Draft A Report

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(EURAMET Project No: 1538)

EURAMET Supplementary Comparison on Magnetic Field Strength Measurements for Frequencies up to 30 MHz

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1. Introduction

Magnetic field probes are widely utilized in the measurement of non-ionizing radiation magnetic fields emanating from high voltage lines, high voltage power transformers, welding or induction heating equipment [1] and in electromagnetic compatibility (EMC) testing (IEC 62233 [2] and IEC 62311 [3]) and other applications in the frequency range of 5 Hz – 1 GHz. Therefore, the calibration of magnetic field probes is of fundamental importance for the traceability of the magnetic field measurements. They must be calibrated by National Metrology Institutes (NMIs) or accredited calibration laboratories in accordance with international standards such as IEEE Std. 1309 [4] and IEEE Std. 1308 [5]. The NMIs should participate in international inter-laboratory comparisons in order to demonstrate the international equivalence of their measurement standards and the calibration and measurement certificates they issue and to support their CMCs in the CIPM KCDB.

It has been discussed to organize a comparison on Magnetic Field Strength Measurements during the EURAMET TC-EM Subcommittee Radiofrequency and Microwave (SC-MW) meeting, including an EMC meeting, organized as a virtual (online) meeting on 20-21 April 2021.

The comparison was conducted in accordance with the Technical Protocol of "Comparison of Magnetic Field Strength Measurements for Frequencies up to 30 MHz, EURAMET Project No: 1538, EURAMET.EM.RF – S46", given in Appendix A, which was prepared by the TÜBİTAK UME and approved by the participants.

2. Organisation of the Comparison

2.1. Pilot Institute

This comparison was piloted by TÜBİTAK UME. The pilot laboratory is responsible for preparing the technical protocol, determining the stability of the travelling standard, calculating the results and preparing the comparison report.

2.2. Participating Institutes

The participating institutes are listed in Table 1.

Table 1. List of participants

Acronym of Institute	Country	Contact Person	Shipping Address
TÜBİTAK UME	Türkiye	Osman Şen osman.sen@tubitak.gov.tr Tel: +90 262 679 50 00	TÜBİTAK Ulusal Metroloji Enstitüsü (UME) TÜBİTAK Gebze Yerleşkesi Barış Mah. Dr. Zeki Acar Cad. No:1 41470 Gebze-Kocaeli, Türkiye
CMI	Czech Republic	Tomáš Pavlíček tpavlicek@cmi.cz Tel: +420 266 020 185	Český metrologický institut Radiová 1136/3 CZ-10200 Praha, Czech Republic
PTB	Germany	Franziska Weickert Franziska.weickert@ptb.de Tel: +47 592 2510	Physikalisch-Technische Bundesanstalt 2.51 Magnetische Messtechnik Bundesallee 100 38116 Braunschweig, Germany

Acronym of Institute	Country	Contact Person	Shipping Address
INRIM	Italy	Gabriella Crotti g.crotti@inrim.it Tel: +39 011 3919826	Istituto Nazionale di Ricerca Metrologica Strada delle Cacce, 91 10135 Torino, Italy
GUM	Poland	Arkadiusz Podgórni arkadiusz.podgorni@gum.gov.pl Tel : +48 22 581 9452	Central Office of Measures (GUM), Microwaves, Electromagnetic Field and Electromagnetic Compatibility Section Electricity and Magnetism Laboratory, 00-139 Warszawa, Poland
SASO NMCC	Saudi Arabia	Saleh Almojaewel s.mojaewel@saso.gov.sa Tel: +966 11 252 97 30	Saudi Standards, Metrology and Quality Organization of The Kingdom of Saudi Arabia (SASO) Riyadh 11471, P.O. Box 3437 Kingdom of Saudi Arabia
RISE	Sweden	Mats Cedheim mats.cedheim@ri.se Tel : +46 10 516 60 86	Research Institutes of SWEDEN (RISE) Mats Cedheim/Hus 15 Brinellgatan 4, 504 62 Borås Sweden
METAS	Switzerland	Frédéric Pythoud frederic.pythoud@metas.ch Tel: +41 58 387 03 35	Federal Institute of Metrology (METAS), Laboratory EMC, Lindenweg 50 3003 Bern-Wabern, Switzerland
NPL	United Kingdom	Stuart Harmon stuart.harmon@npl.co.uk Tel: +44 20 8943 6908	National Physical Laboratory (NPL) Hampton Road, Teddington, Middlesex, TW11 0LW, UK

2.3. Unexpected Incidents

According to the comparison protocol, a part of the comparison measurements circle was supposed to be performed in the sequence of GUM – RISE – TÜBİTAK UME, but due to customs problems in Poland, the aforementioned part was performed in the sequence of GUM – RISE – SASO NMCC – TÜBİTAK UME as given in Table 2. Due to this delay caused by the customs problems, the measurements were completed on 11 May 2023 instead of 03 March 2023.

2.4. Comparison Schedule

The time schedule for the comparison is given in Table 2. The circulation of the travelling standard was organized to monitor the performance of the travelling standard. Each laboratory had two weeks to carry out the measurements.

Table 2. The time schedule for the comparison

Participant	Country	Measurement Dates
TÜBİTAK UME	Türkiye	03 January 2022 – 11 January 2022 (Measurement and Stability Control)
CMI	Czech Republic	02 February 2022 – 17 February 2022

Participant	Country	Measurement Dates
METAS	Switzerland	21 March 2022 – 25 March 2022
TÜBİTAK UME	Türkiye	18 April 2022 – 21 April 2022 (Stability Control)
PTB	Germany	11 May 2022 – 18 May 2022
NPL	United Kingdom	27 June 2022– 08 July 2022
TÜBİTAK UME	Türkiye	01 August 2022 – 03 August 2022 (Stability Control)
GUM	Poland	27 September 2022 – 30 September 2022
RISE	Sweden	15 October 2022 – 16 October 2022
SASO NMCC	Saudi Arabia	12 December 2022 – 25 December 2022
TÜBİTAK UME	Türkiye	16 January 2023 – 18 January 2023 (Stability Control)
INRIM	Italy	16 February 2023 – 15 March 2023
TÜBİTAK UME	Türkiye	09 May 2023 – 11 May 2023 (Stability Control)

3. Travelling Standard and Measurement Instructions

3.1. Description of the Standard

The travelling standards were supplied by TÜBİTAK UME. These standards were chosen for their high accuracy and stability over time. The photos and the general specifications of the travelling standards are presented in Figure1 and Table 3 respectively.

(a)   (b)

Figure 1. The photo of the travelling standards, a) ELT 400, b) HF3061 with NBM-550

Table 3. The general specifications of the travelling standard

Name	Manufacturer / Model Number	Serial Number	General Specifications
Magnetic Field Probe (Low frequency)	Narda Safety Test Solutions / ELT Probe 100 cm²	M-1859	✓ Frequency Range: 10 Hz – 400 kHz ✓ Measurement Range: 0.5 μT – 160 mT ✓ Noise Level: 0,24 μT (320 μT – HIGH range)
Low Frequency Field Meter	ELT – 400	O-0450	✓ Power Supply: 9 V/2000 mA
Magnetic Field Probe (High frequency)	Narda Safety Test Solutions / HF3061	D-0934	✓ Frequency Range: 300 kHz – 30 MHz ✓ Measurement Range: 0,012 A/m – 16 A/m ✓ Noise Level: 0,01 A/m
High Frequency Field Meter	NBM 550	B-1002	✓ Power Supply: 9 V/1.5 A

3.2. Measured Quantities and Conditions of the Measurement

The correction factor defined below is determined for each frequency given in Table 4. The correction factors are obtained using the following equation;

$$\text{Correction Factor (dB)} = 20 \times \log_{10}\left(\frac{\text{Actual Field (μT or A/m)}}{\text{Indicated Field (μT or A/m)}}\right)$$

Table 4. Measurement frequencies & levels for magnetic field probes

Measurement Frequency	Level for Magnetic Field Measurements	Measurement Range for ELT – 400	Relevant Travelling Standard
53 Hz	10 μT	320 μT – Low	ELT Probe 100 cm²
	100 μT	320 μT – High	
	300 μT	320 μT – High	
	1000 μT	80 mT – Low	
	2000 μT	80 mT – Low	
400 Hz	10 μT	320 μT – Low	
10 kHz	10 μT	320 μT – Low	
100 kHz	10 μT	320 μT – Low	
300 kHz	3 μT	320 μT – Low	
500 kHz	0.15 A/m	-	HF3061 with NBM-550
5 MHz	0.15 A/m	-	
10 MHz	0.15 A/m	-	
20 MHz	0.15 A/m	-	
30 MHz	0.15 A/m	-	

3.3. Deviations from the Protocol

With the approval of the participants, the weighted mean method was used instead of the arithmetic mean method in order to calculate the reference value.

4. Methods of Measurement

The measurements were performed according to participants' measurement procedure. The detailed measurement methods used by the participants were given in the comparison reports of the participants in Annex B.

5. Stability of Standards

The stability measurements of the travelling standards were performed periodically by TÜBİTAK UME throughout the comparison to monitor their stability. The measured stability results are shown in Figure 2 to Figure 4.
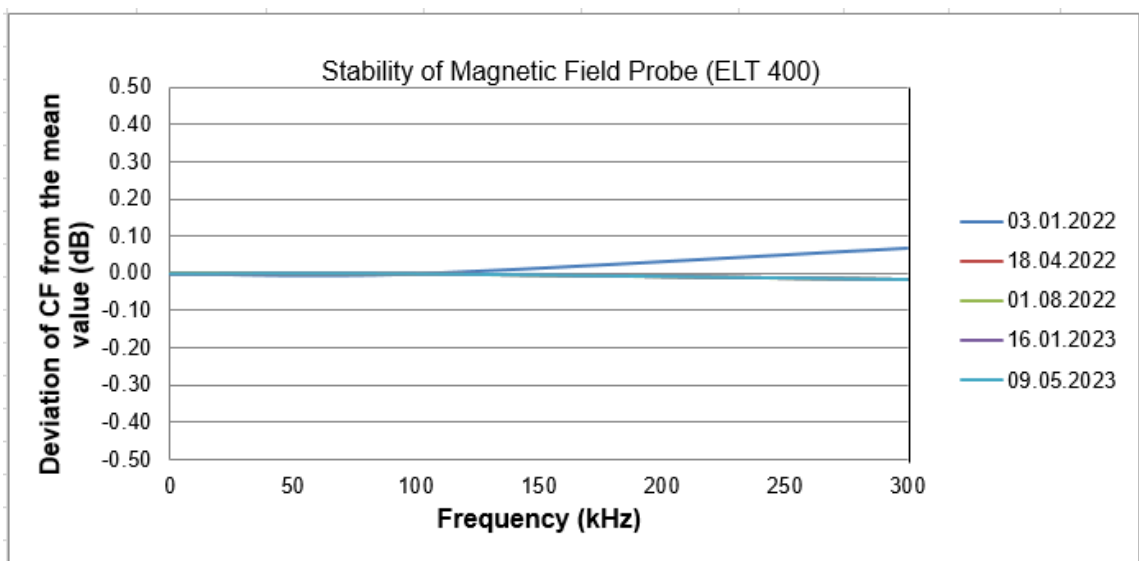
Figure 2. Stability measurement results of the travelling standard (ELT400, Frequency response)
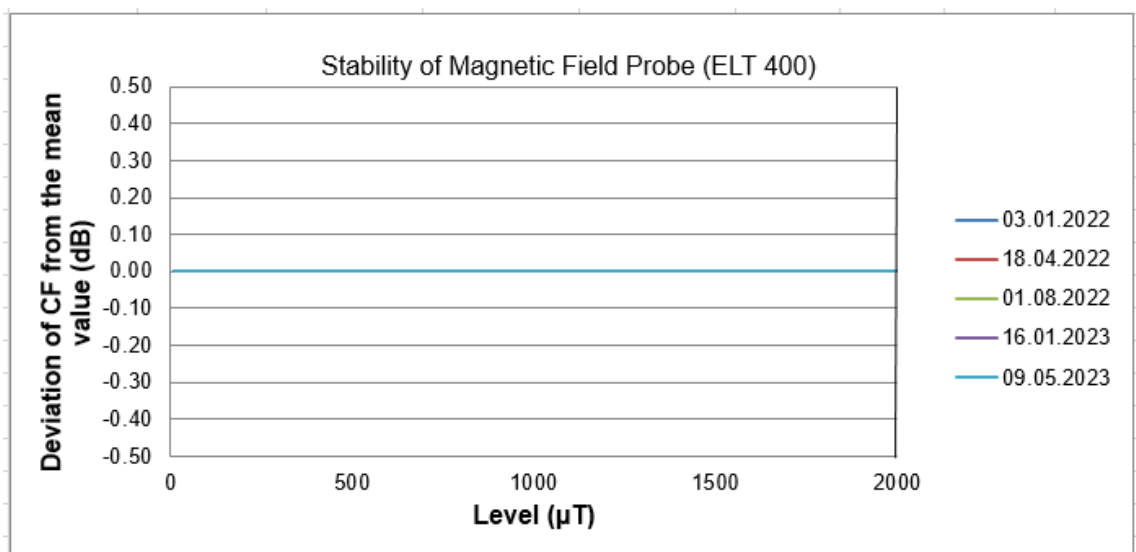
Figure 3. Stability measurement results of the travelling standard (ELT400, Linearity response)
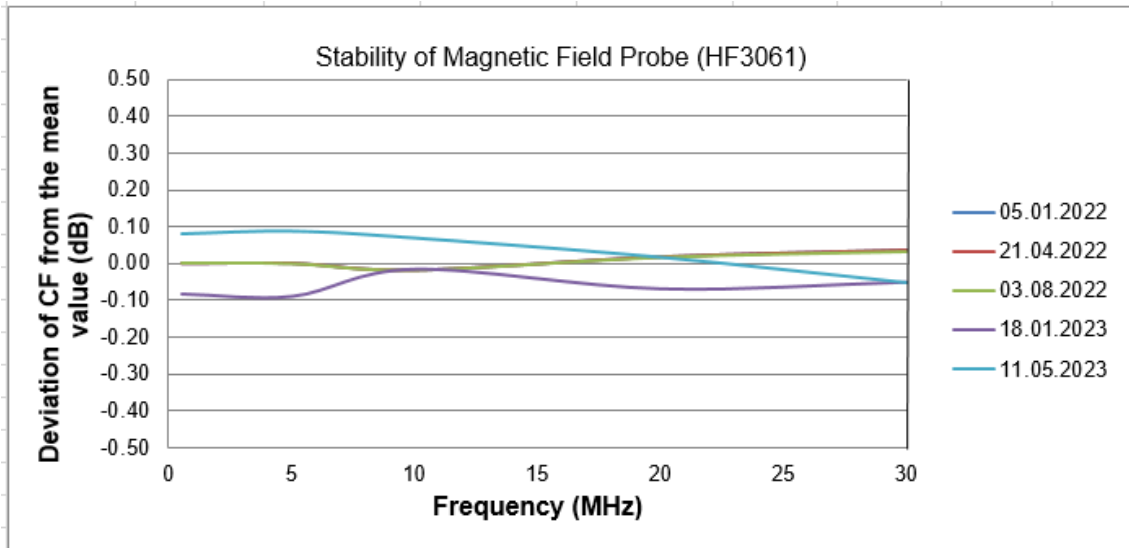
Figure 4. Stability measurement results of the travelling standard (NBM-550, Frequency response)

All the stability measurements were performed exactly in the same measurement setup including the Helmholtz coil, resistor, 6 ½ multimeter, TEM Cell, power meter etc. The observed deviation values from the mean value were in any case less than ± 0.1 dB. It can be concluded that the stability of the standards are considered to be satisfactory. Based on the low drift of the magnetic field probes, no additional correction factors were added to the participant's results in the process of obtaining the reference values.

6. Results of the Participating Institutes

The measurement results of the participating institutes (x_i) and their standard uncertainties ($u(x_i)$) are presented for each frequency in Table 5 to Table 18.

Table 5. Results of the participating institutes at 53 Hz and 10 µT

Participating Institute	Correction Factor (dB)	Standard Uncertainty (k=1) (dB)
TÜBİTAK UME	0.09	0.045
CMI	0.12	0.02
PTB	0.12	0.00285
INRIM	0.13	0.015
GUM	0.154	0.016
SASO NMCC	0.172	0.370
RISE	No Data	No Data
METAS	0.15	0.055
NPL	0.1340	0.0085

Table 6. Results of the participating institutes at 53 Hz and 100 µT

Participating Institute	Correction Factor (dB)	Standard Uncertainty (k=1) (dB)
TÜBİTAK UME	0.17	0.045
CMI	0.13	0.02
PTB	0.14	0.00275
INRIM	0.13	0.015
GUM	0.159	0.0175
SASO NMCC	0.257	0.370
RISE	No Data	No Data
METAS	0.16	0.065
NPL	0.1313	0.0085

Table 7. Results of the participating institutes at 53 Hz and 300 µT

Participating Institute	Correction Factor (dB)	Standard Uncertainty (k=1) (dB)
TÜBİTAK UME	0.17	0.045
CMI	0.13	0.02
PTB	0.14	0.0031
INRIM	0.14	0.015
GUM	0.156	0.017
SASO NMCC	No Data	No Data
RISE	No Data	No Data
METAS	0.15	0.065
NPL	0.1336	0.0085

Table 8. Results of the participating institutes at 53 Hz and 1000 µT

Participating Institute	Correction Factor (dB)	Standard Uncertainty (k=1) (dB)
TÜBİTAK UME	0.09	0.045
CMI	0.06	0.02
PTB	-0.007	0.0055
INRIM	0.07	0.015
GUM	0.072	0.0445
SASO NMCC	No Data	No Data
RISE	No Data	No Data
METAS	0.05	0.065
NPL	0.0600	0.0085

Table 9. Results of the participating institutes at 53 Hz and 2000 µT

Participating Institute	Correction Factor (dB)	Standard Uncertainty (k=1) (dB)
TÜBİTAK UME	0.00	0.045
CMI	0.06	0.02
PTB	No Data	No Data
INRIM	0.08	0.015
GUM	0.077	0.0445
SASO NMCC	No Data	No Data
RISE	No Data	No Data
METAS	0.04	0.065
NPL	0.0692	0.0085

Table 10. Results of the participating institutes at 400 Hz and 10 µT

Participating Institute	Correction Factor (dB)	Standard Uncertainty (k=1) (dB)
TÜBİTAK UME	0.09	0.045
CMI	0.09	0.02
PTB	0.15	0.00285
INRIM	0.08	0.015
GUM	0.113	0.016
SASO NMCC	0.172	0.370
RISE	No Data	No Data
METAS	0.14	0.055
NPL	0.0895	0.0085

Table 11. Results of the participating institutes at 10 kHz and 10 µT

Participating Institute	Correction Factor (dB)	Standard Uncertainty (k=1) (dB)
TÜBİTAK UME	0.09	0.045
CMI	0.10	0.02
PTB	0.08	0.00455
INRIM	0.10	0.015
GUM	0.190	0.024
SASO NMCC	0.172	0.370
RISE	0.05	0.21
METAS	0.13	0.07
NPL	0.1014	0.011

Table 12. Results of the participating institutes at 100 kHz and 10 µT

Participating Institute	Correction Factor (dB)	Standard Uncertainty (k=1) (dB)
TÜBİTAK UME	0.00	0.05
CMI	0.02	0.025
PTB	0.25	0.01
INRIM	0.09	0.02
GUM	No Data	No Data
SASO NMCC	0.172	0.370
RISE	-0.26	0.21
METAS	0.11	0.07
NPL	0.0781	0.052

Table 13. Results of the participating institutes at 300 kHz and 3 µT

Participating Institute	Correction Factor (dB)	Standard Uncertainty (k=1) (dB)
TÜBİTAK UME	0.09	0.075
CMI	0.09	0.14
PTB	No Data	No Data
INRIM	0.24	0.125
GUM	No Data	No Data
SASO NMCC	0.424	0.37
RISE	-0.24	0.21
METAS	0.19	0.175
NPL	No Data	No Data

Table 14. Results of the participating institutes at 500 kHz and 0.15 A/m

Participating Institute	Correction Factor (dB)	Standard Uncertainty (k=1) (dB)
TÜBİTAK UME	1.06	0.13
CMI	1.35	0.175
PTB	0.71	0.305
INRIM	0.83	0.305
GUM	No Data	No Data
SASO NMCC	0.506	0.29
RISE	0.93	0.21
METAS	1.56	0.285
NPL	No Data	No Data

Table 15. Results of the participating institutes at 5 MHz and 0.15 A/m

Participating Institute	Correction Factor (dB)	Standard Uncertainty (k=1) (dB)
TÜBİTAK UME	-0.18	0.235
CMI	0.43	0.195
PTB	-0.13	0.305
INRIM	-0.07	0.32
GUM	No Data	No Data
SASO NMCC	-0.175	0.29
RISE	-0.03	0.21
METAS	0.72	0.285
NPL	No Data	No Data

Table 16. Results of the participating institutes at 10 MHz and 0.15 A/m

Participating Institute	Correction Factor (dB)	Standard Uncertainty (k=1) (dB)
TÜBİTAK UME	-0.09	0.235
CMI	0.38	0.32
PTB	0.00	0.305
INRIM	0.04	0.34
GUM	No Data	No Data
SASO NMCC	0.086	0.29
RISE	-0.25	0.21
METAS	0.83	0.285
NPL	No Data	No Data

Table 17. Results of the participating institutes at 20 MHz and 0.15 A/m

Participating Institute	Correction Factor (dB)	Standard Uncertainty (k=1) (dB)
TÜBİTAK UME	0.09	0.235
CMI	0.46	0.305
PTB	0.17	0.31
INRIM	0.18	0.40
GUM	No Data	No Data
SASO NMCC	0.086	0.29
RISE	-0.04	0.21
METAS	0.84	0.285
NPL	No Data	No Data

Table 18. Results of the participating institutes at 30 MHz and 0.15 A/m

Participating Institute	Correction Factor (dB)	Standard Uncertainty (k=1) (dB)
TÜBİTAK UME	0.09	0.235
CMI	0.27	0.39
PTB	0.09	0.31
INRIM	0.14	0.445
GUM	No Data	No Data
SASO NMCC	0.086	0.29
RISE	-0.77	0.21
METAS	0.97	0.305
NPL	No Data	No Data

7. The Comparison Reference Value (CRV)

The Comparison Reference Value (CRV) for each frequency was determined according to Reference [6, 7]. Outlying results were not taken into account in the calculation of the CRV. The outlier values were specified by using the Median of Absolute Deviations (MAD) which is defined in Equation 2.

$$\sigma \approx S(MAD) \equiv k_1 \, median \, |x_i - x_{med}| \tag{2}$$

Where;

k_1 is a multiplier obtained in Reference [6]
x_i is the result of each participant,
x_{med} is the median value of the measurement results.

If the condition given in Equation 3 is met for any result $(x_i,)$, this value is defined as an outlier.

$$|x_i - x_{med}| > 1.5 \times S(MAD) \tag{3}$$

When calculating the CRV, the result of the outlier institute which met the criterion given in Equation 3 was not taken into account. The Comparison Reference Value (x_{CRV}) and its uncertainty $(u(x_{CRV}))$ were calculated using Equations 4, 5 and 6.

$$x_{CRV} = \frac{x_1/u(x_1)^2 + \cdots + x_N/u(x_N)^2}{1/u(x_1)^2 + \cdots + 1/u(x_N)^2} \tag{4}$$

$$\frac{1}{u(x_{REF})^2} = \frac{1}{u(x_1)^2} + \cdots + \frac{1}{u(x_N)^2} \tag{5}$$

$$u(x_{CRV}) = \sqrt{u(x_{drift})^2 + u(x_{REF})^2} \tag{6}$$

Where;

x_i is the participant result which passes the $S(MAD)$ test,

$u(x_i)$ is the participant uncertainty value (k=1) which passes the $S(MAD)$ test,

N is the number of participants.

x_{drift} is uncertainty value due to the stability of the comparison device

While calculating the comparison measurement uncertainties, the uncertainty values of the comparison device (obtained from the standard deviation of the stability measurements) given in Table 19 were taken into account (See Equation 6).

The expanded uncertainty of the Comparison Reference Values ($U(x_{CRV})$) was calculated by:

$$U(x_{CRV}) = 2 \times u(x_{CRV}) \tag{7}$$

The Comparison Reference Values (x_{CRV}) and their corresponding standard uncertainties ($u(x_{CRV})$) and expanded uncertainties $U(x_{CRV})$ are presented in Table 19 for each frequency.

Table 19. Comparison Reference Values and corresponding uncertainties

Measurement Frequencies	Field Level	x_{CRV} (dB)	Uncertainty Value about Comparison Device (dB)	$u(x_{CRV})$ (dB)	$U(x_{CRV})$ (dB)
53 Hz	10 µT	0.1226	0.00	0.0026	0.0052
	100 µT	0.1393	0.00	0.0025	0.0050
	300 µT	0.1396	0.00	0.0028	0.0056
	1000 µT	0.0622	0.00	0.0068	0.0136
	2000 µT	0.0702	0.00	0.0068	0.0136
400 Hz	10 µT	0.0922	0.00	0.0063	0.0126
10 kHz	10 µT	0.0852	0.00	0.0039	0.0078
100 kHz	10 µT	0.0610	0.00	0.0141	0.0282
300 kHz	3 µT	0.1296	0.04	0.0693	0.1386
500 kHz	0,15 A/m	1.0219	0.06	0.1039	0.2078
5 MHz	0,15 A/m	-0.1103	0.06	0.1356	0.2712
10 MHz	0,15 A/m	-0.0819	0.04	0.1286	0.2572
20 MHz	0,15 A/m	0.0668	0.04	0.1310	0.2620
30 MHz	0,15 A/m	0.0944	0.05	0.1630	0.3260

8. Degrees of Equivalence (D_i)

The results of the comparison are reported as the degree of equivalence between the participant's result and the Comparison Reference Values (x_{CRV}). The degree of equivalence of each participant (D_i), was calculated according to Equation 8.

$$D_i = x_i - x_{CRV} \tag{8}$$

Where;

x_i is the result of the participants

x_{CRV} is the Comparison Reference Value.

The expanded uncertainty of the degree of equivalence for a participant's result $U(D_i)$ was calculated using Equation 9 and Equation 10. Equation 10 was used in the case where the participant result failed in the $S(MAD)$ test and did not contribute to the Comparison Reference Value (x_{CRV}).

$$U(D_i) = 2 \times \sqrt{u(x_i)^2 - u(x_{CRV})^2} \tag{9}$$

$$U(D_i) = 2 \times \sqrt{u(x_i)^2 + u(x_{CRV})^2} \tag{10}$$

Where $u(x_i)$ is the uncertainty of the result of the participant (k =1) and $u(x_{CRV})$ is the uncertainty of the Comparison Reference Value.

The degrees of equivalence of the participants for each comparison point are presented in Table 21 to Table 34 and Figure 5 to Figure 18 where the limit lines demonstrate the calculated $U(D_i)$ at each point.

Table 20. The degrees of equivalence (D_i), its uncertainties ($U(D_i)$) for 53 Hz and 10 µT

Participating Institute	D_i (dB)	$U(D_i)$ (dB)
TÜBİTAK UME	-0.033	0.091
CMI	-0.003	0.040
PTB	-0.003	0.002
INRIM	0.007	0.030
GUM	0.031	0.032
SASO NMCC	0.049	0.773
RISE	–	–
METAS	0.027	0.111
NPL	0.011	0.016

Figure 5. Degrees of equivalence for 53 Hz and 10 µT

Table 21. The degrees of equivalence (D_i), its uncertainties ($U(D_i)$) for 53 Hz and 100 µT

Participating Institute	D_i (dB)	$U(D_i)$ (dB)
TÜBİTAK UME	0.031	0.090
CMI	-0.009	0.040
PTB	0.001	0.002
INRIM	-0.009	0.030
GUM	0.020	0.035
SASO NMCC	0.118	0.773
RISE	–	–
METAS	0.021	0.131
NPL	-0.008	0.016

Figure 6. Degrees of equivalence for 53 Hz and 100 µT

Table 22. The degrees of equivalence (D_i), its uncertainties ($U(D_i)$) for 53 Hz and 300 µT

Participating Institute	D_i (dB)	$U(D_i)$ (dB)
TÜBİTAK UME	0.030	0.091
CMI	-0.010	0.040
PTB	0.000	0.003
INRIM	0.000	0.030
GUM	0.016	0.034
SASO NMCC	–	–
RISE	–	–
METAS	0.010	0.131
NPL	-0.006	0.016
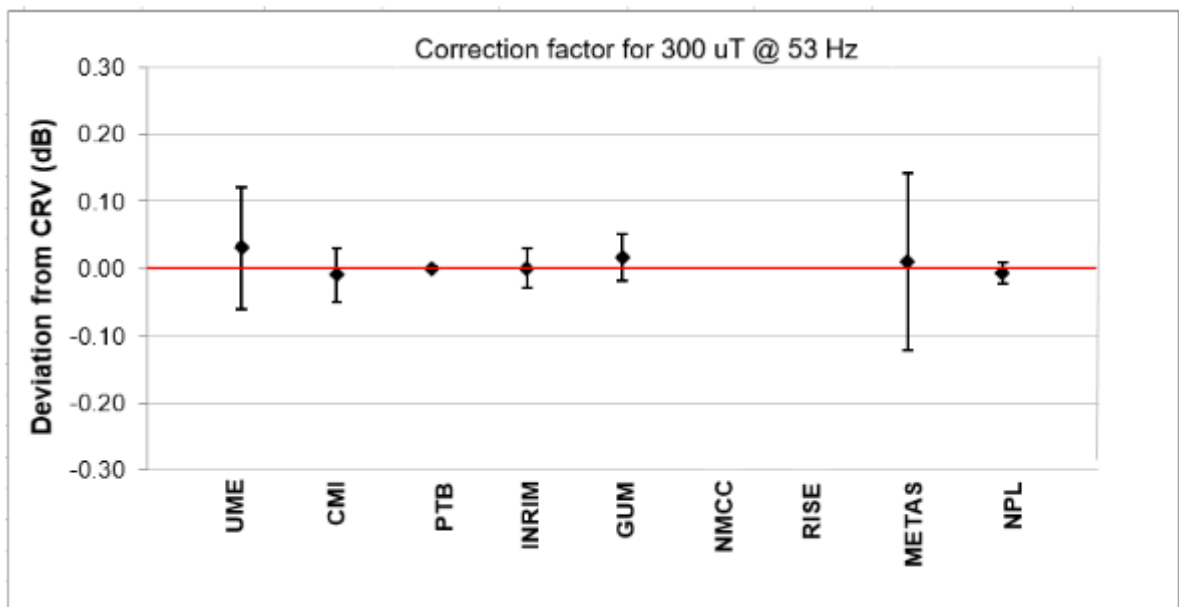
Figure 7. Degrees of equivalence for 53 Hz and 300 µT

Table 23. The degrees of equivalence (D_i), its uncertainties ($U(D_i)$) for 53 Hz and 1000 µT

Participating Institute	D_i (dB)	$U(D_i)$ (dB)
TÜBİTAK UME	0.028	0.091
CMI	-0.002	0.038
PTB	-0.069	0.018
INRIM	0.008	0.027
GUM	0.010	0.088
SASO NMCC	–	–
RISE	–	–
METAS	-0.012	0.130
NPL	-0.002	0.010
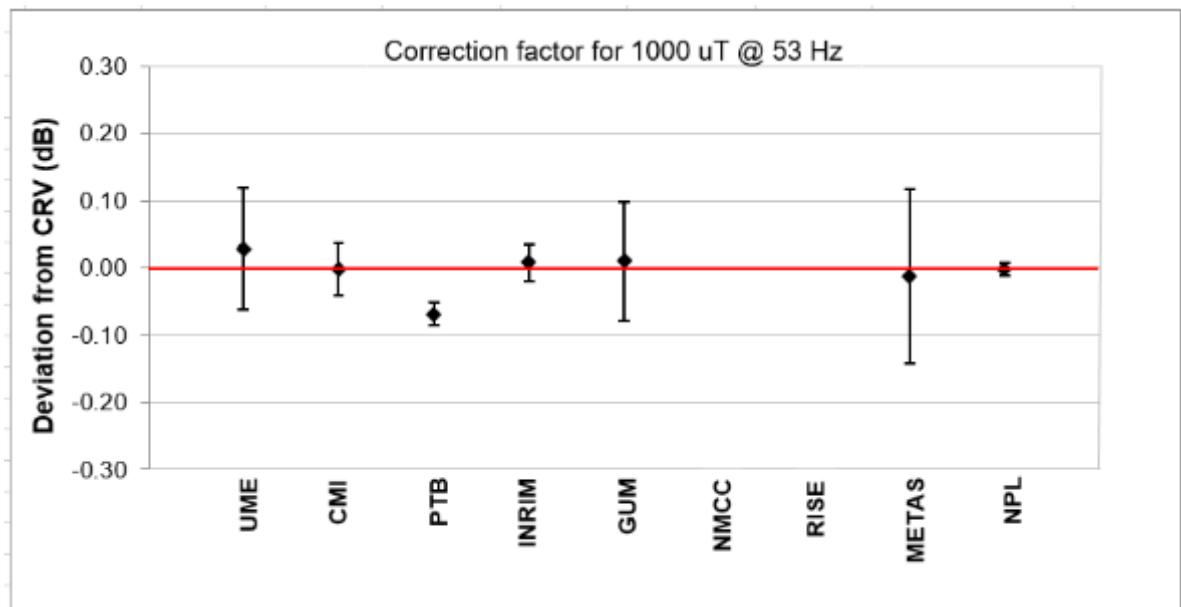
Figure 8. Degrees of equivalence for 53 Hz and 1000 µT

Table 24. The degrees of equivalence (D_i), its uncertainties ($U(D_i)$) for 53 Hz and 2000 µT

Participating Institute	D_i (dB)	$U(D_i)$ (dB)
TÜBİTAK UME	-0.070	0.091
CMI	-0.010	0.038
PTB	–	–
INRIM	0.010	0.027
GUM	0.007	0.088
SASO NMCC	–	–
RISE	–	–
METAS	-0.030	0.130
NPL	-0.001	0.010
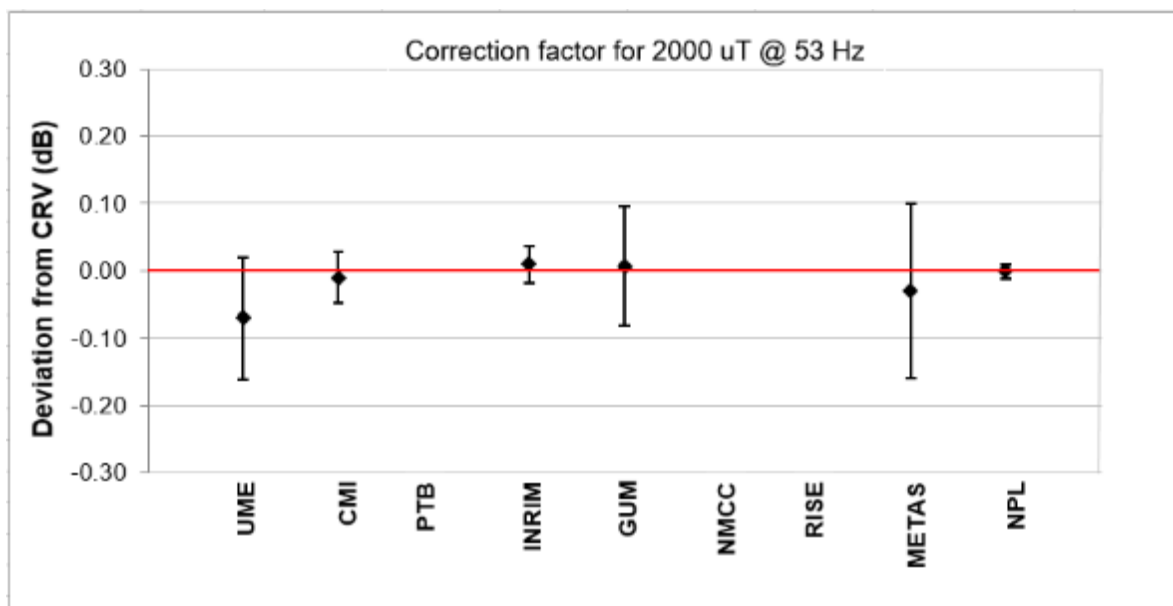
Figure 9. Degrees of equivalence for 53 Hz and 2000 µT

Table 25. The degrees of equivalence (D_i), its uncertainties ($U(D_i)$) for 400 Hz and 10 µT

Participating Institute	D_i (dB)	$U(D_i)$ (dB)
TÜBİTAK UME	-0.002	0.090
CMI	-0.002	0.038
PTB	0.058	0.014
INRIM	-0.012	0.027
GUM	0.021	0.030
SASO NMCC	0.080	0.773
RISE	–	–
METAS	0.048	0.110
NPL	-0.003	0.012
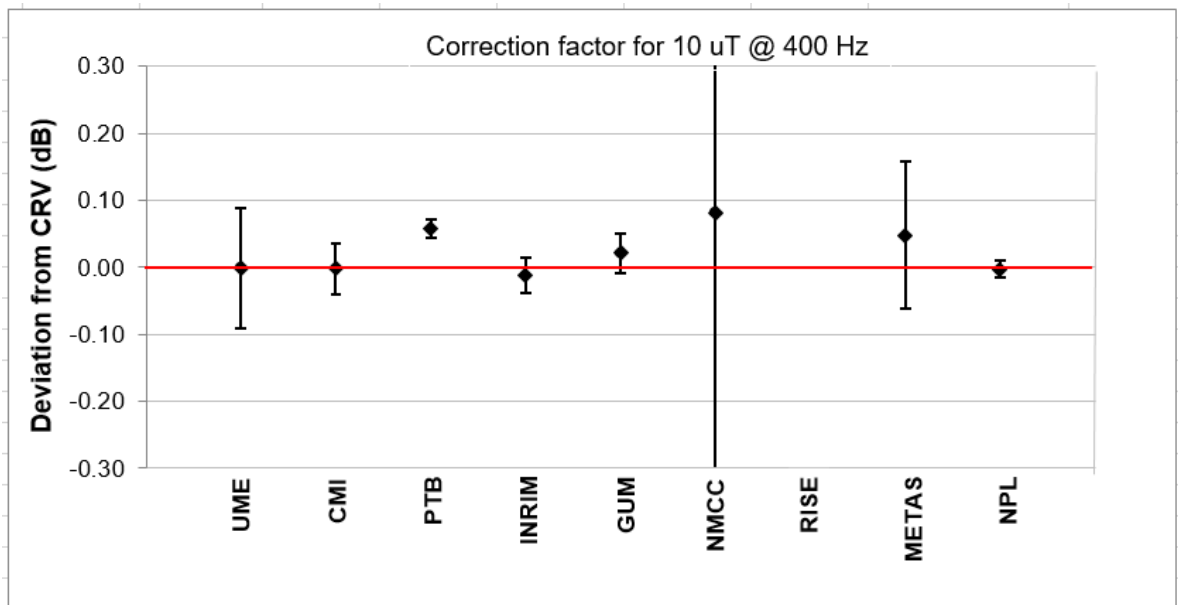
Figure 10. Degrees of equivalence for 400 Hz and 10 µT

Table 26. The degrees of equivalence (D_i), its uncertainties ($U(D_i)$) for 10 kHz and 10 µT

Participating Institute	D_i (dB)	$U(D_i)$ (dB)
TÜBİTAK UME	0.005	0.090
CMI	0.015	0.039
PTB	-0.005	0.005
INRIM	0.015	0.029
GUM	0.105	0.049
SASO NMCC	0.087	0.773
RISE	-0.035	0.430
METAS	0.045	0.141
NPL	0.016	0.021
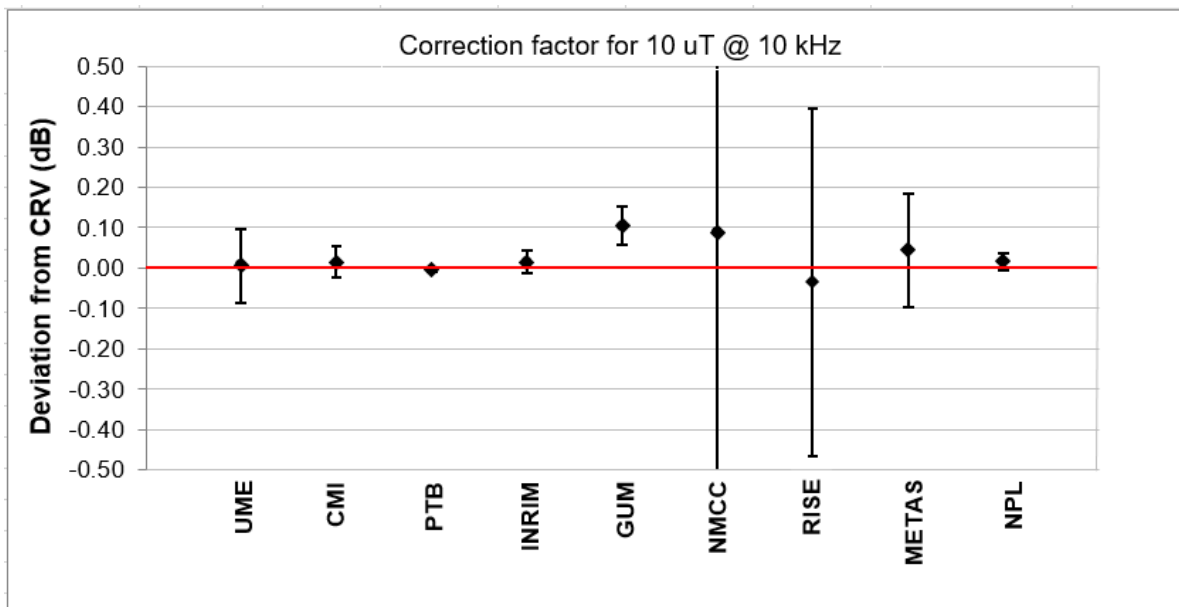
Figure 11. Degrees of equivalence for 10 kHz and 10 µT

Table 27. The degrees of equivalence (D_i), its uncertainties ($U(D_i)$) for 100 kHz and 10 µT

Participating Institute	D_i (dB)	$U(D_i)$ (dB)
TÜBİTAK UME	-0.061	0.097
CMI	-0.041	0.041
PTB	0.189	0.035
INRIM	0.029	0.029
GUM	–	–
SASO NMCC	0.111	0.772
RISE	-0.321	0.431
METAS	0.049	0.138
NPL	0.017	0.101
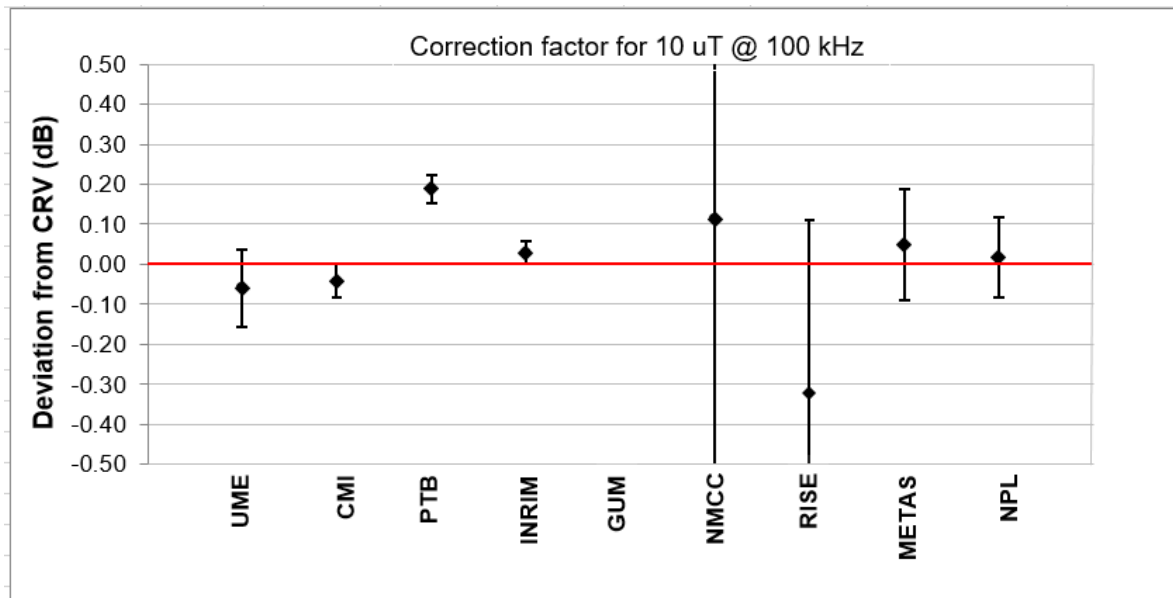
Figure 12. Degrees of equivalence for 100 kHz and 10 µT

Table 28. The degrees of equivalence (D_i), its uncertainties ($U(D_i)$) for 300 kHz and 3 µT

Participating Institute	D_i (dB)	$U(D_i)$ (dB)
TÜBİTAK UME	-0.040	0.061
CMI	-0.040	0.248
PTB	–	–
INRIM	0.110	0.212
GUM	–	–
SASO NMCC	0.294	0.786
RISE	-0.370	0.453
METAS	0.060	0.329
NPL	–	–
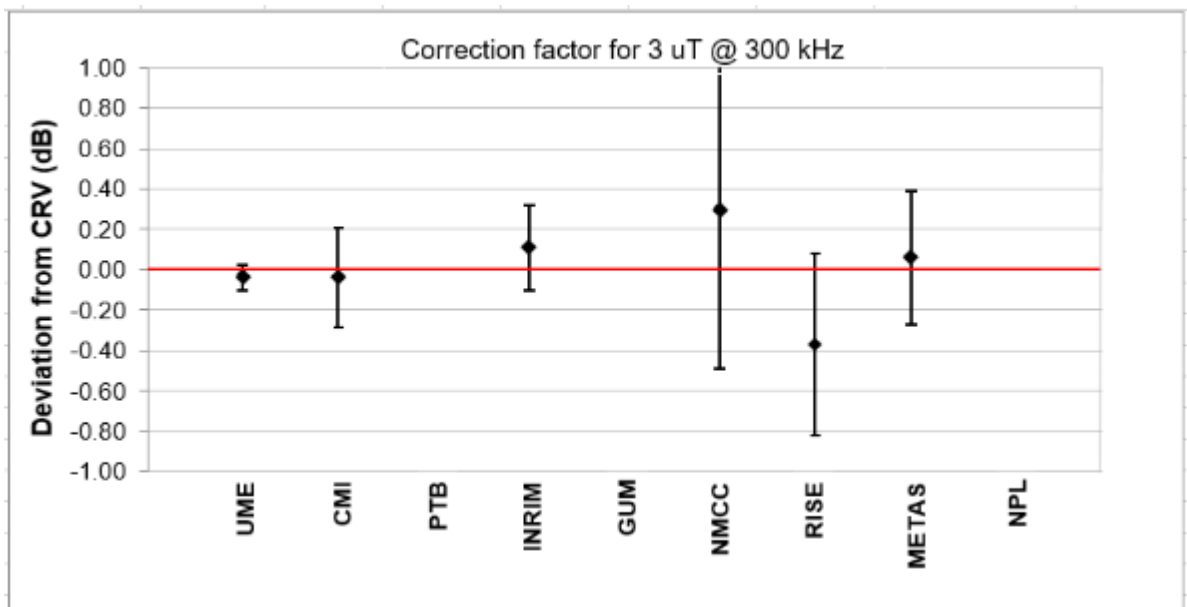
Figure 13. Degrees of equivalence for 300 kHz and 3 µT

Table 29. The degrees of equivalence (D_i), its uncertainties ($U(D_i)$) for 500 kHz and 0.15 A/m

Participating Institute	D_i (dB)	$U(D_i)$ (dB)
TÜBİTAK UME	0.038	0.162
CMI	0.328	0.289
PTB	-0.312	0.596
INRIM	-0.192	0.596
GUM	–	–
SASO NMCC	-0.516	0.561
RISE	-0.092	0.376
METAS	0.538	0.626
NPL	–	–
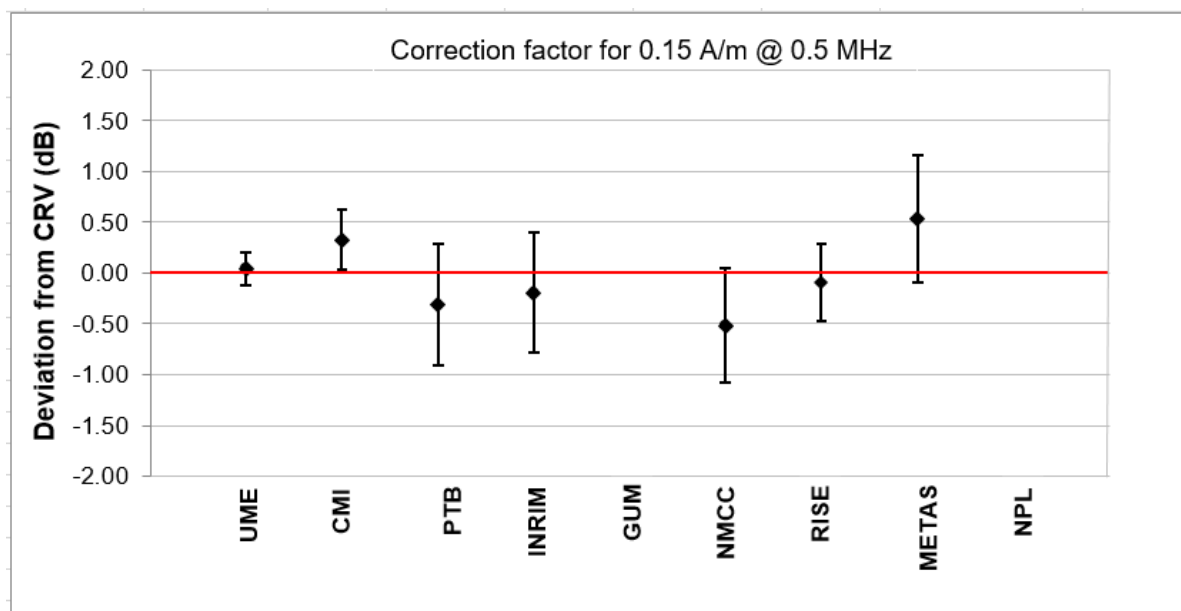
Figure 14. Degrees of equivalence for 500 kHz and 0.15 A/m

Table 30. The degrees of equivalence (D_i), its uncertainties ($U(D_i)$) for 5 MHz and 0.15 A/m

Participating Institute	D_i (dB)	$U(D_i)$ (dB)
TÜBİTAK UME	-0.070	0.398
CMI	0.540	0.484
PTB	-0.020	0.569
INRIM	0.040	0.604
GUM	–	–
SASO NMCC	-0.065	0.533
RISE	0.080	0.332
METAS	0.830	0.651
NPL	–	–
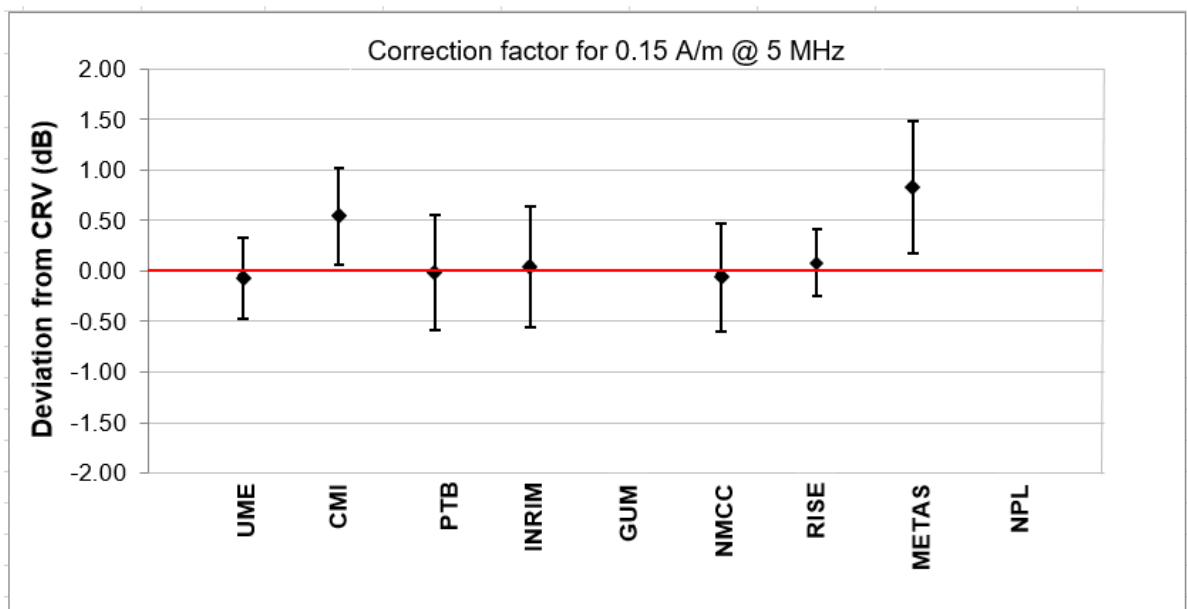
Figure 15. Degrees of equivalence for 5 MHz and 0.15 A/m

Table 31. The degrees of equivalence (D_i), its uncertainties ($U(D_i)$) for 10 MHz and 0.15 A/m

Participating Institute	D_i (dB)	$U(D_i)$ (dB)
TÜBİTAK UME	-0.008	0.407
CMI	0.462	0.715
PTB	0.082	0.575
INRIM	0.122	0.657
GUM	–	–
SASO NMCC	0.168	0.540
RISE	-0.168	0.343
METAS	0.912	0.645
NPL	–	–
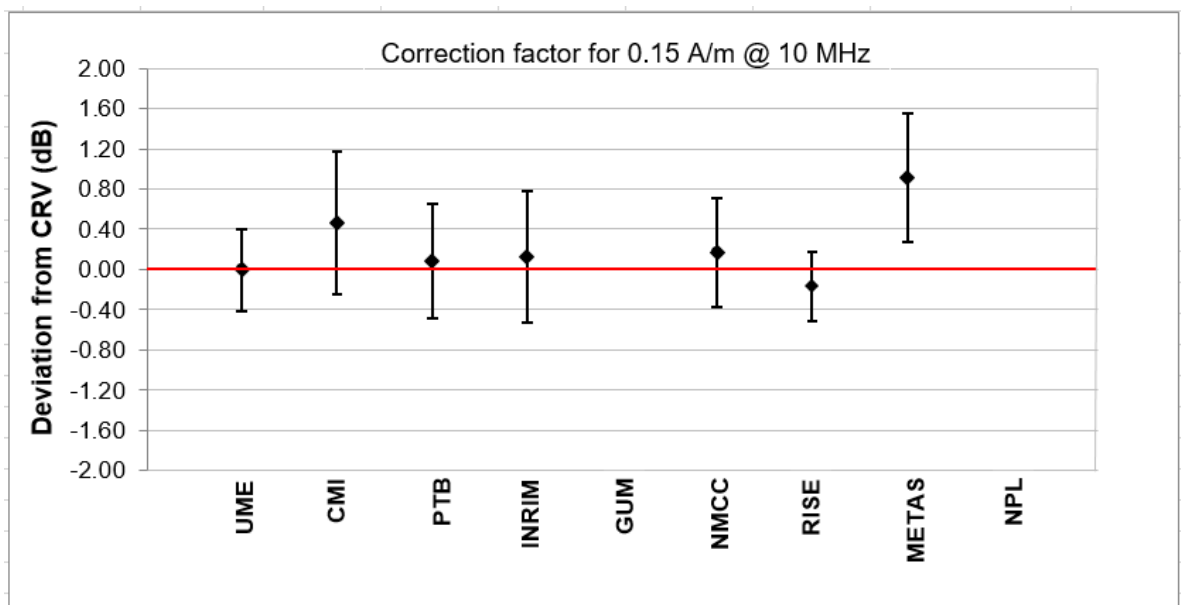
Figure 16. Degrees of equivalence for 10 MHz and 0.15 A/m

Table 32. The degrees of equivalence (D_i), its uncertainties ($U(D_i)$) for 20 MHz and 0.15 A/m

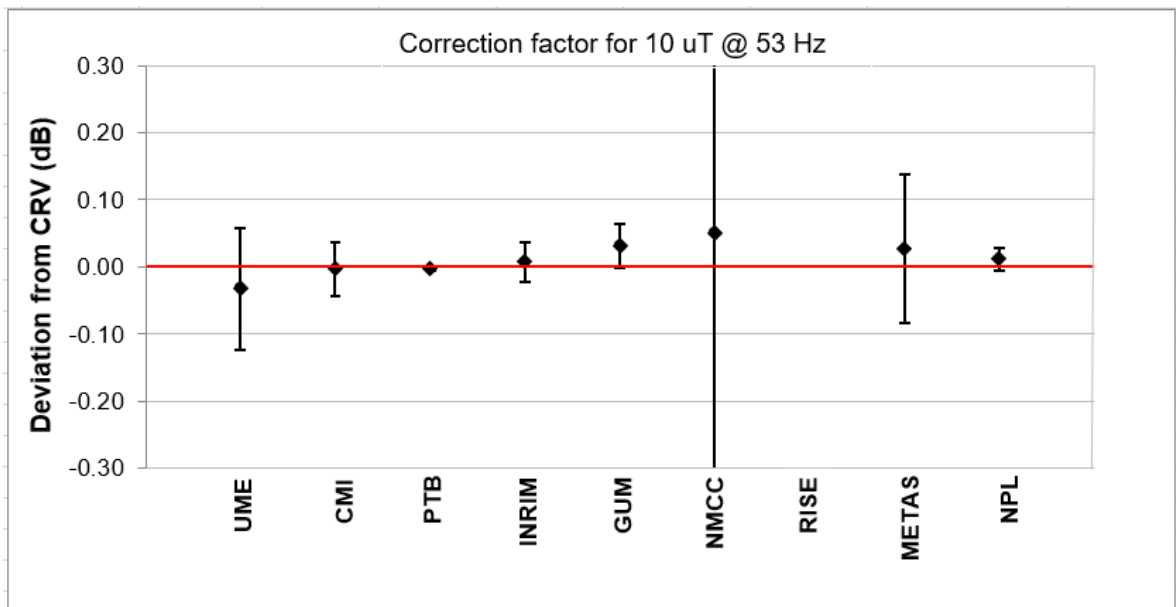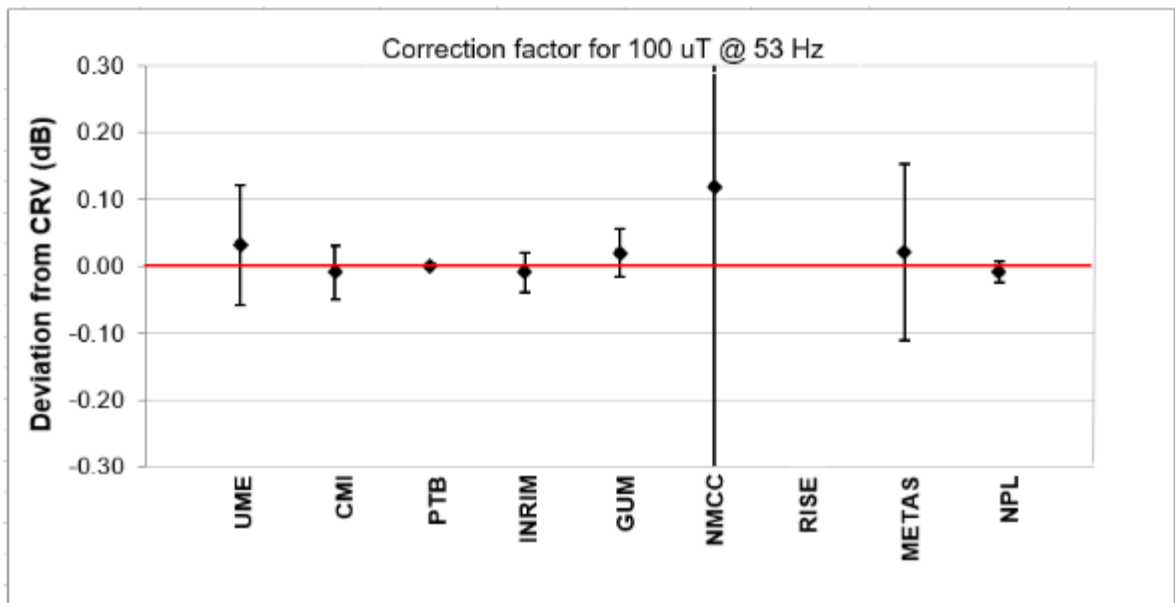| Participating Institute	D_i (dB)	$U(D_i)$ (dB)
TÜBİTAK UME	0.023	0.404
CMI	0.393	0.686
PTB	0.103	0.585
INRIM	0.113	0.794
GUM	–	–
SASO NMCC	0.019	0.538
RISE	-0.107	0.340
METAS	0.773	0.647
NPL	–	–
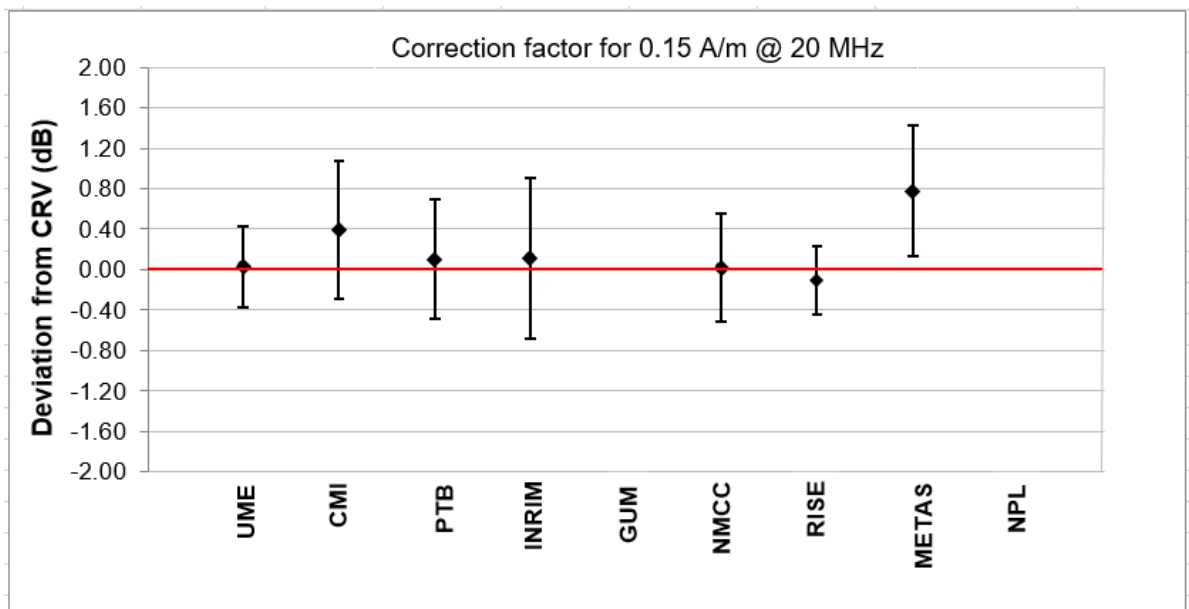
Figure 17. Degrees of equivalence for 20 MHz and 0.15 A/m

Table 33. The degrees of equivalence (D_i), its uncertainties ($U(D_i)$) for 30 MHz and 0.15 A/m

Participating Institute	D_i (dB)	$U(D_i)$ (dB)
TÜBİTAK UME	-0.004	0.354
CMI	0.176	0.883
PTB	-0.004	0.551
INRIM	0.046	0.876
GUM	–	–
SASO NMCC	-0.008	0.501
RISE	-0.864	0.542
METAS	0.876	0.714
NPL	–	–
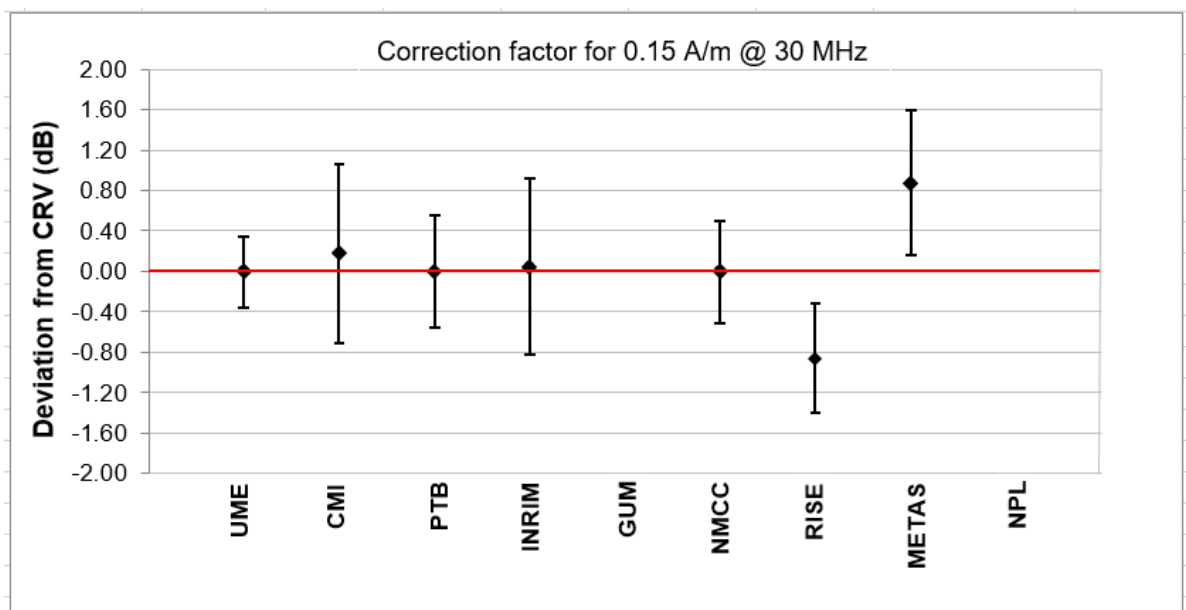
Figure 18. Degrees of equivalence for 30 MHz and 0.15 A/m

9. Conclusion

EURAMET.EM.RF-S46 (EURAMET Project 1538) comparison which aimed at evaluating the deviation from CRV of measurements of the magnetic field probe was conducted with 9 participants.

The transfer standard was the Magnetic Field probe set, Narda ELT – 400 and HF3061 with NBM – 550 and it was circulated without a major problem from January 2022 to May 2023.

The CRV was determined by using the weighted mean of the measurement results of the participants except the outlier values. In the calculations, the values used in the comparison report were obtained by converting the decibel values to linear values.

For the comparison results in the frequency range of 53 Hz – 30 MHz, with the exception of a few participants, most of the results supplied by the participants show good agreement with the CRV within the expanded uncertainty.

Probable reasons in participants where there is deviation from the CRV may be as follows;

 ➢ Very low uncertainty value
 ➢ Different calibration environments

The comparison results were very consistent with each other, thus confirming the quality of their measurements as well as the stability of the travelling standard. This comparison results will lead some participants to improve their calibration setups and revise their uncertainty budgets.

10.   References

[1] IEC 61786-1:2013 Measurement of DC magnetic, AC magnetic and AC electric fields from 1 Hz to 100 kHz with regard to exposure of human beings - Part 1: Requirements for measuring instruments

[2] IEC 62233:2005, Measurement methods for electromagnetic fields of household appliances and similar apparatus with regard to human exposure

[3] IEC 62311:2019, Measurement methods for electromagnetic fields of household appliances and similar apparatus with regard to human exposure, 2005Assessment of electronic and electrical equipment related to human exposure restrictions for electromagnetic fields (0 Hz to 300 GHz),

[4] IEEE Std. 1309:2013, "IEEE Standard for calibration of electromagnetic field sensors and probes, excluding antennas, from 9 kHz to 40 GHz".

[5] IEEE Std. 1308:1994, "Magnetic Flux Density and Electric Field Strength Meters -10 Hz to 3 kHz"

[6] J. Randa, "Proposal for KCRV and Degree of Equivalence for GTRF Key Comparisons," GT-RF/2000-12, August 2000.

[7] W. Bich, M. Cox, T. Estler, L. Nielsen, W. Woeger, "Proposed guidelines for the evaluation of key comparison data", April 2002. Available at:
https://iopscience.iop.org/article/10.1088/0026-1394/39/6/10/pdf

ANNEX A. Technical Protocol

EURAMET

TÜBİTAK
UME

TECHNICAL PROTOCOL

Comparison of Magnetic Field Strength Measurements for Frequencies up to 30 MHz

EURAMET.EM.RF-S46
(EURAMET Project No: 1538)

TÜBİTAK UME
(Version 1.1)
June 21, 2023

Contents

1. Introduction

Magnetic field probes are widely utilized in the measurement of non-ionizing radiation magnetic fields emanating from high voltage lines, high voltage power transformers, welding or induction heating equipment [1] and in electromagnetic compatibility (EMC) testing (IEC 62233 [2] and IEC 62311 [3]) and other applications in the frequency range of 5 Hz – 1 GHz. Therefore, the calibration of magnetic field probes is of fundamental importance for the traceability of the magnetic field measurements. They must be calibrated by National Metrology Institutes (NMIs) or accredited calibration laboratories in accordance with international standards such as IEEE 1309 [4] and IEEE 1308 [5]. The existing NMIs or emerging NMIs should participate in international comparison measurements in order to assure the quality of their measurement results or support their CMCs in the CIPM KCDB.

It has been discussed to organize a comparison on Magnetic Field Strength Measurements during the EURAMET TCEM SC RFMW including EMC meeting organized as a virtual (online) meeting on 20-21 April 2021.

The comparison will be carried out in accordance with the CCEM Guidelines for Planning, Organizing, Conducting and Reporting Key, Supplementary and Pilot Comparisons [6].

TÜBİTAK UME will act as the pilot institute. The travelling standards will be provided by TÜBİTAK UME. TÜBİTAK UME will be responsible for monitoring the performance of the travelling standards during the circulation and also for the evaluation & reporting of the comparison results.

2. Travelling Standards

The travelling standards will be supplied by TÜBİTAK UME. These standards were chosen for their high accuracy and stability over time. The photos and the general specifications of the travelling standards are presented in Figure1 and Table 1 respectively.

Figure 1. The photo of the travelling standards, a) ELT 400, b) HF3061 with NBM-550

Table 1. The general specifications of the travelling standard

Name	Manufacturer / Model Number	Serial Number	General Specifications
Magnetic Field Probe (Low frequency)	Narda Safety Test Solutions / ELT Probe 100 cm^2	M-1859	✓ Frequency Range: 10 Hz – 400 kHz ✓ Measurement Range: 0.5 µT – 160 mT ✓ Noise Level: 0,24 µT (320 µT – HIGH range)
Low Frequency Field Meter	ELT – 400	O-0450	✓ Power Supply: 9 V/2000 mA
Magnetic Field Probe (High frequency)	Narda Safety Test Solutions / HF3061	D-0934	✓ Frequency Range: 300 kHz – 30 MHz ✓ Measurement Range: 0,012 A/m – 16 A/m ✓ Noise Level: 0,01 A/m
High Frequency Field Meter	NBM 550	B-1002	✓ Power Supply: 9 V/1.5 A

3. Participant Institutes

The pilot laboratory for this comparison is TÜBİTAK UME (Turkey). The participating laboratories and contact persons with their addresses are presented in Table 2.

Table 2. The information of the participant institutes

Acronym of Institute	Country	Contact Person	Shipping Address
TÜBİTAK UME	Turkey	Osman Şen osman.sen@tubitak.gov.tr Tel: +90 262 679 50 00	TÜBİTAK Ulusal Metroloji Enstitüsü (UME) TÜBİTAK Gebze Yerleşkesi Barış Mah. Dr. Zeki Acar Cad. No:1 41470 Gebze-Kocaeli, Turkey
CMI	Czech Republic	Tomáš Pavlíček tpavlicek@cmi.cz Tel: +420 266 020 185	Český metrologický institut Radiová 1136/3 CZ-10200 Praha, Czech Republic
PTB	Germany	Franziska Weickert Franziska.weickert@ptb.de Tel: +47 592 2510	Physikalisch-Technische Bundesanstalt 2.51 Magnetische Messtechnik Bundesallee 100 38116 Braunschweig, Germany
INRIM	Italy	Gabriella Crotti g.crotti@inrim.it Tel: +39 011 3919826	Istituto Nazionale di Ricerca Metrologica Strada delle Cacce, 91 10135 Torino, Italy
GUM	Poland	Arkadiusz Podgórni arkadiusz.podgorni@gum.gov.pl Tel : +48 22 581 9452	Central Office of Measures (GUM), Microwaves, Electromagnetic Field and Electromagnetic Compatibility Section Electricity and Magnetism Laboratory, 00-139 Warszawa, Poland

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Acronym of Institute	Country	Contact Person	Shipping Address
SASO NMCC	Saudi Arabia	Saleh Almojaewel s.mojaewel@saso.gov.sa Tel: +966 11 252 97 30	Saudi Standards, Metrology and Quality Organization of The Kingdom of Saudi Arabia (SASO) Riyadh 11471, P.O. Box 3437 Kingdom of Saudi Arabia
RISE	Sweden	Mats Cedheim mats.cedheim@ri.se Tel : +46 10 516 60 86	Research Institutes of SWEDEN (RISE) Mats Cedheim/Hus 15 Brinellgatan 4, 504 62 Borås Sweden
METAS	Switzerland	Frédéric Pythoud frederic.pythoud@metas.ch Tel: +41 58 387 03 35	Federal Institute of Metrology (METAS), Laboratory EMC, Lindenweg 50 3003 Bern-Wabern, Switzerland
NPL	United Kingdom	Stuart Harmon Stuart.harmon@npl.co.uk Tel: +44 20 8943 6908	National Physical Laboratory (NPL) Hampton Road, Teddington, Middlesex, TW11 0LW, UK

4. Time Schedule

The time schedule for the comparison measurement is given in Table 3. The circulation of the travelling standards will be organized by the pilot laboratory to allow the participants to perform the measurements. Each institute will have two weeks to carry out the measurements and three weeks to send the travelling standards to the next participant. Any deviation in the agreed plan should be approved by the pilot laboratory.

Table 3. The time schedule for the comparison measurements

Participant	Country	Measurement Dates
TÜBİTAK UME (first measurement)	Turkey	03 January 2022 – 14 January 2022
CMI	Czech Republic	07 February 2022 – 18 February 2022
METAS	Switzerland	14 March 2022 – 25 March 2022
TÜBİTAK UME	Turkey	18 April 2022 – 29 April 2022
PTB	Germany	23 May 2022 – 03 June 2022
NPL	United Kingdom	27 June 2022– 08 July 2022
TÜBİTAK UME	Turkey	01 August 2022 – 12 August 2022

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Participant	Country	Measurement Dates
GUM	Poland	05 September 2022 – 16 September 2022
RISE	Sweden	10 October 2022 – 21 October 2022
TÜBİTAK UME	Turkey	14 November 2022 – 25 November 2022
SASO NMCC	Saudi Arabia	19 December 2022 – 30 December 2022
INRIM	Italy	23 January 2023 – 03 February 2023
TÜBİTAK UME (last measurement)	Turkey	20 February 2023 – 03 March 2023

5. Transport Case

The travelling standard will be packed in a strong carrying case, which must be used while the comparison is in progress. The overall dimensions of the case are approximately 70 cm x 46 cm x 30 cm and the case has a total weight of 12 kg. There will be the following items in the carrying case.

- Magnetic Field Probes (ELT 400 with probe, HF3061 probe with NBM-550 monitor)
- Technical Protocol of Magnetic Field Strength Comparison up to 30 MHz

After the receipt of the carrying case, each participant must check it against any damage to the items inside the box. If the travelling standards have any damage due to the transportation, this situation must be reported to the pilot laboratory by using the form presented in Table 4 before reinitiating or resuming the comparison.

When the participated laboratory finishes the measurement, the next laboratory and the pilot laboratory shall be informed about the shipment by using the form given in Table 5. If there are not any foreseen problems with the shipment, all the items shall be checked and re-packed into the carrying case and it shall be dispatched to the next laboratory.

6. Transportation of Travelling Standards

The participants will be responsible for arranging transportation to the next participant.

The participants shall inform the pilot laboratory by filling and emailing the following form when the travelling standards arrive.

Table 4. Sample form for the information of arrival of the travelling standard

Confirmation Note For Receipt		
Date of Arrival		
NMI		
Name of Responsible Person		
Travelling standard	☐ Damaged	☐ Not Damaged
Additional Notes:		

The participants shall also inform the next participant and the pilot institute by e-mail about the shipment of the travelling standards by filling the following form.

Table 5. Sample form for the information of dispatch of the travelling standard

Confirmation Note For Dispatch	
Date of Shipment	
NMI	
Name of Responsible Person	
Shipment Information (company name etc.)	
Additional Notes:	

6.1. Failure of Travelling Standards

In case of any damage or malfunction of the travelling standards, the comparison will be reinitiated after the travelling standards are repaired.

6.2. Financial aspects

The participants will be responsible for the costs of the shipment to the next recipient (transportation and customs formalities) as well as any damage that may occur within their countries.

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Each participant is also responsible for the insurance of the standard from the arrival in their institute until the arrival in the subsequent institute. The value for insurance purposes can be assumed to be approximately 15000 Euros.

7. Measurement Quantities and Frequency Points

The correction factor defined below is determined for each frequency given in Table 6. The correction factors are obtained using the following equation;

$$\text{Correction Factor (dB)} = 20 * \log_{10}\left(\frac{\text{Actual Field (}\mu\text{T or A/m)}}{\text{Indicated Field (}\mu\text{T or A/m)}}\right)$$

Table 6. Measurement frequencies & levels for magnetic field probes

Measurement Frequency	Level for Magnetic Field Measurements	Measurement Range for ELT – 400	Relevant Travelling Standard
53 Hz	10 μT	320 μT – Low	ELT Probe 100 cm²
	100 μT	320 μT – High	
	300 μT	320 μT – High	
	1000 μT	80 mT – Low	
	2000 μT	80 mT – Low	
400 Hz	10 μT	320 μT – Low	
10 kHz	10 μT	320 μT – Low	
100 kHz	10 μT	320 μT – Low	
300 kHz	3 μT	320 μT – Low	
500 kHz	0,15 A/m	-	HF3061 with NBM-550
5 MHz	0,15 A/m	-	
10 MHz	0,15 A/m	-	
20 MHz	0,15 A/m	-	
30 MHz	0,15 A/m	-	

During the comparison measurements, the participating laboratories are responsible for performing measurements, taking necessary precautions, and taking into account the magnetic field limit values given in the EU directive [7] or other national directives on worker safety. If required, the calibration levels above the safety limits may be removed from the comparison by the related participating laboratories and they become exempt from the comparison and analysis of these high magnetic field levels.

8. Method of Computation of the Reference Value

The comparison reference value (CRV) for each measurement point will be calculated using the results of all the participant institutes. The method used will be the weighted mean of the participants not considered as outliers. The determination of outliers will be based on the 1.5·MAD criterion, which makes use of the median of all participants and of the calculated 'median of absolute deviations' (MAD). The participants whose difference with respect to the median is demonstrated to be more than 1.5 times the median of absolute deviations will be considered as outliers, and as such will not be taken into account in the determination of the CRV [8].

9. Measurement Instructions

9.1. Environmental Conditions

➢ The ambient temperature and humidity must be measured. No corrections will be applied for temperature and humidity effects.

➢ Preferably, the measurements should be carried out at the ambient conditions given below;

Temperature : (22 ± 2) °C

Relative humidity : (45 ± 10) %rh

9.2. Before Measurements

➢ The travelling standards should be allowed to stabilize in a temperature and humidity controlled environment for at least 24 hours without operating before starting the measurements.

➢ The travelling standards should be allowed to warm up for 10 minutes minimum before starting the measurements

➢ Before the measurements, the batteries of the travelling standards should be fully charged.

9.3. Powering of the standard during the measurements

➢ During the calibration process, the travelling standards shall not be connected to the charging unit.

9.4. Method of Measurement

➢ Each participant institute may use their own measurement method.

➢ The magnetic field measurements shall be performed in a fixed position and shall not be rotated. During the measurements, the display of the ELT-400 or NBM-550 field analyzer/meter shall point to the ceiling as shown Figure 2.

Figure 2. The position of magnetic field probe during comparison measurements

> ➤ The measurement parameters of the field analyser (ELT-400. See Fig. 3) and field meter (NBM-550) are given in Table 7 and Table 8 respectively.

Table 7. ELT-400 Measurement Parameters

Range	Low Cut	Detector	Max Hold
320 µT-High	10 Hz	RMS	OFF

Table 8. NBM-550 Measurement Parameters

Result Type	Apply Correction Frequency	Unit
Actual	OFF	A/m

a) 320 µT – Low Range*   b) 320 µT – High Range

c) 80 mT – Low Range*

Figure 3. Measurement settings of the ELT-400 during measurements

* When the low measuring range is selected, the low measuring range indicator does not appear on the ELT – 400 screen.

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10. Measurement Uncertainty

The measurement uncertainty shall be calculated according to the JCGM 100 "Guide to the Expression of Uncertainty in Measurement" [7] for the coverage probability of approximately 95%.

The detailed measurement uncertainty budget shall be provided for each of the following frequencies:

53 Hz, 400 Hz, 10 kHz, 100 kHz, 300 kHz, 500 kHz, 5 MHz, 10 MHz, 20 MHz and 30 MHz.

The example uncertainty budget shown below for the magnetic field probe measurement may be used by the participant laboratories. In the event that other uncertainty sources occur, the participant laboratories may apply them in the uncertainty table given below.

Uncertainty budget @ the frequency of Hz						
Source of uncertainty	Type	Value	Probability distribution	k-factor	Sensitivity coefficient	Standard Uncertainty (dB)
Standard resistor uncertainty						
Multimeter uncertainty						
The probe position						
Non-uniformity of field						
....						
....						
Total Uncertainty (k=2)						

11. Reporting of Results

For the measurement results of the participants, the measurement report format given in Annex A will be used and the measurement report containing the measurement results of the participants will be sent to the pilot laboratory by e-mail within three weeks after the completion of the measurements.

12. Final Report of the Comparison

The pilot laboratory is responsible for the preparation of a final comparison report.

The Draft A version of the comparison report will be issued by the pilot institute within two months after the receipt of the participant reports. The Draft A report will be sent to the participants for discussion and approval. The participants will have two weeks to send their comments on the Draft A Report.

After the approval, the Draft A report will become the Draft B report. The Draft B report will be approved by all the participants before being released to the appropriate technical committee and EURAMET Secretary for their approval.

13. References

[1] IEC 61786-1:2013 Measurement of DC magnetic, AC magnetic and AC electric fields from 1 Hz to 100 kHz with regard to exposure of human beings - Part 1: Requirements for measuring instruments

[2] IEC 62233:2005, Measurement methods for electromagnetic fields of household appliances and similar apparatus with regard to human exposure

[3] IEC 62311:2019, Measurement methods for electromagnetic fields of household appliances and similar apparatus with regard to human exposure, 2005Assessment of electronic and electrical equipment related to human exposure restrictions for electromagnetic fields (0 Hz to 300 GHz).

[4] IEEE Std. 1309:2013, "IEEE Standard for calibration of electromagnetic field sensors and probes, excluding antennas, from 9 kHz to 40 GHz".

[5] IEEE Std. 1308:1994, "Magnetic Flux Density and Electric Field Strength Meters -10 Hz to 3 kHz"

[6] CCEM Guidelines for Planning, Organizing, Conducting and Reporting Key, Supplementary and Pilot Comparisons, Ver. 2.1, 2017 (available on the BIPM website: https://www.bipm.org/utils/common/pdf/CC/CCEM/ccem_guidelines.pdf).

[7] EMF Directive (2013/35/EU), 26 June 2013

[8] W. Bich, M. Cox, T. Estler, L. Nielsen, W. Woeger, "Proposed guidelines for the evaluation of key comparison data", April 2002. Available at: http://www.bipm.org/cc/CCAUV/Allowed/3/CCAUV02 36.pdf.

[9] W. Bich, M. Cox, T. Estler, L. Nielsen, W. Woeger, "Proposed guidelines for the evaluation of key comparison data", April 2002. Available at: https://iopscience.iop.org/article/10.1088/0026-1394/39/6/10/pdf

<u>**ANNEX A**</u>

Measurement Report for EURAMET.EM.RF-S46 (EURAMET Project No: 1538) Supplementary Comparison

1. Participant Information

Institute Name	
Contact Person	
Telephone No	
Fax No	
E-mail	
Address	

2. Measurement Date

Measurement Dates	.... – ....

3. Environmental Condition

Temperature (°C)	
Relative Humidity (%rh)	

4. References Used In Measurement

Name of Equipment	Manufacturer	Type / Model	Serial No

5. Measurement Procedure

6. Measurement Results

Frequency	Level for Magnetic Field Measurements	Correction Factor (dB)	Measurement Uncertainty (dB) (k=2)
53 Hz	10 µT		
	100 µT		
	300 µT		
	1000 µT		
	2000 µT		
400 Hz	10 µT		
10 kHz	10 µT		
100 kHz	10 µT		
300 kHz	3 µT		
500 kHz	0,15 A/m		
5 MHz	0,15 A/m		
10 MHz	0,15 A/m		
20 MHz	0,15 A/m		
30 MHz	0,15 A/m		

7. Detailed Uncertainty Budget

Uncertainty budget @ the frequency of Hz						
Source of uncertainty	Type	Value	Probability distribution	k-factor	Sensitivity coefficient	Standard Uncertainty (dB)
Total Uncertainty (k=2)						

ANNEX B. Participants Measurement Results and Uncertainty Budget

B.1. TÜBİTAK UME Measurement Results and Uncertainty Budgets

Measurement Report for EURAMET.EM.RF-S46 (EURAMET Project No: 1538) Supplementary Comparison

1. Participant Information

Institute Name	TÜBİTAK UME
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2. Measurement Date

Measurement Dates	03.01.2022 – 11.01.2022

3. Environmental Condition

Temperature (°C)	22 ± 2
Relative Humidity (%rh)	45 ± 10

4. References Used In Measurement

Name of Equipment	Manufacturer	Type / Model	Serial No
Arbitrary Function Generator	Agilent Technologies	33120A	MY40023800
0.5 Ohm Resistor	Solar Electronics	9225-0.5	EMC009
50 Ohm Termination	Schaffner	50R50WCW	Yūk1
Helmholtz Coil	TUBİTAK UME	HC11	002
Helmholtz Coil	TUBİTAK UME	HC36	003
Helmholtz Coil	TUBİTAK UME	HC03	001
6 ½ Digit Multimeter	Agilent Technologies	34401A	MY41031015
Oscilloscope	Keysight Technologies	DSOX3012T	MY58260862
AF Amplifier	Bryston	7B-SST-230	7B-SST-000202
Signal Generator	IFR Inc.	2023A	202304/699
Power Meter	Keysight Technologies	N1914A	MY60270004
Power Sensor	Keysight Technologies	U8481A	MY60290002
Attenuator	AEROFLEX	58-40-34	QC997
TEM Cell	IFI	CC102S-MAN01	L506-1007
RF Amplifier	BONN Elektronik	BSA 0140 – 250	18121514

5. Measurement Procedure

5.1. Helmholtz Coil Method

The magnetic field probe calibration was performed in accordance with the IEEE Std 1309:2013 by using two pairs of Helmholtz coils for frequencies up to 500 kHz. The magnetic field probe to be calibrated was placed at the centre of the Helmholtz coil and the magnetic field value at the center of the coil was calculated by using Equation 1. A resistor (50 Ω or 0.5 Ω) was connected in series with the Helmholtz coil. The RMS value of the current flowing through the Helmholtz coil was calculated by using Equation 2. The measurement setup is depicted in Figure 1.

$$H = K * I \quad A/m \tag{1}$$

$$I = \frac{V}{R} \tag{2}$$

Where;

H is the magnetic field strength value at the center of the Helmholtz coil (A/m)
K is coil constant
I is the current in the Helmholtz coil
V is the induced voltage across the load
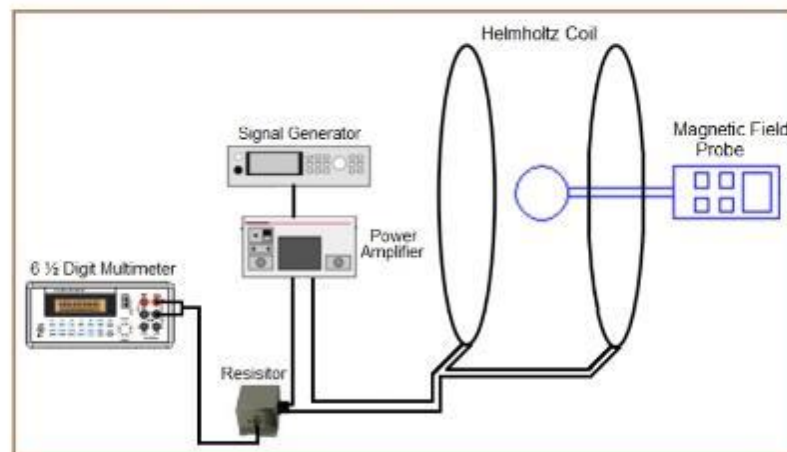
Figure 1. Example Helmholtz coil calibration setup

5.2. TEM Cell Method

The measurements were performed in accordance with the IEEE Std 1309:2013 Calibration Method B using calculated field strength. In the frequency range 5 MHz to 30 MHz Transverse Electromagnetic (TEM) cell with a septum height of 0.45 m was used to generate a calculable magnetic field level. The calculable magnetic field was calculated from the dimensions of the TEM Cell, its impedance, and the net power of the TEM Cell input as shown in the following equations. The example measurement setup is illustrated in Figure 2.

$$E = \frac{V_{TEM}}{b} = \frac{\sqrt{P_{net}Z_0}}{b} \ V/m$$

$$H = \frac{E}{\eta_0} = \frac{E}{377} \ A/m$$

Where;

E and H are electric and magnetic fields,
V_{TEM} is the voltage at the input or output port of the cell,
Z_0 is the real part of the characteristic impedance of the cell,
P_{net} is the net power at the input of the cell,
b is the distance from the upper wall to the center plate,
V_{out} is the output voltage at the cell
η_0 is impedance of free space.
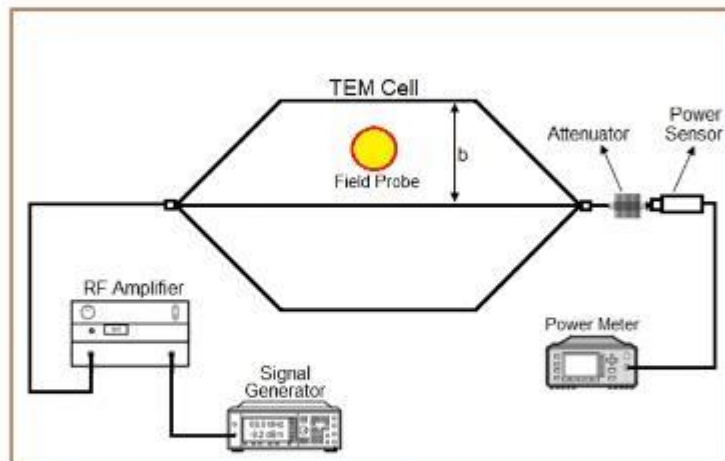
Figure 2. Example TEM Cell calibration setup

6. Measurement Results

Frequency	Level for Magnetic Field Measurements	Correction Factor (dB)	Measurement Uncertainty (dB) (k=2)
53 Hz	10 μT	0.09	0.09
	100 μT	0.17	0.09
	300 μT	0.17	0.09
	1000 μT	0.09	0.09
	2000 μT	0.00	0.09
400 Hz	10 μT	0.09	0.09
10 kHz	10 μT	0.09	0.09
100 kHz	10 μT	0.00	0.10
300 kHz	3 μT	0.09	0.15
500 kHz	0.15 A/m	1.06	0.26
5 MHz	0.15 A/m	-0.18	0.47
10 MHz	0.15 A/m	-0.09	0.47
20 MHz	0.15 A/m	0.09	0.47
30 MHz	0.15 A/m	0.09	0.47

7. Detailed Uncertainty Budget

Uncertainty budget @ the frequency of 53 Hz (100 µT - 2 mT)						
Source of uncertainty	Type	Value (dB)	Probability distribution	k-factor	Sensitivity coefficient	Standard Uncertainty (dB)
Calibration of Helmholtz coil	B	0.026	Normal	2	1	0.013
Calibration of DVM	B	0.002	Normal	2	1	0.001
Calibration of 0,5 Ohm resistor	B	0.014	Normal	2	1	0.007
Non uniformity of field	B	0.049	Rectangular	1.732	1	0.028
Misalignment	B	0.050	Rectangular	1.732	1	0.029
Repeatability	A	0.000	Normal	1	1	0.000
Total Uncertainty (k=2)						0,09

Uncertainty budget @ the frequency of 53 Hz to 10 kHz (10 µT)						
Source of uncertainty	Type	Value (dB)	Probability distribution	k-factor	Sensitivity coefficient	Standard Uncertainty (dB)
Calibration of Helmholtz coil	B	0.026	Normal	2	1	0.013
Calibration of DVM	B	0.002	Normal	2	1	0.001
Calibration of 50 Ohm termination	B	0.027	Normal	2	1	0.014
Non uniformity of field	B	0.049	Rectangular	1.732	1	0.028
Misalignment	B	0.050	Rectangular	1.732	1	0.029
Repeatability	A	0.000	Normal	1	1	0.000
Total Uncertainty (k=2)						0,09

Uncertainty budget @ the frequency of 100 kHz (10 μT)						
Source of uncertainty	Type	Value (dB)	Probability distribution	k-factor	Sensitivity coefficient	Standard Uncertainty (dB)
Calibration of Helmholtz coil	B	0.026	Normal	2	1	0.013
Frequency response of Helmholtz coil	B	0.026	Rectangular	1.732	1	0.015
Calibration of DVM	B	0.002	Normal	2	1	0.001
Calibration of 50 Ohm termination	B	0.027	Normal	2	1	0.014
Non uniformity of field	B	0.049	Rectangular	1.732	1	0.028
Misalignment	B	0.050	Rectangular	1.732	1	0.029
Repeatability	A	0.001	Normal	1	1	0.001
Total Uncertainty (k=2)						0,10

Uncertainty budget @ the frequency of 300 kHz (3 μT)						
Source of uncertainty	Type	Value (dB)	Probability distribution	k-factor	Sensitivity coefficient	Standard Uncertainty (dB)
Calibration of Helmholtz coil	B	0.026	Normal	2	1	0.013
Frequency response of Helmholtz coil	B	0.101	Rectangular	1.732	1	0.058
Calibration of DVM	B	0.002	Normal	2	1	0.001
Calibration of 50 Ohm termination	B	0.027	Normal	2	1	0.014
Non uniformity of field	B	0.049	Rectangular	1.732	1	0.028
Misalignment	B	0.050	Rectangular	1.732	1	0.029
Repeatability	A	0.002	Normal	1	1	0.002
Total Uncertainty (k=2)						0,15

Uncertainty budget @ the frequency of 500 kHz (0.15 A/m)						
Source of uncertainty	Type	Value (dB)	Probability distribution	k-factor	Sensitivity coefficient	Standard Uncertainty (dB)
Calibration of Helmholtz coil	B	0.026	Normal	2	1	0.013
Frequency response of Helmholtz coil	B	0.200	Rectangular	1.732	1	0.115
Calibration of oscilloscope	B	0.075	Normal	2	1	0.038
Calibration of 50 Ohm termination	B	0.027	Normal	2	1	0.014
Non uniformity of field	B	0.049	Rectangular	1.732	1	0.028
Misalignment	B	0.050	Rectangular	1.732	1	0.029
Repeatability	A	0.002	Normal	1	1	0.002
Total Uncertainty (k=2)						0.26

Uncertainty budget @ the frequency of 5 MHz to 30 MHz (0,15 A/m)						
Source of uncertainty	Type	Value (dB)	Probability distribution	k-factor	Sensitivity coefficient	Standard Uncertainty (dB)
Calibration of power meter with sensor	B	0.100	Normal	2	0.5	0.025
Calibration of attenuator	B	0.300	Normal	2	0.5	0.075
TEM cell septum distance	B	0.080	Rectangular	1.732	1	0.046
Field homogeneity	B	0.320	Rectangular	1.732	1	0.185
TEM cell impedance	B	0.287	Rectangular	1.732	0.5	0.083
TEM cell output mismatch	B	0.081	U-shape	1,414	0.5	0.029
Repeatability	A	0.062	Normal	1	1	0.062
Total Uncertainty (k=2)						0,47

B.2. CMI Measurement Results and Uncertainty Budgets

Measurement Report for EURAMET.EM.RF-S46 (EURAMET Project No: 1538) Supplementary Comparison

1. Participant Information

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Note	8017 Department of electromagnetic quantities, in the following text denoted as CMI_8017 1013 Department of primary metrology of RF electrical quantities, in the following text denoted as CMI_1013

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2. Measurement Date

Measurement Dates	11.2.2022 – 17.2.2022 (CMI_8017) 2.2.2022 – 3.2.2022 (CMI_1013)

3. Environmental Condition

Temperature (°C)	23.0 ± 2.0
Relative Humidity (%rh)	25 ± 10

4. References Used In Measurement

CMI_8017

Name of Equipment	Manufacturer	Type / Model	Serial No
multimeter	HP	34401A	3146A20999
multimeter	HP	3458A	MY45048935
magnetic flux density coil standard	CMI	Helmholtz	1201
magnetic flux density coil standard	CMI	Helmholtz	052
special search coil	CMI	1-layer	EP02/00
AC/DC current shunt	CMI	10A	CMI/10A/10/15

CMI_1013

Name of Equipment	Manufacturer	Type / Model	Serial No
Helmholtz coil	CMI	2 × single turn, diameter 0.4 m	01
Crawford TEM cell	CMI	septum height 0.25 m	01
generator	Keysight	33600A	MY53801294
amplifier	BONN Elektronik	BLWA 0210-25	974436-02
coaxial shunt	RAO	CSR2	005
power meter	Rohde & Schwarz	NRVD	835843/022
power meter	Hewlett-Packard	436A	2410A19598
power sensor	Rohde & Schwarz	NRV-Z4	848264/008
power sensor	Rohde & Schwarz	NRV-Z51	836400/024
power sensor	Hewlett-Packard	8481B	2350A02744
power splitter	Hewlett-Packard	11667A	19396
steel scale	Preisser	500 mm	67

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5. Measurement Procedure

CMI_8017

Two coil standards of magnetic flux density were used. A massive multi-layer Helmholtz type solenoid Ser. No. 052 [1] with a textit frame and with a DC value of the constant of (1.94428 ± 0.00097) mT/A determined by the nuclear magnetic resonance (NMR) method with flowing water [2] was used at 53 Hz up to 2 mT. The single-layer Helmholtz type solenoid Ser. No. 1201 [3] with a glass-textit frame and with the constant of (0.105683 ± 0.000053) mT/A was used at 400 Hz, 10 kHz and 100 kHz. It was calibrated by comparing with the primary standard quartz solenoid for DC. The single-layer solenoid constant (its frequency dependence) was calibrated up to 150 kHz by the method with AC current shunt [1]. Both solenoids were fed with the generator Agilent 33220A and AE Techron 7224 power amplifier. Current through windings was measured by calibrated voltmeter 34401A or 34581A and precise cage-type AC current shunt [4] with an AC-DC difference of (82 ± 60) ppm at 200 kHz. The value of magnetic flux density at 100 kHz was set using special single-layer search coil Ser. No. EP02/00. The induced voltage from the search coil was measured by voltmeter 3458A.

[1] M. Ulvr: „AC Magnetic Flux Density Standards and Their Use in Metrology", Disertation Thesis, CTU Prague, 2020.

[2] M. Ulvr, J. Kupec: „Improvements to the NMR method with flowing water at CMI", *IEEE Transaction on Instrumentation and Measurement*, vol. 67, No. 1, 2018, pp. 204-208.

[3] M. Ulvr: „Setup for generating an AC magnetic field from 3 kHz up to 100 kHz", *IEEE Transaction on Magnetics*, vol. 51, No. 1, 2015.

[4] V. Nováková Zachovalová: „On the Current Shunts Modeling", *IEEE Transaction on Instrumentation and Measurement*, vol. 63, no. 6, 2014, pp. 1620-1627.

CMI_1013

The calibration of Narda ELT-400 (freq. point 300 kHz) and Narda HF 3061 (freq. points 500 kHz, 5 MHz) was performed using the unshielded single turn Helmholtz coil (H. C.) with a diameter of 0.4 m. For the frequency point 300 kHz, the input current was measured using a coaxial shunt and a power sensor. For frequency points 500 kHz, 5 MHz, the H. C. was fed using a two-resistor power splitter. The calibration of Narda HF 3061 for frequencies 10 MHz and higher was performed using Crawford TEM cell with a septum height of 0.25 m. The power delivered to the TEM cell was monitored using a power sensor.

6. Measurement Results

Frequency	Level for Magnetic Field Measurements	Correction Factor (dB)	Measurement Uncertainty (dB) (k=2)	Note
53 Hz	10 µT	0.12	0.04	CMI_8017
	100 µT	0.13	0.04	
	300 µT	0.13	0.04	
	1000 µT	0.06	0.04	
	2000 µT	0.06	0.04	
400 Hz	10 µT	0.09	0.04	
10 kHz	10 µT	0.10	0.04	
100 kHz	10 µT	0.02	0.05	
300 kHz	3 µT	0.09	0.28	CMI_1013
500 kHz	0.15 A/m	1.35	0.35	
5 MHz	0.15 A/m	0.43	0.39	
10 MHz	0.15 A/m	0.38	0.64	
20 MHz	0.15 A/m	0.46	0.61	
30 MHz	0.15 A/m	0.27	0.78	

7. Detailed Uncertainty Budget

CMI_8017

Uncertainty budget @ the frequency of 53, 400 and 10000 Hz						
Source of uncertainty	Type	Value (%)	Probability distribution	k-factor	Sensitivity coefficient	Standard Uncertainty (dB)
Calibration of coil standard constant	B	0.12	Norm.	1	1	0.010
Homogeneity of coil standard	B	0.15	Norm.	1	1	0.013
AC/DC current shunt calibration	B	0.04	Norm.	1	1	0.003
Measurement of voltage drop across current shunt	B	0.06	Norm.	1	1	0.005
Repeatability (current. voltage. LSD of DUT)	A	0.10	Norm.	1	1	0.009
Total Uncertainty (k=2)						0.040

Uncertainty budget @ the frequency of 100 kHz						
Source of uncertainty	Type	Value (%)	Probability distribution	k-factor	Sensitivity coefficient	Standard Uncertainty (dB)
Measurement of induced voltage form the search coil	B	0.10	Norm.	1	1	0.009
Calibration of search coil constant	B	0.10	Norm.	1	1	0.009
Homogeneity of coil standard	B	0.20	Norm.	1	1	0.017
Repeatability (place of search coil in coil standard. current. voltage. LSD of DUT)	A	0.15	Norm.	1	1	0.013
Total Uncertainty (k=2)						0.050

CMI_1013

Uncertainty budget @ the frequency of 300 kHz						
Source of uncertainty	Type	Value (dB)	Probability distribution	k-factor	Sensitivity coefficient	Standard Uncertainty (dB)
Repeatability	A	0.001	normal	1	1	0.001
Display resolution	B	0.001	rectangular	1.73	1	0.001
Probe position	B	0.038	rectangular	1.73	1	0.022
H. C. diameter	B	0.069	rectangular	1.73	1	0.040
H. C. distance between loops	B	0.104	rectangular	1.73	1	0.060
Field homogeneity	B	0.122	rectangular	1.73	1	0.070
Coaxial shunt	B	0.086	normal	1	1	0.086
Power sensor	B	0.035	normal	1	1	0.035
Total Uncertainty (k = 2)						0.28

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Uncertainty budget @ the frequency of 500 kHz						
Source of uncertainty	Type	Value (dB)	Probability distribution	k-factor	Sensitivity coefficient	Standard Uncertainty (dB)
Repeatability	A	0.004	normal	1	1	0.004
Display resolution	B	0.003	rectangular	1.73	1	0.002
Probe position	B	0.021	rectangular	1.73	1	0.012
H. C. diameter	B	0.069	rectangular	1.73	1	0.040
H. C. distance between loops	B	0.104	rectangular	1.73	1	0.060
Field homogeneity	B	0.155	rectangular	1.73	1	0.090
Power splitter asymmetry	B	0.050	rectangular	1.73	1	0.029
Mismatch error	B	0.172	U-shape	1.41	1	0.122
Power sensor	B	0.035	normal	1	1	0.035
Total Uncertainty (k = 2)						0.35

Uncertainty budget @ the frequency of 5 MHz						
Source of uncertainty	Type	Value (dB)	Probability distribution	k-factor	Sensitivity coefficient	Standard Uncertainty (dB)
Repeatability	A	0.004	normal	1	1	0.004
Display resolution	B	0.003	rectangular	1.73	1	0.002
Probe position	B	0.051	rectangular	1.73	1	0.029
H. C. diameter	B	0.069	rectangular	1.73	1	0.040
H. C. distance between loops	B	0.104	rectangular	1.73	1	0.060
Field homogeneity	B	0.214	rectangular	1.73	1	0.124
Power splitter asymmetry	B	0.050	rectangular	1.73	1	0.029
Mismatch error	B	0.172	U-shape	1.41	1	0.122
Power sensor	B	0.035	normal	1	1	0.035
Total Uncertainty (k = 2)						0.39

Uncertainty budget @ the frequency of 10 MHz						
Source of uncertainty	Type	Value (dB)	Probability distribution	k-factor	Sensitivity coefficient	Standard Uncertainty (dB)
Repeatability	A	0.006	normal	1	1	0.006
Display resolution	B	0.003	rectangular	1.73	1	0.002
Probe position	B	0.183	rectangular	1.73	1	0.106
Sensitivity to E-field	B	0.112	rectangular	1.73	1	0.065
Field homogeneity	B	0.273	rectangular	1.73	1	0.158
Power sensor	B	0.086	normal	1	1	0.086
Mismatch error	B	0.092	U-shape	1.41	1	0.065
Harmonic distortion	B	0.222	normal	1	1	0.222
Total Uncertainty (k = 2)						0.64

Uncertainty budget @ the frequency of 20 MHz						
Source of uncertainty	Type	Value (dB)	Probability distribution	k-factor	Sensitivity coefficient	Standard Uncertainty (dB)
Repeatability	A	0.006	normal	1	1	0.006
Display resolution	B	0.003	rectangular	1.73	1	0.002
Probe position	B	0.164	rectangular	1.73	1	0.095
Sensitivity to E-field	B	0.233	rectangular	1.73	1	0.135
Field homogeneity	B	0.262	rectangular	1.73	1	0.152
Power sensor	B	0.086	normal	1	1	0.086
Mismatch error	B	0.092	U-shape	1.41	1	0.065
Harmonic distortion	B	0.172	normal	1	1	0.172
Total Uncertainty (k = 2)						0.61

Uncertainty budget @ the frequency of 30 MHz						
Source of uncertainty	Type	Value (dB)	Probability distribution	k-factor	Sensitivity coefficient	Standard Uncertainty (dB)
Repeatability	A	0.006	normal	1	1	0.006
Display resolution	B	0.003	rectangular	1.73	1	0.002
Probe position	B	0.254	rectangular	1.73	1	0.147
Sensitivity to E-field	B	0.382	rectangular	1.73	1	0.221
Field homogeneity	B	0.368	rectangular	1.73	1	0.213
Power sensor	B	0.086	normal	1	1	0.086
Mismatch error	B	0.092	U-shape	1.41	1	0.065
Harmonic distortion	B	0.157	normal	1	1	0.157
Total Uncertainty (k = 2)						0.78

Measurement Report for EURAMET.EM.RF-S46 (EURAMET Project No: 1538) Supplementary Comparison

1. Participant Information

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2. Measurement Date

Measurement Dates	11.05.2022 – 12.05.2022

3. Environmental Condition

Temperature (°C)	(22,2 ± 0,3) °C
Relative Humidity (%rh)	---

4. References Used In Measurement

Name of Equipment	Manufacturer	Type / Model	Serial No
EBS10	PTB, AG 2.51	0,1 Ω	2527
EBS3	PTB, AG 2.51	1 Ω	2500
EBS6	PTB, AG 2.51	10 Ω	2503
DVM	Keithley	2002	2580
Counter	Agilent	53131A	2511
Helmholtz coil	PTB, AG 2.51	HeHogroß	2465
Helmholtz coil	PTB, AG 2.51	HeHoNoVo	2575

5. Measurement Procedure

The measurement setup consists of a field coil, a digital voltmeter (DVM), a function generator (FG), a power amplifier (LV) and a device which provides i) potential tracking of the inner shield of the connecting cable between field coil and measuring resistor RN and ii) a reactive load compensation for the field. This is necessary to reach the required flux density values at technical frequencies.
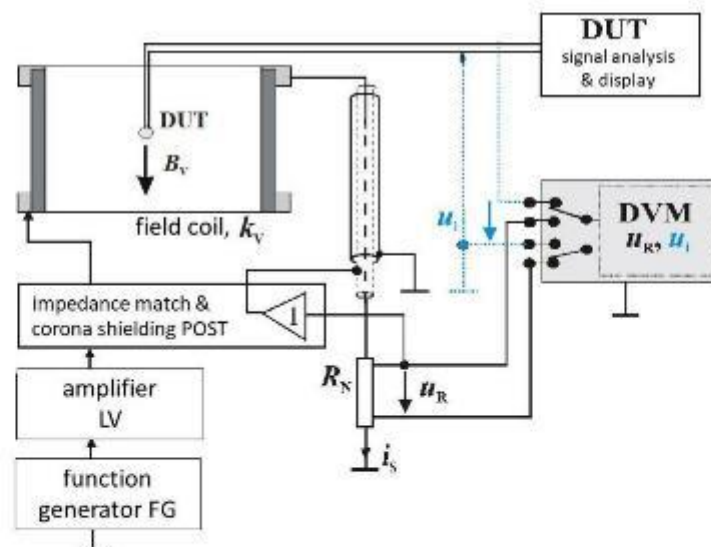
Fig. 1 Measurement setup for calibratiom of magnetometers with alternating fields. The dotted blue line indicates an induction coil without electronics for data analysis.

1. All devices of the measurement setup must be powered on for at least 1 hour.

2. The field coil is selected based on sensor size, field and frequency range and it is connect to the power amplifier via POST input. It may be necessary to use different field coils.

3. The current $i_{S,max}$ is estimated for the highest desired flux density depending on the respective coil constant. Next, a resistor EBS suitable to measure $i_{S,max}$ is selected and integrated into the circuit at the POST input.

4. The required current values are calculated for all desired flux densities. The values are entered into measurement records. The coil is powered by switching on the current.

5. An oscilloscope is used to check that the shielding potential is present on the current measuring line.

6. The sensor from the DUT is installed inside the center of field producing coil. If the sensor does not have a reference surface, the sensor needs to be moved till it shows the maximum field value on the display.

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7. Now, the measurement program can be started. For each field and frequency point, at least three measurement values I, are recorded together with the respective current value i_S. The DVM (to measure the current) is operated in "Synchronous Sub-sampled Mode". Note, the finite input resistance of the DVM (1 MΩ) must be taken into account, if the resistor EBS 8 with nominal value 100 Ω is used.

Comment: For calibrations at 50Hz, data at f= 40 Hz, 45 Hz, 55 Hz and 60 Hz are taken and interpolated to f= 50 Hz. A sequence of measurements in the right order is automatically implemented into the software.

8. For multi-axis sensors, the realignment of the sensor and the measurement procedure are repeated for the other 2 spacial directions.

9. After the measurements, the current through the field coil is switched off, the sensor is removed and the cables disconnected from the field coil. The value showing at the display at zero flux density is noted in the measurement log.

10. At last, the room temperature, air pressure and relative humidity is measured.

11. The sensor is removed and the DUT marked with a calibration label.

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6. Measurement Results

Frequency	Level for Magnetic Field Measurements	Correction Factor (dB)	Measurement Uncertainty (dB) (k=2)
53 Hz	10 μT	0,12	0,0057
	100 μT	0,14	0,0055
	300 μT	0,14	0,0062
	1000 μT	-0,007	0,011
	2000 μT	-	-
400 Hz	10 μT	0,15	0,0057
10 kHz	10 μT	0,08	0,0091
100 kHz	1,9 μT	0,25	0,020
300 kHz	3 μT	-	-
500 kHz	0,15 A/m	-	-
5 MHz	0,15 A/m	-	-
10 MHz	0,15 A/m	-	-
20 MHz	0,15 A/m	-	-
30 MHz	0,15 A/m	-	-

7. Detailed Uncertainty Budget

Uncertainty budget @ the frequency of Hz						
Source of uncertainty	Type	Value	Probability distribution	k-factor	Sensitivity coefficient	Standard Uncertainty (%)
Coil constant k_{V0} : large Helmholtz coil (HeHogroß) up to 1kHz, HF Helmholtz coil (HeHoNoVo) up to 10kHz, ... up to 50kHz, ... up to 100kHz	A	k_{V0}	normal distribution	1	$p(f)\dfrac{u_R}{R_N}\cos\varepsilon$	0.021 0.046 0.068 0,1
Frequency dependence of the coil constant	A	$p(f)$	rectangular distribution	1	$k_{V0}\dfrac{\partial p}{\partial f}\dfrac{u_R}{R_N}\cos\varepsilon$	
current sense resistor : EBS10 EBS3 EBS6	A	R_N	normal distribution	1	$-k_{V0}p(f)\dfrac{u_R}{R_N^2}\cos\varepsilon$	0.01 0.005 0,005
voltage at R_N	A	u_R	normal distribution	1	$k_{V0}p(f)\dfrac{1}{R_N}\cos\varepsilon$	0,01
default field		B_v				< 0.11
default field	A	B_v	normal distribution	1	$\cos\varepsilon \cdot g(\rho)$	< 0.11
misalignment	A	ε	rectangular distribution	1	---	0,013
scattering DUT values	B	y	normal distribution	1	1	depends on the value, see Table 6
Field distribution over sensor area	A	$g(\rho_S)$	rectangular distribution	1	$B_v \cdot \cos\varepsilon$	0.01
Total Uncertainty (k=2)						see Table 6

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Measurement Report for EURAMET.EM.RF-S46 (EURAMET Project No: 1538) Supplementary Comparison

1. Participant Information

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2. Measurement Date

Measurement Dates	2022-05-18

3. Environmental Condition

Temperature (°C)	22.7 ± 0.5
Relative Humidity (%rh)	43.0 ± 5

4. References Used In Measurement

Name of Equipment	Manufacturer	Type / Model	Serial No
Crawford TEM-Cell	Amplifier Research	TC3020	11514
attenuator	EMC Technology	20 dB	-
RF power sensor	Rohde & Schwarz	NRV-Z51	841918/049
temperature & humidity logger	Almemo, Co. Ahlborn	MA 2590-3S + FH A646-E1	MA 2590-3S + FH A646-E1

5. Measurement Procedure

The magnetic field probe HF3061 with NBM-550 has been calibrated in a Crawford TEM cell. Figure 1 shows a schematic drawing of the calibration facility.
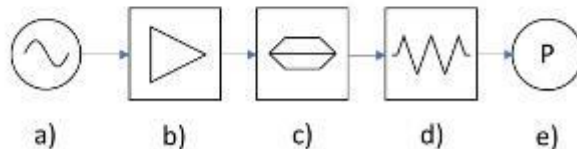
Figure 1: schematic of the calibration facility, consisting of the following components:
a) RF signal generator
b) RF power amplifier
c) Crawford TEM-Cell
d) attenuator
e) RF power meter

The RMS value of the magnetic field strength is calculated from the power measured behind the attenuator at the TEM cell output, according to the following equation:

$$H = \frac{E}{Z_0} = \frac{\sqrt{P_m \cdot \eta_{pm} \cdot k_{pm} \cdot k_{drift} \cdot D \cdot Z_L}}{d \cdot Z_0} \cdot k_{VSWR}$$

with : H = magnetic field strength,

E = electric field strength,

Z_0 = impedance of free space (376.730313668(57) Ω),

P_m = RF power measured at the attenuator output,

η_{pm} = correction-factor of the power meter,

k_{pm} = factor for modeling the influence of mismatch between attenuator and power sensor,

k_{drift} = factor for modeling the influence of drift of the RF power,

D = frequency-dependent attenuation factor of the attenuator,

Z_L = line impedance, here: 50 Ohm,

d = septum height of the TEM cell,

k_{VSWR} = factor for modeling the standing wave in the TEM cell.

Due to the underlying principle of the Crawford TEM cell, an electric field is always generated when the magnetic field is generated. The sensitivity of the probe to electric fields must therefore be taken into account in the measurement uncertainty of the probe's correction factor. The probe correction factor cf is calculated by the following expression:

$$cf = \frac{H}{H_{indic}} \cdot k_{FS} \cdot k_{inhom} = \frac{H \cdot k_{FS} \cdot k_{inhom}}{H_{indic}}$$

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with : H_{indic} = indicated magnetic field strength,

k_{FS} = factor for modeling the influence of the probe on the field inside the TEM-cell,

k_{inhom}= factor for modeling the influence of field strength inhomogeneity.

6. Measurement Results

Frequency	Level for Magnetic Field Measurements	Correction Factor (dB)	Measurement Uncertainty (dB) (k=2)
500 kHz	0,15 A/m	0.71	0.61
5 MHz	0,15 A/m	-0.13	0.61
10 MHz	0,15 A/m	0.00	0.61
20 MHz	0,15 A/m	0.17	0.62
30 MHz	0,15 A/m	0.09	0.62

The uncertainty stated is the expanded measurement uncertainty obtained by multiplying the standard measurement uncertainty by the coverage factor $k = 2$. It has been determined in accordance with the "Guide to the Expression of Uncertainty in Measurement (GUM)". The value of the measurand then normally lies, with a probability of approximately 95 %, within the attributed coverage interval.

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7. Detailed Uncertainty Budget

Hint: The uncertainty does only slightly depend on frequency.

Uncertainty budget @ the frequency of 0.5 MHz

Source of uncertainty	Type	Value x_i		Standard Uncertainty $u(x_i)$		Probability distribution	Sensitivity coefficient c_i		Standard Uncertainty $u_c(y)$	
zero offset & noise of power meter	A	0.057198199	W	1.10E-08	W	normal	75.93	dB/W	8.35E-07	dB
calibration of power meter	B	1.0002215929		0.0022		normal	4.34	dB	9.55E-03	dB
mismatch of attenuator & power meter	B	1		0.02		u-shaped	4.34	dB	8.69E-02	dB
drift of RF power	B	1		0.0058		rectangular	4.34	dB	2.52E-02	dB
calibration of attenuator	B	96.3163464		2.217765834		normal	0.05	dB	1.00E-01	dB
septum height of the TEM-cell	B	0.2945	m	0.0025	m	normal	-29.49	dB/m	7.37E-02	dB
standing waves inside TEM-cell	B	1		0.019		u-shaped	8.69	dB	1.65E-01	dB
influence of field-probe	B	1		0.02		rectangular	-8.69	dB	1.74E-01	dB
inhomogeneity of field	B	1		0.012		rectangular	8.69	dB	1.04E-01	dB
sensitivity against e-field	B	1		0.003072197		rectangular	-8.69	dB	2.67E-02	dB
Total Uncertainty (k=2)									0.61	dB

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Uncertainty budget @ the frequency of 5.0 MHz

Source of uncertainty	Type	Value x_i		Standard Uncertainty $u(x_i)$	Probability distribution	Sensitivity coefficient c_i		Standard Uncertainty $u_i(y)$	
zero offset & noise of power meter	A	0.05720581	W	1.10E-08 W	normal	75.92	dB/W	8.4E-07	dB
calibration of power meter	B	1.00215928		0.0022	normal	4.33	dB	9.5E-03	dB
mismatch of attenuator & power meter	B	1		0.02	u-shaped	4.34	dB	8.7E-02	dB
drift of RF power	B	1		0.0058	rectangular	4.34	dB	2.5E-02	dB
calibration of attenuator	B	95.96521567		2.20961032	normal	0.05	dB	1.0E-01	dB
septum height of the TEM-cell	B	0.2945	m	0.0025 m	normal	-29.49	dB/m	7.4E-02	dB
standing waves inside TEM-cell	B	1		0.019	u-shaped	8.69	dB	1.7E-01	dB
influence of field-probe	B	1		0.02	rectangular	-8.69	dB	1.7E-01	dB
inhomogeneity of field	B	1		0.012	rectangular	8.69	dB	1.0E-01	dB
sensitivity against e-field	B	1		0.00338409	rectangular	-8.69	dB	2.9E-02	dB
Total Uncertainty (k=2)								0.61	dB

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Uncertainty budget @ the frequency of 10 MHz

Source of uncertainty	Type	Value x_i		Standard Uncertainty $u(x_i)$		Probability distribution	Sensitivity coefficient c_i		Standard Uncertainty $u_i(y)$	
zero offset & noise of power meter	A	0.0572008	W	1.10E-08	W	normal	75.92	dB/W	8.4E-07	dB
calibration of power meter	B	1.00431857		0.0022		normal	4.32	dB	9.5E-03	dB
mismatch of attenuator & power meter	B	1		0.02		u-shaped	4.34	dB	8.7E-02	dB
drift of RF power	B	1		0.0058		rectangular	4.34	dB	2.5E-02	dB
calibration of attenuator	B	96.0505818		2.2116463B		normal	0.05	dB	1.0E-01	dB
septum height of the TEM-cell	B	0.2945	m	0.0025	m	normal	-29.49	dB/m	7.4E-02	dB
standing waves inside TEM-cell	B	1		0.019		u-shaped	8.69	dB	1.7E-01	dB
influence of field-probe	B	1		0.02		rectangular	-8.69	dB	1.7E-01	dB
inhomogeneity of field	B	1		0.012		rectangular	8.69	dB	1.0E-01	dB
sensitivity against e-field	B	1		0.001		rectangular	-8.69	dB	8.7E-03	dB
Total Uncertainty (k=2)									0.61	dB

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Uncertainty budget @ the frequency of 20 MHz

Source of uncertainty	Type	Value x_i		Standard Uncertainty $u(x_i)$		Probability distribution	Sensitivity coefficient c_i		Standard Uncertainty $u_i(y)$	
zero offset & noise of power meter	A	0.05720259	W	1.10E-08	W	normal	75.92	dB/W	8.4E-07	dB
calibration of power meter	B	1.00601951		0.0021125		normal	4.32	dB	9.1E-03	dB
mismatch of attenuator & power meter	B	1		0.02		u-shaped	4.34	dB	8.7E-02	dB
drift of RF power	B	1		0.0058		rectangular	4.34	dB	2.5E-02	dB
calibration of attenuator	B	96.094825		2.21266511		normal	0.05	dB	1.0E-01	dB
septum height of the TEM-cell	B	0.2945	m	0.0025	m	normal	-29.49	dB/m	7.4E-02	dB
standing waves inside TEM-cell	B	1		0.019		u-shaped	8.69	dB	1.7E-01	dB
influence of field-probe	B	1		0.02		rectangular	-8.69	dB	1.7E-01	dB
inhomogeneity of field	B	1		0.012		rectangular	8.69	dB	1.0E-01	dB
sensitivity against e-field	B	1		0.00653595		rectangular	-8.69	dB	5.7E-02	dB
Total Uncertainty (k=2)									0.62	dB

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Uncertainty budget @ the frequency of 30 MHz

Source of uncertainty	Type	Value x_i		Standard Uncertainty $u(x_i)$		Probability distribution	Sensitivity coefficient c_i		Standard Uncertainty $u_i(y)$	
zero offset & noise of power meter	A	0.05719983	W	1.10E-08	W	normal	75.93	dB/W	8.4E-07	dB
calibration of power meter	B	1.00772046		0.002025		normal	4.31	dB	8.7E-03	dB
mismatch of attenuator & power meter	B	1		0.02		u-shaped	4.34	dB	8.7E-02	dB
drift of RF power	B	1		0.0058		rectangular	4.34	dB	2.5E-02	dB
calibration of attenuator	B	96.2941713		2.21725523		normal	0.05	dB	1.0E-01	dB
septum height of the TEM-cell	B	0.2945	m	0.0025	m	normal	-29.49	dB/m	7.4E-02	dB
standing waves inside TEM-cell	B	1		0.019		u-shaped	8.69	dB	1.7E-01	dB
influence of field-probe	B	1		0.02		rectangular	-8.69	dB	1.7E-01	dB
inhomogeneity of field	B	1		0.012		rectangular	8.69	dB	1.0E-01	dB
sensitivity against e-field	B	1		0.00660066		rectangular	-8.69	dB	5.7E-02	dB
Total Uncertainty (k=2)									0.62	dB

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B.4. INRIM Measurement Results and Uncertainty Budgets

Measurement Report for EURAMET.EM.RF-S46 (EURAMET Project No: 1538) Supplementary Comparison

1. Participant Information

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2. Measurement Date

Measurement Dates	From 16 February to 15 March 2023

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3. Environmental Condition

Temperature (°C)	23±1 (53 Hz to 400 kHz) From 21.7 to 23.2 (500 kHz to 30 MHz)
Relative Humidity (%rh)	From 45 to 60 (53 Hz to 400 kHz) From 26 to 40 (500 kHz to 30 MHz)

4. References Used In Measurement

Name of Equipment	Manufacturer	Type / Model	Serial No
Helmholtz coil 1	INRIM	Helm1	95.91 99.91
Helmholtz coil 2	INRIM	Helm2	434.06
Digital multimeter AT1	Agilent	3458A	US28032486
Digital multimeter FL1	Fluke	8508A	291868839
Standard resistor 100 Ω	Tinsley	1659	257388
Standard resistor 1 Ω	Tinsley	1659	257383
Standard resistor 0.050 Ω	Tinsley	1682	263889
AC current shunt 10 Ω	Guildline	7350	72970
Magnetic field meter	Monitor industries	AC 42B-1	1262
RF Signal generator	Rohde & Schwarz	SML 03	100309
RF Power amplifier	Amplifier Research	10W1000C	300641
TEM cell	Amplifier Research	TC3020	11908
Coaxial attenuator	Narda	768-20	8101
Coaxial attenuator	Agilent Technologies	8491B 20 dB	51487
RF Power meter	Rohde & Schwarz	NRVD	100090
RF Power sensor	Rohde & Schwarz	NRV-Z51	839917/0028

5. Measurement Procedure

Two different calibration methods were used: one for the lower frequency range (52 Hz to 300 kHz) and one for the higher frequency range (500 kHz to 30 MHz), as detailed in the following subsections.

5.1 Measurement Procedure 1 (53 Hz to 300 kHz)

From 52 Hz to 300 kHz the travelling standard Narda Safety test solution/ ELT probe 100 cm^2 (S/N M-1859) with the ELT-400 low frequency field meter (S/N-04509) was calibrated by the INRIM Helmholtz coil systems for the generation of reference magnetic fields.

Two different reference generation and measurement systems (Helm1) and (Helm2) were used for the measurements carried out at 52 Hz and from 400 Hz to 300 kHz respectively. The Correction factor (dB) as defined in the protocol was obtained as the ratio of the measurement value of the generated reference magnetic flux density to the indication provided by the travelling standard.

The generated magnetic flux density was estimated by the product of the system coil constant (generated mag field per unit current) and the current flowing in the coils, measured by a non-inductive resistor and a reference voltmeter. The DC coil constant value of the Helmholtz coil system was determined by means of a Hall effect meter, traceable to the national reference for DC magnetic field and the measurement value of the DC current measurement. Correction factors were introduced to take into account the circuital stray parameter effects as a function of the frequency and the presence of the environmental stray low frequency magnetic field.

The generated reference magnetic flux density is modelled as:

$$B_r = B_0 \cdot h_u \cdot d_{bf} = K_S \cdot \frac{V_m}{Z_{m,f}} \cdot h_u \cdot d_{bf} \qquad f = 52\ \text{Hz} \qquad (1)$$

$$B_r = B_0 \cdot h_u \cdot h_{us,f} \cdot h_{sf} \cdot d_{bf} = K_S \cdot \frac{V_m}{Z_{m,f}} \cdot h_u \cdot h_{us,f} \cdot h_{sf} \cdot h_{bf} \qquad f \geq 400\ \text{Hz} \qquad (2)$$

where

B_0 is the generated magnetic flux density in the centre of the coil system;
K_s is the DC coil constant of the Helmoltz coil system;
V_m is the measured voltage drop across the reference shunt;
Z_m is the shunt impedance at the at the frequency f;
h_u is the correction factor for the non-uniformity of the generated magnetic flux density in the correspondence of the probe volume;
$h_{us,t}$ is the correction factor that takes into account the effect of the stray capacitances of the connection cables between the shunt and the coils and those among the coil turns;
h_{sf} takes into account the perturbation introduced by the floor and walls;
h_{bf} is the correction factor that takes into account the stray environmental magnetic field;

The magnetic flux density measurement value is modelled by:

$$B_m = B_L \qquad (3)$$

where: B_L is the indication of the applied magnetic flux density provided by the travelling standard

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The correction factor at each frequency f (CF) is then obtained as:

$$CF = 20 \cdot log_{10} \frac{B_r}{B_m} \tag{4}$$

5.2 Measurement Procedure 2 (500 kHz to 30 MHz)

From 500 kHz to 30 MHz the travelling standard was calibrated by means of the so-called "Standard-Field Method".

The electromagnetic field was produced by means of a synthesized radio-frequency (RF) signal generator, a power amplifier and a transverse electromagnetic (TEM) cell.

The nominal dimensions of the cell employed were the following: length = 2 m; width = 1 m; height = 0,6 m; septum height = 0,30 m.

The field probe was positioned in the centre of the test volume of the TEM cell. Both the H-field probe and the field meter were placed inside the cell during the measurements and the signal was measured with a PC connected to the probe by means of the optical cable. The main axis (handle) of the HF 3061 H-field probe was aligned perpendicular to the electric field lines and to the direction of the wave propagation inside the cell. To investigate the effects of the probe position, an equal number of measurements were carried out positioning the probe in the bottom and top sections of the cell.

In both cases the NBM-550 field meter was positioned with the display pointing up, according to the guidelines provided by the comparison protocol.

In accordance with the requirements of the protocol, the RF power delivered to the TEM cell was adjusted to achieve a magnetic field amplitude inside the cell equal to 0.15 A/m. The actual power flowing through the TEM cell was then measured with a power meter connected to the TEM cell output through two attenuators to reduce the power level by 40 dB.

The correction factor (CF) at each measuring frequency is given by the following expression:

$$CF = \frac{\sqrt{P \cdot Z_0}}{H^r \cdot b \cdot Z_\infty} \cdot c_h \cdot c_{pos} \tag{5}$$

where:

Z_0 is the characteristic impedance of the TEM cell;
P is the net power supplied to the input of the cell at the measuring frequency;
b is the distance between the septum and the top or bottom wall of the cell;
Z_∞ is the free space impedance;
H^r is the indicated magnetic field at the measuring frequency;
c_h is a unitary average correction factor accounting for the non-perfect magnetic field homogeneity in the test volume of the cell;
c_{pos} is a unitary average correction factor accounting for the magnetic field probe positioning.

Since some systematic, albeit small, difference was observed between the measurements performed in the two cell sections (top versus bottom half of the cell), the correction factor closest to the average of all computed factors was selected as a "reference" value and shown in Table 6 for each frequency in the range from 500 kHz to 30 MHz. The other values were exploited to evaluate the uncertainty associated with the above mentioned factor c_{pos}.

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6. Measurement Results

Frequency	Level for Magnetic Field Measurements	Correction Factor (dB)	Measurement Uncertainty (dB) (k=2)
53 Hz	10 µT	0.13	0.03
	100 µT	0.13	0.03
	300 µT	0.14	0.03
	1000 µT	0.07	0.03
	2000 µT	0.08	0.03
400 Hz	10 µT	0.08	0.03
10 kHz	10 µT	0.10	0.03
100 kHz	10 µT	0.09	0.04
300 kHz	3 µT	0.24	0.25
500 kHz	0,15 A/m	0.83	0.61
5 MHz	0,15 A/m	-0.07	0.64
10 MHz	0,15 A/m	0.04	0.68
20 MHz	0,15 A/m	0.18	0.80
30 MHz	0,15 A/m	0.14	0.89

7. Detailed Uncertainty Budget

Uncertainty budget 53 Hz						
Source of uncertainty	Type	Value	Probability distribution	k-factor	Sensitivity coefficient	Standard Uncertainty (dB)
V_m	B	0.00150	Uniform	1.732	1	0.0075
K_s	B	0.00251	Normal	2	1	0.0109
Z_m	B	0.00173	Normal	2	1	0.0075
h_u	B	0.00122	Uniform	1.732	1	0.0061
h_{ref}	B	0.00000	Uniform	1.732	1	0.0000
$h_{ef}t$	B	0.00000	Uniform	1.732	1	0.0000
B_n	B	0.0001	Uniform	1.732	1	0.0003
Total Uncertainty (k=2)						0.03 dB

Uncertainty budget @ 10 µT – 400 Hz						
Source of uncertainty	Type	Value	Probability distribution	k-factor	Sensitivity coefficient	Standard Uncertainty (dB)
V_m	B	0.0017	Uniform	2	1	0.0075
K_s	B	0.0025	Normal	2	1	0.0109
Z_m	B	0.0017	Normal	2	1	0.0075
h_u	B	0.0012	Uniform	1.732	1	0.0061
h_{ref}	B	0.0000	Uniform	1.732	1	0.0000
h_{wt} t	B	0.0000	Uniform	1.732	1	0.0000
h_{bt}	B	0.0000	Uniform	1.732	1	0.0000
B_m	B	0.0001	Uniform	1.732	1	0.003
Total Uncertainty (k=2)						0.03 dB

Uncertainty budget @ 10 µT – 10 kHz						
Source of uncertainty	Type	Value	Probability distribution	k-factor	Sensitivity coefficient	Standard Uncertainty (dB)
V_m	B	0.00150	Uniform	1.732	1	0.00752
K_s	B	0.00251	Normal	2	1	0.0109
Z_m	B	0.00173	Normal	2	1	0.0075
h_u	B	0.00122	Uniform	1.732	1	0.0061
h_{ref}	B	0.00002	Uniform	1.732	1	0.0001
h_{wt} t	B	0.00000	Uniform	1.732	1	0.0000
h_{bt}	B	0.00000	Uniform	1.732	1	0.0000
B_m	B	0.0001	Uniform	1.732	1	0.0030
Total Uncertainty (k=2)						0.03 dB

8. Detailed Uncertainty Budget

Uncertainty budget @ 10 µT – 100 kHz						
Source of uncertainty	Type	Value	Probability distribution	k-factor	Sensitivity coefficient	Standard Uncertainty (dB)
V_m	B	0.00150	Uniform	2	1	0.00752
K_s	B	0.00251	Normal	2	1	0.0109
Z_m	B	0.00173	Normal	2	1	0.0075
h_u	B	0.00122	Uniform	1.732	1	0.0061
$h_{mt,f}$	B	0.00205	Uniform	1.732	1	0.0103
$h_{wf\,t}$	B	0.00100	Uniform	1.732	1	0.005
h_{bf}	B	0.00000	Uniform	1.732	1	0.0000
B_m	B	0.0001	Uniform	1.732	1	0.003
Total Uncertainty (k=2)						0.04 dB

Uncertainty budget @ 3 µT – 300 kHz						
Source of uncertainty	Type	Value	Probability distribution	k-factor	Sensitivity coefficient	Standard Uncertainty (dB)
V_m	B	0.00321	Uniform	1.732	1	0.016
K_s	B	0.00251	Normal	2	1	0.011
Z_m	B	0.00315	Normal	2	1	0.014
h_u	B	0.00122	Uniform	1.732	1	0.0061
$h_{mt,f}$	B	0.02463	Uniform	1.732	1	0.123
$h_{wf\,t}$	B	0.00299	Uniform	1.732	1	0.015
h_{bl}	B	0.00000	Uniform	1.732	1	0.0000
B_m	B	0.00018	Uniform	1.732	1	0.0009
Total Uncertainty (k=2)						0.25 dB

9. Detailed Uncertainty Budget

Uncertainty budget @ the frequency of 0.5 MHz						
Source of uncertainty	Type	Value	Probability distribution	k-factor	Sensitivity coefficient	Standard Uncertainty (dB)
Power Measurement	B	0.03	Normal	2	0.5	0.15
TEM Cell Impedance	B	0.05	Uniform	1.732	0.5	0.26
Magnetic Field Homogeneity	B	0.07	Triangular	2.449	1	0.25
Distance Between TEM Cell Central Section and Shield	B	0.02	Uniform	1.732	1	0.09
Magnetic Field Meter Resolution	B	0.00	Uniform	1.732	1	0.00
Magnetic Field Probe Position	B	0.00	Uniform	1.732	1	0.02
Total Uncertainty (k=2)						0.61 dB

Uncertainty budget @ the frequency of 5 MHz						
Source of uncertainty	Type	Value	Probability distribution	k-factor	Sensitivity coefficient	Standard Uncertainty (dB)
Power Measurement	B	0.03	Normal	2	0.5	0.15
TEM Cell Impedance	B	0.06	Uniform	1.732	0.5	0.31
Magnetic Field Homogeneity	B	0.07	Triangular	2.449	1	0.25
Distance Between TEM Cell Central Section and Shield	B	0.02	Uniform	1.732	1	0.09
Magnetic Field Meter Resolution	B	0.00	Uniform	1.732	1	0.00
Magnetic Field Probe Position	B	0.01	Uniform	1.732	1	0.06
Total Uncertainty (k=2)						0.64 dB

Uncertainty budget @ the frequency of 10 MHz						
Source of uncertainty	Type	Value	Probability distribution	k-factor	Sensitivity coefficient	Standard Uncertainty (dB)
Power Measurement	B	0.03	Normal	2	0.5	0.15
TEM Cell Impedance	B	0.07	Uniform	1.732	0.5	0.36
Magnetic Field Homogeneity	B	0.07	Triangular	2.449	1	0.25
Distance Between TEM Cell Central Section and Shield	B	0.02	Uniform	1.732	1	0.09
Magnetic Field Meter Resolution	B	0.00	Uniform	1.732	1	0.00
Magnetic Field Probe Position	B	0.02	Uniform	1.732	1	0.08
Total Uncertainty (k=2)						0.68 dB

Uncertainty budget @ the frequency of 20 MHz						
Source of uncertainty	Type	Value	Probability distribution	k-factor	Sensitivity coefficient	Standard Uncertainty (dB)
Power Measurement	B	0.03	Normal	2	0.5	0.15
TEM Cell Impedance	B	0.11	Uniform	1.732	0.5	0.53
Magnetic Field Homogeneity	B	0.07	Triangular	2.449	1	0.25
Distance Between TEM Cell Central Section and Shield	B	0.02	Uniform	1.732	1	0.09
Magnetic Field Meter Resolution	B	0.00	Uniform	1.732	1	0.00
Magnetic Field Probe Position	B	0.02	Uniform	1.732	1	0.12
Total Uncertainty (k=2)						0.80 dB

Uncertainty budget @ the frequency of 30 MHz						
Source of uncertainty	Type	Value	Probability distribution	k-factor	Sensitivity coefficient	Standard Uncertainty (dB)
Power Measurement	B	0.03	Normal	2	0.5	0.15
TEM Cell Impedance	B	0.13	Uniform	1.732	0.5	0.64
Magnetic Field Homogeneity	B	0.07	Triangular	2.449	1	0.25
Distance Between TEM Cell Central Section and Shield	B	0.02	Uniform	1.732	1	0.09
Magnetic Field Meter Resolution	B	0.00	Uniform	1.732	1	0.00
Magnetic Field Probe Position	B	0.03	Uniform	1.732	1	0.14
Total Uncertainty (k=2)						0.89 dB

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B.5. GUM Measurement Results and Uncertainty Budgets

Measurement Report for EURAMET.EM.RF-S46 (EURAMET Project No: 1538) Supplementary Comparison

1. Participant Information

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2. Measurement Date

Measurement Dates	27.09.2022 – 30.09.2022

3. Environmental Condition

Temperature (°C)	21,4
Relative Humidity (%rh)	48,9

4. References Used In Measurement

Name of Equipment	Manufacturer	Type / Model	Serial No
Helmholtz coils	GUM	SWOPH 0.6/64	N/8-08-39-038221
Helmholtz coils	GUM	SWOPH 0,4/324	N/8-08-39-038222
Multimeter	Keithley	2015	1068131
Precision AC Shunt	Guildline Instruments	7350-0.1 Ω	73707
Precision AC Shunt	Guildline Instruments	7350-10 Ω	73149
Calibrator	Calmet	C101FK	26290
AF Generator	Rohde & Schwartz	APN04	830742/009
Power Amplifier	ADS	LX-1400	N/8-00-12-038796

5. Measurement Procedure

The diagram of the measuring system is shown in Figure 1.
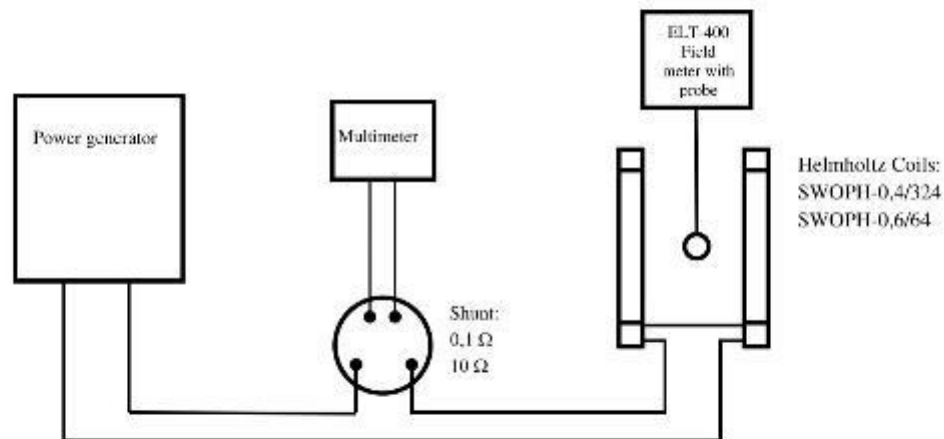
Fig. 1. Schematic diagram of the measuring system

Measurements are performed in a system consisting of a power generator, Helmholtz coils, shunts and a multimeter. After connecting the system and placing the measuring probe inside the coils, the devices are turned on and left for the time necessary to warm up. Then readings are made for the next measurement points. A current of a given frequency is applied as to obtain the reading on the field meter in accordance with the given in protocol. After obtaining a stable indication, the voltage from the multimeter is written down. The actual value of the magnetic field strength is calculated from the formula:

$$H = K \frac{U}{R}$$

where

K – a coil constant (from calibration),

U – a voltage at the shunt,

R – a shunt resistance (from calibration).

Measurements were made at 7 levels from the protocol, 8 voltage readings for each level.

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6. Measurement Results

Frequency	Level for Magnetic Field Measurements	Correction Factor (dB)	Measurement Uncertainty (dB) (k=2)
53 Hz	10 μT	0,154	0,032
	100 μT	0,159	0,035
	300 μT	0,156	0,034
	1000 μT	0,072	0,089
	2000 μT	0,077	0,089
400 Hz	10 μT	0,113	0,032
10 kHz	10 μT	0,190	0,048
100 kHz	10 μT		
300 kHz	3 μT		
500 kHz	0,15 A/m		
5 MHz	0,15 A/m		
10 MHz	0,15 A/m		
20 MHz	0,15 A/m		
30 MHz	0,15 A/m		

7. Detailed Uncertainty Budget

Uncertainty budget @ the frequency of 53 Hz						
Source of uncertainty	Type	Value	Probability distribution	k-factor	Sensitivity coefficient	Standard Uncertainty (dB)
Non-uniformity of field and the probe position	B	0,000971*B @ SWOPH-0,6 0,004634*B @ SWOPH-0,4	normal	2	From $0,004 \frac{1}{\mu T}$ @ 2000 µT to $0,87 \frac{1}{\mu T}$ @ 10 µT	0,00859 @ SWOPH-0,6 0,0406 @ SWOPH-0,4
Effective resolution of the field meter	B	0,00289 µT @ 10 µT 0,0289 µT @ 100 & 300 µT 0,289 µT @ 1000 & 2000 µT	rectangular	1,73	From $-0,87 \frac{1}{\mu T}$ @ 10 µT to $-0,004 \frac{1}{\mu T}$ @ 2000 µT	From 0,000836 to 0,00251
Standard uncertainty of voltage readings	A	From 3,24E-7 V to 3,59E-6 V	Student's T	2	From $16,42 \frac{1}{V}$ @ 10 µT To $164,12 \frac{1}{V}$ @ 100 µT	From 3,04E-5 to 2,50E-4
Voltmeter uncertainty (from calibraition)	B	From 0,010 to 0,018 % of voltmeter indication	normal	2		From 0,00083 to 0,00156
Uncertainty of the coil constant (from calibration)	B	0,289 µT/A @ SWOPH-0,6 3,14 µT/A @ SWOPH-0,4	normal	2	$0,045 \frac{A}{\mu T}$ @ SWOPH-0,6 $0,0054 \frac{A}{\mu T}$ @ SWOPH-0,4	0,0130 @ SWOPH-0,6 0,0169 @ SWOPH-0,4
Uncertainty of the shunt (from calibration)	B	0,0030 Ω @ 10 Ω 0,000075 Ω @ 0,1 Ω	normal	2	$-0,87 \frac{1}{\Omega}$ @ 10 Ω $-86,85 \frac{1}{\Omega}$ @ 0,1 Ω	0,00261 @ 10 Ohm 0,00651 @ 0,1 Ohm
Total Uncertainty (k=2)						From 0,032 to 0,089

Uncertainty budget @ the frequency of 400 Hz						
Source of uncertainty	Type	Value	Probability distribution	k-factor	Sensitivity coefficient	Standard Uncertainty (dB)
Non-uniformity of field and the probe position	B	0,000971*B @ SWOPH-0,6	normal	2	0,87	0,00855 @ SWOPH-0,6
Effective resolution of the field meter	B	0,00289 µT @ 10 µT	rectangular	1,73	-0,87	0,00251
Standard uncertainty of voltage readings	A	1,56E-6 V	Student's T	2	$16,50 \frac{1}{V}$ @ 10 µT	2,57E-5
Voltmeter uncertainty (from calibraition)	B	0,003 % of voltmeter indication	normal	2		0,000269
Uncertainty of the coil constant (from calibration)	B	0,289 µT/A @ SWOPH-0,6	normal	2	$0,045 \frac{A}{\mu T}$	0,0130 @ SWOPH-0,6
Uncertainty of the shunt (from calibration)	B	0,0020 Ω @ 10 Ω	normal	2	$-0,87 \frac{1}{\Omega}$	0,00174 @ 10 Ohm
Total Uncertainty (k=2)						0,032

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Uncertainty budget @ the frequency of 10 kHz						
Source of uncertainty	Type	Value	Probability distribution	k-factor	Sensitivity coefficient	Standard Uncertainty (dB)
Non-uniformity of field and the probe position	B	0,000971*B @ SWOPH-0,6	normal	2	0,87	0,00862 @ SWOPH-0,6
Effective resolution of the field meter	B	0,00289 μT @ 10 μT	rectangular	1,73	-0,87	0,00251
Standard uncertainty of voltage readings	A	2,27E-5 V	Student's T	2	$16,68\,\frac{1}{V}$ @ 10 μT	3,78E-4
Voltmeter uncertainty (from calibraition)	B	0,003 % of voltmeter indication	normal	2		0,000269
Uncertainty of the coil constant (from calibration)	B	0,491 μT/A @ SWOPH-0,6	normal	2	$0,044\,\frac{A}{\mu T}$	0,0217 @ SWOPH-0,6
Uncertainty of the shunt (from calibration)	B	0,0030 Ω @ 10 Ω	normal	2	$-0,87\,\frac{1}{\Omega}$	0,00261 @ 10 Ohm
Total Uncertainty (k=2)						0,048

B.6. SASO NMCC Measurement Results and Uncertainty Budgets

Saudi Standards
Saudi Standards, Metrology and Quality Org.

NMCC
National Measurement & Calibration Center

Report of
EURAMET.EM.RF-S46 Comparison on
Magnetic Field Probe

Saleh A AlMojaewel
Tariq M AlOtaibi

Saudi Standards, Metrology and Quality Organization
National Measurements and Calibration Center
SASO-NMCC

January 2023

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1. Participant Information

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2. Measurement Date

Measurement Dates	12/12/2022 – 25/12/2022

3. Environmental Condition

Temperature (°C)	23 ± 2
Relative Humidity (%rh)	40 ± 10

4. References Used In Measurement

Name of Equipment	Manufacturer	Model	Serial No.
Waveform Generator	KEYSIGHT /Agilent	33500B	MY52301369
Generator Signal	KEYSIGHT /Agilent	N5171B	MY53050854
Oscilloscope	Agilent Technologies	DSO-X3102A	MY54310233
40 dB Attenuator	Aeroflex / Weinschel	45-40-34	SK826
Directional Coupler	BONN Elektronik	BDC0125-40/500	149823A
Power meter	Rohde & Schwarz	NRP2	103679-MM
Power Sensor	Rohde & Schwarz	NRP-Z55	130469

Power Sensor	Rohde & Schwarz	NRP-Z55	130452-YI
50 Ohm Load	Pasternack	PE6189	001
50 Ohm Load	Pasternack	PE6189	002
TEM CELL	IFI	CC102SEXX	S1764-1014
(TURN 12) Helmholtz Coil	UME	------	HOZ-002
(TURN 36) Helmholtz Coil	UME	------	HOZ-003
AF Amplifier	BRYSTON	7B-SST2-19	7BSSTr2-002953
AF Amplifier	AR	200A400A	0343212

5. Measurement Procedure

5.1 Magnetic field measurement for 53 Hz, 400hz, 10 kHz, 100 kHz, 300 kHz

The measurement was performed in accordance with the IEEE 1309:2005 by using a pair of Helmholtz coils. The magnetic field value at the center of the Helmholtz coil was calculated by using Equation 1. The resistor (50 Ω) was connected in series with the Helmholtz coil. The RMS value of the current flowing through the Helmholtz coil was calculated by using Equation 2. The input impedance of the oscilloscope was adjusted 1 MΩ. The measurement setup is depicted in Figures 1 and 2.

$$H = \frac{N_1 I r_1^2}{2(r_1^2 + a_1^2)^{3/2}} + \frac{N_2 I r_2^2}{2(r_2^2 + a_2^2)^{3/2}} \quad A/m \qquad (1)$$

$$I = \frac{V}{R} \qquad (2)$$

Where;

H: the magnetic field strength value at the center of the Helmholtz coil (A/m)

I : The current in the Helmholtz coil (A)

V: The output voltage across the 50 Ω load (V)

N: The number of turns on each coil

r: The radius of each coil (m)

a: The axial position of the magnetic field (m) from the center of the coil set.
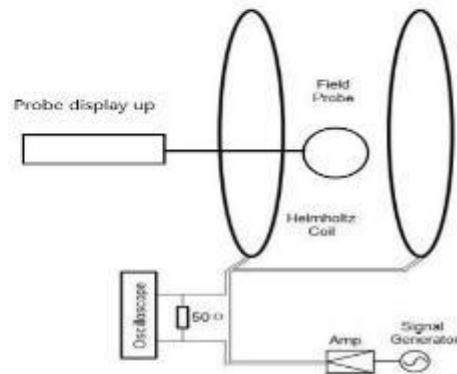
Figure 1. Schematic view of the magnetic field measurement for (53Hz,400Hz,10kHz)
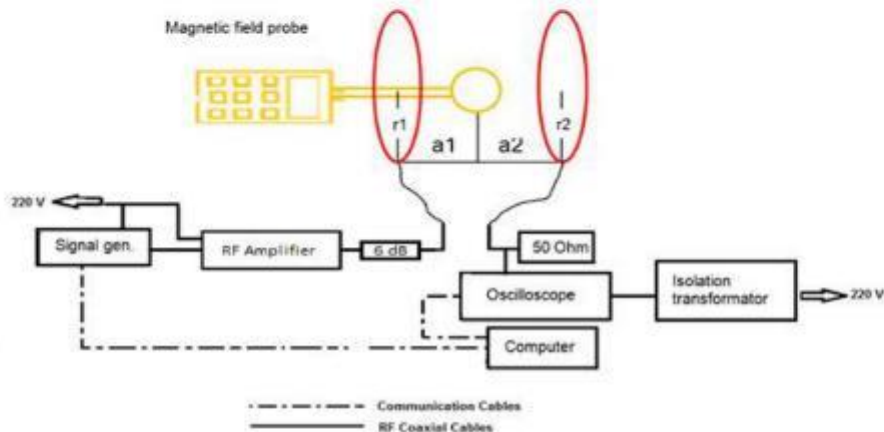
Figure 2. Schematic view of the magnetic field measurement for (100kHz,300kHz)

5.2 Magnetic field measurement for 500 kHz, 5 MHz, 10 MHz, 20 MHz, 30 MHz

The measurements were performed in accordance to the IEEE 1309:2005 Calibration Method B using calculated field strength. In the frequency range 400 kHz to 100 MHz two Transverse Electromagnetic (TEM) cell were used to generate a calculable magnetic field level. The calculable magnetic field was calculated from the dimensions of the TEM cell, its impedance, and from the net power of the TEM Cell input as shown in the following equations :

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$$E = \frac{\sqrt{P_{net}Z_0}}{b} \; V/m \tag{3}$$

$$H = \frac{E}{377} \; A/m \tag{4}$$

Where;

E: RMS Electric field strength (V/m)

H: Magnetic field strength (A/m)

P_{net}: Net power of the TEM Cell input/output (W)

Z_0: The real part of the characteristic impedance of the TEM Cell (Ω)

b: The distance from the upper wall to the center plate (m)
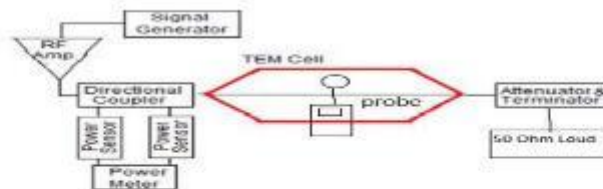
Figure 3. Schematic view of the magnetic field measurement using TEM Cell

6. Measurement Results

Frequency	Level for Magnetic Field Measurements	Correction Factor (dB)	Measurement Uncertainty (dB) (k=2)
53 Hz	10 µT	0.172	0.740
	100 µT	0.257	0.740
	300 µT	--	--
	1000 µT	--	--
	2000 µT	--	--
400 Hz	10 µT	0.172	0.740
10 kHz	10 µT	0.172	0.740
100 kHz	10 µT	0.172	0.740
300 kHz	3 µT	0.424	0.740
500 kHz	0.15 A/m	0.506	0.580

5 MHz	0.15 A/m	-0.175	0.580
10 MHz	0.15 A/m	0.086	0.580
20 MHz	0.15 A/m	0.086	0.580
30 MHz	0.15 A/m	0.086	0.580

7. Uncertainty Budget

A: Model function for (10 µT,100 µT) level field and 53 Hz, 400 Hz, 10kHz, 100kHz, 300kHz frequencies :

$$U_H = U_{frm} + U_{Sgn} + U_{Osc} + U_{Res} + U_{Cl} + U_{Unn} + U_{Prob} + U_{Refle} + U_{PosError} + U_{Mismatch} + U_{Dia} + U_{Datav} + U_{Rept}$$

A-1: Uncertainty budget @ 53 Hz (10 µT)

Component symbol	Source of uncertainty	Unit	Uncertainty Value (+/-)(Uxi)	Probability Distribution	Divisor (PDF)	Sensitivity Coefficient (Ci)	Variances
U$_{Frm}$	Formula error from magnetic field calculation	dB	0.10	Rectangular	1,732	1	0.003
U$_{Sgn}$	Signal generator drift error	dB	0.20	Rectangular	1,732	1	0.013
U$_{Osc}$	Oscilloscope reading error	dB	0.20	Rectangular	1,732	1	0.013
U$_{Res}$	Error from resistor	dB	0.20	Normal	2	1	0.010
U$_{Cl}$	Cable loss error	dB	0.15	Rectangular	1,732	1	0.008
U$_{Unn}$	Non-uniformity field error from Helmholtz coil	dB	0.10	Rectangular	1,732	1	0.003
U$_{Prob}$	Non-uniformity field error from probe	dB	0.20	Rectangular	1,732	1	0.013
U$_{Refle}$	Error from non ideal calibration field	dB	0.15	Rectangular	1,732	1	0.004
U$_{PosError}$	Probe position error	dB	0.20	Rectangular	1.732	1	0.013
U$_{Mismatch}$	Impedance mismatch	dB	0.20	U type	1,414	1	0.020
U$_{Dia}$	Error from dimension and diameter of Helmholtz coil	dB	0.25	Rectangular	1,732	1	0.021
U$_{Datav}$	Error from helmholtz coil heating	dB	0.20	Rectangular	1,732	1	0.013
U$_{Rept}$	Repeatibility	dB	0.007	Normal	1	1	0.000
Total Variance (U$_B$)^2							**0.14 dB^2**
Combined Uncertainty (U$_B$)							**0.37 dB**
Expanded Uncertainty (U$_H$) (k=2, cl=%95)							**0.74 dB**

A-2: Uncertainty budget @ 53 Hz (100 µT)

Component symbol	Source of Uncertainty	Unit	Uncertainty Value (+/-) (Uxi)	Probability Distribution	Divisor (PDF)	Sensitivity Coefficient (Ci)	Variances
U_{Frm}	Formula error from magnetic field calculation	dB	0.10	Rectangular	1,732	1	0.003
U_{Sga}	Signal generator drift error	dB	0.20	Rectangular	1,732	1	0.013
U_{Osc}	Oscilloscope reading error	dB	0.20	Rectangular	1,732	1	0.013
U_{Res}	Error from resistor	dB	0.20	Normal	2	1	0.010
U_{Cl}	Cable loss error	dB	0.15	Rectangular	1,732	1	0.008
U_{Uni}	Non-uniformity field error from Helmholtz coil	dB	0.10	Rectangular	1,732	1	0.003
U_{Prob}	Non-uniformity field error from probe	dB	0.20	Rectangular	1,732	1	0.013
U_{Refie}	Error from non ideal calibration field	dB	0.15	Rectangular	1,732	1	0.004
$U_{PosError}$	Probe position error	dB	0.20	Rectangular	1.732	1	0.013
$U_{Mismatch}$	Impedance mismatch	dB	0.20	U type	1,414	1	0.020
U_{Dist}	Error from dimension and diameter of Helmholtz coil	dB	0.25	Rectangular	1,732	1	0.021
U_{Distor}	Error from helmholtz coil heating	dB	0.20	Rectangular	1,732	1	0.013
U_{Rept}	Repeatibility	dB	0.009	Normal	1	1	0.000
Total Variance (Un)²							0.14 dB²
Combined Uncertainty (U$_{II}$)							0.37 dB
Expanded Uncertainty (U$_{R}$) (k=2, cl=%95)							0.74 dB

A-3: Uncertainty budget @ 400 Hz (10 μT)

Component symbol	Source of Uncertainty	Unit	Uncertainty Value (+/-) (Uxi)	Probability Distribution	Divisor (PDF)	Sensitivity Coefficient (Ci)	Variances
U_{Frm}	Formula error from magnetic field calculation	dB	0.10	Rectangular	1.732	1	0.003
U_{Sgn}	Signal generator drift error	dB	0.20	Rectangular	1.732	1	0.013
U_{Osc}	Oscilloscope reading error	dB	0.20	Rectangular	1.732	1	0.013
U_{Res}	Error from resistor	dB	0.20	Normal	2	1	0.010
U_{Cl}	Cable loss error	dB	0.15	Rectangular	1.732	1	0.008
U_{Uni}	Non-uniformity field error from Helmholtz coil	dB	0.10	Rectangular	1.732	1	0.003
U_{Prob}	Non-uniformity field error from probe	dB	0.20	Rectangular	1.732	1	0.013
U_{Refte}	Error from non ideal calibration field	dB	0.15	Rectangular	1.732	1	0.004
$U_{ProError}$	Probe position error	dB	0.20	Rectangular	1.732	1	0.013
$U_{Mismatch}$	Impedance mismatch	dB	0.20	U type	1.414	1	0.020
U_{Dia}	Error from dimension and diameter of Helmholtz coil	dB	0.25	Rectangular	1.732	1	0.021
U_{Htiour}	Error from helmholtz coil heating	dB	0.20	Rectangular	1.732	1	0.013
U_{Rept}	Repeatibility	dB	0.005	Normal	1	1	0.000
Total Variance $(U_H)^2$						0.14 dB²	
Combined Uncertainty (U_H)						0.37 dB	
Expanded Uncertainty (U_H) (k=2, cl=%95)						0.74 dB	

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A-4: Uncertainty budget @ 10 kHz (10 µT)

Component symbol	Source of uncertainty	Unit	Uncertainty Value (+/-)(Uxi)	Probability Distribution	Divisor (PDF)	Sensitivity Coefficient (Ci)	Variances
U_{Frm}	Formula error from magnetic field calculation	dB	0.10	Rectangular	1,732	1	0.003
U_{Sgn}	Signal generator drift error	dB	0.20	Rectangular	1,732	1	0.013
U_{Osc}	Oscilloscope reading error	dB	0.20	Rectangular	1,732	1	0.013
U_{Res}	Error from resistor	dB	0.20	Normal	2	1	0.010
U_{Cl}	Cable loss error	dB	0.15	Rectangular	1,732	1	0.008
U_{Um}	Non-uniformity field error from Helmholtz coil	dB	0.10	Rectangular	1,732	1	0.003
U_{Prob}	Non-uniformity field error from probe	dB	0.20	Rectangular	1,732	1	0.013
U_{Refle}	Error from non ideal calibration field	dB	0.15	Rectangular	1,732	1	0.004
$U_{PosError}$	Probe position error	dB	0.20	Rectangular	1,732	1	0.013
$U_{Mismatch}$	Impedance mismatch	dB	0.20	U type	1,414	1	0.020
U_{Dia}	Error from dimension and diameter of Helmholtz coil	dB	0.25	Rectangular	1,732	1	0.021
U_{Heat}	Error from helmholtz coil heating	dB	0.20	Rectangular	1,732	1	0.013
U_{Rept}	Repeatibility	dB	0.002	Normal	1	1	0.000
Total Variance (UH)2							0.14 dB2
Combined Uncertainty (UH)							0.37 dB
Expanded Uncertainty (UH) (k=2, cl=%95)							0.74 dB

A-5: Uncertainty budget @ 100 kHz (10 µT)

Component symbol	Source of uncertainty	Unit	Uncertainty Value (+/-)(Uxi)	Probability Distribution	Divisor (PDF)	Sensitivity Coefficient (Ci)	Variances
U_{Frm}	Formula error from magnetic field calculation	dB	0.10	Rectangular	1,732	1	0.003
U_{Sgn}	Signal generator drift error	dB	0.20	Rectangular	1,732	1	0.013
U_{Osc}	Oscilloscope reading error	dB	0.20	Rectangular	1,732	1	0.013
U_{Res}	Error from resistor	dB	0.20	Normal	2	1	0.010
U_{Cl}	Cable loss error	dB	0.15	Rectangular	1,732	1	0.008
U_{Lm}	Non-uniformity field error from Helmholtz coil	dB	0.10	Rectangular	1,732	1	0.003
U_{Prob}	Non-uniformity field error from probe	dB	0.20	Rectangular	1,732	1	0.013
U_{Refle}	Error from non ideal calibration field	dB	0.15	Rectangular	1,732	1	0.004
$U_{PosError}$	Probe position error	dB	0.20	Rectangular	1,732	1	0.013
$U_{Mismatch}$	Impedance mismatch	dB	0.20	U type	1,414	1	0.020
U_{Dia}	Error from dimension and diameter of Helmholtz coil	dB	0.25	Rectangular	1,732	1	0.021
U_{Dissor}	Error from helmholtz coil heating	dB	0.20	Rectangular	1,732	1	0.013
U_{Rept}	Repeatibility	dB	0.005	Normal	1	1	0.000
Total Variance (UH)2							0.14 dB²
Combined Uncertainty (UH)							0.37 dB
Expanded Uncertainty (UH) (k=2, cl=%95)							0.74 dB

A-6: Uncertainty budget @ 300 kHz (3 µT)

Component symbol	Source of uncertainty	Unit	Uncertainty Value (+/-)(Uxi)	Probability Distribution	Divisor (PDF)	Sensitivity Coefficient (Ci)	Variances
U_{Frm}	Formula error from magnetic field calculation	dB	0.10	Rectangular	1,732	1	0.003
U_{Sgn}	Signal generator drift error	dB	0.20	Rectangular	1,732	1	0.013
U_{Osc}	Oscilloscope reading error	dB	0.20	Rectangular	1,732	1	0.013
U_{Res}	Error from resistor	dB	0.20	Normal	2	1	0.010
U_{Cl}	Cable loss error	dB	0.15	Rectangular	1,732	1	0.008
U_{Lm}	Non-uniformity field error from Helmholtz coil	dB	0.10	Rectangular	1,732	1	0.003
U_{Prob}	Non-uniformity field error from probe	dB	0.20	Rectangular	1,732	1	0.013
U_{Refle}	Error from non ideal calibration field	dB	0.15	Rectangular	1,732	1	0.004
$U_{PosError}$	Probe position error	dB	0.20	Rectangular	1,732	1	0.013
$U_{Mismatch}$	Impedance mismatch	dB	0.20	U type	1,414	1	0.020
U_{Dia}	Error from dimension and diameter of Helmholtz coil	dB	0.25	Rectangular	1,732	1	0.021
U_{Heater}	Error from helmholtz coil heating	dB	0.20	Rectangular	1,732	1	0.013
U_{Rept}	Repeatibility	dB	0.002	Normal	1	1	0.000
Total Variance (UH)2							0.14 dB²
Combined Uncertainty (UH)							0.37 dB
Expanded Uncertainty (UH) (k=2, cl=%95)							0.74 dB

B: Model function for 0.15 A/m level field and 500 kHz, 5 MHz, 10 MHz, 20MHz, 30MHz frequencies :

$$U_H = U_{PowMet} + U_{PowSen} + U_{TEMZ} + U_{Dist} + U_{Mismatch} + U_{PosError} + U_{TEM} + U_{Prob} + U_{DCoup} + U_{Rept}$$

B-1: Uncertainty budget @ 500 kHz (0.15 A/m)

Component symbol	Source of uncertainty	Unit	Uncertainty Value	Probability Distribution	Divisor	Sensitivity Coefficient (Ci)	Variances
U_{PowMet}	Power meter	dB	0.17	Rectangular	1,732	1	0.010
U_{PowSen}	Power sensor	dB	0.10	Normal	2	1	0.003
U_{TEMZ}	TEM cell impedance	dB	0.20	Rectangular	1,732	1	0.013
U_{Dist}	Distance	dB	0.20	Rectangular	1,732	1	0.013
$U_{Mismatch}$	Impedance mismatch	dB	0.18	U-Shaped	1,414	1	0.016
$U_{PosError}$	Position error	dB	0.19	Rectangular	1,732	1	0.012
U_{TEM}	TEM cell	dB	0.12	Rectangular	1,732	1	0.005
U_{Prob}	Probe	dB	0.11	Rectangular	1,732	1	0.004
U_{DCoup}	Coupler	dB	0.15	Normal	2	1	0.006
U_{Rept}	Repeatability	dB	0.01	Normal	1	1	0.000
Total Variance (UH)2							**0.08 dB²**
Combined Uncertainty (UH)							**0.29 dB**
Expanded Uncertainty (UH) (k=2, cl=%95)							**0.58 dB**

B-2: Uncertainty budget @ 5 MHz (0.15 A/m)

Component symbol	Source of uncertainty	Unit	Uncertainty Value	Probability Distribution	Divisor	Sensitivity Coefficient (Ci)	Variances
U_{PowMet}	Power meter	dB	0.17	Rectangular	1,732	1	0.010
U_{PowSen}	Power sensor	dB	0.10	Normal	2	1	0.003
U_{TEMZ}	TEM cell impedance	dB	0.20	Rectangular	1,732	1	0.013
U_{Dist}	Distance	dB	0.20	Rectangular	1,732	1	0.013
$U_{Mismatch}$	Impedance mismatch	dB	0.18	U-Shaped	1,414	1	0.016
$U_{PosError}$	Position error	dB	0.19	Rectangular	1,732	1	0.012
U_{TEM}	TEM cell	dB	0.12	Rectangular	1,732	1	0.005
U_{Prob}	Probe	dB	0.11	Rectangular	1,732	1	0.004
U_{DCoup}	Coupler	dB	0.15	Normal	2	1	0.006
U_{Rept}	Repeatability	dB	0.01	Normal	1	1	0.000
Total Variance (UH)2							0.08 dB²
Combined Uncertainty (UH)							0.29 dB
Expanded Uncertainty (UH) (k=2, cl=%95)							0.58 dB

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B-3: Uncertainty budget @ 10 MHz (0.15 A/m)

Component symbol	Source of uncertainty	Unit	Uncertainty Value	Probability Distribution	Divisor	Sensitivity Coefficient (Ci)	Variances
U_{PowMet}	Power meter	dB	0.17	Rectangular	1,732	1	0.010
U_{PowSen}	Power sensor	dB	0.10	Normal	2	1	0.003
U_{TEMZ}	TEM cell impedance	dB	0.20	Rectangular	1,732	1	0.013
U_{Dist}	Distance	dB	0.20	Rectangular	1,732	1	0.013
$U_{Mismatch}$	Impedance mismatch	dB	0.18	U-Shaped	1,414	1	0.016
$U_{PosError}$	Position error	dB	0.19	Rectangular	1,732	1	0.012
U_{TEM}	TEM cell	dB	0.12	Rectangular	1,732	1	0.005
U_{Prob}	Probe	dB	0.11	Rectangular	1,732	1	0.004
U_{DCoup}	Coupler	dB	0.15	Normal	2	1	0.006
U_{Rep}	Repeatability	dB	0.02	Normal	1	1	0.000
Total Variance (UH)2							0.08 dB^2
Combined Uncertainty (UH)							0.29 dB
Expanded Uncertainty (UH) (k=2, cl=%95)							0.58 dB

B-4: Uncertainty budget @ 20 MHz (0.15 A/m)

Component symbol	Source of uncertainty	Unit	Uncertainty Value	Probability Distribution	Divisor	Sensitivity Coefficient (Ci)	Variances
U_{PowMet}	Power meter	dB	0.17	Rectangular	1,732	1	0.010
U_{PowSen}	Power sensor	dB	0.10	Normal	2	1	0.003
U_{TEMZ}	TEM cell impedance	dB	0.20	Rectangular	1,732	1	0.013
U_{Dist}	Distance	dB	0.20	Rectangular	1,732	1	0.013
$U_{Mismatch}$	Impedance mismatch	dB	0.18	U-Shaped	1,414	1	0.016
$U_{PosErnr}$	Position error	dB	0.19	Rectangular	1,732	1	0.012
U_{TEM}	TEM cell	dB	0.12	Rectangular	1,732	1	0.005
U_{Prob}	Probe	dB	0.11	Rectangular	1,732	1	0.004
U_{DCoup}	Coupler	dB	0.15	Normal	2	1	0.006
U_{Rept}	Repeatability	dB	0.01	Normal	1	1	0.000
Total Variance (UH)2							0.08 dB^2
Combined Uncertainty (UH)							0.29 dB
Expanded Uncertainty (UH) (k=2, cl=%95)							0.58 dB

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B-5: Uncertainty budget @ 30 MHz (0.15 A/m)

Component symbol	Source of uncertainty	Unit	Uncertainty Value	Probability Distribution	Divisor	Sensitivity Coefficient (Ci)	Variances
U_{PowMet}	Power meter	dB	0.17	Rectangular	1.732	1	0.010
U_{PowSen}	Power sensor	dB	0.10	Normal	2	1	0.003
U_{TEMZ}	TEM cell impedance	dB	0.20	Rectangular	1.732	1	0.013
U_{Dist}	Distance	dB	0.20	Rectangular	1.732	1	0.013
$U_{Mismatch}$	Impedance mismatch	dB	0.18	U-Shaped	1.414	1	0.016
$U_{PosError}$	Position error	dB	0.19	Rectangular	1.732	1	0.012
U_{TEM}	TEM cell	dB	0.12	Rectangular	1.732	1	0.005
U_{Prob}	Probe	dB	0.11	Rectangular	1.732	1	0.004
U_{DCoup}	Coupler	dB	0.15	Normal	2	1	0.006
U_{Rept}	Repeatability	dB	0.01	Normal	1	1	0.000
Total Variance (UH)2							0.08 dB²
Combined Uncertainty (UH)							0.29 dB
Expanded Uncertainty (UH) (k=2, cl=%95)							0.58 dB

B.7. RISE Measurement Results and Uncertainty Budgets

Measurement Report for EURAMET.EM.RF-S46 (EURAMET Project No: 1538) Supplementary Comparison

1. Participant Information

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2. Measurement Date

Measurement Dates	................2022-10-15.................	–
	.........2022-10-16....................	

3. Environmental Condition

Temperature (°C)	23.7
Relative Humidity (%rh)	35.7

4. References Used In Measurement

Name of Equipment	Manufacturer	Type / Model	Serial No
TEM-cell	RISE	-	RISE inv. Nr: 503 897
Signal Generator	Rohde&Schwarz	SMT 06	844279/006
Power amplifier	Amplifier Research	200A400	0346313
Power meter	Boonton	4242RF	14793
Power sensor1	Boonton	51015-EF	35916
Power sensor2	Boonton	51015-EF	35917
Termination	Inmet	TN020F-300W	RISE inv. Nr: KWP01299
Temperature meter	Testo	615	RISE inv. Nr: 503498

5. Measurement Procedure

The method generates a traceable electromagnetic field inside a TEM-cell. The field is known from calculations and the test object is placed in this known field. The following setup is used
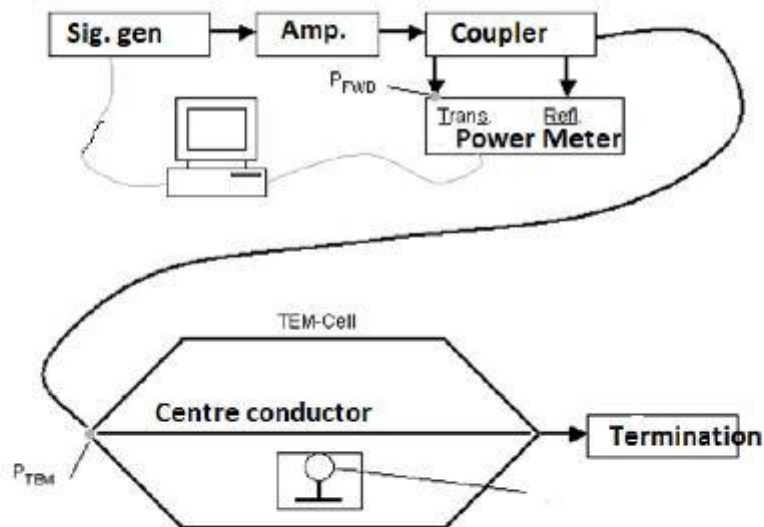
The field strength in the TEM-cell is calculated as:

$$B_{actual} = Z_L^{1/2} * Z_0^{-1} * \left(P_{FWD} \frac{P_2}{P_1}\right)^{\frac{1}{2}} T_{TEM}^{\frac{1}{4}} * d^{-1} * \delta(x,y,z)^1 * corr \qquad (5)$$

where:

Z_L =Characteristic impedance of the TEM-cell.

Z_0 =Free space impedance.

P_{FWD} =Power output from the amplifier (measured at the power forward on the

directional coupler), absolute power measurement.

P_1 =Forward power of the directional coupler, relative power measurement.

P_2 =Power after directional coupler and cable, relative power measurement.

T_{TEM} =Loss through TEM-cell, relative power measurement.

d   =Distance between centre conductor and floor.

$\delta(x, y, z)$: =Uncertainty from location errors in x, y and z-directions.

corr: =Correction factor caused by impedance mismatch of TEM cell.

The power is measured with a power meter calibrated with traceability to other national measurement institutes (last calibration at METAS, Switzerland). The impedance (S11) is measured using a network analyzer calibrated with traceability to the manufacturer Rohde & Schwarz, using a calibration kit with traceability to RISE NMI (CMC for S-parameters). The distance is measured with a laser rangefinder calibrated at RISE, with the traceability to the RISE NMI department for length.

6. Measurement Results

Frequency	Level for Magnetic Field Measurements	Correction Factor (dB)	Measurement Uncertainty (dB) (k=2)
53 Hz	10 µT	-	-
	100 µT	-	-
	300 µT	-	-
	1000 µT	-	-
	2000 µT	-	-
400 Hz	10 µT	-	-
10 kHz	10 µT	0.05*	0.42
100 kHz	10 µT	-0.26*	0.42
300 kHz	3 µT	-0.24*	0.42

500 kHz	0,15 A/m	0.93	0.42
5 MHz	0,15 A/m	-0.03	0.42
10 MHz	0,15 A/m	-0.25	0.42
20 MHz	0,15 A/m	-0.04	0.42
30 MHz	0,15 A/m	-0.77	0.42

*Measured at a level of 0.15 A/m

Our measurement method using a TEM-cell does not work below 10 kHz. This is the reason why no results are presented at 53 Hz and 400 Hz.

7. Detailed Uncertainty Budget

Uncertainty budget @ the frequency of Hz						
Source of uncertainty	Type	Value	Probability distribution	k-factor	Sensitivity coefficient	Standard Uncertainty (dB)
Z_L: Characteristic impedance of the TEM-cell	A	0.08639	Rectangular	$\sqrt{3}$	½	0.02512
P_{FWD}: Power output from the amplifier	A	0.11486	Normal	1	½	0.05781
P_1: Forward power of the directional coupler	A	0.10470	Normal	1	½	0.05266
P_2: Power after directional coupler and cable	A	0.10470	Normal	1	½	0.05266
T_{TEM}: Loss through TEM-cell	A	0.12871	Normal	1	¼	0.03254
d: Distance between centre conductor and floor	A	0.02251	Rectangular	$\sqrt{3}$	1	0.01301
$\delta(x, y, z)$: Uncertainty from location errors	A	0.29373	Rectangular	$\sqrt{3}$	1	0.17200
Corr : Impedance mismatch of TEM cell	A	0.08639	Rectangular	$\sqrt{3}$	1	0.05009
Total Uncertainty (k=2)						0.41059

The budget is valid for all frequencies with results as given in chapter 6.

B.8. METAS Measurement Results and Uncertainty Budgets

Measurement Report for EURAMET.EM.RF-S46 (EURAMET Project No: 1538) Supplementary Comparison

1. Participant Information

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2. Measurement Date

Measurement Dates	21.03.2022........ – ...25.03.2022.............

3. Environmental Condition

Temperature (°C)	23
Relative Humidity (%rh)	45%

4. References Used In Measurement

Name of Equipment	Manufacturer	Type / Model	Serial No
Multimeter	Keithley Instruments SA	2000	0603559
Current Clamp	Pearson	110A	115003
Helmholtz Coil	METAS	Radius 20 cm, 2 windings	MM7107
Helmholtz Coil	METAS	Radius 40 cm, 2 windings	MM8985
Helmholtz Coil	METAS	Radius 50 cm, 78 windings	MM0908
GTEM Cell	MEB Messelektronik	GTEM 1750	11555
Powermeter	Rohde & Schwarz	NRVD	832839/007
Powersensor	Rohde & Schwarz	NRV-Z51	837426/032

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5. Measurement Procedure

The measurement procedure is summarised in the following table:

Frequency	Magnetic flux density	Method	Reference
53 Hz to 400 Hz	10 uT	Helmholtz	Coil with radius 40 cm 2 windings
53 Hz	100 uT to 2000 uT	Helmholtz	Coil with radius 50 cm 78 windings
10 kHz to 300 kHz	3uT to 10 uT	Helmholtz	Coil with radius 20 cm 2 windings
500 kHz to 30 MHz	0.15 A/m	GTEM	-

The calibration in the Helmholtz coil has been obtained using the following equation is:

$$B = CF \cdot I$$

With B being the magnetic flux density, CF the coil factor obtained using geometrical properties of the loop, and I the current. The current was measured with a calibrated voltmeter and with a calibrated current clamp. The following Helmholtz coil has been chosen depending on the frequency and on the field intensity:

The measurements in a GTEM cell of large dimensions (8 m) so that the whole probe can be placed inside. The calibration equation is:

$$H = k_B \cdot \frac{\sqrt{P_{input} \cdot Z_0}}{d \cdot Z_{vaccum}}$$

With

- H is magnetic field intensity
- P_{input} is the input power in the GTEM cell
- Z_0 is the reference impedance: $Z_0 = 50 \, \Omega$
- d is the septum height
- Z_{vaccum} is the impedance of vacuum: $Z_{vaccum} \cong 376.73 \, \Omega$

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- k_B is the calibration factor of the cell obtained from a model the TEM wave propagation in the GTEM cell:

$$k_B = \left| a - b \cdot S_{11} \cdot e^{2\pi \cdot i \cdot 2x \cdot f/c} \right|$$

- S_{11} is the reflection coefficient of the cell, measured with a VNA at the input of the cell
- x is the distance from the tip of the cell to the measurement point
- f is the frequency
- c is the speed of light: $c = 299'782'458$ m/s
- a and b are constants determined by a calibration of the electric field. The experimental measurements are well fitted with the following values: $a = b = 0.97$.

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6. Measurement Results

Frequency	Level for Magnetic Field Measurements	Correction Factor (dB)	Measurement Uncertainty (dB) (k=2)
53 Hz	10 μT	0.15	0.11
	100 μT	0.16	0.13
	300 μT	0.15	0.13
	1000 μT	0.05	0.13
	2000 μT	0.04	0.13
400 Hz	10 μT	0.14	0.11
10 kHz	10 μT	0.13	0.14
100 kHz	10 μT	0.11	0.14
300 kHz	3 μT	0.19	0.35
500 kHz	0,15 A/m	1.56	0.57
5 MHz	0,15 A/m	0.72	0.57
10 MHz	0,15 A/m	0.83	0.57
20 MHz	0,15 A/m	0.84	0.57
30 MHz	0,15 A/m	0.97	0.61

7. Detailed Uncertainty Budget

			Uncertainty budget @ the frequency of 53 Hz and 400 Hz (10 µT)			
Source of uncertainty	Type	Value (%)	Probability distribution	k-factor	Sensitivity coefficient (dB/%)	Standard Uncertainty (dB)
Coil factor	B	0.25	Rectangular	1.73	0.086	0.012
Current clamp factor	B	0.20	Normal	2	0.086	0.009
Voltage Meter	B	0.12	Rectangular	1.73	0.086	0.006
Homogeneity	B	0.04	Rectangular	1.73	0.086	0.002
Restfield	B	1.00	Rectangular	1.73	0.086	0.050
Repeatability	A	0.04	-	1	0.086	0.003
Total Uncertainty (k=2)						0.105

			Uncertainty budget @ the frequency of 53 Hz (100 µT to 2 mT)			
Source of uncertainty	Type	Value (%)	Probability distribution	k-factor	Sensitivity coefficient (dB/%)	Standard Uncertainty (dB)
Coil factor	B	1.20	Rectangular	1.73	0.086	0.060
Current clamp factor	B	0.20	Normal	2	0.086	0.009
Voltage Meter	B	0.12	Rectangular	1.73	0.086	0.006
Homogeneity	B	0.04	Rectangular	1.73	0.086	0.002
Restfield	B	0.26	Rectangular	1.73	0.086	0.013
Repeatability	A	0.20	-	1	0.086	0.017
Total Uncertainty (k=2)						0.129

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Uncertainty budget @ the frequency of 10 kHz and 100 kHz (10 µT)						
Source of uncertainty	Type	Value (%)	Probability distribution	k-factor	Sensitivity coefficient (dB/%)	Standard Uncertainty (dB)
Coil factor	B	0.50	Rectangular	1.73	0.086	0.025
Current clamp factor	B	0.60	Normal	2	0.086	0.026
Voltage Meter	B	0.12	Rectangular	1.73	0.086	0.006
Homogeneity	B	0.50	Rectangular	1.73	0.086	0.025
Restfield	B	1.00	Rectangular	1.73	0.086	0.050
Repeatability	A	0.10	-	1	0.086	0.009
Total Uncertainty (k=2)						0.134

Uncertainty budget @ the frequency of 300 kHz (3 µT)						
Source of uncertainty	Type	Value (%)	Probability distribution	k-factor	Sensitivity coefficient (dB/%)	Standard Uncertainty (dB)
Coil factor	B	0.50	Rectangular	1.73	0.086	0.025
Current clamp factor	B	0.60	Normal	2	0.086	0.026
Voltage Meter	B	0.12	Rectangular	1.73	0.086	0.006
Homogeneity	B	0.50	Rectangular	1.73	0.086	0.025
Restfield	B	3.33	Rectangular	1.73	0.086	0.166
Repeatability	A	0.10	-	1	0.086	0.009
Total Uncertainty (k=2)						0.343

Uncertainty budget @ the frequency from 500 kHz to 20 MHz (0.15 A/m)						
Source of uncertainty	Type	Value	Probability distribution	k-factor	Sensitivity coefficient	Standard Uncertainty (dB)
Septum height	B	1.0%	Rect.	1.73	0.086 dB/%	0.05
GTEM cal. factor	B	2.0%	Rect.	1.73	0.086 dB/%	0.10
Powermeter	B	0.05 dB	Normal	2	1	0.025
Homogeneity	B	0.3 dB	Rectangular	1.73	1	0.17
Restfield	B	3.33%	Rectangular	1.73	0.086 dB/%	0.17
Repeatability	A	0.10 dB	-	1	0.086 dB/%	0.10
Total Uncertainty (k=2)						0.57

Uncertainty budget @ the frequency from 30 MHz (0.15 A/m)						
Source of uncertainty	Type	Value	Probability distribution	k-factor	Sensitivity coefficient	Standard Uncertainty (dB)
Septum height	B	1.0%	Rect.	1.73	0.086 dB/%	0.05
GTEM cal. factor	B	2.0%	Rect.	1.73	0.086 dB/%	0.10
Powermeter	B	0.05 dB	Normal	2	1	0.025
Homogeneity	B	0.3 dB	Rectangular	1.73	1	0.17
Restfield	B	3.3 %	Rectangular	1.73	0.086 dB/%	0.17
Repeatability	A	0.15	-	1	0.086 dB/%	0.15
Total Uncertainty (k=2)						0.61

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B.9. NPL Measurement Results and Uncertainty Budgets

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Test Report

NARDA ELT-400 EXPOSURE LEVEL TESTER
Type 2304/04, Serial No. O-0450
with 100 cm² B-Field Probe, Serial No. M-1859

The measurement results in this report are traceable to the SI system of units, to units of measurement realised at the National Physical Laboratory or other recognised national metrology institutes, or to other internationally recognised standards. This test report may only be published in full, unless permission for the publication of an approved extract has been obtained in writing from NPL Management Ltd. The data included in this report applies only to those items specifically listed as tested, calibrated or sampled and cannot be used to assign any attributes beyond those shown by the data.

COMPARISON TITLE	COMPARISON OF MAGNETIC FIELD STRENGTH MEASUREMENTS FOR FREQUENCIES UP TO 30 MHz
COMPARISON NO.	EURAMET.EM.RF-S46, (EURAMET Project No. 1538)
PILOT LABORATORY	TÜBİTAK Ulusal Metroloji Enstitüsü (UME) TÜBİTAK Gebze Yerleşkesi Barış Mah. Dr. Zeki Acar Cad. No:1 41470 Gebze-Kocaeli Türkiye

This report details the methodology, results and uncertainties submitted by NPL for the calibration of a commercial magnetic field meter up to a frequency of 100 kHz using the Helmholtz coil method.

Reference: MT.41/23/082/EtM 134.085	Page 1 of 9
Date of Issue: 30 June 2023	Signed: _(signature)_ (Authorised Signatory)
Checked by: _DB_	Name: S A C Harmon on behalf of NPLML

NATIONAL PHYSICAL LABORATORY
Continuation Sheet

1. Participant information

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Telephone no.	+44 20 8943 6908

1.1. Date of measurement

Date of measurement	6 -7 July 2022

1.2. Environmental conditions

Temperature (°C)	21 ± 0.5
Relative humidity (%rh)	56 ± 2

1.3. Significant equipment

Table 1: Significant equipment used during comparison

Equipment	Manufacturer	Type / model	Serial No.
Helmholtz coil	NPL	Low frequency	M138
Helmholtz coil	NPL	Mid frequency	M108 & M139
Helmholtz coil	NPL	High frequency	M162
Current shunt	Holt	250 mA shunt	0943500001025
		2.5 A shunt	0943500001026
		20 A shunt	0943500001308
		50 A shunt	0943500001309
Digital multimeter	Keithley	Model 2001	1124481
Frequency counter	Philips	Model PM6673	SM2257

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1.4. Traceability

All measurement results quoted within this report were made using equipment where there is an unbroken traceability chain to UK national standards held and maintained by NPL.

2. Travelling standard

The travelling standard was supplied by TÜBİTAK UME. A photo of the ELT-400 field meter and magnetic field probe is shown in Figure 1, and the instrument details and instrument specifications are given in Tables 2 and 3 respectively.

Figure 1: ELT-400 Field Meter and ELT 100 cm² Magnetic Field Probe

Table 2: Instrument details

Item	Manufacturer	Serial No.
ELT-400 Low Frequency Field Meter	Narda Safety Test Solutions	O-0450
ELT 100 cm² Magnetic Field Probe	Narda Safety Test Solutions	M-1859

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Table 3: Instrument specifications

Frequency range	10 Hz to 400 kHz
Measurement range	0.5 µT to 160 mT
Noise level	0.24 µT (320 µT, HIGH range)
Power Supply	9 V / 2000 mA

3. Measurement quantities and measurement points

The correction factor, in dB, was determined for each measurement point given in Table 4 based on the ELT-400 indicated field and the actual value of the applied magnetic flux density, using the following relationship:

$$\text{Correction Factor (dB)} = 20 \cdot \log_{10}\left(\frac{\text{Actual Field (µT)}}{\text{Indicated Field (µT)}}\right)$$

Table 4: ELT-400 and 100 cm^2 probe measurement frequencies and field levels

Measurement frequency	Level for Magnetic field measurements	ELT-400 measurement range
53 Hz	10 µT	320 µT – Low
	100 µT	320 µT – High
	300 µT	320 µT – High
	1000 µT	80 mT – Low
	2000 µT	80 mT – Low
400 Hz	10 µT	320 µT – Low
10 kHz	10 µT	320 µT – Low
100 kHz	10 µT	320 µT – Low

Reference: MT.41/23/082/EtM 134.085

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4. Measurement Instructions

4.1. Environmental conditions

The ambient temperature and humidity were recorded, but no corrections were applied for temperature and humidity effects on the reported values.

4.2. Preliminary actions

The ELT-400 was allowed to stabilise in a temperature-controlled laboratory for more than 24 hours prior to the start of the measurements.

- At the start of the measurements, the ELT-400 batteries were fully charged.
- The ELT-400 was turned on for a minimum of 10 minutes prior to the start of the measurements.

4.3. Powering of the instrument

During the measurements, the ELT-400 was not connected to the charging unit.

4.4. Instrument alignment and settings

The magnetic field measurements were performed with the ELT-400 in a fixed position and was not rotated. During the measurements, the display of the ELT-400 was pointing up as shown Figure 2. The ELT-400 instrument settings are given in Table 5.

Figure 2: Position of ELT-400 during measurements

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Checked by: SM. DB

Table 5: ELT-400 instrument settings

Low Cut	Detection	Max Hold
10 Hz	RMS	OFF

5. Measurement procedure

The ELT-400 was set up with its 100 cm^2 probe positioned in a region of uniform magnetic field at the centre of a calibrated Helmholtz coil system. The probe was aligned as defined in section 4.4.

The current in the Helmholtz coil system was adjusted to produce a series of indicated magnetic flux densities on the instrument at various frequencies. The current waveform was sinusoidal. The instrument readings were recorded, and the actual values of magnetic flux density were calculated from the measured currents.

6. Results

With no current passing through the Helmholtz coil system, the instrument indicated a scatter with the maximum indicated values observed given in Table 6.

Table 6: Instrument indication with no field applied

Measurement range	Instrument indication (μT)
320 μT – Low	0.042
320 μT – High	0.231
80 mT – Low	7.50

Instrument indications and corresponding correction factors at each frequency are given in Table 7, along with the measurement uncertainties.

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Table 7: Comparison values submitted

Frequency	Instrument indication (µT)	Correction factor (dB)	Measurement uncertainty (dB)
53 Hz	10.00	0.1340	0.017
	100.0	0.1313	0.017
	300.0	0.1336	0.017
	1000	0.0600	0.017
	2000	0.0692	0.017
400 Hz	10.00	0.0895	0.017
10 kHz	10.00	0.1014	0.022
100 kHz	10.00	0.0781	0.104

The reported expanded uncertainties given in Table 7 are based on a standard uncertainty multiplied by a coverage factor $k = 2$, providing a coverage probability of approximately 95%. The quoted uncertainties apply only to the measured values and do not carry any implication as to the long-term stability of the instrument.

7. Declaration of compatibility with published CMC

NPL declares that the results reported for this comparison are consistent with the published Calibration Measurement Capabilities (CMC) in the KCDB.

Shown in Table 8 are the reported expanded uncertainties given in Table 7 compared to the best measurement capabilities (BMC) published in the CMC. The CMC entries match NPL's ISO 17025 UKAS accredited BMC values.

The expanded uncertainty given at a frequency 100 kHz is higher than the published CMC, this is due to the probe size of this specific instrument leading to a higher uncertainty contribution for the non-uniformity of the field.

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Table 8: Comparison of reported uncertainties to CMC / ISO 17025 BMC's

	Frequency		
	53 Hz	10 kHz	100 kHz
Expanded uncertainty, k=2 (%)	0.20	0.25	1.2
Expanded uncertainty, k=2 (dB)	0.017	0.022	0.104
CMC / UKAS ISO 17025 BMC (%)	0.25	0.25	0.70
CMC / UKAS ISO 17025 BMC (dB)	0.022	0.022	0.061

8. Detailed uncertainty budgets

Detailed uncertainty budgets for frequencies of 53 Hz, 10 kHz and 100 kHz are given in Tables 9, 10, and 11 respectively.

Table 9: Uncertainty budget at a frequency of 53 Hz

Source of Uncertainty	Type	Value (%)	Probability distribution	Divisor	c_i	u_i (%)	V_i or V_{eff}
Calibration of Helmholtz coil	B	0.030	normal	2	1	0.0150	inf.
DMM calibration (shunt)	B	0.0715	normal	2	1	0.0358	Inf.
DMM uncertainty (shunt)	B	0.0127	normal	2	1	0.0064	Inf.
Resolution of shunt voltage	B	0.022	rectangular	1.7321	1	0.0127	inf.
Current shunt uncertainty	B	0.0682	normal	2	1	0.0341	inf.
Measurement of Frequency	B	0.010	rectangular	1.7321	1	0.0058	inf.
Frequency meter uncertainty	B	0.0005	normal	2	1	0.0003	inf.
Probe alignment	B	0.011	rectangular	1.7321	1	0.0064	inf.
Probe displaced from centre of axis	B	0.011	rectangular	1.7321	1	0.0064	inf.
Non-uniformity of field	B	0.061	rectangular	1.7321	1	0.0352	inf.
Instrument resolution	B	0.10	rectangular	1.7321	1	0.0577	inf.
Repeatability of measurement	A	0.0056	normal	1	1	0.0056	12
Combined uncertainty (k = 1)						0.087	702305
Expanded uncertainty (k = 2)						0.174	

Reference: MT.41/23/082/EtM 134.085

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Table 10: Uncertainty budget at a frequency of 10 kHz

Source of Uncertainty	Type	Value (%)	Probability distribution	Divisor	c_i	u_i (%)	v_i or v_{eff}
Calibration of Helmholtz coil	B	0.13	normal	2	1	0.0650	inf.
DMM calibration (shunt)	B	0.1155	normal	2	1	0.0578	inf.
DMM uncertainty (shunt)	B	0.014	normal	2	1	0.0070	inf.
Resolution of shunt voltage	B	0.010	rectangular	1.7321	1	0.0058	inf.
Current shunt uncertainty	B	0.0114	normal	2	1	0.0057	inf.
Measurement of Frequency	B	0.010	rectangular	1.7321	1	0.0058	inf.
Frequency meter uncertainty	B	0.0005	normal	2	1	0.0003	inf.
Probe alignment	B	0.010	rectangular	1.7321	1	0.0058	inf.
Probe displaced from centre of axis	B	0.010	rectangular	1.7321	1	0.0058	inf.
Non-uniformity of field	B	0.07	rectangular	1.7321	1	0.0404	inf.
Instrument resolution	B	0.10	rectangular	1.7321	1	0.0577	inf.
Repeatability of measurement	A	0.0045	normal	1	1	0.0045	16
Combined uncertainty ($k = 1$)						0.113	6.4E+06
Expanded uncertainty ($k = 2$)						0.226	

Table 11: Uncertainty budget at a frequency of 100 kHz

Source of Uncertainty	Type	Value (%)	Probability distribution	Divisor	c_i	u_i (%)	v_i or v_{eff}
Calibration of Helmholtz coil	B	0.60	normal	2	1	0.3000	inf.
DMM calibration (shunt)	B	0.1386	normal	2	1	0.0693	inf.
DMM uncertainty (shunt)	B	0.0499	normal	2	1	0.0250	inf.
Resolution of shunt voltage	B	0.010	rectangular	1.7321	1	0.0058	inf.
Current shunt uncertainty	B	0.0114	normal	2	1	0.0057	inf.
Measurement of Frequency	B	0.010	rectangular	1.7321	1	0.0058	inf.
Frequency meter uncertainty	B	0.0005	normal	2	1	0.0003	inf.
Probe alignment	B	0.010	rectangular	1.7321	1	0.0058	inf.
Probe displaced from centre of axis	B	0.010	rectangular	1.7321	1	0.0058	inf.
Non-uniformity of field	B	0.80	rectangular	1.7321	1	0.4619	inf.
Instrument resolution	B	0.10	rectangular	1.7321	1	0.0577	inf.
Repeatability of measurement	A	0.0025	normal	1	1	0.0025	11
Combined uncertainty ($k = 1$)						0.559	2.7E+10
Expanded uncertainty ($k = 2$)						1.12	

Reference: MT.41/23/082/EtM 134.085

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