CIPM key comparison CCEM-K11 and CCEM-K11.1 of 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). The CCEM decided at the meeting in Sèvres, France, in September 2000 on a key comparison CCEM-K11 “ac-dc voltage transfer difference at low voltages” with the Swedish National Testing and Research Institute (SP) as the pilot laboratory and with the Physikalisch-Technische Bundesanstalt and the Nederlands Meetinstituut Van Swinden Laboratorium as support to the pilot laboratory.

This is the first international comparison of ac-dc voltage transfer difference in the mV-range and 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. The comparison is also a natural continuation after the key comparisons CCEM-K6.a “Key comparison of ac-dc voltage at the lowest attainable level of uncertainty” and CCEM-K9 “Comparison of ac-dc high voltage standards.”

A comparison of ac-dc voltage transfer difference at low voltages had been initiated by the EUROMET ac-dc experts meeting in 1997 and the EUROMET project No. 464 was started with SP as project coordinator. After a long period of characterisation and modification of the travelling standard the first loop of the comparison had just started when the CCEM decided on CCEM-K11. Hence, the EUROMET comparison was suspended until the finalization of CCEM-K11.

The aim of the comparison was set to show an agreement at 1 kHz within an expanded uncertainty of 10 µV/V and 50 µV/V at 100 mV and 10 mV respectively. The results show that this aim is mainly achieved.

2 Participants and organisation

The comparison was organised in accordance with the CCEM Guidelines for Planning, Conducting and Reporting Key, Attached, Supplementary and Pilot Comparisons (CCEM Guidelines). The technical protocol of the comparison was prepared by the pilot laboratory and the final version was agreed in cooperation with the support group. As a comparison had been initiated by the EUROMET ac-dc experts meeting in 1997 a suitable travelling standard was readily available. The comparison was organized with one travelling standard circulated in five consecutive loops with one to three participants. The stability of the travelling standard was monitored by measurements of the pilot laboratory between each loop. In case of failure the Nederlands Meetinstituut, Van Swinden Laboratorium had offered to supply a back-up standard of the same type.

The participants are listed in Table 1.

Table 1 Participants listed in chronological order of the first time schedule and final participation in CCEM-K11 or CCEM-K11.1.

Acronym	NMI	Country	Contact persons	Key comparison
SP	SP Technical Research Institute of Sweden[1]	Sweden	K.-E. Rydler V. Tarasso	CCEM-K11 CCEM-K11.1
PTB	Physikalisch-Technische Bundesanstalt,	Germany	M. Klonz G. Schliestedt	CCEM-K11
NPL	National Physical Laboratory	United Kingdom	G. Jones P. Wright	CCEM-K11
NMi	Nederlands Meetinstituut Van Swinden Laboratorium	The Netherlands	J. Th. Dessens C.J. van Mullem	CCEM-K11
VNIIM	D.I. Mendeleyev Institute for Metrology	Russia	G. P. Telitchenko	Withdrawn
NIM	National Institute of Metrology	P. R. China	J. Zhang C. Xu	CCEM-K11
SPRING	Singapore Standards, Productivity and Innovation Board	Singapore	L. Liu	CCEM-K11
NMIA	National Measurement Institute[2]	Australia	I. F. Budovsky.	CCEM-K11
INTI	Instituto Nacional de Tecnología Industrial	Argentina	H. Laiz L. Di Lillo	CCEM-K11
NRC-INMS	National Research Council - Institute of National Measurement Standards	Canada	P. S. Filipski	CCEM-K11
NIST	National Institute of Standards and Technology	U.S.A.	J. R. Kinard T. E. Lipe	CCEM-K11.1

[1] Swedish National Testing and Research Institute at the time of measurement

[2] Commonwealth Scientific and Industrial Research Organisation - National Measurement Laboratory (CSIRO-NML) at the time of measurement

3 Travelling standard and measuring instruction

The travelling standard was a Fluke 792A ac-dc transfer standard, serial number 6765 002, 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 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.

The ac-dc voltage transfer difference δ of the travelling 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}.

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 coefficients of the travelling standard were given and the measuring values should be corrected to a nominal temperature of 23°C applied, Table 2. 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 would 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.

Table 2 Temperature coefficients of the travelling standard

Range	Frequency	Temperature coefficient / (µV/V)K^{-1}	Expanded uncertainty / (µV/V)K^{-1}
220 mV	≤20 kHz	0	1
	100 kHz	1	1
	1 MHz	12	4
22 mV	≤100 kHz	0	2
	1 MHz	15	8

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.

NMI	Reference standard	Measurement method		Source of traceability
		100 mV	10 mV	
PTB	MJTC PTB	Direct comparison PMJTC	μPot step-down	In-house
NPL	MJTC PTB 1 kHz SJTC+900 Ω ≥20 kHz	Direct comparison SJTC	RVD 180:1 and RVD 89:1	In-house
NMi	MJTC PTB 1 kHz VSL-HF-S ≥20 kHz	μPot step-down	μPot step-down	In-house
NMIA	μPot	Direct comparison μPot	Direct comparison μPot	In-house
INTI	PMJTC PTB	Direct comparison PMJTC	μPot step-down	In-house ≤20 kHz PTB ≥100 kHz
NRC	MJTC Guildline 1 kHz, Calorimetric TVC ≥20 kHz	Direct comparison SJTC	Direct comparison Fluke 792A μPot step-down	In-house
SPRING	PMJTC PTB	Direct comparison PMJTC	RVD10:1	PTB
NIM	MJTC NIM and MJTC PTB	IVD	IVD	In-house at 1kHz PTB ≥20 kHz
NIST	MJTC Wilkins and MJTC PTB 1 kHz, SJTC+1 kΩ ≥20kHz	Direct comparison PMJTC and μPot step-down	μPot step-down	In-house
SP	MJTC PTB	μPot step-down	μPot step-down	PTB

5 Measurements of the pilot lab 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 only a few μV/V, Table 6.

The temperature coefficients of the travelling standard were characterized before the comparison started and were given in the technical protocol. The measured ac-dc transfer difference was asked to be reported at the reference temperature of 23 ºC. The power supply voltage coefficients of the travelling standard were also characterized before the comparison Table 4. 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. The influence is quite insignificant but corrections of the participants reported values to a reference voltage of 23.3 V are still made by the pilot laboratory, Table 10 to Table 17.

Table 4 Power supply voltage coefficient α_{PS} and expanded uncertainty $U(\alpha_{PS})$ of the travelling standard in (µV/V)/mV.

Range	1 kHz		20 kHz		100 kHz		1 MHz	
	α_{PS}	$U(\alpha_{PS})$	α_{PS}	$U(\alpha_{PS})$	α_{PS}	$U(\alpha_{PS})$	α_{PS}	$U(\alpha_{PS})$
220 mV	-0.008	0.02	-0.016	0.03	-0.004	0.04	0.27	0.15
22 mV	-0.038	0.06	-0.019	0.08	-0.024	0.12	0.52	0.40

In the end of the comparison it was observed that the stability of the travelling standard seemed correlated with the relative humidity (RH) and after the final loop its RH-coefficient was characterized. The influence of the relative humidity was as large as 2 (µV/V)/% at 10 mV, 1 MHz, Table 5. At the other measuring points it was measured to zero within some uncertainty. As the participants were requested to report min and max relative humidity it has been possible to make a correction of the reported ac-dc transfer differences to a reference value of 45%, Table 10 to Table 17. One laboratory did not measure the relative humidity at the time of the 100 mV measurement but in the evaluation the RH was assumed to have been 45%±10%.

Table 5 Relative humidity coefficient α_{RH} and expanded uncertainty $U(\alpha_{RH})$ of the travelling standard in (µV/V)/%.

Range	1 kHz		20 kHz		100 kHz		1 MHz	
	α_{RH}	$U(\alpha_{RH})$	α_{RH}	$U(\alpha_{RH})$	α_{RH}	$U(\alpha_{RH})$	α_{RH}	$U(\alpha_{RH})$
220 mV	0.00	0.02	0.00	0.04	0.00	0.10	0.0	1.0
22 mV	0.00	0.02	0.00	0.04	0.00	0.10	2.0	1.0

To our knowledge, a relative humidity coefficient has not been reported before for the type of ac-dc transfer standard with amplified mV-ranges, which is used as travelling standard in this comparison. Influence of RH has earlier been reported for thermal voltage converters on high voltage ranges.

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 one of the NMIs used a coverage factor $k_i = 2$. Although not explicitly asked for some of the NMIs also reported the effective degrees of freedom ν_{eff} of the standard uncertainty of the results. Out of these NMIs all but one reports $\nu_{eff} > 80$. For the NMI that reported low effective degrees of freedom the reported standard uncertainty is not used in the calculation of the weighted mean as the weight of this NMI would then be to large, without taking the ν_{eff} into account. Instead a standard uncertainty compensated for the ν_{eff} is calculated as the expanded uncertainty divided by a coverage factor $k=2$. This method was chosen to be able to use the common equation for the weight w_i. But it could also have been achieved by using the expanded uncertainty of results of the NMIs in the weight instead of the standard uncertainty.

6.1 Correction to nominal power supply voltage and relative humidity

Due to the power supply voltage coefficient and the relative humidity coefficient of the travelling standard the reported values were first corrected for the deviation from a nominal power supply voltage, set to 22.3 V, and the nominal relative humidity of 45%, (5). The corrected results δ_{ic} are obtained as:

$$\delta_{\mathrm{ic}} = \delta_{\mathrm{i}} + \Delta\delta_{\mathrm{PS}} + \Delta\delta_{\mathrm{RH}} \tag{1}$$

with a standard uncertainty u_{ic} given by:

$$u_{\mathrm{ic}}^2 = u_{\mathrm{i}}^2 + u_{\mathrm{PS}}^2 + u_{\mathrm{RH}}^2 \tag{2}$$

where

δ_{i}	ac-dc transfer difference reported by NMI i
$\Delta\delta_{\mathrm{PS}}$	correction of ac-dc transfer difference due to deviation of the power supply voltage from the nominal voltage 22.3 V
$\Delta\delta_{\mathrm{RH}}$	correction of ac-dc transfer difference due to deviation of the relative humidity from the nominal value 45%
u_{i}	standard uncertainty of ac-dc transfer difference reported by NMI i
u_{PS}	standard uncertainty of correction of ac-dc transfer difference due to power supply voltage dependence
u_{RH}	standard uncertainty of correction of ac-dc transfer difference due to relative humidity dependence

6.1.1 Correction due to power supply voltage

The correction $\Delta\delta_{\mathrm{PS}}$ of the results of the NMIs due to power supply voltage dependence of the ac-dc transfer difference of the travelling standard is determined as:

$$\Delta\delta_{\mathrm{PS}} = \alpha_{\mathrm{PS}} \Delta V_{\mathrm{PS}} \tag{3}$$

where

α_{PS}	power supply voltage coefficient measured by the pilot laboratory, values and uncertainties in Table 4
ΔV_{PS}	correction of the power supply voltage measured by a NMI relative the nominal voltage 22.3V, which is estimated from the sum of the absolute values of mean positive and negative power supply voltages measured by the NMIs with the reported min and max voltages as limits, rectangular distribution.

with a standard uncertainty u_{PS} given by:

$$u_{\mathrm{PS}}^2 = \Delta V_{\mathrm{PS}}{}^2 u^2(\alpha_{\mathrm{PS}}) + \alpha_{\mathrm{PS}}{}^2 u^2(\Delta V_{\mathrm{PS}}) + u^2(\alpha_{\mathrm{PS}}) u^2(\Delta V_{\mathrm{PS}}) \tag{4}$$

6.1.2 Correction due to relative humidity

During the comparison it was found that the ac-dc transfer difference of the travelling standard has a humidity dependence that was not negligible. The correction $\Delta\delta_{\mathrm{RH}}$ of the NMIs result due to humidity dependence of the ac-dc transfer difference of the travelling standard is:

$$\Delta\delta_{\mathrm{RH}} = \alpha_{\mathrm{RH}} \Delta RH \tag{5}$$

where

α_{RH}	relative humidity coefficient measured by the pilot laboratory, values and uncertainties in Table 5
ΔRH	relative humidity correction for the mean deviation of the relative humidity from the nominal value 45% during the measurement at a NMI estimated as the mean of the reported min and max RH and these values as limits, rectangular distribution

with a standard uncertainty u_{RH} given by:

$$u_{\mathrm{RH}}^2 = \Delta RH^2 u^2(\alpha_{\mathrm{RH}}) + \alpha_{\mathrm{RH}}{}^2 u^2(\Delta RH) + u^2(\alpha_{\mathrm{RH}}) u^2(\Delta RH) \tag{6}$$

6.1.3 Elimination of 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 measured at mean dates t_{j}. The annual drift is given together with the standard deviation of the residuals s_{r} in Table 6. The ac-dc transfer difference of the travelling standard δ_{iP} 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:

$$u_{\mathrm{iP}}^2 = s_{\mathrm{r}}^2 \left[1 + \frac{1}{\mathrm{n}} + \frac{(t_{\mathrm{i}} - \bar{t})^2}{\sum (t_{\mathrm{j}} - \bar{t})^2} \right] \tag{7}$$

where n is seven and $\bar{t}$ 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 from the corrected ac-dc transfer difference of the NMIs, Table 18 to Table 25. The drift compensated ac-dc transfer difference δ_{id} of NMI i is:

$$\delta_{\mathrm{id}} = \delta_{\mathrm{ic}} - \delta_{\mathrm{iP}} \tag{8}$$

with a standard uncertainty u_{id} given by:

$$u_{\mathrm{id}}^2 = u_{\mathrm{ic}}^2 + u_{\mathrm{iP}}^2 \tag{9}$$

Table 6 The estimated annual drift of the travelling standard and the standard deviation of the residuals s_r 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	0.15	0.43	0.00	0.53	0.75	0.66	-3.2	6.8
10 mV	1.1	1.3	-0.1	2.6	1.3	1.7	-0.4	6.8

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:

$$\delta_{\mathrm{id}} = \frac{1}{7}\sum_{\mathrm{k}=1}^{7} \delta_{\mathrm{kd}} \tag{10}$$

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

$$u_{\mathrm{id}}^2 = \frac{1}{7}\sum_{\mathrm{k}=1}^{7} u_{\mathrm{kd}}^2 \tag{11}$$

6.1.4 Reference value

Commonly the key comparison reference value (KCRV) is determined as the weighted mean of NMIs with mutually independent results and reliable uncertainty budgets. In this comparison the results of some NMIs are mutually correlated due to traceability to a common NMI at the reference level maintained by MJTCs or PMJTCs. But as all NMIs have mutually independent step-down procedures the correlation coefficients between NMIs are in the range 0 to 0.3 at 100 mV and in the range 0 to 0.1 at 10 mV. Due to the correlation the uncertainty of a weighted mean based on the results of all NMIs will be larger than if all the NMIs had been mutually independent. Still, the uncertainty of the KCRV based on the results of all NMIs can be smaller than the uncertainty based on the results of the fewer mutually independent NMIs.

An evaluation was done calculating the uncertainty of the KCRVs for NMIs with mutually independent results and for all NMIs in CCEM-K11. For six of the eight measuring points the uncertainty of the KCRV was equal or smaller if it was based on the results of all NMIs, despite the correlation.

Hence, the key comparison reference value δ_{R} for each of the eight measuring points is calculated as the weighted mean of δ_{id} of the nine participating NMIs in CCEM-K11 [1]. That is:

$$\delta_{\mathrm{R}} = \sum_{\mathrm{i}=1}^{9} w_{\mathrm{i}}\delta_{\mathrm{id}} \tag{12}$$

where the weights w_{i} are determined as:

$$w_i = \frac{\dfrac{1}{u_{id}^2}}{\sum\limits_{i=1}^{9} \dfrac{1}{u_{id}^2}} \qquad (13)$$

While the results of some NMIs are mutually correlated due to traceability to a common NMI also the results of all NMIs are mutually correlated as the corrections applied for power supply voltage, relative humidity, temperature and drift are not statistically independent. The standard uncertainty of the KCRV u_R is given by:

$$u_R^2 = u_{R'}^2 \left(1 + 2u_{R'}^2 \sum_{j=1}^{8} \sum_{k>j}^{9} \frac{1}{u_{jd} u_{kd}} \sum_m r_{jkm} \right) \qquad (14)$$

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

$$\frac{1}{u_{R'}^2} = \sum_{i=1}^{9} \frac{1}{u_{id}^2} \qquad (15)$$

and r_{jkm} is the correlation coefficient for the results of NMI$_j$ and NMI$_k$ due to mutual correlation of reason m, where m can be traceability to a common source or corrections applied for power supply voltage, relative humidity, temperature or drift. The correlation coefficient is determined as:

$$r_{jkm} = \frac{u_{jm} u_{km}}{u_{jd} u_{kd}} \qquad (16)$$

where u_{jd} and u_{kd} are the standard uncertainties u_{id} of NMI$_j$ and NMI$_k$ given by equation (9) or (11) and u_{jm} and u_{km} are the standard uncertainties associated with e.g. the traceability of NMI$_j$ and NMI$_k$ to a common source. The standard uncertainty associated with correlation due to correction of the drift u_{jdrift} is:

$$u_{jdrift} = \Delta t_j u(\alpha_{drift}) \qquad (17)$$

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 standard uncertainty associated with correlation due to correction to the nominal relative humidity u_{jRH} is:

$$u_{jRH} = \Delta RH_j u(\alpha_{RH}) \qquad (18)$$

where ΔRH_j is the deviation of the relative humidity during measurement of NMI$_j$ from the nominal relative humidity and $u(\alpha_{RH})$ is the standard uncertainty of the relative humidity coefficient of the travelling standard. The correlation coefficients due to correction to nominal power supply voltage are negligible. Based on the ambient temperatures reported by the participants it is estimated that the correlation coefficients due to, eventual, correction to nominal temperature are also negligible.

A summary of the calculated KCRV and the expanded uncertainties are given in Table 8.

Table 7 The maximum absolute value of correlation coefficients due to traceability to a common source or corrections applied for relative humidity and drift.

Voltage	Reason	Max correlation coefficient at frequency			
		1 kHz	20 kHz	100 kHz	1 MHz
100 mV	Traceability	0.04	0.04	0.08	0.23
	Drift	0.07	0.06	0.05	0.13
	RH	0.00	0.01	0.02	0.08
	Sum of all	0.07	0.06	0.08	0.29
10 mV	Traceability	0.01	0.00	0.01	0.08
	Drift	0.03	0.07	0.01	0.02
	RH	0.00	0.00	0.00	0.01
	Sum of all	0.02	0.07	0.01	0.09

Table 8 The KCRV 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	-0.5	2.3	-0.3	2.9	1.6	4.5	-7	27
10 mV	1.6	9.2	1.0	10.4	2.8	15.8	24	49

6.1.5 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:

$$\chi_{obs}^2 = \sum_{i=1}^{9} \frac{(\delta_{id} - \delta_R)^2}{u_{id}^2} \qquad (19)$$

The degrees of freedom ν = 8.
The consistency check is considered as failing if $\Pr\{ \chi^2(\nu) > \chi_{obs}^2 \} < 5\%$
where Pr denotes "probability of".

Table 9 The result of chi-square test.

	1 kHz	20 kHz	100 kHz	1 MHz
220 mV				
χ_{obs}^2	2,00	1,50	1,82	5,40
N	8	8	8	8
Pr	98%	99%	99%	71%
22 mV				
χ_{obs}^2	2,58	1,75	0,90	4,28
N	8	8	8	8
Pr	96%	99%	100%	83%

The chi-squared test is used although it is only for independent normal distributions. But as the mutual correlation is <0.3 the high probability still confirms the consistency of the results of this comparison for all measurement points. Alternative chi-squared tests taking correlation into account also confirm the consistency [2]. Hence the results in Table 8 can be accepted as the KCRV.

6.1.6 Degree of equivalence with the reference value

For the NMIs included in the determination of the KCRV the degree of equivalence D_i of a NMIs result with the KCRV is calculated as:

$$D_i = \delta_{id} - \delta_R \tag{20}$$

with a standard uncertainty u_{iD} given by:

$$u_{iD}^2 = u_{id}^2 - u_{R'}^2 \left(1 - 2u_{R'}^2 \sum_{j=1}^{8} \sum_{k>j}^{9} \frac{1}{u_{jd} u_{kd}} \sum_{m} r_{jkm} \right) \tag{21}$$

For the NMIs not included in the determination of the KCRV the degree of equivalence D_i of a NMIs result with the KCRV is calculated as:

$$D_i = \delta_{id} - \delta_R \tag{22}$$

with a standard uncertainty u_{iD} given by:

$$u_{iD}^2 = u_{id}^2 + u_R^2 \tag{23}$$

The expanded uncertainty U_i is calculated as:

$$U_i = k_{iD} u_{iD} \tag{24}$$

The coverage factor $k_{iD} = 2$ is used. The degrees of equivalence D_i and associated expanded uncertainties U_i are given in Table 26 and Table 27

6.1.7 Degree of equivalence between pairs of NMIs

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

$$D_{ij} = \delta_{id} - \delta_{jd} \tag{25}$$

with a standard uncertainty u_{ijD} given by:

$$u_{ijD}^2 = u_{id}^2 + u_{jd}^2 - 2u_{id} u_{jd} \sum_{m} r_{ijm} \tag{26}$$

The expanded uncertainty U_{ij} is calculated as:

$$U_{ij} = k_{ijD} u_{ijD} \tag{27}$$

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.

6.1.8 Tables and graphs of corrected results

In Table 10 to Table 17 the values reported by the participants are corrected for the relative humidity and power supply voltage deviations according to equation (1). Corrected values are shown in Figure 1 to Figure 8.

Table 10 Reported values of the participants δ_i and expanded uncertainties U_i, corrections for relative humidity deviations $\Delta\delta_{RH}$ and standard uncertainties u_{RH}, power supply voltage $\Delta\delta_{PS}$ and standard uncertainties u_{RH}, and corrected values δ_{ic} and expanded uncertainties U_{ic}

100 mV, 1 kHz		δ_i	U_i	$\Delta\delta_{RH}$	u_{RH}	$\Delta\delta_{PS}$	u_{PS}	δ_{ic}	U_{ic}
NMI	Date	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V
SP	sep-01	3,2	6,6	0,0	0,1	0,0	0,0	3,2	6,6
PTB	okt-01	3,4	2,8	0,0	0,1	0,0	0,2	3,4	2,8
NPL	dec-01	-2	9	0,0	0,1	0,0	0,1	-2,0	9,0
NMi	jan-02	1,4	8	0,0	0,0	0,0	0,1	1,4	8,0
SP	jul-02	4	6,6	0,0	0,1	0,0	0,0	4,0	6,6
NMIA	aug-02	3	5,9	0,0	0,1	0,1	0,1	3,1	5,9
INTI	okt-02	3	10	0,0	0,1	0,1	0,1	3,1	10,0
SP	jan-03	4,4	6,6	0,0	0,2	0,0	0,1	4,4	6,6
NRC	feb-03	4	5	0,0	0,2	0,0	0,1	4,0	5,0
SP	jun-03	3,5	6,6	0,0	0,1	0,0	0,0	3,5	6,6
SPRING	jul-03	0	18	0,0	0,1	0,0	0,1	0,0	18,0
NIM	aug-03	7	14	0,0	0,1	0,0	0,0	7,0	14,0
SP	okt-03	3,4	6,6	0,0	0,2	0,0	0,0	3,4	6,6
SP	jun-04	3,9	6,6	0,0	0,1	0,0	0,1	3,9	6,6
NIST	aug-04	2,6	12	0,0	0,1	0,0	0,1	2,6	12,0
SP	feb-05	4,2	6,6	0,0	0,2	0,0	0,1	4,2	6,6

Table 11 Reported values of the participants δ_i and expanded uncertainties U_i, corrections for relative humidity deviations $\Delta\delta_{RH}$ and standard uncertainties u_{RH}, power supply voltage $\Delta\delta_{PS}$ and standard uncertainties u_{RH}, and corrected values δ_{ic} and expanded uncertainties U_{ic}

100 mV, 20 kHz		δ_i	U_i	$\Delta\delta_{RH}$	u_{RH}	$\Delta\delta_{PS}$	u_{PS}	δ_{ic}	U_{ic}
NMI	Date	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V
SP	sep-01	4,3	6,8	0,0	0,2	0,0	0,0	4,3	6,8
PTB	okt-01	3,9	4,8	0,0	0,1	0,0	0,2	3,9	4,8
NPL	dec-01	1	9	0,0	0,2	0,0	0,1	1,0	9,0
NMi	jan-02	5,1	12	0,0	0,1	0,0	0,1	5,1	12,0
SP	jul-02	5,4	6,8	0,0	0,1	0,0	0,0	5,4	6,8
NMIA	aug-02	7	7	0,0	0,1	0,0	0,1	7,0	7,0
INTI	okt-02	5	10	0,0	0,1	0,0	0,1	5,0	10,0
SP	jan-03	4,1	6,8	0,0	0,4	0,0	0,1	4,1	6,9
NRC	feb-03	4	6	0,0	0,3	0,0	0,1	4,0	6,0
SP	jun-03	4,2	6,8	0,0	0,2	0,0	0,0	4,2	6,8
SPRING	jul-03	0	24	0,0	0,2	0,0	0,1	0,0	24,0
NIM	aug-03	1	16	0,0	0,2	0,0	0,0	1,0	16,0
SP	okt-03	4,1	6,8	0,0	0,3	0,0	0,1	4,1	6,8
SP	jun-04	4,5	6,8	0,0	0,2	0,0	0,1	4,5	6,8
NIST	aug-04	1,4	12,3	0,0	0,3	0,0	0,1	1,4	12,3
SP	feb-05	4,8	6,8	0,0	0,3	0,0	0,1	4,8	6,8

Table 12 Reported values of the participants δ_i and expanded uncertainties U_i, corrections for relative humidity deviations $\Delta\delta_{RH}$ and standard uncertainties u_{RH}, power supply voltage $\Delta\delta_{PS}$ and standard uncertainties u_{RH}, and corrected values δ_{ic} and expanded uncertainties U_{ic}

100 mV, 100 kHz		δ_i	U_i	$\Delta\delta_{RH}$	u_{RH}	$\Delta\delta_{PS}$	u_{PS}	δ_{ic}	U_{ic}
NMI	Date	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V
SP	sep-01	39	13	0,0	0,4	0,0	0,0	39,0	13,0
PTB	okt-01	39	6,6	0,0	0,3	0,0	0,3	39,0	6,6
NPL	dec-01	38	13	0,0	0,4	0,0	0,1	38,0	13,0
NMi	jan-02	40,1	15	0,0	0,1	0,0	0,1	40,1	15,0
SP	jul-02	40	13	0,0	0,3	0,0	0,1	40,0	13,0
NMIA	aug-02	40	16	0,0	0,3	0,0	0,2	40,0	16,0
INTI	okt-02	41	21	0,0	0,3	0,0	0,2	41,0	21,0
SP	jan-03	40	13	0,0	1,0	0,0	0,1	40,0	13,2
NRC	feb-03	45	7	0,0	0,8	0,0	0,1	45,0	7,2
SP	jun-03	39	13	0,0	0,5	0,0	0,0	39,0	13,0
SPRING	jul-03	36	27	0,0	0,5	0,0	0,1	36,0	27,0
NIM	aug-03	50	30	0,0	0,4	0,0	0,0	50,0	30,0
SP	okt-03	40	13	0,0	0,8	0,0	0,1	40,0	13,1
SP	jun-04	41	13	0,0	0,5	0,0	0,1	41,0	13,0
NIST	aug-04	45,4	22,6	0,0	0,7	0,0	0,1	45,4	22,6
SP	feb-05	42	13	0,0	0,8	0,0	0,1	42,0	13,1

Table 13 Reported values of the participants δ_i and expanded uncertainties U_i, corrections for relative humidity deviations $\Delta\delta_{RH}$ and standard uncertainties u_{RH}, power supply voltage $\Delta\delta_{PS}$ and standard uncertainties u_{RH}, and corrected values δ_{ic} and expanded uncertainties U_{ic}

100 mV, 1 MHz		δ_i	U_i	$\Delta\delta_{RH}$	u_{RH}	$\Delta\delta_{PS}$	u_{PS}	δ_{ic}	U_{ic}
NMI	Date	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V
SP	sep-01	199	60	0,0	4,2	-0,3	0,5	198,7	60,6
PTB	okt-01	162	47	0,0	2,9	0,8	3,4	162,8	47,8
NPL	dec-01	172	65	0,0	3,8	0,3	1,9	172,3	65,6
NMi	jan-02	189	100	0,0	1,4	0,3	1,5	189,3	100,1
SP	jul-02	190	60	0,0	3,3	-0,6	0,5	189,4	60,4
NMIA	aug-02	203	76	0,0	2,9	-2,0	0,7	201,0	76,2
INTI	okt-02	160	60	0,0	2,9	-2,0	0,9	158,0	60,3
SP	jan-03	203	60	0,0	10,4	1,4	0,6	204,4	63,5
NRC	feb-03	200	25	0,0	7,6	0,1	1,9	200,1	29,5
SP	jun-03	192	60	0,0	4,9	-0,4	0,5	191,6	60,8
SPRING	jul-03	180	86	0,0	5,2	-0,3	1,5	179,7	86,7
NIM	aug-03	257	98	0,0	3,8	0,0	0,5	257,0	98,3
SP	okt-03	192	60	0,0	7,6	0,8	0,5	192,8	61,9
SP	jun-04	183	60	0,0	5,3	-1,4	0,6	181,7	61,0
NIST	aug-04	181,7	68,6	0,0	7,0	0,9	1,1	182,6	70,0
SP	feb-05	190	60	0,0	7,6	1,4	0,6	191,4	61,9

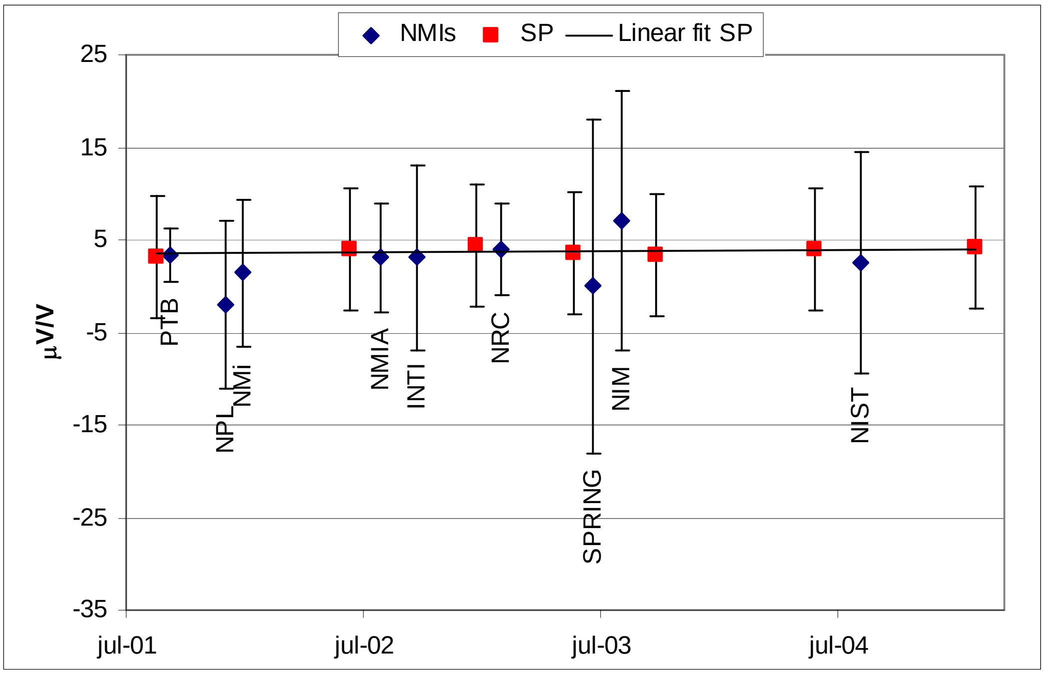

Figure 1 Reported values corrected for power supply voltage and relative humidity deviations (δ_{ic}), 100 mV, 1 kHz.

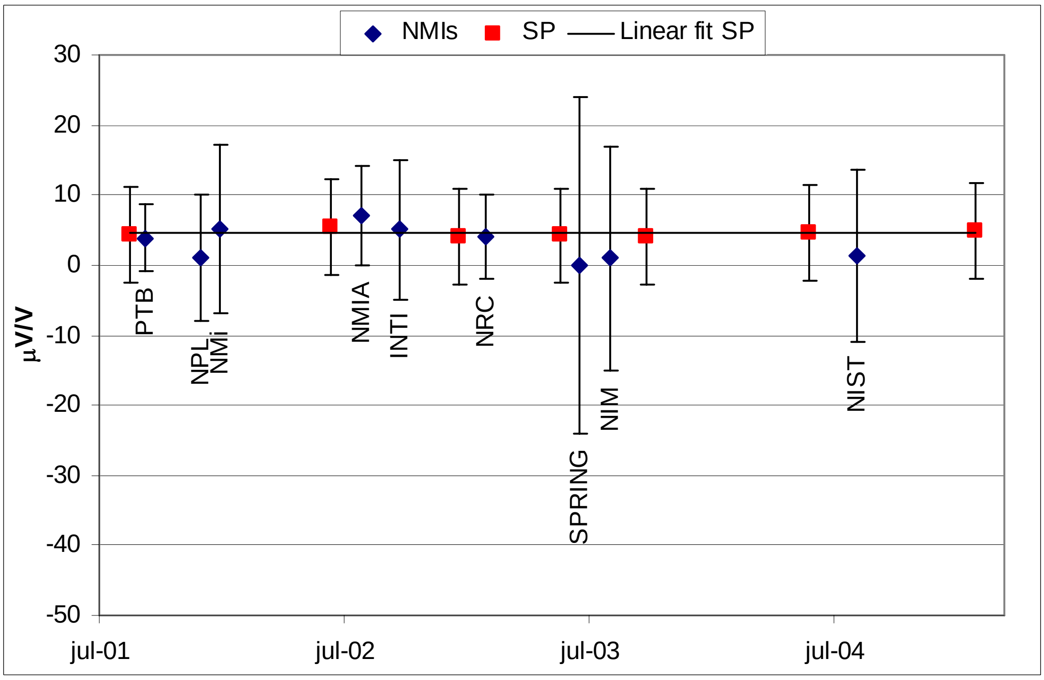

Figure 2 Reported values corrected for power supply voltage and relative humidity deviations (δ_{ic}), 100 mV, 20 kHz

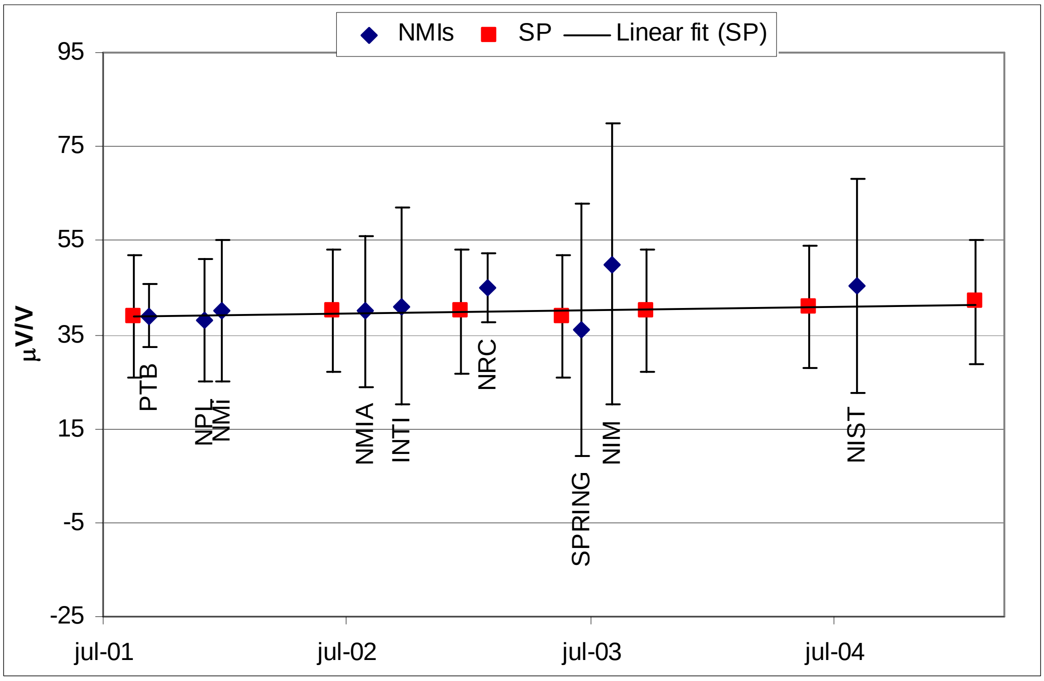

Figure 3 Reported values corrected for power supply voltage and relative humidity deviations (δ_{ic}), 100 mV, 100 kHz

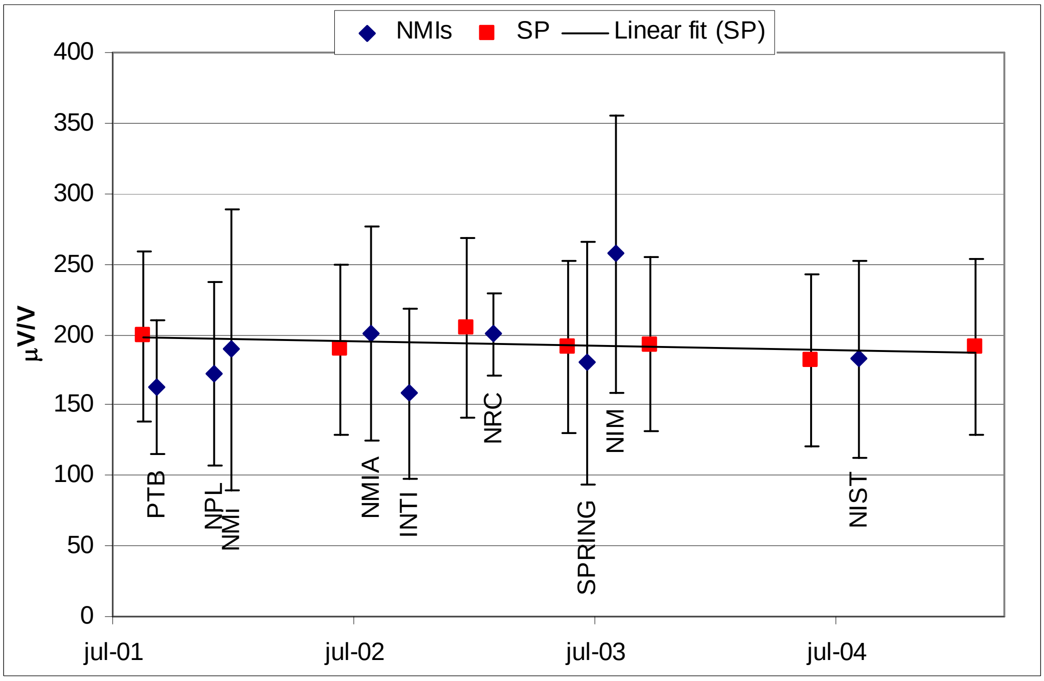

Figure 4 Reported values corrected for power supply voltage and relative humidity deviations (δ_{ic}), 100 mV, 1MHz

Table 14 Reported values of the participants δ_i and expanded uncertainties U_i, corrections for relative humidity deviations $\Delta\delta_\mathrm{RH}$ and standard uncertainties u_RH, power supply voltage $\Delta\delta_\mathrm{PS}$ and standard uncertainties u_RH, and corrected values δ_ic and expanded uncertainties U_ic

10 mV, 1 kHz		δ_i	U_i	$\Delta\delta_\mathrm{RH}$	u_RH	$\Delta\delta_\mathrm{PS}$	u_PS	δ_ic	U_ic
NMI	Date	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V
SP	sep-01	12,2	22	0,0	0,1	-0,2	0,1	12,0	22,0
PTB	okt-01	8	41	0,0	0,1	0,2	0,4	8,2	41,0
NPL	dec-01	11	30	0,0	0,1	0,0	0,3	11,0	30,0
NMi	jan-02	6,1	40	0,0	0,0	0,0	0,3	6,1	40,0
SP	jul-02	12,6	22	0,0	0,1	-0,1	0,1	12,5	22,0
NMIA	aug-02	15	14	0,0	0,1	0,3	0,2	15,3	14,0
INTI	okt-02	28	26	0,0	0,1	0,3	0,3	28,3	26,0
SP	jan-03	15,3	22	0,0	0,2	-0,1	0,1	15,2	22,0
NRC	feb-03	24	36	0,0	0,2	0,0	0,3	24,0	36,0
SP	jun-03	16,6	22	0,0	0,1	0,1	0,1	16,7	22,0
SPRING	jul-03	15	34	0,0	0,1	0,0	0,3	15,0	34,0
NIM	aug-03	-24	78	0,0	0,1	0,0	0,1	-24,0	78,0
SP	okt-03	16,1	22	0,0	0,2	-0,2	0,2	15,9	22,0
SP	jun-04	15	22	0,0	0,1	0,2	0,2	15,2	22,0
NIST	aug-04	23,6	36,4	0,0	0,1	-0,1	0,2	23,5	36,4
SP	feb-05	16	22	0,0	0,2	-0,2	0,2	15,8	22,0

Table 15 Reported values of the participants δ_i and expanded uncertainties U_i, corrections for relative humidity deviations $\Delta\delta_\mathrm{RH}$ and standard uncertainties u_RH, power supply voltage $\Delta\delta_\mathrm{PS}$ and standard uncertainties u_RH, and corrected values δ_ic and expanded uncertainties U_ic

10 mV, 20 kHz		δ_i	U_i	$\Delta\delta_\mathrm{RH}$	u_RH	$\Delta\delta_\mathrm{PS}$	u_PS	δ_ic	U_ic
NMI	Date	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V
SP	sep-01	-9,8	22	0,0	0,2	-0,1	0,2	-9,9	22,0
PTB	okt-01	-21	42	0,0	0,1	0,1	0,4	-20,9	42,0
NPL	dec-01	-12	30	0,0	0,2	0,0	0,3	-12,0	30,0
NMi	jan-02	-14,9	40	0,0	0,1	0,0	0,2	-14,9	40,0
SP	jul-02	-11,5	22	0,0	0,1	0,0	0,1	-11,5	22,0
NMIA	aug-02	-6	16	0,0	0,1	0,1	0,3	-5,9	16,0
INTI	okt-02	3	29	0,0	0,1	0,1	0,3	3,1	29,0
SP	jan-03	-7,9	22	0,0	0,4	-0,1	0,1	-8,0	22,0
NRC	feb-03	-6	32	0,0	0,3	0,0	0,3	-6,0	32,0
SP	jun-03	-5	22	0,0	0,2	0,0	0,1	-5,0	22,0
SPRING	jul-03	-10	37	0,0	0,2	0,0	0,2	-10,0	37,0
NIM	aug-03	-36	78	0,0	0,2	0,0	0,1	-36,0	78,0
SP	okt-03	-9,8	22	0,0	0,4	-0,1	0,2	-9,9	22,0
SP	jun-04	-10,2	22	0,0	0,2	0,1	0,2	-10,1	22,0
NIST	aug-04	16,5	38,5	0,0	0,3	-0,1	0,2	16,4	38,5
SP	feb-05	-10,4	22	0,0	0,3	-0,1	0,3	-10,5	22,0

Table 16 Reported values of the participants δ_i and expanded uncertainties U_i, corrections for relative humidity deviations $\Delta\delta_{RH}$ and standard uncertainties u_{RH}, power supply voltage $\Delta\delta_{PS}$ and standard uncertainties u_{RH}, and corrected values δ_{ic} and expanded uncertainties U_{ic}

10 mV, 100 kHz		δ_i	U_i	$\Delta\delta_{RH}$	u_{RH}	$\Delta\delta_{PS}$	u_{PS}	δ_{ic}	U_{ic}
NMI	Date	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V
SP	sep-01	-5	33	0,0	0,5	-0,1	0,3	-5,1	33,0
PTB	okt-01	-13	45	0,0	0,3	0,1	0,6	-12,9	45,0
NPL	dec-01	0	42	0,0	0,4	0,0	0,5	0,0	42,0
NMi	jan-02	-8,5	50	0,0	0,1	0,0	0,3	-8,5	50,0
SP	jul-02	-5	33	0,0	0,3	-0,1	0,2	-5,1	33,0
NMIA	aug-02	4	42	0,0	0,3	0,2	0,5	4,2	42,0
INTI	okt-02	10	46	0,0	0,3	0,2	0,5	10,2	46,0
SP	jan-03	-7	33	0,0	1,0	-0,1	0,2	-7,1	33,1
NRC	feb-03	5	61	0,0	0,8	0,0	0,4	5,0	61,0
SP	jun-03	-6	33	0,0	0,5	0,0	0,2	-6,0	33,0
SPRING	jul-03	-11	44	0,0	0,5	0,0	0,3	-11,0	44,0
NIM	aug-03	0	96	0,0	0,4	0,0	0,1	0,0	96,0
SP	okt-03	-5	33	0,0	0,9	-0,1	0,3	-5,1	33,1
SP	jun-04	-2	33	0,0	0,5	0,1	0,3	-1,9	33,0
NIST	aug-04	-2,5	50,4	0,0	0,7	-0,1	0,3	-2,6	50,4
SP	feb-05	-1	33	0,0	0,8	-0,2	0,4	-1,2	33,0

Table 17 Reported values of the participants δ_i and expanded uncertainties U_i, corrections for relative humidity deviations $\Delta\delta_{RH}$ and standard uncertainties u_{RH}, power supply voltage $\Delta\delta_{PS}$ and standard uncertainties u_{RH}, and corrected values δ_{ic} and expanded uncertainties U_{ic}

10 mV, 1 MHz		δ_i	U_i	$\Delta\delta_{RH}$	u_{RH}	$\Delta\delta_{PS}$	u_{PS}	δ_{ic}	U_{ic}
NMI	Date	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V
SP	sep-01	-162	96	16,0	12,6	2,1	1,3	-143,9	99,3
PTB	okt-01	-157	105	0,0	11,9	-3,1	4,0	-160,1	108,0
NPL	dec-01	-172	282	10,0	12,2	0,5	3,9	-161,5	283,2
NMi	jan-02	-90	300	0,0	6,0	0,5	2,9	-89,5	300,3
SP	jul-02	-138	96	-2,0	11,9	1,4	1,1	-138,6	98,9
NMIA	aug-02	-99	107	-10,0	6,5	-3,9	1,7	-112,9	107,8
INTI	okt-02	-131	110	-10,0	6,5	-3,9	2,1	-144,9	110,8
SP	jan-03	-177	96	38,0	15,2	1,5	1,1	-137,5	100,7
NRC	feb-03	-105	89	30,0	8,9	0,3	3,7	-74,7	91,1
SP	jun-03	-160	96	18,0	12,7	-0,9	1,0	-142,9	99,3
SPRING	jul-03	-138	370	-20,0	7,8	-0,5	2,9	-158,5	370,4
NIM	aug-03	31	186	-10,0	12,2	0,0	1,0	21,0	187,6
SP	okt-03	-165	96	34,0	14,6	2,8	1,4	-128,2	100,4
SP	jun-04	-163	96	18,0	12,7	-2,3	1,3	-147,3	99,4
NIST	aug-04	-125,4	140	26,0	12,5	1,8	2,2	-97,6	142,3
SP	feb-05	-174	96	28,0	13,8	3,4	1,6	-142,6	99,9

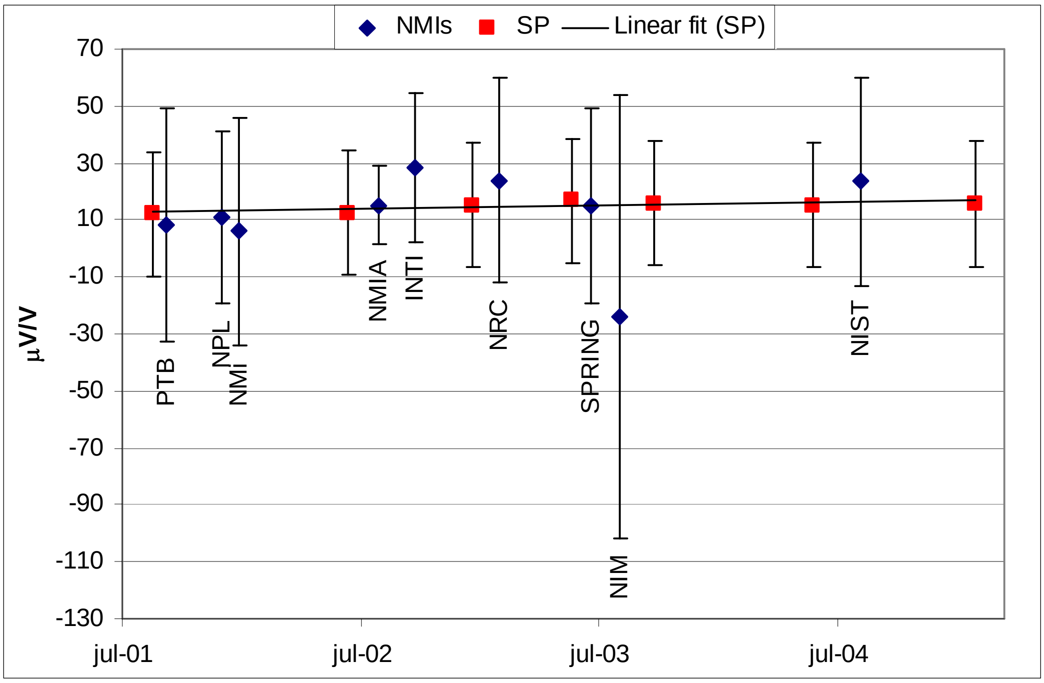

Figure 5 Reported values corrected for power supply voltage and relative humidity deviations (δ_{ic}), 10 mV, 1 kHz

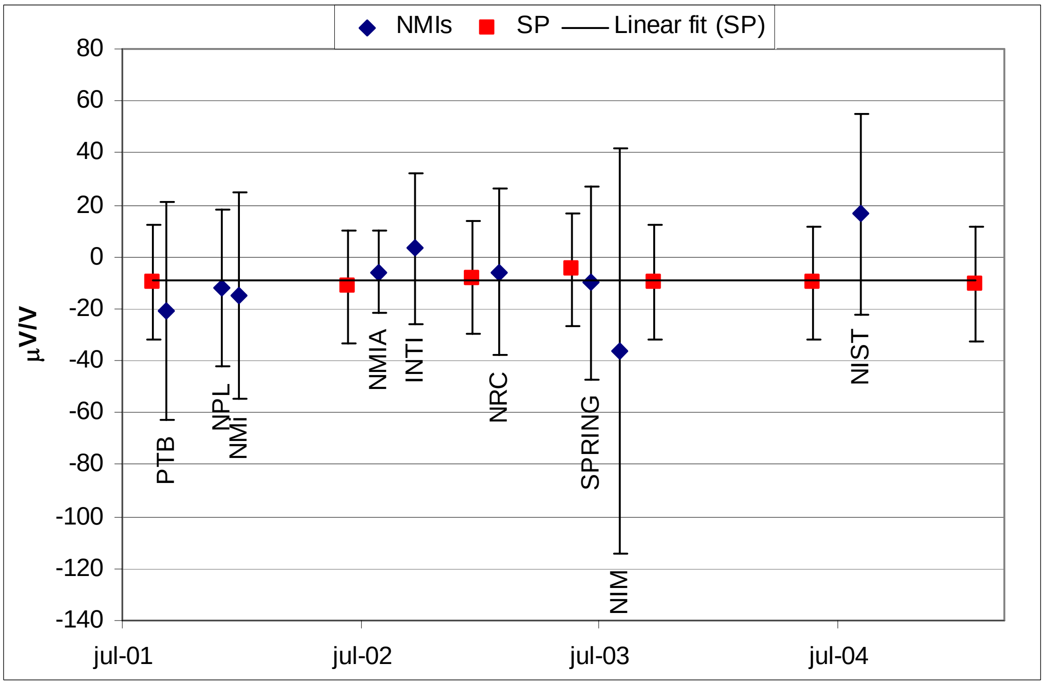

Figure 6 Reported values corrected for power supply voltage and relative humidity deviations (δ_{ic}), 10 mV, 20 kHz

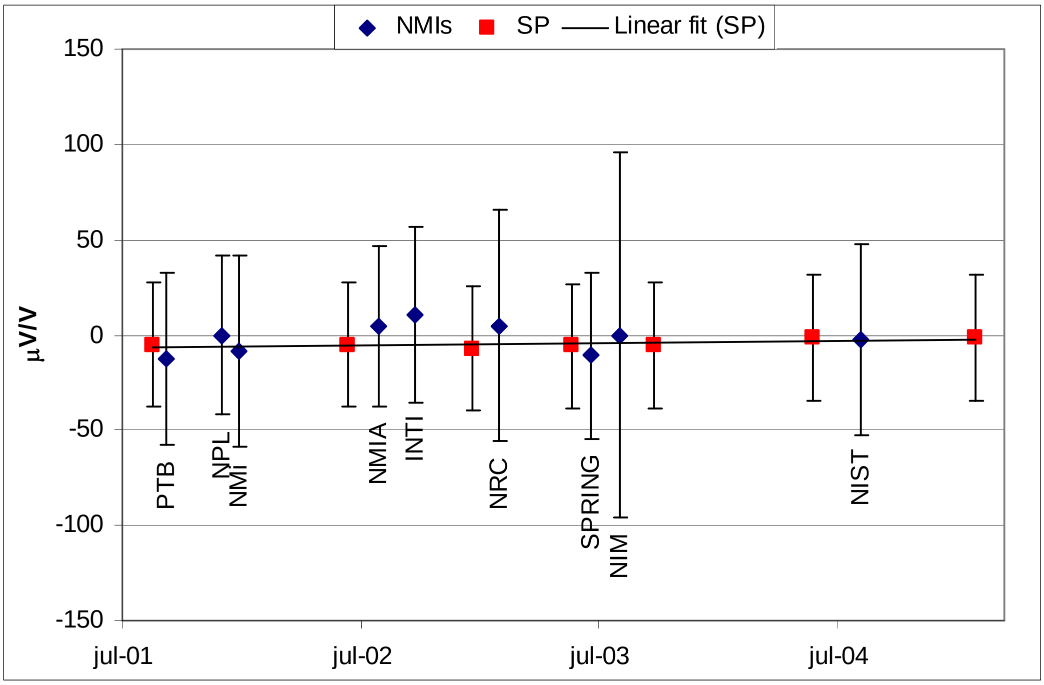

Figure 7 Reported values corrected for power supply voltage and relative humidity deviations (δ_{ic}), 10 mV, 100 kHz

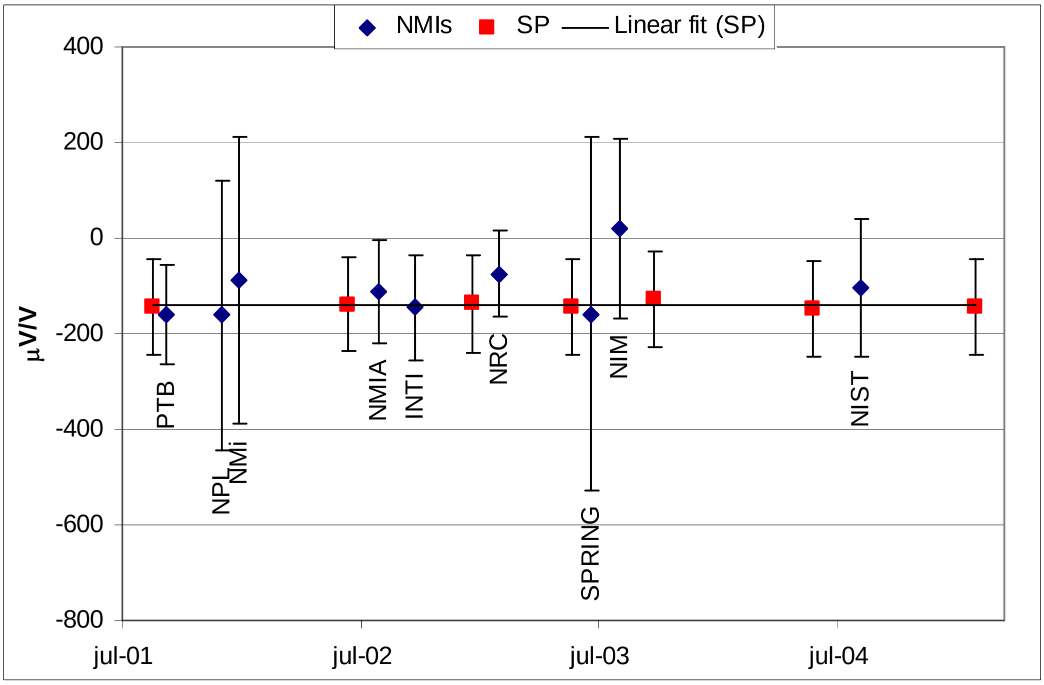

Figure 8 Reported values corrected for power supply voltage and relative humidity deviations (δ_{ic}), 10 mV, 1 MHz

6.1.9 Tables of results after elimination of drift

In Table 18 to Table 25 the drift of the travelling standard is eliminated from the results by subtracting the ac-dc transfer difference predicted by the pilot laboratory from the corrected ac-dc transfer difference of the NMIs according to equation (8).

Table 18 Corrected values of the participants δ_{ic} and expanded uncertainties U_{ic}, values of the travelling standard predicted by the pilot laboratory δ_P and standard uncertainties u_P, and drift compensated values δ_{id} and expanded uncertainties U_{id}

100 mV, 1 kHz		δ_{ic}	U_{ic}	δ_P	u_P	δ_{id}	U_{id}
NMI	Date	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V
SP	sep-01	3,2	6,6	3,5	0,5	-0,3	6,7
PTB	okt-01	3,4	2,8	3,5	0,5	-0,2	3,0
NPL	dec-01	-2,0	9,0	3,6	0,5	-5,6	9,1
NMi	jan-02	1,4	8,0	3,6	0,5	-2,2	8,1
SP	jul-02	4,0	6,6	3,7	0,5	0,4	6,7
NMIA	aug-02	3,1	5,9	3,7	0,5	-0,6	6,0
INTI	okt-02	3,1	10,0	3,7	0,5	-0,6	10,0
SP	jan-03	4,4	6,6	3,7	0,5	0,6	6,7
NRC	feb-03	4,0	5,0	3,8	0,5	0,2	5,1
SP	jun-03	3,5	6,6	3,8	0,5	-0,3	6,7
SPRING	jul-03	0,0	18,0	3,8	0,5	-3,8	18,0
NIM	aug-03	7,0	14,0	3,8	0,5	3,2	14,0
SP	okt-03	3,4	6,6	3,8	0,5	-0,5	6,7
SP	jun-04	3,9	6,6	3,9	0,5	0,0	6,7
NIST	aug-04	2,6	12,0	4,0	0,5	-1,4	12,0
SP	feb-05	4,2	6,6	4,0	0,5	0,1	6,7

Table 19 Corrected values of the participants δ_{ic} and expanded uncertainties U_{ic}, values of the travelling standard predicted by the pilot laboratory δ_P and standard uncertainties u_P, and drift compensated values δ_{id} and expanded uncertainties U_{id}

100 mV, 20 kHz		δ_{ic}	U_{ic}	δ_P	u_P	δ_{id}	U_{id}
NMI	Date	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V
SP	sep-01	4,3	6,8	4,5	0,6	-0,2	6,9
PTB	okt-01	3,9	4,8	4,5	0,6	-0,6	5,0
NPL	dec-01	1,0	9,0	4,5	0,6	-3,5	9,1
NMi	jan-02	5,1	12,0	4,5	0,6	0,6	12,1
SP	jul-02	5,4	6,8	4,5	0,6	0,9	6,9
NMIA	aug-02	7,0	7,0	4,5	0,6	2,6	7,1
INTI	okt-02	5,0	10,0	4,5	0,6	0,6	10,1
SP	jan-03	4,1	6,9	4,5	0,6	-0,4	6,9
NRC	feb-03	4,0	6,0	4,5	0,6	-0,5	6,1
SP	jun-03	4,2	6,8	4,5	0,6	-0,3	6,9
SPRING	jul-03	0,0	24,0	4,5	0,6	-4,5	24,0
NIM	aug-03	1,0	16,0	4,5	0,6	-3,5	16,0
SP	okt-03	4,1	6,8	4,5	0,6	-0,4	6,9
SP	jun-04	4,5	6,8	4,5	0,6	0,0	6,9
NIST	aug-04	1,4	12,3	4,5	0,6	-3,1	12,4
SP	feb-05	4,8	6,8	4,5	0,6	0,3	6,9

Table 20 Corrected values of the participants δ_{ic} and expanded uncertainties U_{ic}, values of the travelling standard predicted by the pilot laboratory δ_P and standard uncertainties u_P, and drift compensated values δ_{id} and expanded uncertainties U_{id}

100 mV, 100 kHz		δ_{ic}	U_{ic}	δ_P	u_P	δ_{id}	U_{id}
NMI	Date	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V
SP	sep-01	39,0	13,0	38,8	0,8	0,2	13,1
PTB	okt-01	39,0	6,6	38,9	0,8	0,1	6,8
NPL	dec-01	38,0	13,0	39,0	0,8	-1,0	13,1
NMi	jan-02	40,1	15,0	39,1	0,8	1,0	15,1
SP	jul-02	40,0	13,0	39,4	0,7	0,6	13,1
NMIA	aug-02	40,0	16,0	39,5	0,7	0,5	16,1
INTI	okt-02	41,0	21,0	39,7	0,7	1,4	21,1
SP	jan-03	40,0	13,2	39,8	0,7	0,1	13,2
NRC	feb-03	45,0	7,2	39,9	0,7	5,1	7,3
SP	jun-03	39,0	13,0	40,1	0,7	-1,1	13,1
SPRING	jul-03	36,0	27,0	40,2	0,7	-4,2	27,1
NIM	aug-03	50,0	30,0	40,3	0,7	9,7	30,0
SP	okt-03	40,0	13,1	40,4	0,7	-0,4	13,2
SP	jun-04	41,0	13,0	40,9	0,7	0,1	13,1
NIST	aug-04	45,4	22,6	41,1	0,8	4,3	22,7
SP	feb-05	42,0	13,1	41,4	0,8	0,6	13,2

Table 21 Corrected values of the participants δ_{ic} and expanded uncertainties U_{ic}, values of the travelling standard predicted by the pilot laboratory δ_P and standard uncertainties u_P, and drift compensated values δ_{id} and expanded uncertainties U_{id}

100 mV, 1 MHz		δ_{ic}	U_{ic}	δ_P	u_P	δ_{id}	U_{id}
NMI	Date	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V
SP	sep-01	198,7	60,6	198,4	8,3	0,4	62,8
PTB	okt-01	162,8	47,8	198,2	8,3	-35,4	50,6
NPL	dec-01	172,3	65,6	197,5	8,0	-25,2	67,5
NMi	jan-02	189,3	100,1	197,2	7,9	-8,0	101,3
SP	jul-02	189,4	60,4	195,8	7,6	-6,4	62,2
NMIA	aug-02	201,0	76,2	195,4	7,5	5,6	77,7
INTI	okt-02	158,0	60,3	194,9	7,4	-36,9	62,1
SP	jan-03	204,4	63,5	194,1	7,3	10,3	65,2
NRC	feb-03	200,1	29,5	193,8	7,3	6,4	32,9
SP	jun-03	191,6	60,8	192,8	7,2	-1,2	62,5
SPRING	jul-03	179,7	86,7	192,6	7,2	-12,8	87,9
NIM	aug-03	257,0	98,3	192,2	7,2	64,8	99,4
SP	okt-03	192,8	61,9	191,7	7,3	1,1	63,6
SP	jun-04	181,7	61,0	189,6	7,6	-8,0	62,8
NIST	aug-04	182,6	70,0	189,0	7,8	-6,4	71,8
SP	feb-05	191,4	61,9	187,5	8,3	3,9	64,1

Table 22 Corrected values of the participants δ_{ic} and expanded uncertainties U_{ic}, values of the travelling standard predicted by the pilot laboratory δ_P and standard uncertainties u_P, and drift compensated values δ_{id} and expanded uncertainties U_{id}

10 mV, 1 kHz		δ_{ic}	U_{ic}	δ_P	u_P	δ_{id}	U_{id}
NMI	Date	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V
SP	sep-01	12,0	22,0	12,8	1,6	-0,7	22,2
PTB	okt-01	8,2	41,0	12,8	1,6	-4,6	41,1
NPL	dec-01	11,0	30,0	13,1	1,5	-2,1	30,2
NMi	jan-02	6,1	40,0	13,2	1,5	-7,1	40,1
SP	jul-02	12,5	22,0	13,7	1,4	-1,2	22,2
NMIA	aug-02	15,3	14,0	13,8	1,4	1,4	14,3
INTI	okt-02	28,3	26,0	14,0	1,4	14,3	26,2
SP	jan-03	15,2	22,0	14,3	1,4	0,9	22,2
NRC	feb-03	24,0	36,0	14,4	1,4	9,6	36,1
SP	jun-03	16,7	22,0	14,8	1,4	1,9	22,2
SPRING	jul-03	15,0	34,0	14,8	1,4	0,2	34,1
NIM	aug-03	-24,0	78,0	15,0	1,4	-39,0	78,0
SP	okt-03	15,9	22,0	15,1	1,4	0,8	22,2
SP	jun-04	15,2	22,0	15,9	1,5	-0,7	22,2
NIST	aug-04	23,5	36,4	16,1	1,5	7,3	36,5
SP	feb-05	15,8	22,0	16,7	1,6	-0,9	22,2

Table 23 Corrected values of the participants δ_{ic} and expanded uncertainties U_{ic}, values of the travelling standard predicted by the pilot laboratory δ_P and standard uncertainties u_P, and drift compensated values δ_{id} and expanded uncertainties U_{id}

10 mV, 20 kHz		δ_{ic}	U_{ic}	δ_P	u_P	δ_{id}	U_{id}
NMI	Date	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V
SP	sep-01	-9,9	22,0	-9,2	2,9	-0,7	22,8
PTB	okt-01	-20,9	42,0	-9,2	2,9	-11,7	42,4
NPL	dec-01	-12,0	30,0	-9,2	2,8	-2,8	30,5
NMi	jan-02	-14,9	40,0	-9,2	2,8	-5,7	40,4
SP	jul-02	-11,5	22,0	-9,2	2,7	-2,3	22,6
NMIA	aug-02	-5,9	16,0	-9,2	2,6	3,4	16,9
INTI	okt-02	3,1	29,0	-9,2	2,6	12,4	29,5
SP	jan-03	-8,0	22,0	-9,2	2,6	1,3	22,6
NRC	feb-03	-6,0	32,0	-9,3	2,6	3,2	32,4
SP	jun-03	-5,0	22,0	-9,3	2,6	4,3	22,6
SPRING	jul-03	-10,0	37,0	-9,3	2,6	-0,7	37,4
NIM	aug-03	-36,0	78,0	-9,3	2,6	-26,7	78,2
SP	okt-03	-9,9	22,0	-9,3	2,6	-0,6	22,6
SP	jun-04	-10,1	22,0	-9,3	2,7	-0,8	22,7
NIST	aug-04	16,4	38,5	-9,3	2,7	25,8	38,9
SP	feb-05	-10,5	22,0	-9,4	2,9	-1,1	22,8

Table 24 Corrected values of the participants δ_{ic} and expanded uncertainties U_{ic}, values of the travelling standard predicted by the pilot laboratory δ_P and standard uncertainties u_P, and drift compensated values δ_{id} and expanded uncertainties U_{id}

10 mV, 100 kHz		δ_{ic}	U_{ic}	δ_P	u_P	δ_{id}	U_{id}
NMI	Date	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V
SP	sep-01	-5,1	33,0	-6,8	2,0	1,7	33,3
PTB	okt-01	-12,9	45,0	-6,7	2,0	-6,2	45,2
NPL	dec-01	0,0	42,0	-6,4	2,0	6,4	42,2
NMi	jan-02	-8,5	50,0	-6,3	1,9	-2,2	50,2
SP	jul-02	-5,1	33,0	-5,7	1,8	0,6	33,2
NMIA	aug-02	4,2	42,0	-5,5	1,8	9,7	42,2
INTI	okt-02	10,2	46,0	-5,3	1,8	15,5	46,2
SP	jan-03	-7,1	33,1	-5,0	1,8	-2,1	33,3
NRC	feb-03	5,0	61,0	-4,9	1,8	9,9	61,1
SP	jun-03	-6,0	33,0	-4,5	1,8	-1,5	33,2
SPRING	jul-03	-11,0	44,0	-4,4	1,8	-6,6	44,2
NIM	aug-03	0,0	96,0	-4,2	1,8	4,2	96,1
SP	okt-03	-5,1	33,1	-4,0	1,8	-1,1	33,2
SP	jun-04	-1,9	33,0	-3,1	1,9	1,2	33,2
NIST	aug-04	-2,6	50,4	-2,9	1,9	0,3	50,6
SP	feb-05	-1,2	33,0	-2,2	2,0	1,1	33,3

Table 25 Corrected values of the participants δ_{ic} and expanded uncertainties U_{ic}, values of the travelling standard predicted by the pilot laboratory δ_P and standard uncertainties u_P, and drift compensated values δ_{id} and expanded uncertainties U_{id}

10 mV, 1 MHz		δ_{ic}	U_{ic}	δ_P	u_P	δ_{id}	U_{id}
NMI	Date	µV/V	µV/V	µV/V	µV/V	µV/V	µV/V
SP	sep-01	-143,9	99,3	-139,5	8,3	-4,4	100,7
PTB	okt-01	-160,1	108,0	-139,5	8,3	-20,6	109,2
NPL	dec-01	-161,5	283,2	-139,6	8,0	-21,9	283,6
NMi	jan-02	-89,5	300,3	-139,6	7,9	50,1	300,7
SP	jul-02	-138,6	98,9	-139,8	7,6	1,1	100,1
NMIA	aug-02	-112,9	107,8	-139,8	7,5	26,9	108,9
INTI	okt-02	-144,9	110,8	-139,9	7,4	-5,0	111,8
SP	jan-03	-137,5	100,7	-140,0	7,3	2,5	101,8
NRC	feb-03	-74,7	91,1	-140,0	7,3	65,3	92,2
SP	jun-03	-142,9	99,3	-140,2	7,2	-2,8	100,4
SPRING	jul-03	-158,5	370,4	-140,2	7,2	-18,3	370,7
NIM	aug-03	21,0	187,6	-140,2	7,3	161,2	188,2
SP	okt-03	-128,2	100,4	-140,3	7,3	12,1	101,5
SP	jun-04	-147,3	99,4	-140,6	7,6	-6,8	100,5
NIST	aug-04	-97,6	142,3	-140,7	7,8	43,1	143,1
SP	feb-05	-142,6	99,9	-140,9	8,3	-1,8	101,3

6.1.10 Tables and graphs of degrees of equivalence with the reference value

Table 26 Degrees of equivalence with the KCRV with corresponding expanded uncertainties (k=2) in µV/V, 100 mV.

D_i	Difference NMI-KCRV							
U_i	Expanded uncertainty of D_i							
Level	100 mV							
	1 kHz		20 kHz		100 kHz		1 MHz	
NMI	D_i	U_i	D_i	U_i	D_i	U_i	D_i	U_i
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
NMi	-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

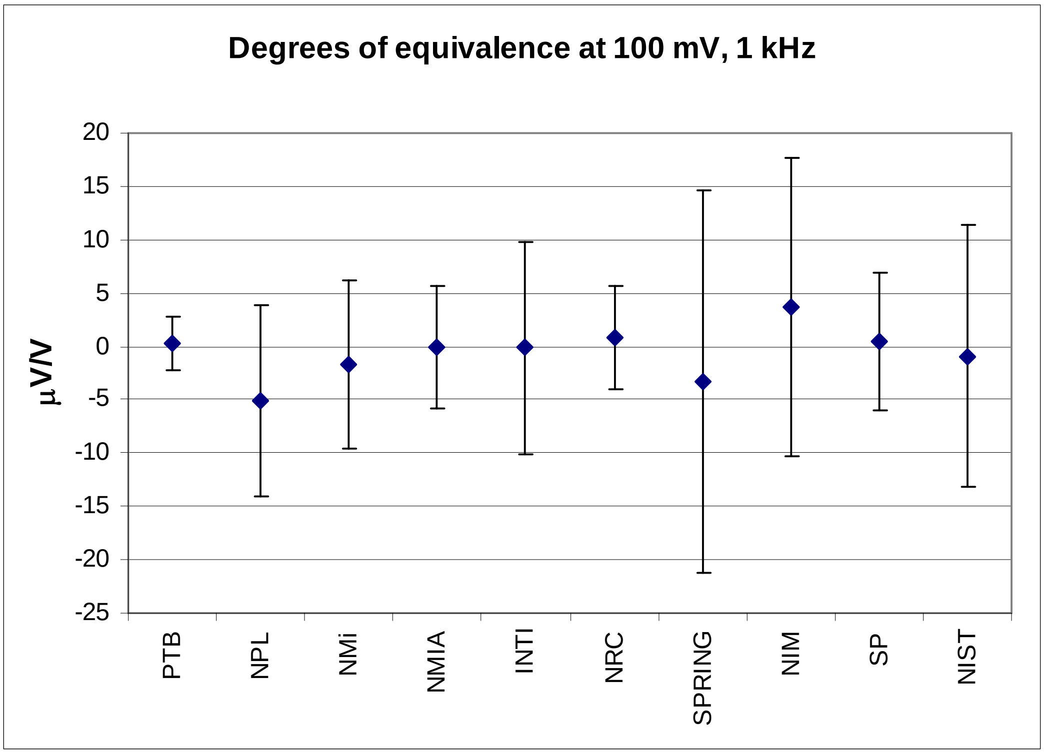

Figure 9 Degrees of equivalence with the KCRV at 100 mV, 1 kHz with corresponding expanded uncertainty bars (k=2).

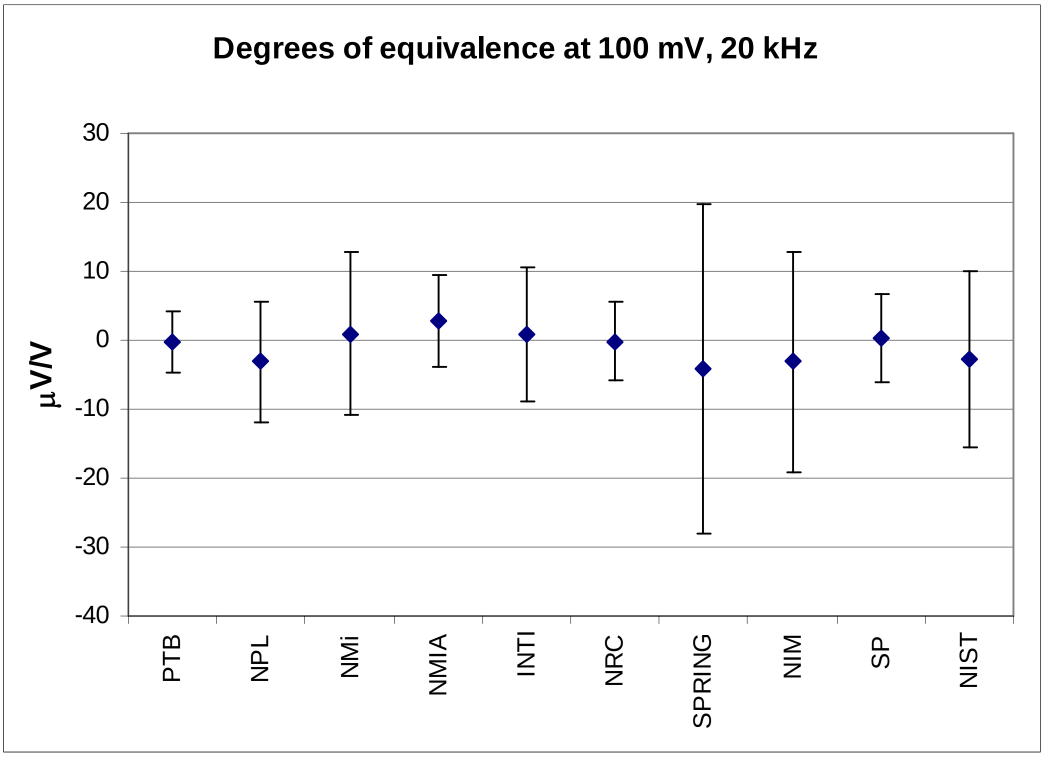

Figure 10 Degrees of equivalence with the KCRV at 100 mV, 20 kHz with corresponding expanded uncertainty bars (*k*=2).

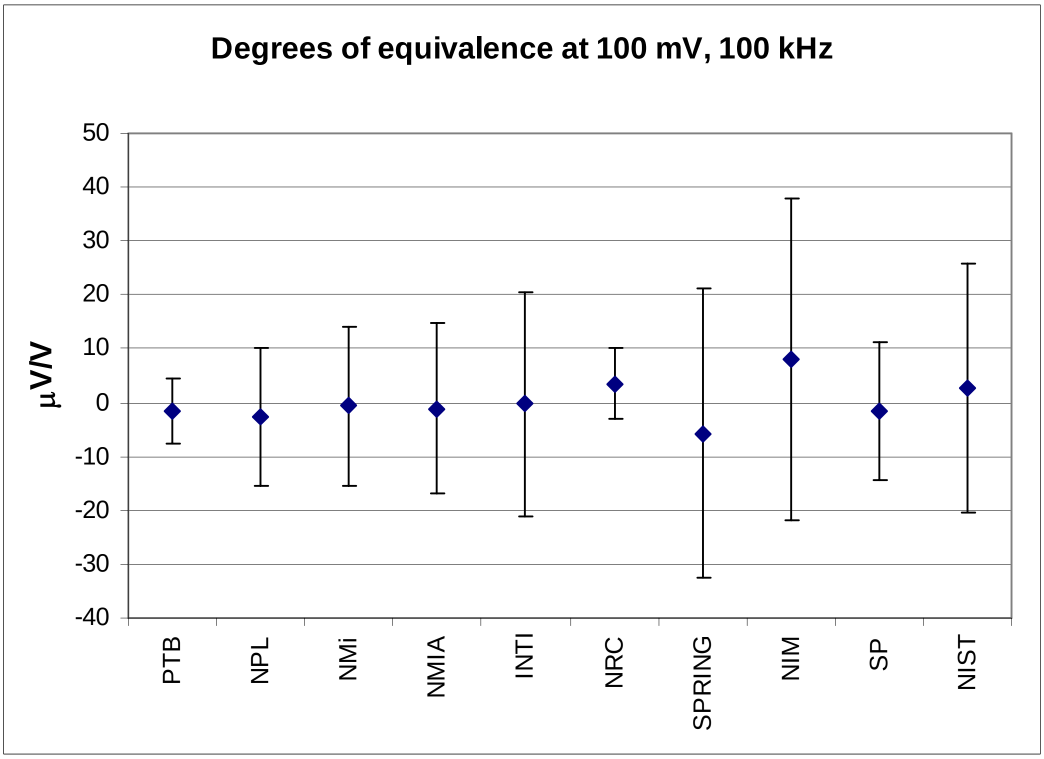

Figure 11 Degrees of equivalence with the KCRV at 100 mV, 100 kHz with corresponding expanded uncertainty bars (*k*=2).

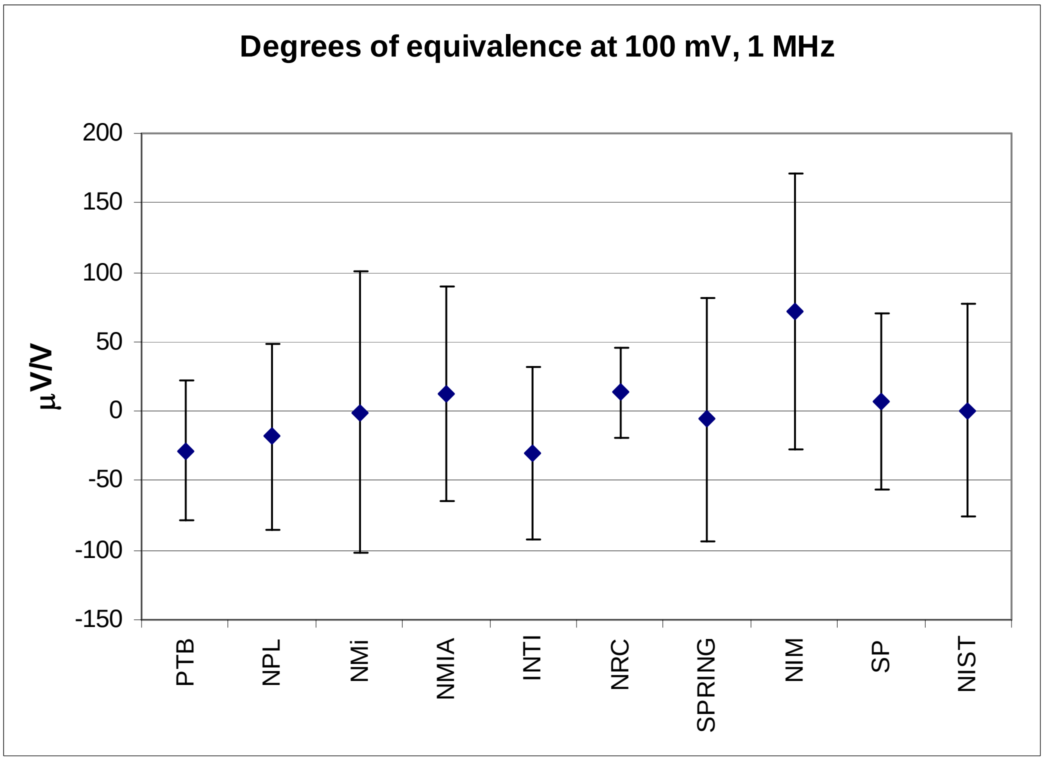

Figure 12 Degrees of equivalence with the KCRV at 100 mV, 1 MHz with corresponding expanded uncertainty bars (*k*=2).

Table 27 Degrees of equivalence with the KCRV with corresponding expanded uncertainties (*k*=2) in µV/V, 10 mV.

D_i	Difference NMI-KCRV							
U_i	Expanded uncertainty of D_i							
Level	10 mV							
	1 kHz		20 kHz		100 kHz		1 MHz	
NMI	D_i	U_i	D_i	U_i	D_i	U_i	D_i	U_i
PTB	-6	40	-13	41	-9	43	-44	100
NPL	-4	29	-4	29	4	40	-46	281
NMi	-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

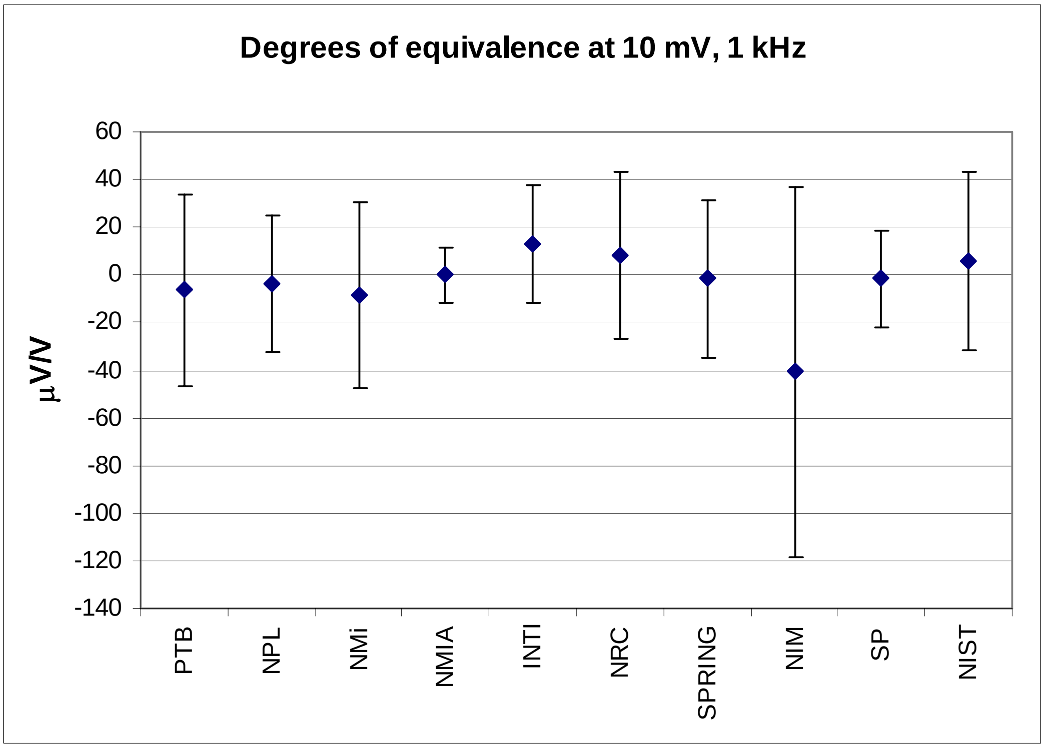

Figure 13 Degrees of equivalence with the KCRV at 10 mV, 20 kHz with corresponding expanded uncertainty bars (*k*=2).

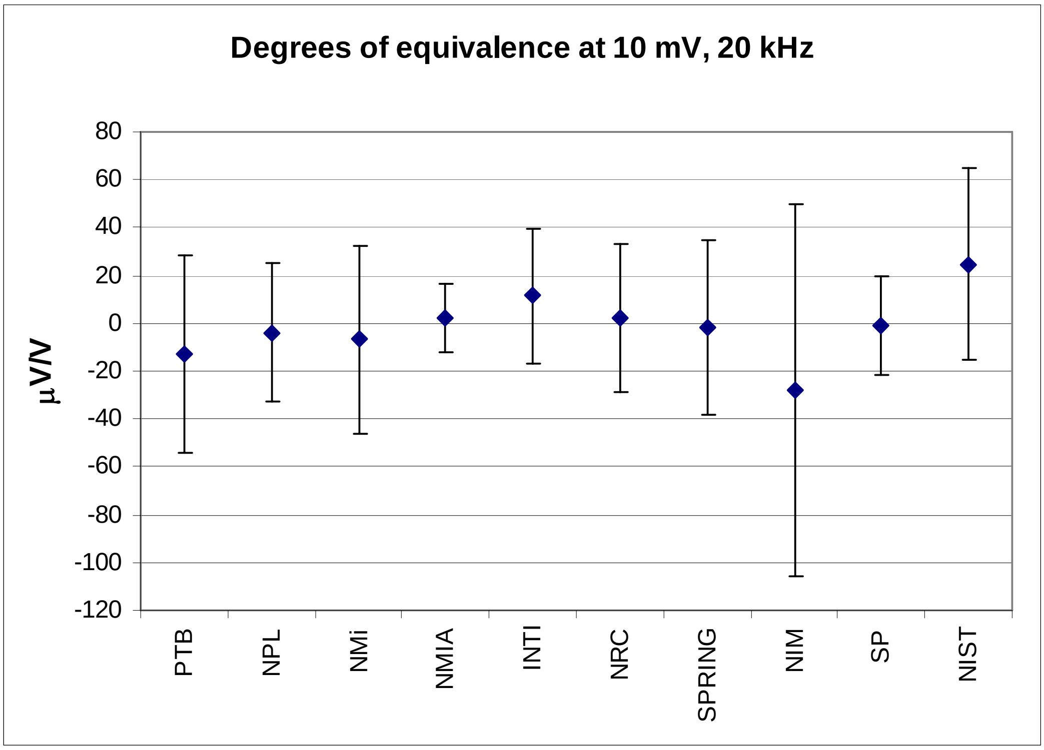

Figure 14 Degrees of equivalence with the KCRV at 10 mV, 20 kHz with corresponding expanded uncertainty bars (*k*=2).

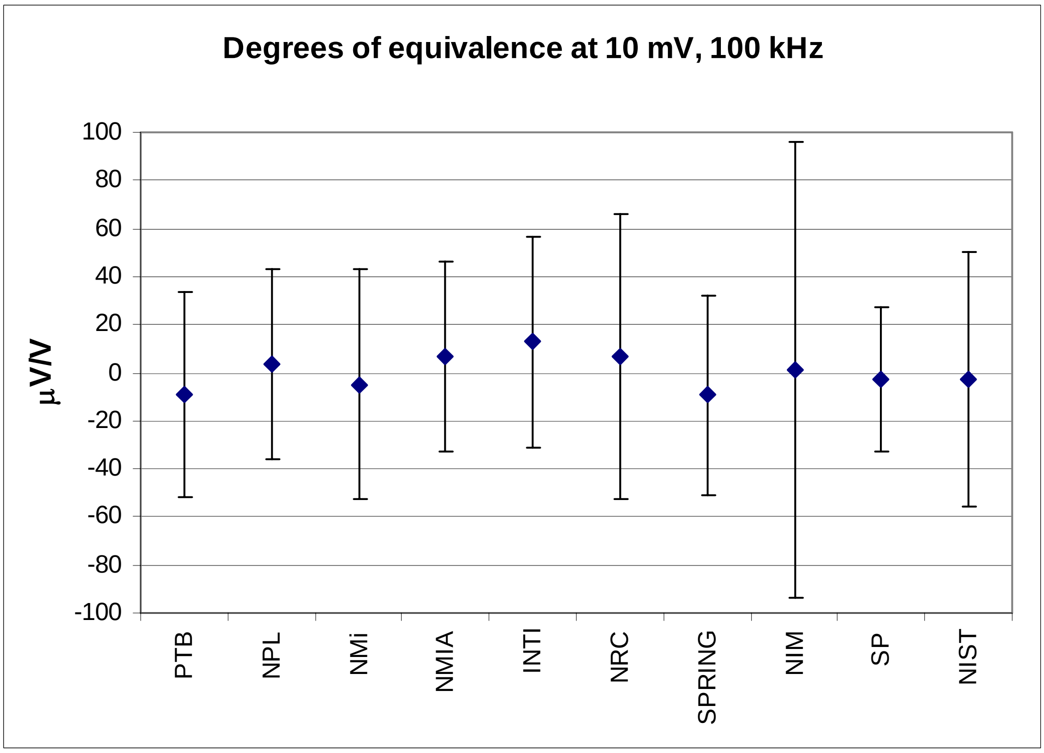

Figure 15 Degrees of equivalence with the KCRV at 10 mV, 100 kHz with corresponding expanded uncertainty bars (*k*=2).

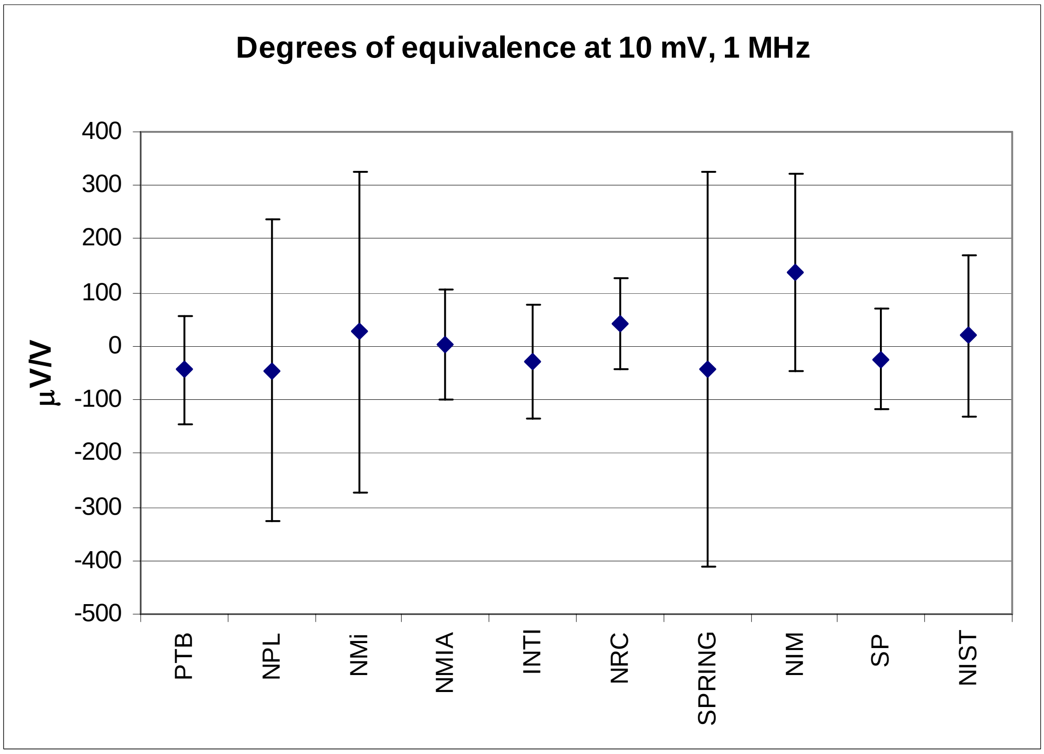

Figure 16 Degrees of equivalence with the KCRV at 10 mV, 1 MHz with corresponding expanded uncertainty bars (*k*=2).

7 Withdrawals and follow up comparison

The measuring period of the D.I. Mendeleyev Institute for Metrology (VNIIM) was scheduled to 15 Feb – 31 Mar 2002 but due to transport problem the measuring period had to be moved to the end of the circulation, in mid 2003. But at that time VNIIM had to withdraw due to staff problems. The National Institute of Standards and Technology (NIST) withdrew from the comparison CCEM-K11 before any results were reported to the pilot laboratory. In 2004 NIST participated in a bilateral comparison CCEM-K11.1, which results are also reported in this report.

8 Summary and conclusion

The circulation of the travelling standard in the CIPM key comparison CCEM-K11 of ac-dc voltage transfer difference at low voltages began in Sep 2001 and was completed in Sep 2003. Out of the eleven participants one NMI withdrew without having performed any measurements due to the staff situation. One NMI withdrew before reporting any results and later participated in a subsequent bilateral key comparison CCEM-K11.1 that was performed in Aug-Sep 2004.

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 key comparison reference values (KCRV) were calculated as the weighted mean of the results of the nine NMIs in CCEM-K11. The degrees of equivalence with the KCRV and between pairs of NMIs have been determined for the measuring points and show very good agreement. All the calculated deviations are within the limits of the expanded uncertainties.

In the technical protocol of the comparison an aim was set to achieve an agreement at 1 kHz within an expanded uncertainty of 10 µV/V and 50 µV/V at 100 mV and 10 mV respectively. For all NMIs the deviations from the KCRV were less than these limits. Also, most of the NMIs deviations from the KCRV and expanded uncertainties were within these limits.

9 References

[1] M. G. Cox and P. M. Harris "Towards an objective approach to key comparison reference values," CIE Expert Symposium on Uncertainty Evaluation, Vienna, Austria, 22-24 Jan 2001

[2] A. G. Steel and R.J. Douglas "Extending Chi-squared Statistics for Key Comparisons in Metrology," CMMSE-2004 / JCAM Submission

10 Acknowledgements

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Appendix 1: Degrees of equivalence CCEM K11 Report

Table 1 Degrees of equivalence 100 mV, 1 kHz 2
Table 2 Degrees of equivalence 100 mV, 20 kHz 2
Table 3 Degrees of equivalence 100 mV, 100 kHz 3
Table 4 Degrees of equivalence 100 mV, 1 MHz..... 3
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Table 8 Degrees of equivalence 10 mV, 1 MHz..... 5

Table 1 Degrees of equivalence 100 mV, 1 kHz

100 mV, 1 kHz			KCRV		PTB		NPL		Nmi		NMIA		INTI		NRC		SPRING		NIM		SP		NIST	
			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}
			-0,5	2,3	-0,2	3,0	-5,6	9,1	-2,2	8,1	-0,6	6,0	-0,6	10,0	0,2	5,1	-3,8	18,0	3,2	14,0	0,0	6,7	-1,4	12,0
	δ_{id}	U_{id}	**D_i**	**U_i**	**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}**
PTB	-0,2	3,0	0,3	2,5			5,4	9,4	2,0	8,4	0,4	6,5	0,5	10,4	-0,4	5,9	3,6	18,2	-3,3	14,4	-0,2	7,2	1,2	12,5
NPL	-5,6	9,1	-5,1	8,9	-5,4	9,4			-3,4	12,0	-5,0	10,8	-4,9	13,5	-5,8	10,4	-1,8	20,2	-8,8	16,7	-5,6	11,3	-4,2	15,2
NMi	-2,2	8,1	-1,7	7,9	-2,0	8,4	3,4	12,0			-1,6	10,0	-1,6	12,8	-2,4	9,5	1,6	19,8	-5,4	16,2	-2,2	10,5	-0,8	14,6
NMIA	-0,6	6,0	-0,1	5,7	-0,4	6,5	5,0	10,8	1,6	10,0			0,0	11,7	-0,9	7,8	3,2	19,0	-3,8	15,3	-0,6	9,0	0,8	13,5
INTI	-0,6	10,0	-0,1	9,9	-0,5	10,4	4,9	13,5	1,6	12,8	0,0	11,7			-0,9	11,3	3,2	20,6	-3,8	17,3	-0,6	12,1	0,8	15,7
NRC	0,2	5,1	0,7	4,8	0,4	5,9	5,8	10,4	2,4	9,5	0,9	7,8	0,9	11,3			4,0	18,7	-2,9	14,9	0,2	8,4	1,6	13,1
SPRING	-3,8	18,0	-3,3	18,0	-3,6	18,2	1,8	20,2	-1,6	19,8	-3,2	19,0	-3,2	20,6	-4,0	18,7			-7,0	22,8	-3,8	19,0	-2,4	21,7
NIM	3,2	14,0	3,7	13,9	3,3	14,4	8,8	16,7	5,4	16,2	3,8	15,3	3,8	17,3	2,9	14,9	7,0	22,8			3,2	15,5	4,6	18,5
SP	0,0	6,7	0,5	6,5	0,2	7,2	5,6	11,3	2,2	10,5	0,6	9,0	0,6	12,1	-0,2	8,4	3,8	19,0	-3,2	15,5			1,4	13,8
NIST	-1,4	12,0	-0,9	12,3	-1,2	12,5	4,2	15,2	0,8	14,6	-0,8	13,5	-0,8	15,7	-1,6	13,1	2,4	21,7	-4,6	18,5	-1,4	13,8		

Table 2 Degrees of equivalence 100 mV, 20 kHz

100 mV, 20 kHz			KCRV		PTB		NPL		Nmi		NMIA		INTI		NRC		SPRING		NIM		SP		NIST	
			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}
			-0,3	2,9	-0,6	5,0	-3,5	9,1	0,6	12,1	2,6	7,1	0,6	10,1	-0,5	6,1	-4,5	24,0	-3,5	16,0	0,0	6,9	-3,1	12,4
	δ_{id}	U_{id}	**D_i**	**U_i**	**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}**
PTB	-0,6	5,0	-0,3	4,3			2,9	10,1	-1,2	12,9	-3,2	8,5	-1,2	11,1	-0,1	7,8	3,9	24,5	2,9	16,8	-0,6	8,4	2,5	13,5
NPL	-3,5	9,1	-3,2	8,7	-2,9	10,1			-4,1	15,0	-6,1	11,4	-4,1	13,5	-3,0	10,9	1,0	25,7	0,0	18,5	-3,5	11,4	-0,4	15,5
NMi	0,6	12,1	0,9	11,8	1,2	12,9	4,1	15,0			-2,0	13,9	0,0	15,7	1,1	13,5	5,1	26,9	4,1	20,1	0,6	13,9	3,7	17,4
NMIA	2,6	7,1	2,9	6,7	3,2	8,5	6,1	11,4	2,0	13,9			2,0	12,3	3,0	9,4	7,0	25,1	6,0	17,6	2,6	9,9	5,7	14,4
INTI	0,6	10,1	0,9	9,8	1,2	11,1	4,1	13,5	0,0	15,7	-2,0	12,3			1,0	11,8	5,0	26,1	4,0	18,9	0,6	12,2	3,7	16,0
NRC	-0,5	6,1	-0,2	5,6	0,1	7,8	3,0	10,9	-1,1	13,5	-3,0	9,4	-1,0	11,8			4,0	24,8	3,0	17,2	-0,5	9,2	2,6	13,8
SPRING	-4,5	24,0	-4,2	23,9	-3,9	24,5	-1,0	25,7	-5,1	26,9	-7,0	25,1	-5,0	26,1	-4,0	24,8			-1,0	28,8	-4,5	24,9	-1,4	27,0
NIM	-3,5	16,0	-3,2	15,8	-2,9	16,8	0,0	18,5	-4,1	20,1	-6,0	17,6	-4,0	18,9	-3,0	17,2	1,0	28,8			-3,5	17,2	-0,4	20,3
SP	0,0	6,9	0,3	6,5	0,6	8,4	3,5	11,4	-0,6	13,9	-2,6	9,9	-0,6	12,2	0,5	9,2	4,5	24,9	3,5	17,2			3,1	14,2
NIST	-3,1	12,4	-2,8	12,7	-2,5	13,5	0,4	15,5	-3,7	17,4	-5,7	14,4	-3,7	16,0	-2,6	13,8	1,4	27,0	0,4	20,3	-3,1	14,2		

Table 3 Degrees of equivalence 100 mV, 100 kHz

100 mV, 100 kHz			KCRV		PTB		NPL		Nmi		NMIA		INTI		NRC		SPRING		NIM		SP		NIST	
			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	4,5	0,1	6,8	-1,0	13,1	1,0	15,1	0,5	16,1	1,4	21,1	5,1	7,3	-4,2	27,1	9,7	30,0	0,0	13,2	4,3	22,7
	δ_{id}	U_{id}	$\boldsymbol{D_i}$	$\boldsymbol{U_i}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$
PTB	0,1	6,8	-1,5	6,0			1,2	14,5	-0,9	16,3	-0,4	17,3	-1,3	21,7	-5,0	9,9	4,3	27,7	-9,6	30,6	0,1	14,3	-4,2	23,9
NPL	-1,0	13,1	-2,6	12,7	-1,2	14,5			-2,0	20,0	-1,5	20,7	-2,4	24,8	-6,1	14,9	3,2	30,1	-10,7	32,8	-1,0	18,6	-5,4	26,3
NMi	1,0	15,1	-0,6	14,7	0,9	16,3	2,0	20,0			0,5	22,0	-0,4	25,8	-4,1	16,7	5,2	31,0	-8,7	33,6	1,0	20,0	-3,3	27,4
NMIA	0,5	16,1	-1,1	15,8	0,4	17,3	1,5	20,7	-0,5	22,0			-0,9	26,5	-4,6	17,7	4,7	31,5	-9,2	34,1	0,5	20,8	-3,8	27,9
INTI	1,4	21,1	-0,2	20,8	1,3	21,7	2,4	24,8	0,4	25,8	0,9	26,5			-3,7	22,3	5,6	34,0	-8,3	36,4	1,4	24,5	-3,0	31,0
NRC	5,1	7,3	3,5	6,6	5,0	9,9	6,1	14,9	4,1	16,7	4,6	17,7	3,7	22,3			9,3	28,1	-4,6	30,9	5,1	14,9	0,8	23,8
SPRING	-4,2	27,1	-5,8	26,9	-4,3	27,7	-3,2	30,1	-5,2	31,0	-4,7	31,5	-5,6	34,0	-9,3	28,1			-13,9	40,2	-4,2	29,8	-8,5	35,3
NIM	9,7	30,0	8,1	29,9	9,6	30,6	10,7	32,8	8,7	33,6	9,2	34,1	8,3	36,4	4,6	30,9	13,9	40,2			9,7	32,5	5,4	37,7
SP	0,0	13,2	-1,6	12,8	-0,1	14,3	1,0	18,6	-1,0	20,0	-0,5	20,8	-1,4	24,5	-5,1	14,9	4,2	29,8	-9,7	32,5			-4,3	26,2
NIST	4,3	22,7	2,7	23,1	4,2	23,9	5,4	26,3	3,3	27,4	3,8	27,9	3,0	31,0	-0,8	23,8	8,5	35,3	-5,4	37,7	4,3	26,2		

Table 4 Degrees of equivalence 100 mV, 1 MHz

10 mV, 1 MHz			KCRV		PTB		NPL		NMi		NMIA		INTI		NRC		SPRING		NIM		SP		NIST	
			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	27	-35	51	-25	67	-8	101	6	78	-37	62	6	33	-13	88	65	99	0	63	-6	72
	δ_{id}	U_{id}	$\boldsymbol{D_i}$	$\boldsymbol{U_i}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$	$\boldsymbol{D_{ij}}$	$\boldsymbol{U_{ij}}$
PTB	-35	51	-28	50			-10	79	-27	109	-41	90	2	68	-42	59	-23	94	-100	106	-35	72	-29	92
NPL	-25	67	-18	67	10	79			-17	122	-31	101	12	90	-32	73	-12	111	-90	121	-25	92	-19	101
NMi	-8	101	-1	101	27	109	17	122			-14	126	29	117	-14	106	5	134	-73	142	-8	119	-2	127
NMIA	6	78	13	77	41	90	31	101	14	126			43	98	-1	85	18	117	-59	126	6	101	12	108
INTI	-37	62	-30	62	-2	68	-12	90	-29	117	-43	98			-43	71	-24	98	-102	109	-37	79	-31	97
NRC	6	33	13	32	42	59	32	73	14	106	1	85	43	71			19	95	-58	105	6	69	13	77
SPRING	-13	88	-6	88	23	94	12	111	-5	134	-18	117	24	98	-19	95			-78	125	-13	101	-6	114
NIM	65	99	72	99	100	106	90	121	73	142	59	126	102	109	58	105	78	125			65	110	71	123
SP	0	63	7	63	35	72	25	92	8	119	-6	101	37	79	-6	69	13	101	-65	110			6	94
NIST	-6	72	1	77	29	92	19	101	2	127	-12	108	31	97	-13	77	6	114	-71	123	-6	94		

Table 5 Degrees of equivalence 10 mV, 1 kHz

10 mV, 1 kHz			KCRV		PTB		NPL		NMi		NMIA		INTI		NRC		SPRING		NIM		SP		NIST	
			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	9,2	-4,6	41,1	-2,1	30,2	-7,1	40,1	1,4	14,3	14,3	26,2	9,6	36,1	0,2	34,1	-39,0	78,0	0,0	22,2	7,3	36,5
	δ_{id}	U_{id}	**D_i**	**U_i**	**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}**
PTB	-4,6	41,1	-6	40			-2	51	3	57	-6	43	-19	49	-14	55	-5	53	34	88	-5	47	-12	55
NPL	-2,1	30,2	-4	29	2	51			5	50	-4	33	-16	40	-12	47	-2	45	37	84	-2	37	-9	47
NMi	-7,1	40,1	-9	39	-3	57	-5	50			-9	42	-21	48	-17	54	-7	53	32	88	-7	46	-14	54
NMIA	1,4	14,3	0	11	6	43	4	33	9	42			-13	30	-8	39	1	37	40	79	1	26	-6	39
INTI	14,3	26,2	13	25	19	49	16	40	21	48	13	30			5	44	14	43	53	82	14	34	7	45
NRC	9,6	36,1	8	35	14	55	12	47	17	54	8	39	-5	44			9	50	49	86	10	42	2	51
SPRING	0,2	34,1	-1	33	5	53	2	45	7	53	-1	37	-14	43	-9	50			39	85	0	40	-7	50
NIM	-39,0	78,0	-41	78	-34	88	-37	84	-32	88	-40	79	-53	82	-49	86	-39	85			-39	81	-46	86
SP	0,0	22,2	-2	20	5	47	2	37	7	46	-1	26	-14	34	-10	42	0	40	39	81			-7	43
NIST	7,3	36,5	6	38	12	55	9	47	14	54	6	39	-7	45	-2	51	7	50	46	86	7	43		

Table 6 Degrees of equivalence 10 mV, 20 kHz

10 mV, 20 kHz			KCRV		PTB		NPL		Nmi		NMIA		INTI		NRC		SPRING		NIM		SP		NIST	
			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}
			1,0	10,4	-11,7	42,4	-2,8	30,5	-5,7	40,4	3,4	16,9	12,4	29,5	3,2	32,4	-0,7	37,4	-26,7	78,2	0,0	22,7	25,8	38,9
	δ_{id}	U_{id}	**D_i**	**U_i**	**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}**
PTB	-11,7	42,4	-13	41			-9	52	-6	58	-15	45	-24	51	-15	53	-11	56	15	89	-12	47	-38	57
NPL	-2,8	30,5	-4	29	9	52			3	50	-6	34	-15	42	-6	44	-2	48	24	84	-3	37	-29	49
NMi	-5,7	40,4	-7	39	6	58	-3	50			-9	43	-18	49	-9	51	-5	54	21	88	-6	46	-32	56
NMIA	3,4	16,9	2	14	15	45	6	34	9	43			-9	33	0	36	4	40	30	80	3	27	-22	42
INTI	12,4	29,5	11	28	24	51	15	42	18	49	9	33			9	43	13	47	39	83	12	36	-13	48
NRC	3,2	32,4	2	31	15	53	6	44	9	51	0	36	-9	43			4	49	30	84	3	39	-23	50
SPRING	-0,7	37,4	-2	36	11	56	2	48	5	54	-4	40	-13	47	-4	49			26	86	-1	43	-26	53
NIM	-26,7	78,2	-28	78	-15	89	-24	84	-21	88	-30	80	-39	83	-30	84	-26	86			-27	81	-52	87
SP	0,0	22,7	-1	21	12	47	3	37	6	46	-3	27	-12	36	-3	39	1	43	27	81			-26	44
NIST	25,8	38,9	25	40	38	57	29	49	32	56	22	42	13	48	23	50	26	53	52	87	26	44		

Table 7 Degrees of equivalence 10 mV, 100 kHz

10 mV, 100 kHz			KCRV		PTB		NPL		NMi		NMIA		INTI		NRC		SPRING		NIM		SP		NIST	
			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}
			2,8	15,8	-6,2	45,2	6,4	42,2	-2,2	50,2	9,7	42,2	15,5	46,2	9,9	61,1	-6,6	44,2	4,2	96,1	0,0	33,2	0,3	50,6
	δ_{id}	U_{id}	$\boldsymbol{D}_{\mathbf{i}}$	$\boldsymbol{U}_{\mathbf{i}}$	$\boldsymbol{D}_{\mathbf{ij}}$	$\boldsymbol{U}_{\mathbf{ij}}$	$\boldsymbol{D}_{\mathbf{ij}}$	$\boldsymbol{U}_{\mathbf{ij}}$	$\boldsymbol{D}_{\mathbf{ij}}$	$\boldsymbol{U}_{\mathbf{ij}}$	$\boldsymbol{D}_{\mathbf{ij}}$	$\boldsymbol{U}_{\mathbf{ij}}$	$\boldsymbol{D}_{\mathbf{ij}}$	$\boldsymbol{U}_{\mathbf{ij}}$	$\boldsymbol{D}_{\mathbf{ij}}$	$\boldsymbol{U}_{\mathbf{ij}}$	$\boldsymbol{D}_{\mathbf{ij}}$	$\boldsymbol{U}_{\mathbf{ij}}$	$\boldsymbol{D}_{\mathbf{ij}}$	$\boldsymbol{U}_{\mathbf{ij}}$	$\boldsymbol{D}_{\mathbf{ij}}$	$\boldsymbol{U}_{\mathbf{ij}}$	$\boldsymbol{D}_{\mathbf{ij}}$	$\boldsymbol{U}_{\mathbf{ij}}$
PTB	-6,2	45,2	-9	43			-13	62	-4	67	-16	62	-22	64	-16	76	0	63	-10	106	-6	56	-6	68
NPL	6,4	42,2	4	40	13	62			9	66	-3	59	-9	62	-3	74	13	61	2	105	6	53	6	66
NMi	-2,2	50,2	-5	48	4	67	-9	66			-12	65	-18	68	-12	79	4	67	-6	108	-2	60	-3	71
NMIA	9,7	42,2	7	39	16	62	3	59	12	65			-6	62	0	74	16	61	6	105	10	53	9	66
INTI	15,5	46,2	13	44	22	64	9	62	18	68	6	62			6	76	22	64	11	106	16	57	15	68
NRC	9,9	61,1	7	59	16	76	3	74	12	79	0	74	-6	76			16	75	6	114	10	69	10	79
SPRING	-6,6	44,2	-9	42	0	63	-13	61	-4	67	-16	61	-22	64	-16	75			-11	106	-7	55	-7	67
NIM	4,2	96,1	1	95	10	106	-2	105	6	108	-6	105	-11	106	-6	114	11	106			4	101	4	108
SP	0,0	33,2	-3	30	6	56	-6	53	2	60	-10	53	-16	57	-10	69	7	55	-4	101			0	60
NIST	0,3	50,6	-3	53	6	68	-6	66	3	71	-9	66	-15	68	-10	79	7	67	-4	108	0	60		

Table 8 Degrees of equivalence 10 mV, 1 MHz

10 mV, 1 MHz			KCRV		PTB		NPL		Nmi		NMIA		INTI		NRC		SPRING		NIM		SP		NIST	
			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}
			24	49	-21	107	-22	284	50	301	27	109	-5	112	65	92	-18	371	161	188	0	101	43	143
	δ_{id}	U_{id}	$\boldsymbol{D}_{\mathbf{i}}$	$\boldsymbol{U}_{\mathbf{i}}$	$\boldsymbol{D}_{\mathbf{ij}}$	$\boldsymbol{U}_{\mathbf{ij}}$	$\boldsymbol{D}_{\mathbf{ij}}$	$\boldsymbol{U}_{\mathbf{ij}}$	$\boldsymbol{D}_{\mathbf{ij}}$	$\boldsymbol{U}_{\mathbf{ij}}$	$\boldsymbol{D}_{\mathbf{ij}}$	$\boldsymbol{U}_{\mathbf{ij}}$	$\boldsymbol{D}_{\mathbf{ij}}$	$\boldsymbol{U}_{\mathbf{ij}}$	$\boldsymbol{D}_{\mathbf{ij}}$	$\boldsymbol{U}_{\mathbf{ij}}$	$\boldsymbol{D}_{\mathbf{ij}}$	$\boldsymbol{U}_{\mathbf{ij}}$	$\boldsymbol{D}_{\mathbf{ij}}$	$\boldsymbol{U}_{\mathbf{ij}}$	$\boldsymbol{D}_{\mathbf{ij}}$	$\boldsymbol{U}_{\mathbf{ij}}$	$\boldsymbol{D}_{\mathbf{ij}}$	$\boldsymbol{U}_{\mathbf{ij}}$
PTB	-21	107	-44	100			1	302	-71	318	-48	151	-16	149	-86	140	-2	383	-182	212	-21	141	-64	177
NPL	-22	284	-46	281	-1	302			-72	413	-49	303	-17	304	-87	297	-4	466	-183	340	-22	300	-65	317
NMi	50	301	26	298	71	318	72	413			23	319	55	320	-15	314	68	477	-111	354	50	316	7	332
NMIA	27	109	3	102	48	151	49	303	-23	319			32	154	-38	142	45	386	-134	216	27	147	-16	179
INTI	-5	112	-29	105	16	149	17	304	-55	320	-32	154			-70	144	13	384	-166	214	-5	143	-48	181
NRC	65	92	42	84	86	140	87	297	15	314	38	142	70	144			84	382	-96	209	65	134	22	168
SPRING	-18	371	-42	369	2	383	4	466	-68	477	-45	386	-13	384	-84	382			-180	413	-18	382	-61	397
NIM	161	188	138	184	182	212	183	340	111	354	134	216	166	214	96	209	180	413			161	208	118	236
SP	0	101	-24	94	21	141	22	300	-50	316	-27	147	5	143	-65	134	18	382	-161	208			-43	173
NIST	43	143	19	151	64	177	65	317	-7	332	16	179	48	181	-22	168	61	397	-118	236	43	173		

PTB, GERMANY **2**
NPL, UNITED KINGDOM **16**
NMI, THE NETHERLANDS **18**
NMIA, AUSTRALIA **22**
INTI, ARGENTINA **23**
NRC, CANADA **25**
SPRING, SINGAPORE **28**
NIM, CHINA **29**
NIST, USA **32**
SP, SWEDEN **34**

PTB, Germany

9 Uncertainty analysis at 100 mV

9.1 Model of the ac-dc transfer difference calibration of the FLUKE 792 A at 100 mV

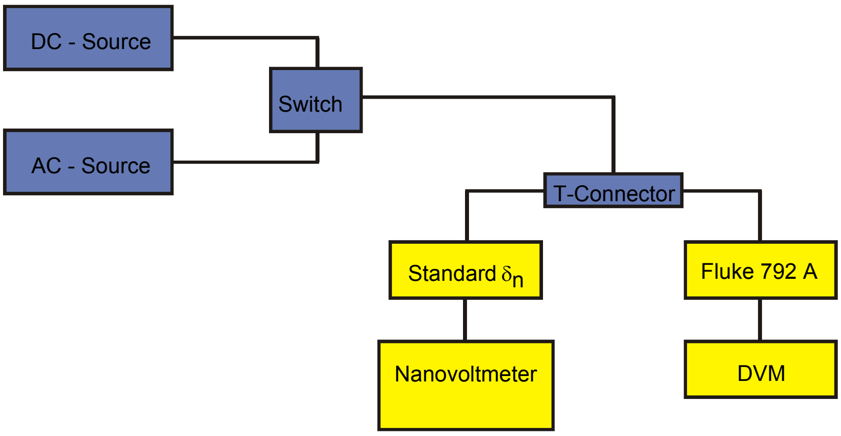

Fig. 2 Schematic calibration set-up for the 2-channel method used for the comparison of the PMJTC with the Fluke 792 A

9.2 Uncertainty analysis of the PTB standards

The basic MJTC has been evaluated in PTB. The model for the calculation is too large to be presented here but is given in [1,2,3]. It basically consists of the sum of several transfer differences

$$\delta_{\mathrm{S}} = \delta_{\mathrm{TH}} + \delta_{\mathrm{L,G,C}} + \delta_{\mathrm{SKIN}} + \delta_{\mathrm{LF}} + \delta_{\mathrm{CONNEC}} + \delta_{\mathrm{LEVEL}} \qquad (9.1)$$

δ_{TH} = transfer difference due to the Thomson and Peltier effect at dc

$\delta_{\mathrm{L,G,C}}$ = transfer difference due to reactive components and dielectric losses in the heater and the connecting leads,

δ_{SKIN} = transfer difference due to the skin effect and proximity effect in the heater and the connecting leads,

δ_{LF} = transfer difference due to PMJTC low frequency effects [3],

δ_{CONNEC} = transfer difference due to different connectors and T-connectors

δ_{LEV} = transfer difference due to the current level effect in the heater. It is zero for 3d-MJTC and PMJTC

The standard measurement uncertainty for the 3d-MJTC at the 0,5-V to 6-V-level for the frequencies from 10 Hz to 1 MHz is given as the sum of the related variances

$$u^2(\delta_{\mathrm{s}}) = u_{\mathrm{TH}}^2 + u_{\mathrm{L,G,C}}^2 + u_{\mathrm{SKIN}}^2 + u_{\mathrm{LF}}^2 + u_{\mathrm{CONNEC}}^2 + u_{\mathrm{LEVEL}}^2 \qquad (9.2)$$

The measured difference δ_d between both the PMJTC and the 3d-MJTC is

$$\delta_d = \delta_A + \delta_C \tag{9.3}$$

δ_A = Mean calculated from a set of determinations of δ_d,
δ_C = Contribution from the calibration set-up

The variance of the standard uncertainty of the measured difference between both converters $u^2(\delta_d)$ is

$$u^2(\delta_d) = u^2(\delta_A) + u^2(\delta_C) \tag{9.4}$$

$u(\delta_A)$ = type A standard uncertainty. It is the standard deviation of the mean calculated from a set of determinations of δ_d,
$u(\delta_C)$ = standard uncertainty of the calibration set-up

The standard uncertainty of the calibration of the PMJTC then is:

$$u^2(\delta_{PMJTC}) = u^2(\delta_d) + u^2(\delta_s) \tag{9.5}$$

9.3 Uncertainty analysis for the comparison of the Fluke 792 A against the PTB-standards

The measured difference of the transfer differences of the unknown Fluke 792 A and the PMJTC is given by

$$\delta_d = \frac{Uo_{792dc} - Uo_{792ac}}{n_{792}\, Uo_{792dc}} - \frac{Uo_{PMJTCdc} - Uo_{PMJTCac}}{n_{PMJTC}\, Uo_{PMJTCdc}} \tag{9.6}$$

where Uo_{792dc} and Uo_{792ac} are the voltages measured by the digital multimeter HP3458 at the output of the Fluke 792 A and $Uo_{PMJTCdc}$ and $Uo_{PMJTCac}$ measured by the nanovoltmeter at the output of the PMJTC with dc and ac input voltages resp.

The uncertainty of the calibration of the Fluke 792 at 100 mV then is:

$$u^2(\delta_{792}) = u^2(\delta_{d\,792}) + u^2(\delta_{PMJTC}) + u^2(\delta_f) \tag{9.7}$$

$$u^2(\delta_{d792}) = u^2(\delta_A) + u^2(\delta_c) + u^2(\delta_{div}) \tag{9.8}$$

$u(\delta_A)$ = type A standard uncertainty. It is the standard deviation of the mean calculated from a set of determinations of δ_d,
$u(\delta_C)$ = standard uncertainty of the calibration set-up

(9.9)

$$u^2(\delta_c) = \left(\frac{\partial\delta_c}{\partial n_{792}}\right)^2 u^2(n_{792}) + \left(\frac{\partial\delta_c}{\partial Uo_{792dc}}\right)^2 u^2(Uo_{792dc}) + \left(\frac{\partial\delta_c}{\partial Uo_{792ac}}\right)^2 u^2(Uo_{792ac})$$

$$+ \left(\frac{\partial\delta_c}{\partial Uo_{792dc}}\right)^2 u^2(Uo_{792dc}) + 2\left(\frac{\partial\delta_c}{\partial Uo_{792ac}}\right)\left(\frac{\partial\delta_c}{\partial Uo_{792dc}}\right) u(Uo_{792ac})\, u(Uo_{792dc})\, r(Uo_{792ac}, Uo_{792dc})$$

$$\left(\frac{\partial\delta_c}{\partial n_{PMJTC}}\right)^2 u^2(n_{PMJTC}) + \left(\frac{\partial\delta_c}{\partial Uo_{PMJTCac}}\right)^2 u^2(Uo_{PMJTCdc}) + \left(\frac{\partial\delta_c}{\partial Uo_{PMJTCac}}\right)^2 u^2(Uo_{PMJTCac})$$

$$+ \left(\frac{\partial\delta_c}{\partial U_{PMJTCdc}}\right)^2 u^2(Uo_{PMJTCdc}) + 2\left(\frac{\partial\delta_C}{\partial Uo_{PMJTCac}}\right)$$

$$\left(\frac{\partial\delta_c}{\partial Uo_{PMJTCdc}}\right) u(Uo_{PMJTCac})\, u(Uo_{PMJTCdc})\, r(Uo_{PMJTCac}, Uo_{PMJTCdc})$$

As Uo_{ac} and Uo_{dc} are measured with one instrument at the output of the 792 and with another instrument at the output of the PMJTC within a few minutes the ac and dc measurements are correlated with $r(U_{ac}, U_{dc}) = 1$. Therefore, the sum of the third, fourth and fifth term in (9.9) equals

$$\left(\frac{1}{n_{792}\ Uo_{ac,dc}}\right)^2 \left(u(Uo_{dc}) - u(Uo_{ac})\right)^2 \tag{9.10}$$

The same applies for the PMJTC in the eighth, ninth and tenth term.

The measuring sequence is ac_1, dc_+, ac_2, dc_-, ac_3, with 90 s waiting time after switching. Hence, the mean

$$\overline{Uo_{ac}} = \frac{1}{3}\left(Uo_{ac1} + Uo_{ac2} + Uo_{ac3}\right) \tag{9.11}$$

corresponds to the time when ac_2 is measured ($t = t_2$).

For the same moment we calculate the mean

$$\overline{Uo_{dc}} = \frac{1}{2}\left(Uo_{dc+} + Uo_{dc-}\right) \tag{9.12}$$

Therefore, this sequence corrects for a linear drift of the output voltage. Moreover, if the drift differs slightly from the linear approach, we can assume that this uncertainty contribution is the same at ac and dc and they cancel each other in (9.9). Thus,

$$u\left(\overline{Uo_{dc}}\right) \cong u(Uo_{dc}) \text{ and } u\left(\overline{Uo_{ac}}\right) \cong u(Uo_{ac}) \tag{9.13}$$

Therefore, we get in (9.9)

$$u^2(\delta_{\mathrm{C}}) = \left(\frac{Uo_{792\mathrm{dc}} - Uo_{792\,\mathrm{ac}}}{Uo\,*_{792\,\mathrm{dc}}\;\; n_{792}^2} \right)^2 u^2(n_{792}) + \left(\frac{Uo_{792\,\mathrm{dc}} - Uo_{792\,\mathrm{ac}}}{n_{792}\;\; Uo\,*_{792\mathrm{dc}}^2} \right)^2 u^2\left(Uo\,*_{792\,\mathrm{dc}}\right)$$
$$+ \left(\frac{1}{n_{792}\;\; Uo\,*_{792\mathrm{dc}}} \right)^2 \left(u\left(Uo_{792\mathrm{dc}}\right) - u\left(Uo_{792\mathrm{ac}}\right)\right)^2$$
$$+ \left(\frac{Uo_{\mathrm{PMJTCdc}} - Uo_{\mathrm{PMJTCac}}}{Uo\,*_{\mathrm{PMJTCdc}}\;\; n_{\mathrm{TC}}^2} \right)^2 u^2(n_{\mathrm{TC}}) + \left(\frac{Uo_{\mathrm{PMJTCdc}} - Uo_{\mathrm{PMJTCac}}}{n_{\mathrm{TC}}\;\; Uo\,*_{\mathrm{PMJTCdc}}^2} \right)^2 u^2\left(Uo\,*_{\mathrm{PMJTCdc}}\right)$$
$$+ \left(\frac{1}{n_{\mathrm{TC}}\;\; Uo\,*_{\mathrm{PMJTCdc}}} \right)^2 \left(u\left(Uo_{\mathrm{PMJTCdc}}\right) - u\left(Uo_{\mathrm{PMJTCac}}\right)\right)^2 \tag{9.14}$$

$u(n)$ is the uncertainty of the exponent of the standards, which is ±1 mV/V for PMJTCs and ±1 mV/V for the 792

$u(Uo*_{792\mathrm{dc}})$, $u(Uo*_{\mathrm{PMJTCdc}})$ are the uncertainties in the measurements of the output voltages, which are better than 1 mV/V

$(u(Uo_{\mathrm{dc}})\text{-}u(Uo_{\mathrm{ac}}))$ corresponds to the uncertainty of the linearity in the voltmeters that measures the difference between ac and dc for both standards, which is 0.1 µV/V.

The standard uncertainty calculated from (9.14) for this comparison is < 0.3 µV/V.

9.4 Additional uncertainty contributions $u(\delta)$ for the voltage 100 mV

For voltages below 1 V down to 100 mV the same PMJTCs are used as at 1 V to calibrate Fluke 792 A down to 100 mV. These are 90-Ω-PMJTCs which have their highest sensitivity at 1 V. Their ac-dc voltage transfer differences are measured at the 1-V-level. In the frequency range from 1 kHz to 1 MHz these transfer differences are taken to be the same down to 100 mV. At low frequencies the ac-dc transfer differences are calculated to decrease with the power coefficient. At lower voltages the output voltage decreases which means that the sensitivity decreases and the standards deviation of the measurement increases.

At the same time at lower voltages the noise of the calibrators increases. Therefore we use a divider in front of the T-connector to increase the calibrator voltage. These dividers together with the standard PMJTC generate different source impedances from 0.4 Ω to 90 Ω. As the Fluke 792 A changes its amplification with source resistance which cannot be corrected we have to introduce the maximum changes as the limit with rectangular distribution into the uncertainty budget.

Moreover at different calibration set-up with different calibrators we measure small differencies at higher frequencies. The reason is unknown. Therefore we introduce the maximum difference between all our four calibration set-ups with rectangular distribution into the uncertainty budget.

9.5 Calculation of the ac-dc voltage transfer difference and uncertainty budget

The model function is: $\delta_{xLV} = \delta_{s} + \delta_{con} + \delta_{f792} + \delta_{temperature} + \delta_{calibrator} + \delta_{divider} + \delta_{d}$

δ_{xLV}	AC-DC Voltage Transfer Difference of the unknown standard at the low voltage
δ_{s}	AC-DC Voltage Transfer Difference of the standard at the 1 V, resp. corrected at low frequencies with the power coefficient
δ_{con}	AC-DC Voltage Transfer Difference due to the different T-connectors especially at high frequencies and electromagnetic influences from outside
δ_{f792}	AC-DC Voltage Transfer Difference due to the frequency correction of Fluke 792A
$\delta_{temperature}$	AC-DC Voltage Transfer Difference due to the contribution of the temperature coefficient of the ac-dc voltage transfer difference of the 792. It depends on the temperature coefficient at the different frequencies. It was only possible to control the temperature between 22,3°C and 23,3°C.
$\delta_{calibrator}$	AC-DC Voltage Transfer Difference with different calibrators and calibration set-ups in the step-down
$\delta_{divider}$	AC-DC Voltage Transfer Difference with different dividers in front of the T-connectors
δ_{d}	measured difference δ_d of the ac-dc transfer differences of the unknown δ_x and the known standard δ_s

Table II: Uncertainty budget for the PTB standard at 1 V with **$u(\delta_s)$**, the PMJTC at 1 V with **$u(\delta_{PMJTC})$** and the calibration of the Fluke 792A at 100 mV with **$u(\delta_{792})$**.

Influence quantity	Standard measurement uncertainty u in µV/V at the frequencies			
	1 kHz	20 kHz	100 kHz	1 MHz
$u(\delta_{TH})$	0,01	0,01	0,01	0,01
$u(\delta_{L,G,C})$	0	0,2	0,9	9,3
$u(\delta_{skin})$	0	0	0	4,4
$u(\delta_{con})$	0	0	0,5	2,4
$u(\delta_{LF})$	0	0	0	0
$u(\delta_s)$	**0,0**	**0,2**	**1,0**	**10,6**
$u(\delta_A)$	0,2	0,1	0,1	0,2
$u(\delta_C)$	0,2	0,2	0,2	0,2
$u(\delta_d)$	**0,3**	**0,2**	**0,2**	**0,3**
$u(\delta_{con})$	**0**	**0**	**0,5**	**2,4**
$u(\delta_{PMJTC})$	**0,3**	**0,3**	**1,2**	**11,9**
$u(\delta_{A792})$	1,0	1,0	1,0	1,0
$u(\delta_{C792})$	0,3	0,3	0,3	0,3
$u(\delta_{d792})$	**1,0**	**1,0**	**1,0**	**1,0**

$u(\delta_{con})$	**0**	**0**	**0,5**	**2,4**
$u(\delta_{f792})$	**0**	**0,2**	**2,0**	**12**
$u(\delta_{temperature})$	**0**	**0**	**0,4**	**5**
$u(\delta_{divider})$	**0,8**	**2**	**1,7**	**8,7**
$u(\delta_{calibrator})$	**0,2**	**0,8**	**1,2**	**13,3**
$u(\delta_{792})$	**1,4**	**2,4**	**3,3**	**23,4**
$U(\delta_{792})$ (k=2)	**2,8**	**4,8**	**6,6**	**47**

Remarks:
$u^2(\delta_S) = u^2(\delta_{TH}) + u^2(\delta_{L,G,C}) + u^2(\delta_{skin}) + u^2(\delta_{con}) + u^2(\delta_{LF})$;
$u^2(\delta_d) = u^2(\delta_A) + u^2(\delta_C)$;
$u^2(\delta_{PMJTC}) = u^2(\delta_s) + u^2(\delta_d) + u^2(\delta_{con})$
$u^2(\delta_{d792}) = u^2(\delta_{A792}) + u^2(\delta_{C792})$;
$u^2(\delta_{792}) = u^2(\delta_{PMJTC}) + u^2(\delta_{d792}) + u^2(\delta_{con}) + u^2(\delta_{f792}) + u^2(\delta_{temperature}) + u^2(\delta_{divider}) + u^2(\delta_{calibrator})$
$U = k\, u(\delta_{792})$; k is taken as 2

11. Uncertainty analysis at 10 mV

11.1 Model of the ac-dc transfer difference calibration by µpot

For all measurements in the step-down procedure towards lower voltages, the ac-dc transfer difference of the standard δ_S has to be added to the measured differences δ_d of the unknown δ_x and the known δ_S.
In this way the transfer difference of the unknown device is obtained as

$$\delta_x = \delta_d + \delta_s \tag{11.1}$$

Using the two-channel method to determine δ_d, i.e. the simultaneous measurement of the voltages of the 792A and the µpot and subsequent calculation of the differences, δ_d can be determined as

$$\delta_d = \frac{U_{792\,ac} - U_{792\,dc}}{U_{792\,dc}} - \frac{U_{\mu pot\,ac} - U_{\mu pot\,dc}}{U_{\mu pot\,dc}} \tag{11.2}$$

and for the measurement of the output voltages

$$\delta_d = \frac{Uo_{792\,dc} - Uo_{792\,ac}}{n_{792} \cdot Uo_{792\,dc}} - \frac{U_{Th\,dc} - U_{Th\,ac}}{n_{TC} \cdot U_{Th\,dc}} \tag{11.3}$$

In the second step b, the input voltages of the µpot are adjusted to give nearly equal output voltages. Therefore this term is nearly zero. It contributes only to the uncertainty.

From (10.1), (11.1) and (11.3) follows

$$\delta_{792} = \frac{Uo_{792\,dc} - Uo_{792\,ac}}{n_{792} \cdot Uo_{792\,dc}} - \frac{U_{Th\,dc} - U_{Th\,ac}}{n_{TC} \cdot U_{Th\,dc}} + \delta_{\mu pot} + \delta_{Zi} \tag{11.4}$$

or in a simplified form $\delta_{792} = \delta_{\mathrm{d}} + \delta_{\mu\mathrm{pot}} + \delta_{\mathrm{Zi}}$ (11.5)

11.2 Step-down procedure

On the basis of the procedure described in 10.2, the µpots are calibrated towards lower voltages by steps in step-down measurements using a 792A, an alternating determination of the ac-dc transfer differences $\delta_{\mu\mathrm{pot}}$ and δ_{792} being carried out. For this purpose, eq. (11.5) is to be resolved reciprocally with respect to $\delta_{\mu\mathrm{pot}}$ and δ_{792}.

In Table III, the step-down procedure is schematically represented.

In the first step, the link-up to the 792A calibrated with a PMJTC at 100 mV is carried out. From the measured δ_{d} the ac-dc transfer difference of the µpot is calculated as

$$\delta_{100\mathrm{mV}_{\mu\mathrm{pot}}} = \delta_{792_{100\mathrm{mV\,PMJTC}}} - \delta_{\mathrm{d}_{100\mathrm{mV}}} - \delta_{100\mathrm{mV}_{\mu\mathrm{pot}||\mathrm{Zi}}} \,. \tag{11.6}$$

In the second step, the transfer difference of the 792A is calibrated at 50 mV with the 100 mV µpot calibrated before. For this it is supposed that the transfer difference of the µpot is constant both at 100 mV and at 50 mV and that the impedance of the 792A does not change from 100 mV to 50 mV. This results, however, in an uncertainty contribution. Then

$$\delta_{792_{50\mathrm{mV}}} = \delta_{\mathrm{d}50\mathrm{mV}_{100\mathrm{mV}/\mu\mathrm{pot}}} + \delta_{100\mathrm{mV}/\mu\mathrm{pot}} + \delta_{100\mathrm{mV}/\mu\mathrm{pot}||\mathrm{Zi}} \tag{11.7}$$

When (11.6) from step 1 is allowed for, the following is obtained for step 2:

$$\delta_{792_{50\mathrm{mV}}} = \delta_{\mathrm{d}50\mathrm{mV}_{100\mathrm{mV}/\mu\mathrm{pot}}} + \delta_{792_{100\mathrm{mV\,PMJTC}}} - \delta_{\mathrm{d}100\mathrm{mV}} - \delta_{100\mathrm{mV}/\mu\mathrm{pot}||\mathrm{Zi}} + \delta_{100\mathrm{mV}/\mu\mathrm{pot}||\mathrm{Zi}} \tag{11.8}$$

and

$$\delta_{792_{50\mathrm{mV}}} = \delta_{\mathrm{d}50\mathrm{mV}_{100\mathrm{mV}/\mu\mathrm{pot}}} + \delta_{792_{100\mathrm{mV\,PMJTC}}} - \delta_{\mathrm{d}100\mathrm{mV}} \tag{11.9}$$

Table IV. Step-down procedure

Step	U_{meas}	µpot		$\delta_{\mu\mathrm{pot}}$	δ_{792}
1	100 mV	100 mV	⟵	$\delta_{100\mathrm{mV}\mu\mathrm{pot}}$	$\delta_{100\mathrm{mV\ PMJTC}}$ –link-up
2	50 mV	100 mV	⟶	$\delta_{100\mathrm{mV}\mu\mathrm{pot}}$	$\delta_{50\mathrm{mV}\mu\mathrm{pot}}$
3	50 mV	50 mV	⟵	$\delta_{50\mathrm{mV}\mu\mathrm{pot}}$	$\delta_{50\mathrm{mV}\mu\mathrm{pot}}$

4		20 mV		50 mV	⟶
	$\delta_{50mV\mu pot}$		$\delta_{20mV\mu pot}$		
5		20 mV		20 mV	⟵
	$\delta_{20mV\mu pot}$		$\delta_{20mV\mu pot}$		
6		10 mV		20 mV	⟶
	$\delta_{20mV\mu pot}$		$\delta_{10mV\mu pot}$		

When all influences are taken into account, the equation (11.6) yields the following model equation for the determination of the ac-dc transfer difference of the μpot in the first step of the step-down procedure

$$\delta_{100mV\,\mu pot} = \delta_{792\ 100\ mV\,MJTC} - \delta_{d\,100mV} - \delta_{100\ mV\ \mu pot||Zi} + \delta_{f5720} + \delta_{connect} + \delta_{TK} \quad (11.10)$$

and from (11.9) the following results for the determination of the ac-dc transfer difference of the 792A in the second step:

$$\delta_{792\ 50\ mV} = \delta_{d50\ mV\ 100mV\,\mu pot} + \delta_{792\ 100\ mV\,MJTC} - \delta_{d100mV} + \delta_{f5720} + \delta_{connect} + \delta_{TK} + \delta_{level} \quad (11.11)$$

The equations for steps 3 to 6 are obtained accordingly.

The terms used in (11.10) and (11.11) are

$\delta_{connect}$	influence of various adapters, line connectors as well as the guarding and grounding,
δ_{level}	change of the AC-DC transfer difference of the μpot from full to half the rated voltage (Thomson and Peltier effect),
δ_{TK}	temperature influence on the transfer difference of the 792A,
δ_{f5720}	influence of a frequency deviation of the output voltage of the calibrator.

11.3 Uncertainty of calibration of the FLUKE 792A by the step-down procedure

The square of the standard uncertainty of measurement $u(\delta_x)$ of the ac-dc transfer difference of the 792A according to eq. (11.1) or (11.5) generally is

$$u^2(\delta_x) = u^2(\delta_d) + u^2(\delta_s) \quad (11.12)$$

or $u^2(\delta_{792}) = u^2(\delta_d) + u^2(\delta_{\mu pot}) + u^2(\delta_{Zi})$ (11.13)

In the first step of the step-down procedure the ac-dc transfer difference of the 100mV-μpot $\delta_{100mV\mu pot}$ against the calibrated 792A follows from (11.10):

(11.14)

$$u^2(\delta_{100\,\mathrm{mV}\,\mu\mathrm{pot}}) = u^2(\delta_{792\ 100\,\mathrm{mV\,MJTC}}) + u^2(\delta_{\mathrm{d}\ 100\,\mathrm{mV}}) + u^2(\delta_{100\,\mathrm{mV}\,\mu\mathrm{pot}||\mathrm{Zi}})$$
$$+u^2(\delta_{\mathrm{f5700}}) + u^2(\delta_{\mathrm{connect}}) + u^2(\delta_{\mathrm{TK}})$$

In the second step, according to (11.11)

$$u^2(\delta_{792\ 50mV}) = u^2(\delta_{d50\,mV}) + u^2(\delta_{100\,mV\mu\mathrm{pot}}) + u^2(\delta_{100\,mV\mu\mathrm{pot}||Zi}) \tag{11.15}$$
$$+u^2(\delta_{\mathrm{f5700}}) + u^2(\delta_{\mathrm{connect}}) + u^2(\delta_{\mathrm{TK}}) + u^2(\delta_{\mathrm{level}})$$

is obtained.

These variances continue according to Table III towards smaller voltages, where

$u(\delta_{\mathrm{f5700}})$ estimated uncertainties due to frequency instability of the calibrator
1 µV/V at all frequencies.

$u(\delta_{\mathrm{connect}})$ influence of the connecting elements, guarding and grounding
up to 15 µV/V.

$u(\delta_{\mathrm{TK}})$ uncertainties for the TK of the 792A can be taken from Table V.

$u(\delta_{\mathrm{level}})$ change of the ac-dc transfer difference of the µpot and thus of
the thermoconverter at different output voltages
1 to 3 µV/V.
Temperature coefficients of the travelling standard are taken from Table I

11.4 Discussion of the uncertainty components

The difference δ_{d} measured in the individual steps between 792A and the µpot is

$$\delta_{\mathrm{d}} = \delta_{\mathrm{A}} + \delta_{\mathrm{C}} \tag{11.16}$$

δ_{A} is the mean value of the δ_{d} determined in a series of 6 to 12 measurements at one frequency,
δ_{C} is a component of the uncertainty of measurement whose expected value is set equal to zero.
The square of the standard uncertainty of measurement of the measured difference then is

$$u^2(\delta_{\mathrm{d}}) = u^2(\delta_{\mathrm{A}}) + u^2(\delta_{\mathrm{C}}) \tag{11.17}$$

$u(\delta_{\mathrm{A}})$ is a type A standard uncertainty of the mean value δ_{A},
$u(\delta_{\mathrm{C}})$ is the standard uncertainty from the measuring set-up.

11.4.1 Determination of $u(\delta_A)$

According to the measuring method described in section 10.2, in step b of the ac-dc transfer, the balancing to equal thermovoltages of the µpot takes place at ac and dc with a tolerance of some µV/V which can be set in the program. In the practical PC- calculation of δ_d the second term of (11.3) is dropped. This method thus leads to an additional scatter of the mean values of a series of measurement, which is calculated in the PC as the standard deviation $u(\delta_A)$.

11.4.2 Calculation of $u(\delta_C)$

We can use (11.3)

$$\delta_d = \frac{Uo_{792\,dc} - Uo_{792\,ac}}{n_{792} \cdot Uo_{792\,dc}} - \frac{U_{Thdc} - U_{Thac}}{n_{TC} \cdot U_{Thdc}}$$

where U_{dc} and U_{ac} are the voltages measured by the DVM with ac and dc input voltages resp.. Because this formula is similar to (9.14) it is not necessary to show the detailed derivation for the variance of $u(\delta_C)$.

The combined variance $u^2(\delta_C)$ is

$$\begin{aligned} u^2(\delta_C) = {} & \left(\frac{U\,o_{792\,dc} - U\,o_{792\,ac}}{U\,o^*_{792\,dc} \cdot n^2_{792}} \right)^2 u^2(n_{792}) + \left(\frac{U\,o_{792\,dc} - U\,o_{792\,ac}}{n_{792} \cdot U\,o^{*2}_{792dc}} \right)^2 u^2(U\,o^*_{792\,dc}) \\ & + \left(\frac{1}{n_{792} \cdot U\,o^*_{792dc}} \right)^2 \left(u(U\,o_{792dc}) - u(U\,o_{792ac}) \right)^2 \\ & + \left(\frac{U_{Thdc} - U_{Thac}}{U^*_{Thdc}\; n^2_{TC}} \right)^2 u^2(n_{TC}) + \left(\frac{U_{Thdc} - U_{Thac}}{n_{TC} \cdot U^{*2}_{Thdc}} \right)^2 u^2(U^*_{Thdc}) \\ & + \left(\frac{1}{n_{TC} \cdot U^*_{Thdc}} \right)^2 \cdot \left(u(U_{Thdc}) - u(U_{Thac}) \right)^2 \end{aligned} \qquad (11.18)$$

with

$u(n)$	uncertainty of the exponent of the ac-dc transfer devices, which is ±50 mV/V for SJTCs and ±5 mV/V for the 792A
$u(Uo^*_{792dc})$, $u(U^*_{Th\,dc})$	are the uncertainties in the measurement of the output voltages
$(u(U_{dc})$-$u(U_{ac}))$	corresponds to the uncertainty of the linearity in the voltmeters that measures the difference between ac and dc.

The standard uncertainty calculated from (11.18) for this comparison is < 9 µV/V.

11.4.3 Determination of $u(\delta_{Zi})$:

The influence of the load due to the output impedance of the µpot at a frequency-dependent input impedance of the 792A is given by the relation

$$\delta_{Zi} = \frac{1}{\sqrt{1+2\frac{R_o}{R_i}+\left(\frac{R_o}{R_i}\right)^2+\omega^2 C_i^2 R_o^2}} - 1 \qquad (11.19)$$

R_o	output impedance of the µpot
R_i	input impedance of the 792A
C_i	input capacitance of the 792A
ω	circular or measuring frequency

The input impedances of the 792A were measured using an automatic RLC measuring bridge of the type HP 4284 A. As the bridge allows various circuits for the guard and ground connections to the test specimen (the circuit according to Fig. 3 cannot be realized in the same way), R_i was measured for different circuits and the mean values and maximum deviations $\delta_{Zi\ connec}$ determined as parts of the uncertainty.

At a maximum deviation $\delta(R_i)$ of 20% for different circuits, standard uncertainties $u(\delta_{Zi\ connec})$ including the HP 4284 A uncertainties of $15 \cdot 10^{-6}$ are obtained at 1 MHz for the 100 mV µpot with 10,7 Ω output impedance.

Another component $\delta_{Zi\ range}$ of the uncertainty of δ_{Zi} is contributed by the assumption of equal impedances within the measurwment range of the 792A. The uncertainty of this component is also effective in those steps of the step-down procedure in which there are no load influences due to the chain formulae. It is estimated to maiximal 5 µV/V.

δ_{Zi} thus is composed of the following components:

$$\delta_{Zi} = \delta_{Zi\ connec} + \delta_{Zi\ range} \qquad (11.20)$$

The square of the standard uncertainty is obtained as the sum of the variances:

$$u^2(\delta_{Zi}) = u^2(\delta_{Zi\ connec}) + u^2(\delta_{Zi\ range}) \qquad (11.21)$$

In steps 2 and 6 of the determination of δ_{792} according to the step-down procedure the first component $\delta_{Zi\ connec}$ of δ_{Zi} is dropped because the load influence in the preceeding step enters with inverse sign [cf eq. (11.8)]. Only in the transition from the 220 mV to the 22 mV range of measurement in step 4 it must be taken into consideration due to different impedances in the two voltage ranges.

The uncertainty budget for the step-down procedure is given in Table V.

Table V Uncertainty budget of the step-down procedure with the 792A travelling standard

Step	Umeas	Standard µpot	Influence quantity	Standard uncertainty in 10^{-6} at the frequencies 1 kHz	20 kHz	100 kHz	1 MHz
1	100 mV	100 mV-µP	$u\,(\delta_{\text{792-PMJTC}})$	1,4	2,4	3,3	23,4
			$u\,(\delta_{\text{A-100mV-100}\mu\text{P}})$	3,0	3,0	3,0	4,0
			$u\,(\delta_{\text{C-100mV-100}\mu\text{P}})$	1,0	2,0	3,0	9,0
			$u\,(\delta_{100\mu\text{P} \,\Vert\, \text{Zi-100mV connec}})$	1,0	1,0	2,0	15,0
			$u\,(\delta_{\text{f 5720}})$	1,0	1,0	1,0	1,0
			$u\,(\delta_{\text{connect}})$	1,0	1,0	2,0	5,0
			$u\,(\delta_{\text{TK}})$	0,5	0,5	0,5	2,0
			$u\,(\delta_{\text{100mV-}\mu\text{P stepdown}})$	**3,9**	**4,7**	**6,2**	**30,0**
			$U\,(\delta_{\text{100 mV-}\mu\text{P stepdown}})$, k=2	**7,8**	**9,4**	**12,4**	**60,0**
2	50 mV	100 mV-µP	$u\,(\delta_{\text{100mV-}\mu\text{P stepdown}})$	3,9	4,7	6,2	30,0
			$u\,(\delta_{\text{A-50mV-100}\mu\text{P}})$	8,0	8,0	8,0	11,0
			$u\,(\delta_{\text{C-50mV-100}\mu\text{P}})$	1,0	1,0	3,0	9,0
			$u\,(\delta_{100\mu\text{P} \,\Vert\, \text{Zi-50mV range}})$	0,0	0,0	1,0	5,0
			$u\,(\delta_{\text{f 5720}})$	1,0	1,0	1,0	1,0
			$u\,(\delta_{\text{connect}})$	1,0	1,0	2,0	5,0
			$u\,(\delta_{\text{TK}})$	0,5	0,5	0,5	2,0
			$u\,(\delta_{\text{level}})$	2,0	2,0	2,0	2,0
			$u(\delta_{\text{792\_50mV stepdown}})$	**9,3**	**9,7**	**11,0**	**34,1**
			$U(\delta_{\text{792\_50 mV stepdown}})$, k=2	**18,6**	**19,3**	**22,0**	**68,1**
3	50 mV	50 mV-µP	$u\,(\delta_{\text{792\_50mV stepdown}})$	9,3	9,7	11,0	34,1
			$u\,(\delta_{\text{A-50mV-50}\mu\text{P}})$	2,0	3,0	3,0	3,0
			$u\,(\delta_{\text{C-50mV-50}\mu\text{P}})$	1,0	1,0	3,0	9,0
			$u\,(\delta_{50\mu\text{P} \,\Vert\, \text{Zi-50mV connec}})$	1,0	1,0	2,0	10,0
			$u\,(\delta_{\text{f 5720}})$	1,0	1,0	1,0	1,0
			$u\,(\delta_{\text{connect}})$	2,0	2,0	4,0	8,0
			$u\,(\delta_{\text{TK}})$	0,5	0,5	0,5	2,0
			$u(\delta_{\text{50mV-}\mu\text{P stepdown}})$	**9,9**	**10,5**	**12,7**	**37,7**
			$U(\delta_{\text{50 mV-}\mu\text{P stepdown}})$, k=2	**19,8**	**20,9**	**25,3**	**75,4**
4	20 mV	50 mV-µP	$u\,(\delta_{\text{50 mV-}\mu\text{P stepdown}})$	9,9	10,5	12,7	37,7
			$u\,(\delta_{\text{A-20 mV-50}\mu\text{P}})$	9,0	9,0	9,0	8,0
			$u\,(\delta_{\text{C-20 mV-50}\mu\text{P}})$	1,0	1,0	3,0	9,0
			$u\,(\delta_{50\mu\text{P} \,\Vert\, \text{Zi-20 mV connec}})$	0,0	0,0	1,0	5,0
			$u\,(\delta_{\text{f5720}})$	1,0	1,0	1,0	1,0
			$u\,(\delta_{\text{connect}})$	2,0	2,0	4,0	8,0
			$u\,(\delta_{\text{TK}})$	1,0	1,0	1,0	4,0
			$u\,(\delta_{\text{level}})$	2,0	2,0	2,0	2,0
			$u(\ \delta_{\text{792\_20 mV stepdown}})$	**13,8**	**14,2**	**16,5**	**40,9**
			$U(\delta\text{-}_{\text{792\_20 mV stepdown}})$, k=2	**27,5**	**28,4**	**33,1**	**81,8**
5	20 mV	20 mV-µP	$u\,(\delta_{\text{ 792\_20 mV stepdown}})$	13,8	14,2	16,5	40,9
			$u\,(\delta_{\text{A-20 mV-20}\mu\text{P}})$	3,0	3,0	4,0	5,0
			$u\,(\delta_{\text{C-20 mV-20}\mu\text{P}})$	1,0	1,0	3,0	9,0
			$u\,(\delta_{20\mu\text{P} \,\Vert\, \text{Zi-20 mV connec}})$	0,0	0,0	1,0	4,0
			$u\,(\delta_{\text{f5720}})$	1,0	1,0	1,0	1,0
			$u\,(\delta_{\text{connect}})$	2,0	2,0	5,0	10,0
			$u\,(\delta_{\text{TK}})$	1,0	1,0	1,0	4,0
			$u(\ \delta_{\text{20 mV-}\mu\text{P stepdown}})$	**14,3**	**14,7**	**18,1**	**43,7**

			$U(\delta_{20\ \mathrm{mV}\text{-}\mu\mathrm{P\ stepdown}})$, k=2	**28,7**	**29,5**	**36,1**	**87,5**
6	10 mV	20 mV-µP	$u\ (\delta_{20\ \mathrm{mV}\text{-}\mu\mathrm{P\ stepdown}})$	14,3	14,7	18,1	43,7
			$u\ (\delta_{\mathrm{A}\text{-}10\ \mathrm{mV}\text{-}20\mu\mathrm{P}})$	8,0	8,0	7,0	9,0
			$u\ (\delta_{\mathrm{C}\text{-}10\ \mathrm{mV}\text{-}20\mu\mathrm{P}})$	1,0	1,0	3,0	9,0
			$u\ (\delta_{20\mu\mathrm{P}\ \|\|\ \mathrm{Zi}\text{-}10\ \mathrm{mV\ range}})$	0,0	0,0	1,0	2,0
			$u\ (\delta_{\mathrm{f}5720})$	1,0	1,0	1,0	1,0
			$u\ (\delta_{\mathrm{connect}})$	2,0	2,0	5,0	10,0
			$u\ (\delta_{\mathrm{TK}})$	1,0	1,0	1,0	4,0
			$u\ (\delta_{\mathrm{level}})$	2,0	2,0	2,0	2,0
			$u(\delta_{792\_10\ \mathrm{mV\ stepdown}})$	**16,8**	**17,1**	**20,4**	**46,9**
			$U(\delta_{792\_10\ \mathrm{mV\ stepdown}})$, k=2	**34**	**34**	**41**	**94**

The final expanded uncertainties have been rounded to two significant figures.

11.5 Summarized uncertainty of the calibration of the 792A travelling standard

For the ac-dc transfer differences of the µpots determined by the step-down procedure with only one 792A there are obviously additional influence quantities if $\delta_{\mu\mathrm{pot}}$ are determined with various 792A. This might be due to different data of the 792A input amplifiers in the mV ranges.

As a result, the $\delta_{\mu\mathrm{pot}}$ values from the step measurement with the travelling 792A and the values determined with other 792A were taken into consideration. Mean values for the final result are calculated for several different 792A.

For the calculation of the standard uncertainties $u(\delta_{\mu\mathrm{pot}})$ and $u(\delta_{792})$, the maximum deviations from the respective mean value of the $\delta_{\mu\mathrm{pot\text{-}various792}}$ are thus added as rectangularly distributed components $u(\delta_{\mu\mathrm{pot\text{-}various792}})$ to the components $u(\delta_{\mu\mathrm{pot\text{-}Stepdown}})$ or $u(\delta_{792\text{-}\mathrm{Stepdown}})$, respectively, obtained by the step-down procedure.

The sum of the variances then is

$$u^2(\delta_{\mu\mathrm{pot}}) = u^2(\delta_{\mu\mathrm{pot\text{-}Stepdown}}) + u^2(\delta_{\mu\mathrm{pot\text{-}various\ 792}}) \tag{11.22}$$

and $$u^2(\delta_{792}) = u^2(\delta_{792\text{-}\mathrm{Stepdown}}) + u^2(\delta_{\mu\mathrm{pot\text{-}various\ 792}}) \tag{11.23}$$

The complete uncertainty budget for the measurements is compiled in Table VI.

Table VI: Uncertainty budget on the basis of the step-down procedure and the ac-dc transfer differences of the µpots determined on various 792A‘s

Step	U_{meas}	Standard µpot	Influence quantity	Standard uncertainty in 10^{-6} at the frequencies			
				1 kHz	20 kHz	100 kHz	1 MHz
1	100 mV	100 mV-µP	$u(\delta_{\text{100mV-µP stepdown}})$	3,9	4,7	6,2	30,0
			$u(\delta_{\text{100mV-µP various792}})$	3,0	5,0	5,0	14,0
			$u(\delta_{\text{100mV-µP}})$	**4,9**	**6,9**	**7,9**	**33,1**
			$U(\delta_{\text{100 mV-µP}})$, k=2	**9,8**	**13,7**	**15,9**	**66,2**
2	50 mV	100 mV-µP	$u(\delta_{\text{792\_50 mV stepdown}})$	9,3	9,7	11,0	34,1
			$u(\delta_{\text{100 mV-µP various792}})$	3,0	5,0	5,0	14,0
			$u(\delta_{\text{792\_50 mV}})$	**9,8**	**10,9**	**12,1**	**36,8**
			$U(\delta_{\text{792\_50 mV}})$, k=2	**19,5**	**21,7**	**24,2**	**73,7**
3	50 mV	50 mV-µP	$u(\delta_{\text{50 mV-µP stepdown}})$	9,9	10,5	12,7	37,7
			$u(\delta_{\text{50 mV-µP various792}})$	5,0	6,0	7,0	14,0
			$u(\delta_{\text{50mV-µP}})$	**11,1**	**12,1**	**14,5**	**40,2**
			$U(\delta_{\text{50 mV-µP}})$, k=2	**22,2**	**24,1**	**29,0**	**80,4**
4	20 mV	50 mV-µP	$u(\delta_{\text{792\_20mV stepdown}})$	13,8	14,2	16,5	40,9
			$u(\delta_{\text{50 mV-µP various792}})$	5,0	6,0	7,0	14,0
			$u(\delta_{\text{792\_20mV}})$	**14,7**	**15,4**	**18,0**	**43,2**
			$U(\delta_{\text{792\_20 mV}})$, k=2	**29,3**	**30,8**	**35,9**	**86,5**
5	20 mV	20 mV-µP	$u(\delta_{\text{20 mV-µP stepdown}})$	14,3	14,7	18,1	43,7
			$u(\delta_{\text{20 mV-µP various792}})$	12,0	12,0	10,0	24,0
			$u(\delta_{\text{20mV-µP}})$	**18,7**	**19,0**	**20,7**	**49,9**
			$U(\delta_{\text{20 mV-µP}})$, k=2	**37,4**	**38,0**	**41,3**	**99,8**
6	10 mV	20 mV-µP	$u(\delta_{\text{792\_10 mV stepdown}})$	16,8	17,1	20,4	46,9
			$u(\delta_{\text{20 mV-µP various792}})$	12,0	12,0	10,0	24,0
			$u(\delta_{\text{792\_10mV}})$	**20,6**	**20,9**	**22,7**	**52,7**
			$U(\delta_{\text{792\_10 mV}})$, k=2	**41**	**42**	**45**	**105**

The final expanded uncertainties have been rounded to two significant figures. Only the uncertainty for 1 MHz shows 3 figures because it is given in 10^{-6}. The right expression should be $0{,}11 \cdot 10^{-3}$.

NPL, United Kingdom

Uncertainties

The uncertainties have been calculated for the measurements made at both the 100 and 10 mV levels. These are given in Table 1.

Table 1 - Breakdown of Uncertainty Calculations

100 mV and 200 mV Uncertainties					
	Divisor	1 kHz	20 kHz	100 kHz	1 MHz
0.5V NPL SJTC Unc		3	3	3	18
Freq Dep Bridge Errors	Rectangular	1	1	1	1
Freq Dep Voltage Change	Rectangular	0	0	0	0
Effect of T Piece	Rectangular	0	0	1	10
No. Of Steps	Rectangular	0	0	0	0
MJTC Diff Levels	Rectangular	0	0	0	0
Bridge Scatter	Normal	1	1	1	1
Effect of connectors	Rectangular	0	0	0	0
Unc of 0.2V NPL Std *k*=1		3	3	4	21
Unc of 0.2V NPL Std *k*=2		**6**	**6**	**7**	**42**
Freq Dep Bridge Errors	Rectangular	1	1	1	1
Freq Dep Voltage Change	Rectangular	0	0	0	0
Effect of T Piece	Rectangular	0	0	1	10
DUT Scatter	Normal	1	1	1	1
Effect of connectors	Rectangular	1	1	2	22
Unc of 792A @ 200 mV *k*=1		4	4	5	32
Unc of 792A @ 200 mV *k*=2		**8**	**8**	**10**	**64**
Freq Dep Bridge Errors	Rectangular	1	1	1	1
Freq Dep Voltage Change	Rectangular	0	0	0	0
Effect of T Piece	Rectangular	0	0	1	10
DUT Scatter	Normal	2	2	2	3
Effect of connectors	Rectangular	1	1	4	22
Unc of 792A @ 100 mV *k*=1		4	4	6	32
Unc of 792A @ 100 mV *k*=2		**9**	**9**	**13**	**65**
Degrees of Freedom		*>100*	*>100*	*>100*	*>100*
10 mV Uncertainties					
		1 kHz	20 kHz	100 kHz	1 MHz
Test at 100 mV Direct(1)		4	4	6	32
Test at 100 mV thro' Attenuator(1)		4	4	6	32
Test at 10 mV thro' Attenuator(1)		4	4	6	32
100 mV Bridge Scatter	Normal	3	2	2	3
100 mV Thro' Att Scatter	Normal	1	1	1	1
10 mV thro' Att Scatter	Normal	3	3	3	3
Input Impedance (180:1) 100 mV	Normal	0	1	1	35
Input Impedance (180:1) 10 mV	Normal	0	1	1	11
Input Impedance (89:1) 100 mV	Normal	1	2	4	129
Input Impedance (89:1) 10 mV	Normal	1	2	4	54
Effect of connectors	Rectangular	1	1	2	9
Reproducibility between runs	Normal	6	7	7	30

NPL, United Kingdom

Correlated Uncs (1)	13	12	19	97
RSS'd Uncs 180:1 *k*=1	15	15	20	108
RSS'd Uncs 180:1 *k*=2	**30**	**30**	**41**	**217**
Degrees of Freedom	*>100*	*>100*	*>100*	*>100*
RSS'd Uncs 89:1 *k*=1	15	15	21	173
RSS'd Uncs 89:1 *k*=2	**30**	**30**	**43**	**346**
Degrees of Freedom	*>100*	*>100*	*>100*	*>100*

NMi, The Netherlands

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 compliance 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 5.

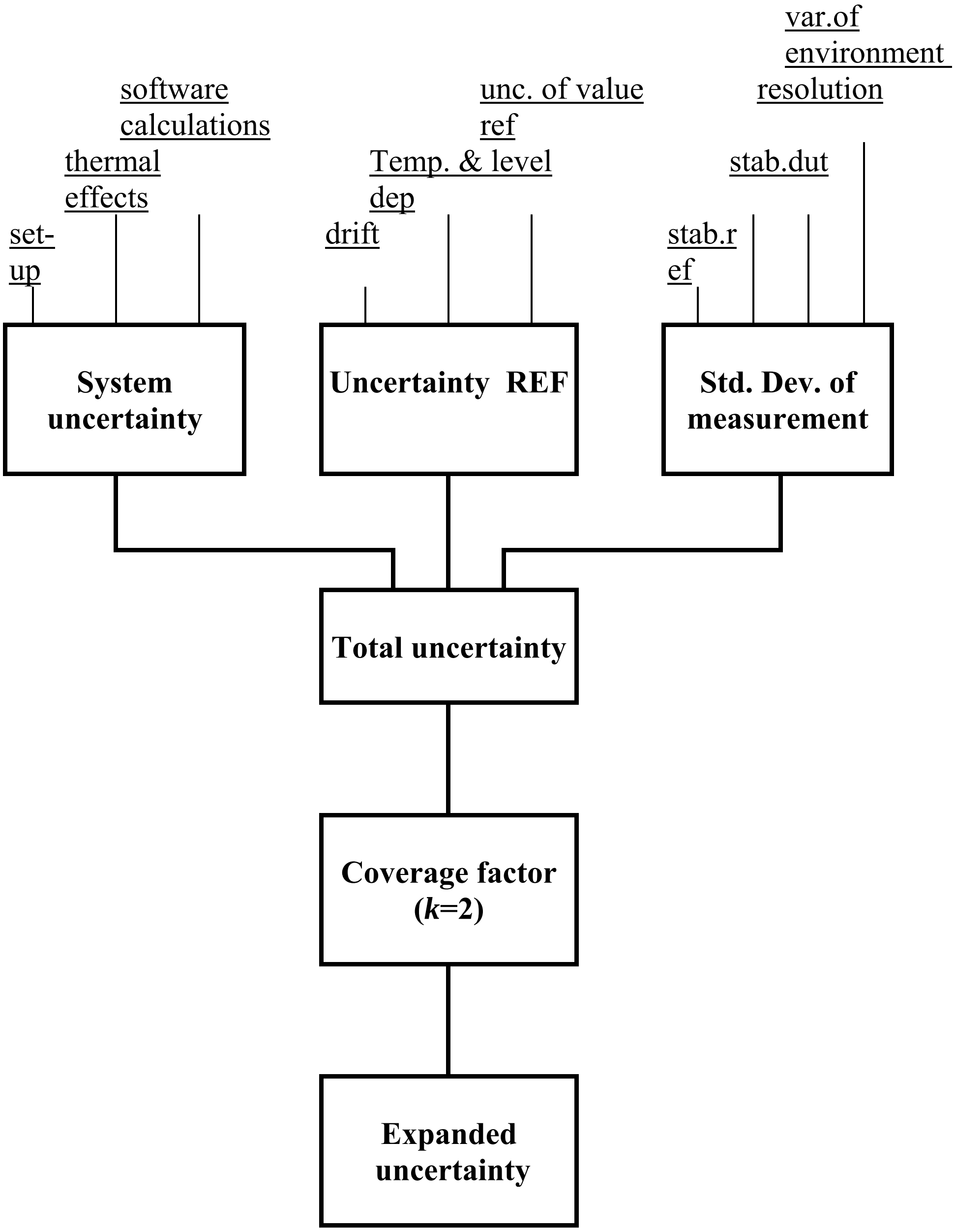

Fig. 5. Expression of the contributions to the expanded uncertainty budget of AV-DV measurements at low voltages.

Normally the set-up contribution of the measurement system contains the estimated errors caused by used cables, connectors, grounding, 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 and the connectors.
Also the temperature was for the Fluke 792A 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:

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

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_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_{therm}	thermal effects of the converter

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 dependence only counts for the Fluke 792A. The pilot lab delivers coefficients and uncertainty. Also the uncertainty in measuring the temperature 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 beneath 1%. The magnitude of the AV-DV difference is deciding here.
- 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.
- Thermal effects of the converter are estimated on the basis of fast reversed DC-source measurements.

For the determination of the AV-DV difference and the belonging 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.
We limited the number of uncertainty tables to the used references and the device under test for the both ranges.

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}	-13.3	1	normal	3.1	3.1
d_{level}	0	1	rectangular	0.5	0.3
$\delta m,REF - \delta m,DUT$	14.7	1	normal	1.5	1.5
d_{S}	1	14.7	rectangular	0.01	0.1
d_{temp}	0	1	rectangular	1.0	0.6
$d_{set\text{-}up}$	0	1	rectangular	2.0	1.2
d_{repr}	0	1	rectangular	2.0	1.2
d_{conn}	0	1	rectangular	0.0	0.0
d_{therm}	0	1	rectangular	2.0	1.2
$\boldsymbol{\delta_{DUT}}$	1.4			U_{TOTAL}	4.0
				$\boldsymbol{U_{EXP(k=2)}}$	**8.0**

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}	-28.4	1	normal	12.8	12.8
d_{level}	0	1	rectangular	0.5	0.3
δm,REF - δm,DUT	34.5	1	normal	0.9	0.9
d_S	1	34.5	rectangular	0.01	0.2
d_{temp}	0	1	rectangular	2.0	1.2
$d_{set\text{-}up}$	0	1	rectangular	20.0	11.5
d_{repr}	0	1	rectangular	2.0	1.2
d_{conn}	0	1	rectangular	0.0	0.0
d_{therm}	0	1	rectangular	5.0	2.9
$\boldsymbol{\delta_{DUT}}$	6.1			U_{TOTAL}	17.6
				$\boldsymbol{U_{EXP}}_{(k=2)}$	**35.2**

NMIA, Australia

Uncertainty Budgets:

100 mV

Source of Uncertainty	Standard Uncertainty (μV/V)				Type	Distributio
	1 kHz	20 kHz	100 kHz	1 MHz		
Reference Standard						
TC (LF)	0.8	0.8	0.8	0.8	B	Normal
TC (HF)	1.2	1.2	3.9	6.6	B	Normal
Resistor	0.8	1.5	3.1	19.4	B	Normal
Stray Admittance	0.0	0.0	2.0	12.0	B	Normal
Repeatability	1	1	3	15	B	Normal
Loading Effect	0	1	1	13	B	Normal
Total Reference Standard	1.9	2.5	6	31	B	Normal
Measuring Set-up	1	1	2	4	B	Normal
Loading Effects on Micropotentiometers	0	0	2	13	B	Normal
Connectors	0	0	2	15	B	Normal
Temperature	0	1	1.5	6	B	Normal
Measuring Frequency	0	0	0	1	B	Normal
Reproducibility	2	2	3	5	A	Normal
Combined Uncertanty (k=1)	2.9	3.5	7.9	37.8		
Expanded Uncertainty (k=2)	5.9	7.0	16	76		

10 mV

Source of Uncertainty	Standard Uncertainty (μV/V)				Type	Distributio
	1 kHz	20 kHz	100 kHz	1 MHz		
Reference Standard						
TC (LF)	3	3	3	3	B	Normal
TC (HF)	1.2	1.2	5.8	23.3	B	Normal
Resistor	0.8	1.5	3.1	23.3	B	Normal
Stray Admittance	1.0	2.0	3.0	10.0	B	Normal
Repeatability	4	4	18	28	B	Normal
Loading Effect	0	1	1	3	B	Normal
Total Reference Standard	5.3	5.8	20	45	B	Normal
Measuring Set-up	4	5	6	12	B	Normal
Loading Effects on Micropotentiometers	0	0	0.2	0.6	B	Normal
Connectors	0	0	1	12	B	Normal
Temperature	1	1	2	7.5	B	Normal
Measuring Frequency	0	0	0	1	B	Normal
Reproducibility	2	2	3	23	A	Normal
Combined Uncertanty (k=1)	7.0	8.0	20.9	53.5		
Expanded Uncertainty (k=2)	14.0	16.0	42	107		

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Ref: RN 45153 *File*: CB/02/0493 *Checked*: *Date*: 14 September 2004

INTI, Argentina

APPENDIX 2. Summary of uncertainty budget

Key comparison CCEM-K11"AC-DC Voltages transfer difference at low voltages"

Institute: INTI, Instituto Nacional de Tecnologia Industrial
Date of measurements: October 16th, 2002 to November 23th, 2002

Measuring voltage: 100 mV

Contribution of:	Std. Unc. f: 1 kHz (10^{-6})	Std. Unc. f: 20 kHz (10^{-6})	Std. Unc. f: 100 kHz (10^{-6})	Std. Unc. f: 1 MHz (10^{-6})	Type A or B	Distri-bution
Standard deviation of 12 measurements (δA)	2,9	2,5	3,0	2,5	A	n
AC-DC transfer difference of the standard	4,0	4,0	9,0	24,0	B	n
Measuring setup	0,2	0,5	3,7	16,5	A	r
Stability of HP 3458A	1,3 x 10^{-5}	1,3 x 10^{-5}	1,3 x 10^{-5}	1,3 x 10^{-5}	B	r
Stability of Keithley 182	2,1 x 10^{-3}	2,1 x 10^{-3}	2,1 x 10^{-3}	2,1 x 10^{-3}	B	r
AC-DC transfer difference due to connectors (δconnect)	1,7	1,2	2,3	5,9	B	r
AC-DC transfer difference due to the temperature coefficient of FLUKE 792 (δTK)	0,3	0,3	0,3	0,3	B	r

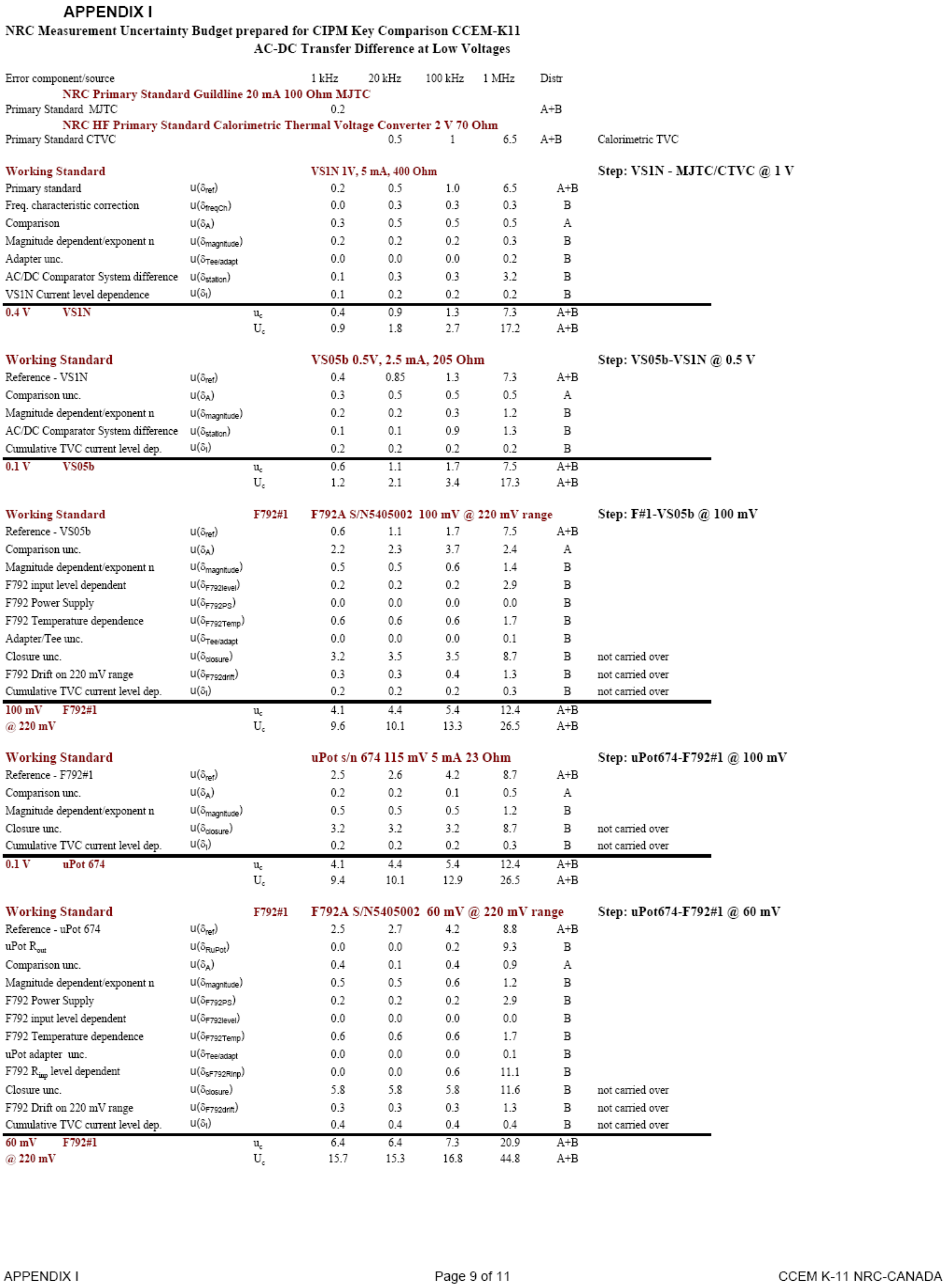
Standard unc (k=1)	5,2	4,9	10,4	29,8
Expanded unc:	10,5	9,8	20,8	59,6

Measuring voltage: 10 mV

Contribution of:	**Std. Unc. f: 1 kHz (10^{-6})**	**Std. Unc. f: 20 kHz (10^{-6})**	**Std. Unc. f: 100 kHz (10^{-6})**	**Std. Unc. f: 1 MHz (10^{-6})**	**Type A or B**	**Distri-bution**
Standard deviation of 12 measurements (δA)	1,4	2,0	1,4	1,4	A	n
Step-down procedure	11,2	12,5	20,7	48,7	B	n
Exponent “n” of µpot	4,6 x 10^{-5}	1,9 x 10^{-7}	1,4 x 10^{-6}	5,2 x 10^{-6}	B	n
Measuring setup	1,0	2,4	1,6	11,3	A	n
Stability of HP 3458A	1,3 x 10^{-5}	0,3	0,3	0,3	B	r
Stability of Keithley 182	1,0 x 10^{-3}	2,0 x 10^{-5}	2,0 x 10^{-5}	2,0 x 10^{-5}	B	r
AC-DC transfer difference due to loading the mpot by the Fluke 792 (δZ_i)	0	2,3	3,5	5,9	B	r
AC-DC transfer difference due to connectors (δconnect)	3,5	3,5	8,2	17,6	B	r
AC-DC transfer difference due to the temperature coefficient of FLUKE 792 (δTK)	0,3	0,3	0,3	0,3	B	r
Change of the AC-DC transfer difference due to the µpot from rated to half of the rated voltage (δlevel)	4,7	4,7	4,7	4,7	B	r
Variations in the imput impedance due to the connections (δZ_i-con)	0	0	0,6	7,6	B	r

Standard unc (k=1)	12,8	14,4	23,2	54,1	
Expanded unc:	25,6	28,8	46,4	108,2	

NRC, Canada



APPENDIX I

NRC Measurement Uncertainty Budget prepared for CIPM Key Comparison CCEM-K11
AC-DC Transfer Difference at Low Voltages

Error component/source			1 kHz	20 kHz	100 kHz	1 MHz	Distr	
NRC Primary Standard Guildline 20 mA 100 Ohm MJTC								
Primary Standard MJTC			0.2				A+B	
NRC HF Primary Standard Calorimetric Thermal Voltage Converter 2 V 70 Ohm								
Primary Standard CTVC				0.5	1	6.5	A+B	Calorimetric TVC
Working Standard			**VS1N 1V, 5 mA, 400 Ohm**					**Step: VS1N - MJTC/CTVC @ 1 V**
Primary standard	$u(\delta_{ref})$		0.2	0.5	1.0	6.5	A+B	
Freq. characteristic correction	$u(\delta_{freqCh})$		0.0	0.3	0.3	0.3	B	
Comparison	$u(\delta_{A})$		0.3	0.5	0.5	0.5	A	
Magnitude dependent/exponent n	$u(\delta_{magnitude})$		0.2	0.2	0.2	0.3	B	
Adapter unc.	$u(\delta_{Tee/adapt}$		0.0	0.0	0.0	0.2	B	
AC/DC Comparator System difference	$u(\delta_{station})$		0.1	0.3	0.3	3.2	B	
VS1N Current level dependence	$u(\delta_{I})$		0.1	0.2	0.2	0.2	B	
0.4 V **VS1N**		u_c	0.4	0.9	1.3	7.3	A+B	
		U_c	0.9	1.8	2.7	17.2	A+B	
Working Standard			**VS05b 0.5V, 2.5 mA, 205 Ohm**					**Step: VS05b-VS1N @ 0.5 V**
Reference - VS1N	$u(\delta_{ref})$		0.4	0.85	1.3	7.3	A+B	
Comparison unc.	$u(\delta_{A})$		0.3	0.5	0.5	0.5	A	
Magnitude dependent/exponent n	$u(\delta_{magnitude})$		0.2	0.2	0.3	1.2	B	
AC/DC Comparator System difference	$u(\delta_{station})$		0.1	0.1	0.9	1.3	B	
Cumulative TVC current level dep.	$u(\delta_{I})$		0.2	0.2	0.2	0.2	B	
0.1 V **VS05b**		u_c	0.6	1.1	1.7	7.5	A+B	
		U_c	1.2	2.1	3.4	17.3	A+B	
Working Standard		**F792#1**	**F792A S/N5405002 100 mV @ 220 mV range**					**Step: F#1-VS05b @ 100 mV**
Reference - VS05b	$u(\delta_{ref})$		0.6	1.1	1.7	7.5	A+B	
Comparison unc.	$u(\delta_{A})$		2.2	2.3	3.7	2.4	A	
Magnitude dependent/exponent n	$u(\delta_{magnitude})$		0.5	0.5	0.6	1.4	B	
F792 input level dependent	$u(\delta_{F792level})$		0.2	0.2	0.2	2.9	B	
F792 Power Supply	$u(\delta_{F792PS})$		0.0	0.0	0.0	0.0	B	
F792 Temperature dependence	$u(\delta_{F792Temp})$		0.6	0.6	0.6	1.7	B	
Adapter/Tee unc.	$u(\delta_{Tee/adapt}$		0.0	0.0	0.0	0.1	B	
Closure unc.	$u(\delta_{closure})$		3.2	3.5	3.5	8.7	B	not carried over
F792 Drift on 220 mV range	$u(\delta_{F792drift})$		0.3	0.3	0.4	1.3	B	not carried over
Cumulative TVC current level dep.	$u(\delta_{I})$		0.2	0.2	0.2	0.3	B	not carried over
100 mV **F792#1**		u_c	4.1	4.4	5.4	12.4	A+B	
@ 220 mV		U_c	9.6	10.1	13.3	26.5	A+B	
Working Standard			**uPot s/n 674 115 mV 5 mA 23 Ohm**					**Step: uPot674-F792#1 @ 100 mV**
Reference - F792#1	$u(\delta_{ref})$		2.5	2.6	4.2	8.7	A+B	
Comparison unc.	$u(\delta_{A})$		0.2	0.2	0.1	0.5	A	
Magnitude dependent/exponent n	$u(\delta_{magnitude})$		0.5	0.5	0.5	1.2	B	
Closure unc.	$u(\delta_{closure})$		3.2	3.2	3.2	8.7	B	not carried over
Cumulative TVC current level dep.	$u(\delta_{I})$		0.2	0.2	0.2	0.3	B	not carried over
0.1 V **uPot 674**		u_c	4.1	4.4	5.4	12.4	A+B	
		U_c	9.4	10.1	12.9	26.5	A+B	
Working Standard		**F792#1**	**F792A S/N5405002 60 mV @ 220 mV range**					**Step: uPot674-F792#1 @ 60 mV**
Reference - uPot 674	$u(\delta_{ref})$		2.5	2.7	4.2	8.8	A+B	
uPot R_{out}	$u(\delta_{RuPot})$		0.0	0.0	0.2	9.3	B	
Comparison unc.	$u(\delta_{A})$		0.4	0.1	0.4	0.9	A	
Magnitude dependent/exponent n	$u(\delta_{magnitude})$		0.5	0.5	0.6	1.2	B	
F792 Power Supply	$u(\delta_{F792PS})$		0.2	0.2	0.2	2.9	B	
F792 input level dependent	$u(\delta_{F792level})$		0.0	0.0	0.0	0.0	B	
F792 Temperature dependence	$u(\delta_{F792Temp})$		0.6	0.6	0.6	1.7	B	
uPot adapter unc.	$u(\delta_{Tee/adapt}$		0.0	0.0	0.0	0.1	B	
F792 R_{inp} level dependent	$u(\delta_{sF792Rinp})$		0.0	0.0	0.6	11.1	B	
Closure unc.	$u(\delta_{closure})$		5.8	5.8	5.8	11.6	B	not carried over
F792 Drift on 220 mV range	$u(\delta_{F792drift})$		0.3	0.3	0.3	1.3	B	not carried over
Cumulative TVC current level dep.	$u(\delta_{I})$		0.4	0.4	0.4	0.4	B	not carried over
60 mV **F792#1**		u_c	6.4	6.4	7.3	20.9	A+B	
@ 220 mV		U_c	15.7	15.3	16.8	44.8	A+B	

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Working Standard			**uPot s/n 1774 68 mV 10 mA 6.8 Ohm**					**Step: uPot1744 - F792#1 @ 60 mV**
Reference - F792#1	$u(\delta_{ref})$		2.7	2.8	4.3	17.3	A+B	
Comparison unc.	$u(\delta_{A})$		0.4	0.2	0.2	1.0	A	
Magnitude dependent/exponent n	$u(\delta_{magnitude})$		0.5	0.5	0.5	0.8	B	
Closure unc.	$u(\delta_{closure})$		5.8	5.8	5.8	11.6	B	not carried over
Cumulative TVC current level dep.	$u(\delta_{I})$		0.4	0.4	0.4	0.4	B	not carried over
60 mV **uPot 674**		u_c	6.4	6.5	7.3	20.9	A+B	
		U_c	15.7	15.3	16.8	44.8	A+B	

Working Standard		**F792#1**	**F792A S/N5405002 20 mV @ 220 mV range**					**Step: uPot1744 - F792#1 @ 20 mV**
Reference - uPot 1774	$u(\delta_{ref})$		2.7	2.8	4.4	17.4	A+B	
uPot R_{out}	$u(\delta_{RuPot})$		0.0	0.0	0.0	0.8	B	
Comparison unc.	$u(\delta_{A})$		1.3	1.4	0.9	1.3	A	
Magnitude dependent/exponent n	$u(\delta_{magnitude})$		0.5	0.5	0.5	0.8	B	
F792 Power Supply	$u(\delta_{F792PS})$		0.2	0.2	0.2	2.9	B	
F792 input level dependent	$u(\delta_{F792level})$		0.0	0.0	0.0	0.0	B	
F792 Temperature dependence	$u(\delta_{F792Temp})$		0.6	0.6	0.6	1.7	B	
uPot adapter unc.	$u(\delta_{Tee/adapt}$		0.0	0.0	0.0	0.5	B	
F792 R_{inp} level dependent	$u(\delta_{sF792RInp})$		0.0	0.0	0.2	3.3	B	
Closure unc.	$u(\delta_{closure})$		8.7	8.7	8.7	17.4	B	not carried over
F792 Drift on 220 mV range	$u(\delta_{F792drift})$		0.3	0.3	0.3	1.3	B	not carried over
Cumulative TVC current level dep.	$u(\delta_{I})$		1.3	1.3	1.3	1.3	B	not carried over
20 mV **F792#1**		u_c	9.3	9.4	9.9	25.2	A+B	
@ 220 mV		U_c	22.9	23.0	23.4	54.0	A+B	

Working Standard		**F792#2**	**F792A S/N6680001 20 mV @ 22 mV range**					**Step: F792#2/22mV-F792#1/220 mV @ 20 mV**
Reference - F792A #1	$u(\delta_{ref})$		3.1	3.3	4.5	18.1	A+B	
Comparison unc.	$u(\delta_{A})$		1.2	2.0	0.7	5.0	A	
Magnitude dependent/exponent n	$u(\delta_{magnitude})$		0.5	0.5	0.7	3.9	B	
F792 Power Supply	$u(\delta_{F792PS})$		0.6	0.6	0.4	4.7	B	
F792 input level dependent	$u(\delta_{F792level})$		0.0	0.0	0.0	0.0	B	
F792 Temperature dependence	$u(\delta_{F792Temp})$		0.6	0.6	0.6	4.6	B	
uPot adapter unc.	$u(\delta_{Tee/adapt}$		0.0	0.0	0.0	0.1	B	
Closure unc.	$u(\delta_{closure})$		11.6	11.6	11.6	23.2	B	not carried over
Cumulative TVC current level dep.	$u(\delta_{I})$		1.3	1.3	1.3	1.3	B	not carried over
20 mV **F792#2**		u_c	12.2	12.3	12.6	30.8		
@ 220 mV		U_c	31.3	30	30.8	67.2		

Working Standard		**F792#1**	**F792A S/N5405002 20 mV @ 22 mV range**					**Step: F792#2/22 mV-F792#1/22mV @ 20 mV**
Reference - F792A #2	$u(\delta_{ref})$		3.5	3.9	4.7	20.3		
Comparison unc.	$u(\delta_{A})$		8.1	3.6	3.7	13.6		
Magnitude dependent/exponent n	$u(\delta_{magnitude})$		0.5	0.5	0.6	6.2		
F792 Power Supply	$u(\delta_{F792PS})$		0.6	0.6	0.4	4.7		
F792 input level dependent	$u(\delta_{F792level})$		0.0	0.0	0.0	0.1		
F792 Temperature dependence	$u(\delta_{F792Temp})$		0.6	0.6	0.6	4.6		
uPot adapter unc.	$u(\delta_{Tee/adapt}$		0.0	0.0	0.0	0.1		
Closure unc.	$u(\delta_{closure})$		11.6	11.6	11.6	23.2		not carried over
F792 drift on 22 mV range	$u(\delta_{F792drift})$		0.4	0.4	0.4	2.0		not carried over
Cumulative TVC current level dep.	$u(\delta_{I})$		1.3	1.3	1.3	1.3		not carried over
20 mV **F792#1**		u_c	14.7	12.9	13.2	35		
@ 22 mV		U_c	34.7	30.5	31.1	73.8		

Working Standard			**uPot s/n 1269 mV 5 mA 6 Ohm**					**Step: uPot1269 - F792#1 @ 20 mV**
Reference - F792#1	$u(\delta_{ref})$		8.9	5.4	6.1	26	A+B	
Comparison unc.	$u(\delta_{A})$		0.5	0.7	0.3	2.8	A	
Magnitude dependent/exponent n	$u(\delta_{magnitude})$		0.5	0.5	0.5	4.9	B	
Closure unc.	$u(\delta_{closure})$		11.6	11.6	11.6	23.2	B	not carried over
Cumulative TVC current level dep.	$u(\delta_{I})$		1.3	1.3	1.3	1.3	B	not carried over
20 mV **uPot 1269**		u_c	14.7	12.9	13.2	35.7	A+B	
		U_c	34.8	30.5	31.2	75.0	A+B	

NRC, Canada

Working Standard		**F792#1**	**F792A S/N5405002 10 mV @ 220 mV range**					**Step: uPot1269 - F792#1 @ 10 mV**
Reference - uPot 1269	$u(\delta_{ref})$		8.9	5.5	6.1	27.1	A+B	
uPot R_{out}	$u(\delta_{RuPot})$		0.0	0.0	0.0	0.5	B	
Comparison unc.	$u(\delta_{A})$		1.5	1.5	2.1	1.3	A	
Magnitude dependent/exponent n	$u(\delta_{magnitude})$		0.6	0.5	0.5	5.2	B	
F792 Power Supply	$u(\delta_{F792PS})$		0.6	0.6	0.4	4.7	B	
F792 input level dependent	$u(\delta_{F792level})$		0.0	0.0	0.0	0.0	B	
F792 Temperature dependence	$u(\delta_{F792Temp})$		0.6	0.6	0.6	4.6	B	
uPot adapter unc.	$u(\delta_{Tee/adpt}$		0.0	0.0	0.0	0.5	B	
F792 R_{inp} level dependent	$u(\delta_{sF792RInp})$		0.0	0.0	0.0	4.6	B	
Closure unc.	$u(\delta_{closure})$		11.6	11.6	23.2	29.0	B	not carried over
F792 drift on 22 mV range	$u(\delta_{F792drift})$		0.4	0.4	0.4	2.0	B	not carried over
Cumulative TVC current level dep.	$u(\delta_{I})$		1.5	1.5	1.5	1.5	B	not carried over
10 mV **F792#1**		u_c	14.8	13.1	24.2	40.9	A+B	
@ **22 mV**		U_c	34.2	30.9	62.1	86.7	A+B	

SPRING, Singapore

Summary of Uncertainty Budget:

100 mV

Contribution of		**1 kHz**	**20 kHz**	**100 kHz**	**1 MHz**	**Distribution**
Type A		4.1	3.6	5	4.9	Normal
Type B	Standard	1	1	2	15	Normal
	Measuring system	8	11	12	40	Normal
	Total Type B	8.1	11.1	12.2	42.7	
Combined	Standard uncertainty	9.0	11.7	13.2	43.0	
Expanded	**Combined uncertainty**	18	24	27	86	

10 mV

Contribution of		1 kHz	20 kHz	100 kHz	1 MHz	Distribution
Type A		6.2	9.6	6.1	7.7	Normal
Type B	Standard	1	1	2	15	Normal
	Measuring system	12	12	13	90	Normal
	Divider	10	10	15	55	Normal
	Loading effect	0	0	7	150	Rectangular
	Total Type B	15.7	15.7	21.2	184.0	
Combined	Standard uncertainty	16.9	18.4	22.0	184.2	
Expanded	Combined uncertainty	34	37	44	370	

NIM, China

Uncertainty budget

The uncertainty budgets of the measurements at 100mV and 10mV at frequency of 1kHz, 20kHz, 100kHz and 1MHz were shown in the following tables.

Table IV Measuring voltage:100mV

Contribution of	Std. unc. f:1kHz	Std. unc. f:20kHz	Std. unc. f:100kHz	Std. unc. f:1MHz	Type A or B	Distribution
Std deviation of measurements	1	1	2	5	A	Gaussian
Cal uncertainty of Fluke 5790A at 0.8V at 1kHz 20kHz 100kHz or 1V at 1MHz	5	6	8	30	B	Gaussian
Uncertainty of the ratio error of IVDs	3	3	10	30	B	Gaussian
Cal uncertainty of HP 3458A at 100mV	3	3	3	3	B	Gaussian
Influence of the unbalance of 792A's outputs between ac and dc inputs	2	2	5	10	B	Gaussian
Uncertainty of loading effects measurements	1	1	5	20	B	Gaussian
*Influence of the dc cable without shielding	2	2	2	2	B	Gaussian
Connector	0	1	2	5	B	Gaussian

Standard unc (k=1):	7	8	15	49
Expanded unc:	**14**	**16**	**30**	**98**

Table V Measuring voltage: 10mV

Contribution of	Std. unc. f:1kHz	Std. unc. f:20kHz	Std. unc. f:100kHz	Std. unc. f:1MHz	Type A or B	Distribution
Std deviation of measurements	3	3	5	10	A	Gaussian
Cal uncertainty of Fluke 5790A at 80mV at 1kHz 20kHz 100kHz or 100mV at 1MHz	10	10	20	60	B	Gaussian
Uncertainty of the ratio error of IVDs	3	3	10	30	B	Gaussian
Uncertainty of Voltage dependence of IVDs	2	2	3	30		Gaussian
Cal uncertainty of HP 3458A at 10mV	20	20	20	20	B	Gaussian
Influence of unbalance of 792A's outputs between ac and dc inputs	10	10	20	30	B	Gaussian
Uncertainty of loading effects measurements	5	5	10	30	B	Gaussian
Connector	0	1	2	5	B	Gaussian
*influence of dc connection shielding (revised)	30	30	30	30	B	Gaussian

Standard unc (k=1):	39	39	48	93
Expanded unc:	**78**	**78**	**96**	**186**

The standard uncertainties of the measurements were calculated according to the square root of the sum of the squares of the uncertainty of the influence components.

*The shielding of the interconnection between dc source, Fluke 5700A, and Fluke 792A and HP3458A were not connected to the common ground during the test. After the traveling standard was send back to the pilot laboratory, in the environment of our lab, in the measurement setup for 10mV, quite a large influence up to 100ppm was found at the output of NIM's Fluke 792A when the shielding was open and ground. The influence was thought to be come from the 50Hz interfering signal in the space. It coupled with the dc voltage to HP 3458A and Fluke 792A via the ungrounded shielding. The dc range of HP3458A has very good ability to reject this interfering signal, so no influence could be found in the reading of HP3458A, but Fluke 792A is much sensitive to it. Two sets of Fluke 792A of NIM were measured in the setup to evaluate the influence to the ac-dc difference at 10mV and 100mV at frequency from 1kHz to 1MHz when the shielding is open and ground. No visible difference

NIM, China

could be found at 100mV, but at 10mV the difference was measured to be from 70ppm to 110ppm. At last, we revised the former measurement results of the travelling standard at 10mV at frequency of 1kHz, 20kHz, 100kHz and 1MHz with -90ppm, and gave the uncertainty of 30ppm for the revise.

NIST, USA

Appendix A. Uncertainty Analysis for CCEM-K11 Intercomparison

Calibration Method 1:

The degrees of freedom for these calculations was greater than 100. The type of distribution is given in parentheses for each contribution.

Table 1. Uncertainty Analysis for Fluke 792A S/N 6765002 at 100 mV

Contribution from NIST Standards	Type	1 kHz	20 kHz	100 kHz	1 MHz
Primary standards MJTCs (normal)	B	0.25	0.25		
Type A component (pooled standard deviation)	A	0.10	0.10		
NIST comparator system (normal)	B	0.68	0.68	1.31	2.13
Frequency extension from 1 kHz reference TVC (normal)	B		0.29	1.15	3.46
Total contribution from NIST standard MJTC (k=1)		0.73	0.79	1.74	4.42
Comparison of Fluke 792A S/N 5405003 to MJTC reference standard at 100 mV					
Type A component (pooled standard deviation)	A	3.00	2.10	1.90	2.40
NIST comparator system (normal)	B	0.68	0.68	1.31	2.13
Contribution of Fluke 792A S/N 5405003					
Ac effects (uniform)	B	1.15	1.15	3.46	7.50
Connector contribution (uniform)	B	0.00	0.00	0.58	1.73
Total contribution of measurement of Fluke 792A S/N 5405003 (k = 1)		3.40	2.60	4.50	9.30
Comparison of Fluke 792A S/N 6765002 to NIST 792A S/N 5405003 at 100 mV					
Type A component (pooled standard deviation)	A	2.20	2.00	1.70	2.20
NIST comparator system (normal)	B	0.68	0.68	1.31	2.13
Contribution of Fluke 792A S/N 6765002					
Ac effects (uniform)	B	1.15	1.15	3.46	7.50
Connector contribution (uniform)	B	0.00	0.00	0.58	1.73
Total contribution of measurement of Fluke 792A S/N 6765002 (k = 1)		2.57	2.41	4.11	8.28
Standard uncertainty (k = 1)		4.20	3.60	6.10	12.30
Expanded uncertainty (k = 2)		**8.40**	**7.20**	**12.20**	**24.60**

Calibration Method 2:

Table 2. Uncertainty Analysis for Fluke 792A S/N 6765002 at 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
TVC	4.0	5	11	37.5	B	Normal
Level dependence	5.0	5.4	7	25	B	Uniform
Connector	0	0	1	3	B	Uniform
Step-down Reproducibility	3.0	2.3	4.8	7.8	A	Normal
Standard unc (k=1):	7.1	7.7	13.9	45.7		
Expanded unc:	14.1	15.4	27.8	91.5		

Table 3. Uncertainty Analysis for Fluke 792A S/N 6765002 at 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
TVC	4	5	11	37.5	B	Normal
Level dependence	15.8	16.6	19.6	55.2	B	Uniform
Connector	0	0	3	10	B	Uniform
μpot loading	1	1	3	10	B	Uniform
Step-down reproducibility	7.9	8.4	10.6	15.5	A	Normal
Degrees of Freedom	>100	>100	>100	>100		
Standard unc (k=1):	18.2	19.3	25.7	70.0		
Expanded unc:	36.4	38.5	51.3	139.9		

The various influence parameters, including measurement frequency and battery pack voltage, are presented in Table 4 below.

Table 4. Influence Parameters

Influence Parameter				
Frequency (Nominal):	1 kHz	20 kHz	100 kHz	1 MHz
Measuring frequency	1 kHz	20 kHz	100 kHz	1 MHz
Expanded uncertainty	10 μHz/Hz	10 μHz/Hz	10 μHz/Hz	10 μHz/Hz
Environmental Conditions	Min	Max		
Ambient temperature in ºC	22.7	23.4		
Relative humidity in %	23	41		
Battery Pack Voltages	Min	Max		
Power supply voltage, positive in V	11.144	11.151		
Power supply voltage, negative in V	11.146	11.152		

SP, Sweden

Uncertainty analysis of the voltage step-down procedure at SP

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). 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 (μPot). 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 of the TTS and the deviation from the nominal temperature. No correction is made for the deviation from the nominal relative humidity as this will be done for all NMIs in the report of the CCEM-K11. 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

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

3. Comparison of TTS at level x V to TTS at level y V via micropotentiometer

The measured ac-dc transfer difference δ_T of the test TTS at the voltage level y V is determined as:

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

where

δ_{A1}	indicated ac-dc transfer difference between the standard TTS and the test µPot at level x V
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 µPot and the test TTS at level y V
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 x V
δ_{LD}	correction for the error in the ac-dc transfer difference of the standard µPot due to level dependence
δ_L	correction for the error in the ac-dc transfer difference of the standard µPot due to changes in loading

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

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

4. Correction of error due to temperature coefficient of TTS

The measured ac-dc transfer difference δ_{yV} of the TTS at nominal temperature is determined as:

$\delta_{yV} = \delta_T + \delta_{TC}$ (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

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

$u^2(\delta_{yV}) = u^2(\delta_T) + u^2(\delta_{TC})$ (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	1	1,6	19
Level dependence 2 V to 1 V	$u(\delta_{LD})$	0,1	0,1	0,1	0,1
Measurement set-up	$u(\delta_B)$	0,5	0,5	1,5	5
Indicated ac-dc difference	$u(\delta_A)$	0,2	0,2	0,2	1
T-connector	$u(\delta_C)$	0,1	0,1	0,2	2
Ac-dc difference PMJTC 1 V	$u(\delta_T)$	0,75	1,14	2,21	19,77
Standard uncertainty 1 V	$\mathbf{u(\delta_{1V})}$	**0,8**	**1,2**	**2,3**	**19,8**
From 1 V to 0,2 V					
1:1 comparison					
Ac-dc difference PMJTC 1 V	$u(\delta_S)$	0,8	1,2	2,3	19,8
Level dependence 1 V to 0,2 V	$u(\delta_{LD})$	0,2	0,2	0,2	0,2
Measurement set-up	$u(\delta_B)$	1	1	3	10
Indicated ac-dc difference	$u(\delta_A)$	0,8	0,8	1	2
T-connector	$u(\delta_C)$	0,1	0,1	0,2	2
Temperature coefficient TTS *	$u(\delta_{TC})$	0,3	0,3	0,7	7
Ac-dc difference TTS 0,2 V	$u(\delta_T)$	1,56	1,79	3,98	23,43
Standard uncertainty 0,2 V	$\mathbf{u(\delta_{0,2V})}$	**1,6**	**1,8**	**4,0**	**23,5**
From 0,2 V to 0,1 V					
1:1 comparison					
Ac-dc difference TTS 0,2 V	$u(\delta_S)$	1,53	1,77	3,92	22,36
Measurement set-up	$u(\delta_{B1})$	1	1	3	10
Indicated ac-dc difference	$u(\delta_{A1})$	0,8	0,8	1	2
Ac-dc difference µPot 0,2 V	$u(\delta_{T1})$	1,99	2,18	5,04	24,58
1:1 comparison					
Ac-dc difference µPot 0,2 V	$u(\delta_{S1})$	1,99	2,18	5,04	24,58
Level dependence 0,2 V to 0,1 V	$u(\delta_{LD})$	1	1	1	1
Loading of µPot	$u(\delta_L)$	0,3	0,6	1,2	12
Measurement set-up	$u(\delta_{B2})$	2	2	3	10
Indicated ac-dc difference	$u(\delta_{A2})$	1,1	1,1	1,5	3
Temperature coefficient TTS *	$u(\delta_{TC})$	0,3	0,3	0,7	7
Ac-dc difference TTS 0,1 V	$u(\delta_{T2})$	3,22	3,38	6,29	30,12
Standard uncertainty 0,1 V	$\mathbf{u(\delta_{0,1V})}$	**3,3**	**3,4**	**6,3**	**30,2**

* The uncertainty due to the temperature coefficient of the TTS and the deviation of the ambient temperature from the nominal temperature 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	$u(\delta_S)$	3,20	3,37	6,25	29,29
Measurement set-up	$u(\delta_{B1})$	2	2	3	10
Indicated ac-dc difference	$u(\delta_{A1})$	1,1	1,1	1,5	3
Ac-dc difference µPot 100 mV	$u(\delta_{T1})$	3,93	4,07	7,09	31,10
1:1 comparison					
Ac-dc difference µPot 100 mV	$u(\delta_{S1})$	3,93	4,07	7,09	31,10
Level dependence 100 mV to 50 mV	$u(\delta_{LD})$	1	1	1	1
Loading of µPot	$u(\delta_L)$	0,1	0,3	0,6	3
Measurement set-up	$u(\delta_{B2})$	3	3	5	15
Indicated ac-dc difference	$u(\delta_{A2})$	1,5	1,5	2	4
Temperature coefficient TTS *	$u(\delta_{TC})$	0,3	0,3	0,7	7
Ac-dc difference TTS 50 mV	$u(\delta_{T2})$	5,28	5,38	9,01	35,60
Standard uncertainty 50 mV	$\mathbf{u(\delta_{50mV})}$	**5,3**	**5,4**	**9,1**	**35,6**
From 50 mV to 20 mV					
1:1 comparison					
Ac-dc difference TTS 50 mV	$u(\delta_S)$	5,27	5,37	8,98	34,90
Measurement set-up	$u(\delta_{B1})$	2	2	3	10
Indicated ac-dc difference	$u(\delta_{A1})$	1,5	1,5	2	4
Ac-dc difference µPot 50 mV	$u(\delta_{T1})$	5,83	5,93	9,68	36,53
1:1 comparison					
Ac-dc difference µPot 50 mV	$u(\delta_{S1})$	5,83	5,93	9,68	36,53
Level dependence 50 mV to 20 mV	$u(\delta_{LD})$	1	1	1	1
Loading of µPot	$u(\delta_L)$	0,1	0,3	0,6	6
Measurement set-up	$u(\delta_{B2})$	3	3	5	15
Indicated ac-dc difference	$u(\delta_{A2})$	2,5	2,5	3	5
Temperature coefficient TTS *	$u(\delta_{TC})$	0,6	0,6	0,6	9
Ac-dc difference TTS 20 mV	$u(\delta_{T2})$	7,11	7,20	11,38	41,37
Standard uncertainty 20 mV	$\mathbf{u(\delta_{20mV})}$	**7,2**	**7,2**	**11,4**	**41,4**

* The uncertainty due to the temperature coefficient of the TTS and the deviation of the ambient temperature from the nominal temperature 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(δ_S)	7,09	7,17	11,36	40,37
Measurement set-up	u(δ_{B1})	3	3	5	15
Indicated ac-dc difference	u(δ_{A1})	2,5	2,5	3	5
Ac-dc difference µPot 20 mV	u(δ_{T1})	8,09	8,17	12,77	43,36
1:1 comparison					
Ac-dc difference µPot 20 mV	u(δ_{S1})	8,09	8,17	12,77	43,36
Level dependence 20 mV to 10 mV	u(δ_{LD})	2	2	2	2
Loading of µPot	u(δ_L)	0	0	0	4
Measurement set-up	u(δ_{B2})	5	5	7	15
Indicated ac-dc difference	u(δ_{A2})	5	5	7	10
Temperature coefficient TTS *	u(δ_{TC})	0,6	0,6	0,6	9
Ac-dc difference TTS 10 mV	u(δ_{T2})	10,95	11,00	16,29	48,02
Standard uncertainty 10 mV	**u(δ_{10mV})**	**11,0**	**11,0**	**16,3**	**48,1**

* The uncertainty due to the temperature coefficient of the TTS and the deviation of the ambient temperature from the nominal temperature is not forwarded to the next step.

6. Summary

		1 kHz	**20 kHz**	**100 kHz**	**1 MHz**
Expanded uncertainty 100 mV	**U = 2u**	**6,6**	**6,8**	**13**	**60**
Expanded uncertainty 10 mV	**U = 2u**	**22**	**22**	**33**	**96**
Degrees of freedom 100 mV		**>80**	**>80**	**>80**	**>80**
Degrees of freedom 10 mV		**>80**	**>80**	**>80**	**>80**

CIPM KEY COMPARISON CCEM-K11
AC-DC VOLTAGE TRANSFER DIFFERENCE AT LOW VOLTAGES
Technical protocol

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1. Introduction

In the Mutual Recognition Arrangement (MRA) is stated, 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). The CCEM decided at the meeting in Sèvres, France, in September 2000 on a key comparison CCEM-K11 “ac-dc voltage transfer difference at low voltages” 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 international 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 Guidelines for CIPM key 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 6765 002, 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.

The temperature 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 resistance of a Fluke 792A is frequency dependent.

The temperature coefficients of the output voltage of the travelling standard with their expanded uncertainties are given in the table below.

Range	Frequency	Temperature coefficient / $10^{-6}\cdot K^{-1}$	Expanded uncertainty / $10^{-6}\cdot K^{-1}$
220 mV	≤20 kHz	0	1
	100 kHz	1	1
	1 MHz	12	4
22 mV	≤100 kHz	0	2
	1 MHz	15	8

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** 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.

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 one 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;
- 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 voltage of the battery pack during measurement as measured with the dummy load;
- the results of the measurements;
- the associated standard uncertainties and the expanded uncertainties
- a detailed uncertainty budget, which will be included in the final report.

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 50000 EURO = 45000 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.

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 comparison has to be finished within a reasonable period of time, only six weeks is allowed for each participant including the time of transportation.

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 technical protocol is prepared in co-operation with Dr. Manfred Klonz, Physikalisch-Technische Bundesanstalt (PTB), Germany and Dr. Cees van Mullem, Nederlands Meetinstituut (NMi), the Netherlands. They will also advice the co-ordinator at the pilot laboratory during the comparison.

The travelling standard will be dispatched from SP in the second half of 2001 and will return after the completion of each loop. The number of loops will depend on the number of participants.

Please inform the pilot laboratory of the arrival of the package by e-mail or fax. Please inform 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.

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 first draft report in co-operation with the advisors and send it to the participants for comments. The reporting of the comparison will follow the BIPM Guidelines.

12. Contact person

If there are any questions concerning the comparison, the contact person at the pilot laboratory is:

Karl-Erik Rydler

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Appendix 1. Summary of results

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

Please send this information by e-mail also.

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 / %			
Power supply voltage, positive / V			Please state with mV resolution
Power supply voltage, negative / V			Please state with mV resolution

Appendix 2. Summary of uncertainty budget

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

Please send this information by e-mail also.

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:				

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:				

Appendix 3. Packing list

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

1 pc. Fluke 792A AC-DC transfer standard, S/N 6765 002.
1 pc. Fluke 792A Power pack, S/N 6765 002.
1 pc. Power pack cable.
1 pc. Power pack testing box.
1 pc. Stainless steel type N extender (should always be connected to the Fluke 792A AC-DC transfer standard).
1 pc. Shorting bar (connected to the Fluke 792A AC-DC transfer standard).
1 pc. Fluke 792A Instruction manual.
1 pc. Technical protocol for the CIPM key comparison CCEM-K11.