Istituto Elettrotecnico Nazionale Galileo Ferraris

FINAL REPORT OF EUROMET.EM-K8 COMPARISON OF DC VOLTAGE RATIO

(EUROMET Project 449)

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1. Introduction

A formal decision about starting a EUROMET comparison project on the measurement of DC voltage ratios was taken at the Electricity and Magnetism annual Contact Persons meeting held in October 1997 in Madrid. When, in July 1998, the Working Group on Key Comparisons of the Comité Consultatif d'Electricité et Magnetisme (CCEM) started the same comparison at the world level, IEN, which was the pilot of both comparisons, decided to carry them out in parallel. Similarly to the CCEM comparison, the purpose was to compare the scaling capabilities in DC voltage of the European National Metrology Institutes (NMI) thus verifying, together with the key comparisons at 1 V and 10 V, the equivalence of their voltage units up to 1000 V DC.

The travelling standard for the EUROMET comparison was kindly offered by the Swedish National Testing and Research Institute (SP), who participated in a preliminary informal comparison with IEN as part of the characterisation work of the standard. The comparison started in October 1998 and continued, without major problems, until February 2001, when the measurements at BEV showed that the divider was drifting. The standard was then called back at IEN where it was systematically measured for several months until the drift subsided. The circulation of the standard resumed in September 2001 and finished in January 2002, with 19 National Metrology Institutes having participated, in addition to the pilot laboratory.

The comparison was started as EUROMET Project 449. When the new nomenclature of the key comparisons was introduced, the identifier in the Key Comparison Data Base became EUROMET.EM-K8, showing the link to the corresponding CCEM comparison, CCEM-K8 [1]. The ratios to be measured were the same as for the CCEM comparison: the ratios 1000 V / 10 V and 100 V / 10 V were mandatory, other ratios were optional. Only the measurements of the mandatory ratios are considered in this report for the evaluation of the degrees of equivalence of the participants. The measurements of the optional ratios are reported in Appendix F. The degrees of equivalence, given in Appendixes B and C, are evaluated with respect to the reference values of the same comparison EUROMET.EM-K8. In a separate document the problem of linking EUROMET.EM-K8 to CCEM-K8 is considered, in order to obtain the degrees of equivalence with respect to the key comparison reference values, i.e. the reference values of CCEM-K8.

Even if the protocol of the comparison, reported in Appendix H, was prepared paying attention to the requirements of the BIPM "Guidelines for CIPM Key Comparisons", then available as a draft, a common scheme to report the uncertainty budgets was not given to the participants. Then, towards the end of the comparison, the participants were requested to report their budgets in two tables provided by the pilot, for the two mandatory ratios, in order to present comparable data. Of course the global uncertainties given in the measurement reports had to be maintained. The uncertainty budgets of the participants are reported in the Appendixes D and E. Some measurement results were changed, after the pilot laboratory asked some participants to check their data, due to large discrepancies with respect to the other laboratories. Also, after release of the Draft A report, some participants asked for changes in their uncertainty budget. All these cases are detailed in Appendix G.

The present comparison is the first EUROMET comparison of DC voltage ratio.

2. Participants and schedule

17 NMIs, plus the pilot, agreed to participate in the comparison since its beginning. OMH from Hungary and EIM from Greece added later on. DFM from Denmark only made measurements for optional ratios (see paragraph 3). Table 1 lists all the participant laboratories in chronological order and the periods of their measurements. In the same table the periods when the travelling standard was at the pilot laboratory are given. The last column of the Table reports the main events

occurred during the comparison. The exact dates of the pilot measurements are reported in Appendix A, with all IEN measurement results.

Table 1. List of participants and measurement dates.

Acronym	*National Metrology Institute*	*Country*	*Standard at the lab.*	*Mean date of Measurements*	*Comment*
IEN	Istituto Elettrotecnico Nazionale Galileo Ferraris - Pilot	Italy	1 Jul 1998 to 25 Sep 1998	_	Initial characterisation of the travelling standard
NPL	National Physical Laboratory	U. K.	29 Sep 1998 to 2 Nov 1998	27 Oct 1998	
INETI	Instituto Nacional de Engenharia e Tecnologia Industrial	Portugal	9 Nov 1998 to 3 Dec 1998	25 Nov 1998	
IEN	Pilot	Italy	4 Dec 1998 to 29 Jan 1999	_	
CEM	Centro Español de Metrologia	Spain	3 Feb 1999 to 1 Mar 1999	17 Feb 1999	
PTB	Physikalisch-Technische Bundesanstalt	Germany	2 Mar 1999 to 25 Mar 1999	16 Mar 1999	
LCIE	Laboratoire Central des Industries Électriques	France	9 Apr 1999 to 11 May 1999	5 May 1999	
DFM	Danish Institute of Fundamental Metrology	Denmark	12 May 1999 to 10 Jun 1999	30 May 1999	Only optional measurements 10V / 0.1V and 10V / 1V
IEN	Pilot	Italy	16 Jun 1999 to 23 July 1999	_	
METAS	Swiss Federal Office of Metrology and Accreditation	Switzerland	2 Aug 1999 to 27 Aug 1999	11 Aug 1999	
CMI	Czech Metrology Institute	Czech Rep.	3 Sep 1999 to 29 Sep 1999	11 Sep 1999	
MIKES	Centre for Metrology and Accreditation	Finland	12 Oct 1999 to 8 Nov 1999	2 Nov 1999	
SP	Swedish National Testing and Research Institute	Sweden	9 Nov 1999 to 14 Dec 1999	29 Nov 1999	
IEN	Pilot	Italy	18 Dec 1999 to 28 Jan 2000	_	
UME	Ulusal Metroloji Enstitüsü	Turkey	10 Feb 2000 to 9 Mar 2000	1 Mar 2000	
SMU	Slovak Institute of Metrology	Slovakia	16 Mar 2000 to 14 Apr 2000	30 Mar 2000	
NMi-VSL	NMi Van Swinden Laboratorium B.V.	The Netherlands	19 Apr 2000 to 11 May 2000	3 May 2000	

Acronym	*National Metrology Institute*	*Country*	*Standard at the lab.*	*Mean date of Measurements*	*Comment*
BEV	Bundesamt für Eich- und Vermessungswesen	Austria	15 May 2000 to 25 May 2000		BEV informed that they were not ready to carry out the measurements, but, by mistake, the standard was shipped to BEV all the same.
IEN	Pilot	Italy	31 May 2000 to 24 Aug 2000	_	
JV	Justervesenet	Norway	28 Aug 2000 to 27 Sep 2000	17 Sep 2000	
SMD	Ministère des Affaires économiques E6-Service de la Métrologie / Metrologische Dienst	Belgium	29 Sep 2000 to 31 Oct 2000	20 Oct 2000	
SIQ	Slovenian Institute of Quality and Metrology	Slovenia	15 Nov 2000 to 19 Dec 2000	16 Dec 2000	
IEN	Pilot	Italy	5 Jan 2001 to 16 Feb 2001	_	Apparently small deviation from usual behaviour detected
BEV	Bundesamt für Eich- und Vermessungswesen	Austria	21 Feb 2001 to 28 Mar 2001	_	Significant drift detected. Measurements postponed, standard back to IEN.
IEN	Pilot	Italy	2 Apr 2001 to 19 Sep 2001	_	Standard monitored, waiting for the drift to subside.
BEV	Bundesamt für Eich- und Vermessungswesen	Austria	21 Sep 2001 to 25 Oct 2001	17 Oct 2001	
OMH	National Office of Measures	Hungary	7 Nov 2001 to 26 Nov 2001	15 Nov 2001	
EIM	Hellenic Institute of Metrology	Greece	3 Dec 2001 to 23 Jan 2002	23 Dec 2001	
IEN	Pilot	Italy	28 Jan 2002 to 28 Feb 2002	_	

Each participant had three weeks to carry out the measurements and was expected to ship the travelling standard to the next scheduled laboratory allowing less than one week for travel. A very solid enclosure, fitted with a digital thermometer and a digital hygrometer, to record the maximum and minimum values of the ambient conditions, was provided so that the travelling standard could be shipped as freight. After arrival the standard had to be maintained in a temperature and possibly humidity controlled room at least three days before use. The standard was accompanied by an ATA carnet for non European-Union countries. Apart from the delay due to the drifting behaviour of the standard, the planned schedule of the comparison was generally complied with.

3. Transfer Standard and required measurements

The chosen travelling standard was a Datron 4902S voltage divider (s/n 12422). It has 100 10-kΩ resistive elements, each made up of two parallel 20 kΩ bulk metal foil resistors. The 100 elements are organised in two 10-section resistive chains, the first dividing a maximum input voltage of 1000 V in multiples of 100 V, the second, making up the base section of the first, dividing 100 V in multiples of 10 V. Adjustment trimmers are provided in the instrument, but, after a preliminary regulation at the pilot laboratory, they were sealed and no more adjusted.

The required voltage ratios were:

100 V / 10 V and 1000 V / 10 V   to be measured at the corresponding terminals of the divider.

Optional voltage ratios were:

30 V / 10 V and 300 V / 10 V	to be measured at the corresponding terminals of the divider,
10 V / 1 V	to be measured at 100 V / 10 V terminals,
and 10 V / 0.1 V	to be measured at 1000 V / 10 V terminals.

The characterisation of the travelling standard of the CCEM-K8 comparison [2] had shown that the Datron 4902S divider may have non negligible temperature and humidity coefficients. The standard ambient conditions recommended for measurement were:

temperature T: (23 ± 0.5) °C
relative humidity H: (45 ± 5) %.

Room temperatures of 20 °C and of 25 °C were also allowed, while it was requested that relative humidity did not exceed 70%. Corrections for deviations of temperature and humidity from the above standard conditions were applied by the pilot laboratory, who also evaluated the corresponding additional uncertainty contribution.

4. Behaviour of the transfer standard

During the first half of 1998 the travelling standard was measured at the pilot laboratory, to verify its stability and its sensitivity to changing ambient conditions. In June 1998 some of the trimmers of the standard were adjusted to obtain non negligible deviations from nominal values and more measurements were carried out to verify stability after adjustment.

Fig. 1 shows the behaviour of some of the ratios of the standard during the comparison, from the measurements of the pilot laboratory. To report more information, instead of the ratios requested by the comparison, all referred to the base section (0-10) V and then highly correlated, ratios referred to the (0 - 100) V section of the divider are also reported. The measurements in the figure were reduced to standard ambient conditions by applying temperature and humidity corrections (see the following paragraph). The figure shows that a significant drift occurred towards the end of the comparison: it is the drift detected by BEV, during their measurements, which caused the comparison to be suspended.

From Fig. 1, b) and d), an important contribution to the drift comes from the (0-10) V base section. These figures also show that first symptoms of the drift were already visible in the measurements around day 900, corresponding to the standard having returned from Slovenia. Indeed the travelling from SIQ to IEN was longer then usual, due to Christmas holidays, and the standard remained at the Italian customs for several days. Unfortunately, it was not possible to identify any specific event to be associated with the occurrence of the drift.

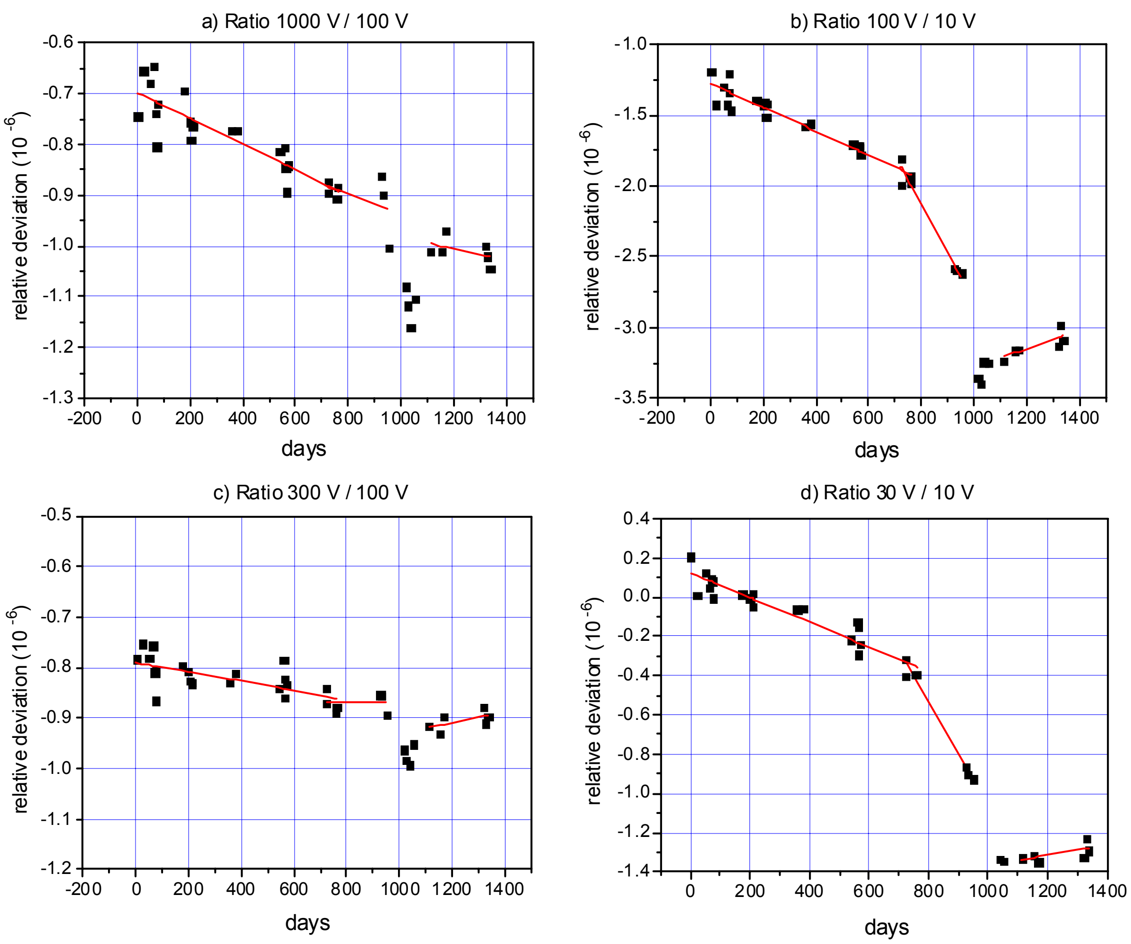


Fig. 1. Behaviour of ratios 1000 V / 100 V, 100 V / 10 V, 300 V / 100 V and 30 V / 10 V of the travelling standard, from the measurements of the pilot laboratory reduced to standard ambient conditions (solid squares). The straight lines are linear interpolations during the periods corresponding to the measurements of the participant laboratories. Days are counted starting on 1 July 1998.

. Due to the behaviour of the standard shown in Fig. 1, to compare the IEN measurements with those of the other participants straight lines will be fitted to three different groups of IEN measurements:

- group A, from 1/7/1998 to 31/7/2000 (23 data, days 0 to 761), corresponding to the measurements of the first 12 participants;
- group B, from 22/6/2000 to 6/2/2001 (7 data, days 722 to 951), corresponding to the measurements of JV, SMD, SIQ;
- group C, from 18/7/2001 to 27/2/2002 (6 data, days 1113 to 1337), corresponding to the measurements of BEV, OMH, EIM.

Groups A and B have some common data.

5. Measurements of the pilot laboratory and temperature and humidity coefficients

The measurement method used at IEN (see par. 7) provides the ratio of each section of the divider to the first section of the corresponding resistive chain. From these values the ratios 1000 V / 100 V, 100 V / 10 V, 300 V / 100 V and 100 V / 10 V were evaluated and were used to calculate the other ratios of interest for the comparison: 1000 V / 10 V and 300 V / 10 V. Low voltage measurements were not carried out each time at IEN, but the low voltage ratios 10 V / 0.1 V and 10 V / 1 V were estimated by applying power corrections to the corresponding resistive ratios measured at nominal voltage (see par. 6). The whole set of IEN measurements is reported in Appendix A.

Temperature and humidity coefficients (C_T and C_H) and drift (C_D) for each relevant ratio can be obtained by applying a multiple linear regression to measurement data taken under different ambient conditions, following the equation:

$$d \equiv (r - r_n)/r_n = D_0 + C_H(H - H_0) + C_T(T - T_0) + C_D(t - t_0) \qquad (1)$$

where r is the ratio of interest, with nominal value r_n, H and T are the relative humidity and the temperature of the measurements, t is time, D_0 is the deviation of the ratio from nominal at starting time t_0 and under standard ambient conditions H_0= 45 % and T_0= 23 °C. The starting time t_0 is chosen as 1st July 1998.

Of the three groups of data, A, B and C, only the first one has enough measurements to obtain significant values for all the parameters of eq. (1). For groups B and C the same temperature and humidity coefficients obtained from group A are assumed and used to reduce the measurements to standard ambient conditions; then a simple linear fitting to the corrected data gives the values of D_0 and C_D for these groups. Table 2, where "p.u." means percentage unit, reports the values of the parameters and the corresponding standard uncertainties. The last column of the table reports the residual standard deviation s of the regressions, which is used as an evaluation of the instability of the transfer standard.

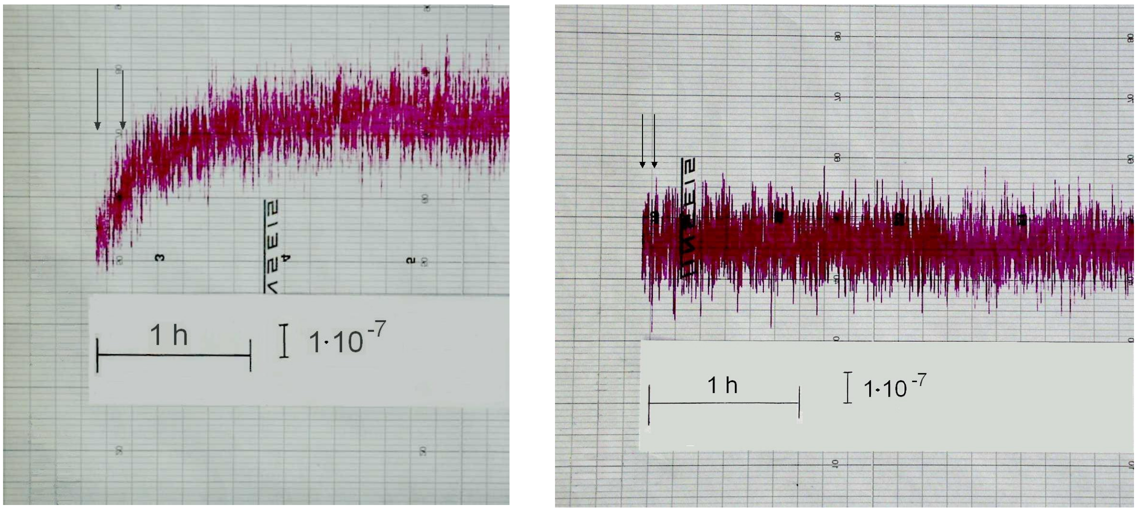
Table 2. Temperature and humidity coefficients and drift

r	C_T (10^{-6}/°C)	$u(C_T)$ (10^{-6}/°C)	C_H (10^{-6}/p.u.)	$u(C_H)$ (10^{-6}/p.u.)	D_0 (10^{-6})	$u(D_0)$ (10^{-6})	C_D (10^{-6}/day)	$u(C_D)$ (10^{-6}/day)	s (10^{-6})
1000/10 (A)	0.0374	0.0091	-0.0013	0.0010	-1.971	0.021	-0.00111	0.00005	0.061
1000/10 (B)	0.0374	0.0091	-0.0013	0.0010	-0.185	0.219	-0.00356	0.00026	0.068
1000/10 (C)	0.0374	0.0091	-0.0013	0.0010	-4.778	0.343	0.00052	0.00028	0.063
100/10 (A)	-0.0211	0.0110	-0.0034	0.0012	-1.276	0.025	-0.00084	0.00006	0.073
100/10 (B)	-0.0211	0.0110	-0.0034	0.0012	0.581	0.222	-0.00339	0.00027	0.069
100/10 (C)	-0.0211	0.0110	-0.0034	0.0012	-3.948	0.302	0.00067	0.00024	0.056
300/10 (A)	-0.0022	0.0102	-0.0020	0.0011	-2.064	0.024	-0.00094	0.00006	0.068
300/10 (B)	-0.0022	0.0102	-0.0020	0.0011	-0.292	0.179	-0.00339	0.00021	0.056
300/10 (C)	-0.0022	0.0102	-0.0020	0.0011	-4.966	0.255	0.00076	0.00020	0.047
30/10 (A)	0.0133	0.0086	-0.0036	0.0010	0.124	0.020	-0.00063	0.00005	0.058
30/10 (B)	0.0133	0.0086	-0.0036	0.0010	1.577	0.127	-0.00264	0.00015	0.040
30/10 (C)	0.0133	0.0086	-0.0036	0.0010	-1.639	0.201	0.00027	0.00016	0.037

6. Power effects

a) Collective heating

Because the measurement technique of IEN is such that only one section of the divider at a time is powered during the measurements, a first step in the evaluation of the power effect was to verify if a different result could arise if all the divider's sections were powered at the same time, as in other measurement methods. To evaluate this effect for the ratios 1000 V / 10 V and 100 V / 10 V, direct comparisons between a Fluke 752A divider and the Datron traveling standard were performed. Before starting the measurements the Fluke divider was powered for at least 12 hours, while the Datron was left unpowered. Then the Datron was connected in parallel to the voltage supply and the output of a detector, monitoring the voltage difference of the two dividers at the 10 V taps, was recorded for at least two hours. Fig. 2 shows the recorded trace for the two ratios.



a) b)

Fig. 2. Recorded output of the detector in the comparison of the travelling standard with a Fluke 752A divider. The Fluke was already in thermal equilibrium, while the travelling standard had just been connected in the circuit. a): ratio 1000 V / 10 V; b): ratio 100 V / 10 V. The vertical arrows show the waiting time requested by the comparison protocol. The variation with time shown in a) goes in the direction of decreasing the value of the ratio of the travelling standard.

No variation with time was found for ratio 100 V / 10 V. For ratio 1000 V / 10 V, Fig. 2a) shows a stabilization process reaching equilibrium after about 1 hour. In this process the ratio of the travelling standard decreases while reaching equilibrium. The comparison protocol had establish a waiting time, after powering the divider, of 5 minutes for ratio 100 V / 10 V and of 10 minutes for ratio 1000 V / 10 V because IEN had verified that, in the measurement of a single divider's section, after these times the detector's reading was stable to within a few parts in 10^{-8}. From Fig. 2a), after the first 10 minutes the residual variation until stabilisation for ratio 1000 V / 10 V is about $2 \cdot 10^{-7}$: all this residual variation can be attributed, for simplicity, to the collective heating, making the hypothesis, supported by the IEN measurements, that during the first 10 minutes the self heating effect of each individual section subsides.

The variation shown in Fig. 2a) goes in the direction of decreasing the value of the ratio 1000 V / 10 V, which is not what one could foresee from the sign of the temperature coefficient of this ratio (see Table 2), which is positive. During some of the measurements, a PT100 thermometer was located inside the divider, at a small distance form the circuit board, and a temperature increase of about (0.4-0.5) °C was detected. Apart from the sign, the amount of this temperature variation is quite low and does not justify a variation of the ratio of $2 \cdot 10^{-7}$, if the applicable temperature coefficient was of the order of that reported in Table 2. However it must be considered that self-heating may produce a less uniform temperature distribution inside the divider, with respect to a change of the ambient temperature: because the temperature coefficients of the individual 20 kΩ resistors used to built the divider (Vishay type HP202) are given as lower than $0.6 \cdot 10^{-6}$ °C^{-1} at 23 °C, a variation of a few tenths of a degree of the temperature of the 0V-10V section, with respect to the others, could easily produce a variation of the ratio of up to a few parts in 10^{-7}.

About the effect of the collective heating on the results of the laboratories, even if the protocol was quite clear about the 10 minutes waiting time this was justified with the stabilisation of the divider, so that participants that have powered the whole divider during their measurements, noticing that the detector reading was not stable, have very probably waited more. For simplicity, and due to their small magnitude with respect to other uncertainty components, the two effects of ambient temperature and collective heating will be considered independent and will be superimposed. From the reports of the participants, the laboratories that have measured the traveling standard by measuring its individual resistive sections (i.e. by powering the divider one section at a time) are IEN, CEM, SP, SMD. Two laboratories (PTB and METAS) have used methods of measurement of both types, calculating the weighted mean of the corresponding results. In conclusion, an error ζ will be subtracted from the results of all laboratories except IEN, CEM, SP and SMD and a standard uncertainty component $u(\zeta)$ will be quadratically added to the uncertainties of the corresponding laboratories, being these quantities given by:

$$\begin{aligned}
&\zeta = 0 && \text{for IEN, CEM, SP, SMD} \\
&\zeta = -1.0 \cdot 10^{-7} && \text{for PTB and METAS} \\
&\zeta = -2.0 \cdot 10^{-7} && \text{for NPL, INETI, LCIE, CMI, MIKES, UME,} \\
& && \quad \text{SMU, NMi - VSL, JV, SIQ, BEV, OMH, EIM} \\
&u(\zeta) = 0 && \text{for IEN, CEM, SP, SMD} \\
&u(\zeta) = 1 \cdot 10^{-7} / \sqrt{3} && \text{for all other laboratories}
\end{aligned} \tag{2}$$

where, for the uncertainty, maximum values of $\pm 1 \cdot 10^{-7}$ with a rectangular distribution have been considered. The choice to leave unchanged the results of the laboratories who have measured the individual sections of the divider was suggested by practical reasons, in order to avoid correction of the many measurements of the pilot laboratory.

b) Power coefficients

Following the comparison protocol, the two optional low voltage ratios 10 V / 0.1 V and 10 V / 1 V had to be measured at the divider's terminals 1000 / 10 and 100 / 10, respectively. The pilot laboratory values for the low voltage ratios were obtained by applying power correction to the values measured, at the given terminals, at rated voltage. To evaluate the power coefficients for the two ratios, measurements were carried out, following the usual IEN method, at several voltages, down to 10% of the rated power. The results are shown in Fig. 3 together with the corresponding linear fittings.

The power coefficients C_P and the corresponding errors η, to be subtracted from the IEN ratio values measured at nominal voltage, are reported in relative terms, with their standard uncertainties, in Table 3, where p.u. means percentage unit. A power variation of 100% has been considered.

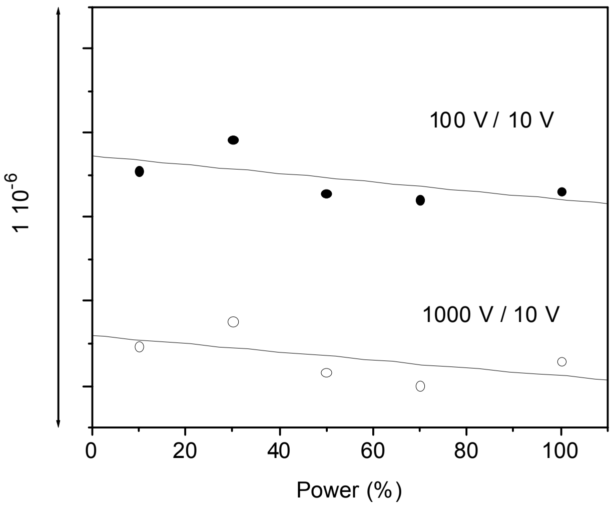


Fig. 3. Effect of power (measured in percentage of the rated power) on ratios 1000 V / 10 V and 100 V / 10 V.

Table 3. Power coefficients C_P and power errors η for the Datron divider

Ratio	C_P (10^{-6}/p.u.)	$u(C_P)$ (10^{-6}/p.u.)	η (10^{-6})	$u(\eta)$
1000 V / 10 V	-0.00095	0.00081	-0.095	0.081
100 V / 10 V	-0.00103	0.00075	-0.103	0.075

7. Measurement methods

Several different methods of measurements were used by the participants. They are briefly described below. This information is intended to cover only the measurements of the mandatory ratios.

IEN - pilot laboratory

The divider calibrations at IEN were carried out by measuring the individual resistive sections: each section of the 10x10 V or of the 10x100 V resistive chains of the divider was successively compared with a transfer resistor included in a Kelvin double bridge with lead compensation (Datron.4901). In this way the ratio of each section of the divider to the base section of the corresponding resistive chain can be evaluated. The measurements were accurately timed to allow the divider to stabilise after application of the voltage. The measurement of the first section of the chain was repeated at the end of the process to correct for linear drifts.

NPL

The divider was calibrated using a standard resistive voltage divider. The dividers were energised from the same voltage source and current sharing networks were used so that there was zero voltage difference between both the low terminals and the high terminals. The difference between the required outputs was measured using a Keithley 181 nanovoltmeter. The overall potential of the divider was adjusted so that negligible voltage difference was present between the output and the case of the instrument.

INETI

The travelling divider was calibrated by comparison with a Fluke 720 Kelvin Varley reference divider previously calibrated. The two dividers were powered in parallel by a DC calibrator (Fluke 335D) using the lead compensator Fluke 721 A. The voltage difference between the output terminals at 10 V was measured by a Keithley 182 digital voltmeter.

CEM

The ratios were measured by comparing the individual resistive elements of the divider, using a Kelvin double bridge Datron model 4901. This bridge has lead compensation but it was not used. Instead the voltage between the main balance terminals was measured using a guarded HP 3458 DMM and the voltage in the leads was measured using an HP 34420 nanovoltmeter. The voltage source for the circuit was a DC voltage calibrator Fluke 5440A.

PTB

For both mandatory ratios, three different measurement methods were used: measurement of the individual resistive sections of the divider using a DMM, substitution using a Fluke 752A as reference divider, substitution using a Datron 4902S as reference divider. The final results given are the weighted mean of the results obtained with the three methods.

LCIE

The Datron divider was calibrated by comparison with a reference divider previously calibrated. The two dividers were supplied with the same potential by means of a lead compensator. The potential difference between the "Sense" terminal of the Datron and the terminal of the reference was measured by means of a nanovoltmeter previously calibrated. The "0 V" terminal was connected to the closest ground terminal and to the earth.
The reference divider was made of one ESI SR1010 and one SR1030 resistance decade boxes or was a Fluke 752A divider calibrated against those boxes. ESI boxes were calibrated by different ways.

METAS

The given results are the weighted mean of the values obtained by two different methods. With the first method, a Fluke 752A reference divider was used to calibrate the 100 V and 1000 V output of a dc voltage calibrator (Fluke 5700A), using a calibrated 10 V reference (Fluke 732A) and a null detector (EM Electronics N1a). Then the ratio of the travelling standard was measured using the same calibrator and voltage source. The Fluke 752A was calibrated using a METAS resistive divider.
With the second method the resistive sections of the travelling standard were measured using a potentiometric method (Measurements International model 6000B High Resistance Bridge).

CMI

The Datron 4902S divider was compared with a Fluke 720A Kelvin Varley reference divider, using a Fluke 721A as lead compensator, a Fluke calibrator 5440B as DC voltage source and a Fluke 845AR as null detector. The Fluke 720A was autocalibrated immediately before the measurements of the Datron divider.

MIKES

The divider under calibration was measured against a Fluke 752A reference divider initially adjusted within specifications. Before each comparison, the adjustment was checked by measuring the unbalance of the 752A's calibration bridge. A Fluke 845AR null detector was used to measure the voltage between the output terminals of the dividers. The detector´s output voltage was recorded using an HP 3458A multimeter. Also the lead compensation umbalance was determined before each comparison by measuring the voltages between the input Hi and Lo terminals of the two dividers. The 1000 V measurements were made by recording the null detector´s readings for about 30 minutes. Exponential curve fitting has been applied to determine the end value of the voltage.

SP

The ratios were determined by measurements of the individual resistive sections of the divider, at nominal voltage. The measurements were done with a current comparator resistance bridge, Guildline 9975, with an external voltage source and an external relay box with reversing switch. The external voltage source also gives a guard voltage used to minimise the error due to leakage. The divider's resistors are compared with a reference resistor. The two resistors in comparison exchange place in the bridge to minimise the bridge error.

UME

The Datron 4902S travelling standard was calibrated against another Datron 4902S divider taken as the reference. The voltage applied to the dividers was given by a Fluke 5700A calibrator and a Fluke 721A lead compensator was used. To measure the voltage difference at the 10 V outputs of the dividers a Keithley 2182 nanovoltmeter was used. The dividers were allowed 20 minutes to stabilise after application of the voltage.

SMU

The Datron 4902S travelling standard was calibrated against a Guildline 9700 PL reference divider. The DC voltage, given by a Datron 4808 calibrator, was applied by means of a Fluke 721A lead compensator. A Fluke 845AB and an EM N11 were used as nanovoltmeters, the Fluke connected alternatively to the high and low voltage input terminals and the EM to the output terminals of the two dividers.

NMi-VSL

The Datron divider was calibrated by comparison with a Fluke 720A Kelvin Varley reference voltage divider. A lead compensator Fluke 721A was used to avoid errors resulting from voltage drops in the connecting cables. A Fluke 5440B DC voltage calibrator and a detector Fluke 845AB were also used. The detector guarding and the shielding of the cables to the detector were connected to the appropriate guard terminal on the Datron divider.

JV

The method used for calibrating the Datron 4902S voltage divider was based upon comparing the voltage across each resistive segment with the voltage across the lowest segment. The mains supply for the whole set-up was isolated and centred on zero voltage using an isolation transformer where the zero voltage is taken from the centre point of the secondary windings. A low pass filter on the transformer output was also used.

A DC-calibrator (Fluke 5700A-II) gave the supply voltage to the divider. The voltage across each resistive segment of the divider was measured using a DC-source (Datron 4808 for both ~10 and ~100V) as backup voltage and a digital voltmeter (DVM, Hewlett Packard 3458A) as zero-detector.

To minimize common mode errors the supply voltage for the Datron calibrator and the DVM was kept floating using an isolation transformer and centred around zero with a resistive divider. For safety reasons, the floating instruments were placed inside a cage covered with grounded chicken wire. The voltage across the lowest segment was monitored during all the measurements using a second DC-calibrator (Fluke 732B for ~10V and Fluke 5440B for ~100V, backup voltage) and DVM (Hewlett Packard 3458A, zero-detector). This made it possible to measure the ratio between the voltage of each segment and the first segment at the same time. A PC, running a LabVIEW program under MS Windows NT, read the two DVMs and timed the measurements and connect/disconnect operations. This made the calibration less sensitive for "change of operators". Four different persons performed the calibrations. The multimeters were read via two optical IEEE 488 connections. All measuring connections were made with gold-coated copper spade lugs and shielded twisted pair cables.

The ratio 100 V / 10 V was measured under two different conditions: when used to evaluate the ratio 1000 V / 10 V it was measured by supplying the whole divider with 1000 V, while the value of ratio 100 V / 10 V, requested by the comparison protocol, was measured by applying 100 V between the 100 V and the 0 V taps.

SMD

Three different methods were used. In method 1, each 10 V section up to 100 V of the DATRON 4902S resistive divider was successively compared with a 1 kΩ standard resistor, placed in a constant temperature oil bath, by means of room temperature DC current comparator (MIL 6010A/B Automated DC Resistance Bridge). In method 2, the 30 V/10 V and the 100 V/10 V ratios were measured by means of an automatic high resistance ratio bridge (MIL 6000B); this method was mainly used to validate the results obtained with method 1 and method 3. In the last method, the same bridge as indicated in method 2 was used to successively compare each 100 V section, from 100 V to 1 kV, with a 10 kΩ Fluke 742A standard resistor placed in a thermoregulated air bath; the applied voltage on each 100 V section was 90 V.

SIQ

The travelling standard was measured against a Fluke 752A reference divider previously self-calibrated. No lead compensation was used.

BEV

The Datron divider was compared with a reference divider Fluke 752A previously self-calibrated. A calibrator Datron 4808 was used as DC voltage source, with lead compensator Fluke 721A. Null detector Keithley 181 was used to adjust the lead compensation. A multimeter Datron 1281 was used to monitor the output voltage of the calibrator. A multimeter HP 3458A was used to measure directly the ratio of the output voltages of the two dividers: the output voltage U_{out1} of the reference divider was connected to the U_{Sense} terminals and the output voltage U_{out2} of the Datron divider was connected to the U_{Input} terminals of the multimeter, using the possiblity given by this DMM to measure directly the „$Ratio_{DMM}$" of two voltages U_{Sense} and U_{Input}. Each ratio was measured for one hour to be sure that there is enough time for the dividers to stabilise.

OMH

The measurements were done by comparing the individual voltage drops at the divider terminals. A Fluke 5700 A calibrator and a Datron 4950 transfer standard were used.

EIM

The travelling standard was compared with a Fluke 752A reference divider. In a first step a

Wavetek-Datron 4808 Voltage Source was connected at the input of the reference divider, while the output of this divider was compensated by a Guildline 4410 10 V Voltage Reference, the difference being monitored by a Keithley 155 Null Detector. After 10 minutes waiting time, the voltage source was adjusted for the minimum Null Detector reading. Then in a second step the reference divider was replaced by the divider under test and the same difference was recorded to the Null Detector output. During this step the output of the voltage source remains constant.

8. Ratio 1000 V / 10 V: results

a) Participants results and differences from pilot

The results reported by the participants must be corrected for deviation of temperature and humidity from the standard conditions established by the comparison protocol, corresponding to T_0= 23 °C and H_0= 45 %. The uncertainty of this correction and that due to temperature and humidity instability, as reported by the laboratory, must be added to the laboratory's uncertainty. This standard uncertainty contribution is calculated following the equation:

$$u(\varepsilon) = \sqrt{[C_T \cdot u(T)]^2 + [u(C_T)\cdot(T-T_0)]^2 + [C_H \cdot u(H)]^2 + [u(C_H)\cdot(H-H_0)]^2} \qquad (3)$$

where ε is the error due to temperature and humidity, and $u(T)$, $u(H)$ are the temperature and humidity standard uncertainties of the participant laboratory.

The results of the participants must also be corrected for the effect of the collective heating of the resistive sections, as explained in par. 6.a). This correction is given in terms of an error ζ and the corresponding standard uncertainty $u(\zeta)$ by eq. (2). ζ and $u(\zeta)$ are different for different laboratories.

Table 4 reports, for each laboratory, the mean date of the measurements, the temperature and humidity conditions, the error ε evaluated by means of the coefficients reported in Table 2, the corresponding standard uncertainty contribution $u(\varepsilon)$ given by eq. (3), the error ζ and the corresponding standard uncertainty $u(\zeta)$ given by eq. (2). In the table the uncertainties δT and δH of temperature and humidity are given as half width of a rectangular distribution. Errors ε and ζ will have to be subtracted from the laboratory result.

Table 4. Ratio 1000 V / 10 V: effects of temperature, humidity and self-heating

Lab	Date	T (°C)	δT (°C)	H (%)	δH (%)	ε (T, H) (10^{-6})	$u(\varepsilon)$ (10^{-6})	ζ (10^{-6})	$u(\zeta)$ (10^{-6})
NPL	27/10/98	20	0.5	55	5	-0.125	0.031	-0.20	0.058
INETI	25/11/98	23	1	36	12	0.012	0.025	-0.20	0.058
CEM	17/02/99	21.7	0.5	30	5	-0.029	0.022	0	0.000
PTB	16/03/99	23	1	40	15	0.007	0.025	-0.10	0.058
LCIE	05/05/99	22.8	0.2	45	5	-0.007	0.006	-0.20	0.058
METAS	11/08/99	23	0.2	46	2	-0.001	0.005	-0.10	0.058
CMI	11/09/99	23	0.5	52	5	-0.009	0.013	-0.20	0.058
MIKES	02/11/99	23	0.3	45	5	0.000	0.007	-0.20	0.058
SP	29/11/99	23	0.3	41	4	0.005	0.008	0	0.000
UME	01/03/00	23	0.7	45	10	0.000	0.017	-0.20	0.058
SMU	30/03/00	23	0.5	35	5	0.013	0.015	-0.20	0.058
NMi-VSL	03/05/00	22.2	0.5	41.7	3.5	-0.026	0.014	-0.20	0.058

Lab	Date	T (°C)	δT (°C)	H (%)	δH (%)	ε (T, H) (10^{-6})	$u(\varepsilon)$ (10^{-6})	ζ (10^{-6})	$u(\zeta)$ (10^{-6})
JV	17/09/00	23.2	0.5	37	5	0.018	0.014	-0.20	0.058
SMD	20/10/00	23	1	45	10	0.000	0.023	0	0.000
SIQ	16/12/00	22.5	0.5	52	10	-0.028	0.016	-0.20	0.058
BEV	17/10/01	23	0.5	45	10	0.000	0.013	-0.20	0.058
OMH	15/11/01	23	0.25	30	5	0.020	0.016	-0.20	0.058
EIM	23/12/01	23.3	0.25	51	1	0.003	0.009	-0.20	0.058
IEN	-	23.1	0.5	42.5	5	0	0.012	0	0.000

For IEN, Table 4 reports the mean temperature and humidity values of all measurements. As all IEN interpolations are already referred to standard ambient conditions, no further correction is needed. Besides temperature and humidity, also the instability of the transfer standard contributes to the uncertainty of the laboratory's results. This contribution, which takes into account the effect of transport, can be evaluated as the standard deviation of the linear regression of the pilot's measurements, given as s in Table 2.

Table 5 reports, for each participant: the time t of the measurements in days, starting from 1 July 1998; the original laboratory result d_L; the result after correction for temperature and humidity and for collective heating effect, $d_{0,L}= (d_L - \varepsilon - \zeta)$; the corresponding interpolated value, at standard ambient conditions, of the pilot laboratory $d_{0,P}$, given by eq. (1) with parameters D_0 and C_D from Table 2; the difference $\Delta_L = (d_{0,L} - d_{0,P})$; the standard uncertainties (type A and type B) reported by the laboratory; the contribution $u(\varepsilon)$ to the standard uncertainty due to temperature and humidity correction; the contribution $u(\zeta)$ to the standard uncertainty due to collective heating effect; the contribution s to the standard uncertainty due to the transfer standard; the corresponding global standard uncertainty $u_{G,L}$.

Table 5. 1000 V / 10 V: results of the laboratories and differences from the pilot laboratory

Lab	t (d)	d_L (10^{-6})	$d_{0,L}$ (10^{-6})	$d_{0,P}$ (10^{-6})	Δ_L (10^{-6})	u_A (10^{-6})	u_B (10^{-6})	$u(\varepsilon)$ (10^{-6})	$u(\zeta)$ (10^{-6})	s (10^{-6})	$u_{G,L}$ (10^{-6})
NPL	118	-2.91	-2.585	-2.102	-0.483	0.08	0.2	0.031	0.058	0.061	0.233
INETI	147	1.85	2.038	-2.134	4.172	0.085	2.9	0.025	0.058	0.061	2.903
CEM	231	-2.06	-2.031	-2.227	0.197	0.06	0.39	0.022	0.000	0.061	0.400
PTB	258	-2.39	-2.297	-2.257	-0.039	0	0.16	0.025	0.058	0.061	0.182
LCIE	308	-1.9	-1.693	-2.313	0.620	0	0.14	0.006	0.058	0.061	0.163
METAS	406	-2.51	-2.409	-2.422	0.013	0	0.31	0.005	0.058	0.061	0.321
CMI	437	-3.4	-3.191	-2.456	-0.735	0.013	4.1	0.013	0.058	0.061	4.101
MIKES	489	-2.534	-2.334	-2.514	0.180	0.01	0.22	0.007	0.058	0.061	0.236
SP	516	-2.41	-2.415	-2.544	0.129	0.032	0.16	0.008	0.000	0.061	0.174
UME	609	-5.41	-5.210	-2.647	-2.563	0.05	0.46	0.017	0.058	0.061	0.471
SMU	638	-3.7	-3.513	-2.679	-0.834	0.04	1.2	0.015	0.058	0.061	1.204
NMi-VSL	672	-2.5	-2.274	-2.717	0.443	0.12	2.62	0.014	0.058	0.061	2.624
JV	809	-3.57	-3.388	-3.065	-0.323	0.009	0.14	0.014	0.058	0.068	0.167
SMD	842	-2.909	-2.909	-3.183	0.274	0	0.46	0.023	0.000	0.068	0.466
SIQ	899	-3.5	-3.272	-3.385	0.113	0.01	0.32	0.016	0.058	0.068	0.333
BEV	1204	-4.5	-4.300	-4.152	-0.148	0.22	0.66	0.013	0.058	0.063	0.701
OMH	1233	-4.58	-4.400	-4.137	-0.263	0.34	0.63	0.016	0.058	0.063	0.721
EIM	1271	-5.104	-4.907	-4.117	-0.790	0.015	0.09	0.009	0.058	0.063	0.125
IEN	-	-	-	-	0	0.074	0.104	0.012	0.000	0.013	0.129

The uncertainty budgets of the participants, comprised IEN, are given in Appendix E. For IEN, the instability s of the travelling standard is given by the value of the standard deviation of the multiple linear regression, for measurement group A, divided by $\sqrt{n}$, where n = 23 is the number of measurements in that group. In some cases the pilot laboratory found problems in the interpretation of the submitted results, or advised a participant that a large deviation, with respect to the other results, could suggest an editorial or calculation error. These cases are detailed in Appendix G. If, as a consequence of this warning, the participant submitted a revised result, this result is reported in Table 5.

Fig. 4 shows a plot of the corrected laboratory results, $d_{0,L}$, with corresponding global standard uncertainty $u_{G,L}$, compared with the linear fits of the corrected IEN measurements.

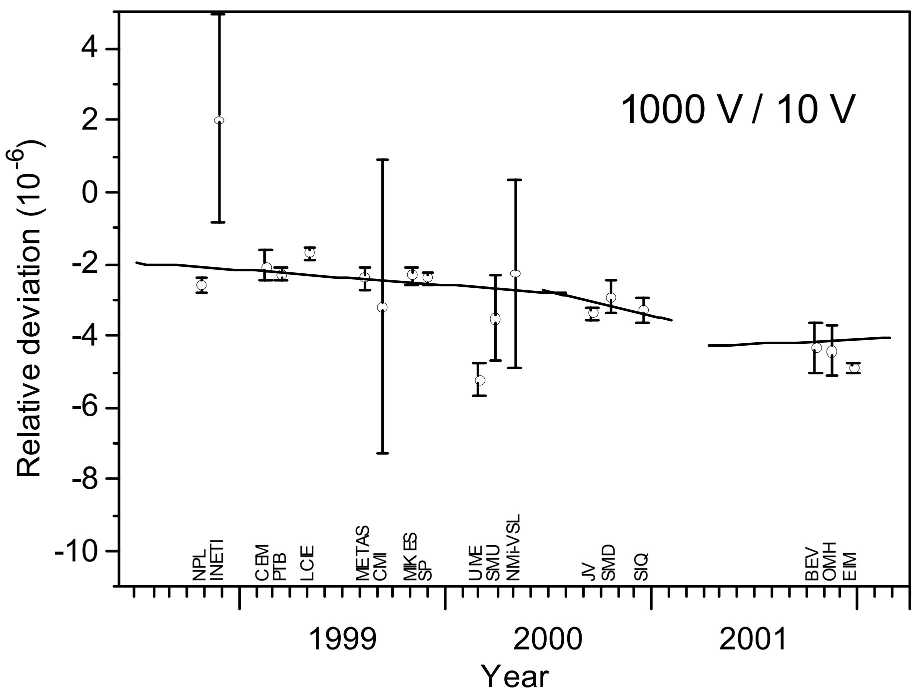


Fig. 4. Ratio 1000 V / 10 : laboratory results corrected to standard ambient conditions, $d_{0,L}$, corresponding global standard uncertainties, $u_{G,L}$, and linear interpolations of IEN results.

b) Comparison reference value and its uncertainty

In principle all laboratories should contribute to the comparison reference value (CRV), because laboratory measurements of voltage ratios are mutually independent[1]. However Fig. 4 shows that some participant results are not compatible with the corresponding global uncertainties $u_{G,L}$. The following approach will then be followed: first the Birge ratio test will be used to show quantitatively that a few participants have underestimated their uncertainties, then a robust estimator will allow to find out those laboratory results that do not belong to the same statistical

[1] Indeed the laboratory differences with respect to the pilot are correlated by the linear regression of the pilot measurements. The influence of this correlation will be discussed in paragraph 10 and will be found negligible.

distribution as the other results, last the CRV will be calculated from the results of the remaining laboratories.

The Birge ratio R_B is defined by:

$$R_B = s_E / s_I$$

$$s_E = \sqrt{\frac{\sum_{L=1}^{n} \frac{1}{u_{G,L}^2} (\Delta_L - \Delta_w)^2}{(n-1)\sum_{L=1}^{n} \frac{1}{u_{G,L}^2}}} \qquad (4)$$

$$s_I = \sqrt{\frac{1}{\sum_{L=1}^{n} \frac{1}{u_{G,L}^2}}}$$

In (4) s_E is the external standard deviation, calculated from the deviations of the laboratory differences Δ_L from their weighted mean Δ_W, and s_I is the internal standard deviation, from the global standard uncertainties $u_{G,L}$. If the uncertainties were compatible with the differences Δ_L, the Birge ratio would be close to 1. Instead, calculation with values of Table 5 shows that $R_B = 2.3$.

A robust estimator of the CRV is the Median Δ_{med}. A robust estimator of the deviation from the Median is the Median of Absolute Deviations (MAD). We will use the equation [3]:

$$S(MAD) = 1.4826 \cdot median\{| \Delta_L - \Delta_{med} |\}. \qquad (5)$$

Here the normalisation coefficient 1.4826 is the inverse of the 75[th] percentile of a Gaussian distribution, so that *S(MAD)* gives the correct estimate of the standard deviation for a Gaussian distribution of the differences (Δ_L - Δ_{med}). A participant will be considered not belonging to the distribution if its result matches the equation:

$$| \Delta_L - \Delta_{med} | > 2.5 \cdot S(MAD) \qquad (6)$$

The results of the calculation are given in Table 6.

Table 6. Ratio 1000 V / 10 V: identification of the members of the distribution

Δ_{med} =	$0.000 \cdot 10^{-6}$
$median\{| \Delta_L - \Delta_{med} |\}$ =	$0.274 \cdot 10^{-6}$
S(MAD) =	$0.406 \cdot 10^{-6}$
2.5 *S(MAD)* =	$1.014 \cdot 10^{-6}$

Applying eq. (6) to the Δ_L values in Table 5, it is found that INETI and UME do not belong to the distribution. A new calculation of the Birge ratio for the remaining laboratories gives

$R_B = 2.0$, showing that even for the reduced group of 17 participants the uncertainty values are not completely reliable. In this situation the choice of the arithmetic mean for the CRV looks more appropriate. The corresponding standard uncertainty will be given by the standard deviation of the mean. The resulting values are given in the following equations:

$$\begin{aligned} \Delta_{R,1000} &= -0.097 \cdot 10^{-6} \\ u(\Delta_{R,1000}) = S(\Delta_L - \Delta_{R,1000})/\sqrt{17} &= 0.103 \cdot 10^{-6} \\ \nu_{\Delta_{R,1000}} &= 16 \end{aligned} \tag{7}$$

where S represents the standard deviation.

c) Degrees of equivalence with respect to the CRV

Following the Mutual Recognition Arrangement of the CIPM [4], the degree of equivalence of a laboratory with respect to the CRV is given by two numbers: the difference of the laboratory's result with respect to the CRV and the expanded uncertainty of this difference. This expanded uncertainty must be calculated at 95% level of confidence, which requires the knowledge of the degrees of freedom, ν, associated with the standard uncertainty of the difference.

For the laboratories, the effective degrees of freedom, ν_{eff}, will be calculated using the Welch-Satterthwaite formula, which combines the degrees of freedom of the components of the global uncertainty $u_{G,L}$:

$$\nu_{eff} = \frac{u_{G,L}^4}{\sum_i \frac{u_{i,L}^4}{\nu_{i,L}}} \tag{8}$$

Here $u_{i,L}$ represents the uncertainty component i of laboratory L, contributing to $u_{G,L}$. and having degrees of freedom $\nu_{i,L}$. Table 7 reports for each participant the uncertainty components and the global uncertainty, already given in Table 5, with the associated degrees of freedom. ν_{LAB} are the degrees of freedom as reported by the laboratories. Because the uncertainty contribution due to temperature and humidity, $u(\varepsilon)$, is small, the corresponding contribution of this component to ν_{eff} is negligible already for $\nu_\varepsilon > 1$. The degrees of freedom associated with the uncertainty $u(\zeta)$ have been evaluated assuming that $u(\zeta)$ is known with an uncertainty of 50%, using the equation:

$$\nu_\varepsilon \approx \frac{1}{2}\frac{u^2(\zeta)}{\sigma^2(u(\zeta))} = \frac{1}{2}\cdot\frac{1}{0.25} \approx 2 \tag{9}$$

where $\sigma(u(\zeta))$ is the uncertainty in the evaluation of $u(\zeta)$. The degrees of freedom associated with the transfer standard, ν_s, are given by the number of data used in the linear fittings minus the number of parameters used. For the last column of Table 7, eq. (8) has been used.

Table 7. Ratio 1000 V / 10 V: degrees of freedom

Lab	$u_{LAB}=\sqrt{u_A^2+u_B^2}$ (10^{-6})	ν_{LAB}	$u(\varepsilon)$ (10^{-6})	ν_ε	$u(\zeta)$	ν_ζ	s (10^{-6})	ν_s	$u_{G,L}$ (10^{-6})	ν_{eff}
NPL	0.215	582	0.031	> 1	0.058	2	0.061	19	0.233	283
INETI	2.901	inf	0.025	> 1	0.058	2	0.061	19	2.903	917846
CEM	0.395	20	0.022	> 1	0	-	0.061	19	0.400	21
PTB	0.160	27	0.025	> 1	0.058	2	0.061	19	0.182	36
LCIE	0.140	726	0.006	> 1	0.058	2	0.061	19	0.163	104
METAS	0.310	59	0.005	> 1	0.058	2	0.061	19	0.321	65
CMI	4.100	inf	0.013	> 1	0.058	2	0.061	19	4.101	979032
MIKES	0.220	inf	0.007	> 1	0.058	2	0.061	19	0.236	491
SP	0.163	1901	0.008	> 1	0	-	0.061	19	0.174	837
UME	0.463	inf	0.017	> 1	0.058	2	0.061	19	0.471	7696
SMU	1.201	inf	0.015	> 1	0.058	2	0.061	19	1.204	250235
NMi-VSL	2.623	150	0.014	> 1	0.058	2	0.061	19	2.624	150
JV	0.140	259	0.014	> 1	0.058	2	0.068	5	0.167	68
SMD	0.460	inf	0.023	> 1	0	-	0.068	5	0.466	10537
SIQ	0.320	inf	0.016	> 1	0.058	2	0.068	5	0.333	1241
BEV	0.696	301	0.013	> 1	0.058	2	0.063	4	0.701	306
OMH	0.716	182	0.016	> 1	0.058	2	0.063	4	0.721	186
EIM	0.091	inf	0.009	> 1	0.058	2	0.063	4	0.125	25
IEN	0.128	79	0.012	> 1	0	-	0.013	19	0.129	81

In order to calculate the standard uncertainty of the difference between a laboratory result and the CRV, their correlation must be taken into account using the variance equation:

$$\mathrm{var}(\Delta_L - \Delta_{R,1000}) = \mathrm{var}(\Delta_{R,1000}) + \mathrm{var}(\Delta_L) - \frac{2}{n}\,\mathrm{var}(\Delta_L) \qquad (10)$$

where n is the number of laboratories contributing to the CRV. Laboratories not contributing are uncorrelated and only the first two terms on the right side of eq. (10) will be used. Table 8 reports the laboratory differences $D_i = \Delta_L - \Delta_{R,1000}$ with respect to the CRV, the standard uncertainty of this difference $u_i(\Delta_L - \Delta_{R,1000})$, the corresponding number of degrees of freedom from eq. (8), the expansion factor k corresponding to a level of confidence of 95% from the Student's distribution and, in the last column, the expanded uncertainty $U(D_i) = k\,u(D_i)$.

It is found that not taking correlation into account would produce an overestimation of $U(D_i)$ of no more than 6.1 %. Not considering the degrees of freedom would produce an underestimation of $U(D_i)$ of no more than 6.7 % , depending on the value of $\nu_{u,eff}$.

Table 8. Ratio 1000 V / 10 V: degrees of equivalence

(Values in Italics for $u(D_i)$ refer to laboratories not correlated with the CRV)

Lab	D_i (10^{-6})	$u(D_i)$ (10^{-6})	$\nu_{u,eff}$	k_{95}	$U(D_i)$ (10^{-6})
NPL	-0.386	0.242	226	1.97	0.477
INETI	4.269	*2.904*	> 1000	1.96	5.693

Lab	D_i (10^{-6})	$u(D_i)$ (10^{-6})	$\nu_{u,eff}$	k_{95}	$U(D_i)$ (10^{-6})
CEM	0.293	0.390	24	2.06	0.804
PTB	0.058	0.200	51	2.01	0.401
LCIE	0.717	0.185	94	1.99	0.367
METAS	0.110	0.319	76	1.99	0.635
CMI	-0.638	3.854	> 1000	1.96	7.553
MIKES	0.277	0.244	298	1.97	0.481
SP	0.225	0.194	177	1.97	0.382
UME	-2.466	*0.482*	> 1000	1.96	0.944
SMU	-0.737	1.135	> 1000	1.96	2.225
NMi-VSL	0.539	2.467	150	1.98	4.875
JV	-0.226	0.188	77	1.99	0.373
SMD	0.370	0.449	> 1000	1.96	0.881
SIQ	0.210	0.329	796	1.96	0.646
BEV	-0.051	0.667	317	1.97	1.311
OMH	-0.166	0.685	193	1.97	1.351
EIM	-0.693	0.156	40	2.02	0.316
IEN	0.097	0.159	65	2.00	0.317

d) Bilateral degrees of equivalence

Similarly to the degrees of equivalence with respect to the CRV, the degrees of equivalence between two laboratories (bilateral degrees of equivalence) are given by the difference between the laboratory results and by the uncertainty of this difference, at 95% confidence level. Indeed in the present case, because voltage ratios and not national standards were the object of the comparison, the bilateral degrees of equivalence are less significant, since differences between laboratories can only be due to systematic errors, and not to differences between their units of measurement. Equivalence between two laboratories could hide a common systematic error, but it is much more unlikely that a common systematic error should influence the CRV considerably. In any case the bilateral degrees of equivalence can easily be calculated by the difference of the D_i values reported in Table 8 and, for the uncertainty, by the double of the quadratic summation of the laboratory standard uncertainties $u_{G,L}$, given in Table 7. The error introduced in the uncertainty by this procedure, which neglects the degrees of freedom and also the correlation among the laboratories, due to the linear regression of the results of the pilot laboratory, is lower than 3 %. An analysis of the approximation introduced by neglecting correlation among the laboratories will be carried out in paragraph 10.

9. Ratio 100 V / 10 V: results

a) Participants results and differences from pilot

As reported in paragraph 8.a), the results of the laboratories must be corrected for deviation from standard temperature and humidity conditions. The corresponding uncertainty contribution can be calculated using eq. (2). Table 9 reports, for each laboratory, the mean date of the measurements, the temperature and humidity conditions, the error ε evaluated by means of the coefficients reported in Table 2 and the corresponding uncertainty contribution $u(\varepsilon)$ given by eq. (3). No correction for collective heating effect is needed for this ratio (see paragraph 6.a). In the table, the uncertainties δT and δH of temperature and humidity are given as half width of a rectangular distribution.

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Table 9. Ratio 100 V / 10 V: effect of temperature and humidity

Lab	Date	T (°C)	δT (°C)	H (%)	δH (%)	ε (T, H) (10^{-6})	$u(\varepsilon)$ (10^{-6})
NPL	27/10/98	20	0.5	55	5	0.029	0.037
INETI	25/11/98	23	1	36	12	0.031	0.029
CEM	17/02/99	21.7	0.5	30	5	0.078	0.026
PTB	16/03/99	23	1	40	15	0.017	0.032
LCIE	05/05/99	22.8	0.2	45	5	0.004	0.010
METAS	11/08/99	23	0.2	46	2	-0.003	0.005
CMI	11/09/99	23	0.5	52	5	-0.024	0.014
MIKES	02/11/99	23	0.3	45	5	0.000	0.010
SP	29/11/99	23	0.3	41	4	0.014	0.010
UME	01/03/00	23	0.7	45	10	0.000	0.021
SMU	30/03/00	23	0.5	35	5	0.034	0.017
NMi-VSL	03/05/00	22.2	0.5	41.7	3.5	0.028	0.013
JV	17/09/00	23.2	0.5	37	5	0.023	0.015
SMD	20/10/00	23	1	45	10	0.000	0.023
SIQ	16/12/00	22.5	0.5	52	10	-0.013	0.023
BEV	17/10/01	23	0.5	45	10	0.000	0.021
OMH	15/11/01	23	0.25	30	5	0.051	0.021
EIM	23/12/01	23.3	0.25	51	1	-0.027	0.009
IEN	-	23.1	0.5	42.4	5	0	0.012

For IEN, Table 9 reports the mean values of the ambient conditions for all measurements. As all IEN interpolations are already referred to standard ambient conditions, no further correction is needed.

Table 10 reports, for each participant: the time t of the measurements in days, starting from 1 July 1998; the original results d_L; the results after correction for temperature and humidity $d_{0,L}= d_L-\varepsilon$; the corresponding interpolated value, at standard ambient conditions, of the pilot laboratory $d_{0,P}$ given by eq. (1) with parameters D_0 and C_D from Table 2; the difference $\Delta_L= (d_{0,L} - d_{0,P})$; the standard uncertainties (type A and type B) reported by the laboratories; the contribution $u(\varepsilon)$ to the standard uncertainty due to temperature and humidity; the contribution s to the standard uncertainty due to the transfer standard; the corresponding global standard uncertainty $u_{G,L}$. The uncertainty budgets of the participants, comprised IEN, are given in Appendix D. For IEN, the instability s of the travelling standard is given by the value of the standard deviation of the multiple linear regression, for measurement group A, divided by $\sqrt{n}$, where n = 23 is the number of measurements in that group. In some cases the pilot laboratory found problems in the interpretation of the submitted results, or advised a participant that a large deviation, with respect to the other participants, could suggest an editorial or calculation error. These cases are detailed in Appendix G. If, as a consequence of this warning, the participant submitted a revised result, this result is reported in Table 10.

Table 10. 100 V / 10 V: results of the laboratories and differences from the pilot laboratory

Lab	t (d)	d_L (10^{-6})	$d_{0,L}$ (10^{-6})	$d_{0,P}$ (10^{-6})	Δ_L (10^{-6})	u_A (10^{-6})	u_B (10^{-6})	$u(\varepsilon)$ (10^{-6})	s (10^{-6})	$u_{G,L}$ (10^{-6})
NPL	118	-1.75	-1.779	-1.375	-0.404	0.03	0.3	0.037	0.073	0.312
INETI	147	-0.97	-1.001	-1.399	0.399	0.034	0.6	0.029	0.073	0.606

Lab	t (d)	d_L (10^{-6})	$d_{0,L}$ (10^{-6})	$d_{0,P}$ (10^{-6})	Δ_L (10^{-6})	u_A (10^{-6})	u_B (10^{-6})	$u(\varepsilon)$ (10^{-6})	s (10^{-6})	$u_{G,L}$ (10^{-6})
CEM	231	-1.36	-1.438	-1.470	0.032	0.05	0.28	0.026	0.073	0.295
PTB	258	-1.69	-1.707	-1.493	-0.214	0	0.11	0.032	0.073	0.136
LCIE	308	-1.5	-1.504	-1.535	0.031	0	0.12	0.010	0.073	0.141
METAS	406	-1.57	-1.567	-1.617	0.050	0	0.14	0.005	0.073	0.158
CMI	437	-2.5	-2.476	-1.643	-0.833	0.014	0.7	0.014	0.073	0.704
MIKES	489	-1.74	-1.740	-1.687	-0.053	0.015	0.046	0.010	0.073	0.088
SP	516	-1.6	-1.614	-1.709	0.096	0.013	0.1	0.010	0.073	0.125
UME	609	-4.79	-4.790	-1.788	-3.002	0.03	0.46	0.021	0.073	0.467
SMU	638	-4.2	-4.234	-1.812	-2.422	0.02	1.2	0.017	0.073	1.203
NMi-VSL	672	-1.5	-1.528	-1.840	0.312	0.23	0.618	0.013	0.073	0.664
JV	809	-2.145	-2.168	-2.162	-0.006	0.0053	0.033	0.015	0.069	0.078
SMD	842	-2.05	-2.050	-2.273	0.223	0	0.31	0.023	0.069	0.318
SIQ	899	-2.9	-2.887	-2.467	-0.420	0.01	0.17	0.023	0.069	0.185
BEV	1204	-3.2	-3.200	-3.141	-0.059	0.18	0.55	0.021	0.056	0.582
OMH	1233	-3.41	-3.461	-3.122	-0.339	0.18	0.51	0.021	0.056	0.544
EIM	1271	-1.24	-1.213	-3.096	1.883	0.01	0.12	0.009	0.056	0.133
IEN	-	-	-	-	0	0.069	0.096	0.012	0.015	0.120

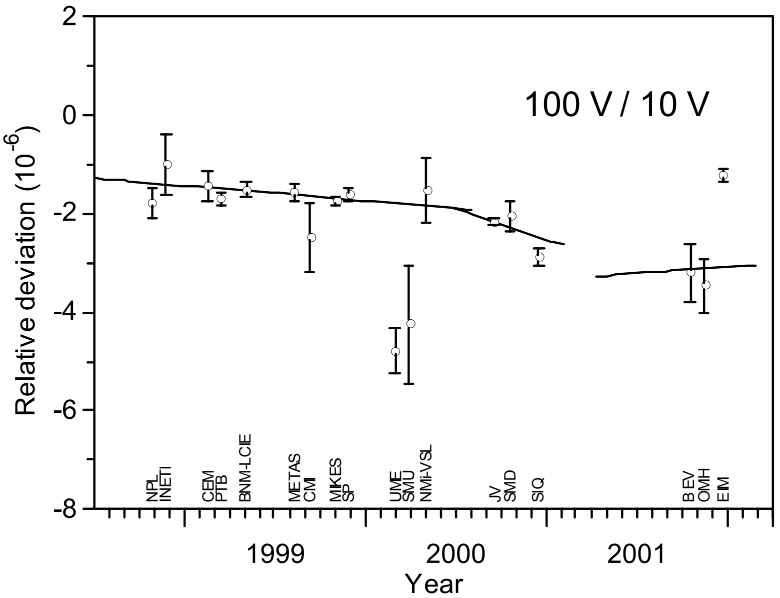


Fig. 5. Ratio 100 V / 10 : laboratory results corrected to standard ambient conditions, $d_{0,L}$, corresponding global standard uncertainties, $u_{G,L}$, and linear interpolations of IEN results.

Fig. 5 shows a plot of the corrected laboratory results, $d_{0,L}$, with corresponding global standard uncertainty $u_{G,L}$, compared with the linear fits of the corrected IEN measurements.

b) Comparison reference value and its uncertainty

For ratio 100/10 a procedure similar to that of paragraph 8.b) will be followed. The calculation of the Birge ratio gives: R_B = 3.7. Table 11 reports the results obtained for the calculations of eq. (5) and (6).

Table 11. Ratio 100 V / 10 V: identification of the members of the distribution.

Δ_{med} =	$-0.006 \cdot 10^{-6}$
$median\{\lvert \Delta_L - \Delta_{med} \rvert\}$ =	$0.230 \cdot 10^{-6}$
$S(MAD)$ =	$0.341 \cdot 10^{-6}$
2.5 $S(MAD)$ =	$0.852 \cdot 10^{-6}$

Applying eq. (6) to the Δ_L values in Table 10, it can be found that UME, SMU and EIM do not belong to the distribution. A new calculation of the Birge ratio for the remaining laboratories gives R_B = 0.9, a value that suggests the use of the weighted mean of these laboratories for the calculation of the CRV and the associated uncertainty. Therefore the CRV will be given by the equations:

$$\Delta_{R,100} = -0.039 \cdot 10^{-6}$$

$$u(\Delta_{R,100}) = \sqrt{\frac{1}{\sum_{L=1}^{n} \frac{1}{u_{G,L}^2}}} = 0.039 \cdot 10^{-6} \qquad (11)$$

$$\nu_{\Delta_{R,100}} = 105$$

For calculation of $\nu_{\Delta_{R,100}}$ by means of eq. (8), the effective degrees of freedom of the laboratories, evaluated in the following paragraph, and the equation of $u(\Delta_{R,100})$ have been used.

c) Degrees of equivalence with respect to the CRV

Following the same procedure as in paragraph 8c), the effective degrees of freedom, ν_{eff}, of the laboratories can be calculated. Table 12 reports for each participant the uncertainty components and the global uncertainty, already given in Table 10, with the associated degrees of freedom. In this Table, ν_{LAB} are the degrees of freedom as reported by the laboratories. Because the uncertainty contribution due to temperature and humidity, $u(\varepsilon)$, is small, the corresponding contribution of this component to ν_{eff} is negligible already for $\nu_\varepsilon > 2$. As for Table 7, ν_s is given by the number of data used in the linear fittings minus the number of parameters used.

Table 12. Ratio 100 V / 10 V: degrees of freedom

Lab	$u_{LAB} = \sqrt{u_A^2 + u_B^2}$ (10^{-6})	ν_{LAB}	$u(\varepsilon)$ (10^{-6})	ν_ε	s (10^{-6})	ν_s	$u_{G,L}$ (10^{-6})	ν_{eff}
NPL	0.301	9121	0.037	> 2	0.073	19	0.312	3150
INETI	0.601	inf	0.029	> 2	0.073	19	0.606	72923
CEM	0.284	11	0.026	> 2	0.073	19	0.295	12
PTB	0.110	56	0.032	> 2	0.073	19	0.136	76
LCIE	0.120	847	0.010	> 2	0.073	19	0.141	225
METAS	0.140	70	0.005	> 2	0.073	19	0.158	89
CMI	0.700	inf	0.014	> 2	0.073	19	0.704	140519
MIKES	0.048	315	0.010	> 2	0.073	19	0.088	39
SP	0.101	8667	0.010	> 2	0.073	19	0.125	161
UME	0.461	inf	0.021	> 2	0.073	19	0.467	29594
SMU	1.200	inf	0.017	> 2	0.073	19	1.203	581605
NMi-VSL	0.659	140	0.013	> 2	0.073	19	0.664	143
JV	0.033	29	0.015	> 2	0.069	5	0.078	8
SMD	0.310	inf	0.023	> 2	0.069	5	0.318	2216
SIQ	0.170	inf	0.023	> 2	0.069	5	0.185	254
BEV	0.579	110	0.021	> 2	0.056	4	0.582	112
OMH	0.541	490	0.021	> 2	0.056	4	0.544	494
EIM	0.120	inf	0.009	> 2	0.056	4	0.133	127
IEN	0.118	59	0.012	> 2	0.015	19	0.120	62

Table 13 reports: the laboratory difference with respect to the CRV, $D_i = \Delta_L - \Delta_{R,100}$; the standard uncertainty of this difference $u(\Delta_L - \Delta_{R,100})$; the corresponding number of degrees of freedom from Table 12 and eqs. (8) and (11)[2]; the expansion factor k corresponding to a level of confidence of 95% from the Student's distribution; the expanded uncertainty $U(D_i) = k\, u(D_i)$. In the calculation of $u(\Delta_L - \Delta_{R,100})$, correlation of the laboratories participating in the evaluation of the CRV is taken into account using the equation:

$$u^2(\Delta_L - \Delta_{R,100}) = u_{G,L}^2 - u^2(\Delta_{R,100}) \tag{12}$$

It is found that not taking correlation with the CRV into account would produce an overestimation of $U(D_i)$ of up to about 24%, the largest effects showing up for MIKES, JV and IEN, who have the smallest uncertainties. Not considering the degrees of freedom would produce an underestimation of $U(D_i)$ of up to about 38.4%, the largest effect showing up for JV, CEM and OMH, who have the smallest degrees of freedom.

[2] The use of eq. (8) (Welch-Satterthwaite) in this case requires a word of caution, because this equation does not take correlation into account. Inaccuracies would concern laboratories strongly correlated with the CRV (i.e. those with lowest uncertainties) and having low degrees of freedom. Because the degree of knowledge of the uncertainty of a difference is higher if the uncertainties of the two terms of the difference are correlated, the inaccuracy would always be in favour of the laboratories, giving to them a lower number of degrees of freedom and then a larger expansion factor.

Table 13. Ratio 100 V / 10 V: degrees of equivalence

(Values in Italics for $u(D_i)$ refer to laboratories not correlated with the CRV)

Lab	D_i (10^{-6})	$u(D_i)$ (10^{-6})	$\nu_{u,\,eff}$	k_{95}	$U(D_i)$ (10^{-6})
NPL	-0.366	0.310	> 1000	1.96	0.608
INETI	0.437	0.605	> 1000	1.96	1.185
CEM	0.070	0.292	11	2.20	0.643
PTB	-0.176	0.130	63	2.00	0.260
LCIE	0.069	0.135	188	1.97	0.267
METAS	0.089	0.153	78	1.99	0.305
CMI	-0.795	0.703	> 1000	1.96	1.378
MIKES	-0.015	0.079	24	2.06	0.163
SP	0.134	0.119	128	1.98	0.235
UME	-2.964	*0.469*	> 1000	1.96	0.919
SMU	-2.384	*1.203*	> 1000	1.96	2.358
NMi-VSL	0.351	0.662	141	1.98	1.310
JV	0.032	0.068	4	2.78	0.187
SMD	0.262	0.316	> 1000	1.96	0.620
SIQ	-0.382	0.181	230	1.97	0.357
BEV	-0.020	0.580	110	1.98	1.150
OMH	-0.301	0.543	488	1.97	1.066
EIM	1.922	*0.139*	148	1.98	0.274
IEN	0.038	0.113	48	2.01	0.227

d) Bilateral degrees of equivalence

As explained in par. 8.d), the bilateral degrees of equivalence are less significant in the present comparison. In any case they can easily be calculated by the difference of the D_i values reported in Table 13 and, for the uncertainty, by the double of the quadratic summation of the laboratory standard uncertainties $u_{G,L}$, given in Table 12. The error introduced in the uncertainty by this procedure, which neglects the degrees of freedom and also the correlation among the laboratories, due to the linear regression of the results of the pilot laboratory, is lower than 7% . An analysis of the approximation introduced by neglecting correlation among the laboratories is carried out in the following paragraph.

10. Effect of correlation among the laboratory differences

Even if the original results of the participant laboratories are not correlated, their differences with respect to the pilot laboratory are correlated, due to the linear regression of the pilot measurements. This can be understood by considering that a change of the slope of the regression line changes the differences in a correlated way. An analysis of the magnitude of the error made by neglecting this correlation was carried out using the equations reported in [5]. Only the measurements of group A (see paragraph 4) were considered, as the error must be higher for the longest series of data.

The effect of correlation on the global standard uncertainties $u_{G,L}$ of the laboratories was found to be lower than $0.002{\cdot}10^{-6}$ in absolute terms and lower than 2% in relative terms (i.e. relative to $u_{G,L}$). The effect of correlation on the uncertainties of the bilateral degrees of equivalence was found to be not larger than $0.001 \cdot 10^{-6}$ in absolute terms and not larger than 0.4% in relative terms (for the global approximation in the evaluation of the expanded uncertainty of the bilateral degrees of equivalence see paragraphs 8.e) and 9e)).

The effect of correlation on the uncertainty of the CRVs was evaluated by comparing the uncertainty of the weighted mean of the laboratory differences Δ_L of group A, evaluated without correlation, with the corresponding value obtained by taking correlation into account. The difference was found to be not higher than $0.003\ 10^{-6}$ in absolute terms and 4% in relative terms.

The effect of correlation on the uncertainty of the degrees of equivalence with respect to the CRV was also evaluated for the laboratories of group A and for the case of a CRV assessed by using the weighted mean. The effect was found to be always lower than $0.002 \cdot 10^{-6}$ in absolute terms and lower than 2% in relative terms.

In conclusion, for both ratios the error in the degrees of equivalence, due to having neglected the correlation introduced by the linear regression of the pilot measurements, is negligible.

11. Conclusions

Twenty National Metrology Institutes, members of EUROMET, participated in comparison EUROMET.EM-K8 aimed at evaluating the degrees of equivalence of the measurements of DC voltage ratios up to 1000 V. All laboratories, except DFM, performed the measurements of the ratios 1000 V / 10 V and 100 V / 10 V, which were used to evaluate the degrees of equivalence, and many also measured some or all of the optional ratios.

Towards the end of the comparison, the resistive divider used as the travelling standard showed a significant drift, which forced the comparison to be suspended and the divider to be monitored at the pilot laboratory. Otherwise the behaviour of the divider was quite satisfactory, showing an instability not higher than about $0.07 \cdot 10^{-6}$ (at one standard uncertainty level). The effects of temperature and humidity on the divider were evaluated by the pilot laboratory and corrections of the results, for deviation from standard ambient conditions, were applied. These corrections are usually negligible.

A significant self-heating effect was detected during the final measurements at the pilot laboratory for the ratio 1000 V / 10 V: it was found that, when all the divider sections are powered at nominal voltage, a variation of the ratio of the order of $0.2 \cdot 10^{-6}$ occurs even after the waiting time of 10 minutes suggested by the comparison protocol. This variation is higher than what one would expect from the instrument specifications. A correction of the results of the participants, depending on the method of measurement used, was then introduced.

Some laboratories underestimated their measurement uncertainty, which suggested a two-step approach in the evaluation of the Comparison Reference Value. First the use of a robust estimator allowed to find out those results which, with high probability, did not belong to the same statistical distribution as the other results, then the arithmetic mean or the weighted mean, depending on the consistency of the remaining results, were used for the reference value.

Comparison EUROMET.EM-K8 was not only useful to determine the degrees of equivalence of the participants, but also to gain more knowledge in the measurement of resistive voltage dividers, as testified by the variety of measurement methods and instrument set-ups used. The participants should then be acknowledged for this achievement in addition to their kind cooperation, which made possible to finalise this comparison.

The link to comparison CCEM-K8 and the degrees of equivalence with respect to the Key Comparison Reference Values (i.e. the reference values of CCEM-K8) are evaluated in a separate document.

12. References

[1] G. Marullo Reedtz and R. Cerri, “Final Report of CCEM-K8 Comparison of DC Voltage Ratio”, IEN Technical Report 653, November 2002, published online in the *Key Comparison Data Base*: http://kcdb.bipm.fr

[2] G. Marullo Reedtz and R. Cerri, “Characterisation of the Travelling Standard for an International Comparison of DC Voltage Ratio”, IEEE Trans. Instrum. Meas, IM-48, pp. 338-341, 1999.

[3] J. Randa, "Proposal for KCRV & Degree of Equivalence for GTRF Key Comparisons", Document of the Working Group on Radio Frequency Quantities of the CCEM, GT-RF/2000-12, September 2000.

[4] Mutual Recognition of National Measurement Standards and of Calibration and Measurement Certificates Issued by National Metrology Institutes, endorsed by the International Committee on Weight and Measures, text available on the BIPM web site (www.bipm.fr).

[5] N. F. Zhang, N. Sedransk, D. G. Jarrett, "Statistical Analysis of Key Comparison CCEM-K2", Document of the Working Group on Key Comparisons of the CCEM, WGKC/2002-06, September 2002.

APPENDIX A

Measurements of the pilot laboratory

As reported in paragraph 7, the method used at IEN provides the ratio of each section of the divider to the first section of the corresponding resistive chain. From these values the ratios 1000 V / 100 V, 100 V / 10 V, 300 V / 100 V and 100 V / 10 V can be evaluated and can be used to calculate the other ratios of interest, namely 1000 V / 10 V and 300 V / 10 V. Low voltage measurements were not carried out at IEN, but the low voltage ratios 10 V / 0.1 V and 10 V / 1 V were estimated by applying power corrections to the corresponding ratios measured at nominal voltage and corrected to standard ambient conditions (see paragraph 6).

Tables A1 and A2 report for each measurement the values of the basic ratios, given as relative deviation d from nominal, the measurement date, the temperature T, the relative humidity H and the corrected values d_0 corresponding to standard ambient conditions (see paragraph 5 for evaluation of temperature and humidity coefficients). From the original values of the basic ratios, the ratios 1000 V / 10 V and 300 V / 10 V were calculated and then processed to evaluate the temperature and humidity coefficients. Table A3 reports for these ratios the same information as the previous tables.

Table A4 reports the values of the ratios 10 V / 0.1 V and 10 V / 1 V.

Table A1.
Ratios 1000 V / 100 V and 100 V / 10 V: IEN original values d and corrected values d_0 at standard ambient conditions.

Ratio 1000 V / 100 V					Ratio 100 V / 10 V (mandatory)				
d (10^{-6})	date	T (°C)	H (%)	$d_{0,\ 1000/100}$ (10^{-6})	d (10^{-6})	date	T (°C)	H (%)	$d_{0,\ 100/10}$ (10^{-6})
-0.687	02/07/1998	23.2	65.0	-0.744	-1.254	02/07/1998	23.3	63.5	-1.186
-0.603	22/07/1998	23.2	63.8	-0.654	-1.496	22/07/1998	23.2	65.5	-1.423
-0.621	19/08/1998	23.3	63.5	-0.678	-1.358	19/08/1998	23.3	62.0	-1.295
-0.606	02/09/1998	23.2	59.0	-0.646	-1.468	02/09/1998	23.1	57.0	-1.425
-0.588	09/09/1998	25.1	58.2	-0.737	-1.424	09/09/1998	25.1	57.3	-1.338
-0.648	11/09/1998	25.1	61.3	-0.804	-1.308	11/09/1998	25.2	61.3	-1.206
-0.625	14/09/1998	25.1	30.9	-0.719	-1.447	14/09/1998	24.9	28.2	-1.463
-0.735	22/12/1998	23.0	25.3	-0.694	-1.326	22/12/1998	23.0	25.4	-1.392
-0.793	14/01/1999	22.9	29.3	-0.755	-1.369	14/01/1999	22.9	29.3	-1.425
-0.816	19/01/1999	23.0	33.2	-0.791	-1.356	19/01/1999	22.9	32.8	-1.399
-0.979	26/01/1999	19.8	32.2	-0.763	-1.309	26/01/1999	20.0	31.7	-1.417
-0.967	27/01/1999	20.0	29.5	-0.760	-1.401	27/01/1999	20.1	30.2	-1.513
-0.809	23/06/1999	22.5	40.5	-0.772	-1.558	23/06/1999	22.5	42.0	-1.579
-0.710	13/07/1999	23.1	69.2	-0.772	-1.648	13/07/1999	23.4	68.7	-1.560
-0.847	23/12/1999	23.0	30.0	-0.813	-1.659	23/12/1999	23.1	30.5	-1.706
-0.834	12/01/2000	23.1	28.8	-0.805	-1.666	12/01/2000	23.2	30.3	-1.711
-0.864	13/01/2000	23.2	30.0	-0.845	-1.658	13/01/2000	23.2	29.0	-1.707
-1.105	17/01/2000	19.9	31.1	-0.893	-1.620	17/01/2000	20.1	31.8	-1.725
-1.039	21/01/2000	20.2	29.0	-0.842	-1.666	21/01/2000	20.0	30.0	-1.779
-0.800	22/06/2000	24.5	48.5	-0.896	-1.848	22/06/2000	24.6	48.0	-1.805
-0.740	23/06/2000	25.1	48.5	-0.872	-2.060	23/06/2000	25.3	50.5	-1.992
-0.864	26/07/2000	23.5	50.5	-0.905	-1.968	26/07/2000	23.5	52.5	-1.933

Ratio 1000 V / 100 V					Ratio 100 V / 10 V (mandatory)				
d (10^{-6})	date	T (°C)	H (%)	$d_{0,\ 1000/100}$ (10^{-6})	d (10^{-6})	date	T (°C)	H (%)	$d_{0,\ 100/10}$ (10^{-6})
-0.874	31/07/2000	23.1	48.1	-0.884	-1.980	31/07/2000	23.0	48.0	-1.970
-0.882	12/01/2001	23.0	35.5	-0.862	-2.552	12/01/2001	23.0	35.8	-2.583
-0.930	16/01/2001	23.1	27.5	-0.899	-2.534	16/01/2001	23.1	27.5	-2.591
-1.032	06/02/2001	22.9	33.5	-1.003	-2.573	06/02/2001	22.8	34.0	-2.613
-1.066	11/04/2001	23.5	39.0	-1.080	-3.344	11/04/2001	23.4	38.3	-3.359
-1.096	20/04/2001	23.6	38.5	-1.117	-3.381	20/04/2001	23.3	37.5	-3.399
-1.097	02/05/2001	23.8	53.5	-1.160	-3.294	02/05/2001	23.6	56.0	-3.244
-1.029	18/05/2001	23.7	60.0	-1.104	-3.312	18/05/2001	23.6	59.0	-3.253
-0.926	18/07/2001	24.2	51.6	-1.012	-3.283	18/07/2001	24.1	52.4	-3.235
-0.905	27/08/2001	24.3	59.5	-1.012	-3.228	27/08/2001	24.3	56.5	-3.162
-0.986	12/09/2001	23.4	26.0	-0.970	-3.097	12/09/2001	23.1	27.4	-3.154
-1.064	11/02/2002	22.4	31.8	-0.999	-3.063	11/02/2002	22.2	30.0	-3.131
-1.087	18/02/2002	22.3	34.7	-1.021	-2.932	18/02/2002	22.3	34.1	-2.984
-1.134	27/02/2002	21.9	34.1	-1.045	-3.031	27/02/2002	22.1	33.8	-3.087

Table A2.
Ratios 300 V / 100 V and 30 V / 10 V: IEN original values d and corrected values d_0 at standard ambient conditions.

Ratio 300 V / 100 V					Ratio 30 V / 10 V (optional)				
d (10^{-6})	date	T (°C)	H (%)	$d_{0,\ 300/100}$ (10^{-6})	d (10^{-6})	date	T (°C)	H (%)	$d_{0,\ 30/10}$ (10^{-6})
-0.751	02/07/1998	23.2	65.0	-0.783	0.146	02/07/1998	23.3	63.5	0.209
-0.724	22/07/1998	23.2	63.8	-0.753	-0.063	22/07/1998	23.2	65.5	0.008
-0.751	19/08/1998	23.3	63.5	-0.782	0.069	19/08/1998	23.3	62.0	0.127
-0.734	02/09/1998	23.2	59.0	-0.756	0.009	02/09/1998	23.1	57.0	0.051
-0.752	09/09/1998	25.1	58.2	-0.809	0.082	09/09/1998	25.1	57.3	0.098
-0.804	11/09/1998	25.1	61.3	-0.866	0.054	11/09/1998	25.2	61.3	0.083
-0.784	14/09/1998	25.1	30.9	-0.805	0.080	14/09/1998	24.9	28.2	-0.006
-0.823	22/12/1998	23.0	25.3	-0.796	0.086	22/12/1998	23.0	25.4	0.015
-0.831	14/01/1999	22.9	29.3	-0.808	0.051	14/01/1999	22.9	29.3	-0.004
-0.843	19/01/1999	23.0	33.2	-0.827	0.036	19/01/1999	22.9	32.8	-0.007
-0.909	26/01/1999	19.8	32.2	-0.830	0.026	26/01/1999	20.0	31.7	0.019
-0.909	27/01/1999	20.0	29.5	-0.831	-0.035	27/01/1999	20.1	30.2	-0.049
-0.845	23/06/1999	22.5	40.5	-0.830	-0.057	23/06/1999	22.5	42.0	-0.061
-0.775	13/07/1999	23.1	69.2	-0.811	-0.140	13/07/1999	23.4	68.7	-0.060
-0.861	23/12/1999	23.0	30.0	-0.840	-0.163	23/12/1999	23.1	30.5	-0.217
-0.804	12/01/2000	23.1	28.8	-0.783	-0.070	12/01/2000	23.2	30.3	-0.126
-0.837	13/01/2000	23.2	30.0	-0.821	-0.087	13/01/2000	23.2	29.0	-0.147
-0.937	17/01/2000	19.9	31.1	-0.859	-0.283	17/01/2000	20.1	31.8	-0.292
-0.908	21/01/2000	20.2	29.0	-0.833	-0.223	21/01/2000	20.0	30.0	-0.237
-0.836	22/06/2000	24.5	48.5	-0.870	-0.307	22/06/2000	24.6	48.0	-0.317
-0.796	23/06/2000	25.1	48.5	-0.841	-0.389	23/06/2000	25.3	50.5	-0.400
-0.873	26/07/2000	23.5	50.5	-0.890	-0.413	26/07/2000	23.5	52.5	-0.392
-0.873	31/07/2000	23.1	48.1	-0.878	-0.402	31/07/2000	23.0	48.0	-0.391

Ratio 300 V / 100 V					Ratio 30 V / 10 V (optional)				
d (10^{-6})	date	T (°C)	H (%)	$d_{0,\ 300/100}$ (10^{-6})	d (10^{-6})	date	T (°C)	H (%)	$d_{0,\ 30/10}$ (10^{-6})
-0.867	12/01/2001	23.0	35.5	-0.854	-0.830	12/01/2001	23.0	35.8	-0.863
-0.878	16/01/2001	23.1	27.5	-0.856	-0.839	16/01/2001	23.1	27.5	-0.903
-0.910	06/02/2001	22.9	33.5	-0.893	-0.890	06/02/2001	22.8	34.0	-0.927
-0.962	11/04/2001	23.5	39.0	-0.962	-1.517	11/04/2001	23.4	38.3	-1.546
-0.98	20/04/2001	23.6	38.5	-0.982	-1.458	20/04/2001	23.3	37.5	-1.489
-0.966	02/05/2001	23.8	53.5	-0.992	-1.366	02/05/2001	23.6	56.0	-1.335
-0.917	18/05/2001	23.7	60.0	-0.951	-1.387	18/05/2001	23.6	59.0	-1.344
-0.884	18/07/2001	24.2	51.6	-0.916	-1.343	18/07/2001	24.1	52.4	-1.331
-0.887	27/08/2001	24.3	59.5	-0.931	-1.341	27/08/2001	24.3	56.5	-1.317
-0.915	12/09/2001	23.4	26.0	-0.897	-1.284	12/09/2001	23.1	27.4	-1.349
-0.909	11/02/2002	22.4	31.8	-0.879	-1.281	11/02/2002	22.2	30.0	-1.324
-0.939	18/02/2002	22.3	34.7	-0.911	-1.198	18/02/2002	22.3	34.1	-1.227
-0.934	27/02/2002	21.9	34.1	-0.898	-1.263	27/02/2002	22.1	33.8	-1.291

Table A3.
Ratios 1000 V / 10 V and 300 V / 10 V: IEN original
values d and corrected values d_0 at standard ambient conditions.

Ratio 1000 V / 10 V (mandatory)					Ratio 300 V / 10 V (optional)				
d (10^{-6})	date	T (°C)	H (%)	$d_{0,\ 1000/10}$ (10^{-6})	d (10^{-6})	date	T (°C)	H (%)	$d_{0,\ 300/10}$ (10^{-6})
-1.941	02/07/1998	23.3	64.3	-1.926	-2.005	02/07/1998	23.3	64.3	-1.966
-2.099	22/07/1998	23.2	64.7	-2.081	-2.220	22/07/1998	23.2	64.7	-2.180
-1.979	19/08/1998	23.3	62.8	-1.967	-2.109	19/08/1998	23.3	62.8	-2.073
-2.074	02/09/1998	23.1	58.0	-2.063	-2.202	02/09/1998	23.1	58.0	-2.176
-2.012	09/09/1998	25.1	57.8	-2.074	-2.176	09/09/1998	25.1	57.8	-2.146
-1.956	11/09/1998	25.1	61.3	-2.016	-2.112	11/09/1998	25.1	61.3	-2.075
-2.072	14/09/1998	25.0	29.6	-2.167	-2.231	14/09/1998	25.0	29.6	-2.257
-2.061	22/12/1998	23.0	25.4	-2.087	-2.149	22/12/1998	23.0	25.4	-2.188
-2.162	14/01/1999	22.9	29.3	-2.178	-2.200	14/01/1999	22.9	29.3	-2.232
-2.172	19/01/1999	23.0	33.0	-2.185	-2.199	19/01/1999	23.0	33.0	-2.223
-2.288	26/01/1999	19.9	32.0	-2.188	-2.218	26/01/1999	19.9	31.9	-2.251
-2.368	27/01/1999	20.0	29.9	-2.277	-2.310	27/01/1999	20.0	29.9	-2.347
-2.367	23/06/1999	22.5	41.3	-2.354	-2.403	23/06/1999	22.5	41.3	-2.412
-2.358	13/07/1999	23.3	68.9	-2.338	-2.423	13/07/1999	23.3	68.9	-2.375
-2.506	23/12/1999	23.0	30.3	-2.526	-2.520	23/12/1999	23.0	30.3	-2.549
-2.5	12/01/2000	23.2	29.5	-2.525	-2.470	12/01/2000	23.2	29.5	-2.501
-2.522	13/01/2000	23.2	29.5	-2.550	-2.495	13/01/2000	23.2	29.5	-2.525
-2.725	17/01/2000	20.0	31.4	-2.630	-2.557	17/01/2000	20.0	31.4	-2.591
-2.705	21/01/2000	20.1	29.5	-2.617	-2.574	21/01/2000	20.1	29.5	-2.611
-2.648	22/06/2000	24.5	48.3	-2.702	-2.684	22/06/2000	24.5	48.3	-2.674
-2.8	23/06/2000	25.2	49.5	-2.878	-2.856	23/06/2000	25.2	49.5	-2.842
-2.832	26/07/2000	23.5	51.5	-2.842	-2.841	26/07/2000	23.5	51.5	-2.827
-2.854	31/07/2000	23.0	48.1	-2.851	-2.853	31/07/2000	23.0	48.1	-2.847
-3.434	12/01/2001	23.0	35.6	-3.446	-3.419	12/01/2001	23.0	35.6	-3.438

Ratio 1000 V / 10 V (mandatory)					Ratio 300 V / 10 V (optional)				
d (10^{-6})	date	T (°C)	H (%)	$d_{0,\ 1000/10}$ (10^{-6})	d (10^{-6})	date	T (°C)	H (%)	$d_{0,\ 300/10}$ (10^{-6})
-3.464	16/01/2001	23.1	27.5	-3.490	-3.412	16/01/2001	23.1	27.5	-3.447
-3.605	06/02/2001	22.9	33.8	-3.615	-3.483	06/02/2001	22.9	33.8	-3.506
-4.410	11/04/2001	23.4	38.6	-4.434	-4.306	11/04/2001	23.4	38.6	-4.318
-4.477	20/04/2001	23.5	38.0	-4.503	-4.361	20/04/2001	23.5	38.0	-4.374
-4.391	02/05/2001	23.7	54.8	-4.404	-4.260	02/05/2001	23.7	54.8	-4.239
-4.341	18/05/2001	23.6	59.5	-4.347	-4.229	18/05/2001	23.6	59.5	-4.199
-4.209	18/07/2001	24.2	52.0	-4.244	-4.167	18/07/2001	24.2	52.0	-4.150
-4.133	27/08/2001	24.3	58.0	-4.164	-4.115	27/08/2001	24.3	58.0	-4.086
-4.083	12/09/2001	23.3	26.7	-4.116	-4.012	12/09/2001	23.3	26.7	-4.048
-4.127	11/02/2002	22.3	30.9	-4.118	-3.972	11/02/2002	22.3	30.9	-4.002
-4.019	18/02/2002	22.3	34.4	-4.005	-3.871	18/02/2002	22.3	34.4	-3.894
-4.165	27/02/2002	22.0	34.0	-4.141	-3.965	27/02/2002	22.0	34.0	-3.989

Table A4.
Ratios 10 V / 0.1 V and 10 V / 1 V at standard ambient conditions.

date	$d_{0,\ 10/0.1}$ (optional) (10^{-6})	$d_{0,\ 10/1}$ (optional) (10^{-6})
02/07/1998	-1.831	-1.083
22/07/1998	-1.986	-1.320
19/08/1998	-1.872	-1.192
02/09/1998	-1.968	-1.322
09/09/1998	-1.979	-1.235
11/09/1998	-1.921	-1.103
14/09/1998	-2.072	-1.360
22/12/1998	-1.992	-1.289
14/01/1999	-2.083	-1.322
19/01/1999	-2.090	-1.296
26/01/1999	-2.093	-1.314
27/01/1999	-2.182	-1.410
23/06/1999	-2.259	-1.476
13/07/1999	-2.243	-1.457
23/12/1999	-2.431	-1.603
12/01/2000	-2.430	-1.608
13/01/2000	-2.455	-1.604
17/01/2000	-2.535	-1.622
21/01/2000	-2.522	-1.676
22/06/2000	-2.607	-1.702
23/06/2000	-2.783	-1.889
26/07/2000	-2.747	-1.830
31/07/2000	-2.756	-1.867
12/01/2001	-3.351	-2.480
16/01/2001	-3.395	-2.488
06/02/2001	-3.520	-2.510

date	$d_{0,\ 10/0.1}$ (optional) (10^{-6})	$d_{0,\ 10/1}$ (optional) (10^{-6})
11/04/2001	-4.339	-3.256
20/04/2001	-4.408	-3.296
02/05/2001	-4.309	-3.141
18/05/2001	-4.252	-3.150
18/07/2001	-4.149	-3.132
27/08/2001	-4.069	-3.059
12/09/2001	-4.021	-3.051
11/02/2002	-4.023	-3.028
18/02/2002	-3.910	-2.881
27/02/2002	-4.046	-2.984

APPENDIX B
Ratio 1000 V / 10 V: degrees of equivalence with respect to the EUROMET comparison reference value

Key comparison EUROMET.EM-K8

MEASURAND: DC Voltage Ratio 1000 V / 10 V NOMINAL VALUE: 100

Pilot laboratory: IEN TRAVELLING STANDARD: Voltage Divider Datron 4902S, s/n 12422

$d_{0,i}$: fractional difference from nominal value of ratio $x_{0,i}$, measured by laboratory *i* and corrected to standard ambient conditions; it is given by $x_{0,i}$ = 100 x (1+ $d_{0,i}$)
The fractional differences $d_{0,\mathrm{IEN}}$ assigned by IEN to the ratio are obtained by interpolation of the IEN measurements results to the measurement dates of the other laboratories.

$\Delta_i = (d_{0,i} - d_{0,\mathrm{IEN}})$

$u_{\mathrm{G},i}$: global standard uncertainty of laboratory *i*

$\nu_{\mathrm{eff},i}$: number of degrees of freedom of laboratory *i*

Lab *i*	$d_{0,i}$ / 10^{-6}	$d_{0,\mathrm{IEN}}$ / 10^{-6}	Δ_i / 10^{-6}	$u_{\mathrm{G},i}$ / 10^{-6}	$\nu_{\mathrm{eff},i}$	Mean date of measurement
NPL	-2.58	-2.10	-0.48	0.23	283	1998-10-27
INETI	2.04	-2.13	4.17	2.90	> 1000	1998-11-25
CEM	-2.03	-2.23	0.20	0.40	21	1999-02-17
PTB	-2.30	-2.26	-0.04	0.18	36	1999-03-16
LCIE	-1.69	-2.31	0.62	0.16	104	1999-05-05
METAS	-2.41	-2.42	0.01	0.32	65	1999-08-11
CMI	-3.19	-2.46	-0.74	4.10	> 1000	1999-09-11
MIKES	-2.33	-2.51	0.18	0.24	491	1999-11-02
SP	-2.42	-2.54	0.13	0.17	837	1999-11-29
UME	-5.21	-2.65	-2.56	0.47	> 1000	2000-03-01
SMU	-3.51	-2.68	-0.83	1.20	> 1000	2000-03-30
NMi-VSL	-2.27	-2.72	0.44	2.62	150	2000-05-03
JV	-3.39	-3.07	-0.32	0.17	68	2000-09-17
SMD	-2.91	-3.18	0.27	0.47	> 1000	2000-10-20
SIQ	-3.27	-3.39	0.11	0.33	> 1000	2000-12-16
BEV	-4.30	-4.15	-0.15	0.70	306	2001-10-17
OMH	-4.40	-4.14	-0.26	0.72	186	2001-11-15
EIM	-4.91	-4.12	-0.79	0.13	25	2001-12-23
IEN	-	-	0	0.13	81	-

Key comparison EUROMET.EM-K8

MEASURAND: DC Voltage Ratio 1000 V / 10 V **NOMINAL VALUE: 100**

The reference value, Δ_R, of this comparison is the arithmetic mean of the differences Δ_i obtained from seventeen participants. (Statistical tests indicate that there is a high probability that the result of each of the two other participants does not belong to the same statistical distribution as the other seventeen). The mean relative deviation of the ratio from nominal is given by the sum $\Delta_R + d_{0,IEN}$. The standard uncertainty associated with Δ_R is the standard deviation of the mean.

Δ_R = -0.097 10^{-6} with standard uncertainty of 0.103 10^{-6} and 16 degrees of freedom.

The degree of equivalence of each laboratory with respect to the reference value is given by a pair of terms: $D_i = (\Delta_i - \Delta_R)$, and the corresponding expanded uncertainty U_i, assessed for a level of confidence of 95%. For the 17 laboratories contributing to the definition of the reference value, the correlation with the reference value is taken into account in the computation of U_i.

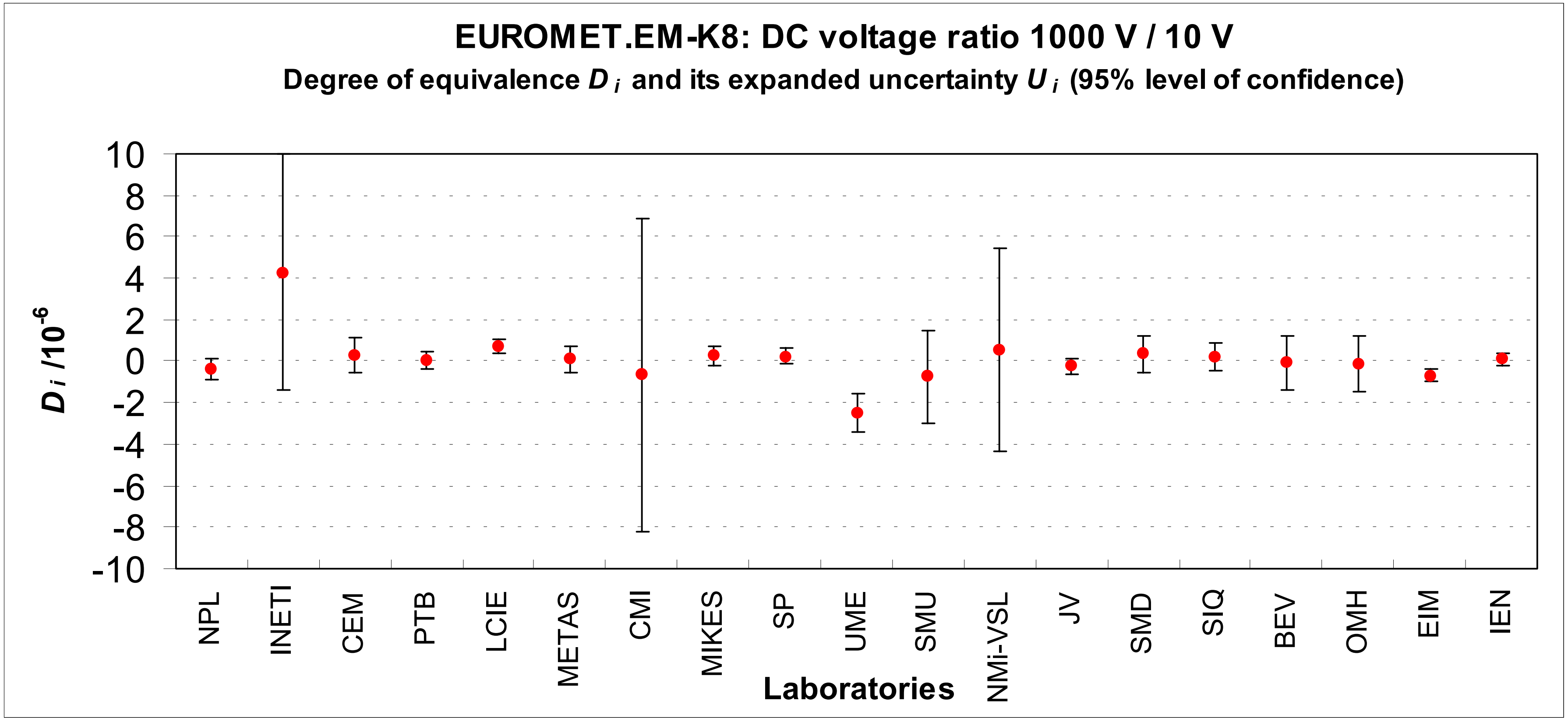
The bilateral degrees of equivalence can be calculated by the difference of the D_i values reported below, with corresponding 95% uncertainty given, within an approximation of about 3% or better, by twice the root-sum-square of the global standard uncertainties $u_{G,i}$ of the two laboratories.

MATRIX OF EQUIVALENCE

	D_i / 10^{-6}	U_i / 10^{-6}
NPL	-0.39	0.48
INETI	4.27	5.69
CEM	0.29	0.80
PTB	0.06	0.40
LCIE	0.72	0.37
METAS	0.11	0.63
CMI	-0.64	7.55
MIKES	0.28	0.48
SP	0.23	0.38
UME	-2.47	0.94

	D_i / 10^{-6}	U_i / 10^{-6}
SMU	-0.74	2.23
NMi-VSL	0.54	4.87
JV	-0.23	0.37
SMD	0.37	0.88
SIQ	0.21	0.65
BEV	-0.05	1.31
OMH	-0.17	1.35
EIM	-0.69	0.32
IEN	0.10	0.32

Note: laboratories in green have not participated in the definition of the reference value



EUROMET.EM-K8: DC voltage ratio 1000 V / 10 V
Degree of equivalence D i and its expanded uncertainty U i (95% level of confidence)
D i /10-6
10
8
6
4
2
0
-2
-4
-6
-8
-10
NPL
INETI
CEM
PTB
LCIE
METAS
CMI
MIKES
SP
UME
SMU
NMi-VSL
JV
SMD
SIQ
BEV
OMH
EIM
IEN
Laboratories

APPENDIX C
Ratio 100 V / 10 V: degrees of equivalence with respect to the EUROMET comparison reference value

Key comparison EUROMET.EM-K8

MEASURAND: DC Voltage Ratio 100 V / 10 V NOMINAL VALUE: 10

Pilot laboratory: IEN TRAVELLING STANDARD: Voltage Divider Datron 4902S, s/n 12422

$d_{0,i}$: fractional difference from nominal value of ratio $x_{0,i}$, measured by laboratory i and corrected to standard ambient conditions; it is given by: $x_{0,i}$ = 10 x (1+ $d_{0,i}$)
The fractional differences $d_{0,\mathrm{IEN}}$ assigned by IEN to the ratio are obtained by interpolation of the IEN measurements results to the measurement dates of the other laboratories.

$\Delta_i = (d_{0,i} - d_{0,\mathrm{IEN}})$

$u_{G,i}$: global standard uncertainty of laboratory i

$\nu_{\mathrm{eff},i}$: number of degrees of freedom of laboratory i

Lab i	$d_{0,i}$ / 10^{-6}	$d_{0,\mathrm{IEN}}$ / 10^{-6}	Δ_i / 10^{-6}	$u_{G,i}$ / 10^{-6}	$\nu_{\mathrm{eff},i}$	Mean date of measurement
NPL	-1.78	-1.38	-0.40	0.31	>1000	1998-10-27
INETI	-1.00	-1.40	0.40	0.61	>1000	1998-11-25
CEM	-1.44	-1.47	0.03	0.29	12	1999-02-17
PTB	-1.71	-1.49	-0.21	0.14	76	1999-03-16
LCIE	-1.50	-1.53	0.03	0.14	225	1999-05-05
METAS	-1.57	-1.62	0.05	0.16	89	1999-08-11
CMI	-2.48	-1.64	-0.83	0.70	>1000	1999-09-11
MIKES	-1.74	-1.69	-0.05	0.09	39	1999-11-02
SP	-1.61	-1.71	0.10	0.12	161	1999-11-29
UME	-4.79	-1.79	-3.00	0.47	>1000	2000-03-01
SMU	-4.23	-1.81	-2.42	1.20	>1000	2000-03-30
NMi-VSL	-1.53	-1.84	0.31	0.66	143	2000-05-03
JV	-2.17	-2.16	-0.01	0.08	8	2000-09-17
SMD	-2.05	-2.27	0.22	0.32	>1000	2000-10-20
SIQ	-2.89	-2.47	-0.42	0.19	254	2000-12-16
BEV	-3.20	-3.14	-0.06	0.58	112	2001-10-17
OMH	-3.46	-3.12	-0.34	0.54	494	2001-11-15
EIM	-1.21	-3.10	1.88	0.13	127	2001-12-23
IEN	-	-	0	0.12	62	-

Key comparison EUROMET.EM-K8

MEASURAND: DC Voltage Ratio 100 V / 10 V **NOMINAL VALUE: 10**

The reference value, Δ_R, of this comparison is the weighted mean of the differences Δ_i obtained from sixteen participants. (Statistical tests indicate that there is a high probability that the result of each of the three other participants does not belong to the same statistical distribution as the other sixteen). The mean relative deviation of the ratio from nominal is given by the sum $\Delta_R + d_{0,IEN}$. The standard uncertainty associated with Δ_R is the weighted standard uncertainty.

Δ_R= -0.039 10^{-6} with standard uncertainty of 0.039 10^{-6} and 105 degrees of freedom.

The degree of equivalence of each laboratory with respect to the reference value is given by a pair of terms: $D_i = (\Delta_i - \Delta_R)$, and the corresponding expanded uncertainty U_i, assessed for a level of confidence of 95%. For the 16 laboratories contributing to the definition of the reference value, the correlation with the reference value is taken into account in the computation of U_i .

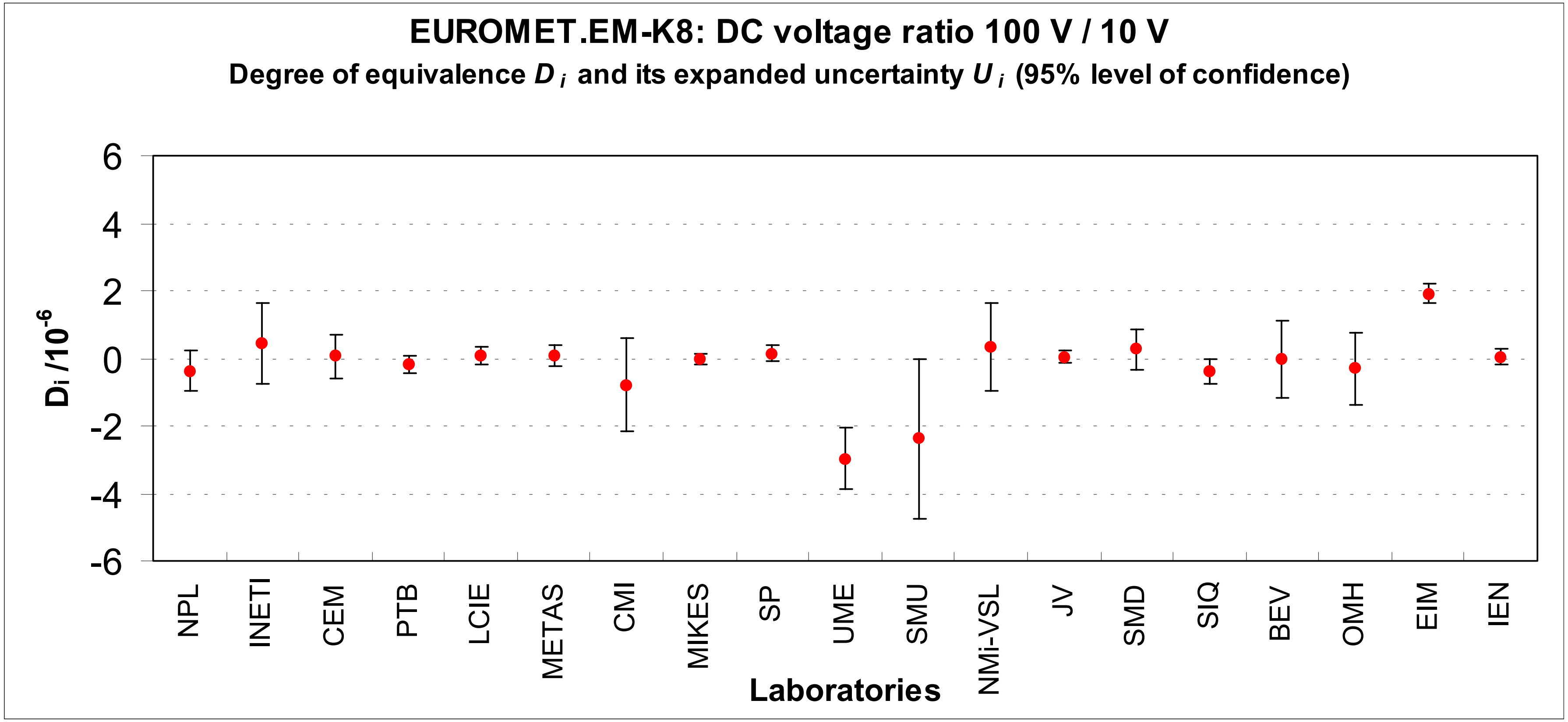
The bilateral degrees of equivalence can be calculated by the difference of the D_i values reported below, with corresponding 95% uncertainty given, within an approximation of about 7% or better, by twice the root-sum-square of the global tandard uncertainties $u_{G,i}$ of the two laboratories.

MATRIX OF EQUIVALENCE

	D_i / 10^{-6}	U_i / 10^{-6}
NPL	-0.37	0.61
INETI	0.44	1.19
CEM	0.07	0.64
PTB	-0.18	0.26
LCIE	0.07	0.27
METAS	0.09	0.30
CMI	-0.79	1.38
MIKES	-0.01	0.16
SP	0.13	0.23
UME	-2.96	0.92

	D_i / 10^{-6}	U_i / 10^{-6}
SMU	-2.38	2.36
NMi-VSL	0.35	1.31
JV	0.03	0.19
SMD	0.26	0.62
SIQ	-0.38	0.36
BEV	-0.02	1.15
OMH	-0.30	1.07
EIM	1.92	0.27
IEN	0.04	0.23

Note: laboratories in green have not participated in the definition of the reference value


EUROMET.EM-K8: DC voltage ratio 100 V / 10 V
Degree of equivalence D i and its expanded uncertainty U i (95% level of confidence)
6
4
2
0
-2
-4
-6
Di /10-6
NPL
INETI
CEM
PTB
LCIE
METAS
CMI
MIKES
SP
UME
SMU
NMi-VSL
JV
SMD
SIQ
BEV
OMH
EIM
IEN
Laboratories

Appendix D
Participant uncertainty budgets for ratio 100 V / 10 V

In the following the participant uncertainty budgets for ratio 100 V / 10 V are given. Because no common scheme to report the uncertainty had been established in the comparison protocol, these budgets were at the beginning difficult to compare. Towards the end of the comparison, the pilot laboratory asked all participants to rewrite their budgets in a common format. Of course the new budgets had to report the same global uncertainty initially submitted, but in some cases there were minor modifications, due to rounding problems.

The method of measurement used by the participants are shortly reminded before presenting their budget (for a more detailed description of these methods see paragraph 7). The equation of the measurement is also given if reported by the participant.

<u>IEN - pilot laboratory</u>

The calibration of ratio 100 V / 10 V was carried out by comparing each of the 10 resistive sections of the divider's 10x10 V chain with a transfer resistor, using a Kelvin double bridge with lead compensation. The model equation of the measurement is:

$$d_n \equiv \frac{r(n)-n}{n} = \frac{(\gamma_2 - \varepsilon_2 - \delta_{C,2} - \delta_{D,2} - \delta_{G,2} - \delta_{L,2} - \delta_{S,2})}{nR_1} + ... + \\ + \frac{(\gamma_n - \varepsilon_n - \delta_{C,n} - \delta_{D,n} - \delta_{G,n} - \delta_{L,n} - \delta_{S,n})}{n\,R_1} - \frac{(n-1)\gamma_1}{nR_1} \qquad \text{(D1)}$$

where the meaning of the symbols is as follows:

- d_n relative deviation of the ratio from nominal;
- n number of the divider's sections involved, equal to 10;
- R_1 first section of the divider;
- γ_i measured deviation of section R_i from the transfer resistor, being deviation of section 1 equal to zero;
- ε_i correction for linear drifts of the measurement system evaluated by repetition of the first measurement;
- $\delta_{C,i}$ correction for imperfect lead compensation on both high and low voltage sides of the bridge, also due to thermal voltages;
- $\delta_{D,i}$ correction for fluctuations of the detector;
- $\delta_{G,i}$ correction for gain error of the detector;
- $\delta_{L,i}$ correction for imperfect electrical insulation and guarding of the divider's main resistors;
- $\delta_{S,i}$ correction for insufficient stabilisation time after application of the voltage to a divider's section.

All corrections δ will be assumed to be zero. To simplify the variance equation, the variance contributions of the same category, pertaining to the measurements of all sections except the first one, will be assessed as equal. Then from (D1) the following equation derives:

$$
\begin{aligned}
u^2(d_n) &= (n-1)u^2(\gamma) + (n-1)u^2(\varepsilon) + (n-1)^2 u^2(\gamma_1) + \\
&\quad + (n-1)\left[u^2(\delta_C) + u^2(\delta_D) + u^2(\delta_L) + u^2(\delta_S) + u^2(\delta_G)\right] \\
&\approx u_A^2(d_n) + (n-1)u^2(\varepsilon) + (n-1)^2 u^2(\gamma_1) + \\
&\quad + (n-1)\left[u^2(\delta_C) + u^2(\delta_D) + u^2(\delta_L) + u^2(\delta_S) + u^2(\delta_G)\right]
\end{aligned}
\qquad \text{(D2)}
$$

Here, the term (n-1)$u^2(\gamma)$ has been approximately assessed as the uncertainty associated with the short term repeatability of the measurement, $u_A^2(d_n)$, which takes into account the short term stability of the divider. The uncertainty budget is given in Table D1. The short term repeatability has been assessed from couples of measurements taken at a distance of no more than 5 days, before and during the comparison.

Table D1. IEN relative uncertainty budget for ratio 100 V / 10 V in units of 10^{-6}

Uncertainty component	Standard uncertainty $u(x_i)$	Probability distribution / method of evaluation(A,B)	Sensitivity coefficient c_i	Standard uncertainty contribution $u_i(R)=c_i\, u(x_i)$	Degrees of freedom ν_i
u_A	0.069	gauss. / A	1	0.069	7
$u(\varepsilon)$	0.016	rect. / B	3	0.048	∞
$u(\gamma_1)$	0.008	rect. / B	9	0.072	∞
$u(\delta_C)$	0.005	rect. / B	3	0.015	∞
$u(\delta_D)$	0.006	rect. / B	3	0.018	∞
$u(\delta_L)$	0.001	rect. / B	3	0.003	∞
$u(\delta_S)$	0.006	rect. / B	3	0.018	∞
$u(\delta_G)$	0.009	rect. / B	3	0.027	∞
$R_{100/10}$				$u(R)$ = 0.118	ν_{eff} = 59

NPL

The divider was calibrated by comparison with a reference divider. The two dividers were energized from the same voltage source and the difference between the required outputs was measured by a nanovoltmeter. The uncertainty budget is given in Table D2.

Table D2. NPL relative uncertainty budget for ratio 100 V / 10 V in units of 10^{-6}

Source of uncertainty	std dev	std unc	mult
Measurement Resolution	0.05	0.029	3
Voltage drop	0.06	0.035	3
nV leakage	0.10	0.058	3
SP box	0.04	0.020	1
nV calibration		0.005	3
Meas Uncert 10:1	0.17	0.07	1
Meas Uncert 100:10	0.11	0.04	1
Total type B contribution		0.3	

INETI

The travelling divider was calibrated by comparison with a Fluke 720 Kelvin Varley reference divider previously calibrated. The two dividers were powered in parallel and the voltage difference between the output terminals at 10 V was measured with a digital voltmeter. The true ratio R and the deviation from nominal value ΔR were calculated using the expressions:

$$R = \frac{V_{in}}{V_{in} \times S + \Delta V}$$
$$\Delta R = \frac{R - R_N}{R_N} \qquad \text{(D3)}$$

Where:

S is the Setting of the Kelvin Varley Divider;
ΔV is the measured voltage difference at the digital voltmeter;
V_{in} is the input voltage to the dividers;
R_N is the nominal value of the ratio.

Table D3. INETI absolute uncertainty budget for ratio 100 V / 10 V

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution / method of evaluation(A,B)	Sensitivity coefficient c_i	Standard uncertainty contribution $u_i(R)$	Degrees of freedom ν_i
R	9,999 990 3	$3{,}4\text{x}10^{-7}$	A normal	1	$3{,}4\text{x}10^{-7}$	
S	0,100 000 1	$5{,}9\text{x}10^{-8}$	B rect.	100	$5{,}9\text{x}10^{-6}$	
ΔV	-1µV	$1{,}0\text{x}10^{-6}$V	B rect.	1 V^{-1}	$1{,}0\text{x}10^{-6}$	
V_{in}	100 V	$2{,}9\text{x}10^{-3}$ V	B rect.	$9{,}9\text{x}10^{-7}$ V^{-1}	$2{,}9\text{x}10^{-9}$	
$\Delta R_{100/10}$	$10\text{-}0{,}97\text{x}10^{-5}$				$u(R) = 6{,}0\text{x}10^{-6}$	$\nu_{eff}=9{,}6\text{x}10^{+5}$

CEM

The ratio was measured by comparing the individual resistive elements of the divider, using a Kelvin double bridge Datron model 4901. The lead compensation provided with the bridge was not used.

Table D4. CEM relative uncertainty budget for ratio 100 V / 10 V

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution / method of evaluation(A,B)	Sensitivity coefficient c_i	Standard uncertainty contribution $u_i(R)$	Degrees of freedom ν_i
$\overline{R}_{100/10}$	9,999 986 4	$5\cdot10^{-8}$	Student/ A	1	$5\cdot10^{-8}$	6
$\delta V_{detector}$	0	100 nV	Rectangular/ B	0,2 V^{-1}	$2\cdot10^{-8}$	∞
δV_{offset}	0	250 nV	Rectangular/ B	0,2 V^{-1}	$5\cdot10^{-8}$	∞
δR_{leads}	0	0.1 mΩ	Rectangular/ B	$2\cdot10^{-4}$ Ω^{-1}	$2\cdot10^{-8}$	∞
$\delta R_{leakage}$	0	$1\cdot10^{-7}$	Rectangular/ B	1	$1\cdot10^{-7}$	∞
δR_{drift}	0	$1{,}5\cdot10^{-7}$	Rectangular/ B	1	$1{,}5\cdot10^{-7}$	5
$\delta R_{reproduc.}$	0	$2\cdot10^{-7}$	Rectangular/ B	1	$2\cdot10^{-7}$	5
$R_{100/10}$	9,999 986 4				$u(R) = 2.8\cdot10^{-7}$	$\nu_{eff}=11$

PTB

The given result is the weighted mean of the results obtained with three different methods: substitution using a Fluke 752A, substitution using a Datron 4902S and measurement of individual resistive sections. The uncertainty budgets for each method are reported in the following tables.

Table D5. PTB relative uncertainty budget for ratio 100 V / 10 V (substitution with Fluke 752A)

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Sensitivity coefficient c_i	Uncertainty contribution $u_i(R)$ in 10^{-6}	Degrees of freedom ν_i
stability of voltage source	0	$3 \cdot 10^{-7}$	rectangular	1	0,17	10.000
voltage at DUT	$2{,}125 \cdot 10^{-6}$	10 µV/100 V	rectangular	1	0,06	10.000
voltage at 752A	0	10 µV/100 V	rectangular	1	0,06	10.000
reading of Null detector @ DUT	0	0,5 µV/10 V	rectangular	1	0,03	10.000
reading of Null detector @ 752A	0	0,5 µV/10 V	rectangular	1	0,03	10.000
ratio of 752A	0	$5 \cdot 10^{-8}$	standard	1	0,05	50
$(R_{100/10} – 10)/10$	$-2{,}125 \cdot 10^{-6}$				$u(R)$ = 0,20	ν_{eff} = 7.671

Table D6. PTB relative uncertainty budget for ratio 100 V / 10 V (substitution with Datron 4902S)

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Sensitivity coefficient c_i	Uncertainty contribution $u_i(R)$ in 10^{-6}	Degrees of freedom ν_i
stability of voltage source	0	$3 \cdot 10^{-7}$	rectangular	1	0,17	10.000
voltage at DUT	$1{,}700 \cdot 10^{-6}$	10 µV/100 V	rectangular	1	0,06	10.000
voltage at 4902S	0	10 µV/100 V	rectangular	1	0,06	10.000
reading of Null detector @ DUT	0	0,5 µV/10 V	rectangular	1	0,03	10.000
reading of Null detector @ 4902S	0	0,5 µV/10 V	rectangular	1	0,03	10.000
ratio of 4902S	0	$1{,}3 \cdot 10^{-7}$	standard	1	0,13	50
$(R_{100/10} – 10)/10$	$-1{,}700 \cdot 10^{-6}$				$u(R)$ = 0,24	ν_{eff} = 526

Table D7. PTB relative uncertainty budget for ratio 100 V / 10 V (meas. of individual sections)

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Sensitivity coefficient c_i	Uncertainty contribution $u_i(R)$ in 10^{-6}	Degrees of freedom ν_i
$\sum_{i=1}^{10} R_i / R_1$ at 10 kΩ	$-1{,}515 \cdot 10^{-6}$	1 mΩ / 10 kΩ	standard	1	0,10	9
stability of DMM at 10 kΩ	0	$1{,}5 \cdot 10^{-7}$	rectangular	1	0,09	10.000
$(R_{100/10} – 10)/10$	$-1{,}515 \cdot 10^{-6}$				$u(R)$ = 0,13	ν_{eff} = 29

LCIE

The Datron divider was calibrated by comparison with a reference divider previously calibrated. The two dividers were supplied with the same potential and the difference between the divided voltages was measured by means of a nanovoltmeter. The equation of the measurement is:

$$N_X = N_E + \frac{u}{U} \tag{D4}$$

where:

N_X ratio of the divider under calibration;
N_E ratio of the standard divider;
u reading value of the detector;
U applied input voltage

Here N_X and N_E are defined as output / input (lower than 1). The variance equation is, in relative terms:

$$\frac{\mathrm{var}(N_X)}{N_X^2} = \frac{\mathrm{var}(N_E)}{N_E^2} + \left(\frac{u}{U_S}\right)^2 \frac{\mathrm{var}(u)}{u^2} + \left(\frac{u}{U_S}\right)^2 \frac{\mathrm{var}(U)}{U^2} \tag{D5}$$

where U_S is the output voltage of the dividers. The uncertainty budget is given in the table below.

Table D8. LCIE relative uncertainty budget for ratio 100 V / 10 V

Quantity	Standard uncertainty $u(x_i)$	Probability distribution / method of evaluation	Sensitivity coefficient $c_i = df/dx_i$	Uncertainty contribution $c_i u(x_i)$ / 10^{-6}	Degrees of freedom
Calibration of ref divider	1.00E-07	B	1.00E+00	0.100	500
Temperature effect (1,1.10-6/°C x 0,1°C)	6.35E-08	rect/B	1.00E+00	0.064	500
Calibration of the nanovoltmeter	1.00E-04	B	3.8E-06	0.000	500
Sensibility (<50 nV)	1.44E-03	rect/B	3.8E-06	0.005	100
Stability input voltage (<5.10^{-8}.U)	1.44E-04	rect/B	3.8E-06	0.001	100
Emf	/	/	/	/	
Leakage resistance	/	/	/	/	
Combined standard uncertainty (k=1)				0.12	851

METAS

The given result is the weighted mean of the results obtained by two different methods. The first method is a comparison by substitution with a Fluke 752A reference divider previously calibrated, the second is the potentiometric measurement of the individual 10-V resistive sections of the divider. The uncertainty budgets for the two methods are reported in the following tables.

Table D9. METAS relative uncertainty budget for ratio 100 V / 10 V
(substitution with Fluke 752A)

Quantity	Estimate µV/V	Probability distribution/method of evaluation	Uncertainty contribution $c_i u(x_i)$ / 10^{-6}	Degrees of freedom
Measurements	-1.55	Gauss/ A	0.03	15
Fluke 752A		Gauss/ B	0.18	20
Datron 4902S		Gauss/ B	0.05	10
Null detector EM1a		Gauss/ B	0.01	15
Stability Fluke 5700A		Gauss/ B	0.08	15
Stability Fluke 732A		Gauss/ B	0.05	50
Uncompensated thermal voltage		Gauss/ B	0.05	10
$R_{100/10}$	-1.55		$u(R)$ = 0.22	40

Table D10. METAS relative uncertainty budget for ratio 100 V / 10 V
(measurement of individual sections)

Quantity	Estimate µV/V	Probability distribution/method of evaluation	Uncertainty contribution $c_i u(x_i)$ / 10^{-6}	Degrees of freedom
Measurements	-1.47	Gauss/ A	0.04	5
Potentiometric bridge		Gauss/ B	0.16	20
Power coefficients	-0.20	Gauss/ B	0.04	3
Temperature		Gauss/ B	0.05	5
Leakage	0.09	Gauss/ B	0.06	20
$R_{100/10}$	-1.58		$u(R)$ = 0.19	34

CMI

The Datron 4902s divider was compared with a Fluke 720A Kelvin Varley reference divider previously calibrated. The two dividers were powered in parallel using a lead compensator and the voltage difference between the output terminals was measured.

Table D11. CMI absolute uncertainty budget for ratio 100 V / 10 V

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution / method of evaluation (A,B)	Sensitivity coefficient c_i	Standard uncertainty contribution $u_i(R)$	Degrees of freedom ν_i
residual lead unbalance	0		Rectangular / B		0.16E-6	infinite
Microvoltmeter calibration error	0		Rectangular / B		0.06E-6	infinite
residual thermal voltages	0		Rectangular / B		0.12E-6	infinite
Reference divider error	0		Rectangular / B		7.00E-6	infinite
measurement repeatability	9.999975		Normal / A		0.14E-6	5
$R_{100/10}$	9.999975				$u(R)$ =7.0E-6	ν_{eff} = 3E+7

MIKES

The divider under calibration was measured against a Fluke 752A reference divider initially adjusted within specification. The two dividers were supplied with the same potential and the difference between the divided voltages was measured. Before each comparison, the adjustment was checked by measuring the unbalance of the 752A's calibration bridge. The following model equation was used:

$$D_X = D_S\,(1+(U_h - U_l)/U_{1s})\cdot(1-(U_m/k-U_l + d_{cal} + d_{offs})/U_{os})\cdot(1+d_h)\cdot(1+d_l)\cdot(1+d_{sw})-18\cdot d_{a1}/U_{os} \qquad \text{(D6)}$$

where:

D_S = nominal ratio
d_{cal} = detector calibration
d_h = heating of ref. divider
d_{a1} = reference divider's 100/10 adjustment error (meter reading)
dl = leakage resistance
d_{offs} = uncompensated offsets
d_{sw} = Ref.div. switch contacts
k = detector gain
U_{1s} = nominal input voltage
U_{os} = nominal output voltage
U_h = voltage between the dividers´ input Hi terminals
U_l = voltage between the dividers´ input Low terminals
U_m = detector reading

Table D12. MIKES absolute uncertainty budget for ratio 100 V / 10 V

Quantity X_l	Estimate x_l	Standard uncertainty $u(x_i)$	Probability distribution / method of evaluation(A,B)	Sensitivity coefficient c_l	Standard uncertainty contribution $u_l(R)$	Degrees of freedom ν_l
Repeatability Uin/Uout	9.99998214	0.1520 µV/V	normal / A	1	0.1520 µV/V	3
Detector calibration	0 µV	0.0577 µV	rectangular / B	-1 1/V	0.0577 µV/V	infinite
Heating of ref. divider	0 µV/V	0.0050 µV/V	normal / B	10 V/V	0.0500 µV/V	infinite
Ref div. Adjustment 10:1	-0.25168 µV	0.0718 µV	rectangular / B	1.8 1/V	0.1293 µV/V	infinite
Leakage resistance	0 µV/V	0.0329 µV/V	normal / B	10 V/V	0.3290 µV/V	infinite
Uncompens ated offset	0 µV	0.0577 µV	rectangular / B	-1 1/V	-0.0577 µV/V	infinite
Ref. div. Switch contacts	0 µV/V	0.0282 µV/V	rectangular / B	10 V/V	0.2820 µV/V	infinite
$R_{100/10}$ =	9.99998260				$u(R)$ = 0.4866	ν_{eff} = 315

SP

The ratio was determined by measuring the individual resistive sections of the divider at nominal voltage, by means of a current comparator resistance bridge. The deviation from nominal ratio $R_{100/10}$ was obtained from the relationship:

$$R_{100/10} = (1 + r_{100/10}) \cdot (1 + \delta R_{Leak}) \cdot (1 + \delta R_{Heat}) \cdot (1 + \delta R_{Meas}) - 1 \qquad \text{(D7)}$$

where:

δR_{Leak} : error due to leakage resistance,
δR_{Heat} : error due to heating effects due to the calibration method,
δR_{Meas} : error due to measurements of the individual resistances in the divider,
$r_{100/10}$:ratio error, calculated from measurements of the individual resistances in the divider.

Table D13. SP relative uncertainty budget for ratio 100 V / 10 V in units of 10^{-6}

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution / method of evaluation(A,B)	Sensitivity coefficient c_i	Standard uncertainty contribution $u_i(R)$	Degrees of freedom ν_i
δR_{Leak}	0	0,009	rectangular / B	1,0	0,009	∞
δR_{Heat}	0	0,087	rectangular / B	1,0	0,087	∞
δR_{Meas}	0	0,035	rectangular / B	1,0	0,035	∞
$r_{100/10}$	-1,60	0,013	normal / A	1,0	0,013	3
$R_{100/10}$	-1,60				$u(R)$ = 0,10	ν_{eff} = 8667

UME

The Datron 4902S travelling standard was calibrated against another Datron 4902S divider taken as the reference. The same voltage was applied to the two dividers in parallel using a lead compensator and the voltage difference at the 10 V output was measured.

Table D14. UME relative uncertainty budget for ratio 100 V / 10 V

Quantity X_i	Estimate x_i	Standard Uncertainty $u(x_i)$ / 10^{-6}	Probability distribution / method of evaluation(A,B)	Sensitivity coefficient c_i	Uncertainty Contribution $u_i(R)$ / 10^{-6}	Degrees of freedom ν_i
Reference Divider	10	0.8	Rectangular / B	1	0.46	∞
Measured voltage difference	-47.9 μV	0.004	Normal / B	1	0.004	10.6
DVM	0	0.00004	Normal / B	1	0.00004	19.5
Uncompensated Voltage Offset	0	0.004	Rectangular / B	1	0.004	8.0
Poor Lead Compensation	0	0.0015	Rectangular / B	1	0.0015	8.0

Quantity X_i	Estimate x_i	Standard Uncertainty $u(x_i)$ / 10^{-6}	Probability distribution / method of evaluation(A,B)	Sensitivity coefficient c_i	Uncertainty Contribution $u_i(R)$ / 10^{-6}	Degrees of freedom ν_i
Standard Deviation	0	0.03	Normal / A	1	0.03	12.0
R(100V/10V)	9.9999521				*u(R)* = 0.46	$\nu_{eff} = \infty$

SMU

The Datron 4902S travelling standard was calibrated against a Guildline 9700 PL reference divider. The two dividers were supplied in parallel using a lead compensator and the voltage difference at the output terminals was measured. The budget is given in the table below, with the following meaning of the symbols used:

$R_{100/10}$ measured divider ratio related to nominal value,
R_S SMU standard divider ratio,
δR_{NI} difference of dividing ratios established by zero indicator,
δ_{RD} correction for stability of standard divider,
δ_{LR} correction for leakage current,
δ_{TA} correction for change of ambient temperature,
δ_{SH} correction for self heating.

Table D15. SMU relative uncertainty budget for ratio 100 V / 10 V

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution / method of evaluation(A,B)	Sensitivity coefficient c_i	Standard uncertainty contribution $u_i(R)$	Degrees of freedom ν_i
R_S	0,9999957	3,0E-08	normal	1	3,0E-08	1,1E+09
δR_{NI}	0,0000085	5,0E-08	rectangular	1	5,0E-08	
δ_{RD}	0	1,2E-06	rectangular	1	1,2E-06	
δ_{LR}	0	1,0E-08	rectangular	1	1,0E-08	
δ_{TA}	0	1,0E-08	rectangular	1	1,0E-08	
δ_{SH}	0	5,0E-08	rectangular	1	5,0E-08	
$R_{100/10}$	1,0000042				u(R) = 1,2E-06	ν_{eff}=1,1E+09

NMi-VSL

The Datron divider was calibrated by comparison with a Fluke 720A Kelvin Varley reference voltage divider. A lead compensator was used. The ratio R_x of the unknown divider is calculated from:

$$R_x = R_s + dR_s + dR_m + dR_{lc} \tag{D8}$$

where:

- R_s is the ratio of the reference divider with its uncertainty resulting from non-linearity.
- dR_s is a summary of additional uncertainty contributions in the reference divider. It includes:

- temperature (humidity and pressure are negligible)
- power
- leakage resistance
- thermal voltages

- dR_m is the ratio difference between the reference divider and the unknown divider. The uncertainty in dR_m results from:
  - detector reading
  - detector calibration factor
- dR_{lc} is the correction for the influence of imperfect lead compensation on the ratio measurements.

The reproducibility is a type A uncertainty, which is calculated as the standard deviation of the measurements. The budget is given in the table below.

Table D16. NMi-VSL absolute uncertainty budget for ratio 100 V / 10 V

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution / method of evaluation(A,B)	Sensitivity coefficient c_i	Standard uncertainty contribution $u_i(R)$	Degrees of freedom ν_i
R_s	9.999 987 1	0.000 005 8	rectangular / B	1	0.000 005 8	100
dR_s	0.000 000 0	0.000 002 1	rectangular / B	1	0.000 002 1	100
dR_m	-0.000 001 8	0.000 000 5	rectangular / B	1	0.000 000 5	100
dR_{lc}	0.000 000 0	0.000 000 3	rectangular / B	1	0.000 000 3	100
Reproducibility	0.000 000 0	0.000 002 3	normal / A	1	0.000 002 3	16
$R_{x\ 100/10}$	9.999 985 4				$u(R)$ = 0.000 006 6	ν_{eff} = 140

JV

The method used for calibrating the divider under test was based upon comparing the voltage across each resistive segment with the voltage across the lowest segment. A stable backup voltage was used to balance the voltage drops across each divider's segment, while a digital voltmeter was used as zero detector. The first section of the divider was continuously monitored by using a second backup voltage and a second voltmeter. All electronic instruments used were kept floating by means of isolation transformers. Information on the individual uncertainty contributions are given in the notes below.

Table D17. JV relative uncertainty budget for ratio 100 V / 10 V

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Units	Probability distribution / method of evaluation (A,B)	Sensitivity coefficient c_i	Uncertainty contribution $u_i(R)$	Degrees of freedom ν_i	Note
Average Ratio, deviation	-2.145E-06	--	relative	Gauss. / A	--	5.31E-09	22	
Stability calibrator 1	0	2.00E-06	V	Rectang. / B	3.48E-03	4.02E-09	infinite	1
Stability calibrator 2	0	4.00E-06	V	Rectang / B	3.48E-03	8.03E-09	infinite	1
Uncert. absolute value cal 1	0	5.00E-06	V	Rectang / B	7.44E-08	2.15E-13	infinite	2
Uncert. absolute value cal 2	0	1.00E-05	V	Rectang / B	7.44E-08	4.29E-13	infinite	2
Curve fitting offset uncertainty	0	3.00E-07	V	Gauss. / B	3.20E-02	9.60E-09	6	3
Curve fitting ref uncert.	0	6.00E-07	V	Gauss. / B	3.20E-02	1.92E-08	9	4

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Units	Probability distribution / method of evaluation (A,B)	Sensitivity coefficient c_i	Uncertainty contribution $u_i(R)$	Degrees of freedom ν_i	Note
Thermal voltages	0	5.00E-07	V	Rectang / B	3.48E-03	1.00E-09	infinite	5
Current leak from DVM	0	5.00E-07	V	Rectang / B	3.48E-03	1.00E-09	infinite	6
Current leak in setup	0	4.00E-06	V	Rectang / B	3.48E-03	8.03E-09	infinite	7
Temperature coefficient	0	5.00E-01	K	Rectang / B	1.50E-08	7.50E-09	Infinite	8
Humidity coefficient	0	5.00E00	%RH	Rectang. / B	4.00E-09	2.00E-08	infinite	8
Null detector, loading effects	0	2.00E-08	Ohm	Rectang / B	1.80E-07	3.60E-15	Infinite	9
Linearity difference DVMs	0	3.16E-07	V	Rectang / B	1.00E-02	3.16E-09	Infinite	10
Lead resistance	0	2.00E-03	Ohm	Rectang / B	1.58E-15	5.20E-13	Infinite	11
R (100/10) (relative)	-2.145E-06				*u (R)*=	3.3E-08	ν_{eff} = 73	

Notes:

1 The stabilities of the backup voltages are taken from the manufacturers specifications (24 hour stability). The sensitivity coefficient is for one single segment multiplied by √10.

2 The uncertainties of the absolute values of the compensation voltages. The sensitivity coefficient is for one single segment multiplied by √10.

3 The offset is the measured difference between the monitoring set-up and the measuring set-up. The values given are the maximum deviation from the fitted curves. The sensitivity coefficient is for one single segment multiplied by (√10)/2. Division by 2 is justified because the contributions tend to cancel.

4 The curve fitting of the values measured on the first segment, corrected for offset. The values taken as the maximum deviation from the fitted curve. The sensitivity coefficient is for one single segment multiplied by (√10)/2. Division by 2 is justified because the contributions tend to cancel.

5 Residual voltages after polarity reversal on the multimeters. The sensitivity coefficient is for one single segment multiplied by √10.

6 The voltage across one segment due to possible current leaks through the DVM. The values are for a measured current leak of 4.5 pA. The sensitivity coefficient is for one single segment multiplied by √10.

7 Estimated contribution from current leaks in the measurement set-up, based upon the measured insulation resistance >200 Gohm. The sensitivity coefficient is for one single segment multiplied by √10.

8 Values taken from reference 2. The coverage factor is therefore 1 even if the distribution is rectangular.

9 Reduction in segment resistance due to loading by the multimeter and the backup voltage. The values are based upon the largest measured voltage difference and an input resistance of ~10Gohm for the multimeter. The coverage factor is therefore also set to 1.

10 The difference in linearity between the two multimeters influences the uncertainty of the measured voltages of each segment. A "worst case" relative value of 10e-7 is assumed and the coverage factor set to 1. The sensitivity coefficient is for one single segment multiplied by √10.

11 The influence of the lead resistance on the multimeter measurements. The values are for a measured current leak of 4.5 pA. The sensitivity coefficient is for one single segment multiplied by √10.

SMD

Each 10 V section, up to 100 V, of the DATRON 4902S resistive divider was successively compared with a 1 kΩ standard resistor, placed in a constant temperature oil bath, by means of room temperature DC current comparator. The result was calculated following the equation:

$$F_{100V/10V} = \frac{\sum_{i=1}^{10} R_{i-10V}}{R_{1-10V}} \qquad \text{(D9)}$$

Table D18. SMD absolute uncertainty budget for ratio 100 V / 10 V

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution / method of evaluation(A,B)	Sensitivity coefficient c_i	Standard uncertainty contribution $u_i(R)$	Degrees of freedom ν_i
Cal.R1	9995,2978	0,00325	Mixed	-0,0009	-2,93·E-06	Infinite
Cal.R2 to	9995,2907	0,00325	Mixed	0,0001	3,25·E-07	Infinite
Cal.R10	9995,2702	0,00325	Mixed	0,0001	3,25·E-07	Infinite
Self-heat.	0	5·E-07	Rectangular	1	2,89·E-07	Infinite
Leakage	0	3·E-07	Rectangular	1	1,73·E-07	Infinite
Unc. volt.	0	5·E-07	Rectangular	1	2,89·E-07	Infinite
$R_{100/10}$	9,9999795				$u(R)$ = 3,1·E-06	ν_{eff} =infinite

SIQ

The travelling standard was measured against a Fluke 752A reference divider previously self-calibrated. No lead compensation was used. The equation of the measurement is:

$$R_{UUT} = R_{REF} \cdot \left(1 + \frac{\Delta U_{lead}}{U_{inp}}\right) + \frac{\Delta U_{pow}}{U_{inp}} - \frac{\Delta U_{out}}{U_{inp}} \tag{D10}$$

and the sensitivity coefficients are:

$$c_1 = \frac{\partial(R_{UUT})}{\partial(R_{REF})} = \left(1 + \frac{\Delta U_{lead}}{U_{inp}}\right)$$

$$c_2 = \frac{\partial(R_{UUT})}{\partial(\Delta U_{pow})} = \frac{1}{U_{inp}}$$

$$c_3 = \frac{\partial(R_{UUT})}{\partial(\Delta U_{lead})} = \frac{R_{REF}}{U_{inp}} \tag{D11}$$

$$c_4 = \frac{\partial(R_{UUT})}{\partial(\Delta U_{out})} = -\frac{1}{U_{inp}}$$

$$c_5 = \frac{\partial(R_{UUT})}{\partial(U_{inp})} = -\frac{R_{REF} \cdot \Delta U_{lead}}{U_{inp}^2} - \frac{\Delta U_{pow}}{U_{inp}^2} + \frac{\Delta U_{out}}{U_{inp}^2}$$

Table D19. SIQ relative uncertainty budget for ratio 100 V / 10 V

source of uncertainty	estimate x_i	standard uncertainty $u(X_i)$	probability distribution	sensitivity coefficient c_i	uncertainty contribution u_i	Degrees of freedom ν_i
1.) Ratio of the reference divider:	0.1 V/V	2.0E-07	rectangular 1.73	1.0	1.2E-07	3.8E+13
2.) Power coefficient of the ref. div.:	0 V	1.0E-06 V	rectangular 1.73	1.0E-02 V^{-1}	5.8E-08	1.5E+14

source of uncertainty	estimate x_i	standard uncertainty $u(X_i)$	probability distribution	sensitivity coefficient c_i	uncertainty contribution u_i	Degrees of freedom ν_i
3.) Lead compensation:	0 V	2.0E-05 V	rectangular 1.73	1.0E-03 V^{-1}	1.2E-07	3.8E+13
4.) Null detector:	-2.9E-05 V	5.0E-08 V	rectangular 1.73	-1.0E-02 V^{-1}	-2.9E-09	6.1E+16
5.) Abs. value of the input voltage:	100 V	7.0E-04 V	rectangular 1.73	-2.9E-09 V^{-1}	-1.2E-11	3.8E+21
Type B standard uncertainty:					1.7E-07	9.4E+13
Type A standard uncertainty:	0 V/V	7.4E-09	1.00	1.0	7.4E-09	9
Combined standard uncertainty:					1.7E-07	2.7E+06

BEV

The travelling standard was compared with a Fluke 752A divider previously self-calibrated. The two dividers were powered in parallel, using a lead compensator. The output voltages of the two dividers were connected to the "Sense" (the reference) and "Input" (the unknown) terminals of an HP 3458 DMM and the ratio function of this instrument was used. The value of the travelling standard, R_{div2}, was then given by:

$$R_{div2} = \frac{R_{div1} \times U_{Sense}}{U_{Input}} = \frac{R_{div1}}{Ratio_{DMM}} \qquad \text{(D12)}$$

where R_{div1} is the value of the reference standard.

Table D20. BEV relative uncertainty budget for ratio 100 V / 10 V

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$ / 10^{-6}	Probability distribution/ method of evaluation(A,B)	Sensitivity coefficient c_i	Standard uncertainty contribution $u_i(R)$ / 10^{-6}	Degrees of freedom ν_i
R_{div1}	10,000000	0,5	rectangular / B	1	0,29	infinite
Ratio DMM	1,0000032	0,8	rectangular / B	1	0,46	infinite
R_{loaded}	---	0,1	rectangular / B	1	0,06	infinite
R_{lead}	---	0,1	rectangular / B	1	0,06	infinite
$R_{leakage}$	---	0,1	rectangular / B	1	0,06	infinite
$R_{reproducibility}$	---	0,18	normal / A	1	0,18	1
$R_{100/10}$	9,999968				$u(R)$ = 0,58	ν_{eff} = 110

OMH

The measurements were carried out by comparing the individual voltage drops at the divider's terminals. A Fluke calibrator and a Datron multifunction transfer standard were used.

Table D21. OMH relative uncertainty budget for ratio 100 V / 10 V

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution / method of evaluation(A,B)	Sensitivity coefficient c_i	Standard uncertainty contribution $u_i(R)$ / 10^{-6}	Degrees of freedom ν_i
Divider stability		0,2 10^{-6}	normal, B	1	0,2	100
Divider thermal voltage		(0,1 10^{-6}/°C)x0,5 °C	rectangular, B	1	0,05	infinite
Fluke 5700A calibration	100 V	20 μV/100V	normal, B	1	0,2	infinite
Fluke 5700A stability	100 V	25 μV/100V	normal, B	1	0,25	100
Fluke 5700A thermal voltage	100 V	(0,1ppm/°C)x0,5 °C	rectangular, B	1	0,05	infinite
Datron 4950 calibration	10 V	2 μV/10V	normal, B	1	0,2	infinite
Datron 4950 stability	10 V	2 μV/10V	normal, B	1	0,2	100
Datron 4950 thermal voltage	10 V	(0,2ppm/°C)x0,5 °C	rectangular, B	1	0,1	infinite
Datron 4950 zero drift	10 V	1 μV/10V	rectangular, B	1	0,1	infinite
Datron 4950 offset voltage	10 V	1 μV/10V	rectangular, B	1	0,1	infinite
Datron 4950 volt measurement /average std./	10 V		normal, A	1	0,12	5
Standard deviation 100 V/10 V ratio			normal, A	1	0,13	5
$R_{100/10}$ =	9,9999659				$u(R)$ = 0,54	ν_{eff} =490

EIM

The travelling standard was compared with a Fluke 752A reference divider using a substitution method. The equations of the measurement are:

$$R_{REF} = \frac{V_S}{V_Z - (V_{NULL})_{REF}}$$

$$R_{UUT} = \frac{V_S}{V_Z - (V_{NULL})_{UUT}} \qquad \text{(D13)}$$

and then: $$R_{UUT} = \frac{V_Z - (V_{NULL})_{REF}}{Vz - (V_{NULL})_{UUT}} R_{REF}$$

where REF and UUT refer to the reference divider and to the unknown divider, V_S is the input voltage, V_Z is the voltage of a 10 V source, regulated to compensate the reference divider output voltage, and V_{NULL} is the reading of the detector used to measure the voltage difference between the 10 V source and the output of each divider. The uncertainty budget is given in the table below.

Table D22. EIM absolute uncertainty budget for ratio 100 V / 10 V

Quantity X_i	Estimate x_i	Standard Uncertainty $u(x_i)$	Probability distribution / method of evaluation (A,B)	Sensitivity Coefficient c_i	Standard Uncertainty Contribution $u_i(y)$	Degrees of freedom
Null Detector Resolution for the RD N_{1R}	0 V	$6x10^{-3}$ uV	Rectangular/ B	$1x10^{-6}$ $(uV)^{-1}$	6 $x10^{-9}$	∞
Null Detector Accuracy N_{1AC} for the RD	0 V	$1x10^{-2}$ uV	Rectangular/ B	$1x10^{-6}$ $(uV)^{-1}$	1 $x10^{-8}$	∞
Measurements Mean V_{1NULL}	0 V	$3x10^{-2}$ uV	Normal/A	$1x10^{-6}$ $(uV)^{-1}$	3 $x10^{-8}$	24
Null Detector Resolution for the DUT N_{2R}	0 V	0,29 uV	Rectangular/ B	$-1x10^{-6}$ $(uV)^{-1}$	-2,9 $x10^{-7}$	∞
Null Detector Accuracy N_{2AC} for the RD	0 V	0,346 uV	Rectangular/ B	$-1x10^{-6}$ $(uV)^{-1}$	-3,46 $x10^{-7}$	∞
Measurements Mean V_{2NULL}	-12,44 μV	0,1 uV	Normal/A	$-1x10^{-6}$ $(uV)^{-1}$	-1 $x10^{-7}$	24
Zener Temperature Correction Z_T	0 V	0,23 uV	Rectangular/ B	$-1x10^{-12}$ $(uV)^{-1}$	-3 $x10^{-13}$	∞
Zener Calibration Certificate V_Z	9,99993335 V	0,18 uV	Normal/A	$-1x10^{-12}$ $(uV)^{-1}$	-2 $x10^{-13}$	57
RD Accuracy R_{AC}	$2x10^{-6}$	$1,15x10^{-6}$	Rectangular/ B	1	1,15 $x10^{-6}$	∞
$R_{100/10}$	9,9999876				$u(R)$ =$1,24x10^{-6}$	ν_{eff} =∞

Appendix E
Participant uncertainty budget for ratio 1000 V / 10 V

In the following the participant uncertainty budgets for ratio 1000 V / 10 V are given. As for ratio 100 V / 10 V (see Appendix D), the pilot laboratory asked all participants to rewrite their budgets in a common format.

The method of measurement used by the participants is shortly reminded before presenting their budget (for a more detailed description of these methods see paragraph 7). The equation of the measurement is also given if reported by the participant.

IEN - pilot laboratory

The value of ratio 1000 V / 10 V was derived from the basic ratios 1000 V / 100 V and 100 V / 10 V, which were calibrated by comparing their individual resistive sections with a transfer resistor, using a Kelvin double bridge with lead compensation. The model equation of the measurement of the basic ratios and the meaning of the symbols was given in Appendix D, eq. (D1) and (D2). The uncertainty budget for ratio 1000 V / 100 V is given in Table E1. The short term repeatability has been assessed from couples of measurements taken at a distance of no more than 5 days, before and during the comparison. For the uncertainty budget of ratio 100 V / 10 V see Appendix D, Table D1. Table E2 reports the combined uncertainty for ratio 1000 V / 10 V.

Table E1. IEN relative uncertainty budget for ratio 1000 V / 100 V in units of 10^{-6}

Uncertainty component	Standard uncertainty $u(x_i)$	Probability distribution / method of evaluation(A,B)	Sensitivity coefficient c_i	Standard uncertainty contribution $u_i(R)=c_i\, u(x_i)$	Degrees of freedom ν_i
$u_{r,A}$	0.026	gauss. / A	1	0.026	7
$u_r(\varepsilon)$	0.004	rect. / B	3	0.012	∞
$u_r(\gamma_1)$	0.004	rect. / B	9	0.036	∞
$u_r(\delta_C)$	0.001	rect. / B	3	0.003	∞
$u_r(\delta_D)$	0.002	rect. / B	3	0.006	∞
$u_r(\delta_L)$	0.002	rect. / B	3	0.006	∞
$u_r(\delta_S)$	0.003	rect. / B	3	0.009	∞
$u_r(\delta_G)$	0.003	rect. / B	3	0.009	∞
$R_{1000/100}$				$u(R)$ = 0.049	ν_{eff} = 85

Table E2. IEN relative uncertainty budget for the ratio 1000 V / 10 V in units of 10^{-6}

Uncertainty component	Standard uncertainty $u(x_i)$	Probability distribution / method of evaluation(A,B)	Sensitivity coefficient c_i	Standard uncertainty contribution $u_i(R)=c_i\, u(x_i)$	Degrees of freedom ν_i
$u(R_{1000/100})$	0.049	approx. gauss. / B	1	0.049	85
$u(R_{100/10})$	0.118	approx. gauss. / B	1	0.118	59
$R_{1000/10}$				$u(R)$ = 0.128	ν_{eff} = 79

NPL

The divider was calibrated by comparison with a reference divider. The two dividers were energised from the same voltage source and the difference between the required outputs was measured by a nanovoltmeter. The uncertainty budget is given in Table E3.

Table E3. NPL relative uncertainty budget for ratio 1000 V / 10 V in units of 10^{-6}

Source of uncertainty	std dev	std unc	mult
Measurement Resolution	0.05	0.029	2
Voltage drop	0.06	0.035	2
nV leakage	0.10	0.058	2
SP box	0.04	0.020	1
nV calibration		0.005	2
Meas Uncert 10:1	0.17	0.07	1
Total type B contribution		0.2	

INETI

The travelling divider was calibrated by comparison with a Fluke 720 Kelvin Varley reference divider previously calibrated. The two dividers were powered in parallel and the voltage difference between the output terminals at 10 V was measured with a digital voltmeter. The uncertainty budget is reported below; for meaning of symbols see Table D3.

Table E4. INETI absolute uncertainty budget for ratio 1000 V / 10 V

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution / method of evaluation(A,B)	Sensitivity coefficient c_i	Uncertainty contribution $u_i(R)$	Degrees of freedom ν_i
R	100,000 184 8	$8{,}5*10^{-6}$	A normal	1	$8{,}5*10^{-6}$	
S	0,010 000 0	$2{,}9*10^{-8}$	B rect.	10 000	$2{,}9*10^{-4}$	
□V	-20 µV	$1{,}0*10^{-6}$V	B rect.	10 V^{-1}	$1{,}0*10^{-5}$	
V_{in}	990 V	$2{,}9*10^{-2}$ V	B rect.	$2{,}0*10^{-4}$ V^{-1}	$5{,}8*10^{-6}$	
$R_{1000/10}$	+1,85				$u(R) = 2{,}9*10^{-4}$	$\nu_{eff} = 1{,}4*10^{+7}$

CEM

The value of the ratio 1000 V / 10 V was derived from the basic ratios 1000 V / 100 V and 100 V / 10 V, which were calibrated by comparing their individual resistive sections with a transfer resistor, using a Kelvin double bridge. The uncertainty budget is reported in Table.

Table E5. CEM relative uncertainty budget for ratio 1000 V / 10 V

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution / method of evaluation(A,B)	Sensitivity coefficient c_i	Uncertainty contribution $u_i(R)$	Degrees of freedom ν_i
$\overline{R}_{1000/100}$	9,999 993 0	$6 \cdot 10^{-8}$	Student/ A	1	$6 \cdot 10^{-8}$	6
$R_{100/10}$	9,999 986 4	$1.9 \cdot 10^{-7}$	Normal/ A+B	1	$1.9 \cdot 10^{-7}$	11

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution / method of evaluation(A,B)	Sensitivity coefficient c_i	Uncertainty contribution $u_i(R)$	Degrees of freedom ν_i
$\delta V_{detector}$	0	100 nV	Rectangular/ B	0,02 V^{-1}	$2\cdot10^{-9}$	∞
δV_{offset}	0	250 nV	Rectangular/ B	0,02 V^{-1}	$5\cdot10^{-9}$	∞
δr_{lead}	0	0.1 mΩ	Rectangular/ B	$2\cdot10^{-5}$ Ω^{-1}	$2\cdot10^{-9}$	∞
$\delta R_{leakage}$	0	$1\cdot10^{-7}$	Rectangular/ B	1	$1\cdot10^{-7}$	∞
δR_{drift}	0	$1,5\cdot10^{-7}$	Rectangular/ B	1	$1,5\cdot10^{-7}$	5
$\delta R_{reproduct}$	0	$1,5\cdot10^{-7}$	Rectangular/ B	1	$2\cdot10^{-7}$	5
R $_{1000/10}$	99,999 794				$u(R) = 3.9\cdot10^{-7}$	ν_{eff}=20

PTB

The given result is the weighted mean of the results obtained with three different methods: substitution using a Fluke 752A, substitution using a Datron 4902S and measurement of individual resistive sections. The uncertainty budget for each method is reported in the following tables.

Table E6. PTB relative uncertainty budget for ratio 1000 V / 10 V (substitution with Fluke 752A)

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Sensitivity coefficient c_i	Uncertainty contribution $u_i(R)$ in 10^{-6}	Degrees of freedom ν_i
stability of voltage source	0	$3\cdot10^{-7}$	rectangular	1	0,17	10.000
voltage at DUT	$2,425\cdot10^{-6}$	100 µV/1000 V	rectangular	1	0,06	10.000
voltage at 752A	0	100 µV/1000 V	rectangular	1	0,06	10.000
reading of Null detector @ DUT	0	0,5 µV/10 V	rectangular	1	0,03	10.000
reading of Null detector @ 752A	0	0,5 µV/10 V	rectangular	1	0,03	10.000
ratio of 752A	0	$2,1\cdot10^{-7}$	triangular	1	0,17	50
(R $_{1000/10}$ – 100)/100	$-2,425\cdot10^{-6}$				$u(R)$ = 0,26	ν_{eff} = 264

Table E7. PTB rel. uncertainty budget for the ratio 100 V / 10 V (substitution with Datron 4902S

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Sensitivity coefficient c_i	Uncertainty contribution $u_i(R)$ in 10^{-6}	Degrees of freedom ν_i
stability of voltage source	0	$3\cdot10^{-7}$	rectangular	1	0,17	10000
voltage at DUT	$2,450\cdot10^{-6}$	100 µV/1000 V	rectangular	1	0,06	10000
voltage at 4902S	0	100 µV/1000 V	rectangular	1	0,06	10000
reading of Null detector @ DUT	0	0,5 µV/10 V	rectangular	1	0,03	10000
reading of Null detector @ 4902S	0	0,5 µV/10 V	rectangular	1	0,03	10000
ratio of 4902S	0	$1,8\cdot10^{-7}$	standard	1	0,18	50

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Sensitivity coefficient c_i	Uncertainty contribution $u_i(R)$ in 10^{-6}	Degrees of freedom ν_i
$(R_{1000/10} - 100)/100$	$-2{,}450 \cdot 10^{-6}$				$u(R) = 0{,}27$	$\nu_{eff} = 237$

Table E8. PTB relative uncertainty budget for ratio 1000 V / 10 V (meas. of individual resistors)

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution	Sensitivity coefficient c_i	Uncertainty contribution $u_i(R)$ in 10^{-6}	Degrees of freedom ν_i
$\sum_{i=1}^{10} R_i / R_1$ at 10 kΩ	$-1{,}515 \cdot 10^{-6}$	1 mΩ / 10 kΩ	standard	1	0,10	9
$\sum_{i=1}^{10} R_i / R_1$ at 100 kΩ	$-0{,}780 \cdot 10^{-6}$	10 mΩ / 100 kΩ	standard	1	0,10	9
stability of DMM at 10 kΩ	0	$1{,}5 \cdot 10^{-7}$	rectangular	1	0,09	10.000
stability of DMM at 100 kΩ	0	$1{,}5 \cdot 10^{-7}$	rectangular	1	0,09	10.000
$(R_{1000/10} - 100)/100$	$-2{,}295 \cdot 10^{-6}$				$u(R) = 0{,}18$	$\nu_{eff} = 58$

<u>LCIE</u>

The Datron divider was calibrated by comparison to a reference divider previously calibrated. The two dividers were supplied with the same potential and the difference between the divided voltages was measured by means of a nanovoltmeter. The equation of the measurement and the variance equation were given as (D4) and (D5) in Appendix D.

Table E9. LCIE relative uncertainty budget for the ratio 1000 V / 10 V in 10^{-6}

Quantity	Standard uncertainty $u(x_i)$	Probability distribution/method of evaluation	Sensitivity coefficient $c_i = df/dx_i$	Uncertainty contribution $c_i u(x_i)$	Degrees of freedom
Calibration of ref divider	1.30E-07	B	1.00E+00	0.130	500
Temperature effect (1,1.10-6/°C x 0,1°C)	6.35E-08	rect/B	1.00E+00	0.064	500
Calibration of the nanovoltmeter	1.00E-04	B	3.80E-06	0.000	500
Sensitivity (<50 nV)	1.44E-03	rect/B	3.80E-06	0.005	100
Stability input voltage ($<5.10^{-8}$.U)	1.44E-04	rect/B	3.80E-06	0.001	100
Emf	/	/	/	/	
Leakage resistance	/	/	/	/	
Combined standard uncertainty (k=1)				0.14	728

<u>METAS</u>

The given result is the weighted mean of the results obtained by two different methods. The first method is a comparison by substitution with a Fluke 752A reference divider previously calibrated, the second is the potentiometric measurement of the individual 100-V resistive sections of the divider. The uncertainty budgets for the two methods are given in the tables below.

Table E10. METAS relative uncertainty budget for ratio 1000 V / 10 V
(substitution with Fluke 752A)

Quantity	Estimate µV/V	Probability distribution/method of evaluation	u_i (ppm)	Degrees of freedom
Measurements	-2.42	Gauss/ A	0.05	15
Fluke 752A		Gauss/ B	0.37	20
Datron 4902S		Gauss/ B	0.16	10
Null detector EM1a		Gauss/ B	0.01	15
Stability Fluke 5700A		Gauss/ B	0.08	15
Stability Fluke 732A		Gauss/ B	0.05	50
Uncompensated thermal voltage		Gauss/ B	0.05	10
$R_{1000/10}$	-2.42		$u(R)$ =0.42	30

Table E11. METAS relative uncertainty budget for ratio 1000 V / 10
(measurement of individual sections)

Quantity	Estimate µV/V	Probability distribution/method of evaluation	ui (ppm)	Degrees of freedom
Measurements	-3.33	Gauss/ A	0.04	5
Potentiometric bridge		Gauss/ B	0.18	20
Power coefficients	-0.22	Gauss/ B	0.08	3
Temperature		Gauss/ B	0.05	5
Leakage	0.95	Gauss/ B	0.41	20
$R_{1000/10}$	-2.60		$u(R)$ = 0.46	30

CMI

The travelling divider was calibrated by comparison with a Fluke 720 Kelvin Varley reference divider previously calibrated. The two dividers were powered in parallel using a lead compensator and the voltage difference between the output terminals was measured.

Table E12. CMI absolute uncertainty budget for ratio 1000 V / 10 V

Quantity X_i	Estimate x_i	Probability distribution / method of evaluation(A,B)	Uncertainty contribution $u_i(R)$	Degrees of freedom ν_i
residual lead unbalance	0	Rectangular / B	0.13E-5	infinite
Microvoltmeter calibration error	0	Rectangular / B	0.06E-5	infinite

Quantity X_i	Estimate x_i	Probability distribution / method of evaluation(A,B)	Uncertainty contribution $u_i(R)$	Degrees of freedom ν_i
residual thermal voltages	0	Rectangular / B	0.12E-5	infinite
Reference divider error	0	Rectangular / B	41.00E-5	. infinite
measurement repeatability	99.99966	Normal / A	0.13E-5	5
$R_{1000/10}$	99.99966		$u(R)$ = 41E-5	ν_{eff} = 5E+10

MIKES

The divider under calibration was measured against a Fluke 752A reference divider initially adjusted within specification. The two dividers were supplied with the same potential and the difference between the divided voltages was measured. Before each comparison, the adjustment was checked by measuring the unbalance of the 752A's calibration bridge. The equation of the measurement is:

$$D_X = D_S\,(1+(U_h - U_l)/U_{1s})\cdot(1-(U_m/k-U_l + d_{cal} + d_{offs})/U_{os})\cdot(1+d_h)\cdot(1+d_l)\cdot(1+d_{sw})-180\,(d_{a1} + d_{a2})/U_{os} \quad \text{(E1)}$$

where d_{a1} and d_{a2} are, respectively, the reference divider's 100/10 and 1000/10 adjustment errors, from the meter readings, and the other symbols were explained in Appendix D, eq. (D6).

Table E13. MIKES absolute uncertainty budget for ratio 1000 V / 10 V

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution / method of evaluation(A,B)	Sensitivity coefficient c_i	Uncertainty contribution $u_i(R)$ / 10^{-6}	Degrees of freedom ν_i
Repeatability Uin/Uout	99.9997618	1.0012 µV/V	normal / A	1	1.0012	3
Detector calibration	0 µV	0.0577 µV	rectangular / B	-10 1/V	-0.5770	infinite
Heating of ref. divider	-0.09350 µV/V	0.0050 µV/V	normal / B	100 V/V	0.5000	infinite
Ref div. Adjustment, 100:1	0.57316 µV	0.0510 µV	rectangular / B	18 1/V	0.9185	infinite
Ref div. Adjustment, 10:1	-0.25168 µV	0.0718 µV	rectangular / B	18 1/V	1.2931	infinite
Leakage resistance	0 µV/V	0.2194 µV/V	normal / B	100 V/V	21.9400	infinite
Uncompensated offset	0 µV	0.0577 µV	rectangular / B	-10 1/V	-0.5770	infinite
Ref. div. Switch contacts	0 µV/V	0.0254 µV/V	square / B	100 V/V	2.5400	infinite
$R_{1000/10}$	99.9997466			$u(R)$ =	22.187	ν_{eff} = 723449

SP

The ratio was determined by measuring the individual resistive sections of the divider, at nominal voltage, by means of a current comparator resistance bridge. For the measurement equation and meaning of symbols see Appendix D, eq. (D7).

Table E14. SP relative uncertainty budget for ratio 1000 V / 10 V

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution / method of evaluation(A,B)	Sensitivity coefficient c_i	Uncertainty contribution $u_i(R)$	Degrees of freedom ν_i
δR_{Leak}	0	0,087	rectangular / B	1,0	0,087	∞
δR_{Heat}	0	0,115	rectangular / B	1,0	0,115	∞
δR_{Meas}	0	0,062	rectangular / B	1,0	0,062	∞
$r_{1000/10}$	-2,41	0,032	normal / A	1,0	0,032	3
$R_{1000/10}$ =	-2,41				$u(R)$ = 0,16	ν_{eff} = 1901

UME

The Datron 4902S travelling standard was calibrated against another Datron 4902S divider taken as the reference. The same voltage was applied to the two dividers in parallel using a lead compensator and the voltage difference at the 10 V output was measured.

Table E15. UME relative uncertainty budget for ratio 1000 V / 10 V

Quantity X_i	Estimate x_i	Standard Uncertainty $u(x_i)$ / 10^{-6}	Probability distribution / method of evaluation(A,B)	Sensitivity coefficient c_i	Uncertainty contribution $u_i(R)$ / 10^{-6}	Degrees of freedom ν_i
Reference Divider	100 V	0.8	Rectangular / B	1	0.46	∞
Measured voltage difference	-54.05 µV	0.004	Normal / B	10	0.04	10.4
DVM	0	0.00004	Normal / B	1	0.00004	19.5
Uncompensated Voltage Offset	0	0.004 nV	Rectangular / B	1	0.004	8.0
Poor Lead Compensation	0	0.0015	Rectangular / B	1	0.0015	8.0
Standard Deviation	0	0.05	Normal / A	1	0.05	12.0
$R_{1000/10}$	99.9994595				u(R) = 0.46	ν_{eff} = ∞

SMU

The Datron 4902S travelling standard was calibrated against a Guildline 9700 PL reference divider. The two dividers were supplied in parallel using a lead compensator and the voltage difference at the output terminals was measured. The budget is given in the table below, with the following meaning of the symbols used:

$R_{1000/10}$ measured divider ratio related to nominal value,

R_S SMU standard dividing ratio,
δR_{NI} difference of dividing ratios established by zero indicator,
δ_{RD} correction for stability of standard divider,
δ_{LR} correction for leakage current,
δ_{TA} correction for change of ambient temperature,
δ_{SH} correction for self heating.

Table E16. SMU relative uncertainty budget for ratio 1000 V / 10 V

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution / method of evaluation(A,B)	Sensitivity coefficient c_i	Uncertainty contribution $u_i(R)$	Degrees of freedom ν_i
R_S	0,9999957	3,0E-08	normal	1	3,0E-08	6,6E+07
δR_{NI}	0,0000080	5,00E-08	rectangular	1	5,00E-08	
δ_{RD}	0	1,20E-06	rectangular	1	1,20E-06	
δ_{LR}	0	1,00E-08	rectangular	1	1,00E-08	
δ_{TA}	0	1,00E-08	rectangular	1	1,00E-08	
δ_{SH}	0	5,00E-08	rectangular	1	5,00E-08	
$R_{1000/10}$	1,0000037				$u(R)$ = 1,2E-06	ν_{eff} = 6,6E+07

NMi-VSL

The Datron divider was calibrated by comparison with a Fluke 720A Kelvin Varley reference voltage divider. A lead compensator was used. For the equation of measurement and meaning of symbols see eq. (D8).

Table E17. NMi-VSL absolute uncertainty budget for ratio 1000 V / 10 V

Quantity X_i	Estimate x_i (V/V)	Standard uncertainty $u(x_i)$	Probability distribution / method of evaluation(A,B)	Sensitivity coefficient c_i	Uncertainty contribution $u_i(R)$ (V/V)	Degrees of freedom ν_i
R_s	100.000 000	0.000 231	rectangular / B	1	0.000 231	100
dR_s	0.000 000	0.000 121	rectangular / B	1	0.000 121	100
dR_m	-0.000 249	0.000 008	rectangular / B	1	0.000 008	100
dR_{lc}	0.000 000	0.000 029	rectangular / B	1	0.000 029	100
Reproducibility	0.000 000	0.000 012	normal / A	1	0.000 012	10
$R_{1000/10}$	99.999 751			$u(R)$ =	0.000 263	ν_{eff} = 150

JV

The method used for calibrating the divider under test was based upon comparing the voltage across each resistive segment with the voltage across the lowest segment. A stable backup voltage was used to balance the voltage drops across each divider's segment, while a digital voltmeter was used as zero detector. The first section of the divider was continuously monitored by using a second backup voltage and a second voltmeter. All electronic instruments used were kept floating by means of isolation transformers. The value of ratio 100 V / 10 V, used to evaluate the ratio 1000 V / 10 V, was measured by supplying the whole divider by 1000 V, and its uncertainty does not coincide with the one reported in Table D17. The uncertainty budget is presented in the table below; for the notes see Table D17.

Table E18. JV relative uncertainty budget for ratio 1000 V / 10 V

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Units	Probability distribution / method of evaluation (A,B)	Sensitivity coefficient c_i	Uncertainty contribution $u_i(R)$	Degrees of freedom ν_i	Note
Average Ratio, deviation	-1.337E-06	--	relative	Gaussian / A	--	8.78E-09	24	
Stability calibrator 1	0	8.00E-05	V	Rectangular / B	3.48E-04	1.61E-08	infinite	1
Stability calibrator 2	0	6.00E-05	V	Rectangular / B	3.48E-04	1.20E-08	infinite	1
Uncert. absolute value cal. 1	0	1.00E-04	V	Rectangular / B	1.65E-08	9.50E-13	infinite	2
Uncert. absolute value cal. 2	0	1.00E-04	V	Rectangular / B	1.65E-08	9.50E-13	infinite	2
Curve fitting offset uncertainty	0	1.28E-05	V	Gaussian / B	3.20E-03	4.08E-08	6	3
Curve fitting ref uncert.	0	8.90E-06	V	Gaussian / B	3.20E-03	2.85E-08	9	4
Thermal voltages	0	5.00E-07	V	Rectangular / B	3.48E-04	1.00E-10	infinite	5
Current leak from DVM	0	1.00E-06	V	Rectangular / B	3.48E-04	2.01E-10	infinite	6
Current leak in setup	0	2.00E-05	V	Rectangular / B	3.48E-04	4.02E-09	infinite	7
Temperature coefficient	0	5.00E-01	K	Rectangular / B	1.50E-07	7.50E-08	Infinite	8
Humidity coefficient	0	5.00E00	%RH	Rectang. / B	1.00E-08	5.00E-08	Infinite	8
Null detector, loading effects	0	5.00E-06	Ohm	Rectangular / B	2.00E-05	1.00E-10	Infinite	9
Linearity difference DVMs	0	3.16E-07	V	Rectangular / B	1.00E-04	3.16E-11	Infinite	10
Lead resistance	0	2.00E-02	Ohm	Rectangular / B	1.58E-15	5.20E-15	Infinite	11
Division ratio 100:10	-2.235E-06		relative	Gaussian / B		3.88E-08	29	(*)
$R_{1000/10}$ (relative)	-3.57E-06				$u(R)$ =	1.4E-07	ν_{eff} >259	(*)

(*)The uncertainty contributions from the two ratios 1000:100 and 100:10 have been added linearly, even if they may be assumed to be fully independent.

SMD

An automatic high resistance ratio bridge was used to successively compare each 100 V section, from 100 V to 1 kV, with a 10 kΩ standard resistor placed in a thermo-regulated air bath. The form of the measurement equation is the same as eq. (D9) in Appendix D.

Table E19. SMD absolute uncertainty budget for ratio 1000 V / 10 V

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution / method of evaluation(A,B)	Sensitivity coefficient c_i	Uncertainty contribution $u_i(R)$	Degrees of freedom ν_i
$R_{100/10}$	9,9999795	3,12·E-06	Mixed	9,9999914	3,12·E-05	Infinite
Cal.R1	99952,204	0,0243	Mixed	-0,0009	-3,02·E-05	Infinite
Cal.R2 to	99952,033	0,0243	Mixed	0,0001	3,35·E-06	Infinite
Cal.R10	99952,265	0,0243	Mixed	0,0001	3,35·E-06	Infinite
Self-heat.	0	7·E-06	Rectangular	1	4,04·E-06	Infinite

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution / method of evaluation(A,B)	Sensitivity coefficient c_i	Uncertainty contribution $u_i(R)$	Degrees of freedom ν_i
Leakage	0	2·E-05	Rectangular	1	1,16·E-05	Infinite
Unc. volt.	0	3·E-06	Rectangular	1	1,73·E-06	Infinite
$R_{1000/10}$	99,999709				$u(R)$=4,6·E-05	ν_{eff} =infinite

SIQ

The travelling standard was measured against a Fluke 752A reference divider previously self-calibrated. No lead compensation was used. For the equation of the measurement see Appendix D, eq. (D10).

Table E20. SIQ relative uncertainty budget for ratio 1000 V / 10 V

source of uncertainty	estimate X_i	standard uncertainty $u(X_i)$	probability distribution	sensitivity coefficient c_i	uncertainty contribution u_i (10^{-6})	Degrees of freedom ν_i
1.) Ratio of the reference divider:	0.01 V/V	5E-07	rectangular 1.73	1	0.29	Infinite
2.) Power coefficient of the ref. div.:	0 V	0.000001 V	rectangular 1.73	0.001 V^{-1}	0.06	Infinite
3.) Lead compensation:	0 V	0.0002 V	rectangular 1.73	0.00001 V^{-1}	0.12	Infinite
4.) Null detector:	-3.5E-05 V	5.01E-08 V	rectangular 1.73	-0.001 V^{-1}	0.00	Infinite
5.) Abs. value of the input voltage:	1000 V	0.0064 V	rectangular 1.73	-3.5E-11 V^{-1}	0.00	Infinite
Type B standard uncertainty:					0.32	Infinite
Type A standard uncertainty:	0 V/V	9.09E-09	normal 1	1	0.01	9
$R_{1000/10}$	99.99965				$u(R)$=0.32	ν_{eff} = infinite

BEV

The travelling standard was compared with a Fluke 752A divider previously self-calibrated. The two dividers were powered in parallel, using a lead compensator. The output voltages of the dividers were connected to the "Sense" (the reference) and "Input" (the unknown) terminals of an HP 3458 DMM and the ratio function of this instrument was used. For the equation of the measurement see Appendix D, eq. (D12).

Table E21. BEV relative uncertainty budget for ratio 1000 V / 10 V

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$ / 10^{-6}	Probability distribution/ method of evaluation(A,B)	Sensitivity coefficient c_i	Uncertainty contribution $u_i(R)$ / 10^{-6}	Degrees of freedom ν_i
R_{div1}	100,00000	0,8	rectangular / B	1	0,46	infinite
Ratio DMM	1,0000045	0,8	rectangular / B	1	0,46	infinite
R_{loaded}	---	0,1	rectangular / B	1	0,06	infinite

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$ / 10^{-6}	Probability distribution/ method of evaluation(A,B)	Sensitivity coefficient c_i	Uncertainty contribution $u_i(R)$ / 10^{-6}	Degrees of freedom ν_i
R_{lead}	---	0,1	rectangular / B	1	0,06	infinite
$R_{leakage}$	---	0,1	rectangular / B	1	0,06	infinite
$R_{reproducibility}$	---	0,22	normal / A	1	0,22	3
$R_{1000/10}$	99,99955				$u(R)$ = 0,70	ν_{eff} = 301

OMH

The measurements were carried out by comparing the individual voltage drops at the divider's terminals. A Fluke calibrator and a Datron multifunction transfer standard were used.

Table E22. OMH relative uncertainty budget for ratio 1000 V / 10 V

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution / method of evaluation (A,B)	Sensitivity coefficient c_i	Standard uncertainty contribution $u_i(R)$ (ppm)	Degrees of freedom ν_i
Divider stability		0,2 10^{-6}	normal, B	1	0,2	100
Divider thermal voltage		$(0{,}1\cdot10^{-6}/°C)$x0,5°C	rectangular, B	1	0,05	infinite
Fluke 5700A calibration	1000 V	200 μV /1000V	normal, B	1	0,2	infinite
Fluke 5700A stability	1000 V	300 μV /1000V	normal, B	1	0,3	100
Fluke 5700A thermal voltage	1000 V	$(0{,}2\cdot10^{-6}/°C)$x0,5°C	rectangular, B	1	0,1	infinite
Datron 4950 calibration	10 V	2 μV/10V	normal, B	1	0,2	infinite
Datron 4950 calibration	100 V	20 μV/100V	normal, B	1	0,2	infinite
Datron 4950 stability	10 V	2 μV/10V	normal, B	1	0,2	100
Datron 4950 stability	100 V	20 μV/100V	normal, B	1	0,2	100
Datron 4950 thermal voltage	10 V	$(0{,}2\cdot10^{-6}/°C)$x0,5°C	rectangular, B	1	0,1	infinite
Datron 4950 thermal voltage	100 V	$(0{,}2\cdot10^{-6}/°C)$x0,5°C	rectangular, B	1	0,1	infinite
Datron 4950 zero drift	10 V	1 μV/10V	rectangular, B	1	0,1	infinite
Datron 4950 zero drift	100 V	10 μV/100V	rectangular, B	1	0,1	infinite
Datron 4950 offset voltage	10 V	1 μV/10V	rectangular, B	1	0,1	infinite
Datron 4950 offset voltage	100 V	10 μV/100V	rectangular, B	1	0,1	infinite
Datron 4950 volt measurement /average std./	10 V		normal, A	1	0,12	5

Quantity X_i	Estimate x_i	Standard uncertainty $u(x_i)$	Probability distribution / method of evaluation (A,B)	Sensitivity coefficient c_i	Standard uncertainty contribution $u_i(R)$ (ppm)	Degrees of freedom ν_i
Datron 4950 volt measurement /average std./	100 V		normal, A	1	0,14	5
Standard deviation 1000 V/10 V ratio			normal, A	1	0,28	5
$\boldsymbol{R}_{1000/10}$	99,999542				$u(R)$ = 0,72	ν_{eff} =182

EIM

The travelling standard was compared with a Fluke 752A reference divider using a substitution method. For the equations of the measurement and the meaning of symbols see Appendix D, eq (D13).

Table E23. EIM absolute uncertainty budget for ratio 1000 V / 10 V

Quantity X_i	Estimate x_i	Standard Uncertainty $u(x_i)$	Probability distribution / method of evaluation (A,B)	Sensitivity Coefficient c_i	Standard Uncertainty Contribution $u_i(y)$	Degrees of freedom ν_i
Null Detector Resolution for the RD N_{1R}	0 V	0,006 uV	Rectangular/B	$1x10^{-5}$ $(uV)^{-1}$	6 $x10^{-8}$	∞
Null Detector Accuracy N_{1AC} for the RD	0 V	0,01 uV	Rectangular/B	$1x10^{-5}$ $(uV)^{-1}$	1 $x10^{-7}$	∞
Measurements Mean V_{1NULL}	$8,8x10^{-3}$ uV	0,07 uV	Normal/A	$1x10^{-5}$ $(uV)^{-1}$	7 $x10^{-7}$	56
Null Detector Resolution for the DUT N_{2R}	0 V	0,58 uV	Rectangular/B	$-1x10^{-5}$ $(uV)^{-1}$	-5,8 $x10^{-6}$	∞
Null Detector Accuracy N_{2AC} for the RD	0 V	0,58 uV	Rectangular/B	$-1x10^{-5}$ $(uV)^{-1}$	-5,8 $x10^{-6}$	∞
Measurements Mean V_{2NULL}	-51,035 uV	0,13 uV	Normal/A	$-1x10^{-5}$ $(uV)^{-1}$	-1,3 $x10^{-6}$	56
Zener Temperature Correction Z_T	0 V	0,2 uV	Rectangular/B	$-1x10^{-11}$ $(uV)^{-1}$	-1 $x10^{-11}$	∞
Zener Calibration Certificate V_Z	9,99993335 V	0,18 uV	Normal/A	$-1x10^{-11}$ $(uV)^{-1}$	-1 $x10^{-11}$	57
RD Accuracy R_{AC}	$5x10^{-6}$	$2,9x10^{-6}$	Rectangular/B	1	2,9 $x10^{-6}$	∞
$\boldsymbol{R}_{1000/10}$	100,0005104				$u(R)$ =$8,8x10^{-6}$	ν_{eff} =∞

Appendix F
Optional measurements

F1) Ratio 300 V / 10 V
F2) Ratio 30 V / 10 V
F3) Ratio 10 V / 0.1 V
F4) Ratio 10 V / 1 V

F1) Ratio 300 V / 10 V

F1.1) Behaviour of the standard from the measurements of the pilot laboratory

The measurements of the pilot laboratory, corrected to standard ambient conditions, are given in Appendix A, Table A3. They are shown graphically in Fig. F1.1, where also the interpolations corresponding to the coefficients of Table 2, for the three groups of data (see paragraph 4), are shown.

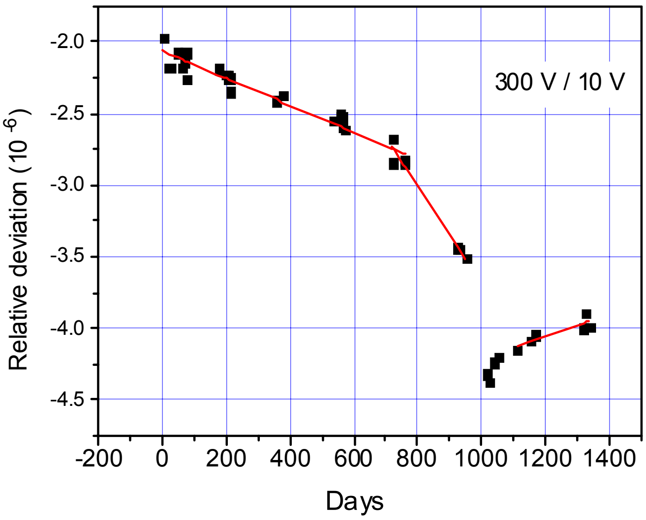


Fig. F1.1. Pilot results for ratio 300 V / 10 V, corrected to standard ambient conditions. The time origin is on 1 July 1998.

F1.2) Participant results and differences from pilot laboratory

Corrections ε to the participant results, for deviation from standard ambient conditions, and corresponding additional uncertainties $u(\varepsilon)$ are calculated by using the coefficients reported in Table 2 for ratio 300 V / 10 V and for the specified group of data, A, B or C. No correction ζ is applied for collective heating, but an additional uncertainty, limited by $\pm 0.1 \cdot 10^{-6}$, is added to all laboratories except IEN, CEM, SP and SMD (see paragraph 6.a). In the table the uncertainties δT and δH are given as half width of a rectangular distribution.

Table F1.1. Ratio 300 V / 10 V: temperature and humidity corrections

Lab	Date	T (°C)	δT (°C)	H (%)	δH (%)	$\varepsilon\,(T, H)$ (10^{-6})	$u(\varepsilon)$ (10^{-6})	$u(\zeta)$ (10^{-6})
INETI	25/11/98	23	1	36	12	0.018	0.017	0.058
CEM	17/02/99	21.7	0.5	30	5	0.033	0.022	0
PTB	16/03/99	23	1	40	15	0.010	0.018	0.058
LCIE	05/05/99	22.8	0.2	45	5	0.000	0.006	0.058
CMI	11/09/99	23	0.5	52	5	-0.014	0.010	0.058
SP	29/11/99	23	0.3	41	4	0.008	0.006	0
SMU	30/03/00	23	0.5	35	5	0.020	0.012	0.058
NMi-VSL	03/05/00	22.2	0.5	41.7	3.5	0.008	0.010	0.058
SMD	20/10/00	23	1	45	10	0.000	0.012	0
BEV	17/10/01	23	0.5	45	10	0.000	0.012	0.058

Lab	Date	T (°C)	δT (°C)	H (%)	δH (%)	$\varepsilon\,(T, H)$ (10^{-6})	$u(\varepsilon)$ (10^{-6})	$u(\zeta)$ (10^{-6})
IEN	-	23.1	0.5	42.5	5	0	0.006	0

In Table F1.1, for IEN the mean values of temperature and humidity for all measurements are reported. As all IEN interpolations are already referred to standard ambient conditions, no further correction ε is needed.

Table F1.2 reports the differences Δ_L of the corrected laboratory results, d_{0L}, with respect to the interpolated values of the pilot laboratory, $d_{0,P}$, and the participant global standard uncertainties $u_{G,L}$. The meaning of the symbols is the same as in Tables 5 and 10. The coefficients of the interpolations and the values of s are those reported in Table 2. For IEN, s in group A has been divided by $\sqrt{n}$, where n = 23 is the number of data in such group.

Table F1.2. Ratio 300 V / 10 V: results of the laboratories and differences from pilot laboratory

Lab	t (d)	d_L (10^{-6})	$d_{0,L}$ (10^{-6})	$d_{0,P}$ (10^{-6})	Δ_L (10^{-6})	u_A (10^{-6})	u_B (10^{-6})	$u(\varepsilon)$ (10^{-6})	$u(\zeta)$ (10^{-6})	s (10^{-6})	$u_{G,L}$ (10^{-6})
INETI	147	-0.08	-0.098	-2.202	2.104	0.13	1.3	0.017	0.058	0.068	1.310
CEM	231	-2.200	-2.233	-2.281	0.048	0.12	0.39	0.022	0	0.068	0.414
PTB	258	-2.46	-2.470	-2.307	-0.163	0	0.19	0.018	0.058	0.068	0.211
LCIE	308	-2.5	-2.500	-2.354	-0.147	0	0.17	0.006	0.058	0.068	0.192
CMI	437	-3.1	-3.086	-2.475	-0.611	0.014	1.6	0.010	0.058	0.068	1.603
SP	516	-2.45	-2.458	-2.549	0.091	0.02	0.16	0.006	0	0.068	0.175
SMU	638	-8.1	-8.120	-2.664	-5.456	0.02	1.2	0.012	0.058	0.068	1.204
NMi-VSL	672	-2.7	-2.708	-2.696	-0.013	0.222	1.292	0.010	0.058	0.068	1.314
SMD	842	-3.11	-3.110	-3.146	0.036	0.404	0.512	0.012	0	0.056	0.655
BEV	1204	-4.1	-4.100	-4.374	0.274	0.32	0.66	0.012	0.058	0.056	0.738
IEN	-	-	-	-	0	0.073	0.105	0.006	0	0.014	0.129

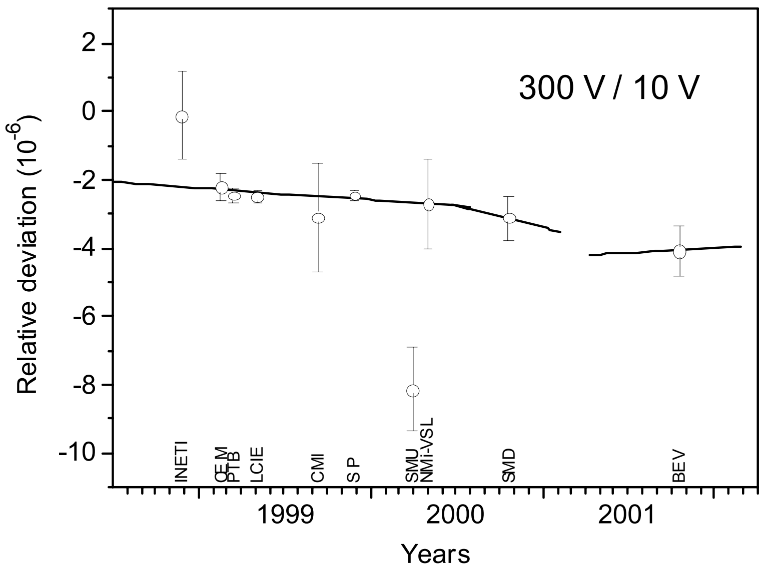


Fig. F1.2. Ratio 300 V / 10 V: laboratory results, $d_{0,L}$, corresponding global standard uncertainties, $u_{G,L}$, and linear interpolations of IEN results. All data are at standard ambient conditions.

Fig. F1.2 shows a plot of the laboratory results corrected to standard ambient conditions, with corresponding global standard uncertainties, compared with the linear fits of the corrected IEN measurements.

Table F1.3 reports the degrees of freedom associated with the participant results, ν_{LAB}, those of the other uncertainty contributions given in the previous table and the effective degrees of freedom ν_{eff} associated with $u_{G,L}$, evaluated by means of eq. (8).

Table F1.3. Ratio 300 V / 10 V: degrees of freedom

Lab	ν_{LAB}	ν_{ε}	ν_{ζ}	ν_{s}	ν_{eff}
INETI	inf.	2	2	19	> 1000
CEM	20	2	2	19	21
PTB	15	2	2	19	21
LCIE	1698	2	2	19	189
CMI	inf.	2	2	19	> 1000
SP	500	2	2	19	379
SMU	inf.	2	2	19	> 1000
NMi-VSL	130	2	2	19	131
SMD	225	2	2	5	227
BEV	55	2	2	5	56
IEN	79	2	2	19	81

F1.3) Reference value

Because the Birge ratio is high (R_B = 1.57), the MAD criterion (see paragraph 8.b) will be applied to find results that are not members of the statistical distribution of the other results The data for this check are reported in Table F1.4.

Table F1.4. Ratio 300 V / 10 V: identification of the members of the distribution

Δ_{med} =	0.000
$median\{\lvert \Delta_L - \Delta_{med} \rvert\}$ =	0.147
$S(MAD)$ =	0.218
2.5 $S(MAD)$ =	0.545

Applying eq. (5) to the Δ_L values in Table F1.2, it is found that INETI, SMU and CMI do not belong to the distribution. Because the Birge ratio of the remaining participants is lower than one (R_B = 0.47), their weighted mean will be used as the KCRV. In practice weighted and arithmetic mean are nearly identical, but the number of degrees of freedom is higher for the weighted mean. The KCRV is given by:

$$\Delta_{R,300} = -0.025 \cdot 10^{-6}$$

$$u(\Delta_{R,300}) = \sqrt{\frac{1}{\sum_{L=1}^{n} \frac{1}{u_{G,L}^2}}} = 0.081 \cdot 10^{-6} \qquad \text{(F1.1)}$$

$$\nu_{\Delta_{R,300}} = 227$$

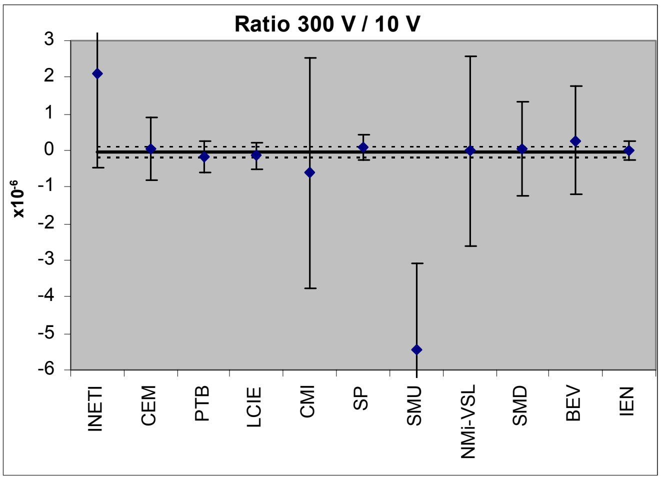
For calculation of $\nu_{\Delta_{R,300}}$ by means of eq. (8), the effective degrees of freedom of the laboratories and the equation of $u(\Delta_{R,300})$ have been used.

F1.4) Evaluation of compatibility

Fig. F1.3 shows the participant results Δ_L compared with the reference value $\Delta_{R,300}$. Close to the graph, a table reports, for each laboratory, the compatibility index I_C . This index is given by:

$$I_C = \frac{\Delta_L - \Delta_{R,300}}{U(\Delta_L - \Delta_{R,300})} \qquad \text{(F1.2)}$$

where $U(\Delta_L - \Delta_{R,300})$ is the expanded uncertainty (95% confidence level) of the difference between the value of the laboratory and the reference value. This uncertainty is evaluated by taking into account both the correlation of the reference value with the laboratories contributing to its determination and the degrees of freedom[3]. If correlation was not taken into account, the values of I_C would be lower by as much as 50 % for the laboratories having the lowest uncertainties (IEN, SP, LCIE and PTB). If the degrees of freedom were not taken into account, I_C values would be higher by no more than 9%.



Ic	
INETI	0.83
CEM	0.09
PTB	-0.33
LCIE	-0.35
CMI	-0.19
SP	0.38
SMU	-2.30
NMi-VSL	0.00
SMD	0.05
BEV	0.20
IEN	0.12

Fig. F1.3. Normalised laboratory results Δ_L, with uncertainty $U_{G,L}$, compared with the reference value. Horizontal lines show the reference value and its uncertainty. All uncertainties are at 95% confidence level.

[3] See Note 2 in paragraph 9.c) of the main report about inaccuracies in the use of eq (8) (Welch-Satterthwaite) when the uncertainties to be combined are correlated, as in the present case.

F2) Ratio 30 V / 10 V

F2.1) Behaviour of the standard from the measurements of the pilot laboratory

The measurements of the pilot laboratory, corrected to standard ambient conditions, are given in Appendix A, Table A2. They are shown graphically in Fig. F2.1, where also the interpolations corresponding to the coefficients of Table 2 are shown.

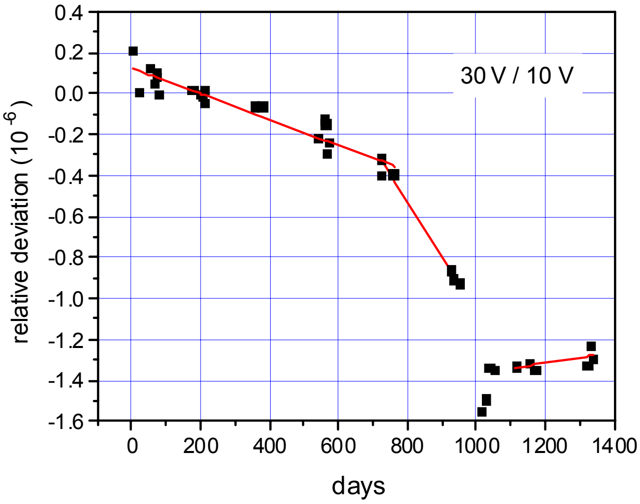


Fig. F2.1. Pilot results for ratio 30 V / 10 V, corrected to standard ambient conditions. The time origin is on 1 July 1998.

F2.2) Participant Results and differences from pilot laboratory

Corrections ε to the participant results for deviations from standard ambient conditions and corresponding standard uncertainties $u(\varepsilon)$ are reported in Table F2.1 (see paragraph F1.2 for more explanations). No correction ζ for collective heating effect is needed for this ratio (see paragraph 6.a).

Table F2.1. Ratio 30 V / 10 V: temperature and humidity corrections

Lab	Date	T (°C)	δT (°C)	H (%)	δH (%)	$\varepsilon\,(T, H)$ (10^{-6})	$u(\varepsilon)$ (10^{-6})
CEM	17/02/1999	21.7	0.5	30	5	0.037	0.022
PTB	16/03/1999	23	1	40	15	0.018	0.033
LCIE	05/05/1999	22.8	0.2	45	5	-0.003	0.011
CMI	11/09/1999	23	0.5	52	5	-0.025	0.013
SP	29/11/1999	23	0.3	41	4	0.014	0.010
SMU	30/03/2000	23	0.5	35	5	0.036	0.015
NMi-VSL	03/05/2000	22.2	0.5	41.7	3.5	0.001	0.011
SMD	20/10/2000	23	1	45	10	0.000	0.022
BEV	17/10/2001	23	0.5	45	10	0.000	0.021
IEN	-	23.1	0.5	42.4	5	-	0.011

Table F2.2 reports the participant results corrected to standard ambient conditions, $d_{0,L}$, their differences Δ_L with respect to the interpolated pilot result, $d_{0,P}$, and the participant global standard uncertainties $u_{G,L}$ (see par. F1.2 for more explanations).

Table F2.2. Ratio 30 V / 10 V: results of the laboratories and differences from pilot laboratory

Lab	t (d)	d_L (10^{-6})	$d_{0,L}$ (10^{-6})	$d_{0,P}$ (10^{-6})	Δ_L (10^{-6})	u_A (10^{-6})	u_B (10^{-6})	$u(\varepsilon)$ (10^{-6})	s (10^{-6})	$u_{G,L}$ (10^{-6})
CEM	231	0.0600	0.023	-0.022	0.045	0.03	0.28	0.022	0.058	0.288
PTB	258	0.029	0.011	-0.039	0.050	0	0.13	0.033	0.058	0.146
LCIE	308	-0.4	-0.397	-0.070	-0.327	0	0.12	0.011	0.058	0.134
CMI	437	-0.9	-0.875	-0.151	-0.723	0.014	2.6	0.013	0.058	2.601
SP	516	-0.11	-0.124	-0.201	0.077	0.01	0.08	0.010	0.058	0.100
SMU	638	-0.3	-0.336	-0.278	-0.058	0.02	1.2	0.015	0.058	1.202
NMi-VSL	672	-0.23	-0.231	-0.299	0.068	0.066	0.189	0.011	0.058	0.209
SMD	842	-0.487	-0.487	-0.406	-0.081	0.17	0.235	0.022	0.058	0.297
BEV	1204	-1.2	-1.200	-1.412	0.212	0.25	0.55	0.021	0.037	0.606
IEN	-	-	-	-	0	0.039	0.111	0.011	0.012	0.119

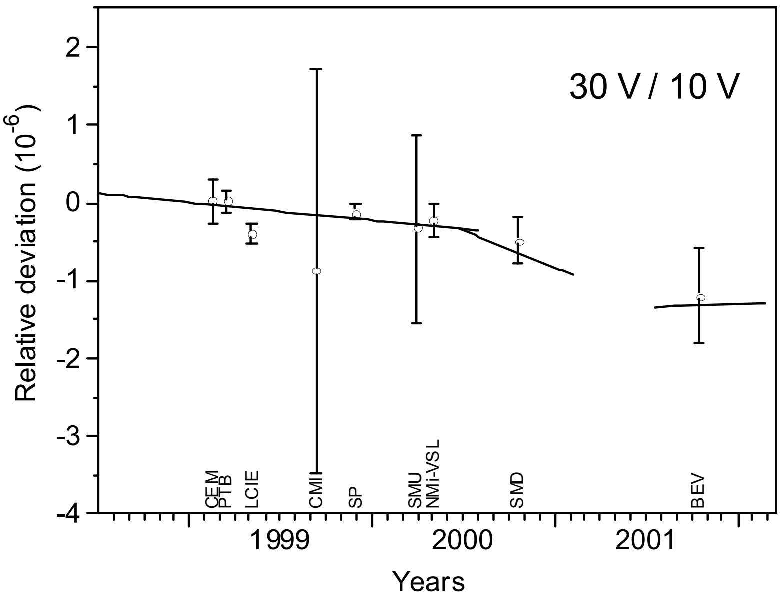


Fig. F2.2. Ratio 30 V / 10 V: laboratory results, $d_{0,L}$, corresponding global standard uncertainties, $u_{G,L}$, and linear interpolations of IEN results. All data are at standard ambient conditions.

Fig. F2.2 shows a plot of the laboratory results corrected to standard ambient conditions, with corresponding global standard uncertainties, compared with the linear fits of the corrected IEN measurements.

Table F2.3 reports the degrees of freedom associated with the participant results, ν_{LAB}, those of the other uncertainty contributions given in the previous table and the effective degrees of freedom ν_{eff} associated with $u_{G,L}$, evaluated by means of eq. (8).

Table F2.3. Ratio 30 V / 10 V: degrees of freedom

Lab	ν_{LAB}	ν_{ε}	ν_{S}	ν_{eff}
CEM	11	2	19	12
PTB	20	2	19	29
LCIE	847	2	19	377
CMI	inf.	2	19	> 1000
SP	500	2	19	144
SMU	inf.	2	19	> 1000
NMi-VSL	140	2	19	157
SMD	3858	2	19	> 1000
BEV	35	2	5	35
IEN	421	2	19	428

F2.3) Reference value

Since the Birge ratio is close to 1 (R_B = 0.87), the reference value will be given by the weighted mean of all results.

$$\Delta_{R,30} = -0.021 \cdot 10^{-6}$$

$$u(\Delta_{R,30}) = \sqrt{\frac{1}{\sum_{L=1}^{n} \frac{1}{u_{G,L}^2}}} = 0.056 \cdot 10^{-6} \qquad \text{(F2.1)}$$

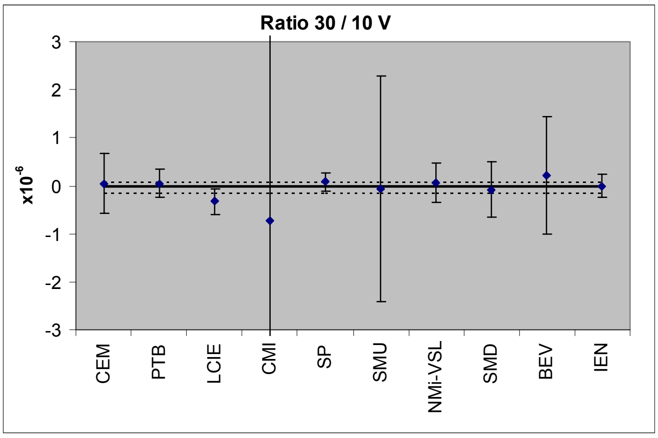
$$\nu_{\Delta_{R,30}} = 643$$

For the calculation of $\nu_{\Delta_{R,30}}$ by means of eq. (8), the effective degrees of freedom of the laboratories and the equation of $u(\Delta_{R,30})$ have been used.

F2.4) Evaluation of compatibility

Fig. F2.3 shows the participant results Δ_L compared with the reference value $\Delta_{R,30}$ of eq. (F2.1). Close to the graph, a table gives for each laboratory the compatibility index I_C, evaluated by means of eq. (F1.2). The calculations have taken correlation with the reference value and degrees of freedom into account[4]. If correlation was disregarded, the values of I_C would be lower by as much

[4] See Note 2 in paragraph 9.c) of the main report about inaccuracies in the use of eq (8) (Welch-Satterthwaite) when the uncertainties to be combined are correlated, as in the present case.



Ic	
CEM	0.11
PTB	0.25
LCIE	-1.28
CMI	-0.14
SP	0.59
SMU	-0.02
NMi-VSL	0.22
SMD	-0.10
BEV	0.19
IEN	0.10

Fig. F2.3. Normalised laboratory results Δ_L , with uncertainty $U_{G,L}$, compared with the reference value. Horizontal lines show the reference value and its uncertainty. All uncertainties are at 95% confidence level.

as 40 % for the laboratories having the lowest uncertainties (SP, IEN, LCIE and PTB). If the degrees of freedom were not taken into account, I_C values would be higher by no more than 12.5%.

F3) Ratio 10 V / 0.1 V

F3.1) Behaviour of the standard from the measurements of the pilot laboratory

The measurements of the pilot laboratory for low voltage ratios are obtained from those at rated voltage and standard ambient conditions by applying the power correction evaluated in par. 6.b) and reported in Table 3. The corrected results are given in Appendix A, Table A4. The behaviour of the standard is shown in Fig. F3.1.

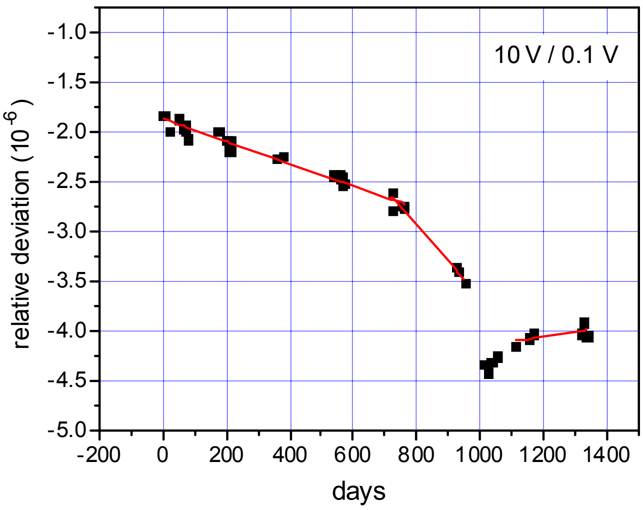


Fig. F3.1. Pilot results for ratio 10 V / 0.1 V, corrected to standard ambient conditions. The time origin is on 1 July 1998.

F3.2) Participant Results and differences from pilot laboratory

Corrections ε to the participant results for deviations from standard ambient conditions and corresponding standard uncertainties $u(\varepsilon)$ are reported in Table F3.1. Except for DFM, who did not measure the mandatory ratios, they are practically identical to those already given in Table 4 for ratio 1000 V / 10 V, because temperature and humidity are the same.

Table F3.1. Ratio 10 V / 0.1 V: temperature and humidity corrections

Lab	Date	T (°C)	δT (°C)	H (%)	δH (%)	$\varepsilon(T, H)$ (10^{-6})	$u(\varepsilon)$ (10^{-6})
NPL	27/10/1998	20	0.5	55	5	-0.125	0.031
LCIE	05/05/1999	22.8	0.2	45	5	-0.007	0.006
DFM	30/05/1999	23	0.5	45	5	0.000	0.011
CMI	11/09/1999	23	0.5	52	5	-0.009	0.013
MIKES	02/11/1999	23	0.3	45	5	0.000	0.007
NMi-VSL	03/05/2000	22.2	0.5	41.7	3.5	-0.026	0.014
SIQ	16/12/2000	22.5	0.5	52	10	-0.028	0.016
IEN	-	23.1	0.5	42.5	5	-	0.012

Table F3.2 reports the participant results corrected to standard ambient conditions, $d_{0,L}$, their difference Δ_L with respect to the interpolated pilot result, $d_{0,P}$, and the associated global standard uncertainty $u_{G,L}$ (see paragraph F1.2 for more explanations). The interpolated values of the pilot laboratory are the same values, $d_{0,P}$, already given in Table 5, decreased by η (Table 3) to correct for power effect.

Table F3.2. Ratio 10 V / 0.1 V. Results of the laboratories and differences from pilot laboratory

Lab	t (d)	d_L (10^{-6})	$d_{0,L}$ (10^{-6})	$d_{0,P}$ (10^{-6})	Δ_L (10^{-6})	u_A (10^{-6})	u_B (10^{-6})	$u(\varepsilon)$ (10^{-6})	s (10^{-6})	$u_{G,L}$ (10^{-6})
NPL	118	-2.57	-2.445	-2.007	-0.438	0.1	0.3	0.031	0.061	0.324
LCIE	308	-1.9	-1.893	-2.218	0.325	0	0.31	0.006	0.061	0.316
DFM	333	-3.08	-3.080	-2.246	-0.834	0	0.22	0.011	0.061	0.229
CMI	437	-2.9	-2.891	-2.361	-0.530	1.5	3.5	0.013	0.061	3.808
MIKES	489	-2.79	-2.790	-2.419	-0.371	0.06	0.02	0.007	0.061	0.088
NMi-VSL	672	-3.53	-3.474	-2.622	-0.852	0.5	3.622	0.014	0.061	3.657
SIQ	899	-3.4	-3.372	-3.290	-0.082	0.03	0.42	0.016	0.068	0.427
IEN	-	-	-	-	0	0.074	0.132	0.012	0.013	0.152

Fig. F3.2 shows a plot of the laboratory results corrected to standard ambient conditions, with corresponding global standard uncertainties, compared with the linear fits of the corrected IEN measurements.

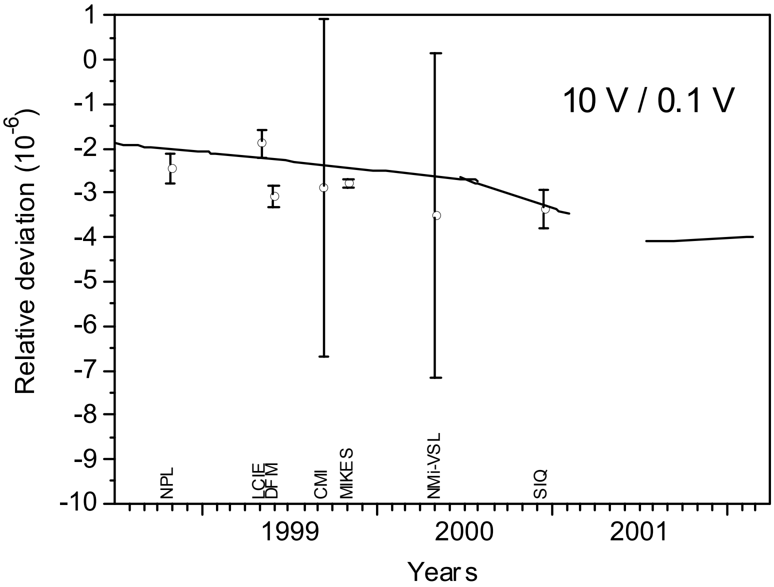


Fig. F3.2. Ratio 10 V / 0.1 V: laboratory results, $d_{0,L}$, corresponding global standard uncertainties, $u_{G,L}$, and linear interpolations of IEN results. All data are at standard ambient conditions.

Table F3.3 reports the degrees of freedom associated with the participant results, ν_{LAB}, those of the other uncertainty contributions given in the previous table and the effective degrees of freedom ν_{eff} associated with $u_{G,L}$, evaluated by means of eq. (8).

Table F3.3. Ratio 10 V / 0.1 V: degrees of freedom

Lab	ν_{LAB}	ν_{ε}	ν_{S}	ν_{eff}
NPL	500	2	19	516
LCIE	164	2	19	174
DFM	101	2	19	114
CMI	206	2	19	206
MIKES	21	2	19	40
NMi-VSL	340	2	19	340
SIQ	inf.	2	5	7651
IEN	43	2	19	44

F3.3) Reference value

In this case the Birge ratio is higher than 1 (R_B= 1.43) but the usual MAD criterion shows that no laboratory can be discarded. The data for application of MAD criterion are given in Table F3.4.

Table F3.4. Ratio 10 V / 0.1 V: identification of the members of the distribution

Δ_{med} =	-0.405
$median\{\lvert \Delta_L - \Delta_{med} \rvert\}$ =	0.364
$S(MAD)$ =	0.539
2.5 $S(MAD)$ =	1.348

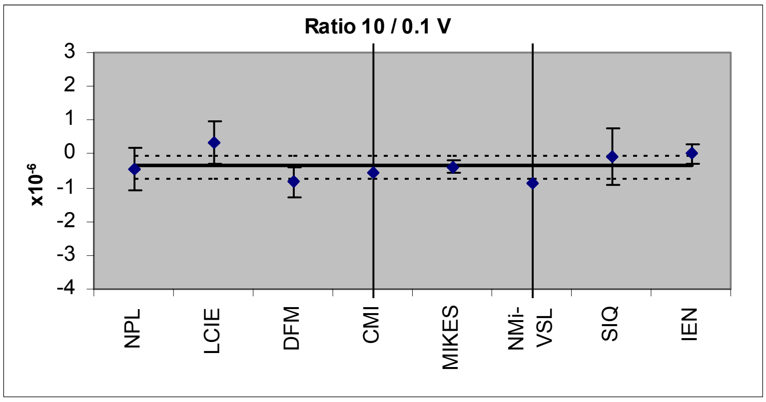
The reference value will be assessed as the arithmetic mean of the results of the 8 laboratories participating in this measurement. The calculations give:

$$\Delta_{R,10/0.1} = -0.352 \cdot 10^{-6}$$
$$u(\Delta_{R,10/0.1}) = S(\Delta_L - \Delta_{R,10/0.1})/\sqrt{8} = 0.147 \cdot 10^{-6} \qquad \text{(F3.1)}$$
$$\nu_{\Delta_{R,10/0.1}} = 7$$

where S represents the standard deviation.

F3.4) Evaluation of compatibility

Fig. F3.3 shows the participant results Δ_L compared with the reference value $\Delta_{R,10/0.1}$ of eq. (F3.1). Close to the graph, a table gives for each laboratory the compatibility index I_C, from eq. (F1.2). The calculations have taken correlation and degrees of freedom into account. Disregarding correlation would produce an underestimation of I_C not higher than 16%; disregarding the degrees of freedom, would produce an overestimation of I_C not higher than 13%.



Ic	
NPL	-0.14
LCIE	1.10
DFM	-0.97
CMI	-0.03
MIKES	-0.05
NMi-VSL	-0.09
SIQ	0.34
IEN	0.85

Fig. F3.3. Normalised laboratory results Δ_L , with uncertainties $U_{G,L}$, compared with the reference value. Horizontal lines show the reference value and its uncertainty. All uncertainties are at 95% confidence level.

F4) Ratio 10 V / 1 V

F4.1) Behaviour of the standard from the measurements of the pilot laboratory

The results of the pilot laboratory for low voltage measurements are obtained from those at rated voltage by applying the power correction evaluated in paragraph 6.b) and reported in Table 3. The corrected results are given in Appendix A, Table A4. The behaviour in time is shown in Fig. F4.1, which is very similar to Fig. 1b) of the main report.

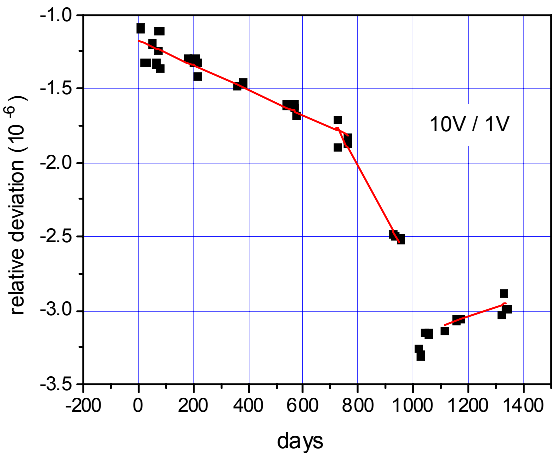


Fig. F4.1. Pilot results for ratio 10 V / 1 V, corrected to standard ambient conditions. The time origin is on 1 July 1998.

F4.2) Participant Results and differences from pilot laboratory

Table F4.1 reports, for each participant, the correction ε for deviation from standard ambient conditions with corresponding uncertainty $u(\varepsilon)$. Except for DFM, who did not measure the mandatory ratios, these values are identical to those already given in Table 9 for ratio 100 V / 10 V, because temperature and humidity are the same.

Table F4.1. Ratio 10 V / 1 V: temperature and humidity corrections

Lab	Date	T (°C)	δT (°C)	H (%)	δH (%)	$\varepsilon\,(T, H)$ (10^{-6})	$u(\varepsilon)$ (10^{-6})
NPL	27/10/1998	20	0.5	55	5	0.029	0.037
LCIE	05/05/1999	22.8	0.2	45	5	0.004	0.010
DFM	30/05/1999	23	0.5	45	5	0.000	0.012
CMI	11/09/1999	23	0.5	52	5	-0.024	0.014
MIKES	02/11/1999	23	0.3	45	5	0.000	0.010
NMi-VSL	03/05/2000	22.2	0.5	41.7	3.5	0.028	0.013
SIQ	16/12/2000	22.5	0.5	52	10	-0.013	0.023
IEN	-	23.1	0.5	42.4	5	-	0.012

Table F4.2 reports the participant results corrected to standard ambient conditions, $d_{0,L}$, their differences Δ_L with respect to the interpolated pilot result, $d_{0,P}$, and the participant global standard uncertainties $u_{G,L}$ (see paragraph F1.2 for more explanations). The interpolated values of the pilot laboratory are the same values, $d_{0,P,}$ already given in Table 10, decreased by η (Table 3) to correct for power effect

Table F4.2. Ratio 10 V / 1 V. Results of the laboratories and differences from pilot laboratory

Lab	t (d)	d_L (10^{-6})	$d_{0,L}$ (10^{-6})	$d_{0,P}$ (10^{-6})	Δ_L (10^{-6})	u_A (10^{-6})	u_B (10^{-6})	$u(\varepsilon)$ (10^{-6})	s (10^{-6})	$u_{G,L}$ (10^{-6})
NPL	118	-1.56	-1.589	-1.272	-0.317	0.07	0.2	0.037	0.073	0.227
LCIE	308	-1.5	-1.504	-1.432	-0.072	0	0.12	0.010	0.073	0.141
DFM	333	-1.43	-1.430	-1.453	0.023	0	0.11	0.012	0.073	0.133
CMI	437	-2.1	-2.076	-1.540	-0.536	0.15	0.68	0.014	0.073	0.700
MIKES	489	-1.68	-1.680	-1.584	-0.096	0.008	0.02	0.010	0.073	0.077
NMi-VSL	672	-1.56	-1.628	-1.737	0.109	0.12	0.74	0.013	0.073	0.753
SIQ	899	-2.7	-2.687	-2.364	-0.323	0.01	0.18	0.023	0.069	0.194
IEN	-	-	-	-	0	0.069	0.122	0.012	0.015	0.141

Fig. F4.2 shows a plot of the laboratory results corrected to standard ambient conditions, with corresponding global standard uncertainties, compared with the linear fits of the corrected IEN measurements.

Table F4.3 reports the degrees of freedom associated with the participant results, ν_{LAB}, those of the other uncertainty contributions given in the previous table and the effective degrees of freedom ν_{eff} associated with $u_{G,L}$, evaluated by means of eq. (8).

Table F4.3. Ratio 10 V / 0.1 V: degrees of freedom

Lab	ν_{LAB}	ν_{ε}	ν_s	ν_{eff}
NPL	168	2	19	184
LCIE	897	2	19	227
DFM	101	2	19	104
CMI	2400	2	19	2417
MIKES	inf.	2	19	23
NMi-VSL	230	2	19	234
SIQ	inf.	2	5	305
IEN	43	2	19	44

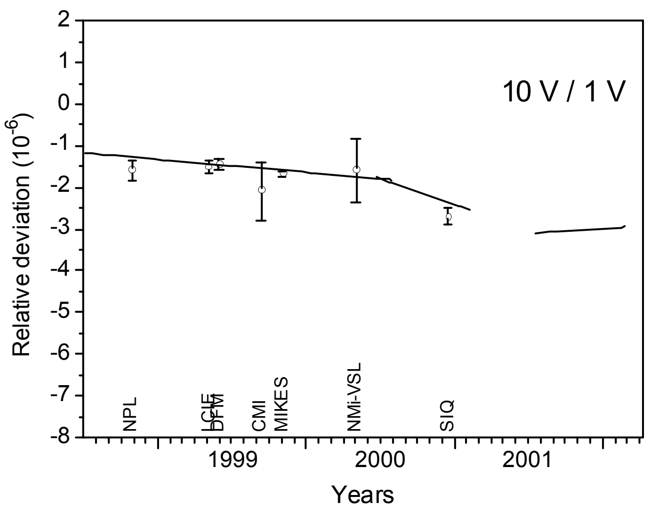


Fig. F4.2. Ratio 10 V / 1 V: laboratory results, $d_{0,L}$, corrected to standard ambient conditions, corresponding global standard uncertainties, $u_{G,L}$, and linear interpolations of IEN results.

F4.3) Reference value

Since the Birge ratio is lower than 1 (R_B= 0.76) the weighted mean of all results is chosen to calculate the KCRV. The calculations give:

$$\Delta_{R,10/1} = -0.091 \cdot 10^{-6}$$

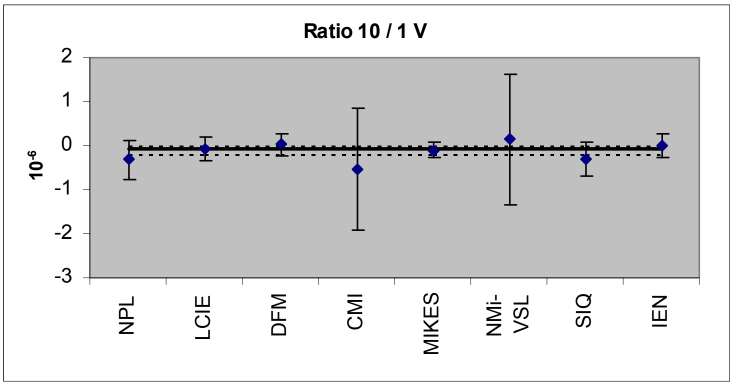
$$u(\Delta_{R,10/1}) = \sqrt{\frac{1}{\sum_{L=1}^{n} \frac{1}{u_{G,L}^{2}}}} = 0.052 \cdot 10^{-6} \qquad \text{(F4.1)}$$

$$\nu_{\Delta_{R,10/1}} = 104$$

For calculation of $\nu_{\Delta_{R,10/1}}$ by means of eq. (8), the effective degrees of freedom of the laboratories and the equation of $u(\Delta_{R,10/1})$ have been used.

F4.4) Evaluation of compatibility

Fig. F4.2 shows the participant results Δ_L compared with the reference value $\Delta_{R,10/1}$ of eq. (F4.1). Close to the graph, a table gives for each laboratory the compatibility index I_C, from eq. (F1.2). The calculations have taken correlation and degrees of freedom into account[5]. Disregarding correlation would produce an underestimation of I_C that is highest (63%) for MIKES, who has the lowest uncertainty; disregarding the degrees of freedom, would produce an overestimation of I_C not higher than 25%, which again applies to MIKES.



Ic	
NPL	-0.52
LCIE	0.07
DFM	0.47
CMI	-0.33
MIKES	-0.04
NMi-VSL	0.16
SIQ	-0.63
IEN	0.34

Fig. F4.2. Normalised laboratory results Δ_L , with uncertainties $U_{G,L}$, compared with the reference value. Horizontal lines show the reference value and its uncertainty. All uncertainties are at 95% confidence level.

[5] See Note 2 in paragraph 9.c) of the main report about inaccuracies in the use of eq (8) (Welch-Satterthwaite) when the uncertainties to be combined are correlated, as in the present case.

APPENDIX G

Changes of the participant results

Changes before the release of the Draft A report

INETI

In the uncertainty budget of INETI, the divider ratio was written as lower than 1 (output/input), and this interpretation of the ratio was confirmed by the fact that, dividing the resulting absolute uncertainty by this value, it was possible to obtain the relative uncertainty reported in the table of results. On the contrary in this table, whose model was provided by the pilot laboratory ("Summary of result" form), the ratio was interpreted as larger than 1, as requested by the protocol. After checking the measurement report, INETI answered that all deviations from nominal (ratios 1000 V / 10 V, 100 V / 10 V, 300 V / 10 V) had to be changed in sign and provided a new report. The uncertainties remained the same.

UME

Also UME had reported uncertainty budgets with ratio values lower than 1, contrary to the requested interpretation of the ratio, and the contact person was asked by the pilot laboratory to check the results. UME answered that not only the sign of the ratios (1000 V / 10 V and 100 V / 10 V) had to be changed, but also the values. Asked about the reason for changing the values, UME answered that they had applied corrections for ambient conditions. Indeed, following the comparison protocol, those corrections had to be applied by the pilot laboratory, so that UME was . invited to consider the problem again, but they maintained their position and the pilot had to use the new values. The global uncertainties remained the same.

SMU

In case of SMU, being the results far from those of the other participants, the contact person was invited to make a check. The answer was that all the results (1000 V / 10 V, 100 V / 10 V, 300 V / 10 V, 30 V / 10 V) had to be changed in sign. SMU explained that the Slovak written standard describes the inverted ratio and this was probably the cause of the mistake. The uncertainties remained the same.

EIM

Also in this case the pilot laboratory asked for a check, due to the large discrepancies with respect to the results of the other laboratories. After some time, by checking the EIM report better, the pilot found that the scheme of the circuit did not agree with the interpretation of the sign in the measurement equation. As a consequence he asked more precisely EIM for checking the sign of the results with respect to the scheme of the measurement circuit. EIM reported corrected equations and asked for changing the sign of their results.

Changes after the release of the Draft A report

NMi-VSL

After the release of Draft A, NMi-VSL informed that the values given for their type B uncertainty components were the maximum uncertainty limits and not the standard uncertainties. They asked to reduce these components by dividing them by $\sqrt{3}$. Under request of the pilot laboratory, the participants approved. As a consequence, also the degrees of freedom of NMi-VSL were slightly modified. The change does not affect the situation of NMi-VSL concerning compliance with the reference values of the comparison.

JV

After the release of Draft A, JV reported that they had improved their uncertainty budget by taking humidity effects into account. They requested to change their submitted type B uncertainty accordingly. They pointed out that the same request was presented to the pilot before the release of Draft A, but the pilot did not make the change. Under request of the pilot, the participants approved the change. The increase of the JV type B global uncertainty (from $0.1\cdot10^{-6}$ to $0.14\cdot10^{-6}$ for ratio 1000 V / 10 V and from $0.026\cdot10^{-6}$ to $0.033\cdot10^{-6}$ for ratio 100 V / 10 V) has no influence on the compliance of JV with the reference values.

OMH

After the release of Draft A, OMH found that their calculation of the degrees of freedom was wrong and submitted new degrees of freedom for both mandatory ratios. Under request of the pilot, the participants approved this change, which resulted in an increase of the degrees of freedom of OMH. Also in this case the compliance of OMH with the reference values was not affected.

APPENDIX H

Comparison protocol and schedule

H1) Technical Protocol

EUROMET.EM-K8: COMPARISON OF DC VOLTAGE RATIO

(18 September 1998 - Final edition)

Purpose, participation and schedule

At its 21st meeting the Consultative Committee on Electricity identified a set of key international comparisons to serve as the basis for agreement between national metrology institutes (NMI) for the equivalence of national measurement standards. Specifically a comparison of DC voltage ratio was proposed in order to test the capabilities of the NMIs in scaling up voltage from 10 V to 100 V and 1000 V. This comparison was identified as CCEM 97-2.

A similar comparison has been proposed at the European level during the Euromet Electricity Contact Person Meeting held in October 1997 at the CEM in Spain. This comparison, identified as Euromet Project 449, will be linked up with the CCEM comparison.

The Istituto Elettrotecnico Nazionale (IEN, Italy) has agreed to act as the pilot laboratory and co-ordinator for both comparisons and 14 laboratories have agreed to participate in the Euromet comparison. The agreed schedule of the Euromet comparison is reported in Annex A. The list of the participant laboratories, the addresses of their contact persons and those for dispatching the travelling standard are reported in Annex B.

In this comparison we intend to follow the Euromet guidance document no. 3 "Guidelines for the organisation of comparisons" and the BIPM "Guidelines for key comparisons carried out by Consultative Committees". The present protocol is consistent with those documents.

Travelling standard and uncertainty requirement

The travelling standard is a Datron 4902S voltage divider (s/n 12422). It has dimensions 132x433x327 mm and a weight of 5 kg. This instrument can divide the maximum input voltage of 1000 V in multiples of 10 V, up to 100 V, and in multiples of 100 V up to 900 V. Adjustment trimmers are provided on the instrument, but they will be sealed. We do not intend to adjust the trimmers during the comparison.

The ratios to be measured are

- 1000 V / 10 V
- 100 V / 10 V

and, optionally

- 300 V / 10 V
- 30 V / 10 V
- 10 V / 1 V (at the 100 V / 10 V terminals of the divider)
- 10 V / 0.1 V (at the 1000 V / 10 V terminals of the divider)

The goal of the comparison is to achieve, for the ratios 1000 V / 10 V and 100 V / 10 V, a relative standard uncertainty (combined type A and type B) of $5 \cdot 10^{-7}$ or less at k= 1 coverage factor.

Preliminary characterisation work on the travelling standard has shown that, at this accuracy level, its temperature and humidity coefficients are not negligible, while drift in time and transport effects, if the standard is handled with care, are very low. The results of the characterization of the twin unit, used in the CCEM 97-2 comparison, were presented at the Conference CPEM '98 and given also to the laboratories participating in the Euromet comparison.

The circulation of travelling standard

The circulation has been organised in loops of no more than four laboratories in order to allow close monitoring of the behaviour of the standard. Each laboratory will have three weeks to carry out the measurements and is expected to ship or to carry the standard to the next scheduled laboratory allowing less than one week for travel.

The laboratory's results should be sent to IEN within 30 days from the end of its measurements. If unforeseen circumstances prevent a laboratory from carrying out its measurements within the time allotted, it should send the divider without delay to the laboratory next in line. If time allow, the laboratory will be able to carry out measurements at a later time.

A very solid enclosure, fitted with a thermo-hygrometer, is provided for the divider so that it can be shipped as freight. This enclosure has dimensions 60x70x35 cm and a weight of about 22 kg, including the divider. Extreme temperatures or pressure changes as well as violent impacts should be avoided. After arrival the divider should be allowed to stabilise in a temperature and, possibly, humidity controlled room at least three days before use. With the divider, a copy of its instruction manual, the final edition of this technical protocol, 1 receiving and 2 shipping forms, 1 receiving and 1 shipping checklist forms, a summary-of-results form and a protective plexiglass plate for measurements on the 100 V sections (see the following) will also be sent. Each arrival and departure of the standard must be communicated to the pilot laboratory using the forms provided; a form is also given to notify the laboratory next in line of the shipment of the standard. While shipping the standard, the shipping checklist should be carefully followed in order to include all the material for the next laboratory. Annex C should help the participant laboratory in following the right sequence of operations.

In case of damage or evident malfunctioning of the divider, the laboratory will report immediately to the pilot laboratory, who will give specific instructions. If the damage can not be repaired the comparison will be carried on using a backup unit.

The divider will normally be accompanied by an ATA carnet for non European-Union countries. As usual each participant laboratory is responsible for its own costs for the measurements, transportation and any customs charges as well as any damage that may occur within its country.

Conditions and methods of measurement

The required and the optional ratios should be measured at the corresponding voltage terminals of the divider, except for the 10 V / 1 V and 10 V / 0.1 V ratios, which will be measured at the 100 V / 10 V and 1000 V / 10 V terminals respectively. All ratios should be measured at the nominal powers corresponding to the voltage ratio being measured.

The standard ambient condition for measurements is

temperature:	(23 ± 0.5) °C
relative humidity:	45% ± 5%

Room temperatures of (20 ± 0,5) °C or of (25± 0,5) °C may also be used, while relative humidity should never exceed 70%. Corrections for deviations of temperature and humidity from the above standard condition will be applied by the pilot laboratory, which will also add the corresponding contribution to the uncertainty.

Any method can be used for calibrating the ratios. In particular the following techniques have been mentioned by the participant laboratories:

- comparison with a reference divider;
- comparison of the individual resistive sections;
- comparison of the individual voltage drops at the divider terminals;
- measurement with respect to a Josephson array (for low voltages).

Of course the calibration method must be reported. To allow enough time for the divider to stabilise following the application of each value of voltage, waiting times of 5 and 10 minutes respectively should be used when measuring the ratios 100 V / 10 V and 1000 V / 100 V. Measurement methods that correct for residual drifts are also suggested. When measuring on 100 V sections, the given plexiglass plate preventing accidental access to the 10 V sections should be used.

At the beginning of the comparison the pilot laboratory will regulate some of the trimmers of the divider so that its ratios do not deviate too much from their nominal value. These trimmers will then be covered by a tape and must not be touched in any way during the comparison.

Measurement uncertainty

All contributions to the uncertainty budget should be listed in the report submitted by each participant. The uncertainty calculation should be carried out according to the ISO "Guide to the expression of uncertainty in measurement" for a coverage factor k=1. The number of degrees of freedom should be reported.

Even though some contributions to the uncertainty are specific to each method of measurement, it may be useful to consider the following list to try to assure more comparable uncertainty evaluations. In the following list not all contributions apply to all methods:

1) reference divider
2) detector calibration
3) uncompensated voltage offset
4) poor lead compensation
5) stability of source or reference voltages
6) leakage resistance
7) heating effects
8) reproducibility

The pilot laboratory will evaluate contributions to the uncertainty from temperature and humidity, due both to their instability and to the corrections for reducing the results to the standard condition. The effect of pressure on the divider has been estimated negligible. The effect of leakage in the divider should be negligible if the guard circuit of the instrument is used.

Measurement reports of the laboratories

Within 30 days after finishing the measurements a report should be sent to the pilot laboratory. An early report helps in evaluating the behaviour of the travelling standard. A summary-of-results form is given in order to help summarising the essential information: it should be included in the report. In case of unforeseen difficulties, a preliminary and simplified report should be sent within 30 days to the pilot laboratory, while a conclusive report, which supersedes the previous one, should be sent within 60 days. The report should contain:

- an explanation of the method;
- the conditions of the measurement: values of temperature, humidity, pressure, with their limits of variation;
- the results;
- the associated standard uncertainties (k = 1);
- the number of degrees of freedom;
- the detailed uncertainty budget.

Final report of the comparison

The process which will lead to the preparation of the final report of the comparison is explained in the Euromet guidance document no. 3. In short it is reported here.

After the conclusion of the circulation of the travelling standard the pilot laboratory will prepare a report and will send it to the participants. This draft will be confidential. The draft will be prepared within 4 months from the end of the measurements.

The participants will have two months to send their comments on the draft report. If a laboratory's result is anomalous, it can decide, at this stage, to withdraw its result or, if an explanation is found, can correct it. A laboratory may eventually request to make a second measurement of the travelling standard, but this will not hold up the final report.

On the basis of the comments received and within three months the pilot laboratory prepares the second draft, where the withdrawn results will not appear or, in case of correction, the original and the corrected results, with the given explanation, will be reported. This draft will be submitted to the Euromet Electricity Contact Person Meeting and will become the Final Report. The Final Report will form the basis for publication of the results.

Co-ordinator and communications

The person responsible for the pilot laboratory and his whereabouts are:

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Communication by e-mail is most welcome. All incoming messages will be immediately acknowledged so that communication problems can be identified and corrected.

Giancarlo Marullo Reedtz

Enclosed: Annex A: Proposed schedule
Annex B: List of participants
Annex C: Timing

Forms provided: 1 receive and 2 shipping forms
Summary-of-results form
1 receiving and 1 shipping checklist forms

Timing

At reception of the divider	Check the material against the receiving-the-standard checklist form. Fill in the receiving-the-standard form and send to the pilot as soon as possible. Leave the divider in the measurement laboratory for at least 3 days.
Before the end of week three	Make the measurements. Contact the laboratory next in line about the coming shipment.
Beginning of week four	Prepare the package for shipment using the shipping-the-standard checklist form. Transport or ship the divider to the laboratory next in line (shipping address in Annex B, right column). Fill in the two shipping-the-standard forms and send them to the pilot and the laboratory as soon as possible.
Next 30 days	Prepare the measurement report and send to the pilot

H2) Original Schedule

Period	Laboratory	Country
October **1998**	**NPL**	**UK**
November	**INETI**	**Portugal**
December	**Pilot - Italy**	
January **1999**	**Pilot - Italy**	
February	**CEM**	**Spain**
March	**PTB**	**Germany**
April	**BNM-LCIE**	**France**
May	**DFM**	**Denmark**
June	**Pilot - Italy**	
July	**Pilot - Italy**	
August	**OFMET**	**Switzerland**
September	**CMI**	**Czech Republic**
October	**VTT**	**Finland**
November	**SP**	**Sweden**
December	**Pilot - Italy**	
January **2000**	**Pilot - Italy**	
February	**UME**	**Turkey**
March	**SMU**	**Slovakia**
April	**NMi-VSL**	**The Netherlands**
May	**BEV**	**Austria**
June	**Pilot - Italy**	

H3) Final Schedule

(Here the final planned periods of measurement are given.
For effective dates of measurement see Table 1 in the main report)

Period	Laboratory	Country
October **1998**	**NPL**	**United Kingdom**
November	**INETI**	**Portugal**
December	**Pilot - Italy**	
January **1999**	**Pilot - Italy**	
February	**CEM**	**Spain**
March	**PTB**	**Germany**
April	**LCIE**	**France**
May	**DFM**	**Denmark**
June	**Pilot - Italy**	
July	**Pilot - Italy**	
August	**METAS**	**Switzerland**
September	**CMI**	**Czech Republic**
October	**MIKES**	**Finland**
November	**SP**	**Sweden**
December	**Pilot - Italy**	
January **2000**	**Pilot - Italy**	
February	**UME**	**Turkey**
March	**SMU**	**Slovakia**
April	**NMi-VSL**	**The Netherlands**
May	**Pilot - Italy**	
June	**Pilot - Italy**	
July	**Pilot - Italy**	
August	**Pilot – Italy**	
September	**JV**	**Norway**
October	**SMD**	**Belgium**
November	**SIQ**	**Slovenia**
December	**Pilot - Italy**	
January **2001**	**Pilot - Italy**	
September	**BEV**	**Austria**
October	**OMH**	**Hungary**
November	**EIM**	**Greece**
December	**Pilot - Italy**	

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