Final Report
for the EURAMET-Cooperation in Research (1110):

Determination of Magnetic Properties of Mass Standards

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1. Introduction

In March 2008 during the annual EURAMET TC-M meeting in Bucharest, Romania, it was decided to initiate an interlaboratory comparison concerning the magnetic properties of mass standards within the framework of a "cooperation in research". The Physikalisch-Technische Bundesanstalt (PTB) acted as pilot laboratory for organization, collecting the data and preparing of the reports.

The special aim of this comparison is to compare the results obtained by the participating laboratories when measuring the volume magnetic susceptibility and the permanent magnetic polarization of mass standards with different geometrical shapes and nominal values using the test procedures recommended by the OIML R 111 [1].

2. Organisation and protocol

2.1. Transfer standards

Altogether five stainless steel mass standards with different nominal values and outer shapes were provided by PTB and chosen as transfer standards (see figures 1 and 2):

- cylindrical 2 g-OIML shaped weight with recessed base,
- cylindrical 1 kg-OIML shaped weight with flat bottom (marking "Z2" on the knob),
- cylindrical 1 kg-OIML shaped weight with recessed base,
- cylindrical 5 kg-OIML shaped weight with flat bottom (marking "5 kg" on the knob),
- hollow cylinder (nominal value 1 kg) with the marking "●" on the top.

The external shapes and sizes of the OIML travelling standards were required when determining the magnetic properties. For this reason the outer dimensions of the transfer standards and their standard uncertainties were given to all participants (cf. figure 3a and table 1). Both outer and inner dimensions were required for the hollow cylinder and were also provided to the participants (cf. figure 3b and table 1).

2.2. Measurement of magnetic properties

For the determination of the magnetic properties only the measurement procedures recommended by the OIML R 111 [1] were allowed. In order to avoid the increased risk of magnetizing the transfer standards the attraction method (OIML R 111, section B.6.5) and the fluxgate method (OIML R 111, section B.6.6) were allowed to be applied only on the 1 kg-OIML shaped weight with flat bottom (marking "Z2") and the hollow cylinder (cf. table 2).

The participating laboratories were free to choose one or more methods listed in table 2 for the determination of the volume magnetic susceptibility and the permanent magnetic polarization. The measurements had to be carried out according to the OIML R 111 [1] and in accordance with the professional practice of the corresponding participant. Generally the measurements were performed only at the bottom of the travelling standards. Neither at the beginning nor at the end of the measurements it was allowed to demagnetize the transfer standards in order to avoid unclear measurement results. Furthermore each participating laboratory had to ensure that the transfer standards were not magnetized or demagnetized by the measurement procedure or any other circumstances.

Figure 1: Photograph of the first three transfer standards used for this intercomparision: 1 kg-knob weight with flat bottom (marking "Z2") on the left, 1 kg-knob weight with recessed base in the middle and 5 kg-knob weight with flat bottom (marking "5 kg") on the right.

Figure 2: Photograph of the two other weights used for this intercomparision: 2 g-knob weight with recessed base on the left and 1 kg-hollow cylinder (marking "●") on the right.

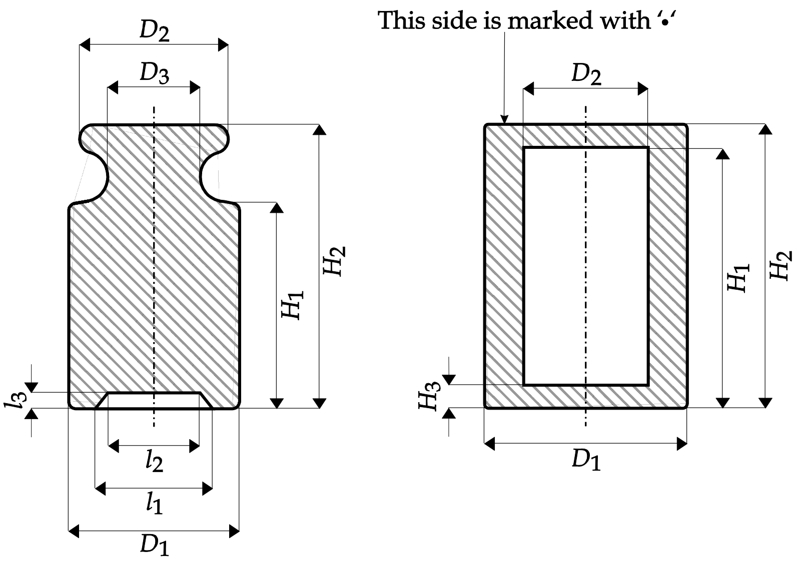


Figure 3: Schematic cross-sections of the travelling standards with the most important outer dimensions (cf. table 1). a) cross-sections of the OIML weights (2 g to 5 kg), b) cross-section of the hollow cylinder.

Table 1: Outer dimensions of the travelling standards (cf. figure 3). All dimensions are in millimetres and the standard uncertainties (coverage factor k = 1) are given in parentheses (concise notation).

	2 g OIML *recessed*	1 kg OIML *flat bottom* *'Z2'*	1 kg OIML *recessed*	5 kg OIML *flat bottom* *'5 kg'*	hollow cylinder '●'
diameter D_1	5.790(18)	48.001(18)	47.825(21)	80.016(20)	
height H_1	8.272(20)	61.604(25)	59.082(19)	106.895(27)	
knob diameter D_2	5.272(19)	42.980(18)	42.814(18)	72.051(19)	
neck diameter D_3	2.906(19)	27.316(19)	27.212(23)	46.127(19)	
overall height H_2	11.062(19)	83.023(22)	80.520(26)	142.820(31)	
max. recess diameter l_1	4.064(57)		33.70(17)		
min. recess diameter l_2	4.064(57)		30.311(69)		
recess depth l_3	0.146(20)		0.394(37)		
outer diameter D_1					57.186(19)
overall height H_2					79.898(20)
inner diameter D_2					37.010(19)
height H_1					75.330(44)
bottom height H_3					6.766(29)

Table 2: Measurement procedures for the determination of the volume magnetic susceptibility χ and the permanent magnetic polarization $\mu_0 M_z$; ✓ = measurement procedure is allowed, ⦸ = measurement procedure is not allowed.

	2 g OIML *recessed*		1 kg OIML *flat bottom* *'Z2'*		1 kg OIML *recessed*		5 kg OIML *flat bottom* *'5 kg'*		hollow cylinder '●'	
	χ	$\mu_0 M_z$	χ	$\mu_0 M_z$	χ	$\mu_0 M_z$	χ	$\mu_0 M_z$	χ	$\mu_0 M_z$
Fluxgate magnetometer OIML R 111 [1], section B.6.2		⦸		✓		✓		✓		✓
Hall sensor OIML R 111 [1], section B.6.2		✓		✓		✓		✓		✓
Susceptometer method OIML R 111 [1], section B.6.4	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Attracting method OIML R 111 [1], section B.6.5	⦸		✓		⦸		⦸		✓	
Fluxgate method OIML R 111 [1], section B.6.6	⦸		✓		⦸		⦸		✓	

2.3. Reports of participants

The measurement results and information about measurement parameters were reported to the pilot laboratory by filling the corresponding Excel-sheets which were submitted to each participant. All uncertainties had to be computed and reported according to the "Guide to the Expression of Uncertainty in Measurement" [2]. The uncertainties had to be expressed as standard uncertainties (coverage factor k = 1). Without an associated uncertainty a result was not considered complete and therefore not included in this report.

2.4. Participants and schedule

Table 3 gives a survey of the participating laboratories, their acronyms and the timetable of the measurements.

Table 3: Survey of the participants and the timetable of this intercomparision.

Participant	Acronym	Country	Contact person	Time of Measurement
		PETAL 1		
Physikalisch-Technische Bundesanstalt	PTB	Germany	Michael Borys	06/2009
Bureau International des Poids et Mesures	BIPM	International	Richard Davis, Hao Fang	07/2009
FPS Economy, DG Quality and Safety, Metrology Division	SMD	Belgium	Antoine Condereys	08/2009
Van Swinden Laboratorium	VSL	Netherlands	Inge van Andel	08/2009
National Physical Laboratory	NPL	United Kingdom	Stuart Davidson	11/2009
		PETAL 2		
Physikalisch-Technische Bundesanstalt	PTB	Germany	Michael Borys	11/2009
Centre for Metrology and Accreditation	MIKES	Finland	Kari Riski	01/2010
Czech Metrology Institute	CMI	Czech Republic	Ivan Kriz	05/2010
Bundesamt für Eich- und Vermessungswesen	BEV	Austria	Christian Buchner	06/2010
Istituto Nazionale di Ricerca Metrologica	INRIM	Italy	Walter Bich, Andrea Malengo	07/2010
		PETAL 3		
Physikalisch-Technische Bundesanstalt	PTB	Germany	Michael Borys	07/2010
Metrology Institute of the Republic of Slovenia	MIRS	Slovenia	Matej Grum	08/2010

Table 3: Survey of the participants and the timetable of this intercomparision (continued).

Participant	Acronym	Country	Contact person	Time of Measurement
Hungarian Trade Licensing Office Metrology Department	MKEH	Hungary	Csilla Vámossy	09/2010
National Institute of Metrology	INM	Romania	George Florian Popa	10/2010
Hellenic Institute of Metrology	EIM	Greece	Chris Mitsas	11/2010
Centro Español de Metrología	CEM	Spain	Nieves Medina, Angel Lumbreras	01/2011
		PETAL 4		
Physikalisch-Technische Bundesanstalt	PTB	Germany	Michael Borys	02/2011
State Office for Metrology	DZM	Croatia	Martin Glogovšek	03/2011
Ulusal Metroloji Enstitüsü	UME	Turkey	Umit Akcadag	04/2011
National Institute of Standards	NIS	Egypt	Alas eldin A. El-Tawil	05-09/2011
		PETAL 5		
Physikalisch-Technische Bundesanstalt	PTB	Germany	Michael Borys	10/2011
Technical Research Institute of Sweden	SP	Sweden	Mathias Johansson	12/2011
SAMC Metrology Bureau	LATMB	Latvia	Tatjana Zandarova	01/2012
Vilnius Metrology Centre	VMC	Lithuania	Ilona Milkamanaviciene	02/2012
AS Metrosert	Metrosert	Estonia	Viktor Vabson	03/2012
Bureau of Metrology	BoM	Macedonia	Bianca Stoilkovska	05/2012
Physikalisch-Technische Bundesanstalt	PTB	Germany	Michael Borys	01-06/2013

3. Results

3.1. Results reported by the participants

The analysis of this intercomparision is based on the results of the participants reported in the corresponding Excel-sheets. In the tables 4 and 5 the results of all participating laboratories for the volume magnetic susceptibility χ and the permanent magnetic polarization $\mu_0 M_z$ are summarized. Since not all laboratories agreed explicitly to a non-anonymous presentation the results were made anonymous according to the protocol of this intercomparision by assigning a letter code to each participant. In the case different measurement procedures were used by a participant to determine the magnetic properties of the transfer standards a number code is added to the corresponding letter code.

Table 4: Results of the participants for the determination of the volume magnetic susceptibility χ and the assigned standard uncertainty $u(\chi)$ (coverage factor k = 1).

Code	Measurement procedure	2 g OIML *recessed*		1 kg OIML *flat bottom* *'Z2'*		1kg OIML *recessed*		5 kg OIML *flat bottom* *'5 kg'*		hollow cylinder '●'	
		χ	$u(\chi)$	χ	$u(\chi)$	χ	$u(\chi)$	χ	$u(\chi)$	χ	$u(\chi)$
A	Susceptometer	0.00396	0.00034	0.00274	0.00013	0.00405	0.00016	0.1451	0.0073	0.00377	0.00019
B	Susceptometer	0.00380	0.00017	0.00290	0.00018	0.00410	0.00017	0.1645	0.0058	0.00320	0.00015
C	Susceptometer	0.0041	0.0010	0.00278	0.00067	0.00409	0.00098	0.14	0.21	0.00383	0.00092
D	Susceptometer	0.00388	0.00042	0.00260	0.00012	0.00376	0.00023	0.1335	0.0067	0.00351	0.00024
E	Susceptometer	0.0043	0.0012	0.00273	0.00017	0.00406	0.00023	0.149	0.017	0.00377	0.00022
F	Susceptometer	0.00392	0.00029	0.00285	0.00015	0.00402	0.00024			0.00376	0.00023
G	Susceptometer	0.003790	0.000090	0.002740	0.000060	0.004000	0.000080	0.1450	0.0032	0.003730	0.000080
H	Susceptometer	0.00410	0.00020	0.00270	0.00010	0.00410	0.00020	0.1460	0.0070	0.00290	0.00010
I	Susceptometer	0.00417	0.00034	0.002970	0.000080	0.004290	0.000050	0.1775	0.0023	0.01276	0.00011
J	Susceptometer	0.00408	0.00030	0.00276	0.00013	0.00410	0.00018	0.1450	0.0070	0.00382	0.00017
K1	Susceptometer	0.00435	0.00044	0.00288	0.00029	0.00432	0.00043	0.160	0.016	0.00399	0.00040
K2	Attracting method			0.0120	0.0036					0.0120	0.0036
L	Susceptometer	0.00050	0.00010	0.00130	0.00010	0.00190	0.00020	0.093	0.010	0.00790	0.00080
M1	Susceptometer	0.00400	0.00030	0.00280	0.00020	0.00380	0.00030	0.145	0.010	0.00370	0.00030
N	Susceptometer	0.00408	0.00042	0.00275	0.00041	0.00407	0.00043	0.1431	0.0051	0.00379	0.00052
O	Susceptometer	0.00374	0.00035	0.00275	0.00020	0.00413	0.00022	0.146	0.015	0.00386	0.00020
P	Susceptometer	0.00384	0.00016	0.002685	0.000037	0.003938	0.000058	0.1390	0.0011	0.00369	0.00047
Q	Susceptometer	0.00420	0.00030	0.00277	0.00012	0.00407	0.00017			0.00382	0.00016
R1	Susceptometer	0.00437	0.00021	0.002786	0.000061	0.00402	0.00011	0.1480	0.0021	0.003792	0.000082
R2	Fluxgate			0.00253	0.00016					0.00299	0.00018
R3	Attracting method			0.0100	0.0020					0.0100	0.0020
S	Susceptometer	0.00400	0.00020	0.00260	0.00010	0.00400	0.00020	0.0940	0.0036	0.00360	0.00020
T	Susceptometer	0.00370	0.00030	0.00270	0.00010	0.00400	0.00020	0.1560	0.0050	0.00370	0.00020
U	Susceptometer	0.00459	0.00030	0.00270	0.00014	0.00400	0.00030	0.1443	0.0073	0.00372	0.00019

Table 5: Results of the participants for the determination of the (absolute value of the) permanent magnetic polarization $\mu_0 M_z$ and the assigned standard uncertainty $u(\mu_0 M_z)$ (coverage factor k = 1).

Code	Measurement procedure	2 g OIML *recessed*		1 kg OIML *flat bottom* *'Z2'*		1kg OIML *recessed*		5 kg OIML *flat bottom* *'5 kg'*		hollow cylinder '●'	
		$\mu_0 M_z$ / µT	$u(\mu_0 M_z)$ / µT	$\mu_0 M_z$ / µT	$u(\mu_0 M_z)$ / µT	$\mu_0 M_z$ / µT	$u(\mu_0 M_z)$ / µT	$\mu_0 M_z$ / µT	$u(\mu_0 M_z)$ / µT	$\mu_0 M_z$ / µT	$u(\mu_0 M_z)$ / µT
A	Susceptometer	0.220	0.019	1.330	0.067	0.0300	0.0045	39.6	2.0	0.0400	0.0060
B	Susceptometer	0.5	23	2.3	1.3	0.4	1.2	66.5	3.0	0.2	1.2
C	Susceptometer	0.340	0.044	1.640	0.029	0.060	0.043	50.4	8.5	0.050	0.040
D	Susceptometer	0.15	0.23	0.215	0.011	0.011	0.041	18.5	1.4	0.283	0.041
E	Susceptometer	0.5	2.1	1.11	0.12	0.09	0.13	18.36	0.82	0.10	0.22
F	Susceptometer	0.059	0.041	0.700	0.030	0.0850	0.0080			0.0710	0.0060
G	Susceptometer	0.034	0.020	1.092	0.013	0.0373	0.0045	18.45	0.28	0.0344	0.0049
H	Susceptometer	0.40	0.10	0.780	0.080	0.020	0.010	19.0	2.0	0.050	0.010
I	Susceptometer	0.16	0.76	1.73	0.14	0.300	0.060	47.7	3.9	0.75	0.22
J	Susceptometer	0.20	0.15	0.36	0.12	0.024	0.013	6.10	0.50	0.041	0.017
K1	Susceptometer	0.81	0.16	0.150	0.030	0.100	0.020	68.8	13.8	0.160	0.032
L	Susceptometer	0.075	0.015	0.540	0.050	0.190	0.020	41.3	4.2	0.710	0.070
M1	Susceptometer	0.20	0.12	1.400	0.090	0.020	0.050	38.0	3.0	0.000	0.050
M2	Fluxgate			0.75	0.20			32.0	2.0		
N	Susceptometer	0.30	0.18	1.33	0.20	0.310	0.060	68.6	10.2	0.23	0.10
O	Susceptometer	0.05	0.30	0.390	0.070	0.13	0.10	59.1	3.4	0.110	0.090
P	Susceptometer	0.12	0.49	1.122	0.010	0.032	0.012	57.60	0.50	0.032	0.012
Q	Susceptometer	0.06	0.16	0.700	0.020	0.010	0.011			0.010	0.021
R1	Susceptometer	0.10	0.21	0.247	0.011	0.031	0.013	65.95	0.52	0.029	0.020
R2	Fluxgate			0.45	0.40	0.12	0.42	62.0	2.3	0.3	1.6
S	Susceptometer	0.91	0.38	1.106	0.043	0.123	0.016	31.47	0.85	0.076	0.024
T	Susceptometer	0.10	0.30	1.50	0.20	0.00	0.10	45.0	5.0	0.00	0.10
U	Susceptometer	0.220	0.025	0.950	0.095	0.0700	0.0075	38.7	3.9	0.0400	0.0020

After the Draft A of this intercomparision was completed and sent to the participating laboratories, the participant with the identifier "B" reported an error in his program for the calculation of the results and informed the pilot laboratory about the following corrected data:

Table 6: Results of the participant with the identifier "B" for the determination of the volume magnetic susceptibility χ and the assigned standard uncertainty $u(\chi)$ (coverage factor k = 1) after Draft A was completed.

Code	Measurement procedure	2 g OIML *recessed*		1 kg OIML *flat bottom* *'Z2'*		1kg OIML *recessed*		5 kg OIML *flat bottom* *'5 kg'*		hollow cylinder '●'	
		χ	$u(\chi)$	χ	$u(\chi)$	χ	$u(\chi)$	χ	$u(\chi)$	χ	$u(\chi)$
B	Susceptometer	0.0038	0.0002	0.0029	0.0002	0.0041	0.0003	0.163	0.003	0.0039	0.0002

Table 7: Results of the participant with the identifier "B" for the determination of the (absolute value of the) permanent magnetic polarization $\mu_0 M_z$ and the assigned standard uncertainty $u(\mu_0 M_z)$ (coverage factor k = 1) after Draft A was completed.

Code	Measurement procedure	2 g OIML *recessed*		1 kg OIML *flat bottom* *'Z2'*		1kg OIML *recessed*		5 kg OIML *flat bottom* *'5 kg'*		hollow cylinder '●'	
		$\mu_0 M_z$ µT	$u(\mu_0 M_z)$ µT	$\mu_0 M_z$ µT	$u(\mu_0 M_z)$ µT	$\mu_0 M_z$ µT	$u(\mu_0 M_z)$ µT	$\mu_0 M_z$ µT	$u(\mu_0 M_z)$ µT	$\mu_0 M_z$ µT	$u(\mu_0 M_z)$ µT
B	Susceptometer	0.49	0.19	2.35	0.2	0.39	0.2	66.3	2.6	0.70	0.2

Please note that all results presented in the following were determined with the values originally given by the participant (cf. table 4 and 5).

3.2. Stability of transfer standards

In order to check the stability of the transfer standards and to estimate the reproducibility of the susceptometer measurements the pilot laboratory determined the magnetic properties of the transfer standards at the beginning and at the end of each petal according to the timetable in table 3. The observed changes of these measurement results are listed in table 8. For the 5 kg-OIML weight the difference given for the permanent magnetic polarization was already corrected by a significant change of the reference values (see the corresponding reference values in table 10 and figure 7). The uncertainties given in the column "$u_{\text{stability}}$" were estimated under the assumption of a rectangular distribution of the intermediate measurement results:

$$u_{\text{stability}} = \frac{\text{Max. -Min.}}{\sqrt{12}}. \qquad (1)$$

These uncertainty contributions must be taken into account when assessing the differences between the results of a participating laboratory and the corresponding reference value (cf. equation (3)).

Table 8: Differences between the maximum and minimum values of the volume magnetic susceptibility χ and the permanent magnetic polarization $\mu_0 M_z$ measured with the susceptometer method by the pilot laboratory during the intermediate measurements of the magnetic properties at the beginning and at the end of each petal. The uncertainties given in the column "$u_{\text{stability}}$" must be taken into account when the measurement results of the participants are judged.

	Magnetic property	*Max. – Min.*	$u_{\text{stability}}$ (k = 1)
2 g OIML *recessed*	χ $\mu_0 M_z$ / µT	0.00041 0.47	0.00012 0.14
1 kg OIML *flat bottom* *'Z2'*	χ $\mu_0 M_z$ / µT	0.000147 1.58	0.000042 0.46
1 kg OIML *recessed*	χ $\mu_0 M_z$ / µT	0.000080 0.0210	0.000023 0.0061
5 kg OIML *flat bottom* *'5 kg'*	χ $\mu_0 M_z$ / µT	0.0069 20.4	0.0020 5.9
hollow cylinder '●'	χ $\mu_0 M_z$ / µT	0.000226 0.182	0.000065 0.053

3.3. Reference values

According to the protocol of this intercomparision the participating laboratories were free to choose one or more methods listed in table 2 for the determination of the volume magnetic susceptibility and the permanent magnetic polarization. All participants used the susceptometer method for the determination of both magnetic properties. Additional alternative measurement procedures were used by three of totally 21 participants. For this reason and due to the recommendation, that in cases where the different measurement procedures give inconsistent results, the susceptometer method should be preferred (cf. OIML R 111, section B.6.1.2), all reference values were calculated on the basis of the susceptometer measurements.

Before the reference values were calculated a consistency check was made by applying a chi-squared test [3] (see table 9). The consistency check failed for all measurement results of both magnetic properties. Since in contrast to the mean value or the weighted mean the median is largely insensitive to the existence of outliers, the reference values were calculated on the basis of the median [4] (cf. table 10). By the use of the median no results need to be eliminated from the analysis in the case of inconsistency. The intermediate measurements of the magnetic properties at the beginning and at the end of each petal showed significant changes for the permanent magnetic polarization of the 5 kg-OIML weight, which required the calculation of three different reference values (see table 10).

Table 9: Results of the consistency check for the measurements of the volume magnetic susceptibility χ and the permanent magnetic polarization $\mu_0 M_z$; ν = degrees of freedom, N = number of measurements, X^2_{obs} = observed chi-squared value.

	2 g OIML *recessed*		1 kg OIML *flat bottom* *'Z2'*		1 kg OIML *recessed*		5 kg OIML *flat bottom* *'5 kg'*		hollow cylinder '●'	
	χ	$\mu_0 M_z$	χ	$\mu_0 M_z$	χ	$\mu_0 M_z$	χ	$\mu_0 M_z$	χ	$\mu_0 M_z$
$\nu = N - 1$	20	20	20	20	20	20	18	18	20	20
$X^2(\nu)$	31.4	31.4	31.4	31.4	31.4	31.4	28.9	28.9	31.4	31.4
X^2_{obs}	956	128	212	6352	146	196	477	12433	6319	188
consistency check	failed	failed	failed	failed	failed	failed	failed	failed	failed	failed

Table 10: Reference values for the volume magnetic susceptibility χ and the permanent magnetic polarization $\mu_0 M_z$ and the assigned standard uncertainties u (coverage factor k = 1).

	Magnetic property	Median
2 g OIML *recessed*	χ	0.004000
	$u(\chi)$	0.000072
	$\mu_0 M_z$ / µT	0.200
	u ($\mu_0 M_z$) / µT	0.053
1 kg OIML *flat bottom* *'Z2'*	χ	0.002744
	u (χ)	0.000019
	$\mu_0 M_z$ / µT	1.11
	u ($\mu_0 M_z$) / µT	0.17
1 kg OIML *recessed*	χ	0.004050
	u (χ)	0.000021
	$\mu_0 M_z$ / µT	0.060
	u ($\mu_0 M_z$) / µT	0.017
5 kg OIML *flat bottom* *'5 kg'*	χ	0.1450
	u (χ)	0.0013
	$\mu_0 M_z$ / µT *(participants A-C and S-U)*	42.3
	u ($\mu_0 M_z$) / µT *(participants A-C and S-U)*	5.0
	$\mu_0 M_z$ / µT *(participants D-J)*	18.48
	u ($\mu_0 M_z$) / µT *(participants D-J)*	0.27
	$\mu_0 M_z$ / µT *(participants K-R)*	59.1
	u ($\mu_0 M_z$) / µT *(participants K-R)*	7.3
hollow cylinder '●'	χ	0.003770
	u (χ)	0.000030
	$\mu_0 M_z$ / µT	0.050
	u ($\mu_0 M_z$) / µT	0.017

The differences D_i between the results x_i of the participating laboratories and the reference values x_{median}:

$$D_i = x_i - x_{\text{median}} \tag{2}$$

and the assigned expanded measurement uncertainties (coverage factor k = 2):

$$U(D_i) = 2\sqrt{u_{xi}^2 + u_{\text{median}}^2 + u_{\text{stability}}^2} \tag{3}$$

are listed in tables 11 and 12 for both magnetic properties. Hereby no correlations between the input quantities were taken into account.

3.4. Graphical presentation

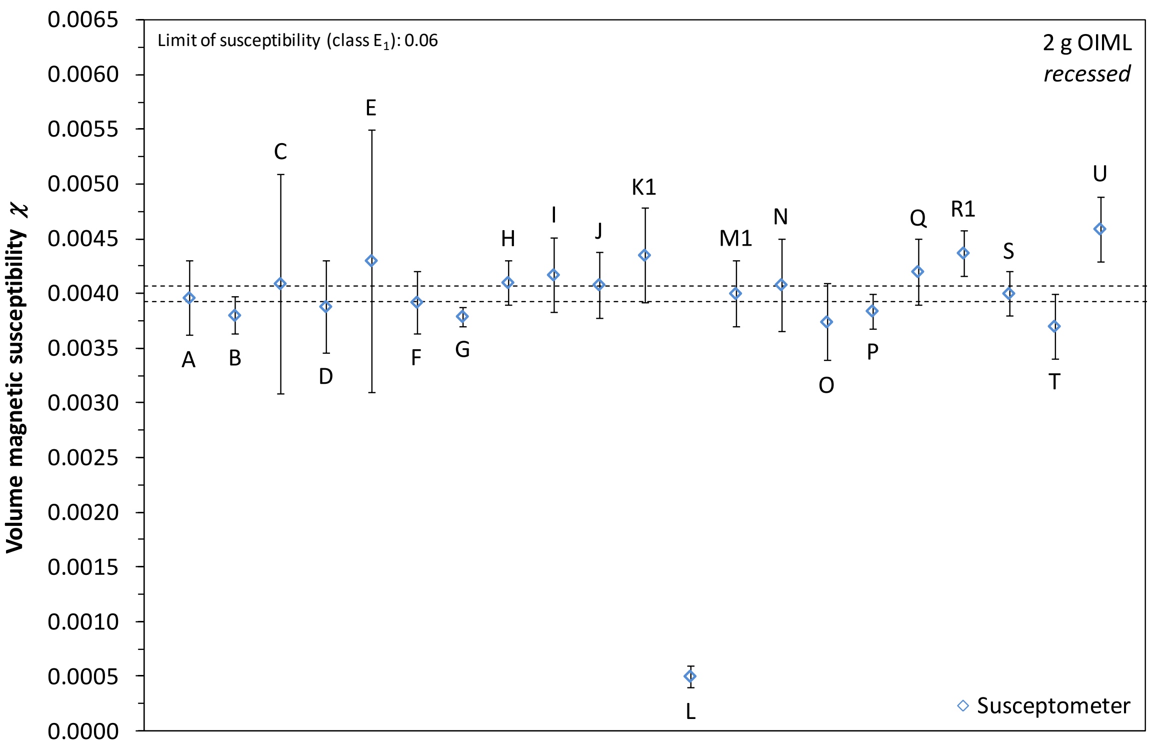
Figures 4 to 8 show plots of the measurement results of all participating laboratories including the calculated reference values (see table 10). In figures 9 to 13 the differences D_i between the results x_i of the participating laboratories and the reference values x_{median} and the assigned expanded measurement uncertainties $U(D_i)$ (coverage factor k = 2) are presented according to tables 11 and 12. Since the attraction method (OIML R 111, section B.6.5) gives only a maximum value of the volume magnetic susceptibility and in order to enhance the readability the results for the attraction method were not included in the figures. In all cases the attraction method delivered values far beyond the results measured with the other measurement procedures (see K2 and R3 in table 4). In some cases the error bars of the largest uncertainties were trimmed in order to improve legibility of the figures.

Table 11: Differences D_i between the results x_i of the participants and the reference values x_{median} and the assigned expanded measurement uncertainty $U(D_i)$ (coverage factor k = 2) for the volume magnetic susceptibility χ.

Code	Measurement procedure	2 g OIML *recessed*		1 kg OIML *flat bottom* *'Z2'*		1kg OIML *recessed*		5 kg OIML *flat bottom* *'5 kg'*		hollow cylinder '●'	
		$D_i(\chi)$	$U(D_i)$	$D_i(\chi)$	$U(D_i)$	$D_i(\chi)$	$U(D_i)$	$D_i(\chi)$	$U(D_i)$	$D_i(\chi)$	$U(D_i)$
A	Susceptometer	-0.00004	0.00073	0.00000	0.00028	0.00000	0.00033	0.000	0.015	0.00000	0.00041
B	Susceptometer	-0.00020	0.00044	0.00016	0.00037	0.00005	0.00035	0.020	0.013	-0.00057	0.00033
C	Susceptometer	0.0001	0.0020	0.0000	0.0013	0.0000	0.0020	0.00	0.41	0.0001	0.0018
D	Susceptometer	-0.00012	0.00088	-0.00014	0.00026	-0.00029	0.00046	-0.012	0.014	-0.00026	0.00050
E	Susceptometer	0.0003	0.0024	-0.00001	0.00035	0.00001	0.00046	0.004	0.034	0.00000	0.00046
F	Susceptometer	-0.00008	0.00064	0.00011	0.00031	-0.00003	0.00048			-0.00001	0.00048
G	Susceptometer	-0.00021	0.00033	0.00000	0.00015	-0.00005	0.00017	0.0000	0.0080	-0.00004	0.00021
H	Susceptometer	0.00010	0.00049	-0.00004	0.00022	0.00005	0.00040	0.001	0.015	-0.00087	0.00025
I	Susceptometer	0.00017	0.00073	0.00023	0.00018	0.00024	0.00012	0.0325	0.0067	0.00899	0.00026
J	Susceptometer	0.00008	0.00066	0.00002	0.00028	0.00005	0.00037	0.000	0.015	0.00005	0.00037
K1	Susceptometer	0.00035	0.00091	0.00014	0.00058	0.00027	0.00087	0.015	0.032	0.00022	0.00081
K2	Attracting method			0.0093	0.0072					0.0082	0.0072
L	Susceptometer	-0.00350	0.00034	-0.00144	0.00022	-0.00215	0.00040	-0.052	0.021	0.0041	0.0016
M1	Susceptometer	0.00000	0.00066	0.00006	0.00041	-0.00025	0.00060	0.000	0.021	-0.00007	0.00062
N	Susceptometer	0.00008	0.00088	0.00001	0.00083	0.00002	0.00086	-0.002	0.011	0.0000	0.0010
O	Susceptometer	-0.00026	0.00075	0.00001	0.00041	0.00008	0.00044	0.001	0.030	0.00009	0.00042
P	Susceptometer	-0.00016	0.00042	-0.00006	0.00012	-0.00011	0.00013	-0.0060	0.0053	-0.00009	0.00095
Q	Susceptometer	0.00020	0.00066	0.00003	0.00026	0.00002	0.00035			0.00005	0.00035
R1	Susceptometer	0.00037	0.00050	0.00000	0.00015	-0.00003	0.00023	0.0030	0.0064	0.00002	0.00022
R2	Fluxgate			-0.00021	0.00033					-0.00078	0.00039
R3	Attracting method			0.0073	0.0040					0.0062	0.0040
S	Susceptometer	0.00000	0.00049	-0.00014	0.00022	-0.00005	0.00040	-0.0510	0.0087	-0.00017	0.00042
T	Susceptometer	-0.00030	0.00066	-0.00004	0.00022	-0.00005	0.00040	0.011	0.011	-0.00007	0.00042
U	Susceptometer	0.00059	0.00066	-0.00004	0.00030	-0.00005	0.00060	-0.001	0.015	-0.00005	0.00041

Table 12: Differences D_i between the results x_i of the participants and the reference values x_{median} and the assigned expanded measurement uncertainty $U(D_i)$ (coverage factor k = 2) for the permanent magnetic polarization $\mu_0 M_z$.

Code	Measurement procedure	2 g OIML *recessed*		1 kg OIML *flat bottom* *'Z2'*		1kg OIML *recessed*		5 kg OIML *flat bottom* *'5 kg'*		hollow cylinder '●'	
		$D_i(\mu_0 M_z)$ / µT	$U(D_i)$ / µT	$D_i(\mu_0 M_z)$ / µT	$U(D_i)$ / µT	$D_i(\mu_0 M_z)$ / µT	$U(D_i)$ / µT	$D_i(\mu_0 M_z)$ / µT	$U(D_i)$ / µT	$D_i(\mu_0 M_z)$ / µT	$U(D_i)$ / µT
A	Susceptometer	0.02	0.29	0.22	0.98	-0.030	0.037	-3	16	-0.01	0.11
B	Susceptometer	0	46	1.2	2.8	0.3	2.4	24	17	0.2	2.4
C	Susceptometer	0.14	0.30	0.53	0.97	0.000	0.093	8	23	0.00	0.14
D	Susceptometer	-0.05	0.54	-0.89	0.97	-0.049	0.090	0	12	0.23	0.14
E	Susceptometer	0.3	4.2	0.0	1.0	0.03	0.26	0	12	0.05	0.45
F	Susceptometer	-0.14	0.30	-0.41	0.97	0.025	0.040			0.02	0.11
G	Susceptometer	-0.17	0.29	-0.01	0.97	-0.023	0.037	0	12	-0.02	0.11
H	Susceptometer	0.20	0.35	-0.33	0.98	-0.040	0.041	0	12	0.00	0.11
I	Susceptometer	0.0	1.5	0.6	1.0	0.24	0.13	29	14	0.70	0.45
J	Susceptometer	0.00	0.42	-0.7	1.0	-0.036	0.045	-12	12	-0.01	0.12
K1	Susceptometer	0.61	0.44	-0.96	0.97	0.040	0.054	10	33	0.11	0.13
L	Susceptometer	-0.13	0.29	-0.57	0.98	0.130	0.054	-18	21	0.66	0.18
M1	Susceptometer	0.00	0.38	0.29	0.99	-0.04	0.11	-21	20	-0.05	0.15
M2	Fluxgate			-0.4	1.1			-27	19		
N	Susceptometer	0.10	0.46	0.2	1.1	0.25	0.13	10	28	0.18	0.23
O	Susceptometer	-0.15	0.67	-0.72	0.98	0.07	0.20	0	20	0.06	0.21
P	Susceptometer	-0.1	1.0	0.02	0.97	-0.028	0.043	-2	19	-0.02	0.11
Q	Susceptometer	-0.14	0.43	-0.41	0.97	-0.050	0.042			-0.04	0.12
R1	Susceptometer	-0.10	0.51	0.01	0.97	-0.029	0.045	7	19	-0.02	0.12
R2	Fluxgate			-0.7	1.3	0.06	0.84	3	19	0.3	3.3
S	Susceptometer	0.71	0.81	0.00	0.97	0.063	0.048	-11	16	0.03	0.12
T	Susceptometer	-0.10	0.67	0.4	1.1	-0.06	0.20	3	18	-0.05	0.23
U	Susceptometer	0.02	0.30	-0.16	0.99	0.010	0.039	-4	17	-0.01	0.11



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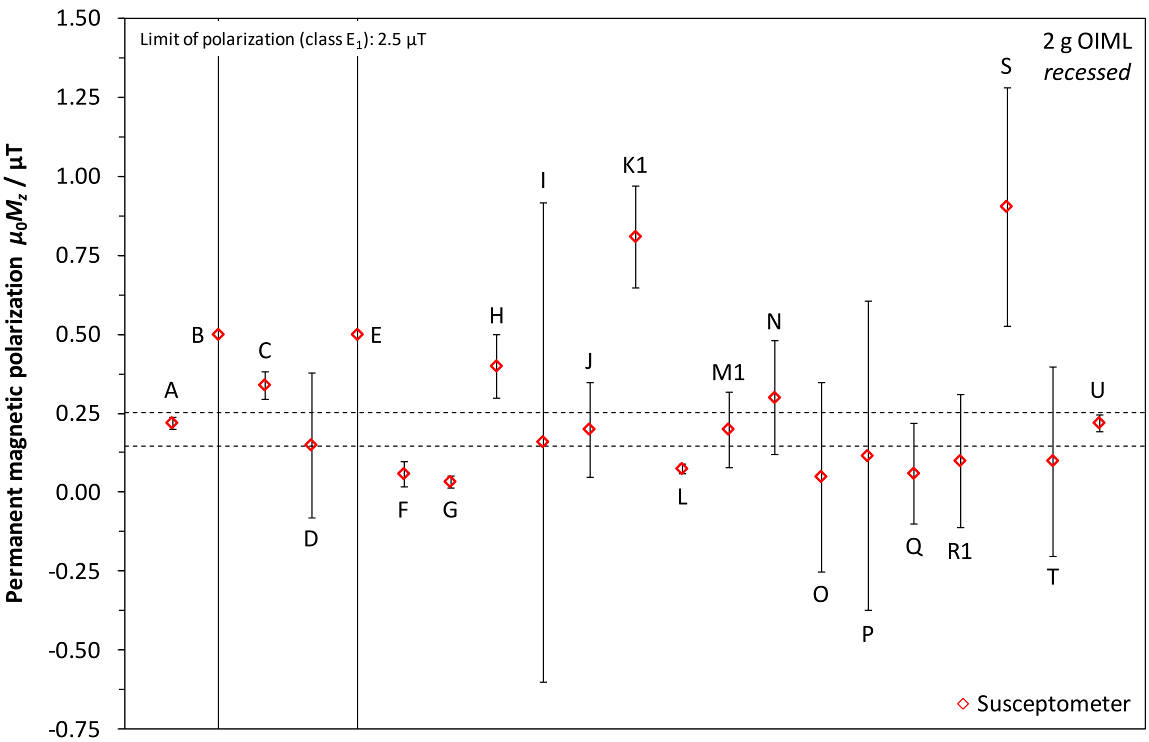
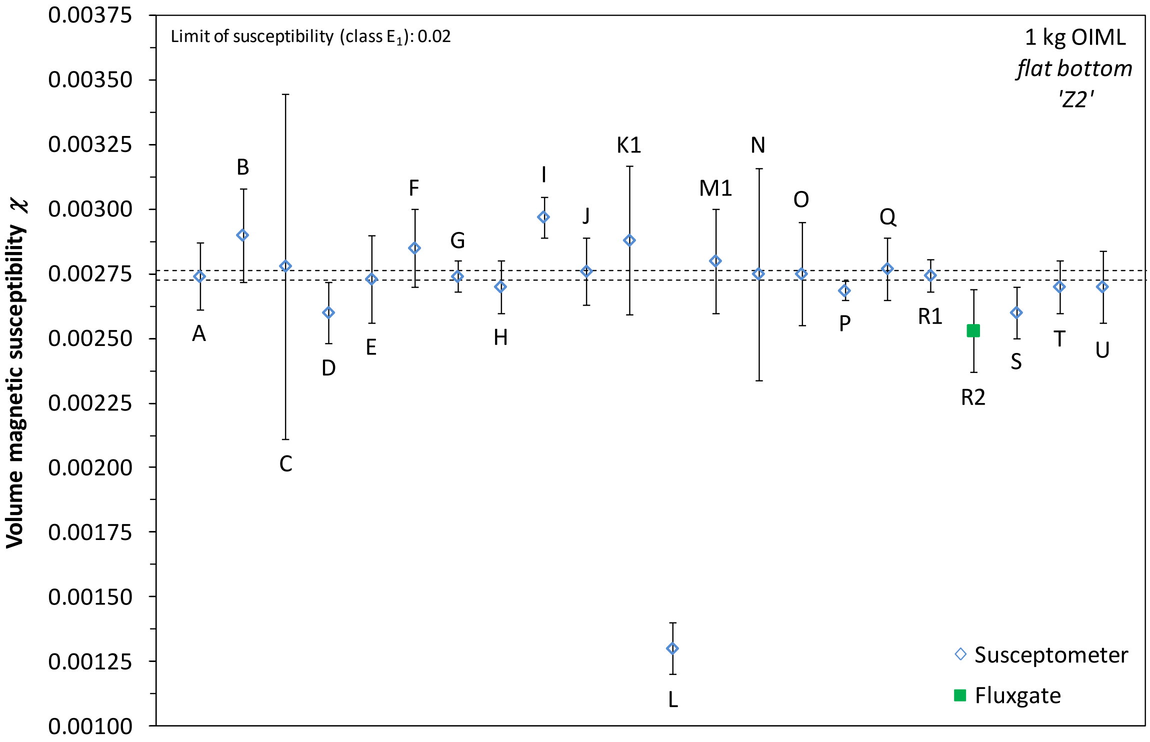


b)

Figure 4: Comparison of the results for the determination of a) the volume magnetic susceptibility χ and b) the permanent magnetic polarization $\mu_0 M_z$ of the 2 g-OIML weight. The uncertainty bars and the median limits (indicated by the dashed lines) correspond to the standard uncertainties (coverage factor k = 1). Due to the enlarged data representation some uncertainty bars were trimmed for the permanent magnetic polarization (participants B and E). The numerical values of the trimmed uncertainty bars can be taken from table 5.



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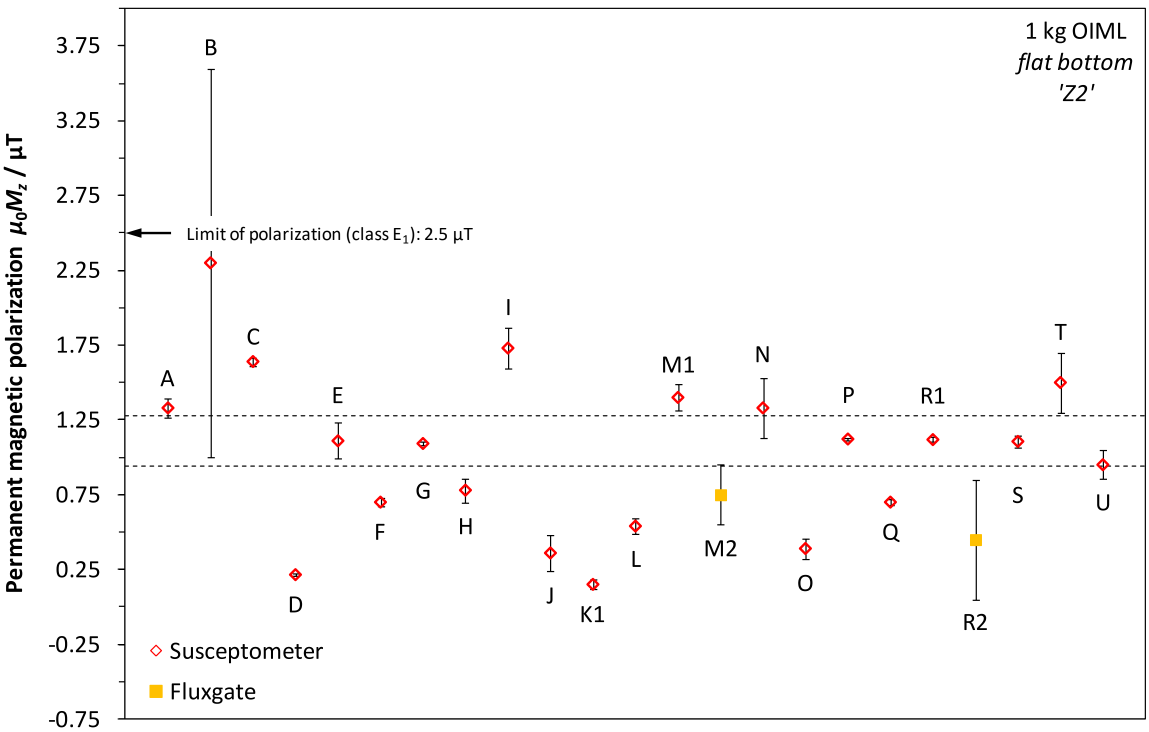
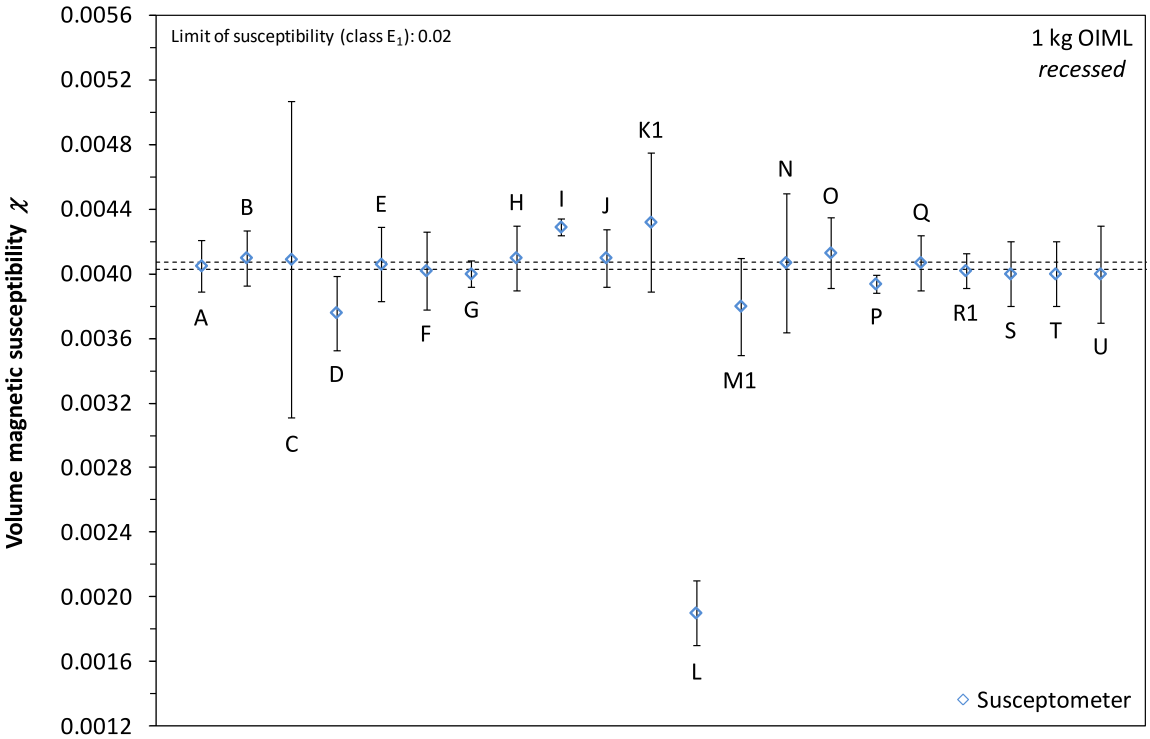


b)

Figure 5: Comparison of the results for the determination of a) the volume magnetic susceptibility χ and b) the permanent magnetic polarization $\mu_0 M_z$ of the 1 kg-OIML weight (flat bottom, 'Z2"). The uncertainty bars and the median limits (indicated by the dashed lines) correspond to the standard uncertainties (coverage factor k = 1).



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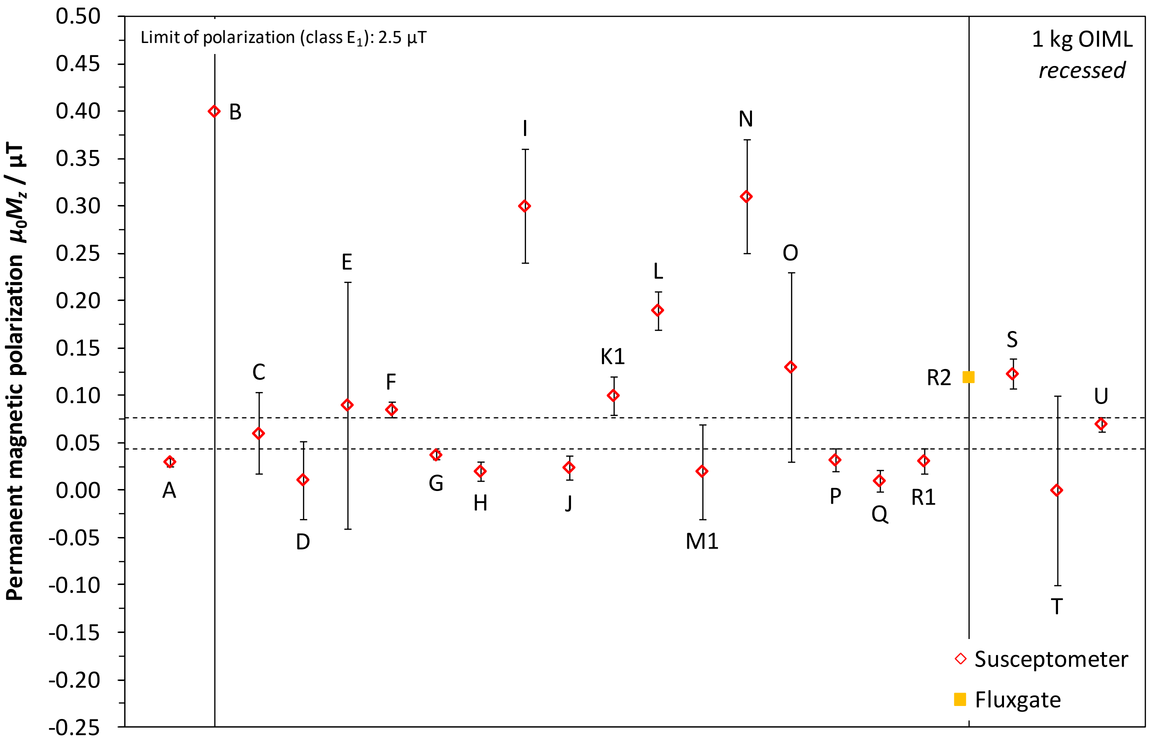
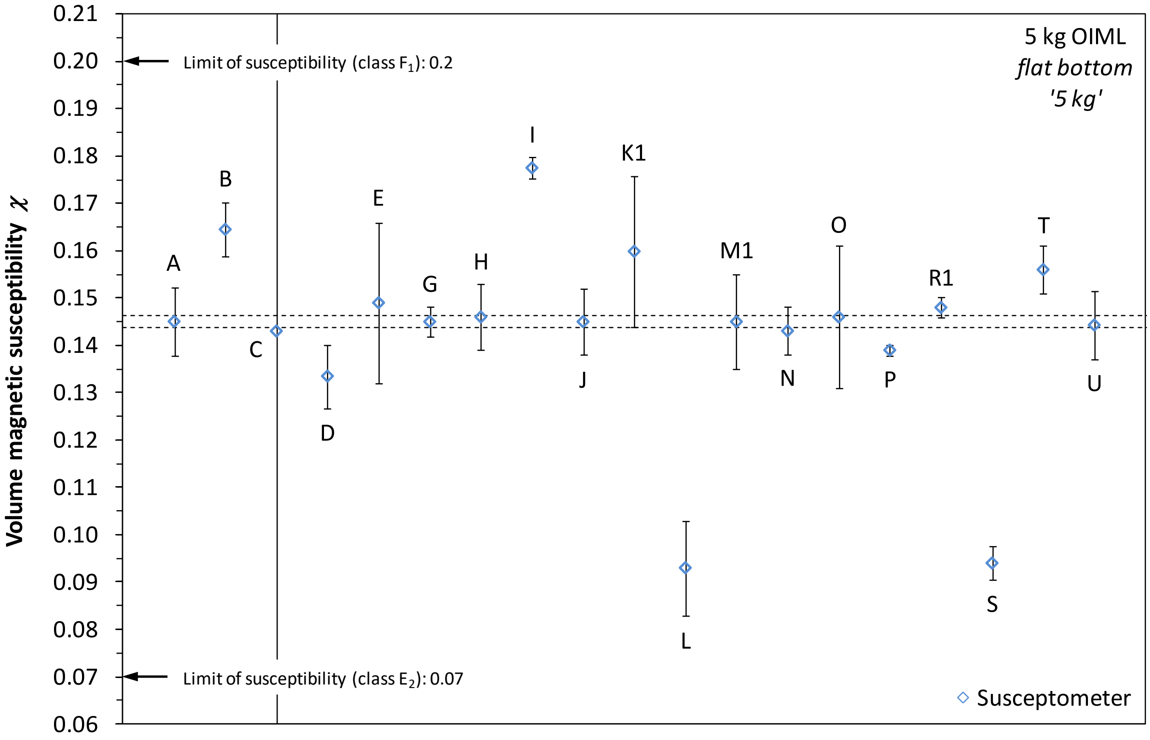


b)

Figure 6: Comparison of the results for the determination of a) the volume magnetic susceptibility χ and b) the permanent magnetic polarization $\mu_0 M_z$ of the 1 kg-OIML weight (recessed bottom). The uncertainty bars and the median limits (indicated by the dashed lines) correspond to the standard uncertainties (coverage factor k = 1). Due to the enlarged data representation some uncertainty bars were trimmed for the permanent magnetic polarization (participants B and R2). The numerical values of the trimmed uncertainty bars can be taken from table 5.



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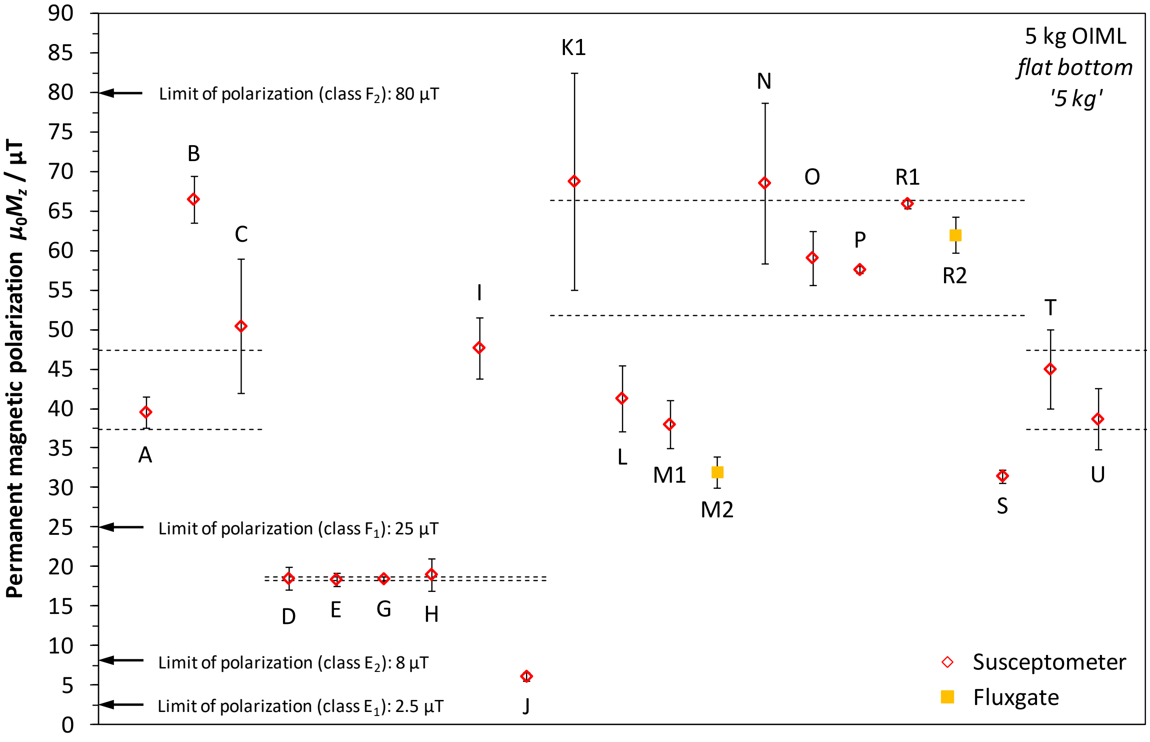
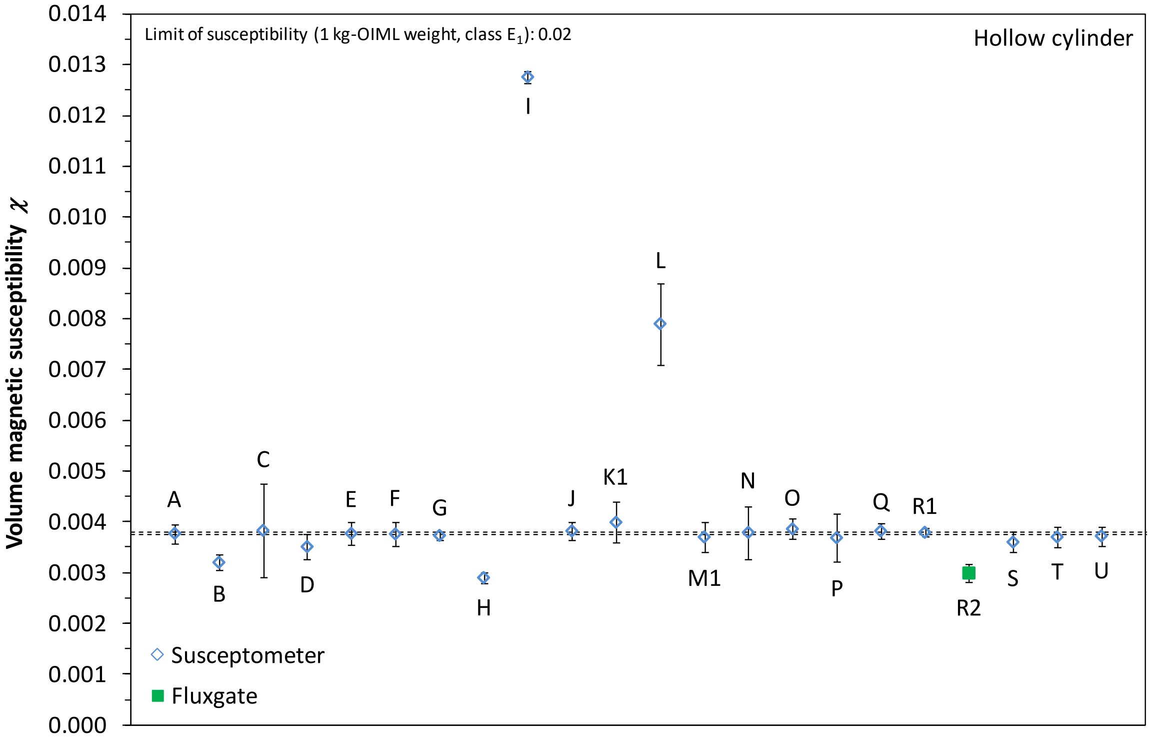


b)

Figure 7: Comparison of the results for the determination of a) the volume magnetic susceptibility χ and b) the permanent magnetic polarization $\mu_0 M_z$ of the 5 kg-OIML weight. The uncertainty bars and the median limits (indicated by the dashed lines) correspond to the standard uncertainties (coverage factor k = 1). Due to the enlarged data representation some uncertainty bars were trimmed for the volume magnetic susceptibility (participant C). The numerical values of the trimmed uncertainty bars can be taken from table 4.



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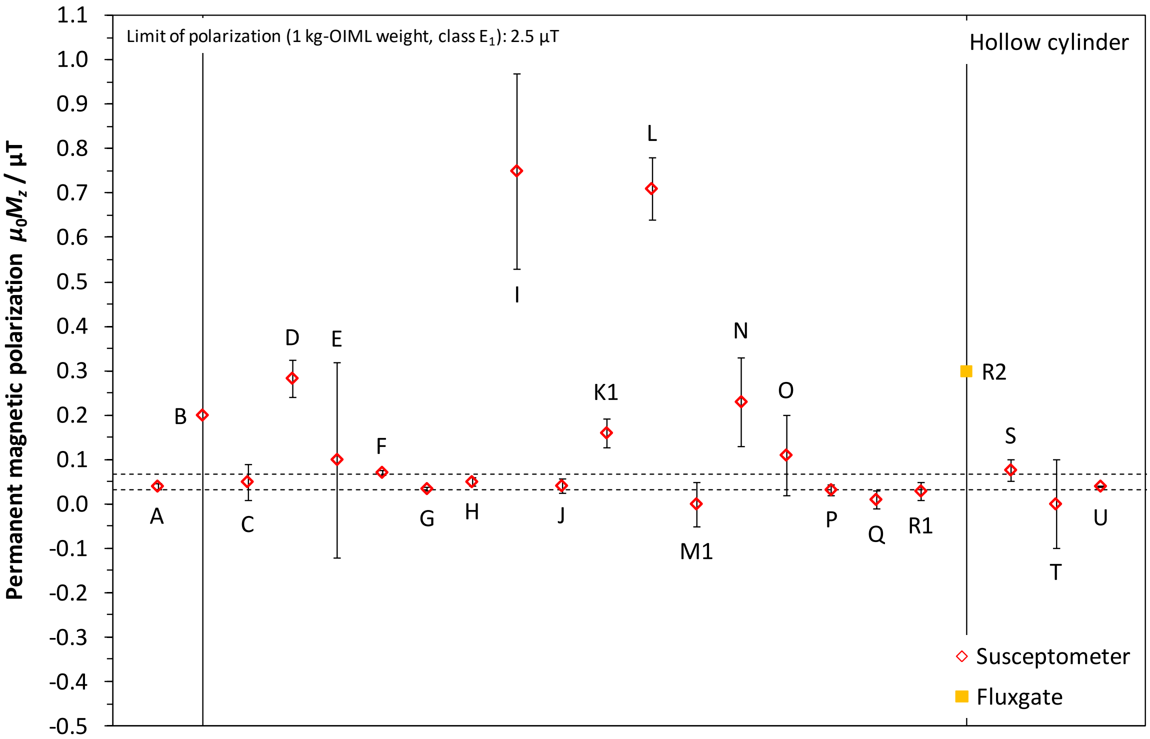
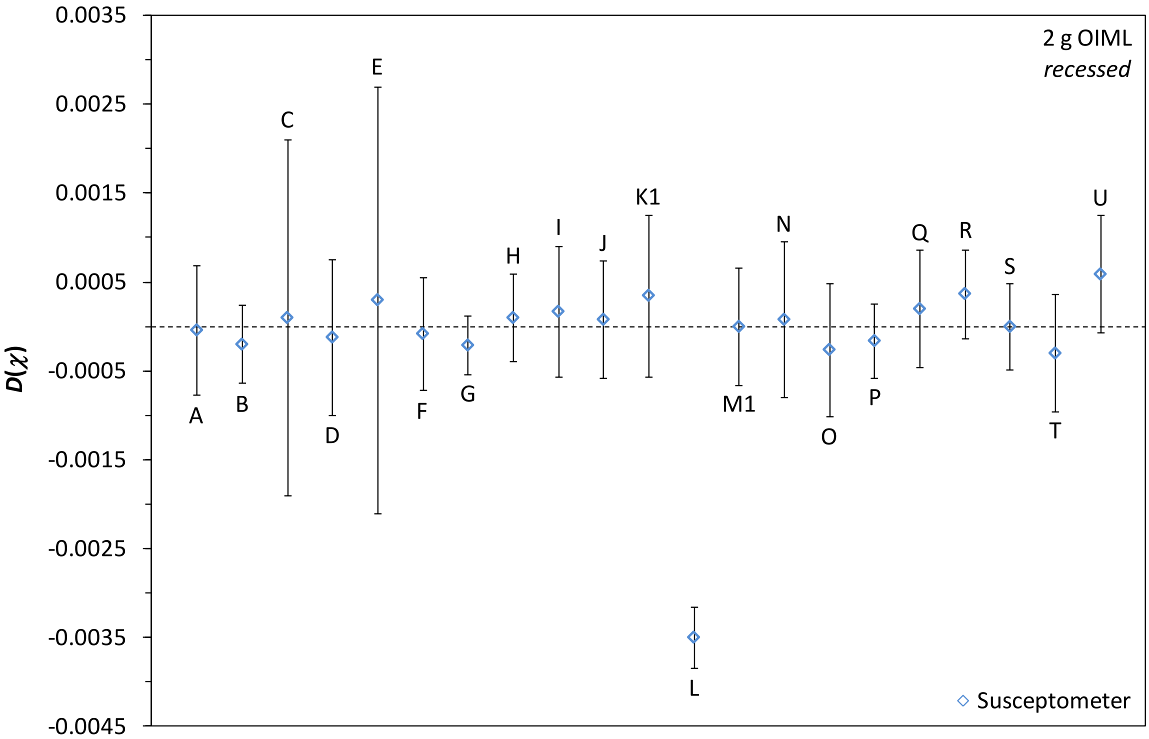


b)

Figure 8: Comparison of the results for the determination of a) the volume magnetic susceptibility χ and b) the permanent magnetic polarization $\mu_0 M_z$ of the hollow cylinder. The uncertainty bars and the median limits (indicated by the dashed lines) correspond to the standard uncertainties (coverage factor k = 1). Due to the enlarged data representation some uncertainty bars were trimmed for the permanent magnetic polarization (participants B and R2). The numerical values of the trimmed uncertainty bars can be taken from table 5. The limits given for the volume magnetic susceptibility and the permanent magnetic polarization correspond to a 1 kg-OIML weight of class E_1 [1].



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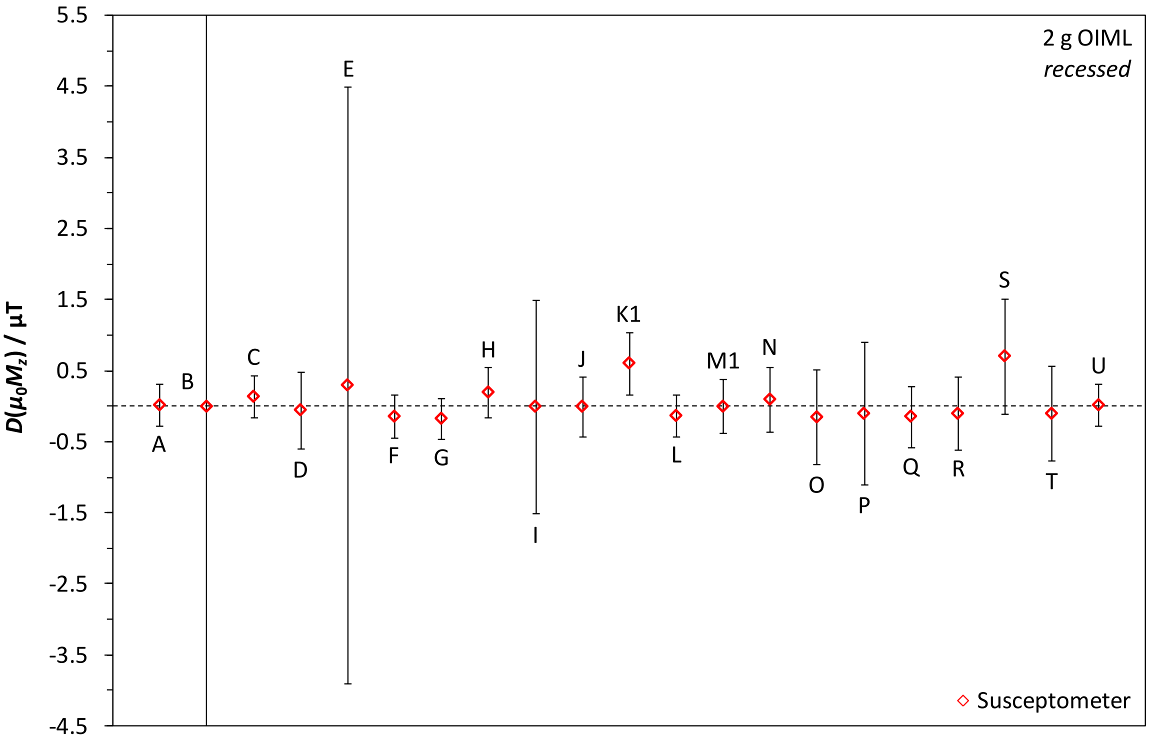
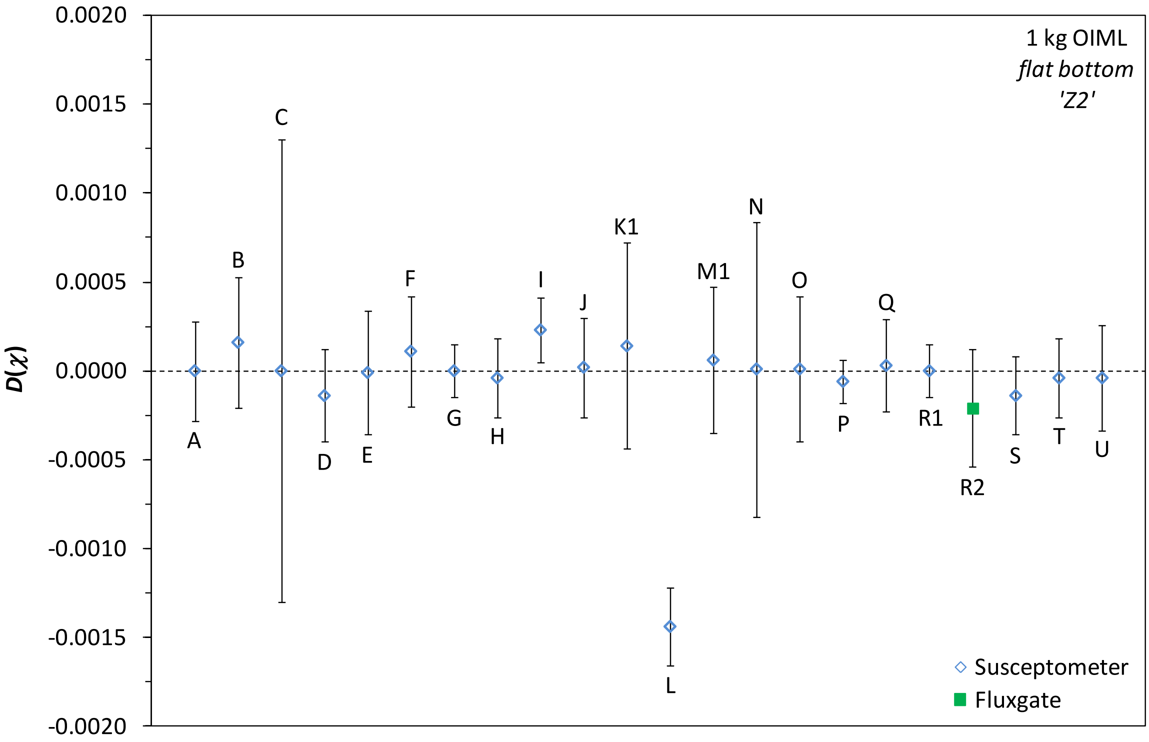


b)

Figure 9: Differences D_i between the results of the participating laboratories and the reference values (median) for the determination of a) the volume magnetic susceptibility χ and b) the permanent magnetic polarization $\mu_0 M_z$ of the 2 g-OIML weight. The uncertainty bars correspond to the expanded measurements uncertainties $U(D_i)$ (coverage factor k = 2). Due to the enlarged data representation some uncertainty bars were trimmed for the permanent magnetic polarization (participant B). The numerical values of the trimmed uncertainty bars can be taken from table 12.



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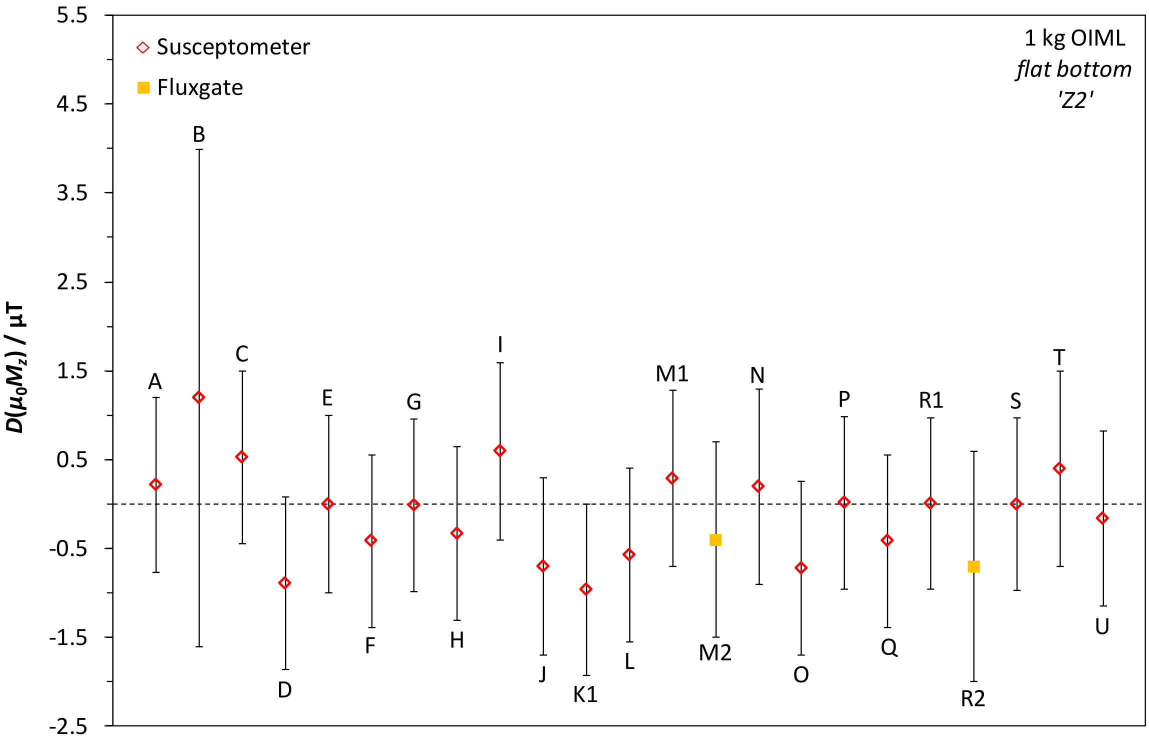
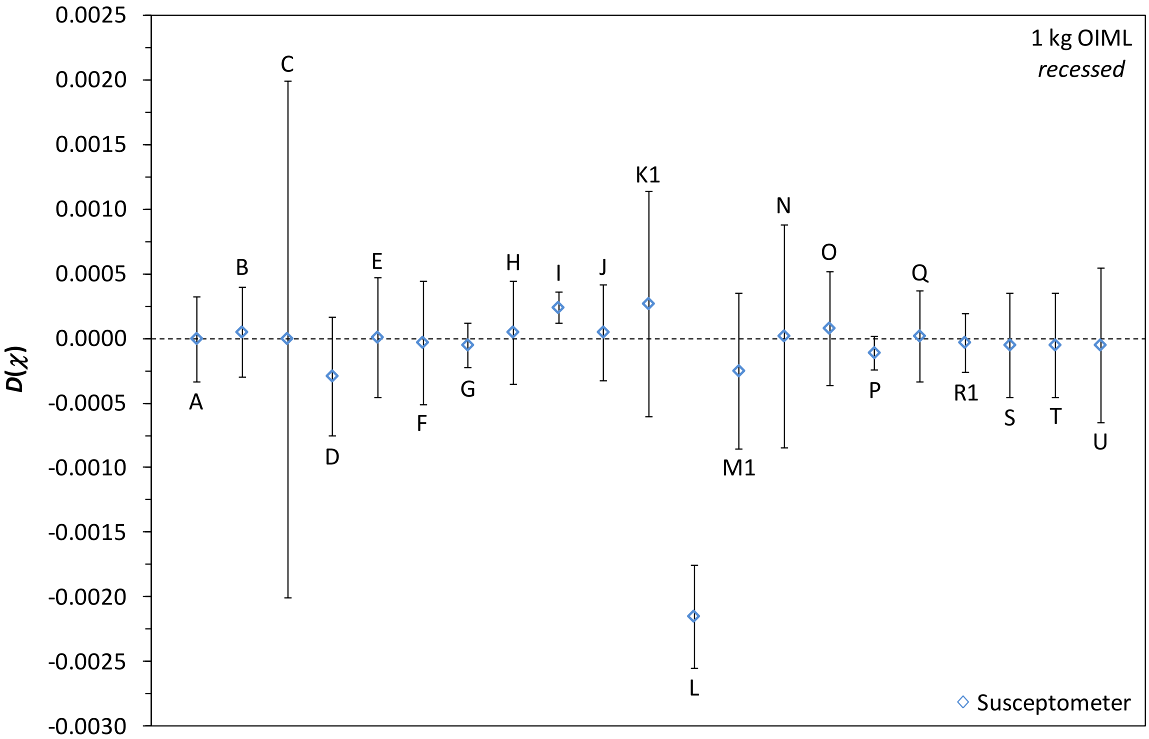


b)

Figure 10: Differences D_i between the results of the participating laboratories and the reference values (median) for the determination of a) the volume magnetic susceptibility χ and b) the permanent magnetic polarization $\mu_0 M_z$ of the 1 kg-OIML weight (flat bottom, 'Z2"). The uncertainty bars correspond to the expanded measurements uncertainties $U(D_i)$ (coverage factor k = 2).



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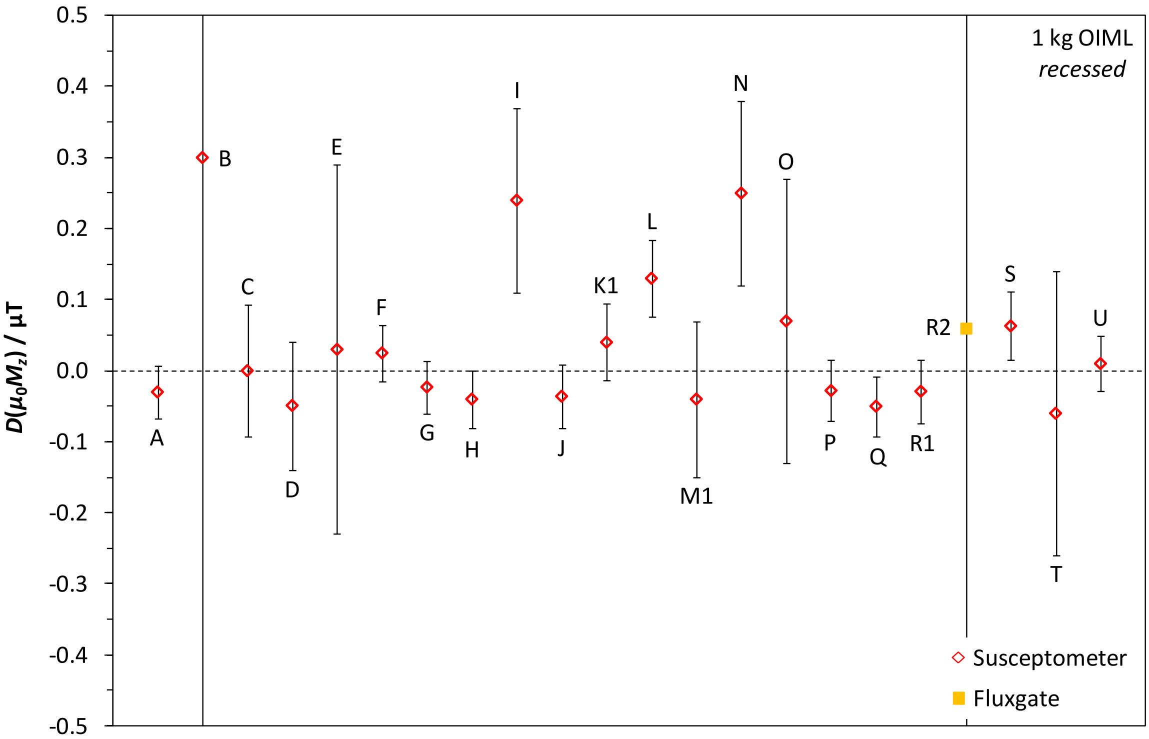
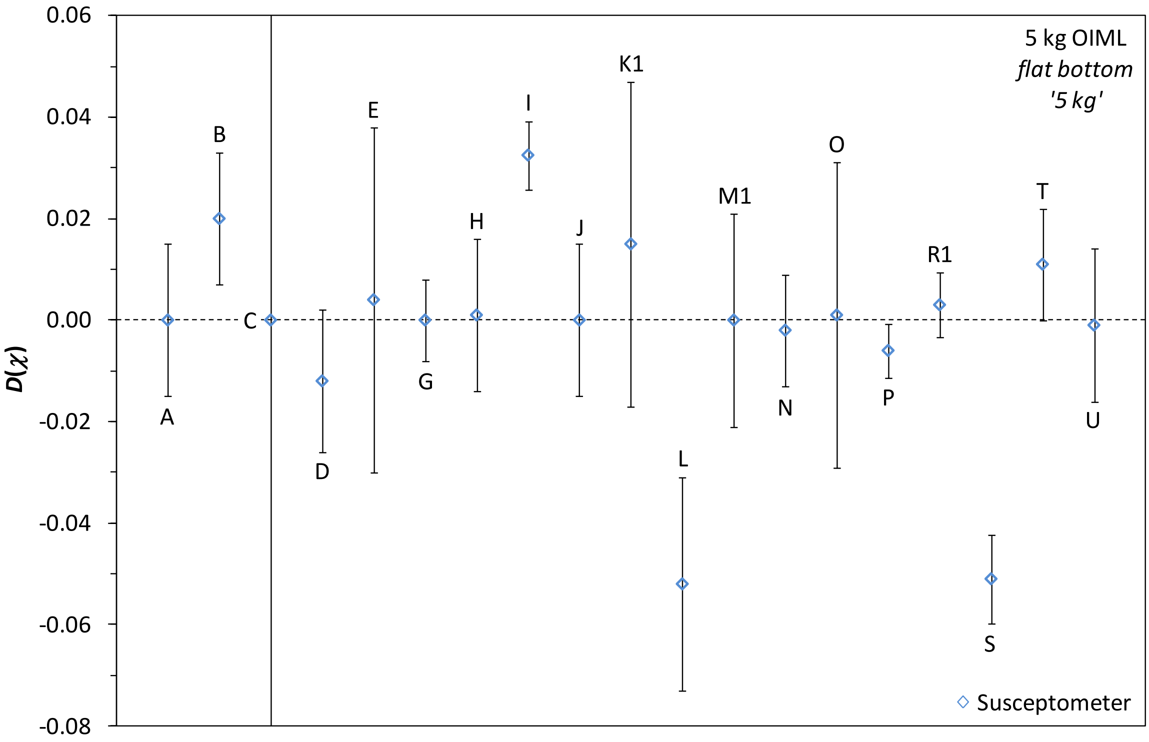


b)

Figure 11: Differences D_i between the results of the participating laboratories and the reference values (median) for the determination of a) the volume magnetic susceptibility χ and b) the permanent magnetic polarization $\mu_0 M_z$ of the 1 kg-OIML weight (recessed bottom). The uncertainty bars correspond to the expanded measurements uncertainties $U(D_i)$ (coverage factor k = 2). Due to the enlarged data representation some uncertainty bars were trimmed for the permanent magnetic polarization (participants B and R2). The numerical values of the trimmed uncertainty bars can be taken from table 12.



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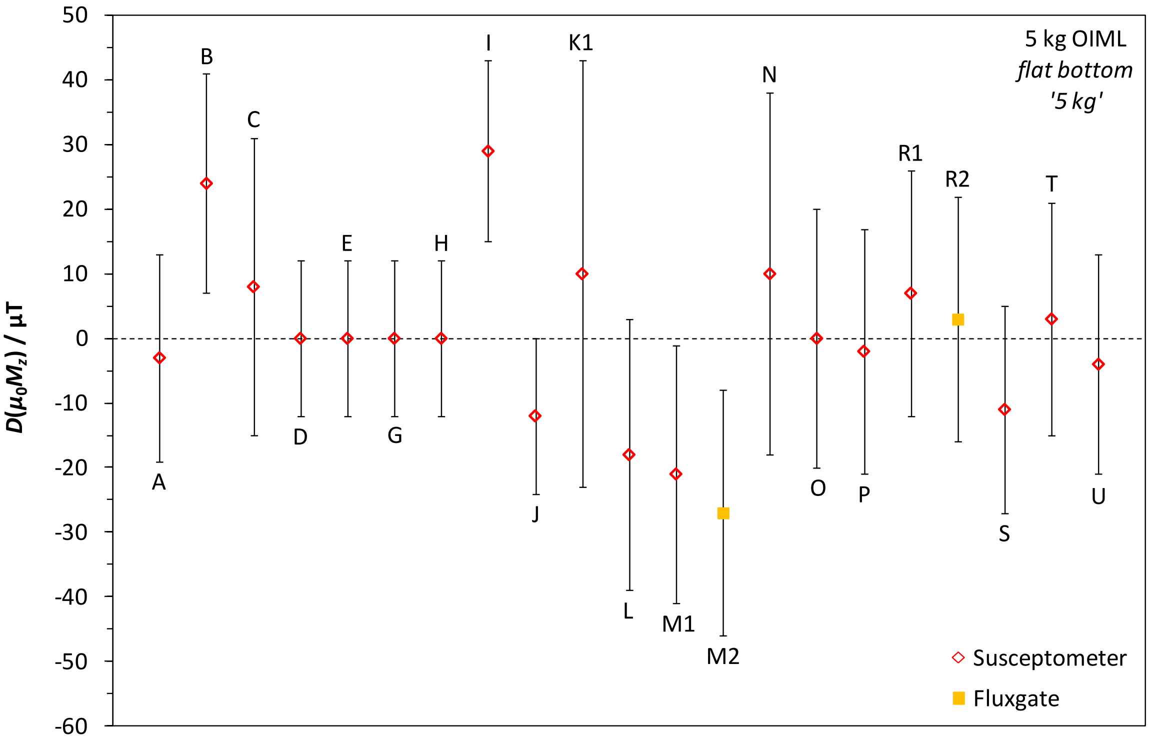
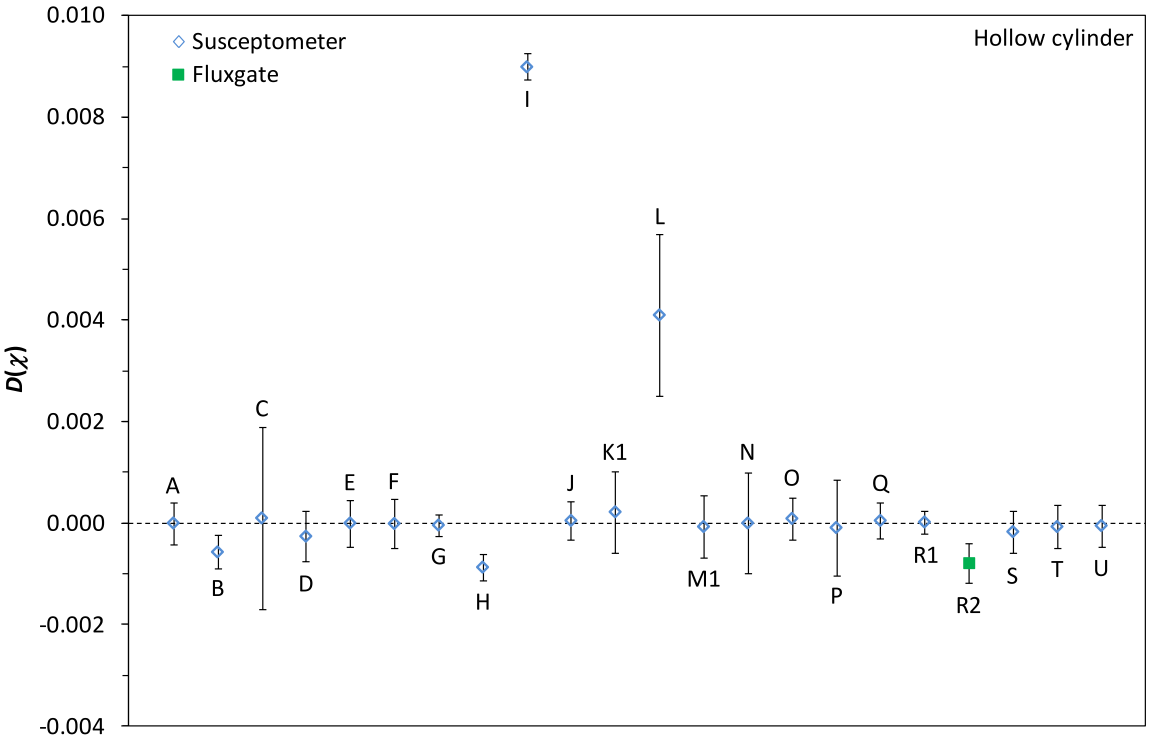


b)

Figure 12: Differences D_i between the results of the participating laboratories and the reference values (median) for the determination of a) the volume magnetic susceptibility χ and b) the permanent magnetic polarization $\mu_0 M_z$ of the 5 kg-OIML weight. The uncertainty bars correspond to the expanded measurements uncertainties $U(D_i)$ (coverage factor k = 2). Due to the enlarged data representation some uncertainty bars were trimmed for the volume magnetic susceptibility (participant C). The numerical values of the trimmed uncertainty bars can be taken from table 11.



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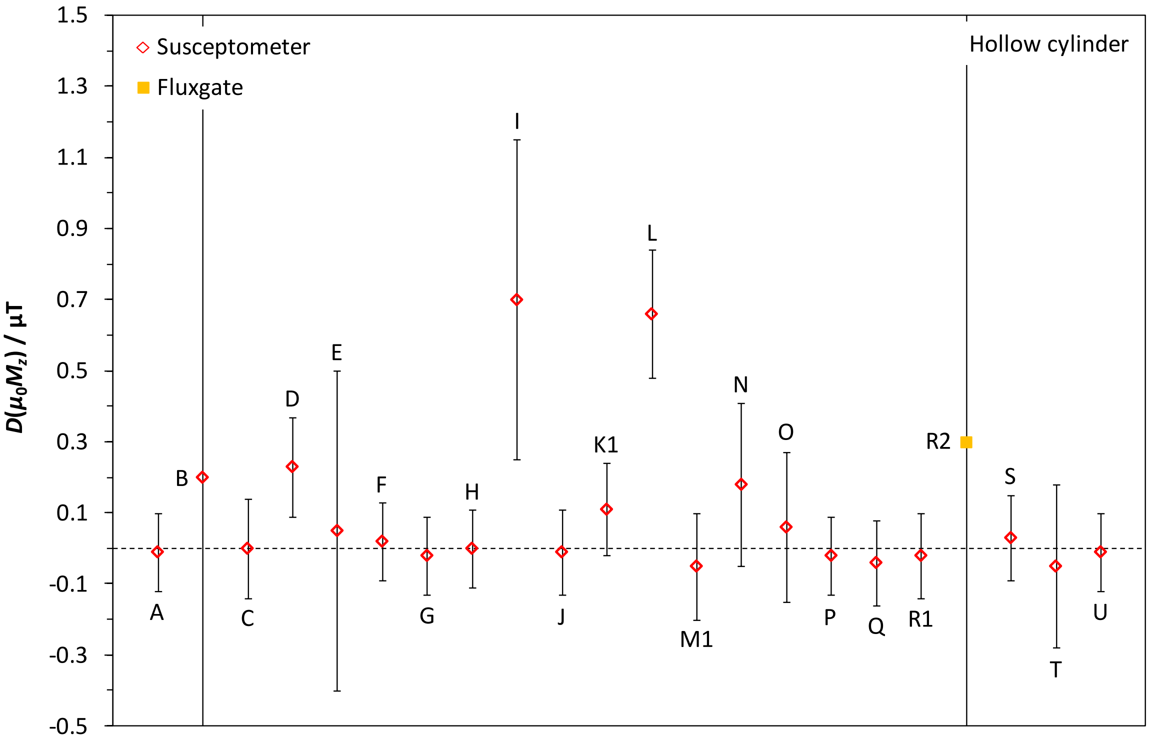

b)

Figure 13: Differences D_i between the results of the participating laboratories and the reference values (median) for the determination of a) the volume magnetic susceptibility χ and b) the permanent magnetic polarization $\mu_0 M_z$ of the hollow cylinder. The uncertainty bars correspond to the expanded measurements uncertainties $U(D_i)$ (coverage factor k = 2). Due to the enlarged data representation some uncertainty bars were trimmed for the permanent magnetic polarization (participants B and R2). The numerical values of the trimmed uncertainty bars can be taken from table 12.

4. Summary

It was the special aim of this comparison to compare the results obtained by the participating laboratories when measuring the volume magnetic susceptibility and the permanent magnetic polarization of mass standards with different geometrical shapes and nominal values using the test procedures recommended by the OIML R 111 [1]. Five stainless steel mass standards with different nominal values (2 g, 1 kg and 5 kg) and outer geometries (cylindrical OIML shaped weights with recess and flat bottom, hollow cylinder) were chosen as transfer standards and sent to the participants. Altogether 21 laboratories determined the magnetic properties of the transfer standards within five petals.

In order to check the stability of the transfer standards and to estimate the reproducibility of the susceptometer measurements the pilot laboratory determined the magnetic properties of the transfer standards at the beginning and at the end of each petal. In some cases the stability of the transfer standards and the reproducibility of the measurement results were much larger than the uncertainties given by the participants. The observed changes of the interim measurement results may arise from the influence of the test procedure, of the handling and of the environmental and transport conditions on the magnetic properties of the transfer standards. Especially for the 5 kg-OIML weight some participants used very high magnetic field strengths (up to 4 kA/m) for the determination of the magnetic properties, although a maximum magnetic field strength of only 0.2 kA/m is recommended in the OIML R 111, section 6.4.5, when testing weights of classes F_1 and F_2. Such high magnetic field strengths can cause permanent magnetization (or demagnetization) of a transfer standard leading to unclear measurement results. On the other side inhomogeneities of a transfer standard can also lead to differences of the interim results, since the equations provided in [1] assume homogenity. Some participants noticed that especially for the 1 kg-OIML weight (marking 'Z2') the permanent magnetic polarization showed a significant dependence on the magnetic field strength used for the determination of the magnetic properties leading to the assumption that this weight was slightly inhomogeneously magnetized.

All participants used the susceptometer method for the determination of the magnetic properties. Additional alternative measurement procedures were used by three of totally 21 participating laboratories. Before the reference values were calculated a consistency check was made by applying a chi-squared test, which failed for all measurement results of both magnetic properties. Therefore the median was used as a reference value for both the volume magnetic susceptibility and the permanent magnetic polarization. No correlations between the different susceptometers (commercially available and self-built devices) used for this intercomparision were observed.

In laboratory practice, the magnetic properties of weights are verified based on the maximum permissible errors recommended by the OIML R111 [1], which were included in the figures 4 to 8. Therefore, it should be mentioned that – except for the instabilities observed in case of the permanent magnetic polarization of the OIML weight with a nominal value of 5 kg – all results reported by the participants would lead to consistent results for the verification of the magnetic susceptibility and permanent magnetic polarization of the travelling standards. It can be concluded that the magnetic properties of the 2 g OIML weight, of the 1 kg OIML weight with flat bottom (marking "Z2"), of the 1 kg OIML weight with recessed base and of the hollow cylinder correspond to a weight of class E_1 according to the OIML R 111 [1].

5. Literature

[1] OIML 2004 *International recommendation R 111 – weights of classes E_1, E_2, F_1, F_2, M_1, $M_{1\text{-}2}$, M_2, $M_{2\text{-}3}$ and M_3. Part 1: metrological and technical requirements* (Paris: International Organization of Legal Metrology (OIML))

[2] JCGM 2008 *Evaluation of measurement data – guide to the expression of uncertainty in measurement*. (Sèvres: International Bureau of Weights and Measures (BIPM))

[3] Cox M G 2002 The evaluation of key comparison data *Metrologia* **39** 589-95

[4] Müller J W 2000 Possible advantages of a robust evaluation of comparisons *J. Res. Natl. Inst. Stand. Technol.* **105** 551-5