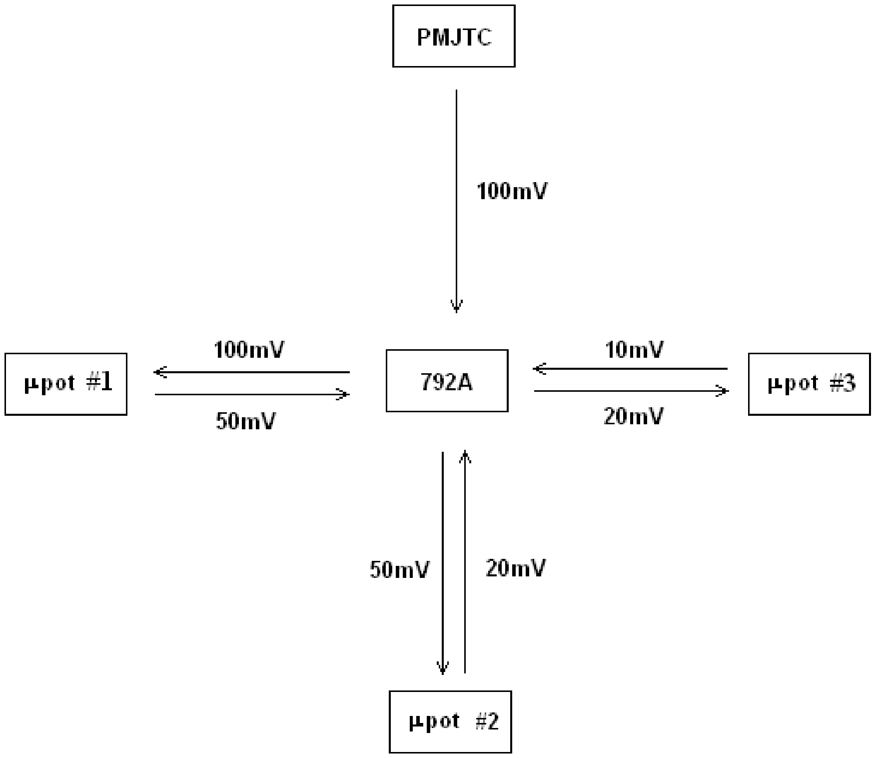

Fig. 1 CMI's traceability chart for low AC voltages

Our reference standard is planar multijunction thermal converter 1V/10mA produced by IPHT Jena, Serial No. 5 PTB/IPHT 1996. Its last calibration was in PTB in 2006.

1.2. AC-DC transfer difference calibration of the FLUKE 792A at 100mV

The reference standard (REF) and the device under test (DUT) are connected in parallel and they are compared (see Fig. 2).

The reference plane for the measurement is in the middle of the T-connector. T-connector is made in CMI; it has input with UHF-twin connector and two outputs with N-connectors. The central point is on the T-connector.

The AC and DC voltages are supplied by AC and DC voltage calibrators and switched by an automatic switch. The switch was made in METAS, Switzerland. For AC voltages lower than 200 mV a coaxial divider is used. Two-channel digital nanovoltmeter is used for measurement of TVCs output voltages (dual-channel method).
The sequence of the measurements is: DC+, AC, DC- with the time delay of 40 second between switching of a AC/DC voltage on the switch and the voltage measurement.

Averaging of the output voltages for dc results in nearly perfect drift compensation is made. Taking the differences of the output voltages at AC and DC for the REF and DUT, the ac-dc difference between the two TVCs δ_{MEAS} is calculated:

$$\delta_{MEAS} = \frac{U_{O\_REF\_AC} - U_{O\_REF\_DC}}{n_{REF} U_{O\_REF\_DC}} - \frac{U_{O\_DUT\_AC} - U_{O\_DUT\_DC}}{n_{DUT} U_{O\_DUT\_DC}}$$

The AC-DC transfer difference of DUT at 100mV δ_{100mV} is got after adding the known ac-dc transfer difference of the standard REF δ_{REF} :

$$\delta_{100mV} = \delta_{MEAS} + \delta_{REF} .$$

Each measurement sequence for one frequency is repeated 10 times and the mean value and standard deviation are calculated.

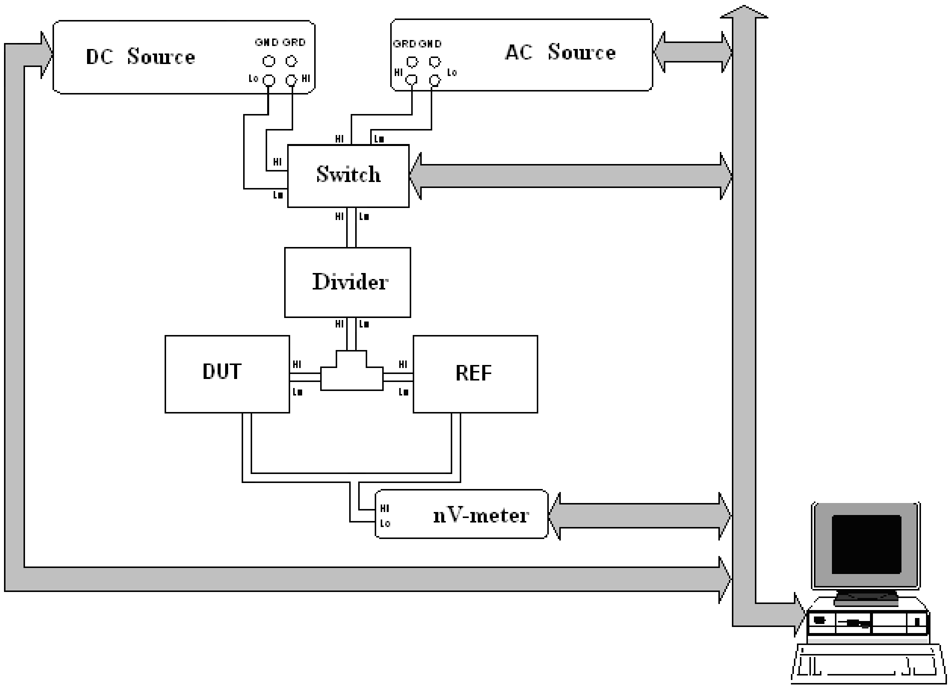

Fig. 2 Measurement system for 100mV

1.3. AC-DC transfer difference calibration of the FLUKE 792A bellow 100mV

Below 100mV the step down procedure with micropots is used for calibration of 792A.The 792A is connected to the output of the micropot (see Fig. 3). Input Lo of 792A is grounded. The central point is on the AC source.

The AC and DC voltages are supplied by AC and DC voltage calibrators and switched by an automatic switch. The switch was made in METAS, Switzerland. Next, a range resistor in series with micropot is used. Two-channel digital nanovoltmeter is used for measurement of TVCs output voltages.

The sequence of the measurements is: DC+, AC, DC- with the time delay of 50 second between switching of AC/DC voltage on the switch and the voltage measurement. Averaging of the output voltages for dc results in nearly perfect drift compensation is made. Taking the differences of the output voltages at AC and DC for the REF and DUT, the ac-dc difference between the two TVCs δ_{MEAS} is calculated:

$$\delta_{MEAS} = \frac{U_{O\_REF\_AC} - U_{O\_REF\_DC}}{n_{REF} U_{O\_REF\_DC}} - \frac{U_{O\_DUT\_AC} - U_{O\_DUT\_DC}}{n_{DUT} U_{O\_DUT\_DC}}$$

For the calibration of a micropot by 792A the AC-DC transfer difference of micropot δ_{upot} is got after adding the known ac-dc transfer difference of the reference standard (792A) δ_{REF} and making the correction on micropot's loading δ_Z :

$$\delta_{upot} = \delta_{MEAS} + \delta_{REF} - \delta_Z ,$$

where the correction on micropot's loading is calculated using following equation:

$$\delta_Z = \frac{1}{\sqrt{1 + 2\frac{R_0}{R_i} + \left(\frac{R_0}{R_i}\right)^2 + \omega^2 C_i^2 R_0^2}} - 1,$$

where R_0 is resistance of disc resistor,

R_i, C_i is input impedance of 792A,

ω is frequency.

For the calibration of 792A by micropot the AC-DC transfer difference of 792A δ_{792A} is got after adding the known ac-dc transfer difference of the reference standard (micropot) δ_{REF} :

$$\delta_{792A} = \delta_{MEAS} + \delta_{REF}$$

Each measurement sequence for one frequency is repeated 10 times and the mean value and standard deviation are calculated.

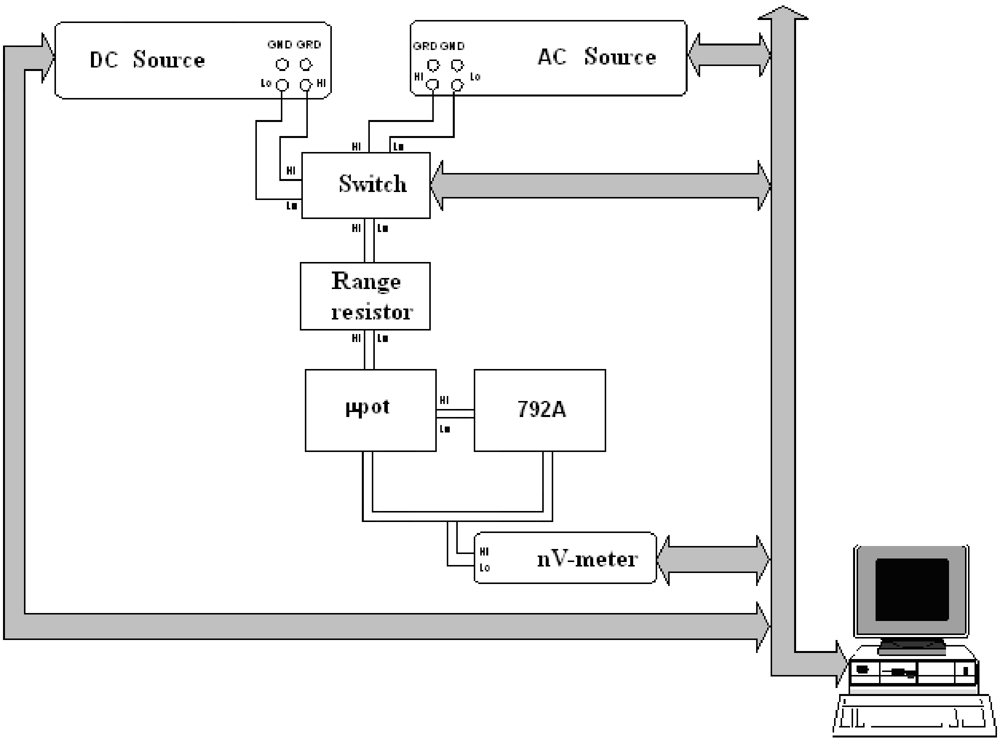

Fig. 3 Measurement system below 100mV

2. Ambient Conditions of the Measurement

	Min	Max
Ambient temperature / °C	22,5	23,5
Relative humidity / %	49	65
Pressure / hPa	966	981

3. Other Influence Parameters

Frequency of the measuring signal:

	Nominal frequency			
	1 kHz	20 kHz	100 kHz	1 MHz
Measuring frequency	1,000 004 5	20,000 095	100,000 45	1,000 004 5
Expanded uncertainty	0,000 000 5	0,000 005	0,000 05	0,000 002 0

Power supply voltage of the battery pack during measurement:

	Min	Max
Pos. power supply voltage / V	11,090	11,103
Neg. power supply voltage / V	-11,166	-11,156

4. Detailed Uncertainty Budget

Combined uncertainty for the calibration at 100mV is given by the following equation:

$$u^2(\delta_{100mV}) = u^2(\delta_{REF}) + u^2(\delta_{S\_DUT}) + u^2(\delta_{SET-UP}) + u^2(\delta_{LEVEL}) + u^2(\delta_{CONN}) + u^2(\delta_{FREQ}) + u^2(\delta_{TEMP}),$$

where $u^2(\delta_{REF})$ is contribution of reference standard (PMJTC),

$u^2(\delta_{S\_DUT})$ is contribution of reproducibility of measured DUT's AC-DC difference (standard deviation),

$u^2(\delta_{SET-UP})$ is contribution of measuring set-up,

$u^2(\delta_{LEVEL})$ is contribution of level dependence,

$u^2(\delta_{CONN})$ is influence of used connectors,

$u^2(\delta_{FREQ})$ is contribution of frequency dependence,

$u^2(\delta_{TEMP})$ is contribution of temperature dependence.

Uncertainty budget for the calibration at 100mV is calculated in Table 1.

Table 1 Uncertainty budget for the calibration at 100mV

Contribution of	frequency (kHz)				Type A or B	Distribution
	1	20	100	1000		
reference standard	0,5	0,5	1,5	5	B	Normal
reproducibility	6	6	8	15	A	Normal
level dependence	5	5	7	15	B	Rectangular
frequency	0	0	0	1	B	Normal
temperature	1	1,5	3	9	B	Rectangular
connectors	2	3	6	20	B	Rectangular
measuring set-up	5	6	7	25	B	Rectangular
combined uncertainty (k=1)	*9,6*	*10,4*	*14,5*	*39,8*		
expanded uncertainty (k=2)	**19**	**21**	**29**	**80**		

Combined uncertainty for the calibration of a micropot No.1 at 100mV, No.2 at 50mV and No.3 at 20mV (see the step-down scheme on Fig.1) is given by the following equation:

$$u^2(\delta_{upot}) = u^2(\delta_{REF}) + u^2(\delta_{S\_DUT}) + u^2(\delta_{SET-UP}) + u^2(\delta_{LEVEL}) + u^2(\delta_{CONN}) + u^2(\delta_{LOAD}) + u^2(\delta_{FREQ}) + u^2(\delta_{TEMP}),$$

where $u^2(\delta_{REF})$ is contribution of reference standard (792A),

$u^2(\delta_{S\_DUT})$ is contribution of reproducibility of measured micropot's AC-DC difference (standard deviation),

$u^2(\delta_{SET-UP})$ is contribution of measuring set-up,

$u^2(\delta_{LEVEL})$ is contribution of level dependence,

$u^2(\delta_{CONN})$ is influence of used connectors,
$u^2(\delta_{LOAD})$ is contribution of loading effects on micropot,
$u^2(\delta_{FREQ})$ is contribution of frequency dependence,
$u^2(\delta_{TEMP})$ is contribution of temperature dependence.

Combined uncertainty for the calibration of 792A at 50mV, 20mV and 10mV is calculated using the following equation:

$$u^2(\delta_{792A}) = u^2(\delta_{REF}) + u^2(\delta_{S\_DUT}) + u^2(\delta_{SET-UP}) + u^2(\delta_{LEVEL}) + u^2(\delta_{CONN}) + u^2(\delta_{LOAD}) + u^2(\delta_{FREQ}) + u^2(\delta_{TEMP}),$$

where $u^2(\delta_{REF})$ is contribution of reference standard (micropot),
$u^2(\delta_{S\_DUT})$ is contribution of reproducibility of measured 792A's AC-DC difference (standard deviation),
$u^2(\delta_{SET-UP})$ is contribution of measuring set-up,
$u^2(\delta_{LEVEL})$ is contribution of level dependence,
$u^2(\delta_{CONN})$ is influence of used connectors,
$u^2(\delta_{LOAD})$ is contribution of loading effects on micropot,
$u^2(\delta_{FREQ})$ is contribution of frequency dependence,
$u^2(\delta_{TEMP})$ is contribution of temperature dependence.

Uncertainty budget for the step-down procedure is calculated in Table 2.

Table 2 Uncertainty budget for the step-down procedure down to 10mV:

Step	Measured voltage	Reference standard	Device under test	Contribution of	frequency (kHz)				Type A or B	Distribution
					1	20	100	1000		
1	100mV	792A	upot 1	reference standard	9,6	10,4	14,5	39,8	B	Normal
				reproducibility	3	3	5	10	A	Normal
				level dependence	5	5	7	15	B	Rectangular
				frequency	0	0	0	1	B	Normal
				temperature	1	1,5	3	9	B	Rectangular
				connectors	2	3	6	20	B	Rectangular
				measuring set-up	5	6	8	27	B	Rectangular
				loading effects on upots	0	1	4	15	B	Rectangular
				combined uncertainty (k=1)	*12,5*	*13,8*	*20,2*	*57,8*		
				expanded uncertainty (k=2)	**25**	**28**	**40**	**116**		
Step	Measured voltage	Reference standard	Device under test	Contribution of	frequency (kHz)				Type A or B	Distribution
					1	20	100	1000		
2	50mV	upot 1	792A	reference standard	12,5	13,8	20,2	57,8	B	Normal
				reproducibility	6	6,5	6,5	12,5	A	Normal
				level dependence	5	5	7	15	B	Rectangular
				frequency	0	0	0	1	B	Normal
				temperature	1	1,5	3	9	B	Rectangular
				connectors	2	3	6	20	B	Rectangular
				measuring set-up	5	6	8	27	B	Rectangular
				loading effects on upots	0	1	4	15	B	Rectangular
				combined uncertainty (k=1)	*15,7*	*17,5*	*25,0*	*71,8*		
				expanded uncertainty (k=2)	**31**	**35**	**50**	**144**		

Step	Measured voltage	Reference standard	Device under test	Contribution of	frequency (kHz) 1	20	100	1000	Type A or B	Distribution
3	50mV	792A	upot 2	reference standard	15,7	17,5	25,0	71,8	B	Normal
				reproducibility	6	6,5	6,5	12,5	A	Normal
				level dependence	5	5	7	20	B	Rectangular
				frequency	0	0	0	1	B	Normal
				temperature	1	1,5	3	9	B	Rectangular
				connectors	2	3	6	20	B	Rectangular
				measuring set-up	5	6	8	27	B	Rectangular
				loading effects on upots	0	1	4	15	B	Rectangular
				combined uncertainty (k=1)	*18,4*	*20,5*	*29,0*	*84,6*		
				expanded uncertainty (k=2)	**37**	**41**	**58**	**169**		

Step	Measured voltage	Reference standard	Device under test	Contribution of	frequency (kHz) 1	20	100	1000	Type A or B	Distribution
4	20mV	upot 2	792A	reference standard	18,4	20,5	29,0	84,6	B	Normal
				reproducibility	8	8	8	15	A	Normal
				level dependence	5	5	7	20	B	Rectangular
				frequency	0	0	0	1	B	Normal
				temperature	1	1,5	3	9	B	Rectangular
				connectors	2	3	6	20	B	Rectangular
				measuring set-up	5	6	8	27	B	Rectangular
				loading effects on upots	0	1	4	15	B	Rectangular
				combined uncertainty (k=1)	*21,4*	*23,6*	*32,8*	*96,0*		
				expanded uncertainty (k=2)	**43**	**47**	**66**	**192**		

Step	Measured voltage	Reference standard	Device under test	Contribution of	frequency (kHz) 1	20	100	1000	Type A or B	Distribution
5	20mV	792A	upot 3	reference standard	21,4	23,6	32,8	96,0	B	Normal
				reproducibility	8	8	8	15	A	Normal
				level dependence	5	5	7	20	B	Rectangular
				frequency	0	0	0	1	B	Normal
				temperature	1	1,5	3	9	B	Rectangular
				connectors	2	3	6	20	B	Rectangular
				measuring set-up	5	6	8	27	B	Rectangular
				loading effects on upots	0	1	4	15	B	Rectangular
				combined uncertainty (k=1)	*24,0*	*26,4*	*36,3*	*106,2*		
				expanded uncertainty (k=2)	**48**	**53**	**73**	**212**		

Step	Measured voltage	Reference standard	Device under test	Contribution of	frequency (kHz) 1	20	100	1000	Type A or B	Distribution
6	10mV	upot 3	792A	reference standard	24,0	26,4	36,3	106,2	B	Normal
				reproducibility	10	10	10	15	A	Normal
				level dependence	5	5	7	20	B	Rectangular
				frequency	0	0	0	1	B	Normal
				temperature	1	1,5	3	9	B	Rectangular
				connectors	2	3	6	20	B	Rectangular
				measuring set-up	5	6	8	27	B	Rectangular
				loading effects on upots	0	1	4	15	B	Rectangular
				combined uncertainty (k=1)	*27,0*	*29,5*	*39,9*	*115,5*		
				expanded uncertainty (k=2)	**54**	**59**	**80**	**231**		

5. Results of the Measurements

Measuring result:

Voltage	Range	Measured ac-dc voltage difference / 10^{-6} at frequency			
		1 kHz	20 kHz	100 kHz	1 MHz
100 mV	220 mV	9,3	-3,5	16,7	-7,9
10 mV	22 mV	10,7	-5,5	-11,2	-70,6

Expanded uncertainty:

Voltage	Range	Expanded uncertainty / 10^{-6} at frequency			
		1 kHz	20 kHz	100 kHz	1 MHz
100 mV	220 mV	19	21	29	80
10 mV	22 mV	54	59	80	231

KEY COMPARISON **EUROMET.EM-K11** : AC-DC VOLTAGE TRANSFER DIFFERENCE AT LOW VOLTAGES

Report of Measurements

Issued by :
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Department of Electrical Measurements
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Description:	Thermal transfer standard
Manufacturer:	FLUKE
Type:	792A
Serial Number:	5495 003
Date of measurement:	From 9/7/2007 to 1/8/2007

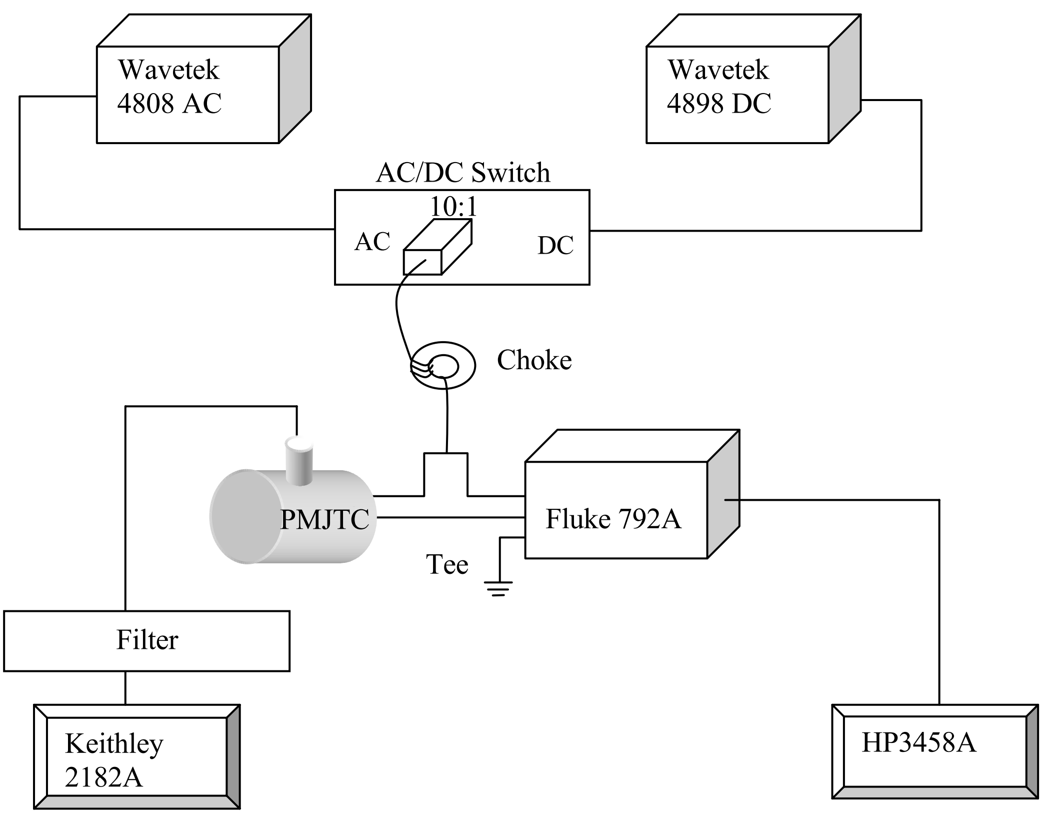
Date of issue:	Measurements Performed by :	Report Approved By:
28 October 2007	Dr. M. Holiastou Head of the Low Frequency Laboratory	Dr I. Flouda Director of the Electrical Measurements Department.

Ambient Conditions	From	To
Temperature	22,4^o C	23,2^o C
Relative Humidity	36 %	59 %

Experimental setup and Measuring Procedure

Two Wavetek 4808 calibrators are used as ac and dc sources. The switching unit[1], which is accompanied by a configurator /filter[2] and a controller is manufactured by Dr. M. Kampik, Silesian Technical University, Gliwice, Poland. The output of Fluke 792 is measured with a HP 3458A DMM and the output of the reference standard is measured with a Keithley 2182A nanovoltmeter, after having passed from a notch filter at 100 Hz. The input signal passes through a choke before reaching the standards. The guardings of the Wavetek 4808 sources, the AC/DC switch, the notch filter and Fluke 792A are all connected to a common ground, that of the Wavetek 4808 AC source. The LO output of Fluke 792A is connected to the common guard through a Guard to LO connection in the HP3458A multimeter and the LO output of the reference standard is connected to the common guard through a Guard to LO connection in the Filters unit. As the LO input and the LO output of Fluke 792A are internally connected, it follows that the LO input and also the Tee coincide with the common Guard potential. The measurements are performed in a temperature controlled environment with ambient conditions: Temperature = 23.00^{o} C ± 0.5^{o} C , Humidity = 45 % ± 15 %. The experimental setup is schematically as follows:

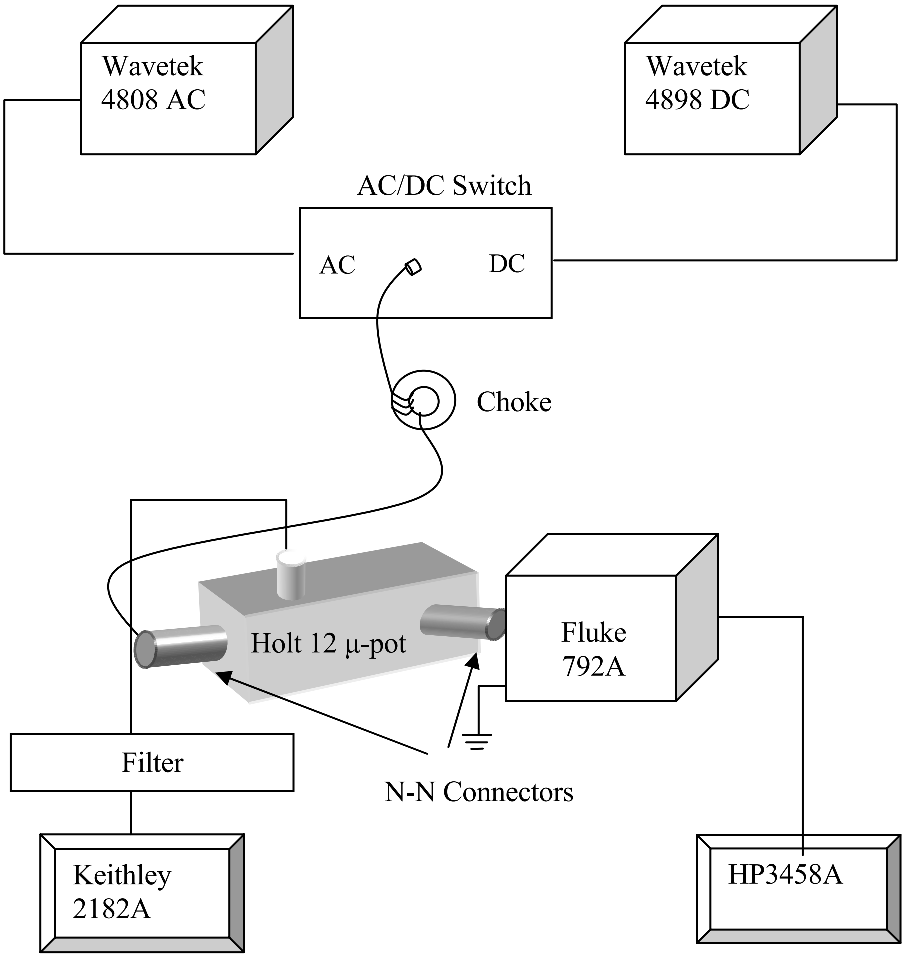
Setup 100 mV



The reference standard is a planar multijunction thermal converter (PMJTC)[4] provided by PTB with a heater resistance of 90 Ω and an output voltage of 100 mV at a rated input of 1 V. Because the Wavetek 4808 source has an output impedance of 30 Ω at the 100 mV range, its 1 V output is used and a 10:1 divider is inserted at the output of the AC/DC switch. Both the reference standard and Fluke 792A have N-type female input connectors therefore a Tee connector of N-type male is used. The reference plane is taken at the middle of the N-Tee connector.

For the measurements of 10mV the experimental setup is as follows:

Setup 10 mV



The reference standard is a Holt-12 type micropotentiometer with 10 V input and seven mV outputs from which the output of 10 mV is used. The input and output connector of the micropot is of N-type male, therefore an N type male-male adaptor is used at both sides. The reference plane is taken at the middle of the N-N male connector.

Traceability

The traceability of the measurement is at PTB through the calibration of the primary standards of EIM, which are a series of thermal converters of the type Holt 11 and the Holt 12 micropotentiometer.

Measurement procedure

The measurement procedure is automated and controlled by a PC. The sequence used is AC, DC^+, AC, DC^-, AC and the time delay is 60 sec in all the steps. After each sequence the average of the three AC steps and the average of the two DC steps is taken and the AC-DC difference of Fluke 792A is calculated. Consequently, a DC adjustment is performed on the reference standard, i.e. the DC of the Wavetek 4808 source is modified so that the output of the reference standard is the same at DC input as at AC input. When an adjustment better than 10 ppm is achieved, 12 sequences are performed and the mean of the 12 AC-DC difference results is taken, which is the measurement result. The mathematical formulation is as follows:
The AC-DC difference of a reference standard is defined as [3]

$\delta = \frac{U_{AC} - U_{DC}}{U_{DC}}\Big|_{out^{AC}=out^{DC}}$ (1), where

U_{AC} is the rms value of the ac input voltage and
U_{DC} is the dc input voltage, which when applied with different polarities gives an average voltage output equal to the voltage output at U_{AC}.

When two standards S, X are compared and adjustment is achieved, it can be shown that the difference $\delta = \delta_X - \delta_S$ between the two ac-dc differences is expressed by

$\delta = \frac{V_{DC}^X - V_{AC}^X}{k^X V_{DC}^X} - \frac{V_{DC}^S - V_{AC}^S}{k^S V_{DC}^S}$ (2), where

V_{DC}^S, V_{AC}^S are the output voltages of the reference standard at dc and ac,
V_{DC}^X, V_{AC}^X are the output voltages of the unknown standard similarly and
k^S, k^X are the characteristic exponents of the two standards.

In our procedure, V_{DC} is the mean of dc+ and dc- steps and V_{AC} is the average of three ac steps:

$V_{DC}^S = \frac{V_{DC+}^S + V_{DC-}^S}{2}$, $V_{AC}^S = \frac{V_{AC1}^S + V_{AC2}^S + V_{AC3}^S}{3}$, $V_{DC}^X = \frac{V_{DC+}^X + V_{DC-}^X}{2}$, $V_{AC}^X = \frac{V_{AC1}^X + V_{AC2}^X + V_{AC3}^X}{3}$.

The characteristic exponent of Fluke 792A is taken to be $k^X = 1$ and for the reference standards it is measured to be k_S =2,0 (PMJTC) and k_S =1,9 (Holt 12) with an uncertainty of 2 ppm.
Given that the known ac-dc difference of the reference standard is δ^S, the ac-dc difference of the unknown is

$$\delta^X = \delta^S + \frac{V_{DC}^X - V_{AC}^X}{k^X V_{DC}^X} - \frac{V_{DC}^S - V_{AC}^S}{k^S V_{DC}^S} \quad (3).$$

Under the fulfillment of adjustment, 12 cycles are executed and the average of the computed values from (3) is the result of the measurement:

$$\delta^X = \frac{\sum_{i=1}^{12} \delta_i^X}{12} \quad (4).$$

The average (4) for all the voltage-frequency points and its standard deviation are presented in Tables I and II. The measurements were repeated at different dates and the mean temperature of the day, its standard deviation, the relative humidity and its standard deviation are also given.

Table I

Fluke 792A ac-dc difference results / 10 mV

	Measurement Result: $\delta^{Fluke\ 792A}$ (10^{-6})	STDEV (10^{-6})	Date	Temp. (°C)	STD_{Temp} (°C)	RH (%)	STD_{RH} (%)
10 mV 1 kHz	17	14.1	16/7/2007	23.01	0.106	54.71	1.37
	13.7	11.1	18/7/2007	23.13	0.074	58.07	0.43
	14.3	8.8	19/7/2007	23.13	0.095	54.24	1.79
	9.1	9.3	24/7/2007	23.24	0.155	57.46	1.88
	7.7	10.8	25/7/2007	23.11	0.152	56.80	1.96
	14.3	10	27/7/2007	23.09	0.093	58.32	0.36
	17.3	9.6	31/7/2007	23.15	0.164	50.83	3.75
10 mV 20 kHz	-13.9	12.9	11/7/2007	23.10	0.145	58.50	0.50
	-10.9	11.5	16/7/2007	23.01	0.106	54.71	1.37
	-10.6	9.8	18/7/2007	23.13	0.074	58.07	0.43
	-6.6	13.6	19/7/2007	23.13	0.095	54.24	1.79
	-12.1	7.5	23/7/2007	23.13	0.095	58.11	0.58
	-8.4	11.9	24/7/2007	23.24	0.155	57.46	1.88
	-9.9	8.8	25/7/2007	23.11	0.152	56.80	1.96
	-9.1	7.3	27/7/2007	23.09	0.093	58.32	0.36
	-12.4	12.5	31/7/2007	23.15	0.164	50.83	3.75
10 mV 100 kHz	34.2	8.2	17/7/2007	22.95	0.070	58.35	0.50
	26.4	5.6	18/7/2007	23.13	0.074	58.07	0.43
	28.4	10.4	19/7/2007	23.13	0.095	54.24	1.79
	21.4	10.8	23/7/2007	23.13	0.095	58.11	0.58
	24.7	16	24/7/2007	23.24	0.155	57.46	1.88

	25.7	8.7	25/7/2007	23.11	0.152	56.80	1.96
	26.5	8.4	31/7/2007	23.15	0.164	50.83	3.75
10 mV 1 MHz	15.1	9.4	24/7/2007	23.24	0.155	57.46	1.88
	26.8	7.7	24/7/2007	23.24	0.155	57.46	1.88
	37.2	14.1	26/7/2007	23.01	0.138	45.18	6.38
	83.6	8.7	27/7/2007	23.09	0.093	58.32	0.36
	21.7	8.9	30/7/2007	23.04	0.103	58.89	0.30
	33.0	9.8	31/7/2007	23.15	0.164	50.83	3.75

Table II

Fluke 792A ac-dc difference results / 100 mV

	Measurement Result: $\delta^{Fluke\ 792A}$ (10^{-6})	STDEV($\delta^{Fluke\ 792A}$) (10^{-6})	Date	Temp. (°C)	STD(Temp) (°C)	RH (%)	STD(RH) (%)
100 mV 1 kHz	8.3	5.1	10/7/2007	22.69	0.125	58.02	1.03
	0.7	4.7	16/7/2007	23.01	0.106	54.71	1.37
	2.8	4.9	17/7/2007	22.95	0.070	58.35	0.50
	11.9	3.7	19/7/2007	23.13	0.095	54.24	1.79
	7.5	3.4	20/7/2007	23.15	0.136	56.86	1.60
	12.2	2.2	23/7/2007	23.13	0.095	58.11	0.58
	4.9	3.5	25/7/2007	23.11	0.152	56.80	1.96
	12.6	2.5	26/7/2007	23.01	0.138	45.18	6.38
	2.5	3.8	30/7/2007	23.04	0.103	58.89	0.30
100 mV 20 kHz	-10.5	3.5	16/7/2007	23.01	0.106	54.71	1.37
	-2.7	3.4	17/7/2007	22.95	0.070	58.35	0.50
	-1.6	3.3	19/7/2007	23.13	0.095	54.24	1.79
	-5.8	2.4	20/7/2007	23.15	0.136	56.86	1.60
	-0.9	2.1	23/7/2007	23.13	0.095	58.11	0.58
	-11.8	2.8	25/7/2007	23.11	0.152	56.80	1.96
	-10.8	4.1	26/7/2007	23.01	0.138	45.18	6.38
	-0.7	2	30/7/2007	23.04	0.103	58.89	0.30
100 mV 100 kHz	21.1	3.6	9/7/2007	22.62	0.196	58.31	0.59
	17.9	3.0	16/7/2007	23.01	0.106	54.71	1.37
	17.2	3.2	18/7/2007	23.13	0.074	58.07	0.43
	10.4	3.4	19/7/2007	23.13	0.095	54.24	1.79
	14.9	2.8	20/7/2007	23.15	0.136	56.86	1.60
	9.5	3.0	23/7/2007	23.13	0.095	58.11	0.58
	19.8	2.8	25/7/2007	23.11	0.152	56.80	1.96
	12.4	2.9	26/7/2007	23.01	0.138	45.18	6.38
	22.3	2.6	30/7/2007	23.04	0.103	58.89	0.30
100 mV 1 MHz	22.4	3.1	18/7/2007	23.13	0.074	58.07	0.43
	24.7	2.2	19/7/2007	23.13	0.095	54.24	1.79
	20.7	3.5	20/7/2007	23.15	0.136	56.86	1.60
	19.6	2.2	20/7/2007	23.15	0.136	56.86	1.60
	23.2	3.7	23/7/2007	23.13	0.095	58.11	0.58
	26.7	3.9	30/7/2007	23.04	0.103	58.89	0.30

From the measurements of Tables I and II, the weighted average $\overline{\delta}$ for each voltage and frequency is computed:

$$\overline{\delta} = \frac{\sum_{j=1}^{m} \delta_j^{Fluke792A} / s^2(\delta_j^{Fluke792A})}{\sum_{j=1}^{m} 1/s^2(\delta_j^{Fluke792A})}, \text{ where,}$$

m is the total number of measurements performed at the specific voltage and frequency and

$$s^2(\delta_j^{Fluke792A}) = \frac{\sum_{i=1}^{12} (\delta_{ji}^{Fluke792A} - \delta_j^{Fluke792A})^2}{12(12-1)}$$ is the variance of the j^{th} measurement with 12 sequences.

The resulting values of $\overline{\delta}$ are presented in Appendix 1.

The average temperature for the measurements of the same voltage and frequency is for all cases 23.1^o C and the average humidity is 55%. The summarized values are given in Table III. Another parameter influencing the measurements is the supply voltage of the battery pack, which was also measured several times during the measuring period. Only the *travelling* battery pack was used and the difference: maximum-minimum voltage of the travelling dummy load was measured and presented in Table III.

Table III

Influence parameters

	Min	Max	Remarks
Ambient Temperature (^{o} C)	23,0	23,2	No correction is applied to δ
Relative humidity (%)	41	59	Correction is applied to $\delta^{Fluke792A}$ at 100 mV, 1 MHz and 10 mV, 1 MHz
Power supply voltage (V)	22,258	22,270	The difference between + and - outputs was measured

The frequency of the ac source is also reported in Table IV as measured with a Fluke PM6681R counter. The values for 10 mV and 100 mV cases were the same within the uncertainty of measurement.

Table IV

Measuring frequency

	Nominal frequency			
	1 kHz	20 kHz	100 kHz	1 MHz
Measuring frequency	999.96 Hz	19.999 kHz	99.996 kHz	999.96 kHz
Expanded uncertainty	2.0 E-04	2.0 E-04	2.0 E-04	2.0 E-04

Uncertainty budget

The results of the measurements are corrected for the existing ac-dc differences that are not due to Fluke 792A intrinsic properties. The complete equation for the ac-dc difference of the unit under test is:

$\delta^{Fluke792A} = \delta_S + \delta - \delta_{Zi} - \delta_C - \delta_{Temp} - \delta_{Hum}$ (5), where

δ_S is the ac-dc difference of the reference standard

δ is the measured difference of the ac-dc differences of the two standards

δ_{Zi} is the correction due to the input impedance of Fluke 792A

δ_C is the correction due to connectors etc.

δ_{Temp} is the correction due to the temperature deviation from the reference value of 23°C and

δ_{Hum} is the correction due to the humidity variation from the reference value of 45%.

The corresponding uncertainty is computed according to "The Guide to the Expression of Uncertainty in Measurement" published by ISO and is given by:

$$u^2\left(\delta^{Fluke792A}\right) = u^2(\delta_S) + u^2(\delta) + u^2(\delta_{Zi}) + u^2(\delta_C) + u^2\left(\delta_{Temp}\right) + u^2(\delta_{Hum}).$$

Each term is discussed below:

***u*(δ_S)**

The PMJTC standard used in the case of 100 mV was calibrated at EIM against a 1 V thermal converter of the type Holt 11. The calibration was performed at 1 V and the level dependence of the PMJTC is taken as insignificant. The uncertainty $u(\delta_S)$ includes the uncertainty of Holt11, which was calibrated in PTB and all the uncertainties involved in the calibration procedure PMJTC-Holt11. The uncertainty budget is given in the following table:

Uncertainty budget for the calibration of PMJTC with Holt 11				
	u (ppm)	*u* (ppm)	*u* (ppm)	*u* (ppm)
Source of uncertainty	1 kHz	20 kHz	100 kHz	1 MHz
Reference standard (Certificate PTB)	0.5	0.5	1.5	5.0
Measuring setup $u(\delta_{Setup})$	0.6	0.6	0.6	0.6
Level dependence of PMJTC	0	0	0	0
Reproducibility (Type A)	0.5	0.7	0.4	0.7
Standard uncertainty (k=1)	1.0	1.1	1.7	5.1

In the case of 10 mV, where a micropotentiometer Holt 12 was used, the corresponding uncertainty is the uncertainty of the calibration which was preformed in PTB. The values are shown in the Table below.

Uncertainty budget for Holt 12 (10mV)				
	u (ppm)	*u* (ppm)	*u* (ppm)	*u* (ppm)
Source of uncertainty	1 kHz	20 kHz	100 kHz	1 MHz
Standard uncertainty of Holt 12 (PTB certificate) at 10 mV	42.5	40	42.5	80
Different connectors	0	0	0	0
Total standard uncertainty (k=1)	42.5	40	42.5	80

$u(\delta)$

The uncertainty of the measured difference between the two standards consists of two terms, the type A uncertainty and the uncertainty of the measuring setup. As a type A uncertainty is taken the maximum STDEV($\delta^{Fluke\ 792A}$) of the results of Tables I and II for each voltage-frequency, divided by the square root of the 12 sequences involved. This is an upper limit approximation for the reproducibility of the results.
The uncertainty of the measuring setup is calculated from equation (2) to be

$$u^2(\delta_{Setup}) = \left(\frac{U_{dc}^{3458} - U_{ac}^{3458}}{k_X^2 U_{dc}^{3458}}\right)^2 u^2(k_X) + \left(\frac{U_{dc}^{3458} - U_{ac}^{3458}}{k_X U_{dc}^{3458}}\right)^2 \left(\frac{u(U^{3458})}{U_{dc}^{3458}}\right)^2 + \left(\frac{1}{k_X}\right)^2 \left(\frac{u(U_{dc}^{3458}) - u(U_{ac}^{3458})}{U_{dc}^{3458}}\right)$$
$$+ \left(\frac{U_{dc}^{Keithley} - U_{ac}^{Keithley}}{k_S^2 U_{dc}^{Keithley}}\right)^2 u^2(k_S) + \left(\frac{U_{dc}^{Keithley} - U_{ac}^{Keithley}}{k_S U_{dc}^{Keithley}}\right)^2 \left(\frac{u(U^{Keithley})}{U_{dc}^{Keithley}}\right)^2 + \left(\frac{1}{k_S}\right)^2 \left(\frac{u(U_{dc}^{Keithley}) - u(U_{ac}^{Keithley})}{U_{dc}^{Keithley}}\right) \quad (6).$$

The first 3 terms correspond to the measurement of Fluke 792A output with the HP3458A multimeter and the last 3 terms correspond to the measurement of the reference standard output (PMJTC of Holt12) with Keithley 182A nanovoltmeter. The uncertainties of the exponents of the two standards are $u(k_X)= u(k_S)$=2ppm and the remaining terms are: $u(U^{3458})$, the measurement uncertainty of HP3458A voltmeter, $u(U^{Keithley})$, the measurement uncertainty of Keithley 182A nanovoltmeter and U^{3458}, $U^{Keithley}$, the corresponding voltage outputs measured with the two standards. The terms $u(U_{dc}^{3458}) - u(U_{ac}^{3458})/U_{dc}^{3458}$ and $u(U_{dc}^{Keithley}) - u(U_{ac}^{Keithley})/U_{dc}^{Keithley}$ represent the linearity of the meters, which is 0,4 ppm and 0,9 ppm respectively and are the basic contribution to the uncertainty. The resulting uncertainty of the measuring setup from equation (6) is $u(\delta_{Setup})$=0,6 ppm for both the 100 mV and 10 mV cases.

***u*(δ_{Zi})**

The correction δ_{Zi} due to the input impedance of Fluke 792A is involved only in the case of the 10 mV measurement and can be shown to be

$$\delta_{Zi} = \frac{1}{\sqrt{\left(1 + \frac{R_0}{R_i}\right)^2 + \omega^2 c_i^2 R_0^2}} - 1 \quad (7), \text{ where}$$

R_0 is the output resistance of the μ-pot and R_i , c_i are the input resistance and capacitance of Fluke 792A. For the Holt 12 type micropot it is R_0=2 Ω and for Fluke 792A the input impedance was measured with a HP4284A LCR meter. Unfortunately, because of the overloading protection that exists in the 22 mV range in Fluke792A, the input parameters could not be measured with any LCR meter for this range. Therefore, the values of the 220 mV range are considered for the 22 mV range too as an approximation and a fairly large uncertainty is added. The values of R_i and c_i, and the corresponding correction δ_{Zi} from (7) are given in Table V for each measuring frequency.

As it can be seen from Table V, the calculated corrections δ_{Zi} are small, except for the case of 1 MHz. Thus, a correction δ_{Zi} =13,5 ppm is implemented to the 1 MHz result only. The associated uncertainty is estimated from equation (7) to be

$$u(\delta_{Zi}) \approx \frac{R_0}{R_i} \cdot \frac{u(R_i)}{R_i}.$$

If it is assumed that the uncertainty $u(R_i)$ can be as large as $4R_i$, then it follows that $u(\delta_{Zi})$=53 ppm.

Table V

Input impedance of Fluke 792A and corresponding correction

22 mV range	R_i (taken from 220 mV range measurements)	c_i (taken from 220 mV range measurements)	δ_{Zi} (ppm)
f= 1 kHz	9 MΩ	48 pF	0,2
f= 20 kHz	4,4 MΩ	44 pF	0,5
f= 100 kHz	2,8 MΩ	43 pF	0,7
f= 1 MHz	152 kΩ	43 pF	13,5

***u*(δ_C)**

The major factors of uncertainty are the N-tee connector in the case of the 100 mV setup and the N-N connector at the 10 mV output of Holt 12 in the 10 mV setup. The 10:1 divider, which is used in the 100 mV setup does not influence the measurement result δ, as the voltage is adjusted on the PMJTC standard *after* the divider. The ac-dc difference of the Tee connector and the N-N connector is found to be insignificant within a measurement uncertainty of 1 ppm at 1 kHz and 2 ppm at 1MHz.

***u*(δ_{Temp})**

From Table III it can be seen that the average temperature during the measurements is within the required limits, therefore no correction δ_{Temp} is applied to the ac-dc difference of Fluke 792A. The associated uncertainty is calculated as $u(\delta_{Temp}) = \sqrt{\alpha_T^2 \cdot u^2(T) + \Delta T^2 \cdot u^2(a_T)}$, where α_T is the temperature coefficient of Fluke 792A, $u(a_T)$ is the coefficient uncertainty and $u(T)$ is the uncertainty of the measurement of the temperature, which was 0,2 K

***u*(δ_{Hum})**

Unlike the temperature, the humidity of the measurement environment was 10% higher than required. A correction is therefore applied to the ac-dc difference of Fluke 792A for the cases 100 mV, 1 MHz and 10 mV, 1 MHz, where it is significant. The value of the correction is estimated from $\delta_{Hum} = \alpha_{RH} \cdot \Delta RH$, where α_{RH} is the humidity coefficient of Fluke 792A given in the technical protocol and ΔRH is the deviation of the lab humidity from 45%. Accordingly, the humidity correction uncertainty is $u(\delta_{Hum}) = \sqrt{\alpha_{RH}^2 \cdot u^2(RH) + \Delta RH^2 \cdot u^2(\alpha_{RH})}$, where $u(\alpha_{RH})$ is the uncertainty of the humidity coefficient of Fluke 792A and $u(RH)$ is the uncertainty of measuring the relative humidity in the lab, which was 6% in the worst case.

The detailed uncertainty budgets for the voltages 100 mV and 10 mV at the frequency of 1 kHz are presented below. For the higher frequencies the uncertainty budgets are the same. A summary of the uncertainty budgets for all voltage and frequency values is given in Appendix 2.

10 mV	**1 kHz**		**UNCERTAINTY BUDGET**							
Quantity	Estimate		Relative standard uncertainty		Probability Distribution	Sensitivity coefficient		Standard uncertainty contribution (k=1)		Degree of freedom
X_i	x_i		$u(x_i)$		(Type A/B)	c_i		$u(\delta_i)$		ν_i
Reference standard ac-dc difference	-20.0	10^{-6}	42.5	10-6	Normal Type B	1.0		42.5	10^{-6}	∞
Measuring setup	0.0	10^{-6}	0.6	10^{-6}	Normal Type B	1.0		0.6	10^{-6}	∞
Reproducibility of measuring result	13.2	10^{-6}	4.1	10^{-6}	Normal Type A	1.0		4.1	10^{-6}	83
Fluke 792A input impedance δ correction	0.0	10^{-6}	0.9	10^{-6}	Rectangular Type B	1.0		0.5	10^{-6}	∞
Connectors	0.0	10^{-6}	0.8	10^{-6}	Rectangular Type A	1.0		0.5	10^{-6}	49
Temperature coefficient of Fluke 792A	1.2	10^{-6}/ K	1.0	10^{-6}/ K	Rectangular Type B	-0.1	K	0.1	10^{-6}	∞
Deviation of lab Temperature from 23° C	-0.1	K	0.2	K	Normal Type A	1.2	10^{-6}/K	0.2	10^{-6}	59
Humidity coefficient of Fluke792A	0.0	10^{-6}/ %	0.0	10^{-6}/ %	Rectangular Type B	-9.8	%	0.1	10^{-6}	∞
Deviation of lab Humidity from 45%	-9.8	%	6.0	%	Normal Type A	0.0	10^{-6}/ %	0.0	10^{-6}	59
Measurement result=	**13.2**	**10^{-6}**			**Expanded uncertainty (k=2)=**			**85.4**	**10^{-6}**	**1005388**
										ν_{eff}

100 mV	**1 kHz**		**UNCERTAINTY BUDGET**							
Quantity	Estimate		Relative standard uncertainty		Probability Distribution	Sensitivity coefficient		Standard uncertainty contribution (k=1)		Degree of freedom
X_i	x_i		$u(x_i)$		(Type A/B)	c_i		$u(\delta_i)$		ν_i
Reference standard ac-dc difference	0.0	10^{-6}	1.0	10^{-6}	Normal Type B	1.0		1.0	10^{-6}	∞
Measuring setup	0.0	10^{-6}	0.6	10^{-6}	Normal Type B	1.0		0.6	10^{-6}	∞
Reproducibility of measuring result	8.7	10^{-6}	1.5	10^{-6}	Normal Type A	1.0		1.5	10^{-6}	107
Connectors	0.0	10^{-6}	1.0	10^{-6}	Rectangular Type A	1.0		0.6	10^{-6}	49
Temperature coefficient of Fluke 792A	0.4	10^{-6}/ K	0.5	10^{-6}/ K	Rectangular Type B	0.0	K	0.0	10^{-6}	∞
Deviation of lab Temperature from 23° C	0.0	K	0.2	K	Normal Type A	0.4	10^{-6}/K	0.1	10^{-6}	59
Humidity coefficient of Fluke792A	0.0	10^{-6}/ %	0.0	10^{-6}/ %	Rectangular Type B	-11.1	%	0.1	10^{-6}	∞
Deviation of lab Humidity from 45%	-11.1	%	6.0	%	Normal Type A	0.0	10^{-6}/ %	0.0	10^{-6}	59
Measurement result=	**8.7**	**10^{-6}**			**Expanded uncertainty (k=2)=**			**3.9**	**10^{-6}**	**320** ν_{eff}

References

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Appendix 1. Summary of results

Key comparison EUROMET.EM-K11 "ac-dc voltage transfer difference at low voltages"
Acronym of institute: EIM
Date of measurements: 1-31 July 2007
Remarks:

Measuring result:

Voltage	Range	Measured ac-dc voltage difference / 10^{-6} at frequency			
		1 kHz	20 kHz	100 kHz	1 MHz
100 mV	220 mV	8.7	-4.1	16	9.0
10 mV	22 mV	13	-10	27	15

Expanded uncertainty:

Voltage	Range	Expanded uncertainty / 10^{-6} at frequency			
		1 kHz	20 kHz	100 kHz	1 MHz
100 mV	220 mV	3.9	3.6	4.6	20
10 mV	22 mV	85	80	86	172

Measuring frequency:

	Nominal frequency			
	1 kHz	20 kHz	100 kHz	1 MHz
Measuring frequency	999.96 Hz	19.999 kHz	99.996 kHz	999.96 kHz
Expanded uncertainty	2.0 E-04	2.0 E-04	2.0 E-04	2.0 E-04

Influence parameters:

	Min	Max	Remarks
Ambient temperature / ºC	23,0	23,2	No correction is applied to δ
Relative humidity / %	41	59	Correction is applied to $\delta^{Fluke792A}$ at 100 mV, 1 MHz and 10 mV, 1 MHz
Power supply voltage (V)	22,258	22,270	The difference between + and - outputs was measured

Appendix 2. Summary of uncertainty budget

Key comparison EUROMET.EM-K11 "ac-dc voltage transfer difference at low voltages"

Acronym of institute: EIM
Date: 1-31 July 2007
Remarks:

Measuring voltage: 100 mV

Contribution of:	Std. unc. f: 1 kHz	Std. unc. f: 20 kHz	Std. unc. f: 100 kHz	Std. unc. f: 1 MHz	Type A or B	Distribution
Reference standard ac-dc difference	1	1	2	5	B	Normal
Measuring setup	1	1	1	1	B	Normal
Reproducibility of measuring result	1	1	1	1	A	Normal
Connectors	1	1	1	1	B	Rectangular
Temperature coefficient of Fluke 792A	0	0	0	0	B	Rectangular
Deviation of lab Temperature from 23^0 C	0	0	0	2	A	Normal
Humidity coefficient of Fluke792A	0	0	0	2	B	Rectangular
Deviation of lab Humidity from 45%	0	0	1	8	A	Normal
Standard unc (k =1):	2	2	2	10		
Expanded unc:	**4**	**4**	**5**	**20**		
Eff. deg. of freedom:	**320**	**475**	**1551**	**147**		

Measuring voltage: 10 mV

Contribution of:	Std. unc. f: 1 kHz	Std. unc. f: 20 kHz	Std. unc. f: 100 kHz	Std. unc. f: 1 MHz	Type A or B	Distribution
Reference standard ac-dc difference	43	40	43	80	B	Normal
Measuring setup	1	1	1	1	B	Normal
Reproducibility of measuring result	4	4	5	4	A	Normal
Fluke 792A input impedance	1	1	2	30	B	Rectangular
Connectors	0	0	0	1	A	Rectangular
Temperature coefficient of Fluke 792A	0	0	0	0	B	Rectangular
Deviation of lab Temperature from 23 °C	0	0	0	3	A	Normal
Humidity coefficient of Fluke792A	0	0	0	1	B	Rectangular
Deviation of lab Humidity from 45%	0	0	1	5	A	Normal

Standard unc(k=1):	43	40	43	86
Expanded unc:	**85**	**80**	**86**	**172**
Eff. deg. of freedom:	**1 005 388**	**1 177 319**	**611 296**	**2 652 856**

REPORT OF EUROMET KEY COMPARISON EUROMET.EM-K11
AC/DC VOLTAGE TRANSFER DIFFERENCE AT LOW VOLTAGES

Inter-comparison of Transfer Standard at low voltages has been carried out during 3 October to 17 October, 2007. The traveling standard Fluke Model 792A was provided by Swedish National Testing and Research Institute (SP). It has been assigned ac/dc transfer difference at 10 mV and 100 mV against micro-potentiometer traceable to primary standards (Multijunction Thermal Converters) of NPL, India at the frequencies of 1, 20, 100 and 1000 kHz.

Reference Standards Used:
Micro-potentiometer with thin film radial resistors has been used as standards for assigning ac/dc transfer difference to travelling standard i.e. thermal Transfer Standard Fluke 792A. The micro-potentiometer Ballantine Model 440 used in assigning transfer difference to Travelling Standard in the frequency range 1 kHz to 1 MHz. It consists of a single junction thermo-element of 15 mA rating and thin film resistors 0.979 ohm for nominal voltage 10 mV and 6.79 ohm for nominal voltage 100 mV connected in series respectively. The calibration technique used is substitution technique against reference standard micro-potentiometer traceable to Primary standard of AC and LF voltage.

Measuring Method:

Fig. 1 shows the block schematic diagram of Inter-comparison for assignment of ac/dc transfer difference to travelling standard Fluke Model 792A. These measurements have been performed using a automation software and IEEE interface. The ac/dc transfer difference has been assigned to thermal transfer standard against micro-potentiometer (NPLI) at 10mV & 100 mV voltage level and frequencies (1 kHz, 20 kHz, 100 kHz and 1 MHz).

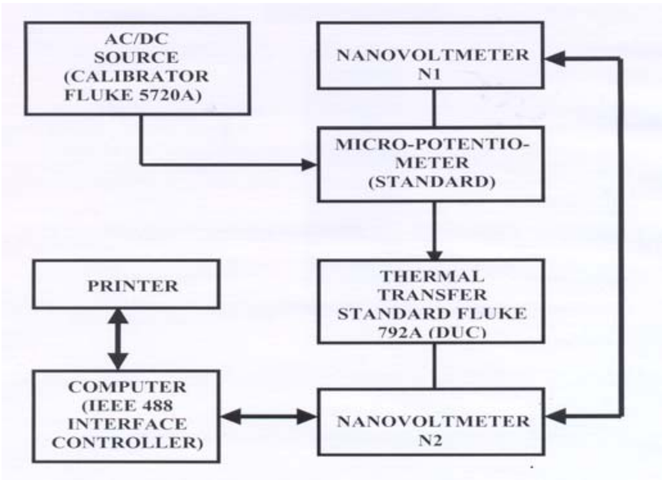

Fig. 1: Block Diagram Of Low Voltage Inter-Comparison For Measurement Of AC-DC Transfer Difference

The AC voltage output of the calibrator (Fluke 5720A) is adjusted for nominal output voltage of 100 mV/10 mV at micro potentiometer terminals. The reading on the 792A is recorded. The AC output of the calibrator is recorded as V_{ac}. The calibrator is then switched to DC positive voltage mode and its output is adjusted to obtain same reading as in case of ac voltage on the travelling standard 792A. This DC positive output voltage of calibrator V_{dc+} is recorded. The above process is repeated for DC negative and output voltage V_{dc-} of the calibrator is also recorded. After DC- the calibrator is switched to ac again and same voltage V_{ac}. is applied. Once these voltages are recorded, the output of the calibrator is not required to be changed during entire measurement process at one voltage level.

The sequence of calibrator output voltage applied to micropotentiometer is $V_{ac,}$ V_{dc+}, V_{dc-} and $V_{ac.}$ The output of micro-potentiometer is fed to the device under calibration (duc) i.e. thermal transfer standard Fluke 792A. The emf output of micro-potentiometer is measured by nanovoltmeter N1 (Keithley 182) and output of thermal transfer standard 792A is measured by nanovoltmeter N2

(Keithley 182). Both are recorded simultaneously in an excel format. This sequence of measurements is used to eliminate the influence of drift in the output because of calibrator. On completion of a set of ten measurements at a particular frequency, the ac/dc transfer difference of the travelling standard and the uncertainty associated with it is calculated by indigenously developed software. The ac-dc transfer difference at other frequencies is assigned by the same procedure both at 10 mV and 100 mV level.

The ac/dc transfer difference (δ_x) assigned to Thermal Transfer Standard Fluke 792A is calculated using equation (1)

$$\delta_x = \frac{S_{ac} - S_{dc}}{n_s S_{dc}} - \frac{X_{ac} - X_{dc}}{n_x X_{dc}} + \delta_s \qquad (1)$$

Where,

S_{ac} and X_{ac} are the mean emf outputs of the standard and device under calibration (duc) respectively when AC is applied.

S_{dc} is the mean emf output of the reference standard when DC positive and DC negative voltages are applied.

X_{dc} is the mean emf outputs of travelling standard (duc) when DC positive and DC negative voltages are applied.

δ_s is the ac/dc transfer difference of the reference standard.

n_s and n_x are the exponents of the reference standard and duc respectively.

Measurement Results:

Uncertainty in measurement is estimated as per "ISO-guide to Expression of Uncertainty in Measurement. The measurement data is statistically analysed and the standard uncertainty in the measurement is estimated by Type A evaluation. Contributions of other influence factors are estimated by Type B evaluation. The expanded uncertainty is given for a coverage factor k = 2 which corresponds to a coverage probability of approximately 95% for a normal distribution

Measuring result:

VoltageE	Range	Measured ac-dc voltage difference /10^{-6} at frequency			
		1 kHz	20 kHz	100 kHz	1 MHz
100 mV	220 mV	- 0.5	- 8.6	+ 1.6	+ 155.1
10 mV	22 mV	+ 1.3	- 15.0	- 34.3	- 114.5

Expanded uncertainty:

Voltage	Range	Expanded uncertainty /10^{-6} at frequency			
		1 kHz	20 kHz	100 kHz	1 MHz
100 mV	220 mV	± 11.1	± 11.4	± 12.9	± 35.7
10 mV	22 mV	±14.4	± 14.9	± 15.6	± 33.8

Measuring frequency:

	Nominal frequency			
	1 kHz	20 kHz	100 kHz	1 MHz
Measuring frequency	1.00001 kHz	19.9996 kHz	99.9979 kHz	999.979 kHz
Expanded uncertainty	±0.00001 kHz	± 0.0001 kHz	±0.0001 kHz	± 0.002 kHz

Influence parameters:

	Min	Max	Remarks
Ambient temperature / ^{0}C	22.6	23.4	
Relative Humidity / %	42	48	
Positive power supply voltage / V	11.098	11.100	Please state with mV resolution
Negative power supply voltage / V	-11.164	-11.162	Please state with mV resolution

Measuring voltage: 100 mV

Contribution of:	Std. Unc. f: 1 kHz	Std. Unc. f: 20 kHz	Std. Unc. f: 100 kHz	Std. Unc. f: 1 MHz	Type A or B	Distribution
Reference Standard	10.6	10.8	12.1	27.6	B	Normal
Measurement Set up	2	2	2	4	B	Rectangular
Loading Effect	0	0	2	15	B	Rectangular
Drift in Calibrator	2	2	2	5	B	Rectangular
Connectors	0	0	1	10	B	Rectangular
Temperature	0	0	1	4	B	Rectangular
Repeatability	0.36	0.67	0.46	0.47	A	Normal

Standard unc (k=1):	±5.56	± 5.68	± 6.44	± 17.83
Expanded unc:	±11.1	± 11.4	±12.9	± 35.7
Eff. Deg. of freedom	∞	∞	∞	∞

Measuring voltage: 10 mV

Contribution of:	Std. unc. f: 1 kHz	Std. nc. f: 20 kHz	Std. Unc. f: 100 kHz	Std. Unc. f: 1 MHz	Type A or B	Distribution
Reference Standard	13.9	14.4	14.9	29.4	B	Normal
Measurement Set up	2	2	2	4	B	Rectangular
Loading Effect	0	0	0.5	1	B	Rectangular
Drift in Calibrator	2	2	2	5	B	Rectangular
Connectors	0	0	1	10	B	Rectangular
Temperature	1	1	2	8	B	Rectangular
Loading Effect	0	0	0.5	1	B	Rectangular
Repeatability	0.56	0.74	0.95	1.15	A	Normal

Standard unc (k=1):	±7.18	± 7.44	± 7.80	± 16.91
Expanded unc:	±14.4	± 14.9	±15.6	± 33.8
Eff. Deg. of freedom	∞	∞	∞	∞

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REPORT

on key comparison EUROMET. EM-K11

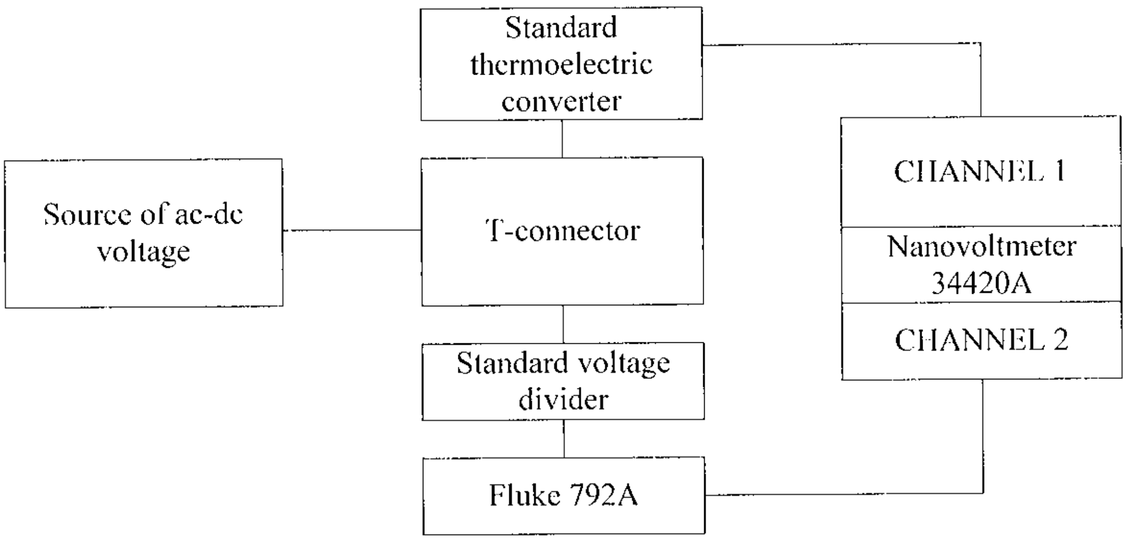
carried out at the D.I. Mendeleev Institute for Metrology (VNIIM)

from 01.02.2008 till 15.02.2008

1. Description of the measurement methods and reference standard.

The comparison was made against the national (primary) measurement standard. The national measurement standard consists of: reference standards – thermoelectric converters with additional resistors; stable a.c. and d.c. voltage sources; two-channel nanovoltmeter and a number of auxiliary devices. Thermoelectric converter used in the comparison is a multi-element air thermal converter. Resistance of the heating element was 100 ohms.

The measurement flow-chart is shown in the figure below:



2. Measurement procedure

The compared transfer Fluke 792A standard and the VNIIM reference standard are plugged in a special T-connector. The transfer standard is switched to a T-connector through the standard voltage divider.

Before the measurement , both the compared standard thermoelectric converter and the transfer standard are heated at the supplied voltage during at least 1 hour.

The transition error is determined at each of the frequencies specified in the technical protocol.

The transition error is determined through a cycle of measurements of the standard thermoelectric converter output voltage and the output voltage of the compared transfer standard.

The compared standards are fed in turn by ac voltage, dc voltage of direct and reverse polarity and again by ac voltage. By regulating the output voltage from the ac-dc voltage source the equality of voltage values of the standard converter is established. The relative ac to dc voltage transition error is calculated as average value of 10 measurement cycles.

The measurement results are shown in Table 1.

Table 1

Voltage	Range	Measured ac-dc voltage difference / 10^{-6} at frequency			
		1 kHz	20 kHz	100 kHz	1 MHz
100 mV	220 mV	+ 8.7	+ 11.4	+ 87.5	+ 279
10 mV	22 mV	+ 10.8	+12.9	+50.0	-60.4

The frequency values at which the measurements were made and the factors influencing the measurement results are shown in Tables 2 and 3.

Table 2

	Nominal frequency			
	1 kHz	20 kHz	100 kHz	1 MHz
Measurement frequency	0.9982	19.9874	100.0524	1.001518
Expanded uncertainty	1.10^{-4}	5.10^{-6}	1.10^{-6}	1.10^{-7}

Table 3

	1 kHz, 20 kHz, 100 kHz		1 MHz	
	Min	Max	Min	Max
Ambient temperature / °C	22.7	24.2	22.7	23.8
Relative humidity / %	27.2	33.7	18.7	26.5
Pos. power supply voltage / V	11.0968	11.1016	11.0952	11.1024
Neg. power supply voltage / V	11.1605	11.1648	11.1608	11.1644

3. Calculation of measurement uncertainty

The results of calculations of the measurements uncertainty for the level of 100 mV are shown in Table 4, for the level of 10 mV – in Table 5.

Table 4

Contribution of:	Std. unc. f: 1 kHz	Std. unc. f: 20 kHz	Std. unc. f: 100 kHz	Std. unc. f: 1 MHz	Type A or B	Distri-bution
1 Reference standard	2	3	5	7.5	B	Uniform
2 Connectors	2	2	2	2	B	Uniform
3 Frequency dependence of the divider	3	4	14	50	B	Uniform
4 The divider is shunted by 792A:						
4.1 active part of this Shunting	3	3	3	3	B	Uniform
4.2 reactive part of this Shunting	-	-	0.2	20	B	Uniform
Experimental standard deviation of the mean Ua	0.1	0.2	0.3	3	A	Normal
Standard unc (k=1):	5.1	6.2	15.3	54.6		
Expanded unc:	10	13	33	118		
Eff. deg. of freedom:	41	36	14	14		

Table 5

Contribution of:	Std. unc. f: 1 kHz	Std. unc. f: 20 kHz	Std. unc. f: 100 kHz	Std. unc. f: 1 MHz	Type A or B	Distri-bution
1 Reference standard	2	3	5	7.5	B	Uniform
2 Connectors	2	2	2	2	B	Uniform
3 Frequency dependence of the divider	8	9	28	70	B	Uniform
4 The divider is shunted by 792A:						
4.1 active part of this Shunting	3	3	3	3	B	Uniform
4.2 reactive part of this Shunting	-	-	0.2	20	B	Uniform
En experimental standard deviation of the mean Ua	0.1	0.2	0.3	3	A	Normal
Standard unc (k=1):	9	10	29	73		
Expanded unc:	19	22	64	161		
Eff. deg. of freedom:	16	16	11	12		

Appendix 3: Comments and corrective actions EURAMET.EM-K11 Final Report

DANIAmet-DPLE, Denmark

METAS, Switzerland

DANIAmet-DPLE (Denmark)
Comment, June 2009

Since our measurement results in general are slightly lower than the majority we have repeated some measurements on our own Fluke 792 A. In particular we have looked at the step from 200 mV, measured with a Planar Multijunction Thermal Converter (PMJTC), to 100 mV, measured with a µ-pot, as described in our measurement report, since this involves the measurement of the µ-pot at 200 mV against the 792 A as an intermediate step. From the raw measurement data it seems that the measurements of the intercomparison, resulting in a value around 7 ppm at 1 kHz for the µ-pot, may be flawed. Since this value is subtracted in the next step, the 100 mV measurement of the DUT, the result will be a low value for the DUT. Although the expected value of the µ-pot is not zero, due to thermal effects, this seems to be a rather large value for the single junction used in the µ-pot. Thermal effects could be measured directly by use of a fast-reversed DC source (not available to us). The responsibility for not observing this rests entirely with the operator (the contact person in this case). No such statement can be made at 1 MHz due to loading effects. Earlier calibrations of our own Fluke 792 A by the same step-down procedure with the same µ-pot resulted in a 1 kHz value around 3,5 ppm for the µ-pot, i.e. somewhat lower than the 7 ppm mentioned above. At 1 kHz various measurements have been carried out with different guarding/no guarding between our Fluke 792 A, the Keithley 182 used to measure its output voltage, and the rest of the setup. The results vary only within ± 1 ppm, so this offers no explanation. Finally we measured our own Fluke 792 at 100 mV at the frequencies of the intercomparison in order to compare this with the history of the instrument. The table below shows the history for 2 V, 1 V, which is the primary level, 200 mV, where the PMJTC is used, and 100 mV, where the µ-pot is used (the 700 mV range is omitted, since the measurements by another NMI and in house are at different voltage levels). Included are the recent measurements at 200 mV and 100 mV, and for clarity all measurement uncertainties are omitted in the table. It seems that the only hint at what might have caused our slightly lower result is the µ-pot values obtained and used in the intercomparison, 7 ppm at 1 kHz compared to 3,5 ppm during earlier measurements, but no explanation as to the cause of this difference has been found.

Table: History of the in house Fluke 792 A – AC-DC voltage transfer difference in 10^{-6}.

		1 kHz	20 kHz	100 kHz	1 MHz
Mar 95, another NMI	2 V	-6	-4	14	-5
Jan 97, another NMI		-6	-2	16	-2
May 2000, another NMI		-6	-2	15	-4
Mar 2004, in house		-5	-2	15	-6
Aug 2007, in house		-6	-2	14	-3
Mar 95, another NMI	1 V	-2	1	14	-2
Jan 97, another NMI		-3	0	17	1
May 2000, another NMI		-2	2	18	-9
Mar 2004, in house		-1	2	18	-1
Aug 2007, in house		-2	1	17	2
Mar 95, another NMI	200 mV	3	-15	3	-85
Jan 97, another NMI		2	-12	8	-47
May 2000, another NMI		1	-13	5	-106
Mar 2004, in house		-4	-17	4	-53
Aug 2007, in house		-2	-12	2	-63
Jun 2009, in house		0	-14	3	-55
Mar 95, another NMI	100 mV	3	-5	10	-6
Jan 97, another NMI		2	-10	9	-20
May 2000, another NMI		0	-10	5	-51
Mar 2004, in house		-3	-18	6	19
Aug 2007, in house		-3	-11	5	-2
Jun 2009, in house		-1	-15	3	2

Mortara Alessandro 04.05.2010

Addendum
Corrective actions following the results of the key comparison EURAMET.EM-K11 (METAS)

1 Background

In December 2006 METAS participated to the EUROMET.EM-K11 comparison on low voltage AC/DC difference measurements. The method used at METAS was a step down procedure using micro-potentiometers. In addition, a second calibration was carried out using as a reference a Fluke 792 A belonging to METAS. The results obtained with the step down procedure have been provided as the comparison results.The preliminary results of the comparison have been presented in the document **Report EURAMET_EM-K11 draft A v3 090511.doc**, indicated as “Draft A” in the following.

2 METAS results for the comparison EM-K11

The results of the comparison EM K-11 have shown a systematically low value of the AC/DC difference measured by METAS. This has prompted an investigation on the origin of the observed discrepancies which this short report summarizes.

3 Origin of the observed discrepancy and corrective actions

The origin of the problem has been traced to two circumstances:

- firstly, the use of micropotentiometers with inappropriate construction. These micropotentiometers were formed using a planar multijunction thermal converter in a brass housing connected via an adapter to a box containing the disk resistor as shown in Figure 1 below:

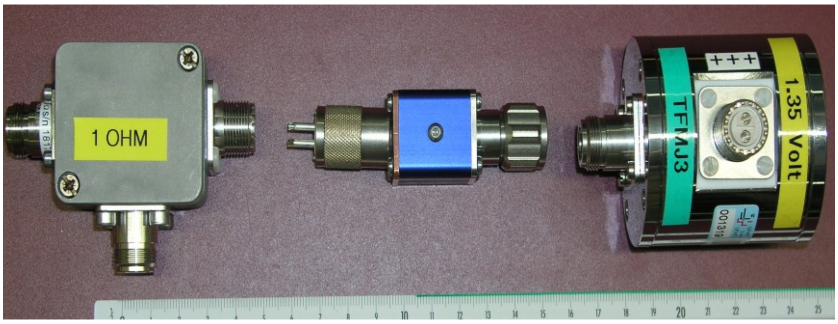


Figure 1: view of a micropotentiometer of inappropriate construction. Left: housing for the disk resistor, middle: adapter, right: planar multijunction converter in brass housing.

- secondly, the steps chosen during the step down were not evenly distributed.

To correct this situation, the micropotentiometers of the type shown in Figure 1 have been replaced with a set of Ballantine micropotentiometers of much more compact design chosen such that the steps of the stepdown procedure consistently moved from a given power level on the thermal converter to one-half that level.

4 Measurement results

The stepdown procedure has then been repeated in the year 2010 on the same 792 A belonging to METAS that was used during the comparison to provide the second calibration of the travelling standard. We then applied the following procedure:

1. Retrieval of the calibration data of the travelling standard with the METAS 792 A
2. Replacement of the calibration data of METAS' own 792 A with those obtained with the new set of micropotentiometers
3. Computation of the travelling standard's calibration values using the new calibration data of METAS' own 792 A.

The data so obtained were compared to those obtained by SP during the comparison (mean value of the SP results of August 2006 and May 2007.)

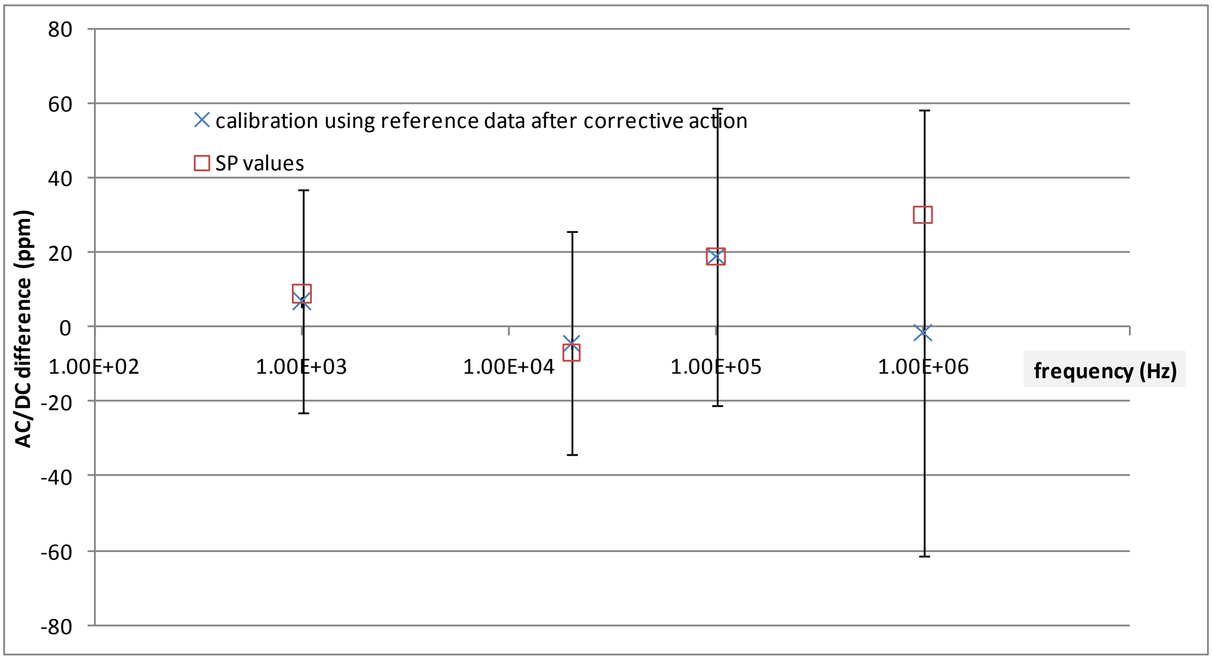


Figure 2: calibration of travelling standard at 100 mV: comparison of the values obtained by SP (squares) and of the METAS measurement during EM-K11 done with own's 792 A (crosses). The calibration values of METAS' own instrument are those obtained in 2010. Error bars correspond to METAS uncertainty (k=2)

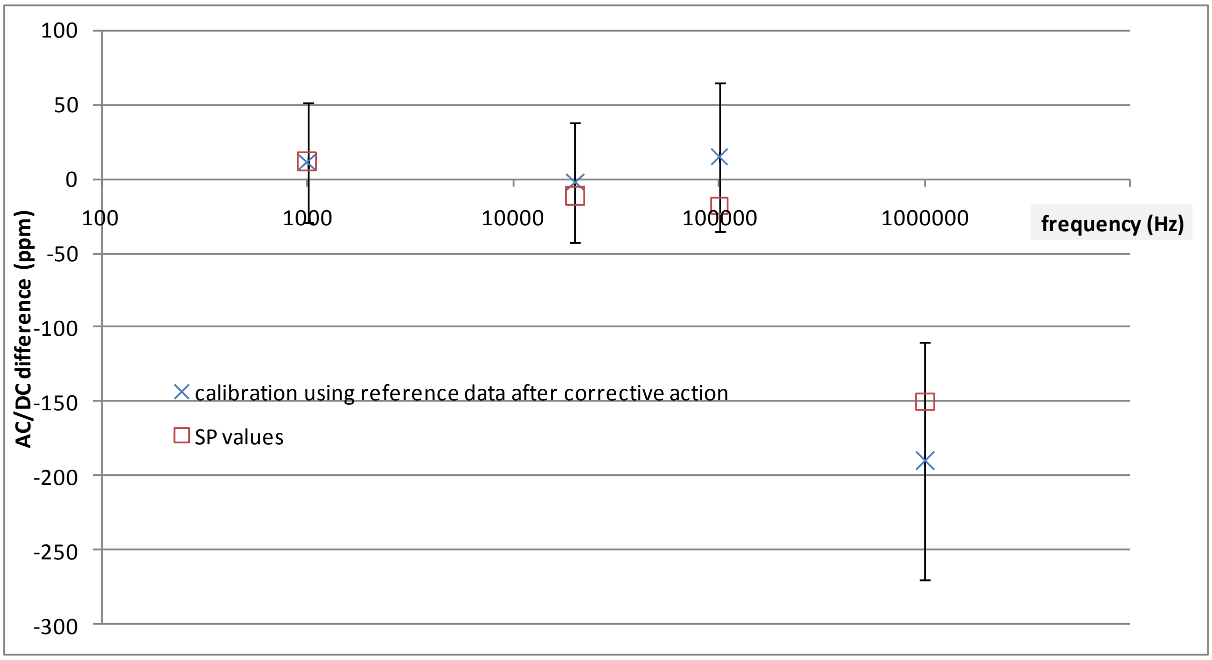


Figure 3: calibration of travelling standard at 10 mV: comparison of the values obtained by SP (squares) and of the METAS measurement during EM-K11 done with own's 792 A (crosses). The calibration values of METAS' own instrument are those obtained in 2010. Error bars correspond to METAS uncertainty (k=2)

The METAS corrected calibration data for the travelling standard are summarized in the following table:

Voltage	Range	Measured ac-dc voltage difference / 10^{-6} at frequency			
		1 kHz	20 kHz	100 kHz	1 MHz
100 mV	220 mV	7	-4	19	-2
10 mV	22 mV	11	-2	15	-190

5 Uncertainty of Measurement

Voltage	Range	Expanded uncertainty / 10^{-6} at frequency			
		1 kHz	20 kHz	100 kHz	1 MHz
100 mV	220 mV	30	30	40	60
10 mV	22 mV	40	40	50	80

KEY COMPARISON EUROMET.EM-K11

AC-DC VOLTAGE TRANSFER DIFFERENCE AT LOW VOLTAGES

Technical protocol

Ver. 10, 2005-09-01

Content

1. Introduction

The CIPM key comparison CCEM-K11 “ac-dc voltage transfer difference at low voltages” started in 2001 and the circulation of the travelling standard has now been finalised. It is time to restart the EUROMET project 464 that now also has the KCDB appendix B identifier EUROMET.EM-K11 with the Swedish National Testing and Research Institute (SP) as the pilot laboratory and with the Physikalisch-Technische Bundesanstalt (PTB) and the Nederlands Meetinstituut (NMi) as support group to the pilot laboratory.

This comparison is needed because of the growing importance of new measuring instruments introduced with the ability to measure or generate ac voltage with small uncertainties in the mV-range. This is the first European comparison for the ac-dc voltage transfer difference in the mV-range. The aim of the comparison is to achieve an agreement at 1 kHz within an expanded uncertainty of $10 \cdot 10^{-6}$ and $50 \cdot 10^{-6}$ at 100 mV and 10 mV respectively. At higher frequencies up to 1 MHz the uncertainties can be ten times larger.

The comparison will be accomplished in accordance with the EUROMET Guidelines on Conducting Comparisons.

2. Definition of the ac-dc voltage transfer difference

The ac-dc voltage transfer difference δ of a transfer standard is defined as:

$$\delta = (V_{ac} - V_{dc}) / V_{dc}$$

where

V_{ac} is the rms value of the ac input voltage

V_{dc} is the dc input voltage which when reversed produces the same mean output voltage of the transfer standard as V_{ac}.

3. The travelling standard

The travelling standard is a Fluke 792A thermal transfer standard, serial number 5495 003, which has amplified low voltage ranges 700 mV, 220 mV and 22 mV. At the rated input voltage the output voltage is approximately 2 V. The input connector of the standard is a type N female (The stainless steel connector saver should always be connected to the input of the Fluke 792A). The output connectors are 4 mm binding posts, female. A battery pack with connecting cable is included, as the travelling standard has to be operated on battery during measurement. **Note** that the 700 mV range is not working properly.

The temperature and relative humidity coefficients of the travelling standard are given below and corrections should be applied. The ac-dc voltage transfer difference of the travelling standard also has a dependence on the power supply voltage. Hence the voltage of the battery pack should be measured a few times during the comparison, before and after recharging. The uncertainty due to the battery pack voltage is estimated to be insignificant compared to other contributions if the battery pack included in the travelling standard is used only. If not insignificant the pilot laboratory will add an uncertainty contribution.

Note that the equivalent input parallel resistance of a Fluke 792A is frequency dependent.

The temperature and relative humidity coefficients, at 23°C and 45% RH, of the ac-dc transfer difference of the travelling standard with their expanded uncertainties are given in the table below.

Range	Frequency	Temperature coefficient 10^{-6}/K	Expanded uncertainty 10^{-6}/K	Relative humidity coefficient 10^{-6}/%	Expanded uncertainty 10^{-6}/%
220 mV	1 kHz	0,4	1	0	0,02
	20 kHz	0,4	1	0	0,05
	100 kHz	0,6	1	0,1	0,1
	1 MHz	10	4	1,3	0,5
22 mV	1 kHz	1,2	2	0	0,02
	20 kHz	1,2	2	0	0,05
	100 kHz	1,3	2	0,1	0,1
	1 MHz	17	8	0,9	0,5

The correction $\Delta\delta_T$ of the ac-dc transfer difference due to temperature dependence of the travelling standard is:

$$\Delta\delta_T = \alpha_T \Delta T$$

where

α_T is the temperature coefficient, values and uncertainties given in table above.

ΔT is the correction for the deviation of the temperature from the reference value 23°C during the measurement (ΔT = 23 – temperature during measurement)

The correction $\Delta\delta_{RH}$ of the ac-dc transfer difference due to humidity dependence of the travelling standard is:

$$\Delta\delta_{RH} = \alpha_{RH} \Delta RH$$

where

α_{RH} is the relative humidity coefficient, values and uncertainties given in table above.
ΔRH is the correction for the deviation of the relative humidity from the reference value 45% during the measurement (ΔRH = 45 - RH during measurement)

The travelling standard has been evaluated and found to be very stable both regarding the long-term drift and the influence due to transportation.

4. Measuring conditions

The participating laboratories are asked to follow their usual measurement procedure to their best measurement capabilities in respect to the time frame of the comparison.

- The **ac-dc voltage transfer difference** of the travelling standard at **23°C, 45 % RH** is to be reported.
- The **reference plane** of the measured ac-dc voltage transfer difference should preferably be at the centre of a type N-Tee connector with type N male output connectors. The type of Tee connector used or the reference plane of the measured ac-dc voltage transfer difference has to be reported.
- The recommended **ambient conditions** are temperature (23±1)°C and relative humidity (45±10)%.
- The low of the input connector and the guard and the ground terminals of the transfer standard have to be connected to common ground in order to maintain a defined calibration condition. Connect the ground terminal to the guard terminal directly. Note that the output low and the input low are internally connected in the Fluke 792A.
- The travelling standard has to be **battery operated** and the battery pack should be disconnected from the mains during measurements. Connect the ground terminal of the Fluke 792A to its guard terminal. Due to the power supply voltage dependence of the ac-dc voltage transfer difference **only the travelling battery pack** has to be used. The maximum and minimum voltage of the battery pack during the measurements, as measured with the supplied dummy load has to be reported. The dummy load corresponds to the load of the 22 mV range of the transfer standard.
- Minimum 15 minutes should be allowed for **stabilisation** after power on and after changing the range.
- The **measuring frequency** has to be within 1 % of the nominal frequency. The frequency and its uncertainty should be reported.

5. Measuring scheme

The ac-dc voltage transfer difference of the travelling standard is to be measured at the voltages 100 mV and 10 mV and at the frequencies 1 kHz, 20 kHz, 100 kHz and 1 MHz. It is the same measuring points as in the key comparison CCEM-K11.

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 for at least the 1 kHz measuring point at each voltage level. If the uncertainty analysis is equal for the other measuring points the uncertainty contributions can be summarised in the uncertainty budget in Appendix 2.

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-down procedure;
- measuring set-up;
- level dependence, e.g. due to dc-effects;
- loading effects on resistive dividers or micropotentiometers;
- connectors;
- temperature;

- relative humidity dependency;
- measuring frequency;
- reproducibility;
- power supply voltage dependency (will be added by the pilot laboratory if significant).

7. Report

Each participating laboratory should send a report of the results to the pilot laboratory within one month after the measurements are completed. The report should contain at least:

- a description of the measuring method;
- the reference standard;
- a statement of traceability, if the national standard is not considered to be a primary standard;
- the ambient conditions of the measurement: the temperature and the humidity with limits of variation;
- the values of other influence parameters: the frequency of the measuring signal and its uncertainty, the maximum and minimum of the of the absolute value of the positive and negative voltage of the battery pack during measurement as measured with the dummy load;
- the results of the measurements;
- the associated standard uncertainties, the effective degrees of freedom and the expanded uncertainties
- a detailed uncertainty budget, which will be included in the final report. If a step-down procedure is used the uncertainty contributions of each step should be reported.

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

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 on each laboratory's own responsibility and cost. Due to the time constraint 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, the time for customs procedures inclusive. Inside the European Union no customs paper is necessary. For the participants outside the European Union an ATA-carnet will be provided. It is the responsibility of each laboratory that the ATA-carnet is used properly. At each transport the carnet must be presented to the customs on leaving the country and upon the arrival in the country of destination. When the package is sent unaccompanied the carnet must be included with the forwarding documents so the courier service can obtain customs clearance. In countries were ATA-carnet is not recognized standard customs procedures will be used. For customs purposes and/or transport insurance the value of the Fluke 792A is 40000 EURO or 50000 USD.

The travelling standard and accessories are packed in a transport case of size 68 cm · 38 cm · 41 cm and a total weight of 33 kg. The transport case can easily be opened for customs inspection.

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

In case of damage or evident malfunctioning of the travelling standard the pilot laboratory shall be informed immediately. If the damage cannot be repaired the comparison will be carried on using a spare travelling standard of the same model.

9. Circulation scheme

The time schedule will be arranged when the list of participating laboratories is completed. As the circulation has to be finished within a reasonable period of time, only four weeks are allowed for each participant including the time of transportation. For participants in other RMOs an extra week is allowed for transport.

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 allow, the laboratory will be able to carry out measurements at a later time.

10. Organisation

The pilot laboratory for the comparison is the Swedish National Testing and Research Institute (SP). The supprot group is Manfred Klonz, Physikalisch-Technische Bundesanstalt (PTB), Germany and Erik Dierikx, Nederlands Meetinstituut (NMi), the Netherlands.

The travelling standard will be dispatched from SP in the second half of 2005 and will return after the completion of each loop. The number of loops will depend on the number of participants.

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. Report of the comparison

Within three month after the completion of the circulation the pilot laboratory will prepare a draft A report and send to the participants for comments. Draft B report will then be prepared in co-operation with the support group. The reporting of the comparison will follow the EUROMET Guidelines.

12. Contact person

If there are any questions concerning the comparison, the contact person at the pilot laboratory is:

Karl-Erik Rydler

Address:

SP Swedish National Testing and Research Institute
Measurement Technology, MTe
Box 857
SE-501 15 BORÅS
Sweden

Delivery address:

SP Swedish National Testing and Research Institute
Measurement Technology, MTe
Brinellgatan 4
SE-504 62 BORÅS
Sweden

Telephone: +46 33 16 50 00 / Direct + 46 33 16 54 01
Fax: +46 33 12 50 38
E-mail: karlerik.rydler@sp.se

Appendix 1. Summary of results

Key comparison EUROMET.EM-K11 "ac-dc voltage transfer difference at low voltages"

Please send this information by e-mail also.

Acronym of institute:

Date of measurements:

Remarks:

Measuring result:

Voltage	Range	Measured ac-dc voltage difference / 10^{-6} at frequency			
		1 kHz	20 kHz	100 kHz	1 MHz
100 mV	220 mV				
10 mV	22 mV				

Expanded uncertainty:

Voltage	Range	Expanded uncertainty / 10^{-6} at frequency			
		1 kHz	20 kHz	100 kHz	1 MHz
100 mV	220 mV				
10 mV	22 mV				

Measuring frequency:

	Nominal frequency			
	1 kHz	20 kHz	100 kHz	1 MHz
Measuring frequency				
Expanded uncertainty				

Influence parameters:

	Min	Max	Remarks
Ambient temperature / ºC			
Relative humidity / %			
Pos. power supply voltage / V			Please state with mV resolution
Neg. power supply voltage / V			Please state with mV resolution

Appendix 2. Summary of uncertainty budget

Key comparison EUROMET.EM-K11 “ac-dc voltage transfer difference at low voltages”

Please send this information by e-mail also.

Acronym of institute:

Date:

Remarks:

Measuring voltage: 100 mV

Contribution of:	Std. unc. f: 1 kHz	Std. unc. f: 20 kHz	Std. unc. f: 100 kHz	Std. unc. f: 1 MHz	Type A or B	Distri- bution

Standard unc (k=1):				
Expanded unc:				
Eff. deg. of freedom:				

Measuring voltage: 10 mV

Contribution of:	Std. unc. f: 1 kHz	Std. unc. f: 20 kHz	Std. unc. f: 100 kHz	Std. unc. f: 1 MHz	Type A or B	Distri- bution

Standard unc (k=1):				
Expanded unc:				
Eff. deg. of freedom:				

Appendix 3. Packing list

Key comparison EUROMET.EM-K11 “ac-dc voltage transfer difference at low voltages”

1 pc. Fluke 792A, AC-DC transfer standard with power pack, power pack cable, instruction manual and accessories, S/N 5495 003.

Consisting of:

1 pc. Fluke 792A AC-DC transfer standard, S/N 5495 003.
1 pc. Fluke 792A Power pack, S/N 5495 003.
1 pc. Power pack cable.
1 pc. Fluke 792A Instruction manual.
and accessories:
1 pc. Stainless steel type N extender (should always be connected to the Fluke 792A AC-DC transfer standard input).
1 pc. Protective cap type N (should always be connected during transport to the Fluke 792A AC-DC transfer standard).
1 pc. Shorting bar (connected to the Fluke 792A AC-DC transfer standard).

1 pc. Power pack testing box, SP, Model 0202, S/N 001

1 pc. Technical protocol for the key comparison EUROMET.EM-K11.

Owner of equipment:

SP Swedish National Testing and Research Institute
Measurement Technology, MTe
Box 857
SE-501 15 BORÅS
Sweden

Delivery address:

SP Swedish National Testing and Research Institute
Measurement Technology, MTe
Brinellgatan 4
SE-504 62 BORÅS
Sweden

Contact person:
Karl-Erik Rydler

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E-mail: karlerik.rydler@sp.se