Final Report on GT-RF Key comparison CCEM.RF-K20

“Comparison of Electrical Field Strength Measurements”

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Summary

The comparison “EUROMET-Project Nr. 520” which started in April 1999 under the responsibility of the Swiss Federal Office of Metrology was extended to a GT-RF comparison “CCEM-RF-K.20” which officially started in September 2000, with more participants. The goal of this comparison was to assess the capability of each participating laboratory to measure electromagnetic field strength by calibrating a circulated field strength meter in the frequency range 10 MHz to 1 GHz. The comparison has been interrupted and further continued and ended finally in September 2004 when we received the measurements from all participants. This document presents the results of this comparison in the form of a Final Report.

Despite the fact that the probe may have suffered instabilities during the 5 long year of duration of this exercise, we consider that the results of all participants are consistent with the claimed uncertainty. The results support the equivalence of national standards laboratories for realization of field strength in the frequency range of 10 MHz … 1000MHz.

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Introduction

Motivation

Electric field strength is not a basic SI-Unit and, like magnetic field strengths and power flux density, cannot be realized as a material object such as the kilogram. Therefore, these units have to be generated by reproducible experiment using appropriate technical equipment. To generate known electromagnetic field strength as a primary standard the national metrology laboratories make use of various techniques. The objective of this project, based on the circulation of one standard field measuring system, was to assess the field strength of the various realizations of field generators and the uncertainties in the frequency range 10 MHz-1GHz.

Historical background

This project is in fact the continuation of another comparison “EUROMET-Project Nr 520” which started in April 1999 under the responsibility of the Swiss Federal Office of Metrology (former called OFMET, today METAS). This project was extended to a GT-RF (CCEM Working Group on Radiofrequency Quantities) comparison “CCEM.RF-K20” (Consultative Committee for Electricity and Magnetism, Radio Frequency) which officially started in September 2000, with participants all around the world. This report covers both the EUROMET-Project Nr 520 as well as the CCEM.RF-K20 comparison.

Scope of the comparison

The goal of the comparison was to calibrate the circulated field strength meter (“Travelling Standard, Electric Field Strength Meter Number 14” from PTB, including polarized E-field sensor and the electronic box). Each participant was asked to expose the probe to his own electrical field and apply measuring facilities and methods as he does for calibrating transfers. Requested was the averaged actual field strength required to produce a probe reading of 20 V/m, and the requested frequencies were defined as: 30 MHz, 100 MHz, 300 MHz, and 900 MHz. It was left to the participant’s choice to add the further frequencies used in the EUROMET comparison 520. These frequencies are within the range of 10 MHz and 1000 MHz: 10 MHz, 30 MHz, 50 MHz, 100 MHz, 200 MHz, 300 MHz, 400 MHz, 500, MHz, 600 MHz, 700 MHz, 800 MHz, 900 MHz, and 1000 MHz. ¨

Participants and organization of the comparison

List of participants

Acronym	National Metrology Institute	Country	Responsible
PTB	Physikalisch-Technische Bundesanstalt	Germany	Klaus Münter
METAS (formerly OFMET)	Swiss Federal Office of Metrology and Accreditation	Switzerland	Jacques Degoumois (until 2001) Frédéric Pythoud
NPL	National Physical Laboratory	United Kingdom	David Gentle
NMi-VSL	Nederlands Meetinstituut Van Swindern Laboratorium	The Netherlands	George Teunisse
STUK	Radiation and Nuclear Safety Authority	Finland	Lauri Puranen
IEN	Instituo Electrotecnico Nazionale	Italy	Michele Borsero
NML-CSIR	National Metrology Laboratory	South Africa	Erik Dressler
SP	Swedish National Testing and Research Institute	Sweden	Jan Welinder
KRISS	Korea Research Institute of Standards and Science	Korea	Jin Seob Kang
CSIRO	National Measurement Laboratory[1]	Australia	Mike Daly
NIM	National Institute of Metrology of China	China	Xie Ming
VNIIFTRI	All-Russian Scientific and Research Institute for Physical-Technical and Radiotechnical Measurement	Russia	Vladimir Tischenko
CMI	Czech Metrology Institute	Czech Republic	Karel Drazil

Comparison schedule

Date	Acronym	Action
EUROMET-Project Nr 520		
May 1999	PTB	Measurement
July 1999	METAS 1	Measurement
August 1999	NPL	Measurement
September 1999	NMi-VSL	Measurement
October 1999	METAS 2	Function and stability test
November 1999	STUK	Measurement
January 2000	IEN	Measurement
February 2000	METAS 3	Function and stability test. Small drift of the probe noticed
March 2000	METAS 4	Function and stability test. Drift of the probe increased
April 2000	PTB	Probe repaired. New calibration of the probe used for further measurements
May 2000	METAS 5	Function and stability test
June 2000	NML-CSIR	Measurement
August 2000	METAS 6	Function and stability test Important drift of the probe
September 2000	PTB	Probe repaired. New calibration of the probe used for further measurements
October 2000	METAS 7	Function and stability test
January 2001	SP	Measurement
January 2001	METAS 8	Function and stability test

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[1] Now the National Measurement Institute, Australia.

Date	Acronym	Action
		Important drift of the probe
March 2001	PTB	Probe repaired. New calibration of the probe used for further measurements
GT-RF comparison “CCEM.RF-K20”		
August 2001	KRISS	Measurement
October 2001		Broken cable of the probe had to be repaired. No new calibration performed
November 2001-August 2003		----- Interruption of the comparison -----
September 2002	METAS 9	Function and stability test
May 2003	METAS 10	Function and stability test
August 2003	CSIRO	Measurement
August 2003	METAS 11	Function and stability test
October 2003	NIM	Measurement
December 2003	VNIIFTRI	Broken cable of the probe had to be repaired. No new calibration performed
January 2004	VNIIFTRI	Measurement
April 2004	CMI	Measurement
July 2004	METAS 12	Function and stability test

Organization of the comparison

The pilot laboratory was METAS and the transfer standard carefully packed in an adapted suitcase has been sent by post.

Unexpected incidents

Several incidents have to be reported here which delayed this comparison considerably:

- The standard suffered drifts and had for these reasons to be repaired and new calibrated several times as shown by the previous table.
- The comparison has been interrupted in 2001 due to the death of Mr Degoumois in charge of this comparison at METAS. The comparison continued in July 2003.
- In addition to the EUROMET-Project Nr 520 participants, KRISS, CSIRO, and VNIIFTRI joined the CCEM.RF-K20 key comparison. Later CMI also joined the comparison.

Traveling standard and measurement instructions

Description of the standard

The traveling standard provided is a high frequency field strength meter system designed by and belonging to PTB. It consists of the miniature field sensor with a high resistance DC connection (conductive plastic) to an electronic box, a bundle of four optical fibres and a control program for a computer running under Window 3.1, Windows 95, or MS-DOS. Field sensor, electronics box and associated reference data files have the serial number S/N 014. The characteristics of the system are:

Technical Data:

The system may have different technical characteristics, depending on the type of field sensor, available are now:

E-Field Reference Sensor	frequency range: 1 MHz ... 1 GHz, field strength range: 15 V/m ... 100 V/m, ambient temperature: 16 ^{0}C... 30 ^{0}C, disc shaped diameter of active area: 12 mm, height: 2 mm
„Electronics box"	aluminium case: shielded, function independent of orientation, dimensions: 160 x 100 x 75 mm, mass / weight: 0.9 kg (with battery pack installed) power supply: built-in NiCd rechargeable battery pack with 8 cells (size AA, „Mignon“), 600 mAh, operating time: max. 10 hours (can be switched to external mains power supply).
Optical interface	cable: bundle of four plastic optical fibers, max. length 30 m, computer interface: modified 25 pin „Min-D“ connector for printer port, power for the optical interface supplied by the computer.
Software supplied with the system	Ready-to-use control programs to operate the system via keyboard and screen: - MS-DOS version on 25 x 80 characters colour text display, - Windows version (16-bit application, runs with Microsoft Windows 3.1 or -95) Driver software to be included in user written control programs: - units with objects for Turbo-Pascal (Version 7 for DOS) or Delphi, - 16-Bit Windows-DLL for access from other programming languages, Calibration data files for the electronics box and field sensor(s).

Photos

Figure 1 Electronic box with field probe and optical interface.

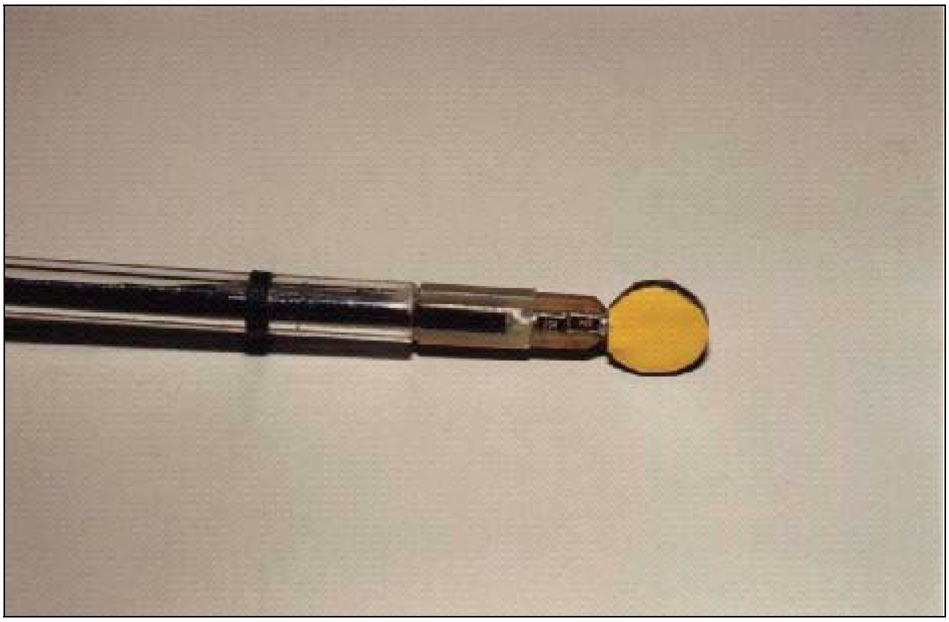

Figure 2 Detailed view of the reference sensor (in yellow is the active area).

Quantities to be measured and conditions of measurement

The goal of the exercise is to calibrate the circulated field strength meter. Each participant should expose the probe to his own electrical field and apply measuring facilities and methods as he does for accurate transfers.

- At the given frequency the field strength should be adjusted for a probe readout of 20 V/m. During all the measurements the readout value should be kept within ± 0.5 V/m of the nominal value of 20.0 V/m.
- The frequencies selected for the GT-RF comparison are:

  30 MHz; 100 MHz; 300 MHz; 900 MHz.

- It is left to the participant's choice to add the further frequencies used in the present EUROMET comparison 520. These frequencies are within the range of 10 MHz to 1000 MHz and include those selected for the key comparison:

  10; **30**; 50; **100**; 200; **300**; 400; 500; 600; 700; 800; **900**; 1000 MHz.

- Temperature of the probe’s test volume: 23 °C ± 1 °C.

The field probe is controlled by a PC program. Note that the ambient temperature of the probe must be entered in designated display in order to activate the temperature compensation. As long as the ambient temperature of the probe remains within +/- 0.2 °C of the entered value, the readout of the meter is taken as accurate.

Measurement instructions

The report submitted by every participant should include the following information:

- Description of the “local realisation” of the electrical field.
- Description of the installed measuring equipment and how it is used.
- Methods of calculation to obtain the field strength
- Final measurement results including measurement uncertainties (uncertainty budget)

To produce easily comparable results the participant converts his set of measured raw data into an equivalent final set, in which the field sensor read-out assumes the value of 20.0 V/m. The transformation is linear.

Methods of measurements

Frequency in MHz	**10**	**50**	**200**	**250**	**300**	**1000**
PTB	**Micro TEM Cell** 10 MHz … 1000 MHz	traceable through Power measurements				
METAS	**Micro TEM Cell** 10 MHz … 1000 MHz	traceable through Power measurements				
NPL	**TEM Cell EMCO,** 10 MHz ... 50 MHz					
	TEM Cell IFI, 10 MHz ... 200 MHz			all traceable to Power measurements		
		TEM Cell Narda, 10 MHz ... 300 MHz				
			Tapered cell, 200 MHz ... 1000 MHz			
NMi-VSL	**Mini TEM Cell** 10 MHz ... 1000 MHz	traceable through Power measurements				
STUK	**TEM Cell** 10 MHz ... 300 MHz	traceable through Power measurements			**Anechoic chamber**, 900 MHz traceable through the waveguide section of a horn antenna (via Power measurements)	
IEN	**TEM Cell** 10 MHz ... 200 MHz	traceable through Power measurements	**GTEM Cell** 200 MHz … 1000 MHz	traceable through Power measurements		
CSIR-NML	**Micro TEM Cell** 10 MHz … 1000 MHz	traceable through Power measurements				
SP	**Micro TEM Cell** 10 MHz … 1000 MHz	traceable through Power measurements				
KRISS	**Micro TEM Cell** 10 MHz … 1000 MHz	traceable through Power measurements				
CSIRO	**GTEM Cell** 10 MHz … 1000 MHz	traceable through Micro TEM Cell (via Power measurements)				
NIM	**Micro TEM Cell** 10 MHz … 1000 MHz	traceable through Power measurements				
VNIIFTRI	**TEM Cell** 30 MHz … 300 MHz	traceable through: a. Calculable four wire feeder (30 MHz) b. Calculable biconical antenna (100 MHz … 300 MHz)			**Anechoic chamber**, 900 MHz traceable through calculable biconical antenna (600 MHz … 900 MHz)	
CMI	**TEM Cell**	traceable through Power measurements	10 MHz … 250 MHz	**Tapered Cell** 250 MHz … 1000 MHz	traceable through Power measurements	

Figure 3 Summary of the field generation methods and of their traceability.

The principles of the above mentioned techniques are briefly mentioned in Annex B.

Measurements of the pilot laboratory

Information about the stability of the traveling standard during the comparison can be obtained from the sets of measurements made by METAS from July 1999 to July 2004 (see Figure 4). The measurement uncertainty on the measured values is 1.8% (one standard deviation).

Frequency (MHz)	July 1999 E-field (V/m)	Oct. 1999 E-field (V/m)	Feb. 2000 E-field (V/m)	Mar. 2000 E-field (V/m)	Apr. 2000 Repair new calibration	May 2000 E-field (V/m)	Aug. 2000 E-field (V/m)	Sep. 2000 Repair new calibration	Oct. 2000 E-field (V/m)
10	19.50	19.50	19.30	18.99		19.61	21.16		19.07
30	19.64	19.65	19.43	19.10		19.81	21.26		19.11
50	19.58	19.63	19.39	19.08		19.76	21.22		19.16
100	19.68	19.70	19.47	19.14		19.79	21.10		19.27
200	19.87	19.87	19.66	19.32		19.99	21.37		19.49
300	20.09	20.08	19.87	19.62		20.23	21.66		19.68
400	20.21	20.19	19.99	19.67		20.35	21.80		19.87
500	20.19	20.18	19.98	19.75		20.44	21.71		19.84
600	20.12	20.11	19.90	19.66		20.37	21.71		19.83
700	20.13	20.10	19.90	19.64		20.34	21.63		19.80
800	20.25	20.23	20.05	19.78		20.41	21.64		19.92
900	20.42	20.41	20.20	20.00		20.65	21.68		20.17
1000	20.65	20.61	20.44	20.26		20.86	21.88		20.41

Frequency (MHz)	Jan. 2001 E-field (V/m)	Mar. 2001 Repair new calibration	Oct. 2001 Repair no new calibration	Sep. 2002 E-field (V/m)	May 2003 E-field (V/m)	Aug. 2003 E-field (V/m)	Dec. 2003 Repair no new calibration	July 2004 E-field (V/m)
10	16.99			18.80	19.80	19.60		19.18
30	17.16			18.80	19.80	19.70		19.36
50	17.26			18.80	20.00	19.60		19.43
100	17.39			18.90	19.90	19.70		19.45
200	17.62			19.00	19.90	19.70		19.49
300	17.85			19.00	19.80	19.70		19.56
400	18.12			19.10	20.00	19.90		19.69
500	18.09			19.30	20.10	20.00		19.83
600	18.20			19.40	20.20	20.30		20.02
700	18.21			19.60	20.50	20.50		20.25
800	18.39			19.90	20.50	20.60		20.44
900	18.66			19.90	20.60	20.70		20.54
1000	18.93			20.00	20.60	20.60		20.60

The data are represented graphically on the next Figure.

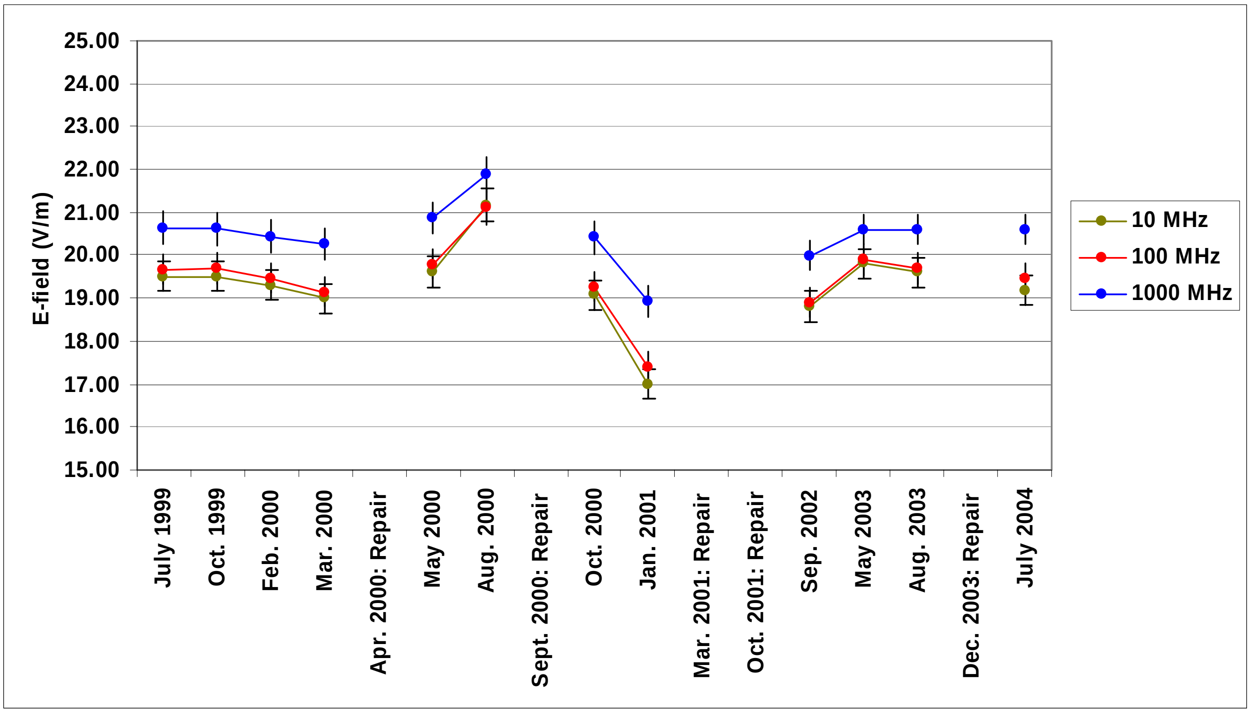

Figure 4 Overview of the stability of the probe.

The measurements definitely show that the probe suffers instability problems. However, after each instability problem noticed, the probe was sent for repair to PTB and was then calibrated again. For the new calibrations performed by PTB, we required that the transfer probe was always calibrated in the same Micro TEM cell as during the original calibration. Without this precaution, the measurements of the laboratories could not have been simply compared. From the comparison schedule (section 2.2) and from the previous figure, we conclude that the probe has been stable for PTB, METAS, NPL, NMi-VSL since their measurements were performed between July 1999 and October 1999. There is also a fair chance that the measurements of STUK and IEN (performed between October 1999 and February 2000) are not affected by the probe drift. More questionable are the measurements of CSIR-NML (June 2000) and SP (January 2001) since the probe has suffered instability during that time.
We therefore must admit that the probe has been instable during the whole duration of the comparison. However we did not perform any correction to the participant's measurements, since precise values for the drift are missing.

Measurement results

Results of participants

Each participant gave the averaged actual field strength (V/m) required to produce a sensor reading of 20 V/m. As the electric field sensor was always calibrated at PTB, their value of the field strength was assumed to be 20V/m.

10 MHz		
Laboratory	Field Strength (V/m)	Standard Uncertainty
PTB	20.00	0.30
METAS 1	19.50	0.35
NPL	20.06	0.35
NMi-VSL	19.82	0.15
STUK	19.70	0.48
IEN	19.20	1.00
CSIR	19.29	0.39
SP		
KRISS	20.32	0.28
CSIRO	21.22	1.01
NIM	20.74	0.41
VNIIFTRI		
CMI	19.15	0.68

30 MHz		
Laboratory	Field Strength (V/m)	Standard Uncertainty
PTB	20.00	0.30
METAS 1	19.64	0.35
NPL	20.18	0.35
NMi-VSL	19.94	0.12
STUK	20.00	0.48
IEN	19.20	1.00
CSIR	19.38	0.39
SP	19.10	0.76
KRISS	20.37	0.27
CSIRO	21.19	0.96
NIM	20.84	0.41
VNIIFTRI	20.90	0.65
CMI	19.86	0.56

50 MHz		
Laboratory	Field Strength (V/m)	Standard Uncertainty
PTB	20.00	0.30
METAS 1	19.58	0.35
NPL	20.12	0.35
NMi-VSL	19.94	0.12
STUK	19.90	0.48
IEN	19.10	1.00
CSIR	19.44	0.39
SP	19.80	0.79
KRISS	20.28	0.28
CSIRO	21.12	1.03
NIM	20.86	0.42
VNIIFTRI		
CMI	19.89	0.56

100 MHz		
Laboratory	Field Strength (V/m)	Standard Uncertainty
PTB	20.00	0.30
METAS 1	19.68	0.35
NPL	19.80	0.34
NMi-VSL	20.00	0.12
STUK	20.40	0.48
IEN	19.50	1.00
CSIR	19.47	0.39
SP	18.90	0.75
KRISS	20.28	0.27
CSIRO	21.12	0.92
NIM	20.90	0.41
VNIIFTRI	21.10	0.65
CMI	20.12	0.55

200 MHz		
Laboratory	Field Strength (V/m)	Standard Uncertainty
PTB	20.00	0.30
METAS 1	19.87	0.36
NPL	20.67	0.36
NMi-VSL	20.23	0.12
STUK	20.40	0.48
IEN	20.80	1.00
CSIR	19.57	0.39
SP	19.30	0.77
KRISS	20.35	0.29
CSIRO	20.99	1.12
NIM	20.99	0.42
VNIIFTRI		
CMI	20.26	0.57

300 MHz		
Laboratory	Field Strength (V/m)	Standard Uncertainty
PTB	20.00	0.30
METAS 1	20.09	0.36
NPL	20.46	0.36
NMi-VSL	20.41	0.14
STUK	20.30	0.48
IEN	20.20	2.40
CSIR	19.74	0.39
SP	19.80	0.79
KRISS	20.60	0.27
CSIRO	21.48	1.01
NIM	21.08	0.42
VNIIFTRI	21.80	0.68
CMI	19.66	0.86

400 MHz		
Laboratory	Field Strength (V/m)	Standard Uncertainty
PTB	20.00	0.30
METAS 1	20.21	0.36
NPL	20.44	0.56
NMi-VSL	20.42	0.14
STUK		
IEN	19.50	2.30
CSIR	19.88	0.40
SP	19.60	0.78
KRISS	20.92	0.28
CSIRO	21.94	1.15
NIM	21.18	0.42
VNIIFTRI		
CMI		

500 MHz		
Laboratory	Field Strength (V/m)	Standard Uncertainty
PTB	20.00	0.30
METAS 1	20.19	0.36
NPL	20.96	0.57
NMi-VSL	20.23	0.15
STUK		
IEN	19.40	2.30
CSIR	20.07	0.40
SP	19.40	0.77
KRISS	21.21	0.29
CSIRO	21.53	1.04
NIM	21.19	0.42
VNIIFTRI		
CMI		

600 MHz		
Laboratory	Field Strength (V/m)	Standard Uncertainty
PTB	20.00	0.30
METAS 1	20.12	0.36
NPL	20.64	0.56
NMi-VSL	20.07	0.16
STUK		
IEN	21.60	2.60
CSIR	20.19	0.40
SP	20.00	0.80
KRISS	21.32	0.28
CSIRO	21.72	1.10
NIM	21.26	0.41
VNIIFTRI		
CMI		

700 MHz		
Laboratory	Field Strength (V/m)	Standard Uncertainty
PTB	20.00	0.30
METAS 1	20.13	0.36
NPL	20.77	0.56
NMi-VSL	20.14	0.17
STUK		
IEN	20.60	3.30
CSIR	20.22	0.40
SP	19.80	0.79
KRISS	21.17	0.29
CSIRO	21.89	1.14
NIM	21.35	0.43
VNIIFTRI		
CMI		

800 MHz		
Laboratory	Field Strength (V/m)	Standard Uncertainty
PTB	20.00	0.30
METAS 1	20.25	0.36
NPL	20.75	0.56
NMi-VSL	20.39	0.18
STUK		
IEN	21.10	3.40
CSIR	20.13	0.40
SP	19.70	0.79
KRISS	20.81	0.29
CSIRO	21.41	1.03
NIM	21.47	0.42
VNIIFTRI		
CMI		

900 MHz		
Laboratory	Field Strength (V/m)	Standard Uncertainty
PTB	20.00	0.30
METAS 1	20.42	0.37
NPL	20.98	0.57
NMi-VSL	20.58	0.20
STUK	19.90	0.50
IEN	20.30	3.20
CSIR	20.05	0.40
SP	19.50	0.78
KRISS	20.69	0.29
CSIRO	21.56	0.98
NIM	21.61	0.43
VNIIFTRI	21.60	0.60
CMI	19.81	0.91

1000 MHz		
Laboratory	Field Strength (V/m)	Standard Uncertainty
PTB	20.00	0.30
METAS 1	20.65	0.37
NPL	21.20	0.58
NMi-VSL	20.53	0.21
STUK		
IEN	21.20	3.40
CSIR	20.16	0.40
SP	19.60	0.78
KRISS	20.93	0.29
CSIRO	21.92	1.05
NIM	21.83	0.42
VNIIFTRI		
CMI		

The ambient conditions are reported in the next Table:

Laboratory	Temperature (°C)
PTB	16 °C … 30 °C (probe calibrated on the whole range)
METAS 1	22.8 °C … 23.2 °C
NPL	22.7 °C … 23.0 °C
NMi-VSL	22.4 °C … 23.5 °C
STUK	20 °C … 22 °C
IEN	22 °C … 24 °C
CSIR	22.8 °C … 23.2 °C
SP	22.8 °C … 23.2 °C
KRISS	22.8 °C … 22.9 °C
CSIRO	22.5 °C … 23.5 °C
NIM	22.98 °C … 23.02 °C
VNIIFTRI	16 °C … 21 °C
CMI	22.8 °C … 23.3 °C

Normalisation of the results

As mentioned in section 5, the drift of the probe has not been corrected. The effect of ambient conditions (temperature) has already been eliminated by the participants since the probe has been calibrated in the temperature range of 16 °C … 30 °C every 2 °C, and the temperature dependence of the field probe calibration factor has been taken into account in the calibration factor used by the participants during their measurements.

Calculation of the reference value

According to reference [3], and taken into account that the field probe suffered instability and had to be calibrated several times in the 5 years duration of this comparison, we preferred the Procedure B (based on Median estimator) rather than on the Procedure A (classical weighted average) to determine the KCRV (Key Comparison Reference Value). The computation of the KCRV and its uncertainty has been performed according to the reference [3], by performing Monte-Carlo simulations with $N=10^6$ (a brief explanation is mentioned in Annex C). For the computation of the KCRV we used PTB, METAS (first measurement only), NPL, NMi-VSL, IEN, CSIR, SP, KRISS, CSIRO, NIM, and VNIIFTRI. STUK and CMI measurements have not been used since both institutes are not members but observers of the CCEM-GT-RF. All METAS measurements except the first one are considered as control measurements and therefore have not been taken into account for the KCRV. With this method we obtained the following estimation of the KCRV.

Frequency (MHz)	KCRV for Field Strength (V/m)	Standard Uncertainty (V/m)
10	19.96	0.17
30	20.04	0.16
50	19.99	0.15
100	20.01	0.15
200	20.23	0.16
300	20.42	0.17
400	20.38	0.19
500	20.39	0.21
600	20.48	0.25
700	20.46	0.24
800	20.48	0.20
900	20.62	0.20
1000	20.68	0.21

Degree of equivalence with respect to the KCRV

The degree of equivalence of all institutes with respect to the KCRV, as well as the shortest coverage interval at the 95% level of confidence (corresponds about to k=2 uncertainty on the deviation of the laboratory measurements to the KCRV) have been determined according to the reference [3]. To determine the uncertainties on the deviation to the KCRV of all measurements that have not been used in the KCRV computation (STUK, CMI, and the pilot laboratory measurements METAS2…METAS12), we used:

$$2\sqrt{s_m^{\ 2} + s_{KCRV}^{\ 2}}$$

where s_m and s_{KCRV} are the standard uncertainties related to the measurement and KCRV respectively.

10 MHz		
Laboratory	Deviation to KCRV (V/m)	Uncertainty at 95% c.l.[2] (V/m)
PTB	0.04	0.59
METAS 1	-0.46	0.68
NPL	0.10	0.67
NMi-VSL	-0.14	0.40
METAS 2	-0.46	0.78
STUK	-0.26	1.00
IEN	-0.76	1.89
METAS 3	-0.66	0.78
METAS 4	-0.97	0.76
METAS 5	-0.35	0.79
CSIR	-0.67	0.76
METAS 6	1.20	0.84
METAS 7	-0.89	0.76
SP		
METAS 8	-2.97	0.76
KRISS	0.36	0.56
METAS 9	-1.16	0.78
METAS10	-0.16	0.78
CSIRO	1.26	1.92
METAS11	-0.36	0.78
NIM	0.78	0.82
VNIIFTRI		
CMI	-0.81	1.38
METAS12	-0.36	0.78

30 MHz		
Laboratory	Deviation to KCRV (V/m)	Uncertainty at 95% c.l. (V/m)
PTB	-0.04	0.59
METAS 1	-0.40	0.69
NPL	0.14	0.68
NMi-VSL	-0.10	0.37
METAS 2	-0.39	0.78
STUK	-0.04	0.99
IEN	-0.84	1.91
METAS 3	-0.61	0.77
METAS 4	-0.94	0.75
METAS 5	-0.23	0.78
CSIR	-0.66	0.76
METAS 6	1.22	0.83
METAS 7	-0.93	0.75
SP	-0.94	1.45
METAS 8	-2.88	0.75
KRISS	0.33	0.54
METAS 9	-1.24	0.77
METAS10	-0.24	0.77
CSIRO	1.15	1.83
METAS11	-0.34	0.77
NIM	0.80	0.83
VNIIFTRI	0.86	1.24
CMI	-0.18	1.14
METAS12	-0.34	0.77

50 MHz		
Laboratory	Deviation to KCRV (V/m)	Uncertainty at 95% c.l. (V/m)
PTB	0.01	0.59
METAS 1	-0.41	0.68
NPL	0.13	0.67
NMi-VSL	-0.05	0.36
METAS 2	-0.36	0.77
STUK	-0.09	0.99
IEN	-0.89	1.91
METAS 3	-0.60	0.76
METAS 4	-0.91	0.75
METAS 5	-0.24	0.77
CSIR	-0.55	0.76
METAS 6	1.23	0.82
METAS 7	-0.83	0.75
SP	-0.19	1.50
METAS 8	-2.73	0.75
KRISS	0.29	0.56
METAS 9	-1.19	0.76
METAS10	0.01	0.76
CSIRO	1.13	1.97
METAS11	-0.39	0.76
NIM	0.87	0.86
VNIIFTRI		
CMI	-0.10	1.14
METAS12	-0.39	0.76

100 MHz		
Laboratory	Deviation to KCRV (V/m)	Uncertainty at 95% c.l. (V/m)
PTB	-0.01	0.59
METAS 1	-0.33	0.68
NPL	-0.21	0.66
NMi-VSL	-0.01	0.37
METAS 2	-0.31	0.77
STUK	0.39	0.99
IEN	-0.51	1.91
METAS 3	-0.54	0.76
METAS 4	-0.87	0.74
METAS 5	-0.22	0.77
CSIR	-0.54	0.75
METAS 6	1.09	0.82
METAS 7	-0.74	0.76
SP	-1.11	1.43
METAS 8	-2.62	0.76
KRISS	0.27	0.54
METAS 9	-1.11	0.76
METAS10	-0.11	0.76
CSIRO	1.11	1.76
METAS11	-0.31	0.76
NIM	0.89	0.86
VNIIFTRI	1.09	1.24
CMI	0.11	1.12
METAS12	-0.31	0.76

200 MHz		
Laboratory	Deviation to KCRV (V/m)	Uncertainty at 95% c.l. (V/m)
PTB	-0.23	0.59
METAS 1	-0.36	0.69
NPL	0.44	0.69
NMi-VSL	-0.00	0.36
METAS 2	-0.36	0.78
STUK	0.17	0.99
IEN	0.57	1.90
METAS 3	-0.57	0.78
METAS 4	-0.91	0.77
METAS 5	-0.24	0.78
CSIR	-0.66	0.77
METAS 6	1.14	0.82
METAS 7	-0.74	0.77
SP	-0.93	1.46
METAS 8	-2.61	0.77
KRISS	0.12	0.57
METAS 9	-1.23	0.77
METAS10	-0.33	0.77
CSIRO	0.76	2.14
METAS11	-0.53	0.77
NIM	0.76	0.83
VNIIFTRI		
CMI	0.03	1.16
METAS12	-0.53	0.77

300 MHz		
Laboratory	Deviation to KCRV (V/m)	Uncertainty at 95% c.l. (V/m)
PTB	-0.42	0.61
METAS 1	-0.32	0.71
NPL	0.04	0.71
NMi-VSL	-0.01	0.43
METAS 2	-0.35	0.80
STUK	-0.12	1.00
IEN	-0.22	4.63
METAS 3	-0.55	0.80
METAS 4	-0.80	0.79
METAS 5	-0.19	0.81
CSIR	-0.68	0.76
METAS 6	1.24	0.85
METAS 7	-0.74	0.78
SP	-0.62	1.51
METAS 8	-2.57	0.78
KRISS	0.18	0.56
METAS 9	-1.42	0.78
METAS10	-0.62	0.78
CSIRO	1.06	1.93
METAS11	-0.72	0.78
NIM	0.66	0.82
VNIIFTRI	1.38	1.37
CMI	-0.76	1.72
METAS12	-0.72	0.78

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[2] Confidence level

400 MHz		
Laboratory	Deviation to KCRV (V/m)	Uncertainty at 95% c.l. (V/m)
PTB	-0.38	0.62
METAS 1	-0.17	0.70
NPL	0.06	1.05
NMi-VSL	0.04	0.43
METAS 2	-0.19	0.82
STUK		
IEN	-0.88	4.43
METAS 3	-0.39	0.81
METAS 4	-0.71	0.80
METAS 5	-0.03	0.82
CSIR	-0.50	0.78
METAS 6	1.42	0.87
METAS 7	-0.51	0.81
SP	-0.78	1.47
METAS 8	-2.26	0.81
KRISS	0.54	0.61
METAS 9	-1.28	0.80
METAS10	-0.38	0.80
CSIRO	1.56	2.19
METAS11	-0.48	0.80
NIM	0.80	0.86
VNIIFTRI		
CMI		
METAS12	-0.48	0.80

500 MHz		
Laboratory	Deviation to KCRV (V/m)	Uncertainty at 95% c.l. (V/m)
PTB	-0.39	0.64
METAS 1	-0.20	0.71
NPL	0.57	1.08
NMi-VSL	-0.16	0.46
METAS 2	-0.21	0.84
STUK		
IEN	-0.99	4.40
METAS 3	-0.41	0.83
METAS 4	-0.64	0.83
METAS 5	0.05	0.85
CSIR	-0.32	0.77
METAS 6	1.32	0.89
METAS 7	-0.55	0.83
SP	-0.99	1.44
METAS 8	-2.30	0.83
KRISS	0.82	0.68
METAS 9	-1.09	0.82
METAS10	-0.29	0.82
CSIRO	1.14	1.97
METAS11	-0.39	0.82
NIM	0.80	0.86
VNIIFTRI		
CMI		
METAS12	-0.39	0.82

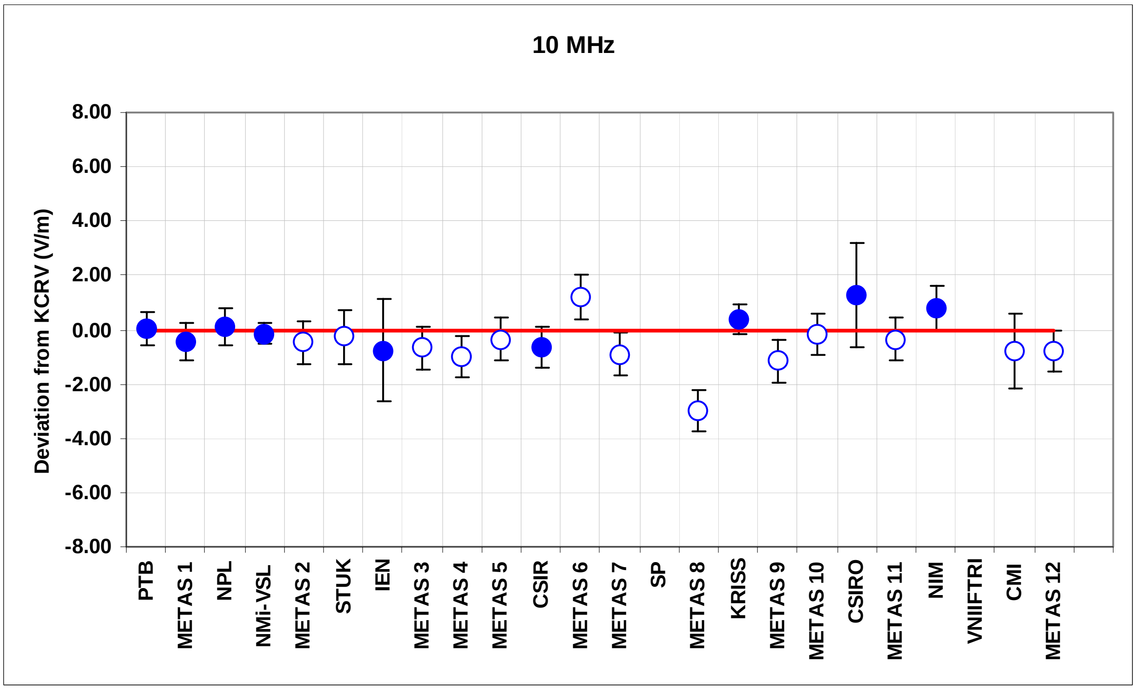
600 MHz		
Laboratory	Deviation to KCRV (V/m)	Uncertainty at 95% c.l. (V/m)
PTB	-0.48	0.69
METAS 1	-0.36	0.75
NPL	0.16	1.06
NMi-VSL	-0.41	0.54
METAS 2	-0.37	0.88
STUK		
IEN	1.12	4.98
METAS 3	-0.58	0.88
METAS 4	-0.82	0.86
METAS 5	-0.11	0.89
CSIR	-0.29	0.81
METAS 6	1.23	0.93
METAS 7	-0.65	0.88
SP	-0.48	1.49
METAS 8	-2.28	0.88
KRISS	0.84	0.72
METAS 9	-1.08	0.86
METAS10	-0.28	0.86
CSIRO	1.24	2.08
METAS11	-0.18	0.86
NIM	0.78	0.87
VNIIFTRI		
CMI		
METAS12	-0.18	0.86

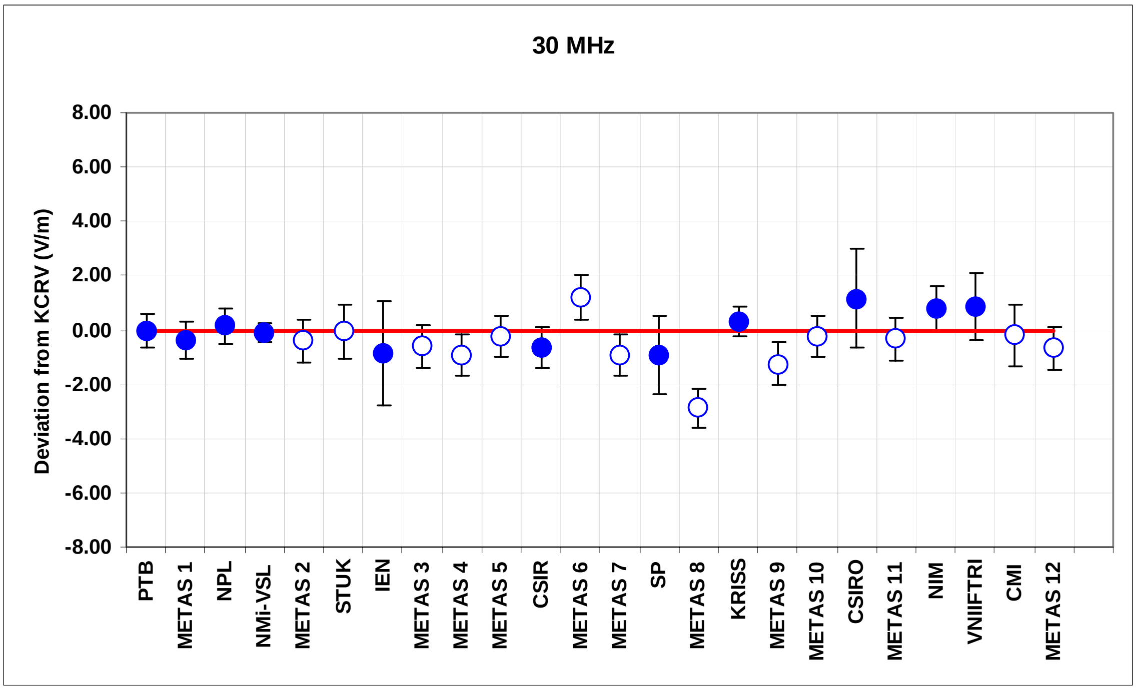
700 MHz		
Laboratory	Deviation to KCRV (V/m)	Uncertainty at 95% c.l. (V/m)
PTB	-0.46	0.68
METAS 1	-0.33	0.74
NPL	0.31	1.06
NMi-VSL	-0.32	0.53
METAS 2	-0.36	0.87
STUK		
IEN	0.14	6.36
METAS 3	-0.56	0.87
METAS 4	-0.82	0.85
METAS 5	-0.12	0.88
CSIR	-0.24	0.80
METAS 6	1.17	0.92
METAS 7	-0.66	0.87
SP	-0.66	1.48
METAS 8	-2.25	0.87
KRISS	0.71	0.70
METAS 9	-0.86	0.85
METAS10	0.04	0.85
CSIRO	1.43	2.16
METAS11	0.04	0.85
NIM	0.89	0.91
VNIIFTRI		
CMI		
METAS12	0.04	0.85

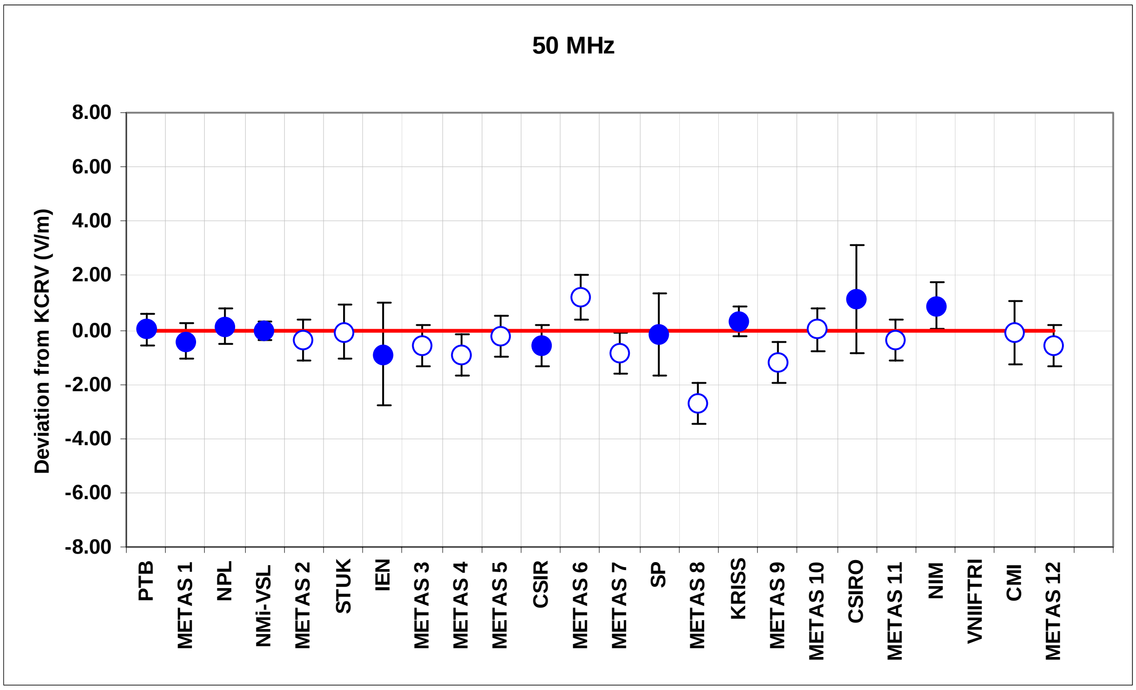
800 MHz		
Laboratory	Deviation to KCRV (V/m)	Uncertainty at 95% c.l. (V/m)
PTB	-0.48	0.64
METAS 1	-0.23	0.72
NPL	0.27	1.06
NMi-VSL	-0.09	0.48
METAS 2	-0.24	0.83
STUK		
IEN	0.62	6.58
METAS 3	-0.43	0.82
METAS 4	-0.70	0.82
METAS 5	-0.06	0.83
CSIR	-0.35	0.78
METAS 6	1.16	0.87
METAS 7	-0.56	0.82
SP	-0.78	1.50
METAS 8	-2.09	0.82
KRISS	0.33	0.60
METAS 9	-0.58	0.80
METAS10	0.02	0.80
CSIRO	0.93	1.96
METAS11	0.12	0.80
NIM	0.99	0.90
VNIIFTRI		
CMI		
METAS12	0.12	0.80

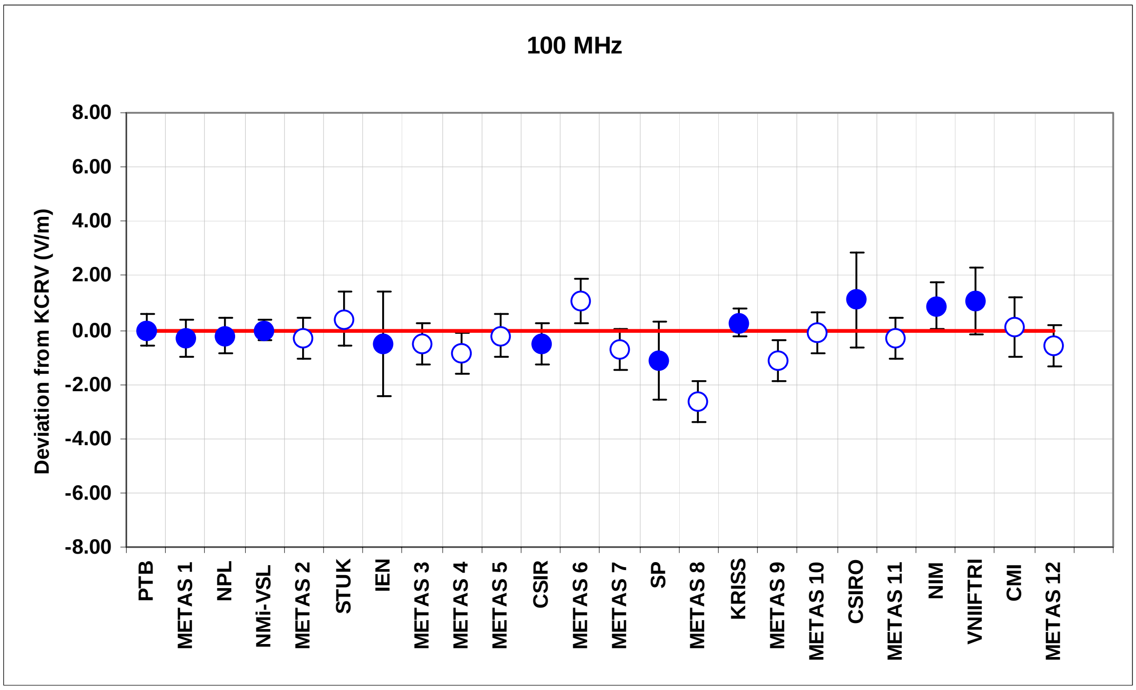
900 MHz		
Laboratory	Deviation to KCRV (V/m)	Uncertainty at 95% c.l. (V/m)
PTB	-0.62	0.66
METAS 1	-0.20	0.74
NPL	0.36	1.09
NMi-VSL	-0.04	0.52
METAS 2	-0.21	0.84
STUK	-0.72	1.06
IEN	-0.32	6.20
METAS 3	-0.42	0.84
METAS 4	-0.62	0.83
METAS 5	0.03	0.85
CSIR	-0.57	0.80
METAS 6	1.06	0.88
METAS 7	-0.45	0.82
SP	-1.12	1.49
METAS 8	-1.96	0.82
KRISS	0.07	0.62
METAS 9	-0.72	0.81
METAS10	-0.02	0.81
CSIRO	0.94	1.87
METAS11	0.08	0.81
NIM	0.99	0.93
VNIIFTRI	0.98	1.15
CMI	-0.81	1.82
METAS12	0.08	0.81

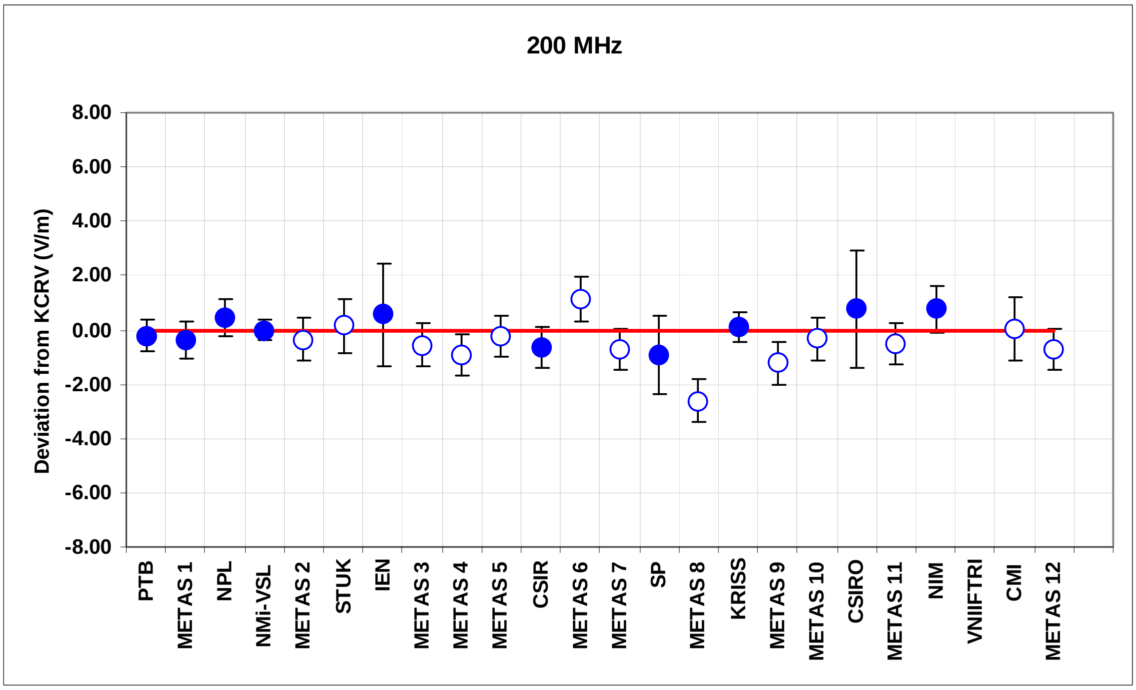
1000 MHz		
Laboratory	Deviation to KCRV (V/m)	Uncertainty at 95% c.l. (V/m)
PTB	-0.68	0.69
METAS 1	-0.03	0.72
NPL	0.52	1.09
NMi-VSL	-0.15	0.52
METAS 2	-0.07	0.85
STUK		
IEN	0.52	6.57
METAS 3	-0.24	0.85
METAS 4	-0.42	0.83
METAS 5	0.18	0.86
CSIR	-0.52	0.79
METAS 6	1.20	0.89
METAS 7	-0.27	0.85
SP	-1.08	1.48
METAS 8	-1.75	0.85
KRISS	0.25	0.61
METAS 9	-0.68	0.82
METAS10	-0.08	0.82
CSIRO	1.24	1.99
METAS11	-0.08	0.82
NIM	1.15	0.92
VNIIFTRI		
CMI		
METAS12	-0.08	0.82

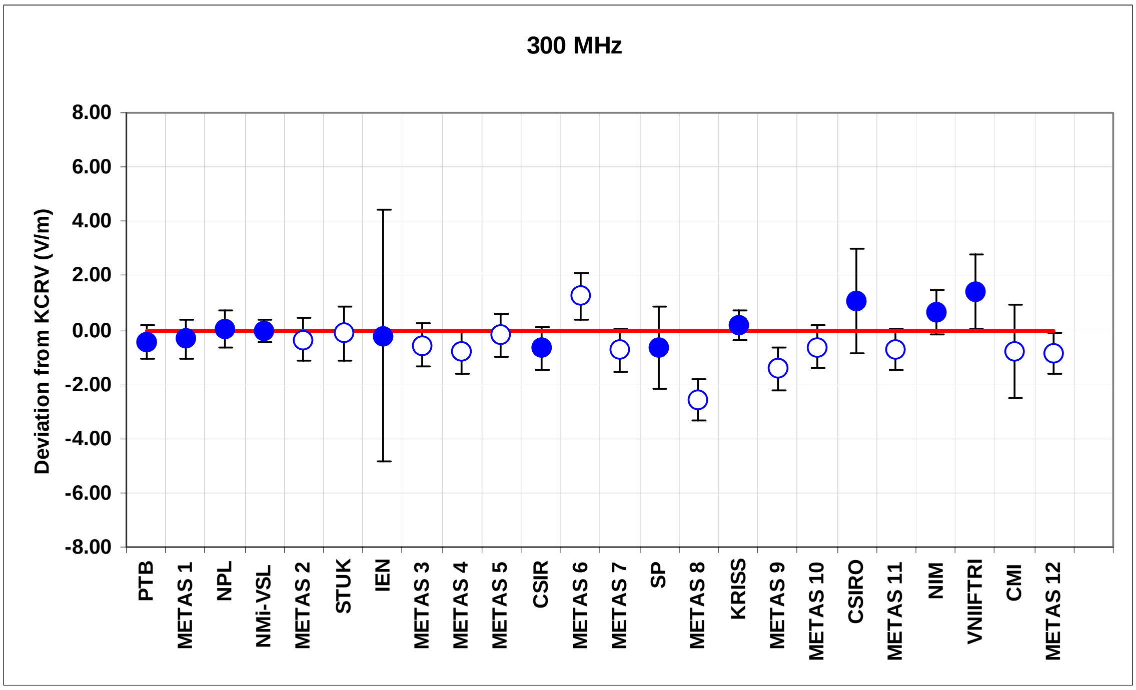


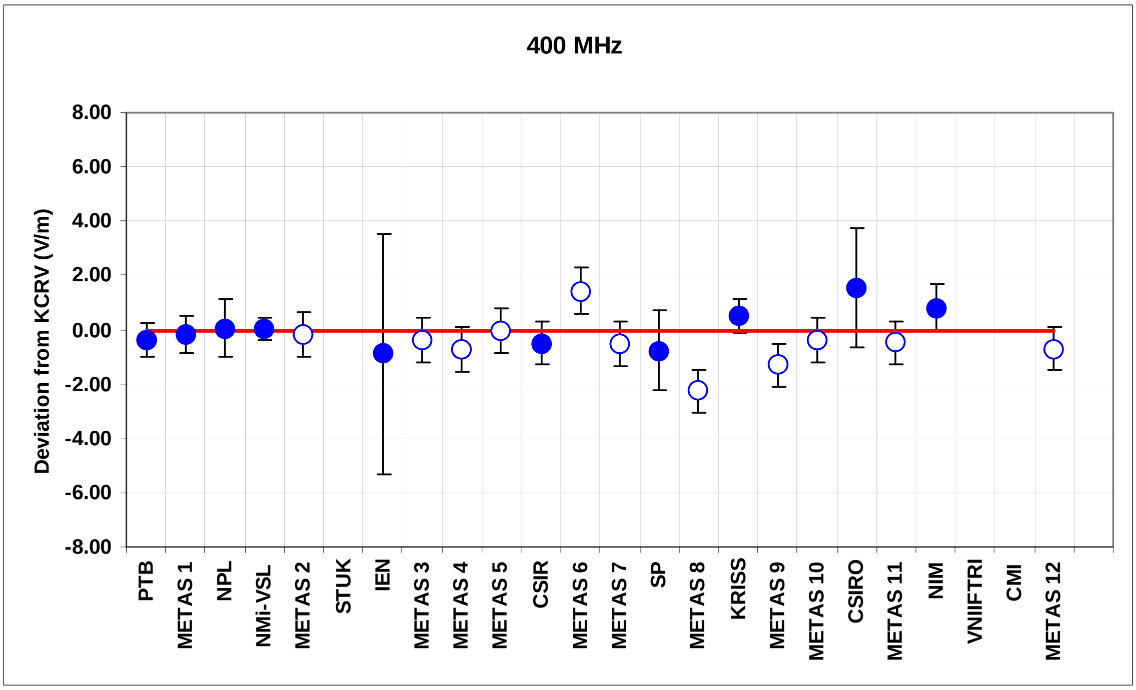

30 MHz
Deviation from KCRV (V/m)
8.00
6.00
4.00
2.00
0.00
-2.00
-4.00
-6.00
-8.00
PTB
METAS 1
NPL
NMi-VSL
METAS 2
STUK
IEN
METAS 3
METAS 4
METAS 5
CSIR
METAS 6
METAS 7
SP
METAS 8
KRISS
METAS 9
METAS 10
CSIRO
METAS 11
NIM
VNIIFTRI
CMI
METAS 12

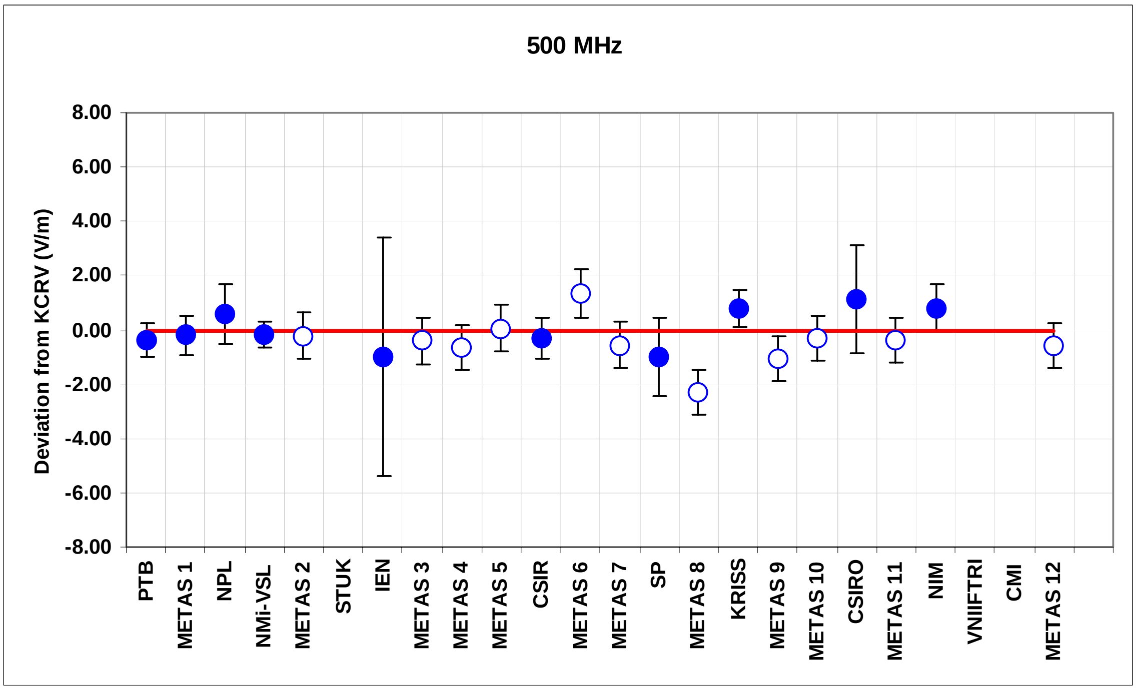

50 MHz
Deviation from KCRV (V/m)
8.00
6.00
4.00
2.00
0.00
-2.00
-4.00
-6.00
-8.00
PTB
METAS 1
NPL
NMi-VSL
METAS 2
STUK
IEN
METAS 3
METAS 4
METAS 5
CSIR
METAS 6
METAS 7
SP
METAS 8
KRISS
METAS 9
METAS 10
CSIRO
METAS 11
NIM
VNIIFTRI
CMI
METAS 12

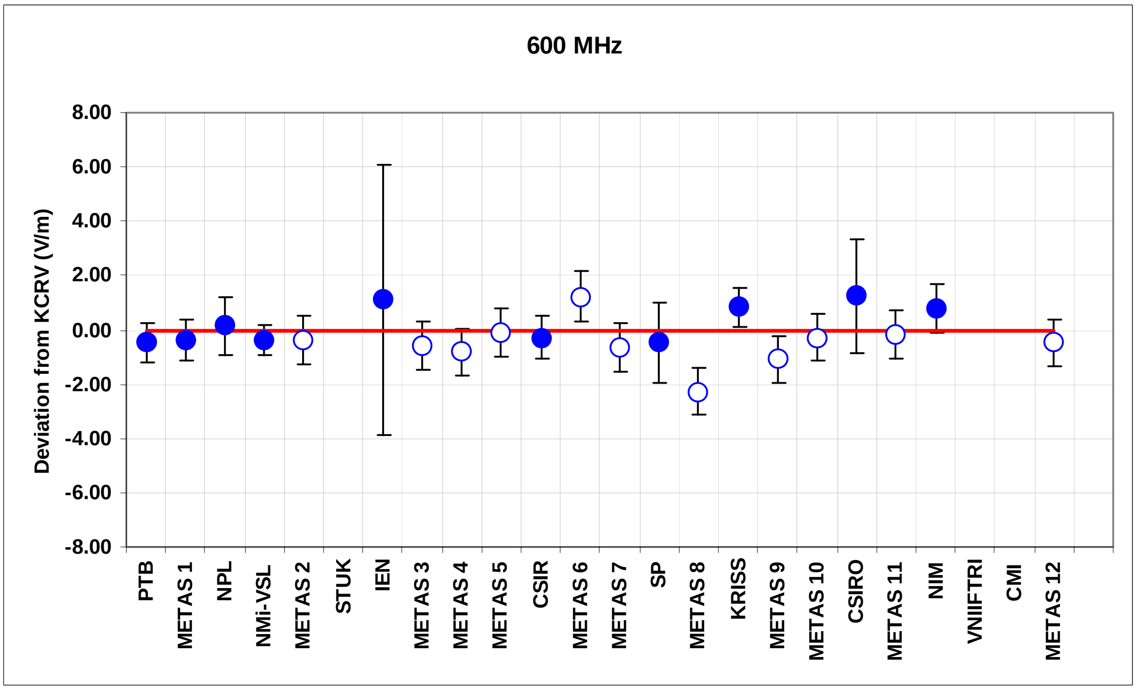

100 MHz
Deviation from KCRV (V/m)
8.00
6.00
4.00
2.00
0.00
-2.00
-4.00
-6.00
-8.00
PTB
METAS 1
NPL
NMi-VSL
METAS 2
STUK
IEN
METAS 3
METAS 4
METAS 5
CSIR
METAS 6
METAS 7
SP
METAS 8
KRISS
METAS 9
METAS 10
CSIRO
METAS 11
NIM
VNIIFTRI
CMI
METAS 12

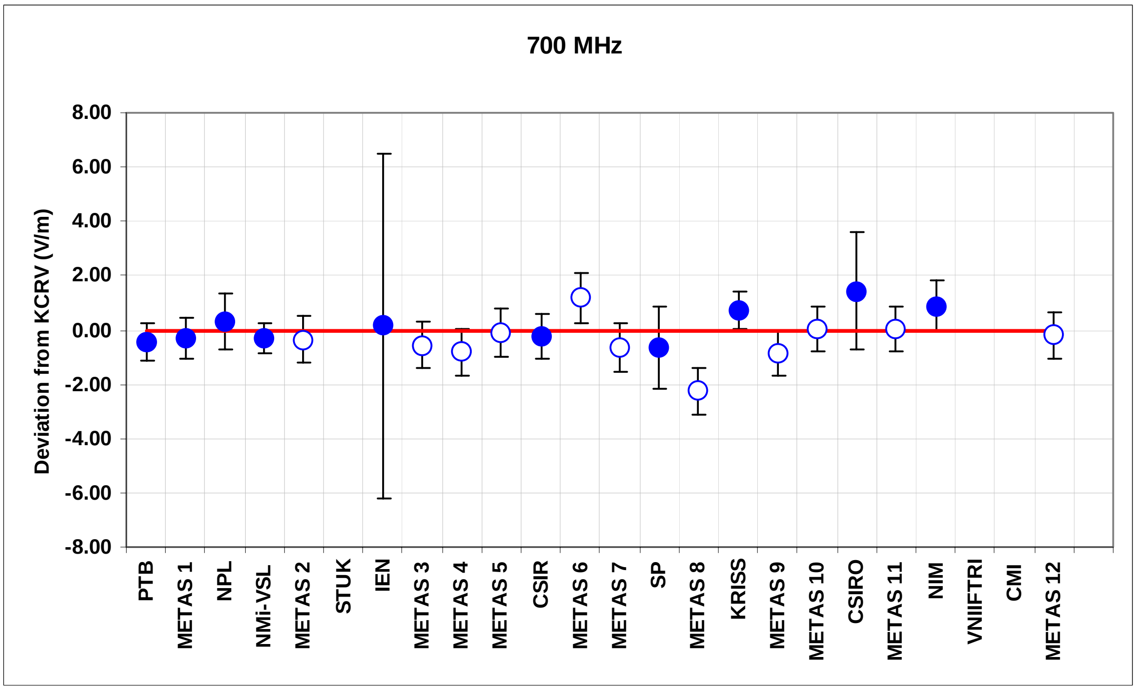

200 MHz
Deviation from KCRV (V/m)
8.00
6.00
4.00
2.00
0.00
-2.00
-4.00
-6.00
-8.00
PTB
METAS 1
NPL
NMi-VSL
METAS 2
STUK
IEN
METAS 3
METAS 4
METAS 5
CSIR
METAS 6
METAS 7
SP
METAS 8
KRISS
METAS 9
METAS 10
CSIRO
METAS 11
NIM
VNIIFTRI
CMI
METAS 12

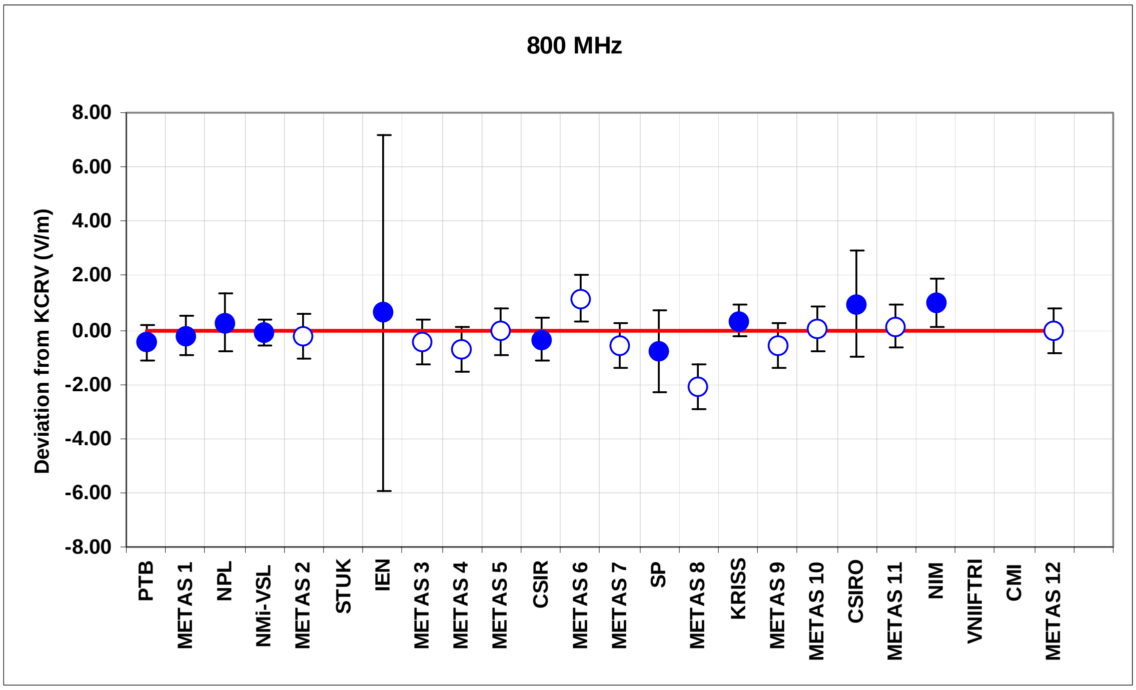

300 MHz
Deviation from KCRV (V/m)
8.00
6.00
4.00
2.00
0.00
-2.00
-4.00
-6.00
-8.00
PTB
METAS 1
NPL
NMi-VSL
METAS 2
STUK
IEN
METAS 3
METAS 4
METAS 5
CSIR
METAS 6
METAS 7
SP
METAS 8
KRISS
METAS 9
METAS 10
CSIRO
METAS 11
NIM
VNIIFTRI
CMI
METAS 12


400 MHz
Deviation from KCRV (V/m)
8.00
6.00
4.00
2.00
0.00
-2.00
-4.00
-6.00
-8.00
PTB
METAS 1
NPL
NMi-VSL
METAS 2
STUK
IEN
METAS 3
METAS 4
METAS 5
CSIR
METAS 6
METAS 7
SP
METAS 8
KRISS
METAS 9
METAS 10
CSIRO
METAS 11
NIM
VNIIFTRI
CMI
METAS 12


500 MHz
Deviation from KCRV (V/m)
8.00
6.00
4.00
2.00
0.00
-2.00
-4.00
-6.00
-8.00
PTB
METAS 1
NPL
NMi-VSL
METAS 2
STUK
IEN
METAS 3
METAS 4
METAS 5
CSIR
METAS 6
METAS 7
SP
METAS 8
KRISS
METAS 9
METAS 10
CSIRO
METAS 11
NIM
VNIIFTRI
CMI
METAS 12


600 MHz
Deviation from KCRV (V/m)
8.00
6.00
4.00
2.00
0.00
-2.00
-4.00
-6.00
-8.00
PTB
METAS 1
NPL
NMi-VSL
METAS 2
STUK
IEN
METAS 3
METAS 4
METAS 5
CSIR
METAS 6
METAS 7
SP
METAS 8
KRISS
METAS 9
METAS 10
CSIRO
METAS 11
NIM
VNIIFTRI
CMI
METAS 12


700 MHz
Deviation from KCRV (V/m)
8.00
6.00
4.00
2.00
0.00
-2.00
-4.00
-6.00
-8.00
PTB
METAS 1
NPL
NMi-VSL
METAS 2
STUK
IEN
METAS 3
METAS 4
METAS 5
CSIR
METAS 6
METAS 7
SP
METAS 8
KRISS
METAS 9
METAS 10
CSIRO
METAS 11
NIM
VNIIFTRI
CMI
METAS 12


800 MHz
Deviation from KCRV (V/m)
8.00
6.00
4.00
2.00
0.00
-2.00
-4.00
-6.00
-8.00
PTB
METAS 1
NPL
NMi-VSL
METAS 2
STUK
IEN
METAS 3
METAS 4
METAS 5
CSIR
METAS 6
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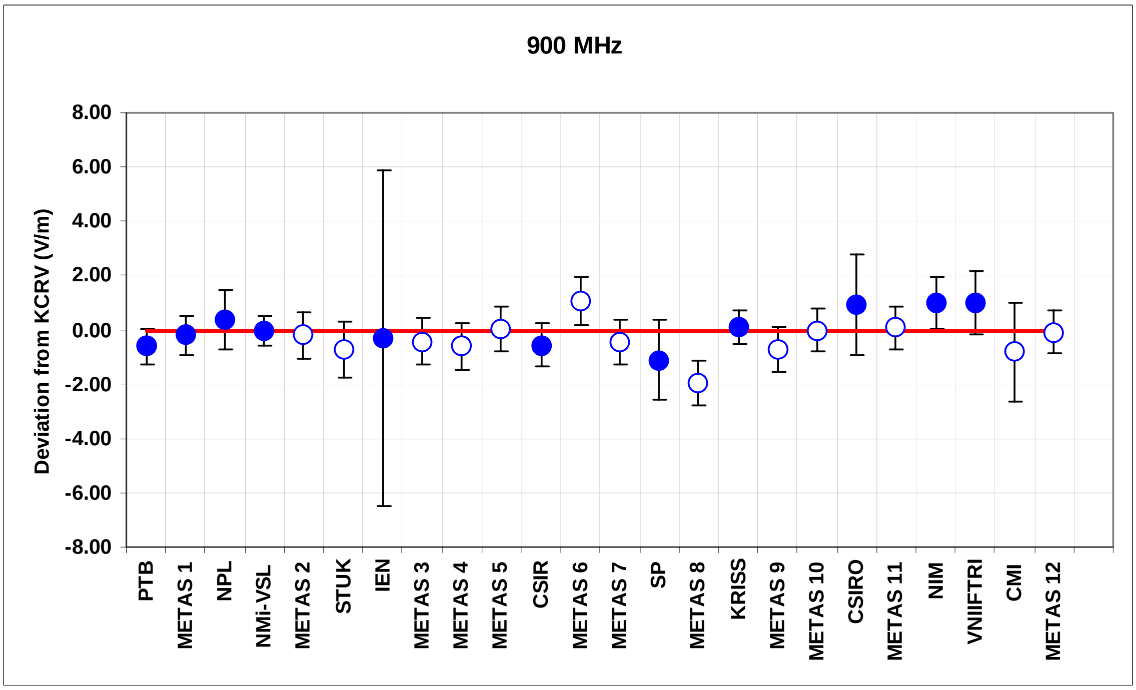
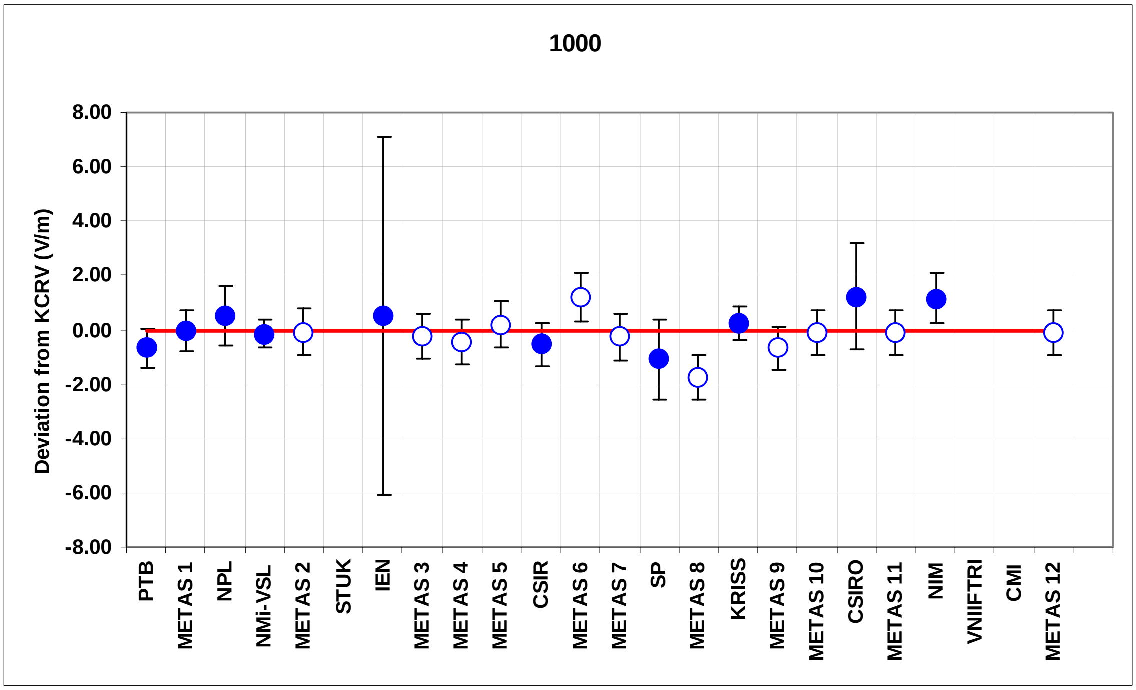
NIM
VNIIFTRI
CMI
METAS 12





The visual inspection of the graphs shows that, despite the stability of the probe, all laboratories are in the target. This is a very acceptable result taken into account of the wide variety of realization of the electric field by the participants.

Matrices of equivalence

The matrices of equivalence have been computed for the mandatory frequencies: 30 MHz, 100 MHz, 300 MHz, and 900 MHz according to the reference [3].

Uncertainty budget

The participants have measured the standard at up to 13 frequencies. The uncertainty budget is very similar for all frequencies when the same infrastructure (e.g. micro TEM cell) is used. Therefore, the uncertainty budgets of each NMI are presented in Annex D at one or several of the measured frequency. In the case where different infrastructures are used to realise E-field at the other frequencies, a corresponding uncertainty budget is also mentioned.

Summary and Conclusions

The maximum stated standard uncertainty for the electric field strength ranges from 0.6% to 17%. We consider that all results are consistent with the claimed uncertainty. The results support the equivalence of national standards laboratories for realization of field strength in the frequency range of 10 MHz … 1000MHz.

References

[1] „CCEM Guidelines for Planning, Organizing, Conducting and Reporting Key, Attached, Supplementary and Pilot Comparisons“, 29th of March 2004.
[2] 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.
[3] W. Bich, M. Cox, T. Estler, L. Nielsen, and W. Woeger „Proposed guidelines fort he evaluation of key comparison data“, Draft for discussion, 16th of April 2002.

Annex A: Matrices of equivalence

Matrix of equivalence: 30 MHz

Lab *i* ⇒

Lab *j* ⇓			PTB		METAS		NPL		NMi-VSL		STUK		IEN		CSIR		SP		KRISS		CSIRO		NIM		VNIFFRI		CMI	
	Di (V/m)	Ui (V/m)	Dij (V/m)	Uij (V/m)	Dij (V/m)	Uij (V/m)	Dij (V/m)	Uij (V/m)	Dij (V/m)	Uij (V/m)	Dij (V/m)	Uij (V/m)	Dij (V/m)	Uij (V/m)	Dij (V/m)	Uij (V/m)	Dij (V/m)	Uij (V/m)	Dij (V/m)	Uij (V/m)	Dij (V/m)	Uij (V/m)	Dij (V/m)	Uij (V/m)	Dij (V/m)	Uij (V/m)	Dij (V/m)	Uij (V/m)
PTB	-0.04	0.59			0.36	0.90	-0.18	0.90	0.06	0.63	0.00	1.11	0.80	2.04	0.62	0.96	0.90	1.60	-0.37	0.79	-1.19	1.97	-0.84	1.00	-0.90	1.40	0.14	1.25
METAS	-0.40	0.69	-0.36	0.90			-0.54	0.97	-0.30	0.73	-0.36	1.16	0.44	2.08	0.26	1.03	0.54	1.64	-0.73	0.87	-1.55	2.00	-1.20	1.06	-1.26	1.45	-0.22	1.30
NPL	0.14	0.68	0.18	0.90	0.54	0.97			0.24	0.73	0.18	1.16	0.98	2.08	0.80	1.03	1.08	1.64	-0.19	0.87	-1.01	2.00	-0.66	1.06	-0.72	1.45	0.32	1.29
Nmi	-0.10	0.37	-0.06	0.63	0.30	0.73	-0.24	0.73			-0.06	0.97	0.74	1.97	0.56	0.80	0.84	1.51	-0.43	0.58	-1.25	1.90	-0.90	0.84	-0.96	1.30	0.08	1.12
STUK	-0.04	0.99	0.00	1.11	0.36	1.16	-0.18	1.16	0.06	0.97			0.80	2.17	0.62	1.21	0.90	1.76	-0.37	1.08	-1.19	2.10	-0.84	1.24	-0.90	1.58	0.14	1.45
IEN	-0.84	1.90	-0.80	2.04	-0.44	2.08	-0.98	2.08	-0.74	1.97	-0.80	2.17			-0.18	2.10	0.10	2.46	-1.17	2.03	-1.99	2.72	-1.64	2.12	-1.70	2.34	-0.66	2.25
CSIR	-0.66	0.76	-0.62	0.96	-0.26	1.03	-0.80	1.03	-0.56	0.80	-0.62	1.21	0.18	2.10			0.28	1.67	-0.99	0.93	-1.81	2.03	-1.46	1.11	-1.52	1.48	-0.48	1.34
SP	-0.94	1.45	-0.90	1.60	-0.54	1.64	-1.08	1.64	-0.84	1.51	-0.90	1.76	-0.10	2.46	-0.28	1.67			-1.27	1.58	-2.09	2.40	-1.74	1.69	-1.80	1.96	-0.76	1.85
KRISS	0.33	0.54	0.37	0.79	0.73	0.87	0.19	0.87	0.43	0.58	0.37	1.08	1.17	2.03	0.99	0.93	1.27	1.58			-0.82	1.95	-0.47	0.96	-0.53	1.38	0.51	1.22
CSIRO	1.15	1.83	1.19	1.97	1.55	2.00	1.01	2.00	1.25	1.90	1.19	2.10	1.99	2.72	1.81	2.03	2.09	2.40	0.82	1.95			0.35	2.04	0.29	2.28	1.33	2.18
NIM	0.80	0.83	0.84	1.00	1.20	1.06	0.66	1.06	0.90	0.84	0.84	1.24	1.64	2.12	1.46	1.11	1.74	1.69	0.47	0.96	-0.35	2.04			-0.06	1.51	0.98	1.36
VNIFFRI	0.86	1.24	0.90	1.40	1.26	1.45	0.72	1.45	0.96	1.30	0.90	1.58	1.70	2.34	1.52	1.48	1.80	1.96	0.53	1.38	-0.29	2.28	0.06	1.51			1.04	1.68
CMI	-0.18	1.14	-0.14	1.25	0.22	1.30	-0.32	1.29	-0.08	1.12	-0.14	1.45	0.66	2.25	0.48	1.34	0.76	1.85	-0.51	1.22	-1.33	2.18	-0.98	1.36	-1.04	1.68		

Note: Uij corresponds to the 95% confidence level (k about equal to 2).

Matrix of equivalence : 100 MHz

Lab *i* ⇒

Lab *j* ⇓			**PTB**		**METAS**		**NPL**		**NMi-VSL**		**STUK**		**IEN**		**CSIR**		**SP**		**KRISS**		**CSIRO**		**NIM**		**VNIFFRI**		**CMI**	
	Di (V/m)	**Ui (V/m)**	**Dij (V/m)**	**Uij (V/m)**	**Dij (V/m)**	**Uij (V/m)**	**Dij (V/m)**	**Uij (V/m)**	**Dij (V/m)**	**Uij (V/m)**	**Dij (V/m)**	**Uij (V/m)**	**Dij (V/m)**	**Uij (V/m)**	**Dij (V/m)**	**Uij (V/m)**	**Dij (V/m)**	**Uij (V/m)**	**Dij (V/m)**	**Uij (V/m)**	**Dij (V/m)**	**Uij (V/m)**	**Dij (V/m)**	**Uij (V/m)**	**Dij (V/m)**	**Uij (V/m)**	**Dij (V/m)**	**Uij (V/m)**
PTB	**-0.01**	0.59			**0.32**	0.90	**0.20**	0.89	**0.00**	0.63	**-0.40**	1.11	**0.50**	2.04	**0.53**	0.96	**1.10**	1.58	**-0.28**	0.79	**-1.12**	1.90	**-0.90**	1.00	**-1.10**	1.40	**-0.12**	1.23
METAS	**-0.33**	0.68	**-0.32**	0.90			**-0.12**	0.96	**-0.32**	0.73	**-0.72**	1.16	**0.18**	2.08	**0.21**	1.03	**0.78**	1.63	**-0.60**	0.87	**-1.44**	1.93	**-1.22**	1.06	**-1.42**	1.45	**-0.44**	1.28
NPL	**-0.21**	0.66	**-0.20**	0.89	**0.12**	0.96			**-0.20**	0.71	**-0.60**	1.15	**0.30**	2.07	**0.33**	1.02	**0.90**	1.62	**-0.48**	0.85	**-1.32**	1.92	**-1.10**	1.04	**-1.30**	1.44	**-0.32**	1.27
Nmi	**-0.01**	0.37	**0.00**	0.63	**0.32**	0.73	**0.20**	0.71			**-0.40**	0.97	**0.50**	1.97	**0.53**	0.80	**1.10**	1.49	**-0.28**	0.58	**-1.12**	1.82	**-0.90**	0.84	**-1.10**	1.30	**-0.12**	1.11
STUK	**0.39**	0.98	**0.40**	1.11	**0.72**	1.16	**0.60**	1.15	**0.40**	0.97			**0.90**	2.17	**0.93**	1.21	**1.50**	1.75	**0.12**	1.08	**-0.72**	2.03	**-0.50**	1.24	**-0.70**	1.58	**0.28**	1.43
IEN	**-0.51**	1.91	**-0.50**	2.04	**-0.18**	2.08	**-0.30**	2.07	**-0.50**	1.97	**-0.90**	2.17			**0.03**	2.10	**0.60**	2.45	**-0.78**	2.03	**-1.62**	2.66	**-1.40**	2.12	**-1.60**	2.34	**-0.62**	2.24
CSIR	**-0.54**	0.75	**-0.53**	0.96	**-0.21**	1.03	**-0.33**	1.02	**-0.53**	0.80	**-0.93**	1.21	**-0.03**	2.10			**0.57**	1.66	**-0.81**	0.93	**-1.65**	1.96	**-1.43**	1.11	**-1.63**	1.49	**-0.65**	1.32
SP	**-1.11**	1.43	**-1.10**	1.58	**-0.78**	1.63	**-0.90**	1.62	**-1.10**	1.49	**-1.50**	1.75	**-0.60**	2.45	**-0.57**	1.66			**-1.38**	1.56	**-2.22**	2.33	**-2.00**	1.68	**-2.20**	1.95	**-1.22**	1.83
KRISS	**0.27**	0.54	**0.28**	0.79	**0.60**	0.87	**0.48**	0.85	**0.28**	0.58	**-0.12**	1.08	**0.78**	2.03	**0.81**	0.93	**1.38**	1.56			**-0.84**	1.88	**-0.62**	0.96	**-0.82**	1.38	**0.16**	1.20
CSIRO	**1.11**	1.76	**1.12**	1.90	**1.44**	1.93	**1.32**	1.92	**1.12**	1.82	**0.72**	2.03	**1.62**	2.66	**1.65**	1.96	**2.22**	2.33	**0.84**	1.88			**0.22**	1.97	**0.02**	2.21	**1.00**	2.10
NIM	**0.89**	0.86	**0.90**	1.00	**1.22**	1.06	**1.10**	1.04	**0.90**	0.84	**0.50**	1.24	**1.40**	2.12	**1.43**	1.11	**2.00**	1.68	**0.62**	0.96	**-0.22**	1.97			**-0.20**	1.51	**0.78**	1.34
VNIFFRI	**1.09**	1.24	**1.10**	1.40	**1.42**	1.45	**1.30**	1.44	**1.10**	1.30	**0.70**	1.58	**1.60**	2.34	**1.63**	1.49	**2.20**	1.95	**0.82**	1.38	**-0.02**	2.21	**0.20**	1.51			**0.98**	1.67
CMI	**0.11**	1.12	**0.12**	1.23	**0.44**	1.28	**0.32**	1.27	**0.12**	1.11	**-0.28**	1.43	**0.62**	2.24	**0.65**	1.32	**1.22**	1.83	**-0.16**	1.20	**-1.00**	2.10	**-0.78**	1.34	**-0.98**	1.67		

Note: Uij corresponds to the 95% confidence level (k about equal to 2).

Matrix of equivalence : 300 MHz

Lab *i* ⇒

Lab *j* ⇓			**PTB**		**METAS**		**NPL**		**NMi-VSL**		**STUK**		**IEN**		**CSIR**		**SP**		**KRISS**		**CSIRO**		**NIM**		**VNIFFRI**		**CMI**	
	Di (V/m)	**Ui (V/m)**	**Dij (V/m)**	**Uij (V/m)**	**Dij (V/m)**	**Uij (V/m)**	**Dij (V/m)**	**Uij (V/m)**	**Dij (V/m)**	**Uij (V/m)**	**Dij (V/m)**	**Uij (V/m)**	**Dij (V/m)**	**Uij (V/m)**	**Dij (V/m)**	**Uij (V/m)**	**Dij (V/m)**	**Uij (V/m)**	**Dij (V/m)**	**Uij (V/m)**	**Dij (V/m)**	**Uij (V/m)**	**Dij (V/m)**	**Uij (V/m)**	**Dij (V/m)**	**Uij (V/m)**	**Dij (V/m)**	**Uij (V/m)**
PTB	**-0.42**	0.61			**-0.09**	0.92	**-0.46**	0.92	**-0.41**	0.65	**-0.30**	1.11	**-0.20**	4.74	**0.26**	0.97	**0.20**	1.66	**-0.60**	0.79	**-1.48**	2.06	**-1.08**	1.01	**-1.80**	1.46	**0.34**	1.78
METAS	**-0.33**	0.71	**0.09**	0.92			**-0.37**	1.00	**-0.32**	0.76	**-0.21**	1.18	**-0.11**	4.75	**0.35**	1.04	**0.29**	1.70	**-0.51**	0.88	**-1.39**	2.10	**-0.99**	1.08	**-1.71**	1.51	**0.43**	1.83
NPL	**0.04**	0.71	**0.46**	0.92	**0.37**	1.00			**0.05**	0.76	**0.16**	1.17	**0.26**	4.75	**0.72**	1.04	**0.66**	1.70	**-0.14**	0.88	**-1.02**	2.10	**-0.62**	1.08	**-1.34**	1.51	**0.80**	1.83
Nmi	**-0.01**	0.42	**0.41**	0.65	**0.32**	0.76	**-0.05**	0.76			**0.11**	0.98	**0.21**	4.71	**0.67**	0.81	**0.61**	1.58	**-0.19**	0.60	**-1.07**	2.00	**-0.67**	0.87	**-1.39**	1.36	**0.75**	1.71
STUK	**-0.12**	1.00	**0.30**	1.11	**0.21**	1.18	**-0.16**	1.17	**-0.11**	0.98			**0.10**	4.79	**0.56**	1.21	**0.50**	1.81	**-0.30**	1.08	**-1.18**	2.19	**-0.78**	1.25	**-1.50**	1.63	**0.64**	1.93
IEN	**-0.22**	4.64	**0.20**	4.74	**0.11**	4.75	**-0.26**	4.75	**-0.21**	4.71	**-0.10**	4.79			**0.46**	4.76	**0.40**	4.95	**-0.40**	4.73	**-1.28**	5.10	**-0.88**	4.77	**-1.60**	4.89	**0.54**	4.99
CSIR	**-0.68**	0.76	**-0.26**	0.97	**-0.35**	1.04	**-0.72**	1.04	**-0.67**	0.81	**-0.56**	1.21	**-0.46**	4.76			**-0.06**	1.73	**-0.86**	0.93	**-1.74**	2.12	**-1.34**	1.13	**-2.06**	1.54	**0.08**	1.85
SP	**-0.62**	1.51	**-0.20**	1.66	**-0.29**	1.70	**-0.66**	1.70	**-0.61**	1.58	**-0.50**	1.81	**-0.40**	4.95	**0.06**	1.73			**-0.80**	1.64	**-1.68**	2.51	**-1.28**	1.75	**-2.00**	2.05	**0.14**	2.29
KRISS	**0.18**	0.56	**0.60**	0.79	**0.51**	0.88	**0.14**	0.88	**0.19**	0.60	**0.30**	1.08	**0.40**	4.73	**0.86**	0.93	**0.80**	1.64			**-0.88**	2.05	**-0.48**	0.98	**-1.20**	1.43	**0.94**	1.77
CSIRO	**1.06**	1.93	**1.48**	2.06	**1.39**	2.10	**1.02**	2.10	**1.07**	2.00	**1.18**	2.19	**1.28**	5.10	**1.74**	2.12	**1.68**	2.51	**0.88**	2.05			**0.40**	2.14	**-0.32**	2.39	**1.82**	2.59
NIM	**0.66**	0.82	**1.08**	1.01	**0.99**	1.08	**0.62**	1.08	**0.67**	0.87	**0.78**	1.25	**0.88**	4.77	**1.34**	1.13	**1.28**	1.75	**0.48**	0.98	**-0.40**	2.14			**-0.72**	1.57	**1.42**	1.88
VNIFFRI	**1.38**	1.37	**1.80**	1.46	**1.71**	1.51	**1.34**	1.51	**1.39**	1.36	**1.50**	1.63	**1.60**	4.89	**2.06**	1.54	**2.00**	2.05	**1.20**	1.43	**0.32**	2.39	**0.72**	1.57			**2.14**	2.15
CMI	**-0.76**	1.72	**-0.34**	1.78	**-0.43**	1.83	**-0.80**	1.83	**-0.75**	1.71	**-0.64**	1.93	**-0.54**	4.99	**-0.08**	1.85	**-0.14**	2.29	**-0.94**	1.77	**-1.82**	2.59	**-1.42**	1.88	**-2.14**	2.15		

Note: Uij corresponds to the 95% confidence level (k about equal to 2).

Matrix of equivalence : 900 MHz

Lab *i* ⇒

Lab *j* ⇓			PTB		METAS		NPL		NMi-VSL		STUK		IEN		CSIR		SP		KRISS		CSIRO		NIM		VNIFFRI		CMI	
	Di (V/m)	Ui (V/m)	Dij (V/m)	Uij (V/m)	Dij (V/m)	Uij (V/m)	Dij (V/m)	Uij (V/m)	Dij (V/m)	Uij (V/m)	Dij (V/m)	Uij (V/m)	Dij (V/m)	Uij (V/m)	Dij (V/m)	Uij (V/m)	Dij (V/m)	Uij (V/m)	Dij (V/m)	Uij (V/m)	Dij (V/m)	Uij (V/m)	Dij (V/m)	Uij (V/m)	Dij (V/m)	Uij (V/m)	Dij (V/m)	Uij (V/m)
PTB	-0.62	0.66			-0.42	0.94	-0.98	1.26	-0.58	0.71	0.10	1.14	-0.30	6.31	-0.05	0.98	0.50	1.64	-0.69	0.82	-1.56	2.01	-1.61	1.03	-1.60	1.31	0.19	1.88
METAS	-0.20	0.74	0.42	0.94			-0.56	1.33	-0.16	0.83	0.52	1.22	0.13	6.32	0.37	1.07	0.92	1.69	-0.27	0.92	-1.14	2.05	-1.19	1.11	-1.18	1.38	0.61	1.92
NPL	0.36	1.09	0.98	1.26	0.56	1.33			0.40	1.18	1.08	1.49	0.68	6.38	0.93	1.37	1.48	1.89	0.29	1.25	-0.58	2.22	-0.63	1.40	-0.62	1.62	1.17	2.11
Nmi	-0.04	0.52	0.58	0.71	0.16	0.83	-0.40	1.18			0.68	1.06	0.29	6.29	0.53	0.88	1.08	1.58	-0.11	0.69	-0.98	1.96	-1.03	0.93	-1.02	1.24	0.77	1.82
STUK	-0.72	1.06	-0.10	1.14	-0.52	1.22	-1.08	1.49	-0.68	1.06			-0.40	6.36	-0.15	1.25	0.40	1.81	-0.79	1.13	-1.66	2.16	-1.71	1.29	-1.70	1.53	0.09	2.03
IEN	-0.32	6.21	0.30	6.31	-0.13	6.32	-0.68	6.38	-0.29	6.29	0.40	6.36			0.24	6.33	0.79	6.47	-0.40	6.30	-1.27	6.57	-1.32	6.34	-1.31	6.39	0.48	6.53
CSIR	-0.57	0.79	0.05	0.98	-0.37	1.07	-0.93	1.37	-0.53	0.88	0.15	1.25	-0.24	6.33			0.55	1.72	-0.64	0.97	-1.51	2.07	-1.56	1.15	-1.55	1.41	0.24	1.94
SP	-1.12	1.49	-0.50	1.64	-0.92	1.69	-1.48	1.89	-1.08	1.58	-0.40	1.81	-0.79	6.47	-0.55	1.72			-1.19	1.63	-2.06	2.46	-2.11	1.74	-2.10	1.93	-0.31	2.35
KRISS	0.07	0.62	0.69	0.82	0.27	0.92	-0.29	1.25	0.11	0.69	0.79	1.13	0.40	6.30	0.64	0.97	1.19	1.63			-0.87	2.00	-0.92	1.02	-0.91	1.31	0.88	1.87
CSIRO	0.94	1.87	1.56	2.01	1.14	2.05	0.58	2.22	0.98	1.96	1.66	2.16	1.27	6.57	1.51	2.07	2.06	2.46	0.87	2.00			-0.05	2.09	-0.04	2.25	1.75	2.62
NIM	0.99	0.93	1.61	1.03	1.19	1.11	0.63	1.40	1.03	0.93	1.71	1.29	1.32	6.34	1.56	1.15	2.11	1.74	0.92	1.02	0.05	2.09			0.01	1.44	1.80	1.97
VNIFFRI	0.98	1.15	1.60	1.31	1.18	1.38	0.62	1.62	1.02	1.24	1.70	1.53	1.31	6.39	1.55	1.41	2.10	1.93	0.91	1.31	0.04	2.25	-0.01	1.44			1.79	2.13
CMI	-0.81	1.82	-0.19	1.88	-0.61	1.92	-1.17	2.11	-0.77	1.82	-0.09	2.03	-0.48	6.53	-0.24	1.94	0.31	2.35	-0.88	1.87	-1.75	2.62	-1.80	1.97	-1.79	2.13		

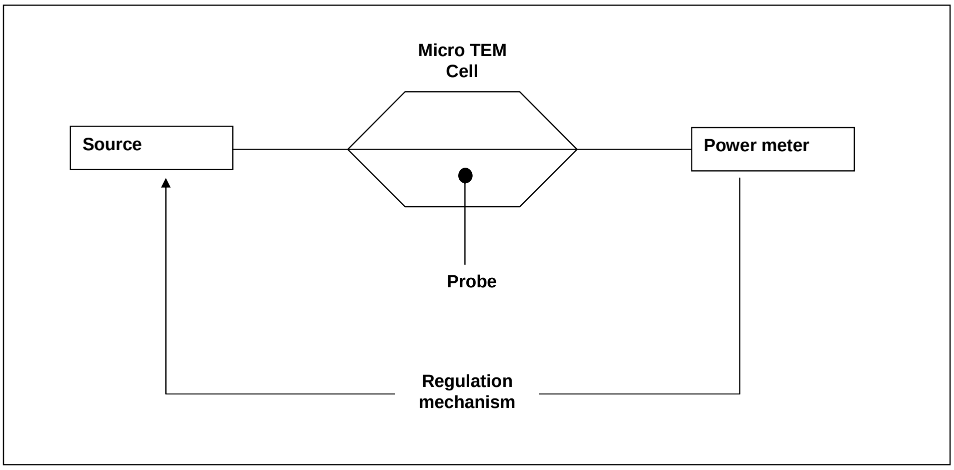
Note: Uij corresponds to the 95% confidence level (k about equal to 2).

Annex B: Methods of measurement

The following different methods have been used to measure the electric field:

Micro TEM cell traceable through power measurements

The method can be schematically represented by the following picture:



The field generation system consists of a signal source part, a micro TEM cell, and a power measurement part. The field in the cell is basically calculated as:

$$E = \frac{\sqrt{P \cdot Z}}{d}$$

where :

- E is the electric field
- P is the power
- Z is the wave impedance of the cell
- d is the height of septum.

The realisations of this experiment by the NMI differ in the regulation mechanism as well as in the consideration (or not) of corrections to the above mentioned formula:

- Power correction taking into account the frequency dependent attenuation of the cell
- Power correction taking into account the mismatch error
- Power correction taking into account standing waves in the micro TEM cell
- Power correction taking into account a calibration factor of the micro TEM cell.

Note that some NMIs do not apply any corrections and use the above mentioned terms in the uncertainty calculation.

Mini TEM, TEM cell, GTEM cell, and Tapered cell

The principles are here exactly the same as for the micro TEM cell. The cells are simply bigger and two variants are foreseen to ensure traceability:

- via power measurements: determination of the electric field in the cell using the same equation as for the micro TEM cell.
- using a transfer field probe calibrated in a micro TEM cell: in some cases, due to the bigger size of the cell, the uncertainties increase when tracing directly into power measurements and therefore an adapted transfer standard is first calibrated in a micro TEM cell and afterwards used to calibrate the bigger cell.
- Using a small dipole which is first calibrated either:
  - in a four-wire feeder (calculable)
  - in the free space with the reference antenna method using a calculable biconical antenna.

Anechoic chamber

The calibration in an anechoic chamber requires a field generation source. This is a transmitting antenna :

- A horn antenna: the field probe is calibrated in the waveguide section of the horn antenna and the magnitude of the E-Field is determined by taking the theoretical equation

$$E = \sqrt{\frac{2P \cdot \eta}{ab\sqrt{1-\left(\frac{\lambda_0}{2a}\right)^2}}}$$

  where :
  - o P is the input power into the horn antenna
  - o $\eta \cong 377 Ohms$ is the wave impedance of vacuum
  - o a , and b are the inner dimensions of the waveguide
  - o λ_0 is the wave length in free space.

- A calculable biconical antenna is used.

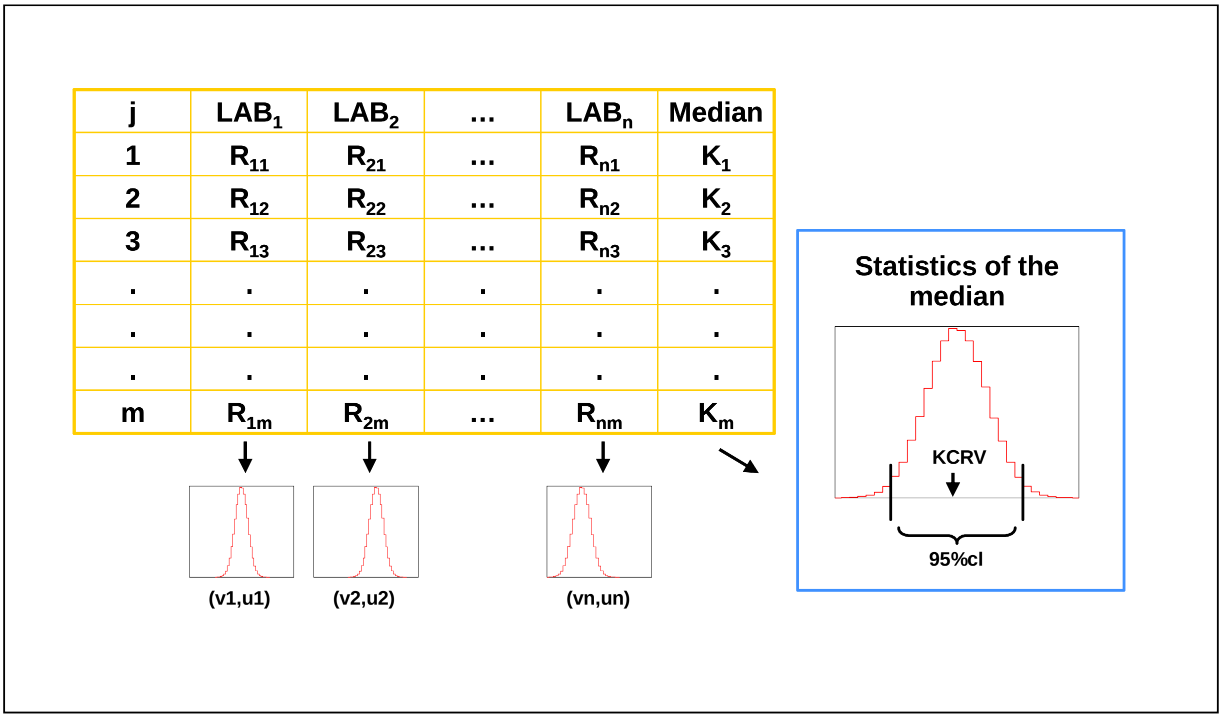
Annex C: Calculation of the KCRV

The computation of the KCRV and its uncertainty has been performed according to the reference [3], by performing Monte-Carlo simulations. The procedure can be explained as follows:

- Assume $n = 11$ labs, and for each a value of field strength v_i with uncertainty u_i ($i = 1..n$)
- For each lab i, generate a random serie R_{ij} ($m = 10^6$ elements, $j = 1..m$) that are Gaussian distributed with average v_i and standard deviation u_i. (So-called Monte-Carlo method)
- Determine a new series K_j ($j = 1..m$) obtained as:

$$K_j = Median\left(R_{1j}, R_{2,}, \ldots, R_{nj}\right)$$

- The K_j describe the statistics of the KCRV:
    - o KCRV value is obtained as average of all K_j
    - o The shortest coverage interval at the 95% level of confidence is determined from the distribution K_j



j	LAB$_1$	LAB$_2$	…	LAB$_n$	Median
1	R$_{11}$	R$_{21}$	…	R$_{n1}$	K$_1$
2	R$_{12}$	R$_{22}$	…	R$_{n2}$	K$_2$
3	R$_{13}$	R$_{23}$	…	R$_{n3}$	K$_3$
.	.	.	.	.	.
.	.	.	.	.	.
.	.	.	.	.	.
m	R$_{1m}$	R$_{2m}$	…	R$_{nm}$	K$_m$

Annex D: Uncertainty Budget

D.1 PTB

Standard Measuring Equipment with "µTEM-Cell"

The standard measuring equipment is designed to produce rf electromagnetic fields up to 1 GHz inside a small "TEM cell" for the calibration of specially designed miniature transfer sensors. A TEM cell is a coaxial line with a rectangular cross section at the center and tapers as transitions to standard circular coaxial connectors and cables. The traceable field strength of the travelling wave inside that transmission line is derived from only few physical quantities, which are easily and accurately measured. The method and the apparatus are described in detail in: "Automatic Calibration System with Temperature Stabilized TEM Cell for Transfer Field Strength Meters (User's Manual)".
From the uncertainty budget (see last page) it is obvious that the main uncertainty contribution to the generated electric field comes from reflected rf energy, producing standing waves along the transmission line system. Therefore only a very high quality TEM cell with a minimum of mechanical imperfections is suitable for this purpose.
PLEASE NOTE: The uncertainty contributions for the attenuator, the power meter and the VSWR correction are worst-case values over the entire frequency range, therefore the uncertainty for the electric field strength is a conservative estimate over that frequency range.

Model Equation:

$E=sqrt(Z_L*P_m/A)/d*\delta_{VSWR}$

List of Quantities:

rw15Quantity	Unit	Definition
Z_L	Ω	characteristic impedance of TEM cell
A		attenuation factor
P_m	W	power measured
d	m	septum distance
δ_{VSWR}		VSWR correction factor
E	V/m	electric field strength inside TEM cell at sensor location

Z_L:
Constant
Value: 50.0 Ω

characteristic impedance of uTEM cell.
PLEASE NOTE: No uncertainty is specified for this parameter, which is seen as an internal constant to convert power into voltage, with any voltage deviation already corrected by the δ_{VSWR} parameter. Geometric imperfections of the TEM cell are also included elsewhere, because the septum distance is mechanically measured and the uncertainty specified.

A:
Type B normal distribution
Value: 0.1
Expanded Uncertainty: 0.003
Coverage Factor: 2

attenuation factor of 10-dB precision attenuator between cell and power meter:

The actual value and the expanded uncertainty are taken from the calibration certificate. The expanded uncertainty is a conservative estimate over most of the frequency range, because the worst-case value is inserted here.

P_m:
Import
Filename: PwrMeter.SMU
Quantity: P_m

RF power measured with "NRVS" power meter:
The method to measure the RF power and to calculate the uncertainty for this type of instrument are discussed elsewhere. The result is imported here from the previous "GUM Workbench" calculation using the model equation and the data given in the specified file.

d:
Type B normal distribution
Value: 0.034597 m
Expanded Uncertainty: $5 \cdot 10^{-6}$ m
Coverage Factor: 2

Septum distance:
The actual value and the expanded uncertainty are taken from the calibration certificate (with the mechanical stability of the cell septum in mind, the uncertainty seems somewhat optimistic, but should be irrelevant, anyhow).

δ_{VSWR}:
Type B U-shaped distribution
Value: 1.0
Halfwidth of Limits: $17.8 \cdot 10^{-3}$

VSWR correction factor:
Even with the highest quality TEM cell the reflection of waves inside cannot be completely avoided, e.g. caused by the transition regions ("tapers") of the cell. The superposition of TEM waves propagating forward and backwards results in a varying voltage or field amplitude along the propagation direction. An additional position-dependent correction δ_{VSWR} in the model equation takes this into account. This situation is similar to the mismatch loss - without detailed informations about the reflection mechanisms the phase relation between the forward and reflected waves remains unknown, as well as δ_{VSWR} at a certain location. Only the mean value is exactly = 1, this value is therefore inserted here as the best estimate for $\delta_{VSWR.}$
An U-shaped distribution is appropriate in this case, the width of the associated interval follows from the return loss measured at the cell input. This should be a conservative estimate, because the wave reflected at the cell input taper is neglected, and it is assumed instead that the total power is reflected at the cell output, therefore resulting in a maximum field strength variation along the cell. To avoid a frequency-dependent uncertainty, the worst return loss measured within the entire range up to 1 GHz is inserted into the uncertainty budget.
Data for the system considered here: Measured worst-case return loss of 35dB gives VSWR = 1,036 and the associated half width interval is 17,8×10-3.

E:
Result

electric field strength generated at sensor location.

Uncertainty Budget:

Quantity	Value	Standard Uncertainty	Degrees of Freedom	Sensitivity Coefficient	Uncertainty Contribution	Index
Z_L	50.0 Ω					
A	0.10000	$1.50\cdot10^{-3}$	50	-100	-0.15 V/m	24.6 %
P_m	$1.0035\cdot10^{-3}$ W	$7.60\cdot10^{-6}$ W	52	10000	0.078 V/m	6.3 %
d	0.03459700 m	$2.50\cdot10^{-6}$ m	50	-590	$-1.5\cdot10^{-3}$ V/m	0.0 %
δ_{VSWR}	1.0000	0.0126	∞	20	0.26 V/m	69.2 %
E	20.47 V/m	0.310 V/m	780			

Result:

Quantity: E
Value: 20.47 V/m
Relative Expanded Uncertainty: ±3.0 %
Coverage Factor: 2.0
Coverage: t-table 95%

D.2 METAS

Model Equations:

$P_{Measured}= P_{CalFactor}\cdot P_{Linearity}\cdot P_{Drift};$
$E_{Cell}=sqrt(Z_{Cell}\cdot P_{Measured}/((S_{21HP}\text{^}2)\cdot(S_{21Cell})\cdot M_1\cdot M_2))/d\cdot s;$
$E_{Transfer}=E_{Cell}\cdot K_{Transfer}$

List of variables:

Variable	Unit	Definition
$P_{Measured}$	W	Measured power at the power sensor
$P_{CalFactor}$	W	Power read from the power meter, including calibration factor of the power sensor (frequency dependent correction).
$P_{Linearity}$		Linearity correction factor, calibrated at 1 mW (therefore uncertainty of 0 at this power)
P_{Drift}		Drift of the power meter (incl. sensor) according to the manufacturer
E_{Cell}	V/m	Field strength at the transfer standard location
Z_{Cell}	Ω	Impedance of the micro TEM cell
S_{21HP}		S21 parameter of the HP attenuator
S_{21Cell}		S21 parameter of the cell (in order to take into account the fact that the transfer standard is at the middle of the cell, the measured S21 is divided by two)
M_1		Mismatch cell/ attenuator HP
M_2		Mismatch attenuator HP / power sensor
d	m	Distance to septum
s		Voltage standing wave ratio at the cell entry, calculated from S11
$E_{Transfer}$	V/m	Field strength measured by the Transfer Standard.
$K_{Transfer}$		Correction factor of the transfer standard (drift, positioning accuracy in the cell etc.)

$P_{CalFactor}$:
Type B Normal distribution
Value: $1\cdot10^{-3}$ W
Expanded uncertainty: $0.007\cdot10^{-3}$ W
Coverage Factor: 2

$P_{Linearity}$:
Type B Normal distribution
Value: 1
Expanded uncertainty: 0
Coverage Factor: 2

P_{Drift}:
Typ B Rectangular distribution

Value: 1
Half width: 0.001

Z_{Cell}:
Constant
Value: 50 Ω

S_{21HP}:
Type B Normal distribution
Value: 0.3118
Extended uncertainty: 0.0021
Coverage Factor: 2

S_{21Cell}:
Type B Normal distribution
Value: 0.9943
Extended uncertainty: 0.0063
Coverage Factor: 2

M_1:
Import from Excel (GUM)

M_2:
Import from Excel (GUM)

d:
Type B Normal distribution
Value: 0.033872 m
Extended uncertainty: 0.00014 m
Coverage Factor: 2

s:
Import from Excel (GUM)

$K_{Transfer}$:
Type A summarized
Value: 1
Standard uncertainty: 1 %
Degree of freedom: 5

Uncertainty-Budgets:

$P_{Measured}$:
Measured power at the power sensor

Quantity	Value	Standard Uncertainty	Distribution	Sensitivity coefficient	Uncertainty contribution	Index
$P_{CalFactor}$	$1.00000\cdot10^{-3}$ W	$3.50\cdot10^{-6}$ W	Normal	1.0	$3.5\cdot10^{-6}$ W	97.4 %
$P_{Linearity}$	1.0	0.0	Normal	0.0	0.0 W	0.0 %
P_{Drift}	1.000000	$577\cdot10^{-6}$	Rectangular	$1.0\cdot10^{-3}$	$580\cdot10^{-9}$ W	2.6 %
$P_{Measured}$	$1.00000\cdot10^{-3}$ W	$3.55\cdot10^{-6}$ W				

E_{Cell}:
Electrical field at location of the transfer standard

Quantity	Value	Standard Uncertainty	Distribution	Sensitivity coefficient	Uncertainty contribution	Index
$P_{CalFactor}$	$1.00000\cdot10^{-3}$ W	$3.50\cdot10^{-6}$ W	Normal	11000	0.037 V/m	3.2 %
$P_{Linearity}$	1.0	0.0	Normal	0.0	0.0 V/m	0.0 %
P_{Drift}	1.000000	$577\cdot10^{-6}$	Rectangular	11	$6.1\cdot10^{-3}$ V/m	0.0 %
Z_{Cell}	50.0 Ω					
S_{21HP}	0.31180	$1.05\cdot10^{-3}$	Normal	-68	-0.072 V/m	11.9 %
S_{21Cell}	0.99430	$3.15\cdot10^{-3}$	Normal	-11	-0.034 V/m	2.6 %
M_1	1.000000	$238\cdot10^{-6}$		-11	$-2.5\cdot10^{-3}$ V/m	0.0 %
M_2	1.000000	$241\cdot10^{-6}$		-11	$-2.6\cdot10^{-3}$ V/m	0.0 %
d	0.0338720 m	$70.0\cdot10^{-6}$ m	Normal	-630	-0.044 V/m	4.5 %
s	1.00000	$8.59\cdot10^{-3}$		21	0.18 V/m	77.6 %
E_{Cell}	21.233 V/m	0.207 V/m				

$E_{Transfer}$:
Electrical Field at location of the transfer standard
(Total uncertainty of the transfer including field generator)

Quantity	Value	Standard Uncertainty	Distribution	Sensitivity coefficient	Uncertainty contribution	Index
$P_{CalFactor}$	$1.00000\cdot10^{-3}$ W	$3.50\cdot10^{-6}$ W	Normal	11000	0.037 V/m	1.6 %
$P_{Linearity}$	1.0	0.0	Normal	0.0	0.0 V/m	0.0 %
P_{Drift}	1.000000	$577\cdot10^{-6}$	Rectangular	11	$6.1\cdot10^{-3}$ V/m	0.0 %
Z_{Cell}	50.0 Ω					
S_{21HP}	0.31180	$1.05\cdot10^{-3}$	Normal	-68	-0.072 V/m	5.8 %
S_{21Cell}	0.99430	$3.15\cdot10^{-3}$	Normal	-11	-0.034 V/m	1.3 %
M_1	1.000000	$238\cdot10^{-6}$		-11	$-2.5\cdot10^{-3}$ V/m	0.0 %
M_2	1.000000	$241\cdot10^{-6}$		-11	$-2.6\cdot10^{-3}$ V/m	0.0 %
d	0.0338720 m	$70.0\cdot10^{-6}$ m	Normal	-630	-0.044 V/m	2.2 %
s	1.00000	$8.59\cdot10^{-3}$		21	0.18 V/m	37.8 %
$K_{Transfer}$	1.0000	0.0100	Normal	21	0.21 V/m	51.3 %
$E_{Transfer}$	21.233 V/m	0.297 V/m				

Results:

Quantity	**Value**	**Extended measurement uncertainty**	**Coverage factor**	**Probability**
$E_{Transfer}$	21.23 V/m	3.0 % (relative)	2.2	95% (t-Tabelle 95.45%)

This budget is our actual budget for the uTEM cell infrastructure. The value of 1.8% standard uncertainty (3.6 % for K=2) mentioned in the report stands for an older version of the software for which the stabilization algorithm was worse.

D.3 NPL

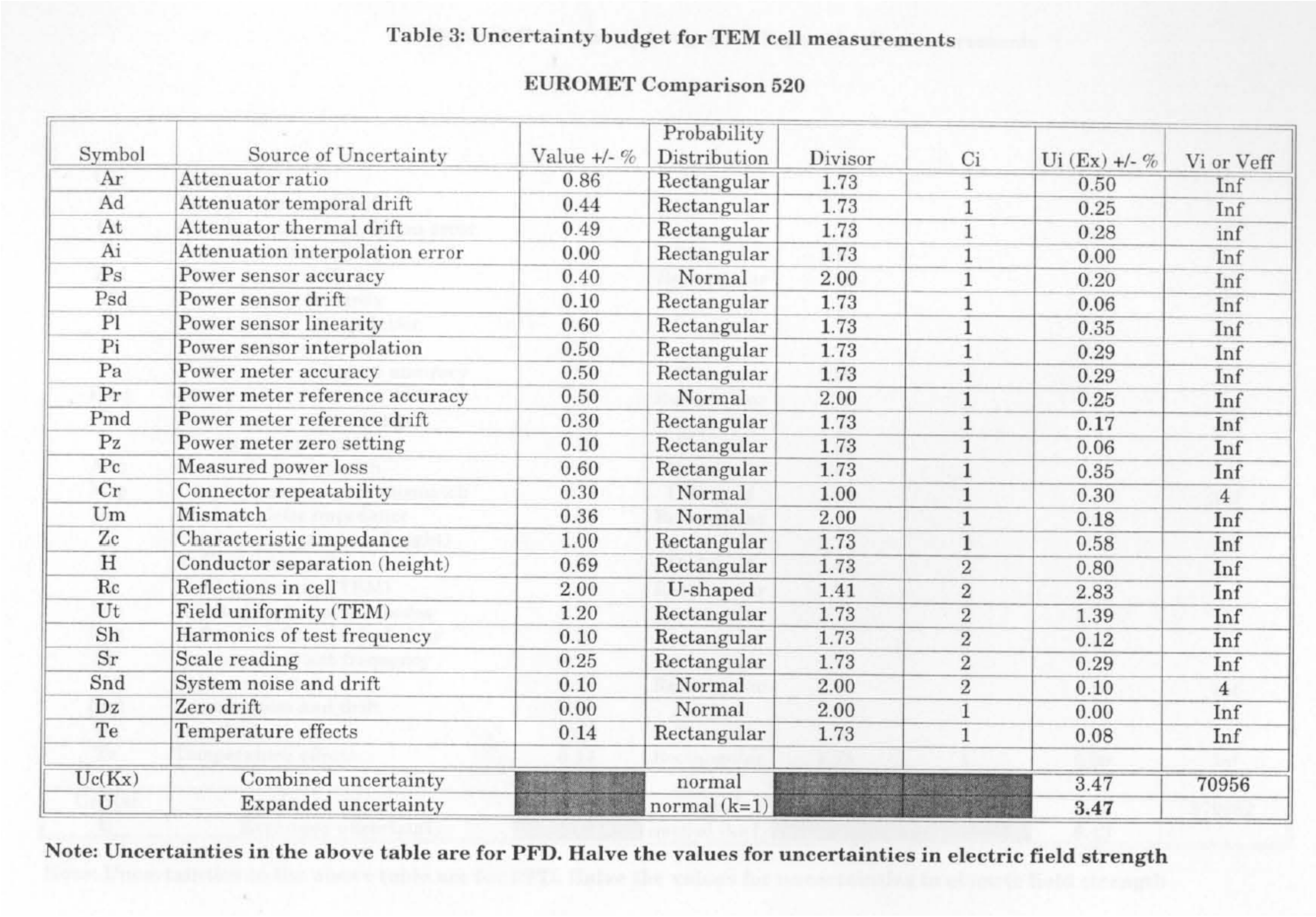


Table 3: Uncertainty budget for TEM cell measurements

EUROMET Comparison 520

Symbol	Source of Uncertainty	Value +/- %	Probability Distribution	Divisor	Ci	Ui (Ex) +/- %	Vi or Veff
Ar	Attenuator ratio	0.86	Rectangular	1.73	1	0.50	Inf
Ad	Attenuator temporal drift	0.44	Rectangular	1.73	1	0.25	Inf
At	Attenuator thermal drift	0.49	Rectangular	1.73	1	0.28	inf
Ai	Attenuation interpolation error	0.00	Rectangular	1.73	1	0.00	Inf
Ps	Power sensor accuracy	0.40	Normal	2.00	1	0.20	Inf
Psd	Power sensor drift	0.10	Rectangular	1.73	1	0.06	Inf
Pl	Power sensor linearity	0.60	Rectangular	1.73	1	0.35	Inf
Pi	Power sensor interpolation	0.50	Rectangular	1.73	1	0.29	Inf
Pa	Power meter accuracy	0.50	Rectangular	1.73	1	0.29	Inf
Pr	Power meter reference accuracy	0.50	Normal	2.00	1	0.25	Inf
Pmd	Power meter reference drift	0.30	Rectangular	1.73	1	0.17	Inf
Pz	Power meter zero setting	0.10	Rectangular	1.73	1	0.06	Inf
Pc	Measured power loss	0.60	Rectangular	1.73	1	0.35	Inf
Cr	Connector repeatability	0.30	Normal	1.00	1	0.30	4
Um	Mismatch	0.36	Normal	2.00	1	0.18	Inf
Zc	Characteristic impedance	1.00	Rectangular	1.73	1	0.58	Inf
H	Conductor separation (height)	0.69	Rectangular	1.73	2	0.80	Inf
Rc	Reflections in cell	2.00	U-shaped	1.41	2	2.83	Inf
Ut	Field uniformity (TEM)	1.20	Rectangular	1.73	2	1.39	Inf
Sh	Harmonics of test frequency	0.10	Rectangular	1.73	2	0.12	Inf
Sr	Scale reading	0.25	Rectangular	1.73	2	0.29	Inf
Snd	System noise and drift	0.10	Normal	2.00	2	0.10	4
Dz	Zero drift	0.00	Normal	2.00	1	0.00	Inf
Te	Temperature effects	0.14	Rectangular	1.73	1	0.08	Inf
Uc(Kx)	Combined uncertainty		normal			3.47	70956
U	Expanded uncertainty		normal (k=1)			**3.47**	

Note: Uncertainties in the above table are for PFD. Halve the values for uncertainties in electric field strength

Table 4: Uncertainty budget for Tapered cell measurements

EUROMET Comparison 520

Symbol	Source of Uncertainty	Value +/- %	Probability Distribution	Divisor	Ci	Ui (Ex) +/- %	Vi or Veff
Cpr	Coupler ratio	1.21	Rectangular	1.73	1	0.70	Inf
Cd	Coupler temporal drift	0.40	Rectangular	1.73	1	0.23	Inf
Cri	Coupler ratio interpolation error	0.00	Rectangular	1.73	1	0.00	Inf
Ps	Power sensor accuracy	0.90	Normal	2.00	1	0.45	Inf
Psd	Power sensor drift	0.30	Rectangular	1.73	1	0.17	Inf
Pl	Power sensor linearity	1.16	Rectangular	1.73	1	0.67	Inf
Pi	Power sensor interpolation	1.00	Rectangular	1.73	1	0.58	Inf
Pa	Power meter accuracy	1.00	Rectangular	1.73	1	0.58	Inf
Pr	Power meter reference accuracy	0.90	Normal	2.00	1	0.45	Inf
Pmd	Power meter reference drift	0.75	Rectangular	1.73	1	0.43	Inf
Pz	Power meter zero setting	0.75	Rectangular	1.73	1	0.43	Inf
Cr	Connector repeatability	0.30	Normal	1.00	1	0.30	4
Mcc	Coupler/cell mismatch	0.80	U-shaped	1.41	1	0.57	Inf
Mcp	Coupler/power sensor mismatch	0.70	U-shaped	1.41	1	0.49	Inf
Zc	Characteristic impedance	1.40	Rectangular	1.73	1	0.81	Inf
H	Conductor separation (height)	0.39	Rectangular	1.73	2	0.45	Inf
Rc	Reflections in cell	2.62	U-shaped	1.41	2	3.71	Inf
Ut	Field uniformity (TEM)	1.31	Rectangular	1.73	2	1.51	Inf
Um	Effect of higher order modes	2.60	Rectangular	1.73	2	3.00	Inf
Rph	Reflections from probe holder	0.50	Rectangular	1.73	2	0.58	Inf
Sh	Harmonics of test frequency	0.10	Rectangular	1.73	2	0.12	Inf
Sr	Scale reading	0.25	Rectangular	1.73	2	0.29	Inf
Snd	System noise and drift	0.09	Normal	1.00	2	0.18	4
Dz	Zero drift	0.00	Normal	2.00	1	0.00	Inf
Te	Temperature effects	0.14	Rectangular	1.73	1	0.08	Inf
Uc(Kx)	Combined uncertainty		normal			5.43	379852
U	Expanded uncertainty		normal (k=1)			**5.43**	

Note: Uncertainties in the above table are for PFD. Halve the values for uncertainties in electric field strength

D.4 NMi-VSL

Type-A evaluation:
The measurements consist of pairs of readings (power meter, DUT). In each measurement run these pairs are recorded for a series of frequencies. In order to avoid the effects of possible covariance, the type-A evaluation is obtained from the spread in the E_m values, taken from a number of independent runs. The reproducibility is investigated by removing and reinserting the field strength probe between the runs. The symmetry is checked by rotating the probe around its axis by 180 degrees. The results are detailed in the tables below.

Type-B evaluation:

E_m The spread in the readings is investigated by type-A evaluation as indicated above.

E_{res} The expectation value for the resolution term is 0. The resolution of the readout of the DUT is 0,1 V/m, leading to a uniform distribution of half-width 0,05 V/m

d The distance was measured with a calibrated digital depth caliper, using a small hole in the top wall of the TEM cell. The value measured was 59,51 mm, with an uncertainty of 0,10 mm (half-width of uniform distribution).

P_m The power readings are automatically translated into field strength values E by the measurement program. The resolution has a negligible uncertainty contribution. The type-A contribution from the spread in readings is already taken care of (see above).

$k(A)$ The correction factor for the power dependent non-linearity of the power sensor (= inverse linearity factor) has been determined (at a frequency of 50 MHz) at a power level of 30 mW, which is very close to the level used during the field strength measurements. The value found was 1,001 with an uncertainty (k=2, normal distribution) of 0,002

$k_1(f)$ The correction for the frequency response was taken from the calibration data of the sensor-meter combination. Due to the internal linearisation of the power meter the result is a frequency independent value of 0,9933. Uncertainty, including drift and temperature sensitivity: 1,7 % (k=2, normal distribution).

$k_2(f)$ The frequency dependent attenuation (S_{21}) of one half of the cell was taken from the calibration data of the cell. (Value: approx. 0,005 dB at 100 MHz to approx 0,02 dB at 1 GHz). Uncertainty: 0,2 % (k=2, normal distribution).

M_{tot} Mismatch term: value = 1. Uncertainty, evaluated from Scalar Network Analysis: 0,02 % (half-width of interval, U-shaped distribution).

Z_L The nominal impedance is 50 Ω, which is taken as the actual value. The uncertainty has been estimated to be 0,2 (half-width of uniform distribution).

$_{sw}$ Estimated value = 0. Uncertainty, from Scalar Network Analysis: 0,01 (half-width of interval, U-shaped distribution.

$f(x,y)$ Calculated value 0,99. Uncertainty, from calculated y-gradient (0,00958 per mm) and estimated uncertainty of y-position of probe: 0,00958[mm^{-1}] 0,3[mm] = 0,00287 (half-width of uniform distribution)

In the following table the uncertainty budget for the frequency 1000 MHz is specified.

Table 1 Uncertainty budget

Contributions:	parameter	unit	value	U_i	dist	$u(x_i)$	C_i	[C_i]	$u_i(y)$ (V/m)	$u(x_i)^2$
Field strength reading	E_m	V/m	19,800	none						
Resolution DUT		V/m	0,000	0,05	uniform	0,0289	1,0000		0,0289	0,00083333
Distance Septum-wall	d	mm	59,51	0,10	uniform	0,0577	0,3441	V.m^{-1}.mm^{-1}	0,0199	0,00039465
Power reading	P_m	W	0,0297	none						
Non-linearity of power sensor	k(A)		1,0010	0,002	normal 2s	0,0010	10,2281	V.m^{-1}	0,0102	0,00010461
Frequency response of power sensor	$k_1(f)$		0,9933	0,017	normal 2s	0,0085	10,3070	V.m^{-1}	0,0876	0,00767539
Frequency dependant attenuation of the cell	k2(f)		1,0046	0,002	normal 2s	0,0010	10,1913	V.m^{-1}	0,0102	0,00010386
Mismatch losses	M_{tot}		1,0000	0,0002	U-shaped	0,0001	10,2383	V.m^{-1}	0,0014	0,00000210
TEM Cell impedance	Z_L		50,00	0,20	uniform	0,1155	0,2048	V.m$^{-1. -1}$	0,0236	0,00055906
Standing waves			0,000	0,012	U-shaped	0,0085	20,4766	V.m^{-1}	0,1738	0,03018900
Form factor	f(x,y)		0,990	0,0029	uniform	0,0017	20,6834	V.m^{-1}	0,0343	0,00117460
Calculated field strenght (intermediate result)	E	V/m	20,272							
Type-A: independent repeat measurements	E_{nor}	V/m	20,477	0,07	normal 1s	0,0668	1,0000		0,0668	0,00446740
RESULT						u(y)	k	U(y)		
Normalised field strength (result)	E_{nor}	V/m	20,477			0,2133	2	0,427	V/m	0,04550400
RESULT								U(y)/E		
Alternative presentation of result: Relative	20/E_{nor}		0,977			0,0104	2	0,021		

N.B. The standing wave effect which contributes about 0,85 % (k=1) is the predominant factor in the uncertainty contribution.

D.5 STUK

The uncertainty of the calibration consists of uncertainties associated with RF power measurements, characteristic impedance of the TEM-300 cell, separation distance between the centre conductor and the upper ground plane, the orientation and the positioning of the probe. Above 150 MHz the standing wave pattern affects the uncertainty although the effect of the standing wave pattern has been taken into account. Mismatches increase the uncertainty of the measurement of the transmitted power. Because the applied electric field is calculated according to the equation (2) the relative combined uncertainty $\frac{u_c(E)}{E}$ consists of different uncertainty factors weighted as follows.

$$\frac{u_c(E)}{E} = \sqrt{\left(\frac{1}{2}\frac{u(P)}{P}\right)^2 + \left(\frac{1}{2}\frac{u(Z_c)}{Z_c}\right)^2 + \left(\frac{1}{2}\frac{u(k_f)}{k_f}\right)^2 + \left(\frac{u(d)}{d}\right)^2 + \left(\frac{u(op)}{op}\right)^2} \quad (4)$$

The uncertainty budget of the calibration of the sensor in the TEM-300 cell is presented in Table 1. The main contribution to the uncertainty is caused by the power measurement. The combined relative standard uncertainty is estimated to be ± 2.4%.

Table 1. Uncertainty budget for the calibration of the sensor in the TEM cell.

Contribution	Error	Probability distribution	Weight	Standard deviation
Power meter	± 6.2%	Rectangular	0.5	3.6%
Mismatch 1	±0.9%	U-shape	0.5	0.7%
Mismatch 2	±0.9%	U-shape	0.5	0.7%
Attenuation of the attenuators	±3.5%	Rectangular	0.5	2.1%
Characteristic impedance	± 2%	Rectangular	0.5	1.2%
Standing wave pattern correction	± 2%	Rectangular	0.5	1.2%
Separation distance	± 0.4%	Rectangular	1	0.3%
Orientation and positioning of the probe	± 1%	Rectangular	1	0.6%
Combined				2.4%

Open field method

The calibration uncertainty in the anechoic chamber consists of uncertainties associated with the power measurements, dimensions of the wave guide section and positioning and orientation of the reference probe and the sensor. The disturbancies caused by the reference probe in the waveguide were also estimated and taken into account. Also in this case the largest uncertainty contribution is caused by the uncertainty concerning the RF power measurements. The combined relative standard uncertainty is estimated to be ± 2.5%.

$$\frac{u_c(E)}{E} = \sqrt{\left(\frac{1}{2}\frac{u(P)}{P}\right)^2 + \left(\frac{1}{2}\frac{u(a)}{a}\right)^2 + \left(\frac{1}{2}\frac{u(b)}{b}\right)^2 + \left(\frac{1}{2}\frac{u(ave)}{ave}\right)^2 + \left(\frac{1}{2}\frac{u(dist)}{dist}\right)^2 + 2\left(\frac{u(op)}{op}\right)^2} \quad (3)$$

Table 2. Uncertainty budget for the calibration of the sensor in the anechoic chamber.

Contribution	Error	Probability distribution	Weight	Standard deviation
Power meter	± 6.2%	Rectangular	0.5	3.6%
Mismatch 1	±0.5%	U-shape	0.5	0.4%
Mismatch 2	±1.3%	U-shape	0.5	0.9%
Coupling of directional coupler	±3.5%	Rectangular	0.5	2.1%
Width of the waveguide	± 0.5%	Rectangular	0.5	0.3%
Height of the waveguide	± 1%	Rectangular	0.5	0.6%
Averaging the standing wave pattern	± 2%	Rectangular	0.5	1.2%
Disturbance of the reference dipole in the waveguide	± 2%	Rectangular	0.5	1.2%
Orientation and positioning of the reference dipole	± 1%	Rectangular	1	0.6%
Orientation and positioning of the probe	± 1%	Rectangular	1	0.6%
Combined				2.5%

D.6 IEN

The following expression shows the combined uncertainty of the electric field *E,* which is obtained by taking the square root of the sum of squares of the single uncertainty contributions, weighted according to equation (1):

$$\frac{\Delta E}{E} = \mathrm{u}_E \cong \sqrt{\mathrm{u}_d^2 + \frac{\mathrm{u}_P^2 + \mathrm{u}_\mathrm{Z}^2}{4} + \mathrm{u}_D^2 + \mathrm{u}_\mathrm{S}^2} \qquad (2)$$

where u_d, u_P and u_Z are the relative uncertainties associated with the measurement of the septum distance, the net power and the cell impedance respectively and u_D is the contribution due to the field non-homogeneity. Equation (2) includes also a term u_s to take into account the repeatability of the measurement system.

Table 3 and Table 4 show the estimated field strength uncertainty calculated according to equation (2) in the case of the TEM and G-TEM cell respectively.

Table 3 – Field strength uncertainty in TEM cell.

	Standard uncertainty (%)
Net power u_P (1)	8
Septum distance u_d	1
Cell impedance u_Z (2)	4
Field non-homogeneity u_D (3)	2,5
System repeatability u_s (4)	1
	5

Table 4 – Field strength uncertainty in G-TEM cell.

	Standard uncertainty (%)	
	300 MHz ≤ f ≤ 600 MHz	f ≥ 700 MHz
Net power u_P (1)	8	8
Septum distance u_d	1	1
Cell impedance u_Z (2)	8	8
Field non-homogeneity u_D (3)	10	15
System repeatability u_s (4)	2	4
	12	**16**

Notes:

(1) This term takes into account the different uncertainty contributions associated with a power measurement made with a power meter and a directional coupler.

(2) The TEM and G-TEM cell impedance in the test volume was evaluated by means of TDR measurements.

(3) A considerable volume inside the cells was mapped in the whole frequency range to evaluate the field homogeneity and to choose a zone useful to calibrate the electric field sensor.

(4) Measurements were repeated on different days to evaluate the repeatability of the measurement system.

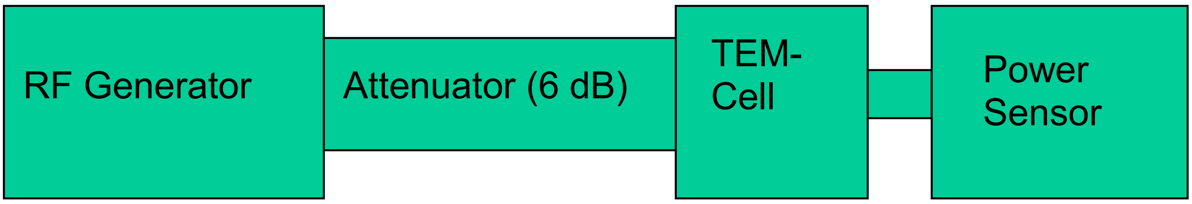
D.7 CSIR-NML

1. The South African Realisation of Electromagnetic Fields in the Frequency Range from DC to 1 GHz.

The electromagnetic field is generated between the inner and outer conductors of a miniature TEM-cell which is of the well-known PTB design. The cell was built by the company Messelektronik Berlin (MEB). The electric field strength is determined from the RF power passing through the cell, the characteristic impedance of the coaxial transmission line system and mechanical data of the TEM-cell.

2. Description of the calibration set-up

A relatively simple set-up as shown below was used:



The RF generator output was for the first three measurement sets directly connected to the input of the TEM-cell. For the fourth and last measurement set a 6 dB fixed attenuator was inserted between generator output and the cell input. No significant difference between the first three and the fourth set was found.

The use of a RF amplifier was not required and potential problems due to the expected high source match of the amplifier could thereby be avoided.

The source match of the RF generator (Model Rohde & Schwarz SMG) was measured employing a procedure contained in the operating manual. It was found that the source match is better than 32 db at 1 GHz at output levels used for the comparison exercise.

The RF power sensor (Model Rohde & Schwarz NRV-Z51) was connected directly to the output of the TEM-cell. The return loss of the power sensor was found to be better than 40 dB up to 1 GHz. The accuracy of the calibration factors is directly traceable to the South African national measurement standard for RF power at three frequencies between 100 kHz and 1 GHz and at DC against DC measurement standards. Interpolated values were used between calibration frequencies with direct traceability. An uncertainty of ±2 % was used for the uncertainty of the power sensor calibration factor from 10 MHz to 1 GHz. No correction for non-linearity of the power sensor reading was made but an additional uncertainty term was used in the uncertainty budget.

The s-parameters of the TEM-cell had been measured previously using a HP 8753D vector network analyser. The s_{11} and s_{22} values were found to be better than 0,02 (34 dB) up to 1 GHz.

The following formula was used to convert a power sensor reading to electric field strength E:

$$E = \sqrt{}(P \times Z_L)/(CF \times 1000) / d$$

Where P is the power reading in mW, Z_L is the characteristic impedance (50 Ω), CF is the calibration factor and d the septum height in metre. No correction for VSWR and inhomogeneities within the cells were made. However two mismatch uncertainty terms were included in the uncertainty budget, for the power sensor and also due to standing waves within the cell. A worst case uncertainty was calculated with a spreadsheet. A repeatability of less than ± 0,25 % was noted over the frequency range. Only one total uncertainty value was calculated since the individual uncertainties remain relatively constant over the frequency range of calibration. The value for k=1 was found to be ±2 %.

D.8 SP

The unexpanded uncertainty for the TEM cell is estimated to 4 %.

Z_L = characteristic impedance of the coaxial system
$A(f)$ = network-analyzer's uncertainty
δP = power meters uncertainty
$\delta(x)$ = inhomogenity correction factor
$\delta(VSWR)$ = SWR correction factor
d = septum distance inside the cell

Qty. X_i	standard uncertainty $u(x_i)$	sens. coeff. c_i	Contrib.. to rel. std. uncertainty. $w_i(y)$
Z_L	0,0126	½	0,0062
$A(f)$	0,029	½	0,0145
δP_1	0,02705	½	0,01353
δP_2	0,02705	½	0,01353
δP_3	0,02705	½	0,01353
$\delta(x)$	0 (calculated)	1,0	0,00
$\delta(VSWR)$	0,0282	1,0	0,0282
d		-1,0	
			$\mathbf{3.99 \cdot 10^{-2}}$

The uncertainty above is for the field inside the TEM cell. The additional contribution from the transfer procedure is probably at least as large. However it is not easy to calculate but requires practical work. Since we will move and refurbish the chamber starting in February this work will not be performed in the current chamber. Similar work has been performed in the microwave range but it is not valid for the current range.

D.9 KRISS

300 MHz

Uncertainty component $u(x_i)$	Source of uncertainty	Type of uncertainty	Value of uncertainty $u(x_i)$	$c_i = \partial f / \partial x_i$	$c_i u(x_i)$ [V/m]	Degree of freedom
$u(System)$	Standard field generation system [V/m]	B	0.215	1	0.215	137
$u(P)$	Power [mW]	B	0.0245	2098.83	0.052	∞
$u(A)$	Attenuation factor	B	0.0076	-20.42	-0.155	50
$u(Z)$	Characteristic impedance [ohm]	B	0.35	0.20	0.072	∞
$u(d)$	Septum distance [m]	B	0.0002	-601.17	-0.120	50
$u(Position)$	Position accuracy [V/m]	B	0.05	1	0.050	13
$u(SW)$	Standing wave [V/m]	B	0.1442	1	0.144	∞
$u(E_i)$	Repeat measurement [V/m]	A	0.0337	1	0.034	9
U(k = 1)	Expanded uncertainty [V/m]	-	0.266	-		307

D.10 CSIRO

Measurement uncertainties

Components of measurement uncertainty are listed in table 4 below.

Table 4
Uncertainty Analysis at 900 MHz

Item	**Notes**	**Type**	**Raw value ratio**	df	**Divisor**	u_c **ratio**
Power in µTEM cell						
Power meter calibration, at 1 mW	0.4% power (95%) express as voltage	B	0.0020	50	2.00	0.0010
Power meter calibration, linearity	0.4% power (95%) express as voltage	B	0.0020	50	2.00	0.0010
Read power, random	0.2% power (1 sigma) express as voltage	B	0.0010	3	1.00	0.0010
Mismatch power meter to pad	Power meter 0.02, pad 0.02	B	0.0004	50	1.41	0.0003
Pad attenuation	0.05 dB (95%) as voltage	B	0.0070	50	2.00	0.0035
Mismatch pad to cell	Pad 0.02, cell 0.02	B	0.0004	50	1.41	0.0003
Harmonics	20 dBc source, 20 dBc amp, 33 dB filter	B	0.0032	50	2.00	0.0016
Field at Transfer Probe in µTEM						
Cell dimension	1% uncertainty in 35 mm (95%)	B	0.0100	50	2.00	0.00500
Cell theoretical field strength at nominal position	3% (95%)	B	0.0300	50	2.00	0.01500
Reflection from cell feed end	Cell reflection coefficient 0.02 (95%)	B	0.0200	50	1.41	0.0142
Reflections in cell from load	Load reflection coefficient 0.02 (95%)	B	0.0200	50	1.41	0.0142
Transfer Probe cal in µTEM						
Read nanovoltmeter, linearity run, random	< 0.1% (rectangular)	B	0.0010	3	1.73	0.0006
Read nanovoltmeter, freq run, random	< 0.1% (rectangular)	B	0.0010	3	1.73	0.0006
Uncertainty in position of probe centre, E field direction	Within 3 mm of nominal (rectangular), 20%/35 mm	B	0.0171	50	1.73	0.0099
Effect of probe on field in µTEM	Estimate 5% (95%)	B	0.0500	50	2.00	0.0250
Settability of signal generator	0.02 dB steps	B	0.0024	50	1.73	0.0014
Temperature effects on Transfer Probe	Estimate for 0.2 degree	B	0.0034	2	1	0.0034
Uncertainty in frequency	1 in 10^5 * 5% for 10 MHz	B	0.0001	50	2.00	0.0000
Harmonics	20 dBc source, 20 dBc amplifier, 33 dB filter	B	0.0032	50	2.00	0.0016

Transfer Probe in GTEM						
Drift in probe	Estimate 1% (rectangular)	B	0.0100	50	1.73	0.0058
Axial angular alignment	5 degrees causes 2.5%	B	0.0250	50	1.73	0.0145
Temperature uncertainty relative to µTEM	3 degrees at 1.3/degree (rectangular)	B	0.0039	50	1.73	0.0023
Read nanovoltmeter, linearity, random	< 0.1% (rectangular)	B	0.0010	3	1.73	0.0006
Read power at GTEM Input (random)	0.2% power (1 sigma) express as voltage	B	0.0010	3	1.00	0.0010
Settability of signal generator	0.02 dB steps	B	0.0024	50	1.73	0.0014
Uncertainty in frequency	1 in 10^5 * 15% for 10 MHz	B	0.0002	50	2.00	0.0001
Harmonics	20 dBc source, 20 dBc amplifier, 33 dB filter	B	0.0032	50	2.00	0.0016
Effective df				247		
k	1.97					
Total 2 sigma voltage ratio			**0.0811**			

Item	**Notes**	**Type**	**Raw value ratio**	df	**Divisor**	u_c **ratio**
Travelling Standard in GTEM						
GTEM at reference Field	GTEM Calibration	B	0.0811	247	1.97	0.0412
Read power at GTEM input	Random	B	0.0010	3	1.00	0.0010
Power meter linearity	0.4% power from 60 V/m to 20 V/m, relative to 20 V/m	B	0.0040	50	2.00	0.0020
Drift in GTEM power monitoring system	Estimate 0.1 dB	B	0.0120	50	1.73	0.0069
Equivalence between transfer probe and Travelling Standard	Due to different position, after averaging	B	0.0100	3	1.73	0.0058
Mean over 20 positions, Method A and B	Standard Deviation of 0.47 V/m in 21 V/m	A	0.0223	39	1.00	0.0223
Read Standard probe, drift	Estimate 1% (rectangular)	B	0.0100	50	1.73	0.0058
Read Standard probe, random & quantisation	Estimate 1% (rectangular)	B	0.0100	3	1.73	0.0058
Settability of signal generator	0.02 dB steps	B	0.0024	50	1.73	0.0014
Temperature effects on Travelling Standard	Estimate for 1degree	B	0.0085	2	1	0.0085
Uncertainty in frequency	1 in 10^5 * 15% for 10 MHz	B	0.0002	50	2.00	0.0001
Harmonics	20 dBc source, 20 dBc amplifier, 33 dB filter	B	0.0032	50	2.00	0.0016
Effective df				274		
k	1					
Uncertainty 1 sigma			**0.0492**			

D.11 NIM

To ensure the uniformity of the measurement value of field strength, we built the reference standard of electric filed strength. It is the primary measurement standard of field strength measurement in metrology. The field strength can be calculated by several parameters which are traceable to the national standard. The Transverse Electric and Magnetic Field Cell (TEM Cell) is a better device to generate electromagnetic field. It can generate electromagnetic field with frequency below the cutoff frequency. The cutoff frequency is corresponding to the dimension of the cell. Our reference standard is a commercial micro TEM Cell MTC 1000. It is symmetrical. The dimensions of the cross section are 70mm×70mm. The outer conductor consists of two screwed aluminum halve-dishes. The inner conductor is a brass plate. Two N sockets are fixed separately at the end of the cell. Small foam blocks support the inner conductor. MTC 1000 was designed for use as standard with solid construction and stable, good electrical and mechanical parameters. It is used to calibrate the corresponding transfer field strength probe.

The field strength can be calculated from only few physical quantities in MTC 1000, the calculated field strength is based on the geometry of the field source and the field source measured input parameters.

The following equation defines the relation of the parameters and the field strength in the center area between septum and outer conductor.

$$E_{rs} = \frac{\sqrt{Z_l \cdot P}}{d} \qquad \text{（1-1）}$$

where E_{rs} ---- field strength generated by the reference standard；

Z_l ----characteristic impedance of the coaxial system (including the cell)

P --- RF power passing through the cell, unit: W；

d ----distance between the septum and the outer conductor (from mechanical measurement), unit: m.

The characteristic impedance of the cell is measured by a traceable calibrated network analyzer. The power passing through the cell is too high to use a power sensor directly. So a precision attenuator is connected in series to reduce the power. For the power meter is not ideal, the power in the equation (1-1) is calculated in equation (1-2).

$$P = \frac{1}{A_f} \cdot k_{dcP} \cdot \mathrm{k}_f \cdot \mathrm{P}_r \quad \text{-------- （1-2）}$$

where A_f is the attenuation factor of Narada 777C-10 10dB attenuator. It is changed with the frequency. We need to convert the logarithmic factor from the calibration report to linear.

$$^{\circ}A_f = 10^{A'/10} = 10^{-10dB/10} = 0.1$$

Two correct factors multiply the reading of the power meter. The first factor k_{dcP} is used to correct the linear error of power meter. The second factor k_f is used to correct the error frequency. When the signal is DC, k_f is equal to 1. After calibration, the frequency response correction data is restored in the NRV-Z51 power sensor's nonvolatile memory by manufacturer. Input the measuring frequency, the power meter uses the frequency respond correction to correct the reading. So k_f is equal to 1. The power sensor NRV-Z51 does not contain any input capacitance, we can connect it to a DC power. That can measure the two correct factors. k_{dcP} is equal to 0.9906. Therefore, the equation (1-2) is changed to the following.

------ $$E_{rs} = \frac{\sqrt{Z_l \cdot k_{dcP} \cdot k_f \cdot P_r / A_f}}{d}$$ --（1-3）

Where P_r, A_f, Z_l and d is traceable to the national standards of power, attenuation, impedance and length separately. So the electric field strength of reference standard, E_{rs} is traceable, too.

For the electric field probe is sensitive to the temperature, the temperature of the cell need to be stable and controllable. We developed a system to control the temperature. A semiconductor component "peltier" which can heating and cooling was sticked on the side wall of the MTC 1000 cell. Two polymethyl boxes wrap the whole cell. The space between the two boxes is packed with foam to reduce the heat exchange. The controller can control the cell's temperature from 16 to 30 ℃. The precision is less than 0.02 ℃.

1.4 Power meter DC calibrator and correct factor k_{dcP}

The power meter in the calibration system work with a sensor, NRV-Z51, which can input DC coupling signal. So a traceable direct volts calibrator, Fluke 5440B is used to calibrate the power meter in the direct voltage range.

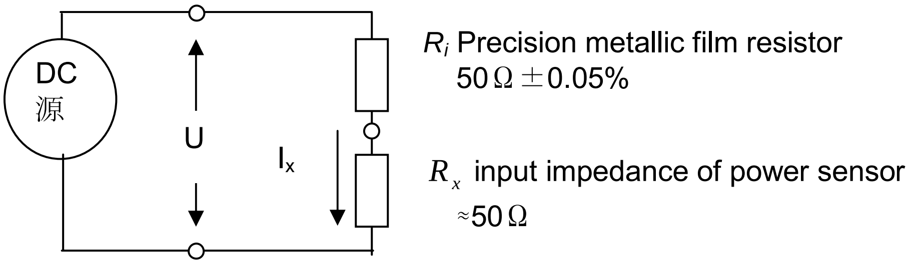


Figure 2 Set-up of power meter DC calibrator

The electronic schematic of direct current calibration system of the power meter is showed above. Fluke 5540B's output matches the power meter working input. When the field strength in the μ TEM Cell is 20 V/m, the reading of the power meter is about 1 mW. A couple of connectors connect the precision voltmeter, another N-socket RF connector connects the power sensor, NRV-Z51. A precision resistor is connected between the output port and RF input port of Fluke 5440B. When the system is calibrating the power meter, the input side of N-socket connector can be regard as a good matched 50 Ω signal generator.

Both the resistor in the power sensor and the power sensor are the parts of the voltage divider. So we can use a traceable precision voltmeter to measure U, the input voltage of the voltage divider. Using U, we can get the P_x, the direct current power inputted into the RF power meter.

$$P_x = I^2 \cdot R_x = \left[\frac{U}{(R_i + R_x)}\right]^2 R_x = \frac{R_x \cdot U^2}{(R_i + R_x)^2} \quad \text{-----（1-4）}$$

The ratio between the calculated dc power and the reading power of the power meter is the dc calibrating factor.

$$k_{dcP} = \frac{P_x}{P_m} \quad \text{-----（1-5）}$$

The values of the measurement are as the following.

$U = 0.423695V$; $R_i = 50.022\Omega$; $R_x = 50.5137\Omega$; $P_m = 0.9057mW$. Using the equation (1-4) and (1-5), we can get k_{dcP} is equal to 0.9906.

1.5 Checking the mismatch error

For the power sensor, NRV-Z51 is better matched at high frequency, the dc input resistor of it is greater than 50 Ω. If we define R_i is equal to 50 Ω, we need to define a correct factor, f to calculate the input resistor of the power sensor, R_x.

$$R_x = f \times R_i \quad \text{or} \quad f = \frac{R_x}{R_i} \quad \text{where：} \quad f \approx 1$$

The current passing through the voltage divider is

$$I = \frac{U}{R_i + R_x}$$

P_x, the input power of the sensor is

$$P_x = \frac{R_x \cdot U^2}{(R_i + R_x)^2} = \frac{(f \cdot R_i) \cdot U^2}{(R_i + f \cdot R_i)^2} = \frac{f \cdot R_i \cdot U^2}{[R_i \cdot (1+f)]^2} = \frac{f \cdot R_i \cdot U^2}{R_i{}^2 \cdot (1+f)^2} = \frac{U^2}{R_i} \times \frac{f}{(1+f)^2}$$

The error of the dc power of the power sensor is inversely proportional to the change of f The relation is shown in logarithmic.

$$\frac{dP_x}{df} = \frac{U^2}{R_i} \cdot \left[\frac{1}{(1+f)^2} - \frac{2f}{(1+f)^3} \right]$$

When the system is matched, f is equal to 1. That means the sensitive of the error is minute. When the measurement value of the input resistor, R_x is equal to 50.5137 Ω, we can get the f is equal to 1.01 or

$$\frac{f}{(1+f)^2} = 0.24999$$

So the system is matched, then the measurement power error is

$$\frac{P_x - P_{50}}{P_{50}} = \frac{\Delta P}{P_{50}} = \frac{P_x}{P_{50}} - 1 = 0.0001 = 0.01\%$$

Because it is minute, we can omit it without any correcting.

BIPM Key-Comparison CCEM.RF-K20

Devece: Travelling standard
Series number: 014

Environmental Conditions	**(℃)**	**± (℃)**
Environmental temperature	23	0.2
Micro TEM Cell temperature	23	0.02

measure frequency **f** **MHz**	**travelling standard display field strength** **V/m**	**measure numbers** **N**	**measured mean power** P_r **W**	**measured mean field strength** E_{rs} **V/m**	**sensitivity coefficient** c_1 V/m	**attenuation factor** $u(A_f)$	**degrees of freedom** ν_1	**sensitivity coefficient** c_2 $V/m \cdot W$	**standard uncertainty of measured mean RF power** $u(P_r)$ **W**	**degrees of freedom** ν_2
10	20.0	10×10	1.0495E-03	20.74	-102	2.19E-03	infinite	9880	2.73E-06	infinite
30	**20.0**	**10×10**	**1.0591E-03**	**20.84**	**-103**	**2.19E-03**	**infinite**	**9841**	**2.75E-06**	**infinite**
50	20.0	10×10	1.0589E-03	20.86	-103	2.19E-03	infinite	9851	2.75E-06	infinite
100	**20.0**	**10×10**	**1.0622E-03**	**20.90**	**-103**	**2.19E-03**	**infinite**	**9841**	**2.81E-06**	**infinite**
200	20.0	10×10	1.0702E-03	20.99	-104	2.19E-03	infinite	9809	2.84E-06	infinite
300	**20.0**	**10×10**	**1.0788E-03**	**21.08**	**-104**	**2.19E-03**	**infinite**	**9770**	**2.86E-06**	**infinite**
400	20.0	10×10	1.0869E-03	21.18	-105	2.19E-03	infinite	9743	2.88E-06	infinite
500	20.0	10×10	1.0866E-03	21.19	-105	2.19E-03	infinite	9749	2.89E-06	infinite
600	20.0	10×10	1.0927E-03	21.26	-106	2.19E-03	infinite	9726	3.02E-06	infinite
700	20.0	10×10	1.0998E-03	21.35	-106	2.19E-03	infinite	9705	3.04E-06	infinite
800	20.0	10×10	1.1120E-03	21.47	-107	2.19E-03	infinite	9656	3.07E-06	infinite
900	**20.0**	**10×10**	**1.1269E-03**	**21.61**	**-108**	**2.19E-03**	**infinite**	**9587**	**3.11E-06**	**infinite**
1000	20.0	10×10	1.1496E-03	21.83	-109	2.19E-03	infinite	9497	3.17E-06	infinite
						Type: B **distribution: normal**			**Type: B** **distribution: normal**	

measure frequency **f** **MHz**	**sensitivity coefficient** c_3 V/m^2	**standard uncertainty of measured septum distance** $u(d)$ **m**	**degrees of freedom** ν_3	**sensitivity coefficient** c_4 V/m	**standard uncertainty of VSWR correction factor** $u(\delta V_{swr})$	**freedom** ν_4	**uncertainty of reference standard field strength** $u_c(E_{rs})$ **V/m**	effective degrees **of freedom of reference standard** $\nu_{eff}(E_{rs})$	**sensitivity coefficient** c_5
10	-601	2.50E-06	50	-21	1.05E-02	infinite	0.31	9.4E+10	1
30	**-604**	**2.50E-06**	**50**	**-21**	**1.05E-02**	**infinite**	**0.31**	**9.4E+10**	**1**
50	-605	2.50E-06	50	-21	1.05E-02	infinite	0.32	9.5E+10	1
100	**-606**	**2.50E-06**	**50**	**-21**	**1.05E-02**	**infinite**	**0.32**	**9.5E+10**	**1**
200	-609	2.50E-06	50	-21	1.05E-02	infinite	0.32	9.5E+10	1
300	**-611**	**2.50E-06**	**50**	**-21**	**1.05E-02**	**infinite**	**0.32**	**9.5E+10**	**1**
400	-614	2.50E-06	50	-21	1.05E-02	infinite	0.32	9.6E+10	1
500	-614	2.50E-06	50	-21	1.05E-02	infinite	0.32	9.6E+10	1
600	-616	2.50E-06	50	-21	1.05E-02	infinite	0.32	9.6E+10	1
700	-619	2.50E-06	50	-21	1.05E-02	infinite	0.32	9.7E+10	1
800	-623	2.50E-06	50	-21	1.05E-02	infinite	0.33	9.7E+10	1
900	**-627**	**2.50E-06**	**50**	**-22**	**1.05E-02**	**infinite**	**0.33**	**9.7E+10**	**1**
1000	-633	2.50E-06	50	-22	1.05E-02	infinite	0.33	9.7E+10	1
		Type: B **distribution: normal**			**Type: B** **distribution: U-shaped**		**distribution: normal**		

measure frequency **f** **MHz**	**measure repeatability** $u(\delta R)$ **V/m**	**degrees of** freedom ν_5	**sensitivity coefficient** c_6	**location of probe** $u(\delta VP)$ **V/m**	**degrees of** freedom ν_6	**standard uncertainty of field strength travelling standard** $u_c(E_{ts})$ **V/m**	**V/m**	effective degrees **of freedom of travelling standard** $\nu_{eff}(E_{ts})$
10	0.10	9	1	0.25	4.5	0.41	0.41	31.8
30	**0.11**	9	**1**	**0.25**	4.5	**0.41**	**0.42**	**33.6**
50	0.09	9	1	0.27	4.5	0.42	0.43	25.9
100	**0.11**	9	**1**	**0.24**	4.5	**0.41**	**0.41**	**35.7**
200	0.11	9	1	0.27	4.5	0.42	0.43	27.4
300	**0.10**	9	**1**	**0.25**	4.5	**0.42**	**0.42**	**36.2**
400	0.10	9	1	0.26	4.5	0.42	0.42	32.5
500	0.09	9	1	0.25	4.5	0.42	0.42	33.5
600	0.09	9	1	0.24	4.5	0.41	0.41	39.2
700	0.09	9	1	0.28	4.5	0.43	0.44	26.7
800	0.09	9	1	0.25	4.5	0.42	0.42	32.5
900	**0.08**	9	**1**	**0.27**	4.5	**0.43**	**0.43**	**30.9**
1000	0.08	9	1	0.25	4.5	0.42	0.42	35.2
	Type: A **distribution: normal**			**Type: A** **distribution: normal**		**distribution: normal**		

D.12 VNIIFTRI

Table 2

Symbol	Source of uncertainty	Type evaluation of standard uncertainty	Limits of error, %	Probability distribution	Divisor	c_i^2	$u(x_i)$, %	v_i or v_{eff}
E_{ST}	Generation of the standard electric field strength	B	-	rectangular	-	1	0,62	∞
P	Power measurement	B	4,2	rectangular	$\sqrt{3}$	1	2,4	∞
K_{E02}	Antenna E02 calibration	A	-	normal	1	1	0,14	9
K_{TEM}	Interaction of the antenna E02 with TEM cell	B	3,0	rectangular	$\sqrt{3}$	1	1,7	∞
K_{TEM}	TEM cell calibration	A	-	normal	1	1	0,29	9
E_{STTEM}	Electric field strength measurement with the traveling standard in TEM cell	A	-	normal	1	1	0,70	9
	Combined uncertainty U_c		-	normal	-	-	3,1	
	Expanded uncertainty U		-	normal (k=1)	-	-	3,1	

$$U_c = \sqrt{\sum_{i=1}^{n} c_i^2 u^2(x_i)}\,, \qquad U = U_c \quad (k=1)$$

Table 3

Symbol	Source of uncertainty	Type evaluation of standard uncertainty	Limits of error, %	Probability distribution	Divisor	c_i^2	$u(x_i)$, %	v_i or v_{eff}
E_{ST}	Generation of the standard electric field strength	B	-	rectangular	-	1	0,62	∞
I_{TA}	Transmitting antenna current measurement	B	1,0	rectangular	$\sqrt{3}$	2	0,58	∞
K_{TA}	Interaction of the biconical antenna with the transmitting antenna	B	4,5	rectangular	$\sqrt{3}$	1	2,6	∞
K_{TA}	Transmitting antenna calibration	A	-	normal	1	1	0,13	9
E_{STTA}	Electric field strength measurement with traveling standard in free space	A	-	normal	1	1	0,44	9
	Combined uncertainty U_c		-	normal	-	-	2,8	
	Expanded uncertainty U		-	normal (k=1)	-	-	2,8	

$$U_c = \sqrt{\sum_{i=1}^{n} c_i^2 u^2(x_i)}\,, \qquad U = U_c \qquad (k = 1)$$

D.13 CMI

100 MHz

Source	Estimate		Standard uncertainty	Degree of freedom	Probability distribution	Sensitivity coefficient	Rel. uncertainty contribution
Power meter	4	%	0.02	18	normal	0.5	0.010
Refl. coeff. (power sensor)	0.01		0.005	∞	normal	1	0.005
Field nonuniformity	3.0	%	0.015	∞	normal	1	0.015
Septum distance	0.8	%	0.0046	∞	rectangular	1	0.005
Characteristic impedance	2.5	%	0.0125	∞	normal	0.5	0.006
Position of the sensor	1	cm	0.58	∞	rectangular	0.03	0.017
Temperature	0.8	°C	0.46	∞	rectangular	0.012	0.006
Type A uncert.				11			0.003
TOTAL							0.027

Tab. 5 Uncertainty budget for the measurement at frequency 100 MHz

300 MHz

Source	Estimate		Standard uncertainty	Degree of freedom	Probability distribution	Sensitivity coefficient	Rel. uncertainty contribution
Power meter	4	%	0.02	13	normal	0.5	0.010
Field nonuniformity	6.5	%	0.0325	∞	normal	1	0.033
Septum distance	2.0	%	0.0115	∞	rectangular	1	0.012
Characteristic impedance	7.0	%	0.035	∞	normal	0.5	0.018
Position of the sensor	2	cm	1.15	∞	rectangular	0.013	0.015
Temperature	0.8	°C	0.46	∞	rectangular	0.012	0.006
Type A uncert.				9			0.002
TOTAL							0.043

Tab. 6 Uncertainty budget for the measurement at frequency 300 MHz