EUROMET Comparison of AC Electric Field Strength

EUROMET.EM-S6

Final report

by

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Summary:

A comparison of the low-frequency electric field strength in the range from 1 V/m to 20 kV/m at frequencies of 16 ⅔ Hz, 50 Hz, 60 Hz and 400 Hz is reported, carried out within the scope of EUROMET. Eight partners from seven European countries were involved in the comparison; the PTB in Berlin acted as the pilot laboratory. Tasks, organization, course, measuring equipment and results of the comparison are described. The measuring tasks were divided into two parts: the main task at 50 Hz line frequency, obligatory for all participants, and the supplementary tasks which could be carried out on a voluntary basis. The report on hand presents and evaluates the results achieved by the participants in the main task. The results of the supplementary tasks will be reported separately.

Zusammenfassung:

Berichtet wird über einen im Rahmen von EUROMET ausgeführten Vergleich der niederfrequenten elektrischen Feldstärke im Bereich von 1 V/m bis 20 kV/m bei Frequenzen von 16 ⅔ Hz, 50 Hz, 60 Hz und 400 Hz, an dem 8 Partner aus 7 europäischen Ländern beteiligt waren. Die Physikalisch-Technische Bundesanstalt in Berlin wirkte als Pilotlabor. Aufgaben, Organisation, Ablauf, Messeinrichtungen und Resultate werden beschrieben. Die Messaufgaben unterteilten sich in eine für alle Teilnehmer verbindliche Hauptaufgabe bei der Netzfrequenz 50 Hz und freiwillige Zusatzaufgaben. Die von den Teilnehmern erzielten Messergebnisse für die Hauptaufgabe werden im vorliegenden Bericht dargestellt und ausgewertet. Über die Ergebnisse der Zusatzaufgaben wird gesondert berichtet werden.

Participating Institutes and Co-authors

Germany	IST	Ingenieurbüro Symann Trebbau GbR, EMV Meßsysteme, Lippstadt Andreas Trebbau
Italy	IEN	Istituto Elettrotecnico Nazionale "Galileo Ferraris", Torino Gabriella Crotti
Poland	GUM	Główny Urząd Miar, Warszawa Wiesław Widłaszewski
	AGH	Akademia Górniczo-Hutnicza, Kraków Barbara Florkowska
Spain	CEM	Centro Español de Metrología, Madrid Agustín Falcón, Guillermo Maté
The Netherlands	NMI VSL	Nederlands Meetinstituut - NMI Van Swinden Laboratorium B.V., Delft George M. Teunisse
United Kingdom	NGC	The National Grid Company, Leatherhead Nigel J. Wilkinson, David Renew
Russia	VNIIFTRI	National Scientific and Research Institute for Physical Technical and Radiotechnical Measurement, (Всероссийский научно-исследовательский институт физико-технических и радиотехнических измерений) Mendeleevo Vladimir A. Tisčenko

1 Objective of the comparison

Growing requirements in the measurement of electric fields, for example for the protection of labour and for health purposes, make a better calibration of E-field meters necessary. To ensure the European conformity of such calibrations, an intercomparison of the electric field strength was proposed using an E-field meter as a travelling standard. After an inquiry conducted by PTB in 1996 and after agreement on the Working Program had been reached, nine participants from seven European countries were left who wished to take part in the comparison. The travelling standard had to be calibrated against known fields used by the participants, e.g. fields corresponding to IEC publication 833, in the range from E = 1 V/m to E = 20000 V/m at defined frequencies between $f = 16\ ^{2}/_{3}$ Hz and f = 400 Hz. A relative uncertainty of measurement of u = 1 % (1σ) or better was aimed at. The task to be carried out comprised a main part, which had to be performed by all participants, and a supplementary part, which could be performed on a voluntary basis.

2 Organization of the Comparison

2.1 Travelling standard

The LF-E-field measuring device EM 100 (manufacturer: IST Symann Trebbau GbR, Lippstadt, Germany) was chosen as the transfer standard and made available for the comparison free of charge by the manufacturer. It consisted of an E-field probe E 52 with two optical cable links, a display unit with microprocessor, a cable for connection to a PC, and a charger for the batteries of the probe and the unit (figure 1). The sensor element of the E-field probe E 52 was a plate capacitor of spherical shape. The displacement current between the two hemispheres was determined as a measure of the electric field strength. The technical data of EM 100 shown in figure 1 are given in Table 1.

Table 1: Technical data of the travelling standard

Parameter	Value
1. Dynamic range	(0,001 ... 20) kV/m
2. Measuring ranges	(0,2; 2; 20) kV/m
3. Resolution	0,05 % of the measuring range
4. Frequency range for a measuring deviation of - 3 dB	(0,005 ... 4) kHz
5. Basic error U_{ts} under reference conditions at a frequency of 50 Hz	±1 % at the temperature (23±3) °C
Maximum of operating time	8 h

A manual "Specifications and Operating Instructions" was sent together with the travelling standard, including a short guide how to handle this transfer device to avoid severe errors during the intercomparison measurements.

Figure 1: Travelling standard EM 100

2.2 Scope of the comparison and measurement report

At the recommendation of the EUROMET contact persons meeting in the field of electricity held in 1995, PTB had asked European national metrology institutes to participate in a comparison of low-frequency electric field strength. Interest was shown by CEM, IEN, NMI VSL, and NPL represented by NGC. Following their advice, PTB worked out a proposal for a project to be carried out within the framework of the SMT program of the EUROPEAN Commission. Further participants were the GUM, the VNIIFTRI, IST (a private German enterprise which made available the transfer standard) and the Federal Institute for Industrial Safety and Occupational Medicine (Bundesanstalt für Arbeitsschutz und Arbeitsmedizin BAFAM, now BAAM), which did not, however, finish the comparison.

Agreement on the proposal was reached in the period between 09/96 and 11/96, and the proposal was submitted to the Commission in November 1996. After it had not been accepted in March 1997 a Working Program for an EUROMET project not funded by the Commission was proposed to the participants and accepted by them. Taking into account the last comments of the participants, a Revised Working Program dated June 1997 was drawn up. The comparison started immediately; its course is shown in table 2.

In the Revised Working Program, code numbers were assigned to the participating laboratories following the preceding proposal for the SMT program. In the present report, these numbers have not been used. The order of the laboratories has been chosen according to the time schedule of the measurements.

Table 2: Time schedule of the measurements

No.	Measure-ments at	started	finished	1997				1998			
				Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
1	PTB	01.02.97	22.04.97								
2	IST	26.04.97	23.06.97								
3	PTB	26.06.97	30.06.97								
4	BAFAM	30.06.97	14.07.97								
5	PTB	14.07.97	15.08.97								
6	NGC	18.08.97	06.10.97								
7	CEM	09.10.97	21.11.97								
8	PTB	24.11.97	17.12.97								
9	NMI	19.12.97	05.02.98								
10	IEN	10.02.98	17.03.98								
11	PTB	19.03.98	01.04.98								
12	GUM	08.04.98	26.05.98								
13	PTB	02.06.98	15.06.98								
14	VNIIFTRI	14.07.98	10.08.98								
15	PTB	14.08.98	03.11.98								

All participants, except BAFAM, had sent their measurement reports to PTB, some of them immediately after the measurements had been completed, others before the end of December 1998. Despite this the final report of PTB has been much delayed, unfortunately. Both scientists engaged in the project had to leave the PTB at this time, and although they continued their work as pensioners' activities, the usual time frame of EUROMET projects could not be adhered to for some reason or other.

After agreement of the Draft A and Draft B reports by the participants, Draft B was approved By the Working Group for Key Comparisons (WGKC) at the BIPM in September 2002.

2.3 Task

According to the agreed program the main task was to calibrate a transfer device in order to compare the primary standards of electric field strength of the participants. Defined amounts of electric field strength and frequency were to be measured with a relative 1σ uncertainty of not more than 1 % or less, if possible. In table 3 the measurement points of the main task have been marked with the letter "M", those of an additional supplementary task (to be carried out if there was any interest on the part of the participants) have been marked with the letter "S".

Furthermore that area of the calibration field was to be determined in which the amount of E was nearby constant (with deviations from homogeneity smaller than 1 %). The influence of the stands accompanying the meter was to be determined.

The measurements of each partner had to follow the Revised Working Program of June 16, 1997 and the other instructions given.

Table 3: Agreed measurement points

Field strength	Frequency in Hz							
in V/m	16 ⅔	50	60	400	1000	2000	5000	10000
1	S	S	S	S				
2	S	S	S	S				
5	S	S	S	S				
10	S	S	S	S				
20	S	S	S	S				
50	S	S	S	S				
100	S	M	S	S				
200	S	M	S	S	S	S	S	S
500	S	M	S	S				
1000	S	M	S	S				
2000	S	M	S	S				
5000	S	M	S	S				
10000	S	M	S	S				
20000	S	M	S	S				

The main task and the supplementary tasks had to be performed under the following reference conditions:
- temperature (23 ± 3) °C
- relative humidity (50 ± 10) %

In compliance with the time schedule, the PTB had to carry out an initial calibration, intermediate calibrations and the final calibration. Besides, PTB had to draw up the final report about the results of the comparison.

2.4 Final report

In order to ensure a uniform presentation of the measurement results (measurement value and associated uncertainty for each calibration point) achieved by the nine laboratories participating in the comparison a measurement report had to be prepared by each participant, which had to include:

- a short description of the measurement system and measurement method used for calibration;
- the measurement conditions, i.e. temperature and relative humidity values during the calibration and any other relevant environmental data (e.g. distances to walls, bottom and ceiling);
- information about the repeatability of measurements (in particular if measurements were repeated on different days);
- the calibration table including, for each calibration point, the measurement values and the uncertainties of the applied quantity and of the corresponding readings of the electric field meter;
- the results for the measurements achieved using the "thread fixed probe" (positioning the probe by means of filaments in the centre of the field) and those achieved using the stand of the probe, delivered with the field meter, to position it in the centre of the field. Later in this report the respective results will be indicated as K_F (K_{Filament}) and K_S (K_{Stand}).
- a brief description of the uncertainty budget, specifying the method applied in the evaluation of each uncertainty component (type A or type B). The components of the measurement uncertainties had to be evaluated according to the ISO "Guide to the Expression of Uncertainty in Measurement" [1].

2.5 Calibration of the travelling standard by the pilot laboratory

2.5.1 Field Generation

A standard field was generated by means of a horizontal plate system according to IEC 833 [2, 3]. The dimensions of the plates, 10,15 mm thick, were 1,5 m x 1,5 m, with a spacing of 0,7502 m between them. A symmetrical voltage in the range from 0.75 V to 30 kV (15 kV + 15 kV) was to be applied to the plates by means of two inversely supplied measuring transformers, thus producing field strengths in the range from 1 V/m to 40 kV/m.

The driving voltage was produced in two different ways. For the measurements carried out in 1997 and in early 1998, the voltage of motor driven generators of different frequencies was fed to the anti-parallel connected low-voltage windings of the two high-voltage measuring transformers. Their high-voltage outputs were connected to the plates and measured either by means of two electrostatic voltmeters or, more precisely, via two measuring transformers by means of a DMM. The block diagram is shown in figure 2.

From 1998 on, the driving voltage could be produced by a computer-controlled commercial function generator and fed by means of a special power amplifier to the low-voltage windings of the measuring transformers connected antiparallel. The sum of the two high voltages applied to the plates could be measured by a resistive divider feeding the input of a digital voltmeter which was connected to the PC by an IEEE interface. For high accuracies the resistive divider was calibrated with the aid of two precision voltage measuring transformers. A block diagram of this electronic generator is shown in figure 3, a view in figure 4, including the measuring field probe carried by the three-dimensional computer-controlled positioning system described below.

To reduce the influence of small non-sinusoidal effects on the field generation, the low-voltage windings of the supplying measuring transformers were fed by the above-mentioned motor-driven generators of higher power, resulting in a low crest factor and a smaller total distortion. In this mode the device worked without PC control.

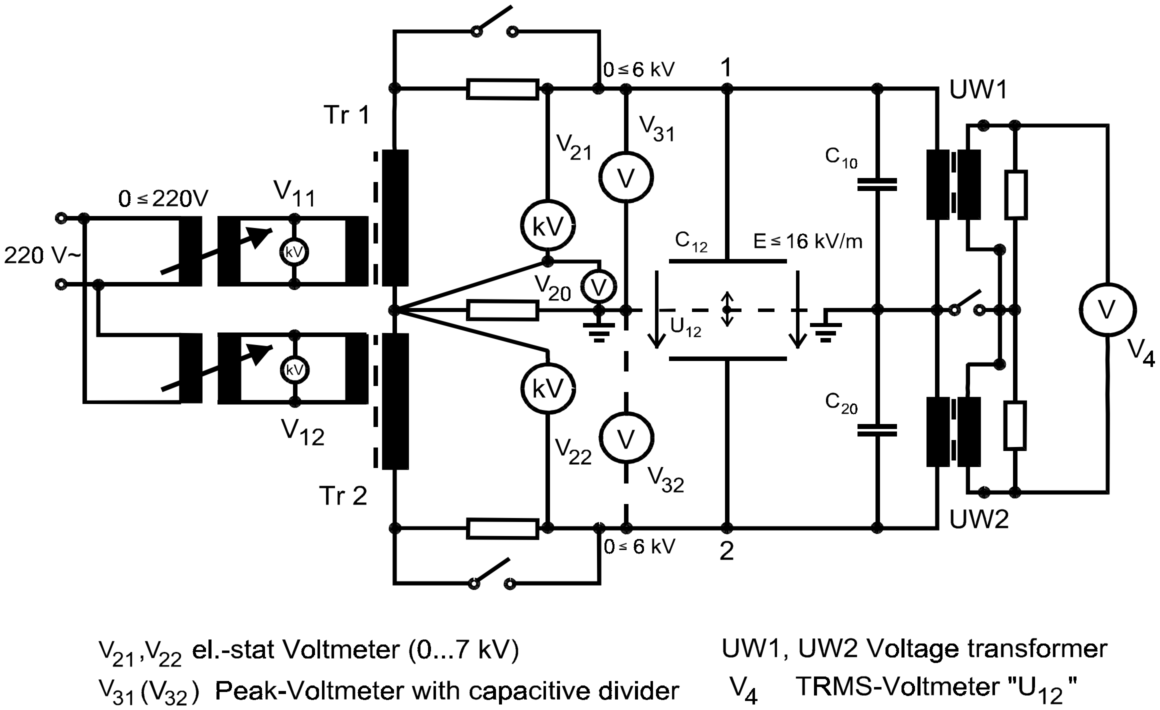

Figure 2: Motor-driven standard field device

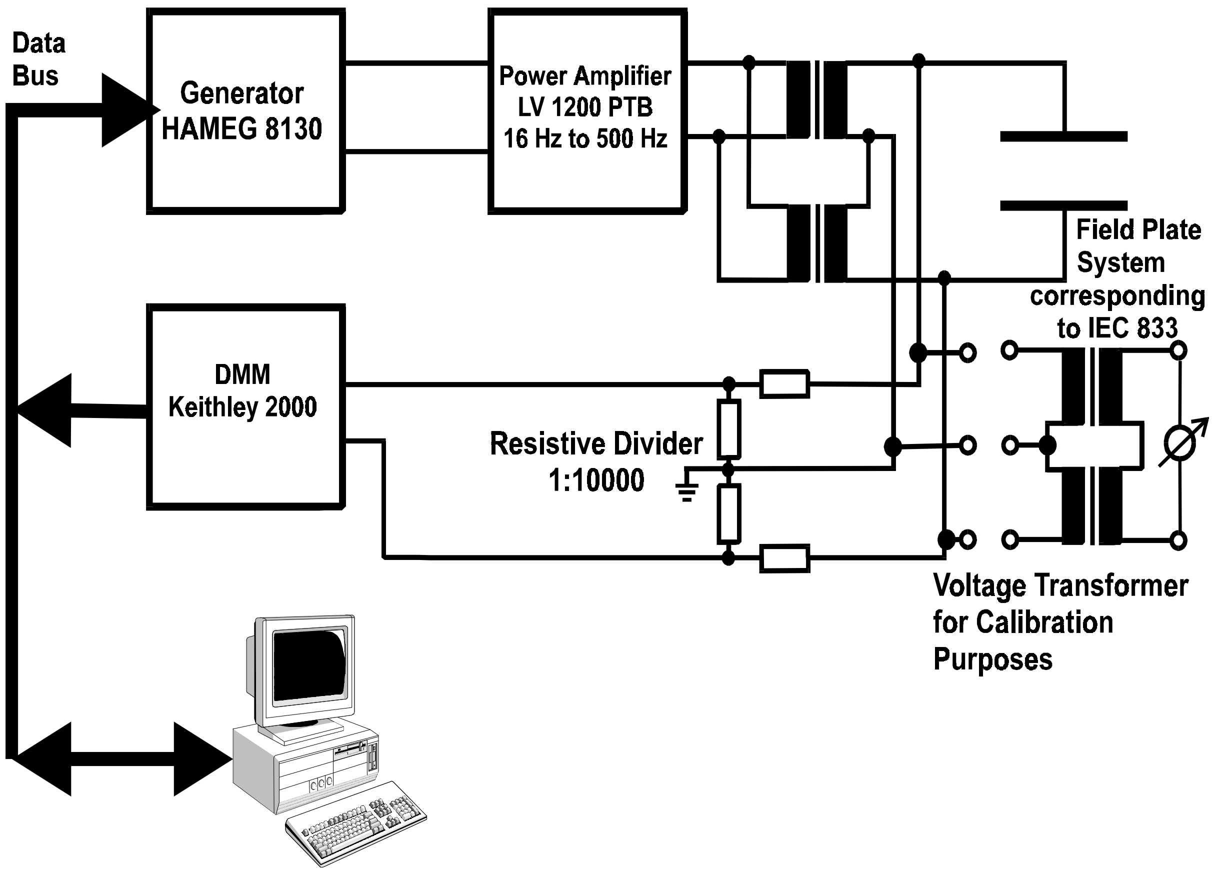

Figure 3: Computer-controlled standard field device

2.5.2 Field measuring device

The field distribution inside the plate system (and outside as well) can be investigated by a three-dimensional positioning system carrying the E-field probe: It made displacements in all three directions in steps of 1 mm possible, which were calibrated by means of a laser interferometer. The system was driven by a second control and data logging PC.

The moduli of the field strength at the respective positions are to be measured with the probe of an E-field meter. Through a glass fibre cable the data are transmitted to the main instrument and sent to the PC. An Excel program allows the scanned field distribution, which is certainly influenced by the material and the dimensions of the probe and the carrier, to be graphically reproduced.

The later-mentioned factor γ which characterizes the field distortion caused by the probe of the field meter can be determined with this device (see 3.1).

Figure 4: Field generating and measuring device
- computer-controlled HV generator in a movable rack (under the window)
- three stable axes of the positioning system in the foreground
- low dielectric carrier with the probe on its end, moved by the different axes
- plate system held by special low-dielectric tubes

The distance of the plane midway between the plates and the floor is about 1,3 m, and it is about 1,5 m between this plane and the ceiling. The space between the edges of the plates and the walls and to the 3D-system is more than 0,8 m.

For the measurements carried out in the comparison the probe of the E field meter was fixed in the centre of the plate system by means of filaments (thread-fixed probe) and by means of the stand delivered with the meter, as well, according to the respective task.

2.5.3 Measurement uncertainty of the standard device

The main type B contributions to the relative measurement uncertainty of the standard field generating and measuring device are composed of the uncertainty with which the undisturbed field distribution is calculated, the uncertainty by which the measurement of the plate distance is affected, the non-uniformity of the plates, the uncertainty with which the applied voltage, including its phase angle, is measured, and the uncertainty caused by the influence of the measuring probe on the charge distribution on the plates.

The expanded relative uncertainty for k = 2 resulting from these contributions is calculated in section 3.1.2 and adds up to U = 0,26 % for the generation of the standard field.

2.6 Calibration of the travelling standard by the participants

2.6.1 Symann Trebbau GbR (IST)

In the range from 1 V/m to 200 V/m, a horizontal plate system 1 m x 1 m in size with the plates spaced 0,5 m apart, was used by IST. In the range 200 V/m to 20 kV/m the calibration was carried out with current injection in compliance with IEC 833 [2]. The current injected was the displacement current which, at the appropriate field strength, flows between the two sensor faces of the probe. The currents to be injected were determined by forming the ratio of the displacement currents to the current flowing in the plate arrangement at E = 200 V/m. For this reason, in the upper ranges could be determined, neither the influence of the stand accompanying the meter nor the field region in which the amount of E was nearby constant (deviating by less than 1 %). The calibration conditions and results are described in the calibration report [8].

2.6.2 The National Grid Company (NGC)

The main elements of the calibration apparatus available at NGC were the parallel horizontal plate rig, two transformers and a high-voltage control unit. To enable electric fields to be generated in the range between 1 V/m to 110 kV/m, without the amplitude stability and the total harmonic distortion of the voltage supplied to each plate being affected, two transformers were required; one was to be used to generate electric fields between 1 V/m and 10 kV/m, the second to generate fields above 10 kV/m. Each of the main elements of the calibration apparatus is described in the report of NGC [8], two photos are added.

2.6.3 Centro Español de Metrología (CEM)

The equipment used at CEM to measure the travelling standard consisted of two aluminium square plates forming a horizontal parallel-plate structure according to the IEC 833 standard. The plate spacing was scaled to 0,5 m for better uniformity. Measurement results were reported also for other plate spacings (0,75 m and 1 m), required to measure the stands accompanying the meter. The plates were energized by a Fluke 5700 A calibrator and a centre-tapped transformer. The applied potential difference was measured with an hp 34401A DMM through two voltage dividers made by Ross Engineering, ratio 1000/1. A more detailed description can be found in the report of CEM [8].

2.6.4 NMI Van Swinden Laboratorium B.V. (NMI VSL)

For the generation of the required fields, NMI VSL used a parallel plate facility consisting of vertically installed square plates 1,5 m x 1,5 m in size, with the plates spaced 0,75 m apart. This facility had been specially designed for this kind of calibrations. In addition, measurements in a symmetrical 50 ohm TEM cell with horizontal septum and a septum height (distance between septum and bottom) of 0,75 m were carried out, focussing especially on the reproducibility of the high-frequency, lower-level results. Depending on the different field strengths and frequencies to be measured, three different kinds of electric circuitry were used. They have been described in the report of NMI VSL[8].

2.6.5 Istituto Elettrotecnico Nazionale "Galileo Ferraris" (IEN)

The IEN system for the generation of low-frequency reference electric fields [4] consisted of two horizontal square aluminium electrodes (electrode side l = 2 m; distance between the electrodes d_m = 1 m) and five equally spaced grading rings, which increase the uniformity of the field and reduce the perturbation of nearby conducting objects located at a distance greater than 1 m. Symmetrical voltages were applied to the electrodes and the rings by means of centrally tapped transformers, whose primary winding was connected to stabilized generators. The voltage applied to the electrodes was measured by a digital hp 3458 multimeter; for voltages higher than 500 V, a voltage measuring transformer had been included in the measurement chain. A photo is included in the report of IEN [8].

2.6.6 Główny Urząd Miar (GUM)

The measurements of GUM were carried out with the set-up of the Metallurgy and Mining Academy (Akademia Górniczo-Hutnicza, AGH) in Kraków. The system for the generation of reference electric fields was composed of two horizontal parallel square plates (1,5 m x 2,5 m). The distance between the plates was 0,75 m. The plates were supplied with voltages symmetrical with respect to ground, the source being an electronic power supply working with feedback. The supply voltage was measured by a digital voltmeter. The plate system did not include grading rings. The range of the electric fields from 100 V/m to 20 kV/m at the frequency 50 Hz was covered by the equipment. Two photos are shown in the report of GUM. The measurements were carried out only with stand [8].

2.6.7 National Scientific and Research Institute for Physical Technical and Radiotechnical Measurement (VNIIFTRI - Vserossiski Naučni Issledovatelski Institut Fisiko-Techničeskich i Radiotechničeskich Ismerenii)

The measurement system in the measuring range from 1 V/m to 200 V/m and for the frequency range from 16,66 Hz to 10000 Hz consisted of a frequency counter, an alternating current generator and a plane capacitor with two flat round plates installed vertically [5]. The diameter of the plates was 1 m, the distance between the plates 0,5005 m. A photo of the capacitor is included in the report of VNIIFTRI [8]. For the measurements in the measuring range from 0,5 kV/m to 20 kV/m, at the frequency f = 50 Hz, a frequency counter, an alternating current generator, a high-voltage transformer, an alternating current voltmeter and a second plane capacitor were used. This plane capacitor consisted of two flat round plates installed vertically. The diameter of the plates was 0,5 m, the distance between them 0,2503 m.

3 Results of the Comparison

As agreed in the Revised Working Program, the participants had to report their measurement results in a data sheet like that shown in fig. 5, which had been made available to the participants by the pilot laboratory.

SUMMARY
OF
LABORATORY RESULTS

International Comparison

'Electrical measurands' EUROMET No. 386

Participating laboratory:

SUMMARY OF THE RESULTS frequency 50.00 Hz – without stand			
Range: 200 V/m			
Measured field E_i (V/m)		Applied field E_o (V/m)	
Value	Uncertainty	Value	Best measurement uncertainty
Range: 2 kV/m			
Measured field E_i (kV/m)		Applied field E_o (kV/m)	
Value	Uncertainty	Value	Best measurement uncertainty
Range 20 kV/m			
Measured field E_i (kV/m)		Applied field E_o (kV/m)	
Value	Uncertainty	Value	Best measurement uncertainty

Figure 5: Data sheet "Summary of Laboratory Results" (example)

This form of presentation was not practicable to give an overall view of the results achieved in the comparison. The pilot laboratory therefore used the method preferred by the NMI VSL to report its results and calculated the calibration factor K from the data of the participants given by

$$K = \frac{E_0}{E_{ind}} \tag{1}$$

where

E_0: field strength applied to the travelling standard
E_{ind}: field strength indicated by the travelling standard (E_i in the data sheet in fig. 5)

3.1 Measurement uncertainty of the pilot laboratory

3.1.1 Model of evaluation

The measurand was the calibration factor of the travelling standard EM 100 defined by eq. (1), where E_{ind} is the electric field strength indicated by the EM 100, and E_0 the field strength that, under the same conditions of measurement, would be indicated by an ideal measuring device.

At PTB, E_0 is approximated by the standard field of a plate system according to IEC 833 [2], which acts on the probe of the E-field meter suspended in the centre of the system. It is given by

$$E_0 = \frac{\beta \gamma V}{d} \tag{2}$$

with

β: factor describing the influence of the finite dimensions of the plates on the field in in the central region of the system
γ: factor describing the influence on the field in the central region caused by the probe of the field meter which produces a changed charge distribution on the plates
V: voltage applied to the plate system
d: distance of the plates

When both equations are combined, the model function for the evaluation of the standard uncertainty of measurement to be associated with the measurement result is found to be

$$K = \frac{\beta \gamma V}{E_{\text{ind}}\, d} \tag{3}$$

Derived from the model function, the following equation must be used for the evaluation of the relative standard uncertainty of measurement to be associated with the value assigned to K:

$$w^2(K) = w^2(\beta) + w^2(\gamma) + w^2(V) + w^2(E_{\text{ind}}) + w^2(d) \tag{4}$$

with

$w(x)$: relative standard uncertainty of the quantity x.

The relative uncertainty components of β, γ, V, E_{ind} and d to be considered when eq. (4) is treated are listed in table 4.

3.1.2 Uncertainty components and expanded uncertainty of measurement

The discussion of the uncertainty components and the determination of the expanded uncertainty of the measurement results obtained for the EM 100 travelling standard will be illustrated by an example: main task, measurement at the full-scale point, 200 V/m and 50 Hz, in range 1 of the instrument.

The correction factor β in the central point of the field due to the finite dimensions of the electrodes of the PTB-plate system was calculated by *G. Crotti* using the charge simulation method [6] to be equal to β = 0,9968 with a standard uncertainty of 0,0001 in accordance with the calculation carried out by *Takuma et al.* in 1985 [7].

The influence caused by the field distortion of the probe was estimated to be described by γ = 1 within the limits of ± 0,00075.

The uncertainty of the applied voltage depends on the uncertainty of the calibration of the voltage measuring transformers and of the DVM shown in figure 2 and on the statistic uncertainty of 15 indications of the DVM at each measurement including its LSB.

The measurement of the plate distance was carried out at 9 measurement points inside a quadratic area of 0,12 m x 0,12 m in the centre of the plates by means of a specially made gauge block of 0,74 m length and additional gauges. A mean value of 0,7502 m with a standard uncertainty of 0,000086 m calculated from 10 measurements each time and 9 measurement points resulted.

Table 4: Evaluation of the standard uncertainties of measurement ()
(Main task, f = 50 Hz, E = 200 V/m, range 1 of the E-field meter)

Input Quantity from	Symbol	Uncertainty component	Type	Relative contribution in 10^{-4}	Distribution	Sensitivity coefficient	Relative standard uncertainty in 10^{-4}
Finite dimensions of the plate system	β	calculated standard uncertainty	B	1	normal	1	1,00
Field distortion by the probe	γ	estimated limits of uncertainty	B	7,5	rectangular	1	4,33
Voltage applied to the plates	V	standard deviation	A	9,77	normal	1	9,77
		calibration of					
		the transformers	B	0,5	normal	1	0,50
		the DVM	B	6,67	normal	1	6,67
Distance of the plates	d	standard deviation	A	1,15	normal	1	1,15
		calibration of					
		the main gauge	B	0,5	normal	1	0,50
		temperature	B	0,5	rectangular	1	0,28
Indicated value of the travelling standard EM100	E_{ind}	standard deviation	A	24,24	normal	1	24,24
		resolution	B	20	rectangular	1	11,55
		drift	B	4	rectangular	1	2,31
		temperature	B	5	rectangular	1	2,89
Total relative uncertainty	$w(K)$						30,04

The expanded relative uncertainty associated with the value of the relative error of the calibration factor K of the EM 100 travelling standard at the measurement point 200 V/m and 50 Hz is given by

$$U = 6 \cdot 10^{-3} \text{ for a coverage factor of } k = 2.$$

3.2 Intermediate calibrations

According to the Revised Working Program PTB had to carry out intermediate calibrations of the travelling standard watching its undamaged state and its metrologic stability each time, when it turned back to the pilot laboratory. The results are given in table 5.

Table 5: Results of the calibrations at PTB

Range	Meas. point	Meas. value	Initial	Interm. 1	Interm. 2	Interm. 3	Interm. 4	Interm. 5	Final
Vm^{-1}	Vm^{-1}		04/97	08/97	12/97	03/98	06/98	08/98	10/98
200	100	K_F U	0,9888 0,02	0,9918 0,02	0,9952 0,007	0,9982 0,007	0,9953 0,007	0,9938 0,010	0,9941 0,006
	200	K_F U	0,9874 0,02	0,9938 0,02	1,0016 0,007	1,0013 0,007	0,9989 0,007	0,9938 0,010	0,9993 0,006
2000	200	K_F U	0,9786 0,02	0,9908 0,02	- -	0,9964 0,009	0,9908 0,009	0,9962 0,012	0,9913 0,008
	500	K_F U	0,9848 0,02	0,9878 0,02	0,9908 0,007	0,9938 0,007	0,9919 0,007	0,9862 0,010	0,9902 0,006
	1000	K_F U	0,9792 0,02	0,9905 0,02	0,9919 0,007	0,9963 0,009	0,9942 0,007	0,9867 0,012	0,9919 0,006
	2000	K_F U	0,9890 0,02	- -	0,9977 0,007	0,9937 0,009	0,9976 0,007	0,9937 0,010	0,9980 0,006
20000	2000	K_F U	0,9787 0,02	- -	- -	- -	0,9935 0,010	0,9896 0,012	0,9953 0,008
	5000	K_F U	0,9815 0,02	- -	0,9899 0,007	0,9928 0,009	0,9931 0,007	0,9810 0,010	0,9916 0,006
	10000	K_F U	0,9779 0,02	- -	0,9910 0,007	0,9931 0,009	0,9910 0,007	0,9861 0,010	0,9912 0,006

K_F: $K_{Filament}$, calibration factor measured with thread-fixed probe
U: measurement uncertainty for k = 2

For time or experimental reasons the intermediate calibrations sometimes could not be carried out at all measurement points and not in every case with the highest measurement uncertainty. Nevertheless, from the diagrams of their results shown in the figures 6 to 13 can be concluded, that there was no significant instability or drift of the transfer standard in the time of the comparison. Moreover, measurements of the transfer standard carried out at PTB up to 2001 have shown a negligible drift of $K < 0{,}0006\ a^{-1}$ in all measuring ranges of the instrument.

As substantiated in section 4.1, the values obtained at the initial measurement might have been too low and, therefore, have not been taken into consideration for the evaluation of the comparison.

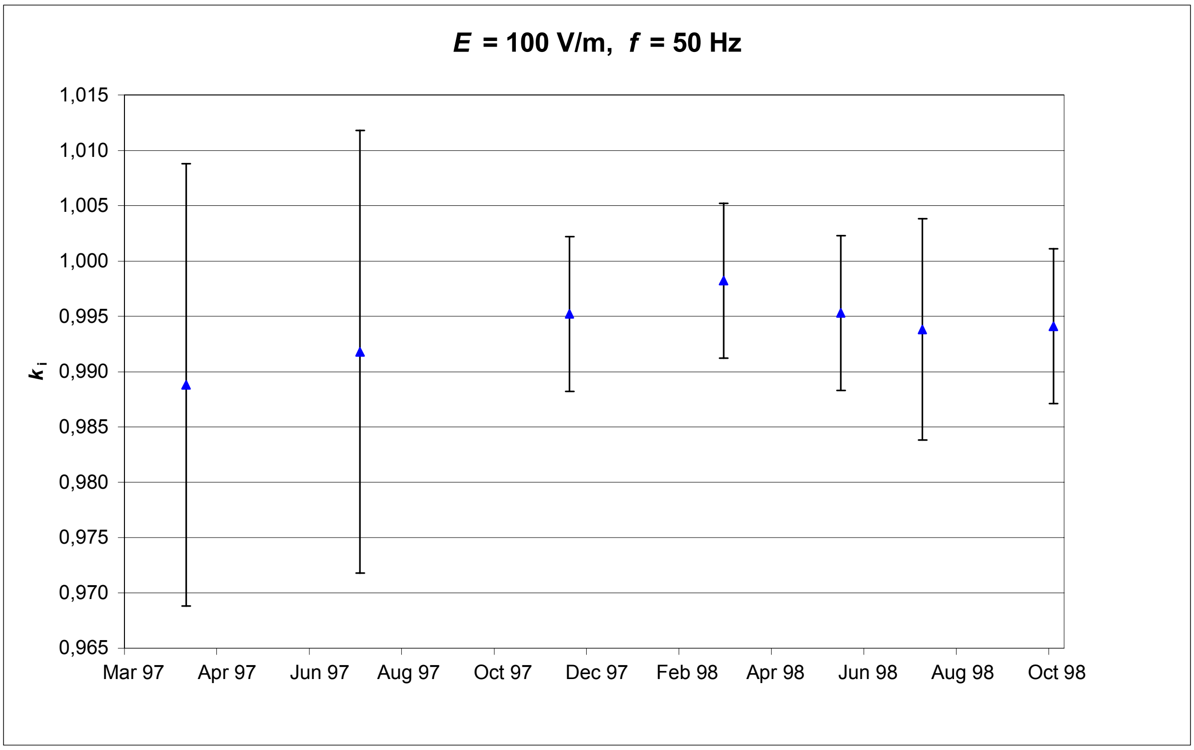

Figure 6: Intermediate calibration at $E = 100$ V/m

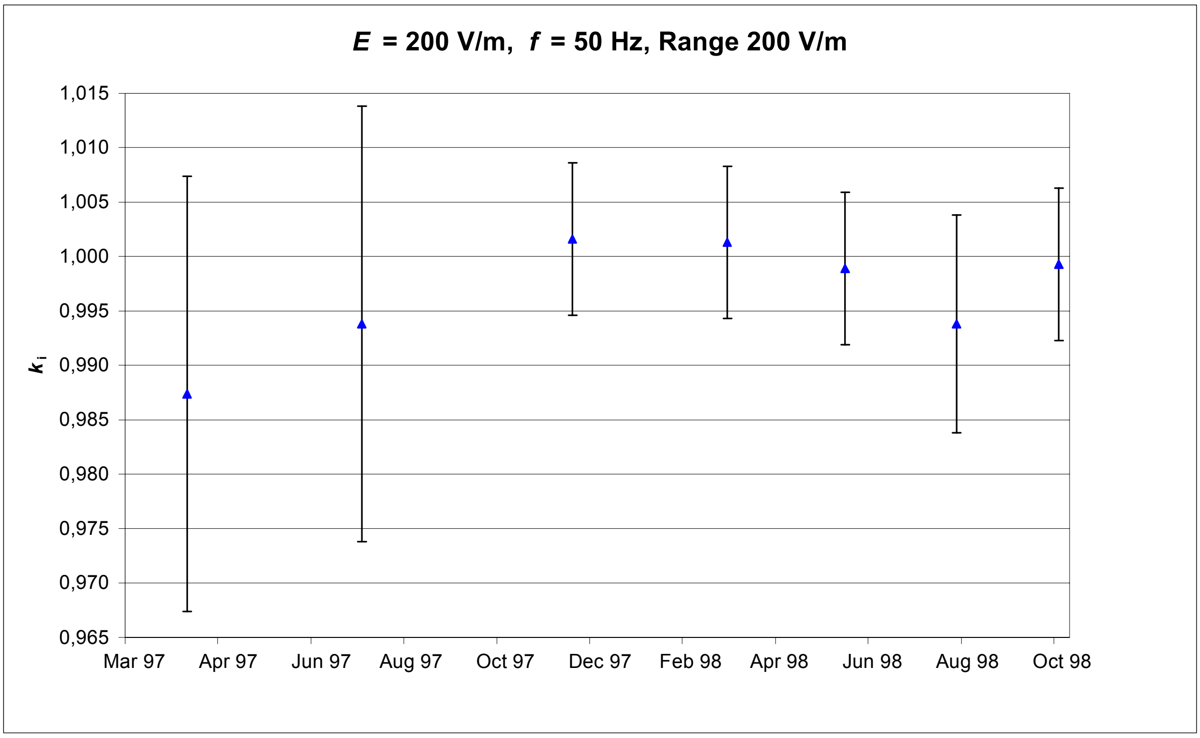

Figure 7: Intermediate calibration at $E = 200$ V/m

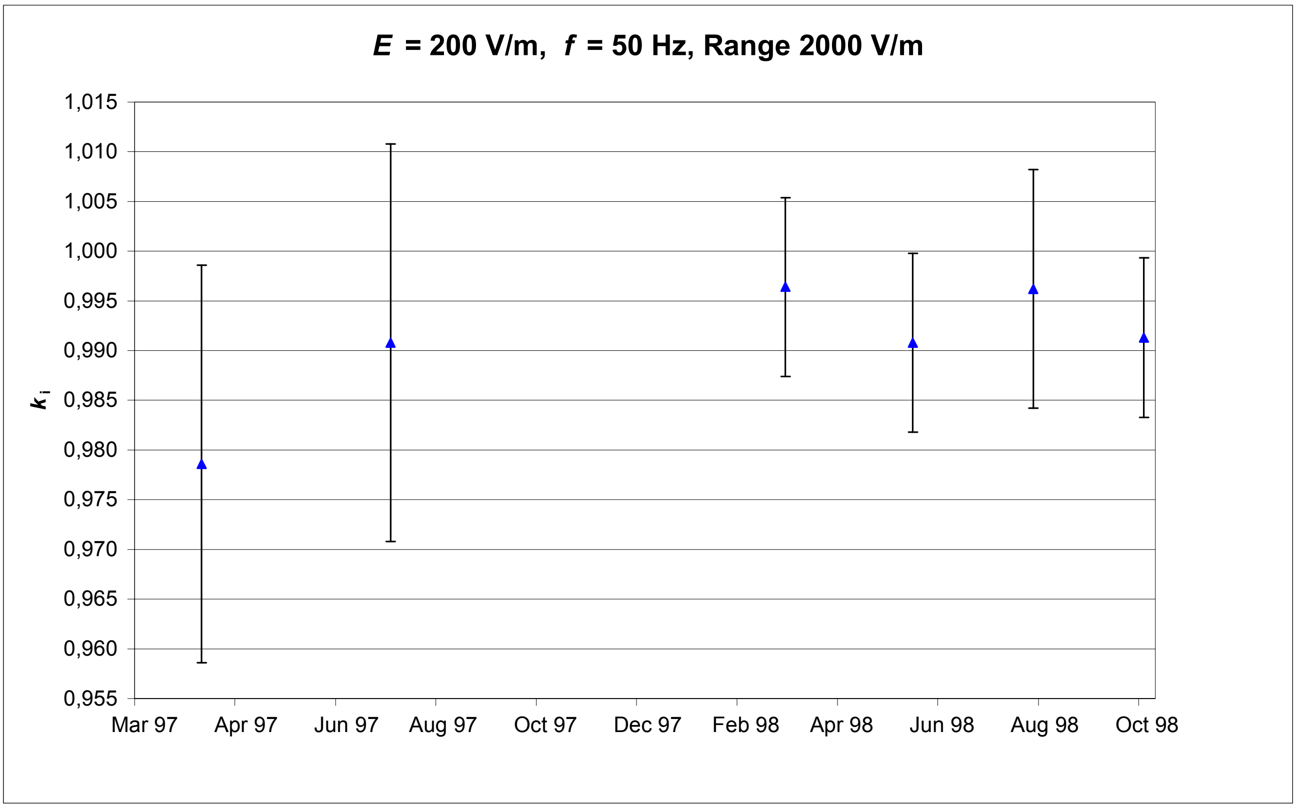

Figure 8: Intermediate calibration at $E = 200$ V/m

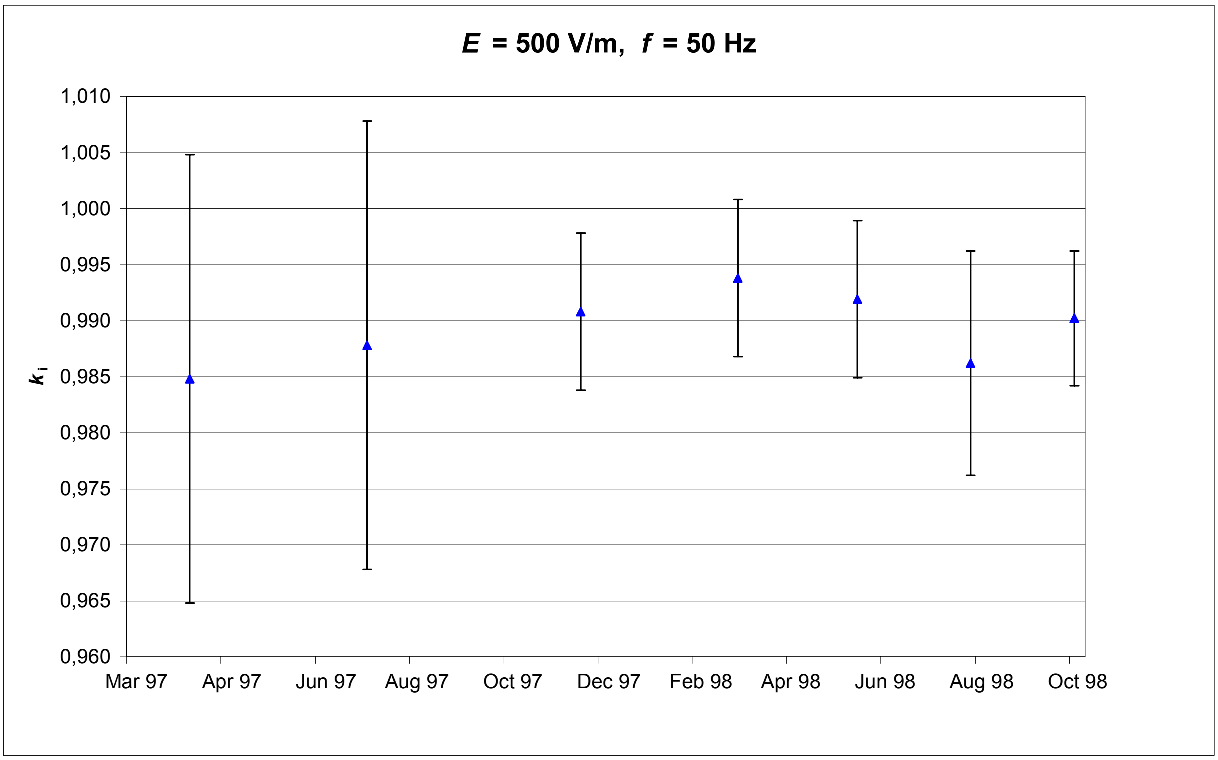

Figure 9: Intermediate calibration at $E = 500$ V/m

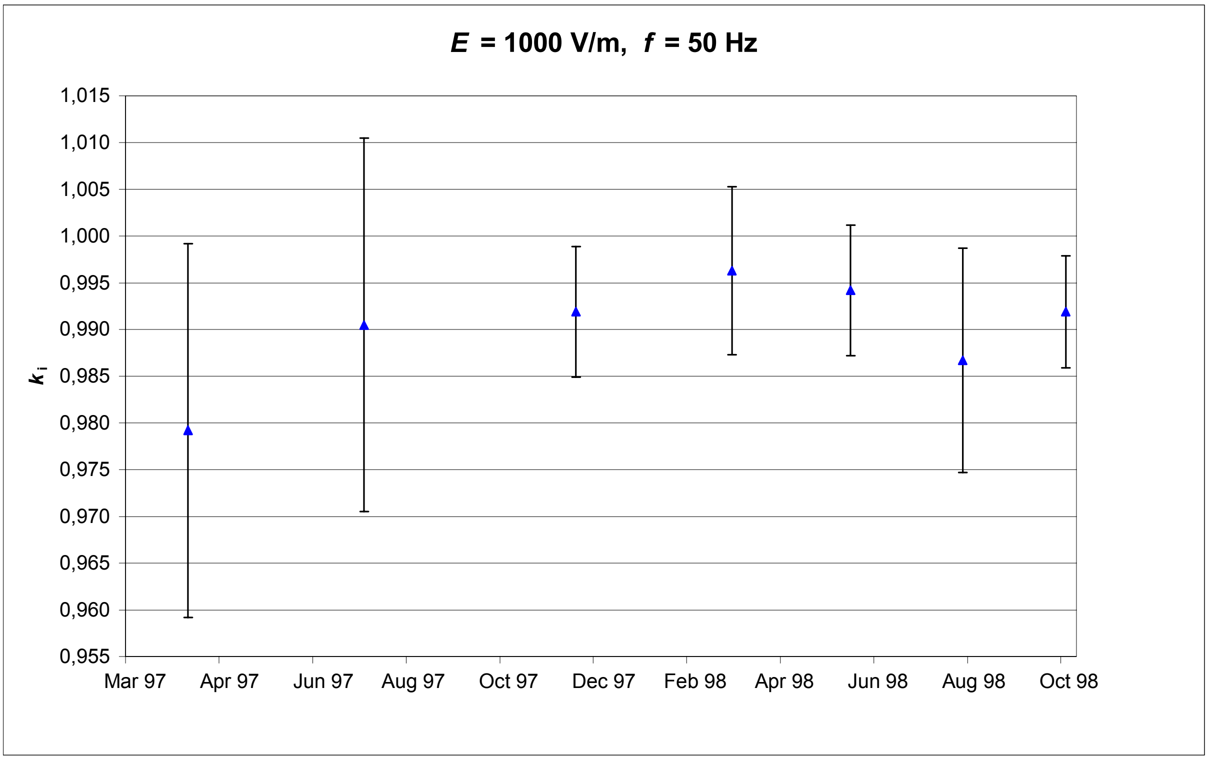

Figure 10: Intermediate calibration at E = 1000 V/m

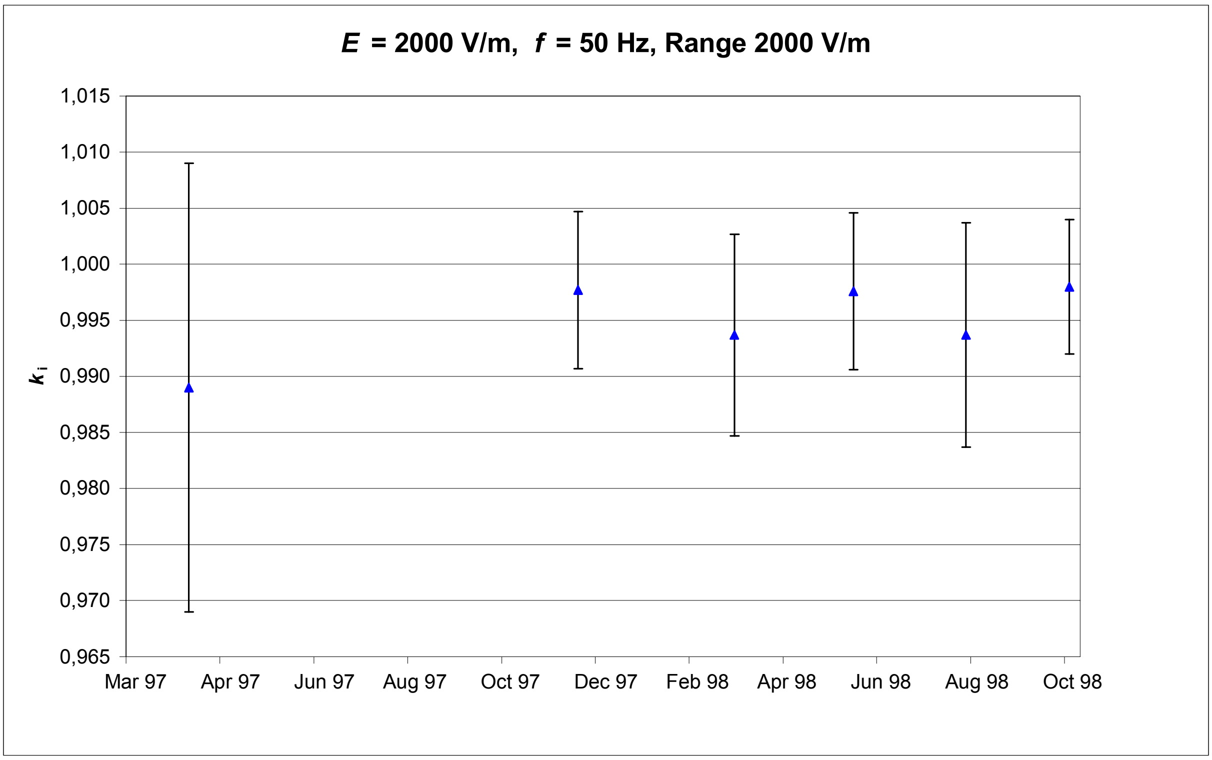

Figure 11: Intermediate calibration at E = 2000 V/m

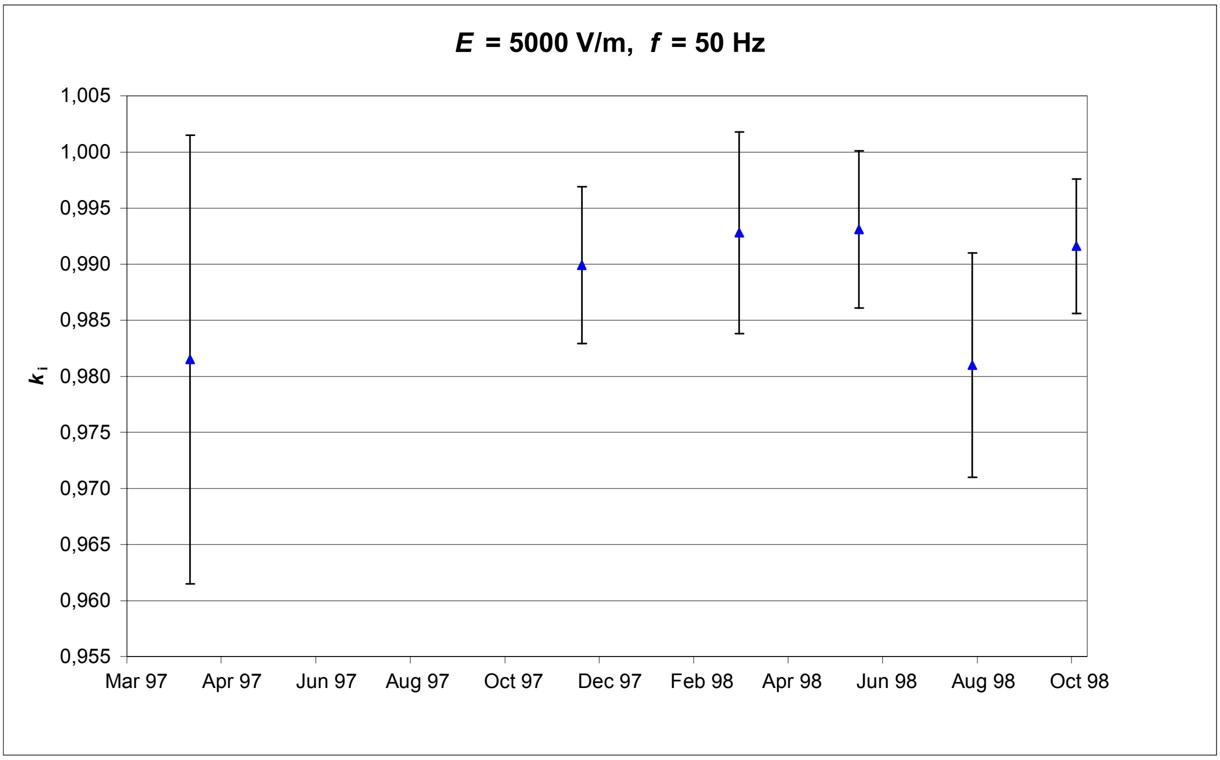

Figure 12: Intermediate calibration at E = 5000 V/m

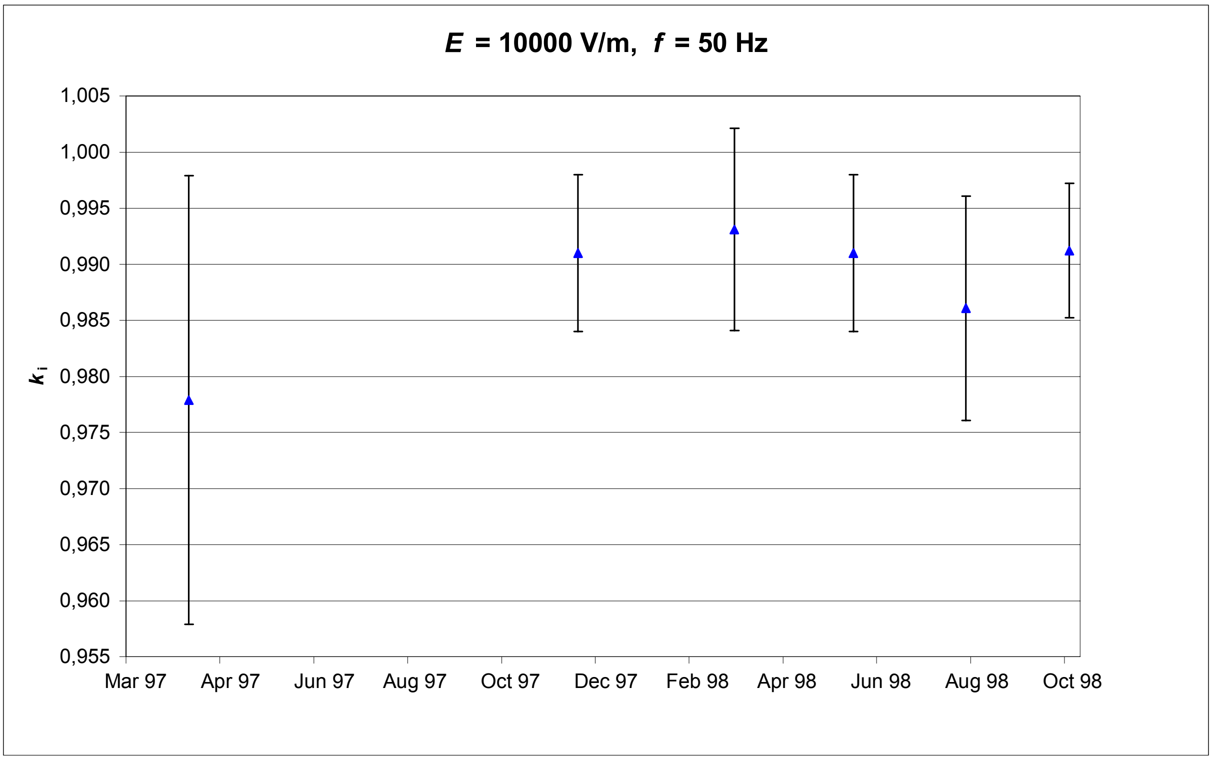

Figure 13: Intermediate calibration at E = 10000 V/m

3.3 Representation of the measurement results

The values for *K* and their associated uncertainties reported by the participants are listed in section 3.3.1. in table 6 for the main task and illustrated in section 3.3.2. in the diagrams of the figures 14 to 23. In Appendix A one example of the uncertainty calculation of each participant is shown for the same measurement point: 200 V/m , full scale.

3.3.1 Reported results for the main task

Table 6: Results of the participants for the field range E = 100 V/m to E = 20000 V/m at the frequency f = 50 Hz

Range	Meas. point	Meas. value	PTB	IST	NGC	CEM	NMI VSL	IEN	GUM	VNIIFTRI	PTB
Vm^{-1}	Vm^{-1}										
200	100	K_F	0,9888	1,0000	0,9852	0,9957	0,9857	0,9980	-	0,9901	0,9941
		K_S	-	0,9869	-	0,9864	-	0,9872	1,0000	-	0,9827
		U	0,02	0,007	0,018	0,010	0,006	0,004	0,006	0,004	0,007
	200	K_F	0,9874	1,0064	0,9926	1,0029	0,9926	1,0035	-	0,9970	0,9993
		K_S	-	0,9931	-	0,9905	-	0,9926	-	-	0,9883
		U	0,02	0,007	0,018	0,010	0,006	0,005	-	0,004	0,007
2000	200	K_F	0,9786	0,9969	-		0,9814	0,9950	-	-	0,9913
		K_S	-	-	-		-	0,9852	1,0152	-	0,9810
		U	0,02	0,011			0,008	0,006	0,006	-	0,008
	500	K_F	0,9848	0,9985	0,9792	0,9977	0,9825	0,9940	-	1,0020	0,9902
		K_S	-	-	-	0,9881	-	0,9843	0,9980	-	0,9843
		U	0,02	0,011	0,018	0,008	0,006	0,005	0,006	0,008	0,006
	1000	K_F	0,9792	0,9994	0,9852	0,9975	0,9823	0,9980	-	1,0060	0,9919
		K_S	-	-	-	0,9874	-	0,9872	1,0142	-	0,9845
		U	0,02	0,010	0,018	0,008	0,006	0,005	0,006	0,008	0,006
	2000	K_F	0,9890	1,0057	0,9963	0,9785	0,9867	1,0025	-	1,0137	0,9980
		K_S	-	-	-	0,9761	-	0,9921	-	-	0,9879
		U	0,02	0,010	0,018	0,013	0,006	0,005	-	0,008	0,006
20000	2000	K_F	0,9787	0,9950	-	-	0,9790	0,9950	-	-	0,9953
		K_S	-	-	-	-	-	0,9843	1,0204	-	0,9798
		U	0,02	0,011	-	-	0,008	0,006	0,006	-	0,008
	5000	K_F	0,9815	0,9973	0,9859	0,9705	0,9787	0,9940	-	1,0040	0,9916
		K_S	-	-	-	0,9546	-	0,9823	1,0204	-	0,9785
		U	0,02	0,011	0,018	0,016	0,006	0,005	0,006	0,008	0,006
	10000	K_F	0,9779	0,9996	0,9907	0,9411	0,9792	0,9950	-	1,0000	0,9912
		K_S	-	-	-	0,9261	-	0,9843	1,0246	-	0,9792
		U	0,02	0,010	0,018	0,016	0,006	0,005	0,006	0,008	0,006
	20000	K_F	-	1,0055	0,9949	-	0,9847	0,9995	-	0,9950	0,9972*
		K_S	-	-	-	-	-	0,9886	1,0325	-	0,9854*
		U	-	0,010	0,018	-	0,006	0,006	0,006	0,008	0,008

* These measurements of PTB could not be carried out in October 1998, the results had been achieved in March 1999

K_F: calibration factor measured with thread-fixed probe (see 2.4)

K_S: calibration factor measured using the stand of the probe (see 2.4)

U: measurement uncertainty for k = 2

3.3.2 Diagrams

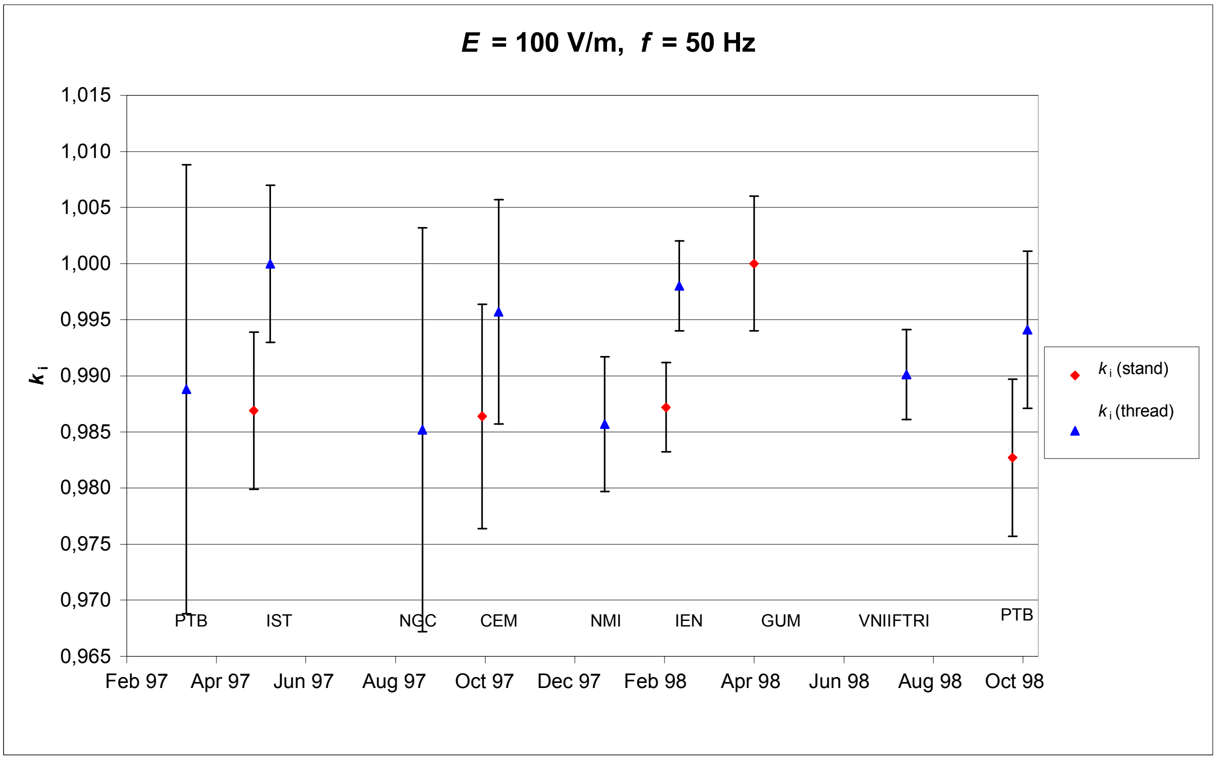

Figure 14: Range 200 Vm^{-1}, measurement point 100 Vm^{-1}

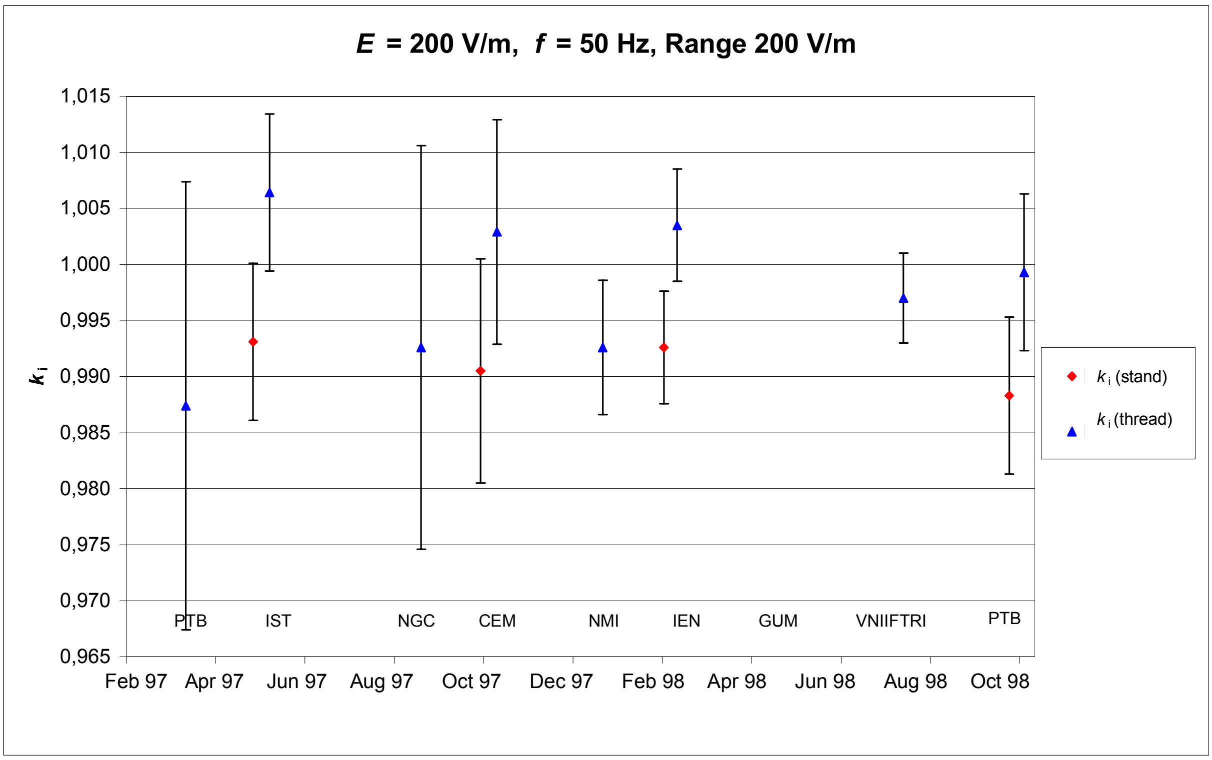

Figure 15: Range 200 Vm^{-1}, measurement point 200 Vm^{-1}

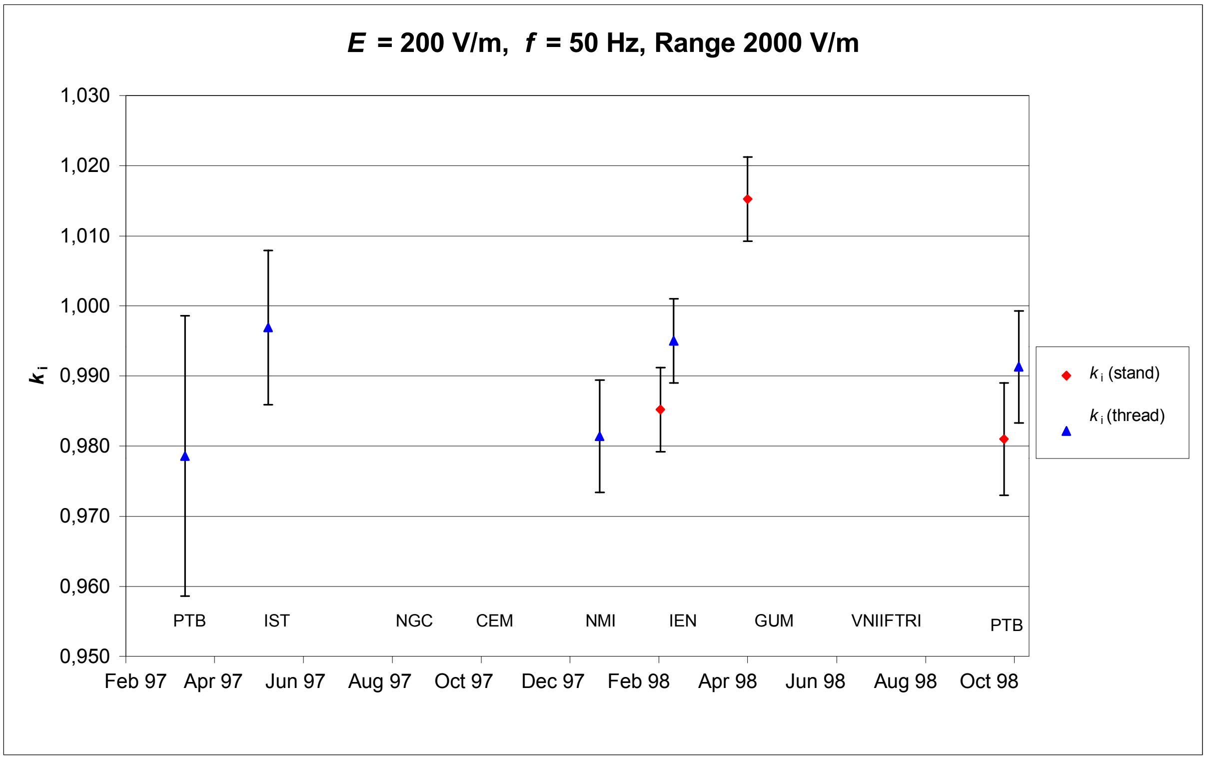

Figure 16: Range 2000 Vm^{-1}, measurement point 200 Vm^{-1}

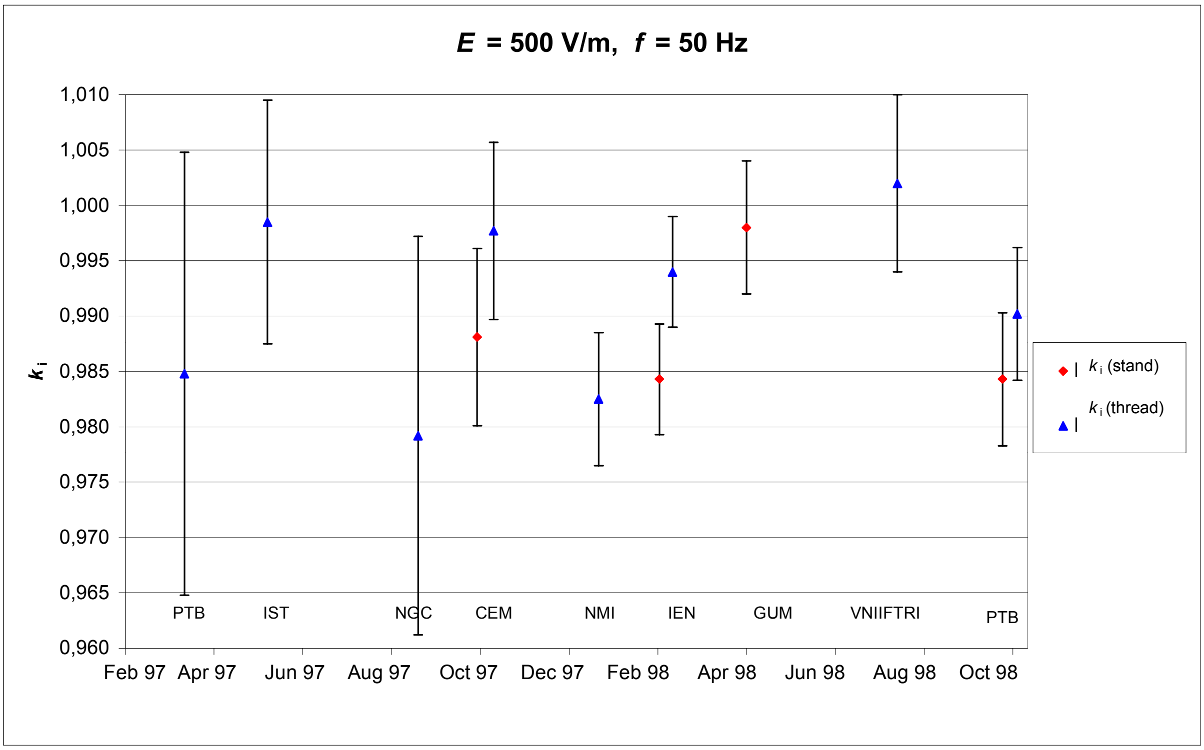

Figure 17: Range 2000 Vm^{-1}, measurement point 500 Vm^{-1}

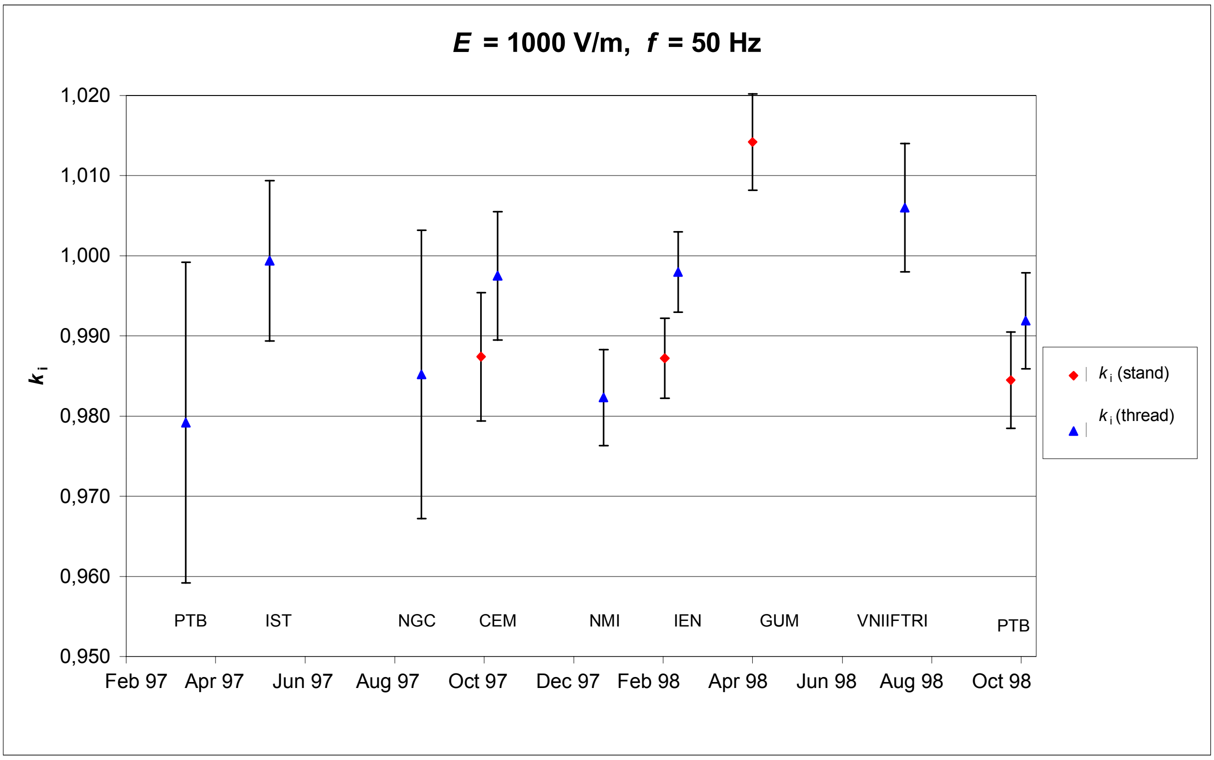

Figure 18: Range 2000 Vm^{-1}, measurement point 1000 Vm^{-1}

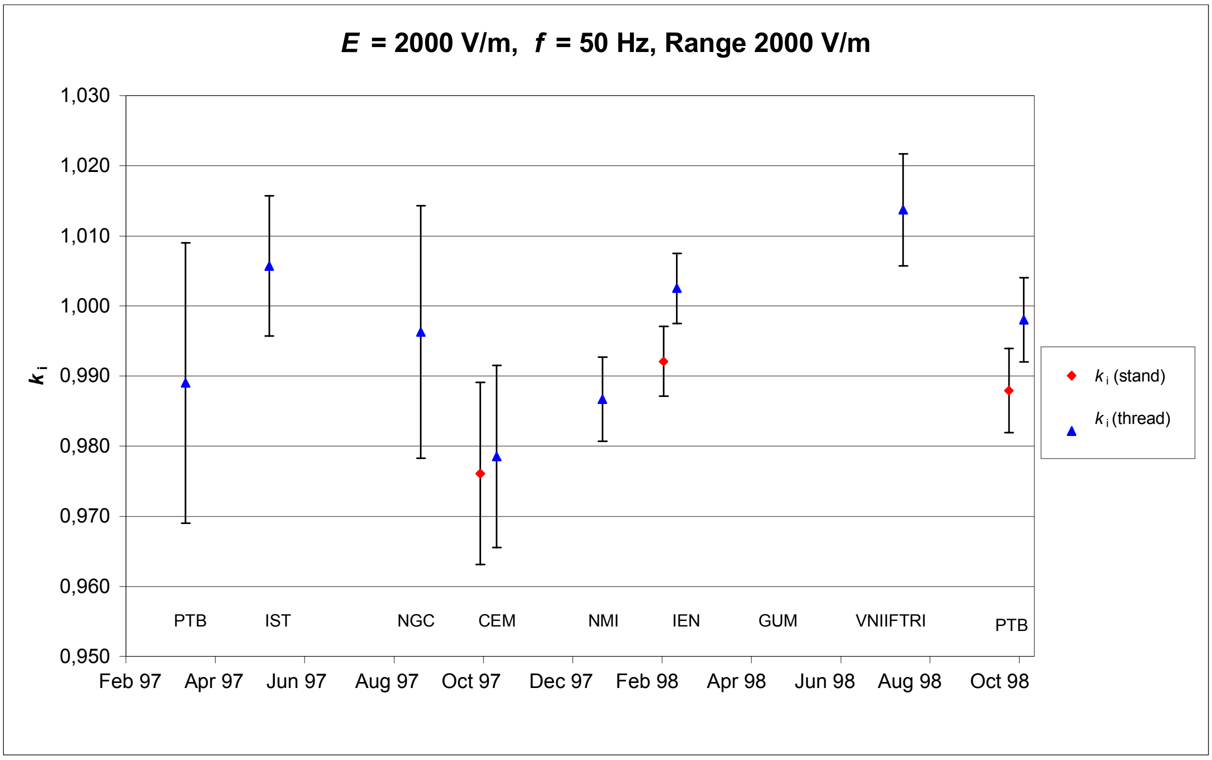

Figure 19: Range 2000 Vm^{-1}, measurement point 2000 Vm^{-1}

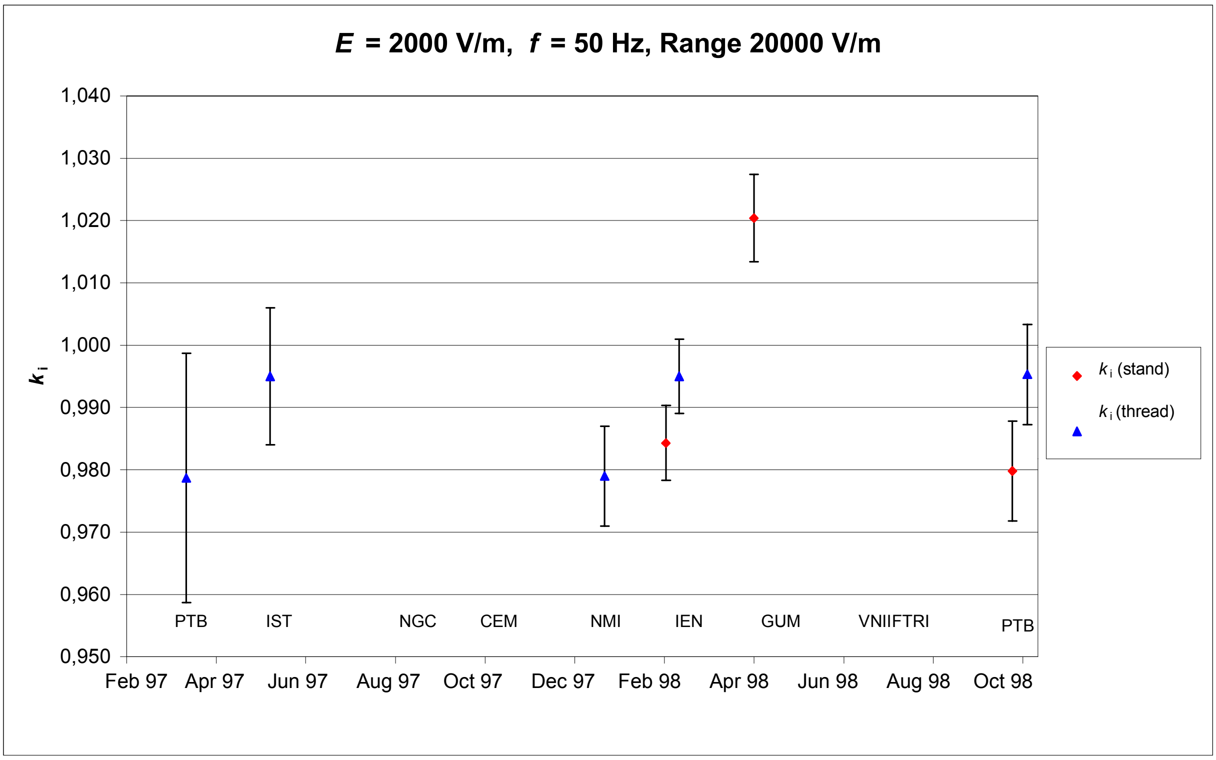

Figure 20: Range 20000 Vm^{-1}, measurement point 2000 Vm^{-1}

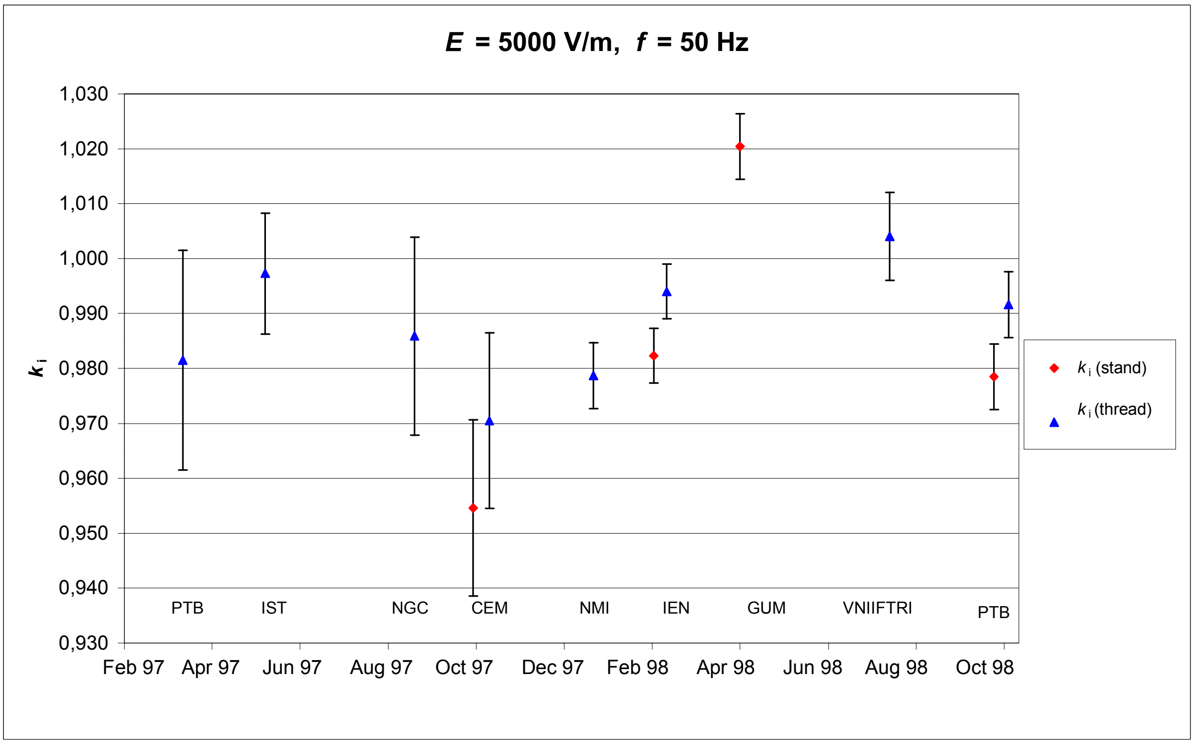

Figure 21: Range 20000 Vm^{-1}, measurement point 5000 Vm^{-1}

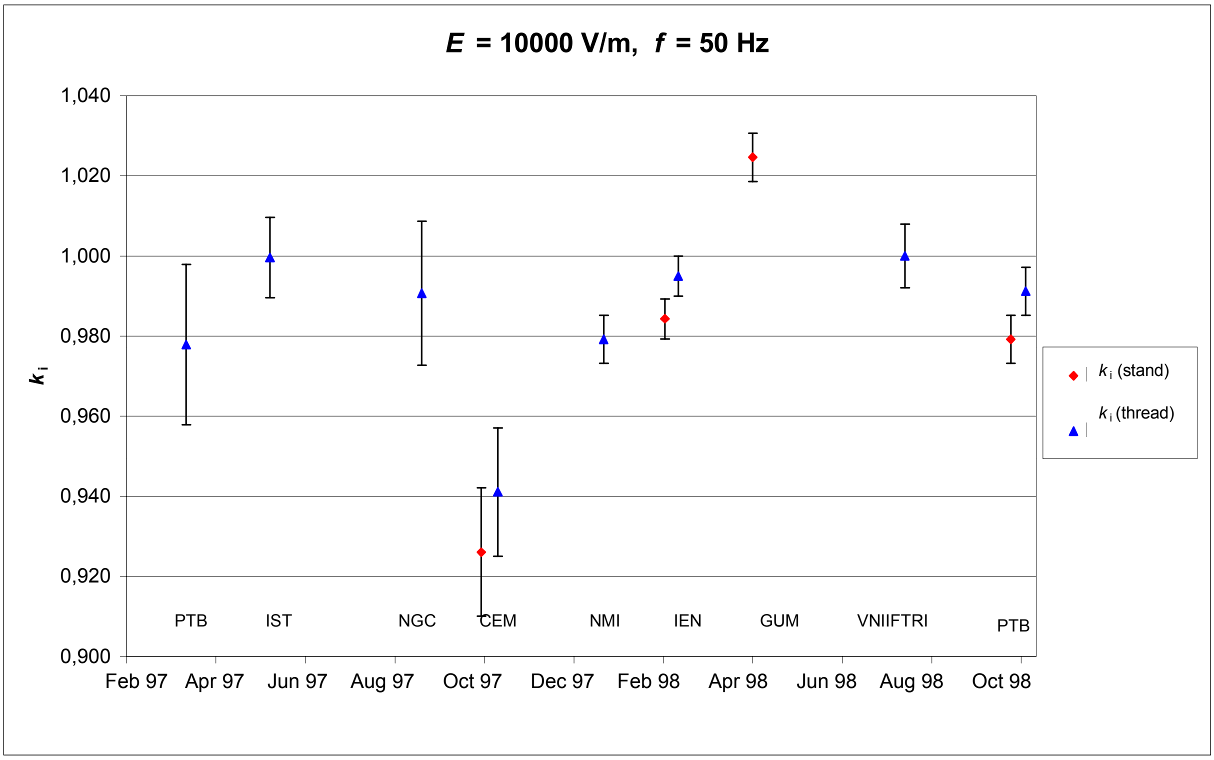

Figure 22: Range 20000 Vm^{-1}, measurement point 10000 Vm^{-1}

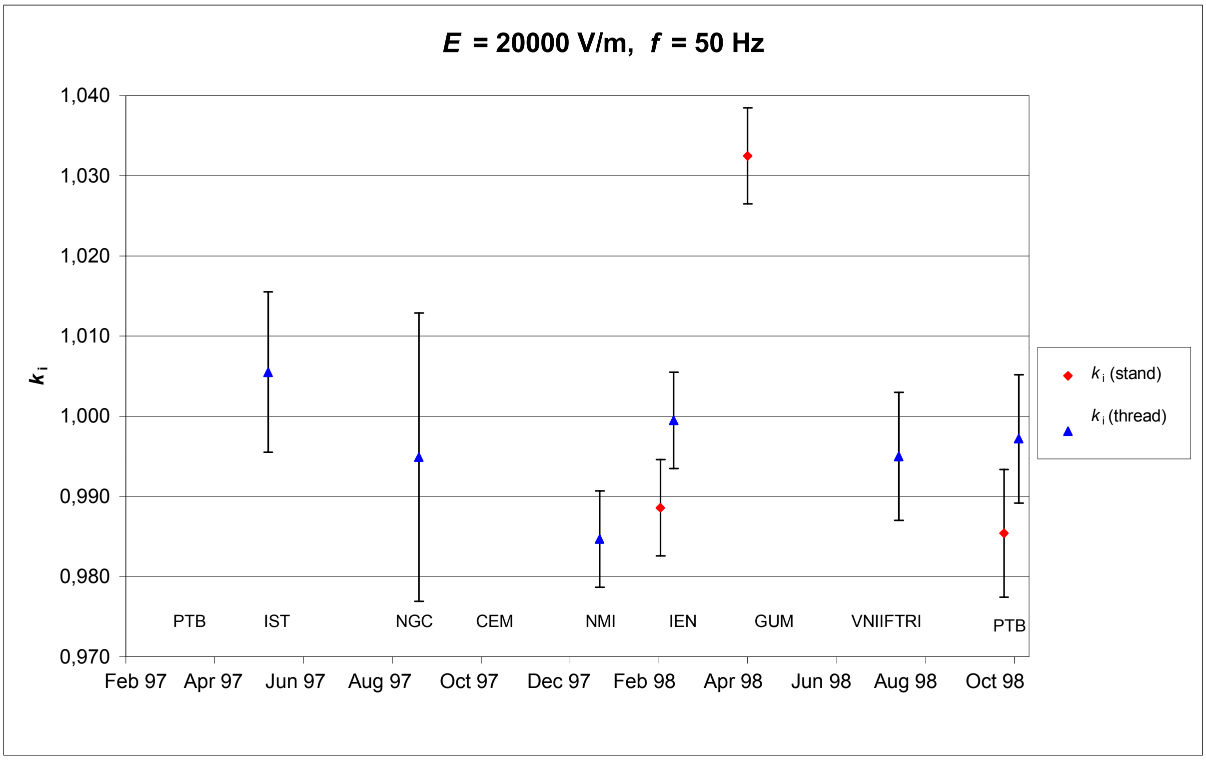

Figure 23: Range 20000 Vm^{-1}, measurement point 20000 Vm^{-1}

4. Evaluation of the comparison

4.1 Measurements of the pilot laboratory

As described above PTB carried out measurements of the transfer standard in April 1997, August 1997, December 1997, March 1998, June 1998, August 1998 and October 1998. Within the scope of a bilateral co-operation, *Dr. Gabriella Crotti* from IEN took part in the final measurements. As the development of the PTB equipment was continued in the course of the comparison, the measurements were carried out with different measuring systems: in 1997 and in the first half of 1998 with the motor-driven standard field device (figure 2), later with the computer-controlled standard field device (figure 3). Unfortunately, the time for the intermediate measurements sometimes was too short for highly precise measurements. In consequence, different measurement uncertainties resulted, and not all measurement points could be measured in all cases (see table 5). In particular, the field strength of 20000 V/m could not be produced with the motor-driven equipment in October 1998.

The initial results of PTB obtained in April 1997 were lower than those of August 1997, although the same measurement procedure was applied and the results agree within the uncertainty limits. It is possible, that the differences were caused by inadequate accuracy of the initial measurement. Another possible reason is, that problems with the transfer standard occurred during the measurements carried out at IST. The instrument was, therefore, opened and repaired by the manufacturer. For this reason, the results of the initial measurement at PTB have been stated in the respective tables and diagrams, but they have not been taken into account in the evaluation of the results. In particular, they have been disregarded in the calculation of the transfer uncertainty of the field meter (see section 4.3)

In 2000/2001, additional measurements of the transfer standard with an improved equipment were carried out at PTB. They will be described separately. The results confirmed the reference values of the comparison calculated, for example, in section 4.3 and represented for all measurement points in Appendix B.

4.2 Measurements of the participants

As shown in the figures 14 to 23, the measurement results of the participants in most cases agree within their respective limits of uncertainty expressed for $k = 2$ (P = 95 %). Obviously, the best agreement in all graphs was achieved by IST, IEN and PTB (values from the final calibration).

For the purpose of a first evaluation of the measurements, as a trial, the mean values of these three participants obtained with the thread-fixed probe were calculated in table 7 for all measurement points according to eq. (5)

$$K_{\text{mean}} = K_{\text{F mean}} = \tfrac{1}{3}\,(K_{\text{F IST}} + K_{\text{F IEN}} + K_{\text{F PTB}}); \quad U_{\text{mean}} = \tfrac{1}{3}\,(U_{\text{IST}}^2 + U_{\text{IEN}}^2 + U_{\text{PTB}}^2)^{1/2} \qquad (5)$$

A more exact method will be used in section 4.3 to calculate the reference values of the comparison. The mean values calculated here were used to show the characteristic of the calibration factor of the transfer instrument in figure 24.

Table 7: Mean value of the calibration factor, calculated from IST, IEN and PTB results

Range Vm^{-1}	Meas. point Vm^{-1}	Meas. value	IST	IEN	PTB	Mean value
200	100	K_F U	1,0000 0,007	0,9980 0,004	0,9941 0,007	0,9974 0,004
	200	K_F U	1,0064 0,007	1,0035 0,005	0,9993 0,007	1,0031 0,004
2000	200	K_F U	0,9969 0,011	0,9950 0,006	0,9913 0,008	0,9944 0,005
	500	K_F U	0,9985 0,011	0,9940 0,005	0,9902 0,006	0,9942 0,004
	1000	K_F U	0,9994 0,010	0,9980 0,005	0,9919 0,006	0,9964 0,004
	2000	K_F U	1,0057 0,010	1,0025 0,005	0,9980 0,006	1,0021 0,004
20000	2000	K_F U	0,9950 0,011	0,9950 0,006	0,9953 0,008	0,9951 0,005
	5000	K_F U	0,9973 0,011	0,9940 0,005	0,9916 0,006	0,9943 0,004
	10000	K_F U	0,9996 0,010	0,9950 0,005	0,9912 0,006	0,9953 0,004
	20000	K_F U	1,0055 0,010	0,9995 0,006	0,9972 0,008	1,0007 0,005

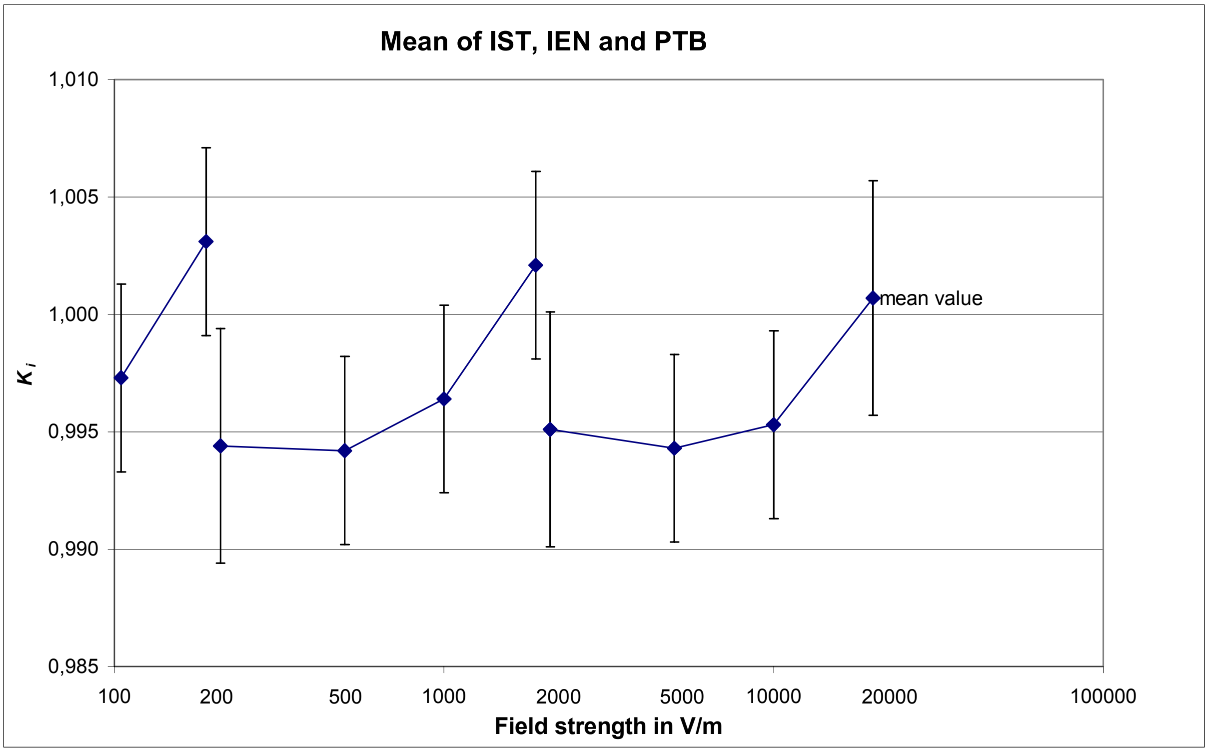

Figure 24: Characteristic of the calibration factor of the transfer instrument, mean of IST, IEN and PTB

Additionally to the good agreement of the results of IST, IEN and PTB, in view of the fact that the slopes of the characteristic curves of figure 24 in the different ranges of the instrument were nearly the same, it seemed highly probable that the mean meets the true field values. Consequently, the measurement results of all participants obtained with the thread-fixed probe have been represented in the figures 25 to 27 in relation to the mean values shown in figure 24.

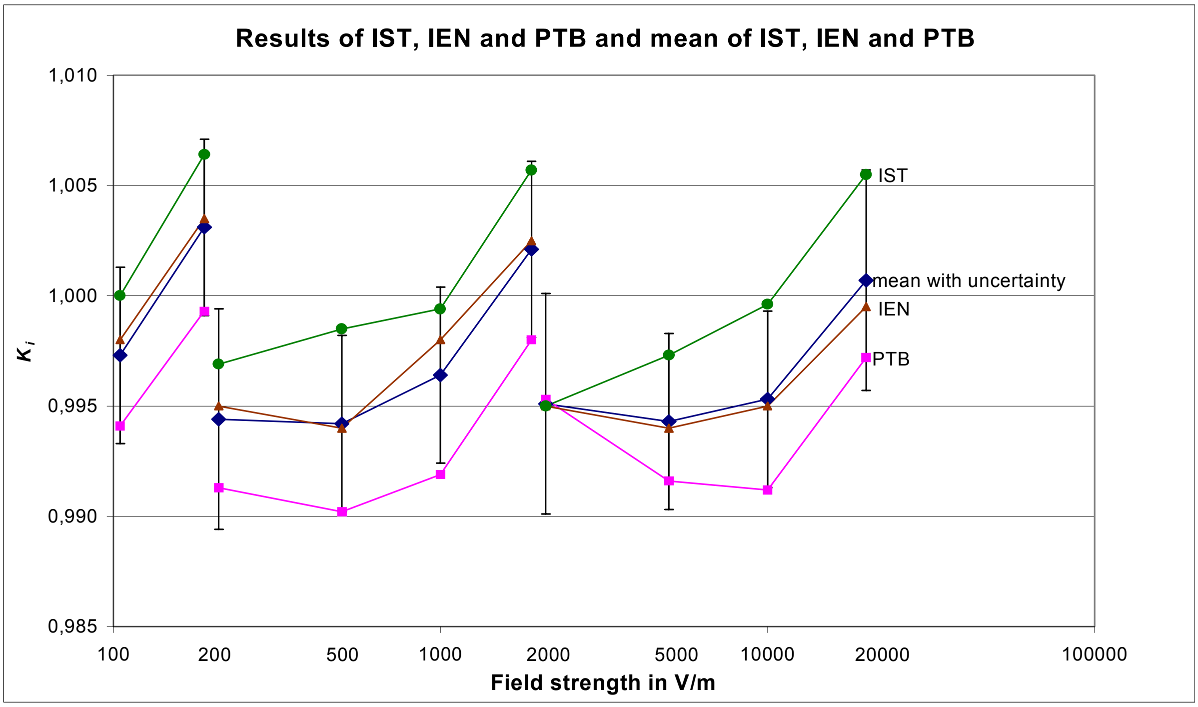

Figure 25: Measurement results of IST, IEN and PTB in relation to the mean of figure 24

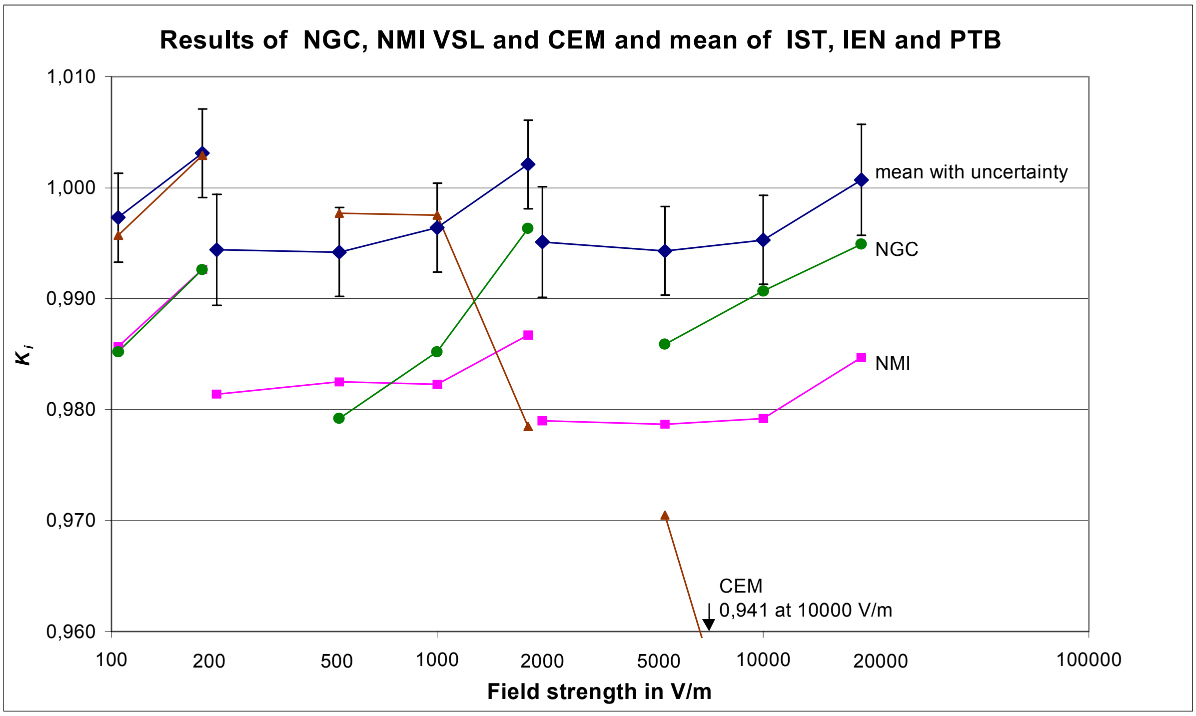

Figure 26: Measurement results of NGC, NMI VSL and CEM in relation to the mean of figure 24

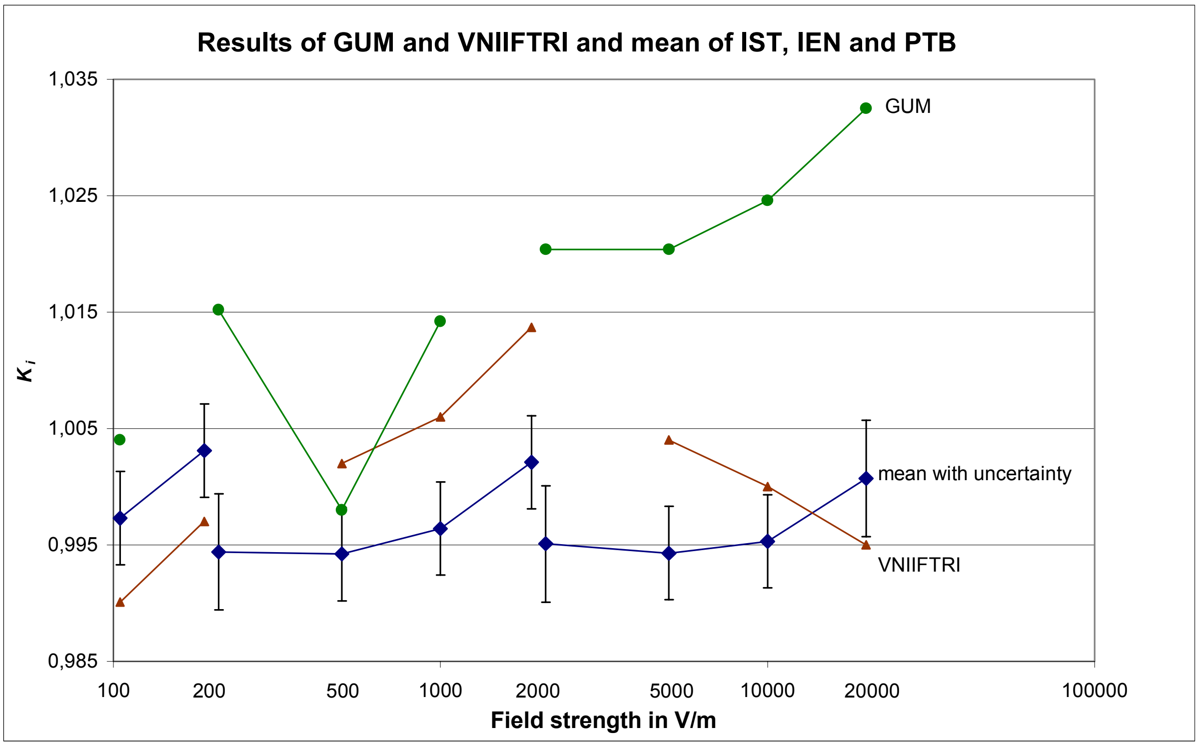

Figure 27: Measurement results of GUM and VNIIFTRI in relation to the mean of figure 24

Remark: The values of GUM are those of K_S, the calibration factor measured with stand. K_F had not been measured. From Table 6 approximately $K_F \approx K_S + 0{,}01$ may be concluded. But, the pilot laboratory did not carry out respective corrections.

4.3 Reference value of the comparison and degrees of equivalence for $E = 1000$ V/m

Unfortunately, with the exception of the results of IST, IEN and PTB, the characteristic of the calibration factor measured by the participants did not agree with regard to the slopes and, more important, with regard to the number of the measurement points in the measurement ranges. It was therefore impossible to calculate a single representative figure characterizing all the results of the respective participant, and, in consequence, to calculate only a single table of the degrees of equivalence of the participants. The calculation had to be carried out for each measurement point.

As an example, a reference value and the degrees of equivalence for one measurement point were therefore calculated. The value of 1000 V/m was chosen, because it had been measured by all participants and no extremely diverging results had been obtained at this point. The results have been presented in table 8.

For the uniform presentation of the results of the comparison and their evaluation equation (6) has been used which expresses the measured calibration factor.

$$K_i = (1 + m_i \times 10^{-3}) \qquad (6)$$

m_i : characterizes the result of the measurement carried out by laboratory i. It is defined as the difference from the rated value $K = 1$, expressed in 10^{-3}.

The uncertainty of m_i consists of the standard uncertainty u_i calculated and reported by the participating laboratory i and of the transfer uncertainty u_t to be attributed to the behaviour of the transfer standard during the time of the comparison, due to influences during transport, different laboratory environments and measurement conditions. The question was, in which way this transfer uncertainty could be estimated. The pilot laboratory proceeded on the assumption that the results of the intermediate measurements carried out at the PTB must reflect such influences, because they had been taken place with different field generators, in different rooms and at different times, each time after transports of the transfer standards between several participants. Therefore, the standard deviation s of a single intermediate measurement has been taken as approach to characterize the transfer uncertainty u_t. On the basis of the results of table 5 for E = 1000 V/m (leaving out the measurement of 04/97 as substantiated in 4.1), the transfer uncertainty (k = 1) amounts to

$$u_t = s = 3{,}3 \cdot 10^{-3}.$$

Table 8: Laboratory individual results of the comparison for E = 1000 V/m
$m_i = (K_F - 1) \cdot 10^3$ and $u_i = U_i/2$ have been taken from table 6

Lab i	m_i	u_i	u_{i+t}	Date of measurement
IST	- 0,6	5	6,0	97-05
NGC	-14,8	9	9,6	97-09
CEM	- 2,5	4	5,2	97-10 ... 97-11
NMI VSL	- 17,7	3	4,5	98-01
IEN	- 2,0	2,5	4,1	98-02
GUM	14,2	3	4,5	98-04
VNIIFTRI	6,0	4	5,2	98-07 98-08
PTB	- 8,1	3	4,5	98-10

u_i: standard uncertainty of m_i reported by laboratory i, given in 10^{-3}
u_t: transfer uncertainty for E = 1000 V/m, $u_t = 3{,}3$; given in 10^{-3}
u_{i+t}: total standard uncertainty of m_i, given in 10^{-3}, $u_{i+t} = (u_i^2 + u_t^2)^{1/2}$

Remark: The values of GUM are those of K_S, the calibration factor measured with stand, because GUM had not measured K_F.

Following the explanation in 4.2 and the diagrams of the figures 25 to 27 the reference value m_R of this comparison was calculated as the weighted mean $m_R = m_{mean}$ of the results of the participants IST, IEN and PTB. Its standard uncertainty u_R was calculated as the uncertainty of the weighted mean $u_R = u_{mean}$ from their total standard uncertainties u_{i+t}:

$$m_{mean} = u_{mean}^2 \sum \frac{m_i}{u_{i+t}^2} \qquad u_{mean}^2 = \frac{1}{\sum \frac{1}{u_{i+t}^2}} \qquad (7)$$

Table 9: Calculation of the weighted mean and its standard uncertainty of the results of the participants IST, IEN and PTB

	IST	IEN	PTB	
m_i	-0,6	-2,0	-8,1	
u_{i+t}	6,0	4,1	4,5	
u_{i+t}^2	36,0	16,81	20,25	
$\frac{m_i}{u_{i+t}^2}$	-0,01667	-0,11898	-0,40000	$\sum \frac{m_i}{u_{i+t}^2} = -0,53565$
$\frac{1}{u_{i+t}^2}$	0,02778	0,05949	0,04938	$\sum \frac{1}{u_{i+t}^2} = 0,13665$

$u^2_{mean} = 1 : 0,13665 = 7,318$ $\quad u_{mean} = 2,7$ $\quad m_{mean} = 7,318 \cdot (-0,53565) = -3,9$

The reference value for E = 1000 V/m and its uncertainty amount to

$$m_R = -3,9 \text{ and } u_R = 2,7; \text{ both expressed in } 10^{-3}. \qquad (8)$$

The degree of equivalence of each laboratory with respect to the reference value is given by D_i and its expanded uncertainty U_i, the degree of equivalence between two laboratories i and j by D_{ij} and its expanded uncertainty U_{ij}. The results are shown in table 10, all figures are stated in 10^{-3}. The influence of correlations on the amounts of the uncertainty U_i in the case of IST, IEN and PTB is described by equation (9a).

$$D_i = m_i - m_R, \qquad U_i = 2\, u_{i+t} \qquad (9)$$

$$D_i = m_i - m_R, \qquad U_i = 2\, (u_{i+t}^2 - u_R^2)^{1/2} \qquad (9a)$$

$$D_{ij} = D_i - D_j = (m_i - m_j), \qquad U_{ij} = (U_i^2 + U_j^2)^{1/2} \qquad (10)$$

Table 10: Matrix of equivalence for E = 1000 V/m, (calculated with the values of table 8 and eq. (8), the green marked values of GUM are not directly comparable)

Lab j → / Lab i ↓		IST	NGC	CEM	NMI	IEN	GUM	VNIIFTRI	PTB
	$D_i \pm U_i$	$D_{ij} \pm U_{ij}$	$D_{ij} \pm U_{ij}$	$D_{ij} \pm U_{ij}$	$D_{ij} \pm U_{ij}$	$D_{ij} \pm U_{ij}$	$D_{ij} \pm U_{ij}$	$D_{ij} \pm U_{ij}$	$D_{ij} \pm U_{ij}$
IST	3,3 ± 10,7	-	14,2 ± 22,0	1,9 ± 14,9	17,1 ± 13,9	1,4 ± 12,4	-14,8 ± 13,9	-6,6 ± 14,9	7,5 ± 12,9
NGC	-10,9 ± 19,2	-14,2 ± 22,0	-	-12,3 ± 21,8	2,9 ± 21,2	-12,8 ± 20,2	-29,0 ± 21,2	-20,8 ± 21,8	-6,7 ± 20,5
CEM	1,4 ± 10,4	-1,9 ± 14,9	12,3 ± 21,8	-	15,2 ± 13,7	-0,5 ± 12,1	-16,7 ± 13,7	-8,5 ± 14,7	5,6 ± 12,6
NMI	-13,8 ± 8,9	-17,1 ± 13,9	-2,9 ± 21,2	-15,2 ± 13,7	-	-15,7 ± 10,9	-31,9 ± 12,6	-23,7 ± 13,7	-9,6 ± 11,5
IEN	1,9 ± 6,2	-1,4 ± 12,4	12,8 ± 20,2	0,5 ± 12,1	15,7 ± 10,9	-	-16,2 ± 10,9	-8,0 ± 12,1	6,1 ± 9.5
GUM	18,1 ± 8,9	14,8 ± 13,9	29,0 ± 21,2	16,7 ± 13,7	31,9 ± 12,6	16,2 ± 10,9	-	8,2 ± 13,7	22,3 ± 11,5
VNIIFTRI	9,9 ± 10,4	6,6 ± 14,9	20,8 ± 21,8	8,5 ± 14,7	23,7 ± 13,7	8,0 ± 12,1	-8,2 ± 13,7	-	14,1 ± 12,6
PTB	-4,2 ± 7,2	-7,5 ± 12,9	6,7 ± 20,5	-5,6 ± 12,6	9,6 ± 11,5	-6,1 ± 9,5	-22,3 ± 11,5	-14,1 ± 12,6	-

The degrees of equivalence of the participating laboratories with respect to the reference value are shown in figure 28.

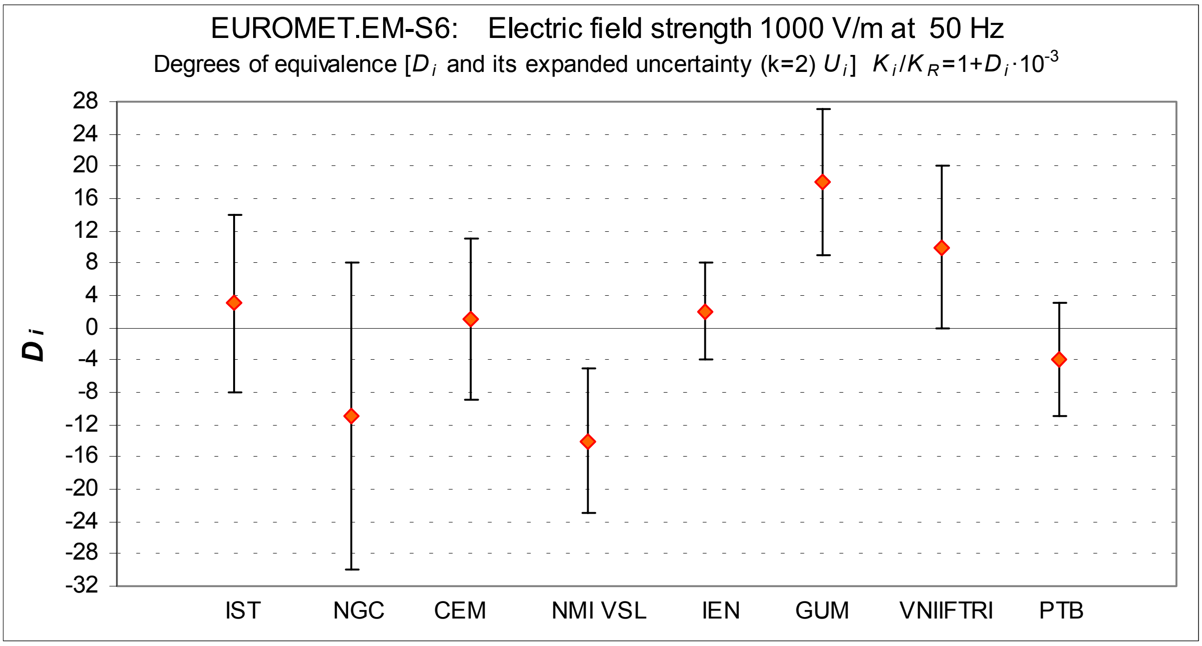

Figure 28: Graph of equivalence of the participating laboratories with respect to the reference value for E = 1000 V/m, the value of GUM is presented only for information.

The laboratory individual results m_i and their uncertainties u_{i+t}, the calculated reference values m_R, the degrees of equivalence with respect to the reference value ($D_i \pm U_i$), and the graphs of equivalence for all measurement points of the main task are presented in Appendix B. Depending on the estimated measurement uncertainties they have been rounded and stated without decimal places.

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References

[1] Guide to the Expression of Uncertainty in Measurement, first edition, 1993, corrected and reprinted 1995, International Organization for Standardization, Geneva, Switzerland, ISBN 92-67-10188-9.

[2] IEC 833 "Measurement of power-frequency electric fields". First edition, 1987. International Electrotechnical Commission, Geneva, Switzerland.

E DIN VDE 0847-26: "Messverfahren zur Beurteilung der Elektromagnetischen Verträglichkeit - Teil 26: Kalibrierung von Feldstärkemessgeräten für EMV- und Personenschutzanwendungen für Frequenzen > 0 Hz". DIN Deutsches Institut für Normung, Frankfurt am Main, 1996.

IEC 61786 "Measurement of low-frequency magnetic and electric fields with regard to exposure of human beings - Special requirements for instruments and guidance for measurements" (1998-08). Ed.1.0, International Electrotechnical Commission, Geneva, Switzerland.

[3] *Eckardt, H.; Lippoldt, R.:* "The traceability of electric field measurements". In: Proc. of the Int. Conference on Actual Problems of Measuring Technique, KPI, Kiyiv (Ukraine), pp. 56-57, 1998.

[4] *Bottauscio,. O., Crotti, G., D'Emilio, S.; Farina, G.,; Mantini, A.:* "Generation of reference electric and magnetic fields for calibration of power-frequency field meters", IEEE Trans. IM, vol. IM-42, no. 2, pp. 547-552, 1993.

[5] *Tisčenko, V.A. and others:* "Calibration of electric field strength measurement standards at 50 Hz". COOMET Report, Moskva 2001 (publication in preparation).

[6] *Crotti, G.; Lippoldt, R.:* "Analysis of systems for the generation of low frequency electric fields". In: "Metrology '99", Conference Report, Bordeaux, 1999.

[7] *Takuma, T.; Kawamoto, T.; Sunaga, Y.:* "Analysis of calibration arrangements for AC field strength meters", In: IEEE Trans PAS, Vol. PAS-104, no.2, 1985.

[8] *Eckardt, H. (editor):* "International Comparison of Electric Field Strength (EUROMET.EM-S6 comparison), Reports of the Participants". In: PTB-Bericht E-..., Braunschweig, 2002 (in preparation).

Appendix A: Uncertainty budgets

Following examples are demonstrated for the evaluation of uncertainties carried out by the participants and dealt with in their reports about the comparison. The full scale value 200 V/m was chosen, because all participants had measured this value and in most of the cases the measurement uncertainty achieved was the best one. The order of the examples has been chosen according to the time schedule of the measurements. According to the agreed task the evaluation had to be based on the "Guide to the Expression of Uncertainties" [1]. A detailed procedure with special regard to the present comparison was not agreed, the participants were free in their way to choose the influence quantities and to calculate their uncertainty budgets.

1. PTB

The determination of the expanded uncertainty of the measurement results obtained for the EM 100 travelling standard is demonstrated by an example given for the full-scale point, 200 V/m and 50 Hz, in range 1 of the instrument. For details see p. 14 of the report.

Table A1: Uncertainty calculation of PTB
E = 200 V/m full scale, frequency: 50 Hz, configuration without stand

Input Quantity from	Symbol	Uncertainty component	Type	Relative contribution in 10^{-4}	Distribution	Sensitivity coefficient	Relative standard uncertainty in 10^{-4}
Finite dimensions of the plate system	β	calculated standard uncertainty	B	1	normal	1	1,0
Field distortion by the probe	γ	estimated limits of uncertainty	B	7,5	rectangular	1	4,3
Voltage applied to the plates	V	standard deviation	A	9,8	normal	1	9,8
		calibration of the transformers	A	0,5	normal	1	0,5
		the DMM	A	6,7	normal	1	6,7
Distance of the plates	d	standard deviation	A	1,2	normal	1	1,2
		calibration of the main gauge	A	0,5	normal	1	0,5
		temperature	B	0,5	rectangular	1	0,3
Indicated value of the travelling standard EM100	E_{ind}	standard deviation	A	24,2	normal	1	24,2
		resolution	B	20	rectangular	1	11,6
		drift	B	4	rectangular	1	2,3
		temperature	B	5	rectangular	1	2,9
Combined rel. uncertainty	$w(K)$						30,0
Expanded relative uncertainty U (k = 2)							$6 \cdot 10^{-3}$

2. IST

For the measurement at 200 V/m, a horizontal plate system 1 m x 1 m in size with the plates spaced (0,5 ± 0,0005) m apart, was used. The calibration factor K was determined by the equation

$$K = \frac{E_0}{E_{ind}} = \frac{1}{E_{ind}} \cdot 0{,}999 \cdot \frac{V}{d}$$

derived from IEC 833. The voltage V was generated with a total harmonic distortion $THD < 0{,}2$ % mainly caused by the 3rd harmonic and measured by means of a Fluke 85 DMM. The measurements were carried out in a temperature range from (22,4 to 24,5) °C.

Table A2: Uncertainty calculation of IST
E = 200 V/m full scale, frequency: 50 Hz, configuration without stand

Quantity	variation of the quantity	Type	Distribution	sensitvity coefficient	relative standard uncertainty
Influence from the instrument					
indication E_{ind}	statistical scatter	A	normal	1	$7{,}4 \cdot 10^{-4}$
resolution	± 0,1 V/m	B	rectangular	1	$2{,}9 \cdot 10^{-4}$
temperature	(22,4...24,5) °C	B	rectangular	1	$2{,}5 \cdot 10^{-4}$
Influence from the standard field E_0					
IEC-factor	0,9985...0,9995	B	rectangular	1	$2{,}9 \cdot 10^{-4}$
voltage V	± 0,5 %	B	rectangular	1	$28{,}9 \cdot 10^{-4}$
harmonics	$THD < 0{,}2$ %	B	rectangular	1	$11{,}6 \cdot 10^{-4}$
plate distance d	(500 ± 0,5) mm	B	rectangular	1	$5{,}8 \cdot 10^{-4}$
Combined relative uncertainty					$32{,}9 \cdot 10^{-4}$
Expanded relative uncertainty U (k = 2)					$7 \cdot 10^{-3}$

3. NGC

The National Grid rig consists of two parallel plates of the dimensions 1,4 m x 1,4 m and a separation of 1,2 m,. Let the separation of the plates be equal to d and their size infinite. The potential difference measured between the plates is V. The electric field, E between the plates may be expressed as

$$E(V,d) = \frac{V}{d}$$

If δE is the standard uncertainty in E, δV the standard uncertainty in the voltage measurements and δd the standard uncertainty in plate separation, then

$$\frac{\delta E}{E} = \sqrt{(\frac{\delta V}{V})^2 + (\frac{\delta d}{d})^2}$$

has to be used to explore the extent to which uncertainties in plate separation and voltage measurement contribute to the combined uncertainty in the generated electric field.

The following effects were considered to be of influence on the combined uncertainty of measurement:

- the uncertainty in voltage: an expanded uncertainty of better ± 0,5 % was achieved
- the uncertainty in plate separation: from 81 measurements a plate distance of 1,216 m with a standard uncertainty of 3,5 mm or 0,3 % was achieved
- the uncertainty associated with fringing: the IEC standard 833 states that the error will be less than 1% for an apparatus conforming with itself and that good laboratory practice results in lower values. Because of the use of a centre tapped transformer to minimise the nonuniformity of the fields between the plates, and of the fact that the experiment was conducted in a spacious high voltage laboratory so that the distance from the plates to (earthed or charged) surfaces is 1.5 m or greater compared with the 0.8 m minimum specified, and the use of an anti-corona system it is considered that the use of a lower value than 1% would be justified and it is considered that 0.7% would be appropriate.
- the uncertainty caused by the total harmonic content estimated to be *THC* < 1 %
- the uncertainty of the standard field meter under test: experiments on the standard field meter would suggest that repeated insertion into the rig operating at a constant 50 Hz 8.6 V/m electric field results in a standard uncertainty of, at best, about ± 0.2% and may decrease with increasing applied field.

Table A3: Uncertainty calculation of NGC
E = 200 V/m full scale, frequency: 50 Hz, configuration without stand

Influence quantity	type of uncertainty	relative value	distribution	sensitivity coefficient	contribution
Voltage	A	0,0025	normal	1	0,003
Plate separation	A	0,003	normal	1	0,003
Fringing and proximity	B	0,007	rectangular	1	0,004
THC	B	0,01	rectangular	1	0,006
Meter indication	A	0,003	normal	1	0,003
Combined relative uncertainty					0,009
Expanded relative uncertainty *U* (k = 2)					0,018

4. CEM

The uncertainty budget of CEM was calculated for a system of parallel plates with A=1,5 m x 1,5 m and h = 0,5 m. As shown in the table, an expanded uncertainty of $8 \cdot 10^{-3}$ resulted. The official report of CEM is related to the upper plate dimensions. Besides, CEM delivered measurement results for a spacing of the plates of 0,75 m. These results were used by the pilot laboratory for the presentation in the report, in order to make them better comparable with those achieved by most of the other participants who used systems with these dimensions in the ratio 2:1 according to [1]. For this reason in table 6 an expanded uncertainty of $10 \cdot 10^{-3}$ is reported instead of the value $8 \cdot 10^{-3}$ resulting in the following table.

With exception of the sensor deviations all uncertainty components were treated as B type contributions with rectangular distribution.

Table A4: Uncertainty calculation of CEM
E = 200 V/m full scale, frequency: 50 Hz, configuration without stand

Influence quantity	Symbol	Standard uncertainty in (‰)	Remarks/ Distribution
Parallel plate system			
Plates spacing deviations	s_h	3,5	$\pm \frac{x}{\sqrt{3}}$
Fringing field effects	s_f	0,58	$\pm \frac{x}{\sqrt{3}}$
Calibrator uncertainty	s_v	0,05	Normal k = 2
Standard uncertainty of the system	u_{si}	3,5	$u_{si} = \sqrt{s_h^2 + s_f^2 + s_v^2}$
Sensor deviations Type A evaluation	$u(\overline{q})_1$	1,9	Relative value according to the tables of results
Combined relative uncertainty of measurement	u_{ti}	4	$u_{ti} = \sqrt{u_{si}^2 + u(\overline{q})_i^2}$
Expanded relative uncertainty of measurement (k = 2)	U_{ti}	8	

5. NMI VSL

For the generation of the field in the parallel plate facility at the levels from 1 V/m until 20 kV/m in the frequency band from 16 2/3 Hz until 400 Hz a circuit consisting of a LF generator, LF amplifier (floating output), followed by, for each of the plates, a potentiometer and high voltage transformer. The voltages supplied to the plates were measured by means of two DMM.

The following sources of uncertainty have been taken into consideration

Basis formula

$$Y = \frac{(r + k_1 \cdot p + k_3 \cdot \partial T)(r_1 \cdot U_1 + r_2 \cdot U_2)}{d}$$

Type B evaluation is used for

- U_1 and U_2: multimeters (0,6 % of reading + 0,3 % of range). So the contribution is dependent on the output quantity.
- d: distance between plates 750 mm ± 0,1 %.
- p: position of the probe: 5 mm uncertainty. contributing 4 % of output quantity /m, (so k_1 = 0,04)
- r_r and r_2: ratio of high voltage transformers: 0,1 %; or ratio of amplifiers: 0,1 %
- field homogeneity 0,2 % of the output quantity, (so k_2 = 0,002)
- ∂T : temperature effect on DUT 0,04 % of output quantity /K, (so k_3 = 0,0004)
- The uncertainty for the reading: 0,03; 0,3 or 3 V/m for range I, II or III respectively

Type A evaluation is used for

- r: ratio between varied input parameters and output parameters (nominal 1)

Table A5: Uncertainty calculation of NMI VSL
E = 200 V/m full scale, frequency: 50 Hz, configuration without stand

Quantity	Estimate	Unit	Standard uncertainty	Unit	Sensitivity coeff	Unit	Probability distribution	Uncertainty contribution	
								V/m	
U_1	1,5	V	0,00069	V	66,67	m^{-1}	rect	0,046	multimeter 1
U_2	1,5	V	0,00069	V	66,67	m^{-1}	rect	0,046	multimeter 2
d	0,75	m	0,00043	m	266,67	Vm^{-2}	rect	0,115	distance
p	0	m	0,005	m	0,04	Vm^{-2}	rect	0,040	position
homogen.	0	x	0,002	x	200	Vm^{-1}	rect	0,400	field
ratio1	50	x	0,05	x	2	Vm^{-1}	normal	0,100	transformer 1
ratio2	50	x	0,05	x	2	Vm^{-1}	normal	0,100	transformer 2
∂T	0	K	1,1547	K	0,08	$Vm^{-1}K^{-1}$	rect	0,092	temperature DUT
resolution	0	V/m	0,0289	V/m	1		rect	0,029	resolution DUT
r	1		0,001		1	Vm^{-1}		0,200	
Y	200	V/m						0,4986	= 0,0025 relative

The expanded relative uncertainty (k = 2) amounts to $U = 5 \cdot 10^{-3}$.

6. IEN

The measurements were carried out using the IEN standard plate system according to the equation

$$K = \frac{E_o}{E_L} = \beta\gamma \frac{V_m}{d_m} \cdot \frac{1}{E_L} ,$$

where E_0: standard field in the centre of the plate system
E_L: field indicated by the transfer standard.

As shown in [6], the relative standard uncertainty of the field $E_0 = \beta\gamma \frac{V_m}{d_m}$ in the range > 100 V/m amounts to the value $1{,}3 \cdot 10^{-3}$. Regarding the indication of the transfer standard the following contributions had to be taken into account: the standard deviation of the mean value of the different measurements, the resolution δE_ρ of the instrument, the influence δE_H of the harmonic distortion of the generating field and the influence δE_θ of the room temperature during the time of the measurements.

Table A6: Uncertainty calculation of IEN,
E = 200 V/m full scale, frequency: 50 Hz, configuration without stand

Quantity	Value	rel. standard uncertainty	probability distribution	degrees of freedom	sensitivity coefficient	rel. uncertainty contribution
E_o	200,00	1,3E-03	normal	> 100	1	1,3E-03
E_L	199,3	4,3E-04	normal	4	1	4,3E-04
δE_ρ	1,0000	1,5E-04	rectangular	∞	1	1,5E-04
δE_H	1,0000	2,2E-03	rectangular	∞	1	2,2E-03
δE_θ	1,0000	4,6E-04	rectangular	∞	1	4,6E-04
K	1,0035	combined relative uncertainty:				2,6E-03
		expanded relative uncertainty (k=2):				5,3E-03

7. GUM

No uncertainty budget for the chosen example (field strength 200 V/m, full scale) was available. Besides, it has to be mentioned that the results of GUM shown in table 6 and in the diagrams figure 14 - 23 of the report were obtained only using the stand of 0,375 m height. Later in the report they were compared with the results of the other participants obtained by installation of the probe with a plastic thread thus avoiding the field distortion by the stand. It must be clear, that the results of GUM in these later tables and diagrams have no quantitative importance, they are shown for information.

8. VNIIFTRI

The measurement system for the frequency f=50 Hz and the electric field strength E_{inst} = 200 V/m consisted of the alternating current generator V1-9, the frequency counter CH3-64, and the plane capacitor CP-1/05 of two flat round plates installed vertically, diameter of the plates 1 m, distance between the plates 0,5005 m.

The expression for determining the electric field in the center of the capacitor CP-1/05 is given by

$$E_{inst}=AU_{V1\text{-}9}/H$$

where
- E_{inst} - TRMS-value (true root mean square) of the electric field strength installed in CP-1/05, V/m;
- A - correction factor depending from relation of distance between plates of the capacitor to diameter of the plates $h=2H/D$, A = 0,994,
- H - distance between the plates, m;
- D - diameter of the plates, m;
- $U_{V1\text{-}9}$ - voltage at the output of the alternating current generator, V.
- E_{int} - uncertainty of interaction

$$E_{int} = \gamma\alpha^3; \quad \gamma = 4{,}8; \quad \alpha = D/2H$$

The uncertainty budget for the measurement performed according to the method described above is given in the following table.

Table A8: Uncertainty calculation of VNIIFTRI
E = 200 V/m full scale, frequency: 50 Hz, configuration without stand

Symbol	Source of uncertainty	value ±%	Probability distribution	Divisor	C_i	u_i ±%
A	Calculation of value A	0,10	rectangular	1,73	1	0,06
H	Geometry of capacitor	0,15	rectangular	1,73	1	0,09
$U_{V1\text{-}9}$	Calibration V1-9	0,25	normal	2,00	1	0,15
E_{int}	Interaction of the probe with the plates of the capacitor	0,06	rectangular	1,73	1	0,03
u_c	Combined relative uncertainty	-	normal	-	-	0,20
δE_{inst}	Expanded relative uncertainty	-	normal (k=2)	-	-	0,40

Appendix B: Individual results and Degrees of equivalence

Following the individual results achieved by the different participating laboratories and their degrees of equivalence with respect to the reference values have been represented in summary for the main task of the comparison (field range from E = 100 V/m to E = 20 kV/m at the frequency f = 50 Hz with thread-fixed probe). The measurements with the thread fixed probe were chosen because the distortion of the generated field caused by the thread is less than that caused by a stand. One exception has to be mentioned: GUM measured only with stand, so the results of GUM are not directly comparable with those of the other participants. They are included only for informative reasons.

The individual results have been described using m_i, characterizing the difference between the calibration factor K_F measured by laboratory i with thread fixed probe and its ideal value 1 and using u_i, the relative standard uncertainty of m_i. m_i is defined by the equation

$$K_{Fi} = (1+m_i \cdot 10^{-3}). \qquad \text{(B1)}$$

m_i and u_i have been taken from table 6 of the report. According to the measurement uncertainties of some parts in 10^{-3} achieved in the comparison they have been rounded to figures without decimal places.

The degrees of equivalence with respect to the reference values have been described by D_i, the difference between the value of m_i and the reference value m_R for the compared quantity and by its expanded uncertainty U_i (k=2). As substantiated in section 4.3 of the report, m_R and its standard uncertainty u_R have been calculated as weighted mean of the results of IST, IEN and PTB according to the equations

$$m_R = u_R^{\,2} \left(\frac{m_{IST}}{u_{i+t\ IST}^{\,2}} + \frac{m_{IEN}}{u_{i+t\ IEN}^{\,2}} + \frac{m_{PTB}}{u_{i+t\ PTB}^{\,2}} \right), \qquad \text{(B2)}$$

and

$$u_R^{\,2} = \frac{1}{\dfrac{1}{u_{i+t\,IST}^{\,2}} + \dfrac{1}{u_{i+t\,IEN}^{\,2}} + \dfrac{1}{u_{i+t\,PTB}^{\,2}}} \qquad \text{(B3)}$$

Calculating m_R and u_R the transfer uncertainty u_t had to be taken into account. It describes the influences of transport, different surroundings and different measurement conditions on the transfer instrument during the time of the comparison. It was calculated as standard uncertainty of a single observation of the intermediate calibrations carried out by PTB as described in section 4.3 of the report. It had been calculated to u_t = 3,3, expressed in 10^{-3}, and had been considered as representative for all measurement points.

The influence of u_t on the uncertainty of the results is described introducing u_{i+t}, the total standard uncertainty of m_i:

$$u_{i+t} = (u_i^{\,2} + u_t^{\,2})^{1/2}. \qquad \text{(B4)}$$

The degree of equivalence D_i of laboratory i with respect to the reference value is characterized by D_i and its expanded uncertainty U_i (k=2):

$$D_i = m_i - m_R \qquad\qquad U_i = 2\, u_{i+t} \qquad \text{(B5) / (B6)}$$

with exception of IST, IEN and PTB. In these cases the correlated U_i was calculated from

$$U_i = 2\,(u_{i+t}^{\,2} - u_R^{\,2})^{1/2} \qquad \text{(B6a)}$$

D_i and U_i are epressed in 10^{-3}. After calculation, according to the measurement uncertainty, they have been rounded to figures without decimal places.

Table B1: Laboratory individual results and reference values

m_i: difference between K_{Fi} and the ideal value K_F =1, expressed in 10^{-3} — $m_i = (K_{Fi} - 1) \cdot 10^3$, K_{Fi} from table 6
u_i: standard uncertainty of m_i, expressed in 10^{-3}, — u_i from table 6
u_t: transfer uncertainty, expressed in 10^{-3}, — u_t = 3,3 , calculated in section 4.3
u_{i+t}: total standard uncertainty of m_i, expressed in 10^{-3}, — u_{i+t} calculated from eq. (B4) ,
m_R: reference value, expressed in 10^{-3}, — m_R calculated from eq. (B2) ,
u_R: standard uncertainty of m_R, expressed in 10^{-3}, — u_R calculated from eq. (B3) ,

Lab i	Range 200 V/m				Range 2 000 V/m						Date of measurement
	100 V/m		200 V/m		200 V/m		500 V/m		1000 V/m		
	m_i	u_{i+t}	m_i	u_{i+t}	m_i	u_{i+t}	m_i	u_{i+t}	m_i	u_{i+t}	
IST	0	5	6	5	-3	6	-2	6	-1	6	97-05
NGC	-15	10	-7	10	-	-	-21	10	-15	10	97-09
CEM	-4	6	3	6	-	-	-2	5	-3	5	97-10...97-11
NMI VSL	-14	4	-7	4	-19	5	-18	4	-18	4	98-01
IEN	-2	4	4	4	-5	4	-6	4	-2	4	98-02
GUM	0	4	-	-	15	4	-2	4	14	4	98-04
VNIIFTRI	-10	4	-3	4	-	-	2	5	6	5	98-07...98-08
PTB	-6	5	-1	5	-9	5	-10	4	-8	4	98-10
	m_R	u_R	m_R	u_R	m_R	u_R	m_R	u_R	m_R	u_R	
Reference value	-3	3	3	3	-6	3	-7	3	-4	3	97-05...98-10

Table B1: Laboratory individual results and reference values (continued)

m_i:	difference between K_{Fi} and the ideal value K_F =1, expressed in 10^{-3}	$m_i = (K_{Fi} - 1) \cdot 10^3$, K_{Fi} from table 6
u_i:	standard uncertainty of m_i, expressed in 10^{-3},	u_i from table 6
u_t:	transfer uncertainty, expressed in 10^{-3},	u_t = 3,3 , calculated in section 4.3
u_{i+t}:	total standard uncertainty of m_i, expressed in 10^{-3},	u_{i+t} calculated from eq. (B4) ,
m_R:	reference value, expressed in 10^{-3},	m_R calculated from eq. (B2) ,
u_R:	standard uncertainty of m_R, expressed in 10^{-3},	u_R calculated from eq. (B3) ,

Lab *i*	Range 2 000 V/m		Range 20 000 V/m								Date of measurement
	2000 V/m		2000 V/m		5000 V/m		10000 V/m		20000 V/m		
	m_i	u_{i+t}	m_i	u_{i+t}	m_i	u_{i+t}	m_i	u_{i+t}	m_i	u_{i+t}	
IST	6	6	-5	6	-3	6	0	6	6	6	97-05
NGC	-4	10	-	-	-14	10	-9	10	-5	10	97-09
CEM	-21	7	-	-	-29	9	-59	9	-	-	97-10...97-11
NMI VSL	-13	4	-21	5	-21	4	-21	4	-15	4	98-01
IEN	3	4	-5	4	-6	4	-5	4	-1	4	98-02
GUM	-	-	20	4	20	4	25	4	33	4	98-04
VNIIFTRI	14	5	-	-	4	5	0	5	-5	5	98-07...98-08
PTB	-2	4	-5	5	-8	4	-9	4	-3	5	98-10
	m_R	u_R	m_R	u_R	m_R	u_R	m_R	u_R	m_R	u_R	
Reference value	1	3	-5	3	-6	3	-5	3	0	3	97-05...98-10

Table B2: Degrees of equivalence

The degree of equivalence of each laboratory i with respect to the reference value is given by D_i and its expanded uncertainty U_i, both expressed in 10^{-3}.

D_i and U_i are calculated from equations (B5), (B6) and (B6a), respectively.

Lab i	Range 200 V/m				Range 2 000 V/m						Date of measurement
	100 V/m		200 V/m		200 V/m		500 V/m		1000 V/m		
	D_i	U_i	D_i	U_i	D_i	U_i	D_i	U_i	D_i	U_i	
IST	3	8	3	8	3	11	5	12	3	11	97-05
NGC	-12	19	-10	19	-	-	-14	19	-11	19	97-09
CEM	-1	12	0	12	-	-	5	10	1	10	97-10...97-11
NMI VSL	-11	9	-10	9	-13	10	-11	9	-14	9	98-01
IEN	1	6	0	6	1	7	1	6	2	6	98-02
GUM	3	9	-	-	21	9	5	9	18	9	98-04
VNIIFTRI	-7	8	-6	8	-	-	9	10	10	10	98-07...98-08
PTB	-3	8	-4	8	-3	8	-3	7	-4	7	98-10

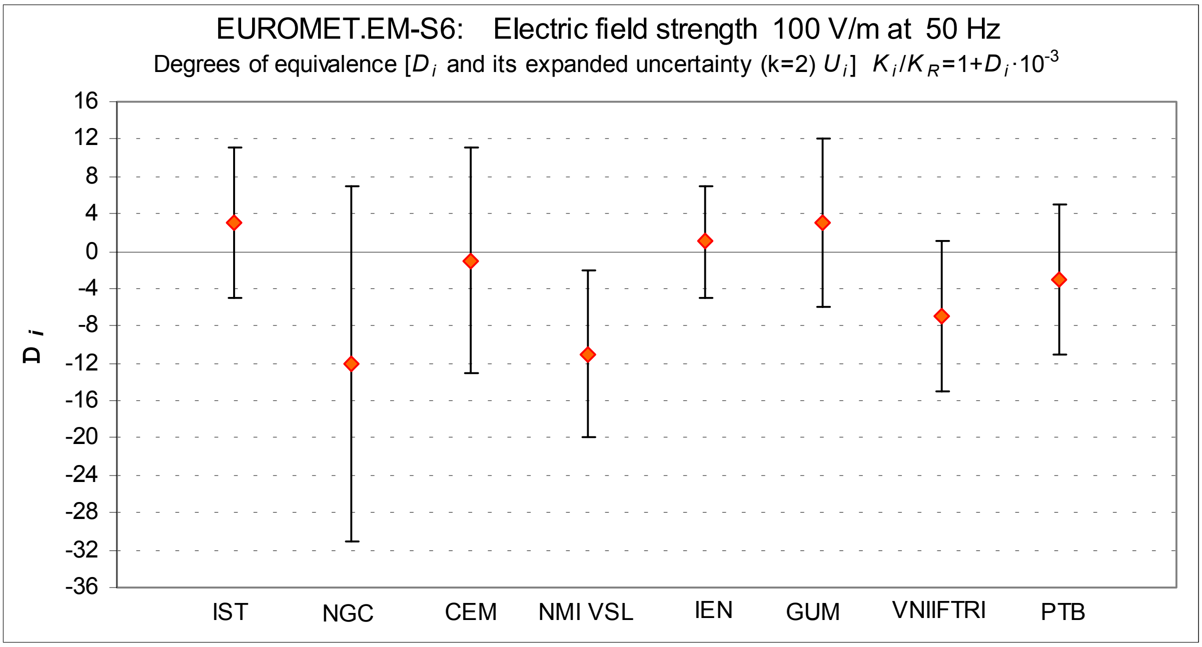
Table B2: Degrees of equivalence (continued)

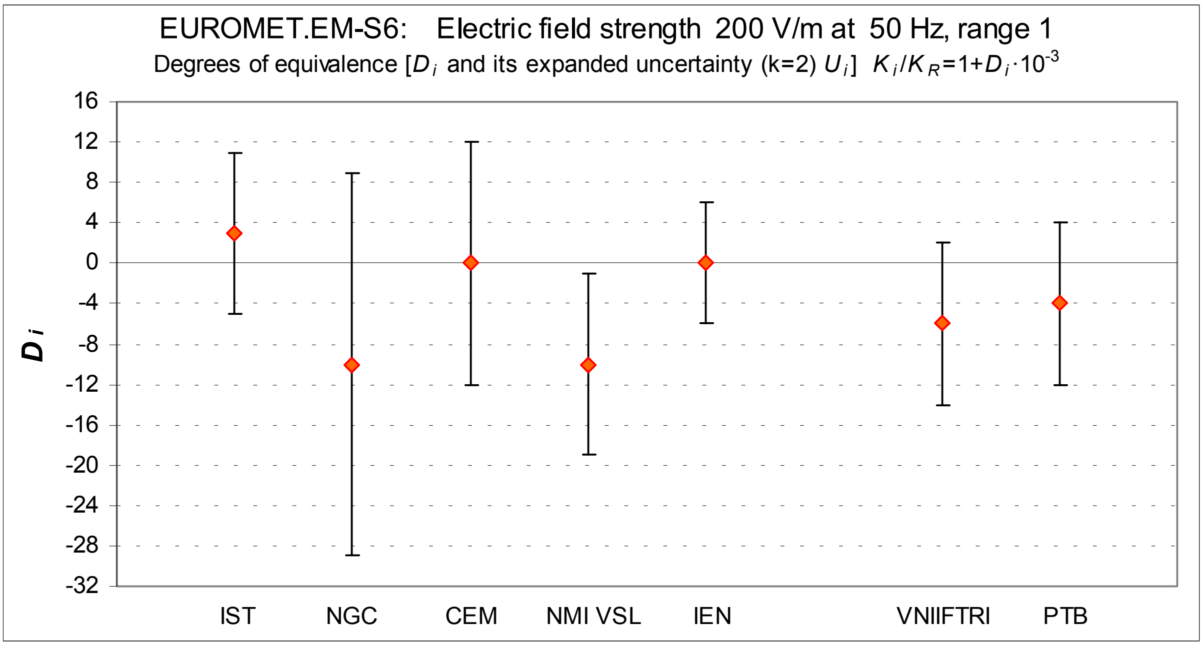
The degree of equivalence of each laboratory *i* with respect to the reference value is given by D_i and its expanded uncertainty U_i, both expressed in 10^{-3}.

D_i and U_i are calculated from equations (B5), (B6) and (B6a), respectively.

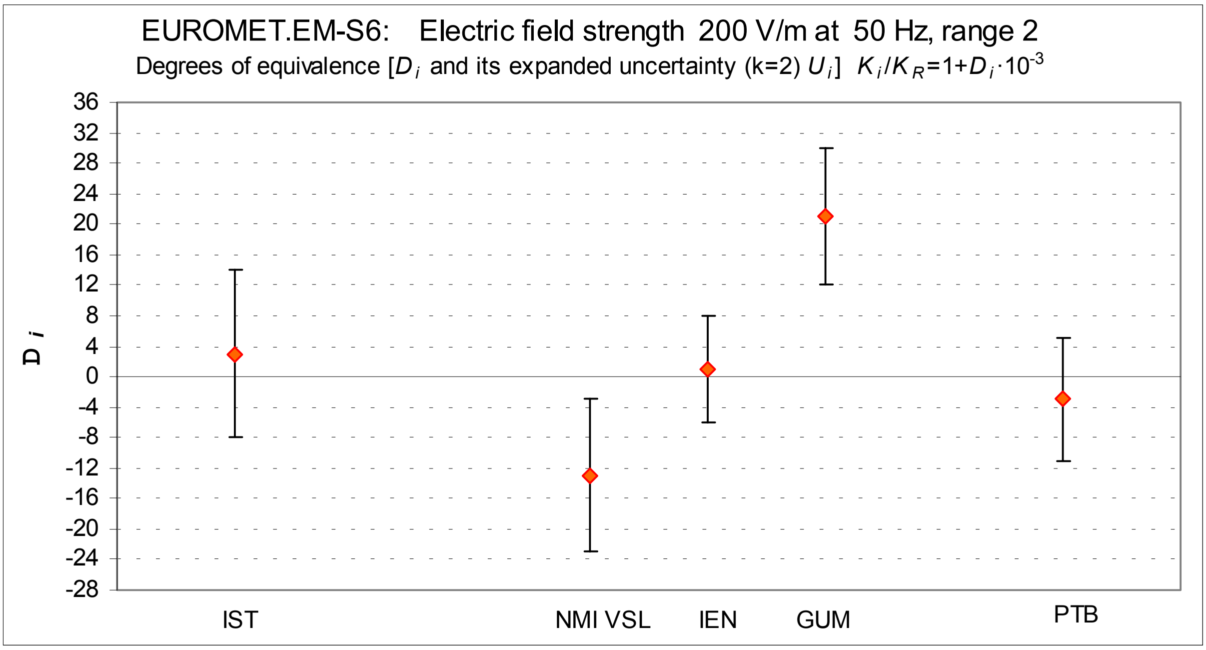
Lab *i*	Range 2 000 V/m		Range 20 000 V/m								Date of measurement
	2000 V/m		2000 V/m		5000 V/m		10000 V/m		20000 V/m		
	D_i	U_i	D_i	U_i	D_i	U_i	D_i	U_i	D_i	U_i	
IST	4	11	0	11	4	12	5	11	5	10	97-05
NGC	-5	19	-	-	-8	19	-4	19	-5	19	97-09
CEM	-23	15	-	-	-23	17	-54	17	-	-	97-10...97-11
NMI VSL	-14	9	-16	10	-15	9	-16	9	-15	9	98-01
IEN	1	6	0	7	0	6	0	6	-1	7	98-02
GUM	-	-	25	9	27	9	30	9	32	9	98-04
VNIIFTRI	12	10	-	-	10	10	5	10	-5	10	98-07...98-08
PTB	-3	7	0	8	-2	7	-3	7	-3	9	98-10

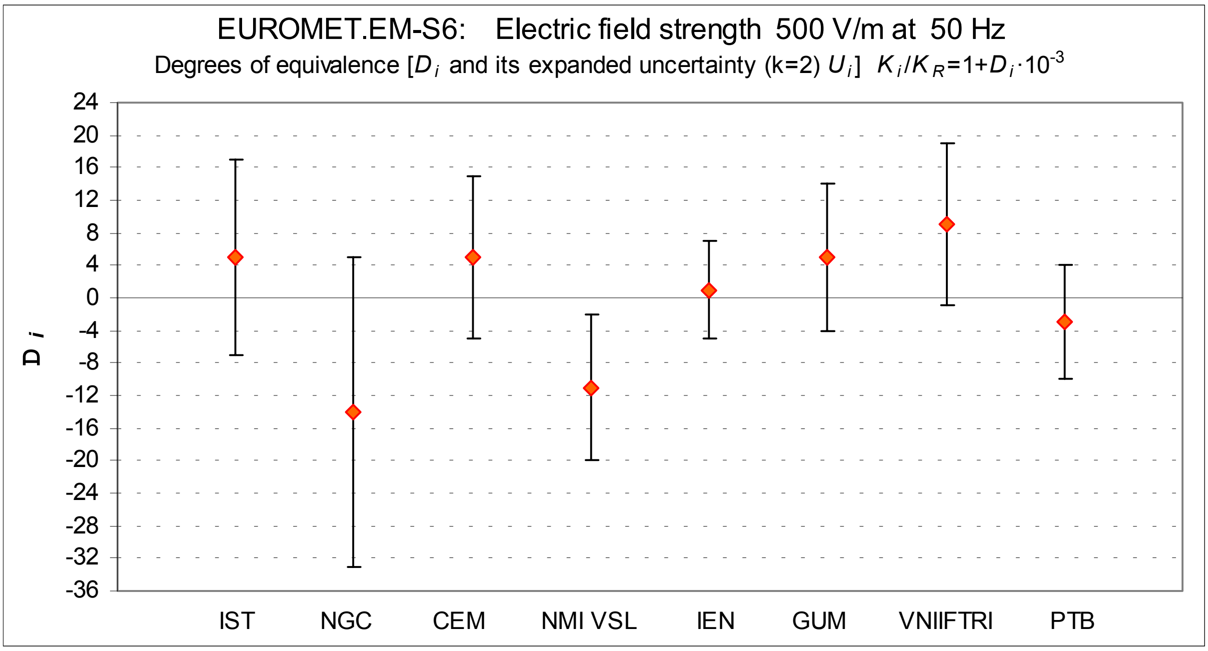
Graphs of equivalence



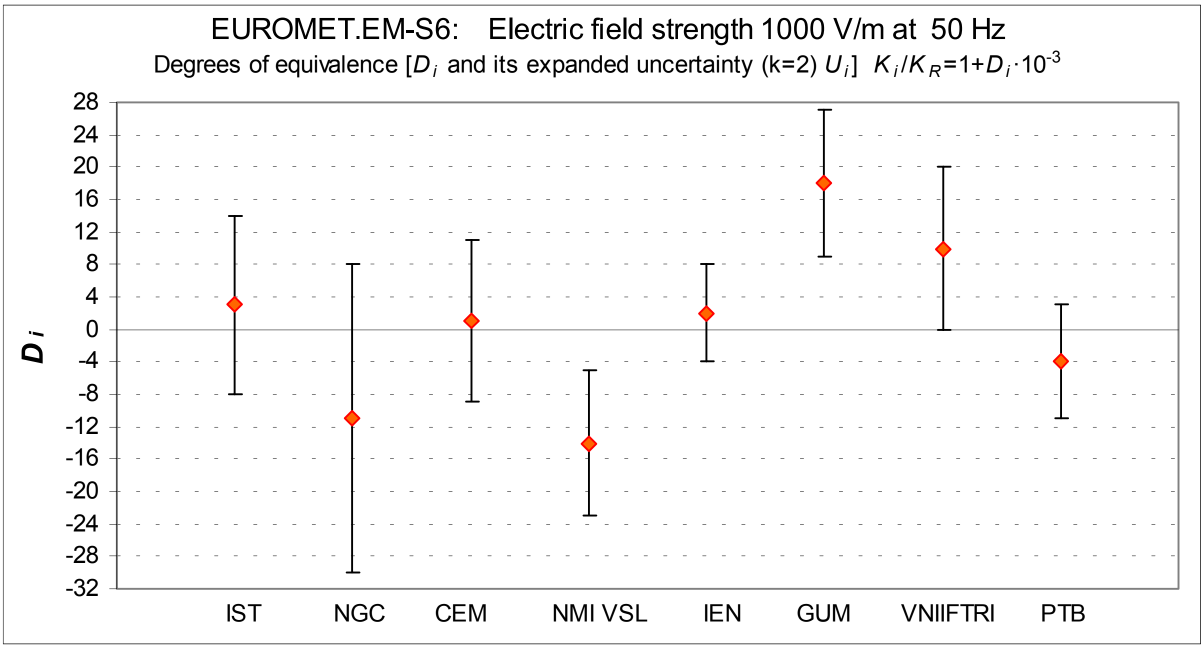


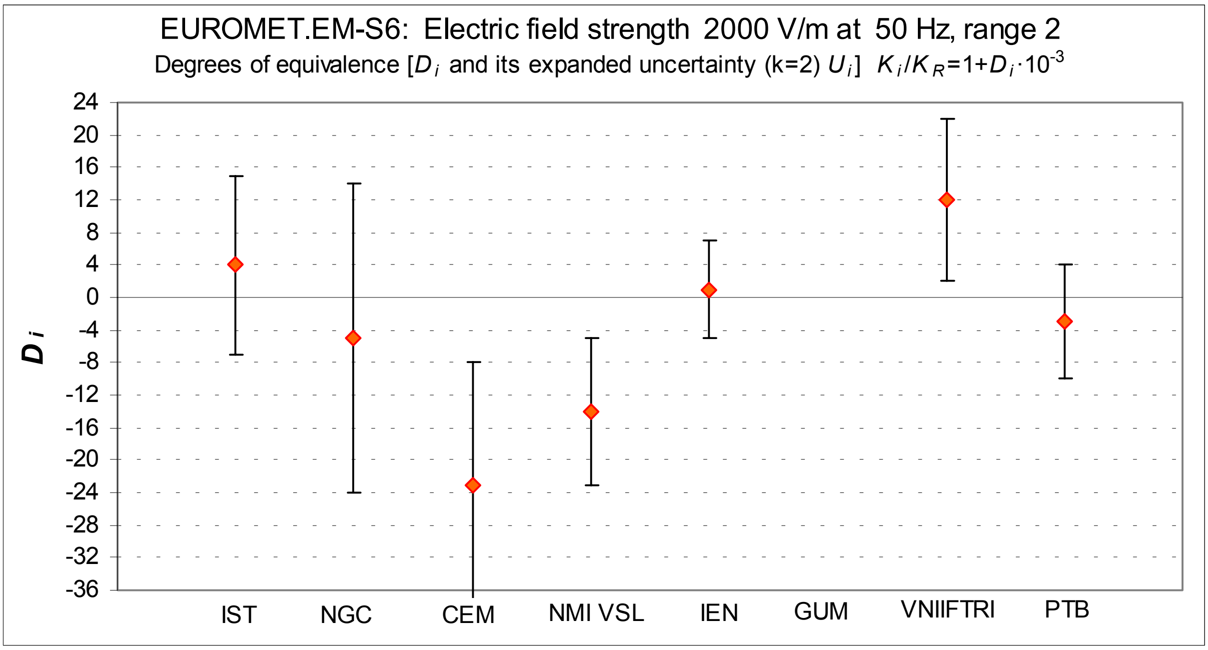
Graphs of equivalence (continued)



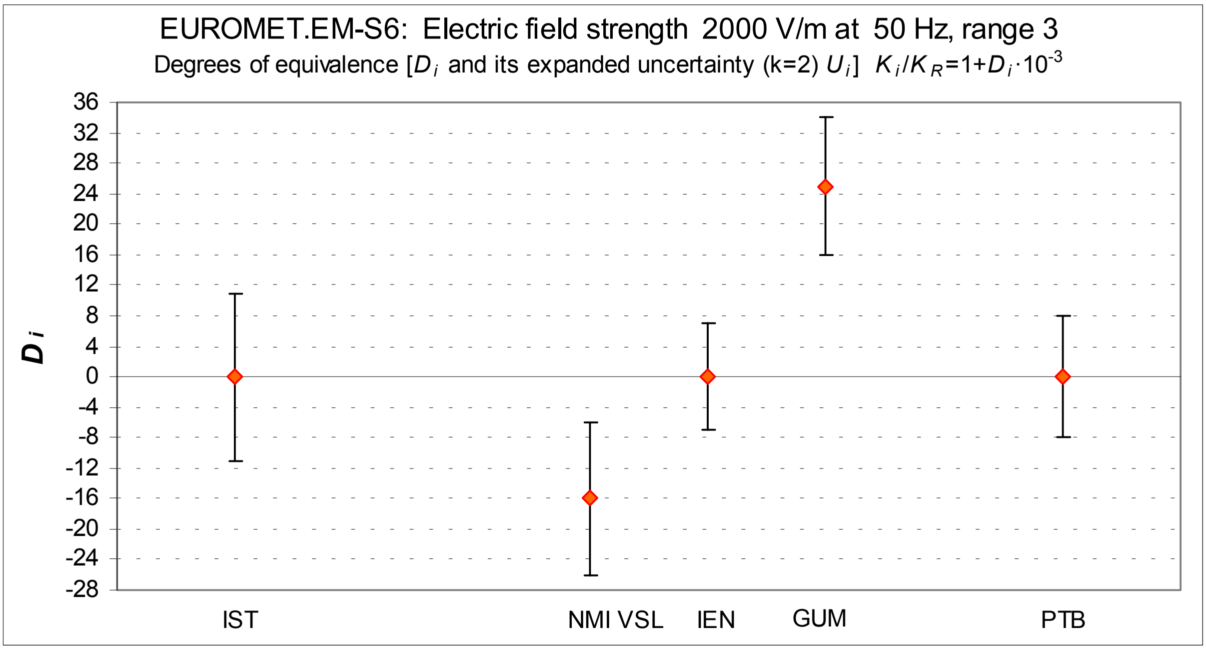


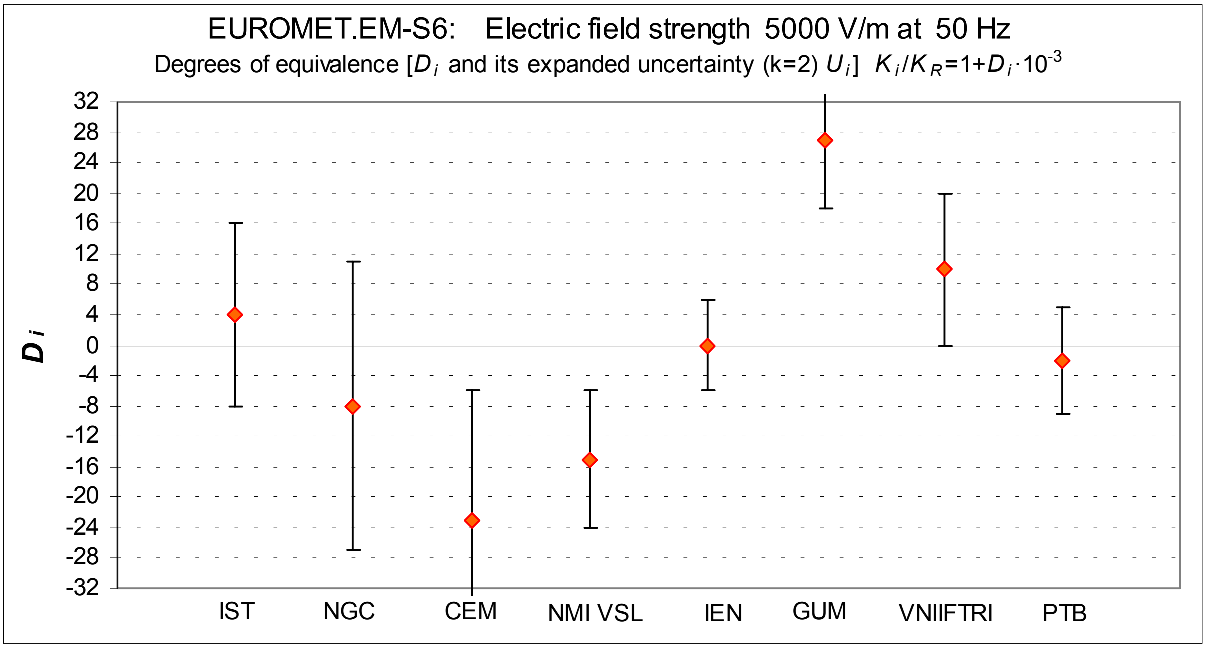
Graphs of equivalence (continued)





Graphs of equivalence (continued)





Graphs of equivalence (continued)