Final Report for GULFMET.M.M.K7

Key Comparison of 5 kg, 100 g, 10 g, 5 g and 500 mg Mass Standards

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ABSTRACT

This report summarizes the results of the key comparison (KC) carried out among seven National Metrology Institutes (NMIs) five of which are member countries of Gulf Association for Metrology (GULFMET). The KC of 5 kg, 100 g, 10 g, 5 g stainless steel knob weights and 500 mg nickel silver flat pentagonal shaped weight was decided during the 11th meeting of GULFMET TC Mass held in Abu Dhabi, 2017. TÜBİTAK UME (Turkey) acted as pilot laboratory. The comparison was linked to CCM.M-K7 via INRIM (Italy) and METAS (Switzerland). The results were evaluated by the generalized least square (GLS) estimation. Majority of results were consistent with each other and with the key comparison reference value of CCM.M-K7 within their expanded uncertainties with the coverage factor of $k = 2$.

1. INTRODUCTION

GULFMET is a Regional Metrology Organization (RMO) bringing together National Metrology Institutes (NMIs) and Designated Institutes (DIs) of the United Arab Emirates, Kingdom of Bahrain, Kingdom of Saudi Arabia, Sultanate of Oman, State of Qatar, State of Kuwait and Republic of Yemen. GULFMET assumes a coordinating role in helping the NMIs and DIs to develop international recognition. The key comparison, GULFMET.M.M-K7 was based on the decision during the 11^{th} meeting of GULFMET TC Mass held in Abu Dhabi, 2017 in an attempt to provide evidence for supporting CMCs of the participating institutes and to evaluate the degree of equivalence between the participants in calibrating mass standards. The comparison was piloted by UME (Turkey), an associate member of GULFMET, and linked to CCM.M-K7 [1] via INRIM (Italy) and METAS (Switzerland). The protocol is prepared by following the rules of *Comité International des Poids et Mesures* (CIPM) Mutual Recognition Arrangement (MRA) [2]. The participants agreed on the technical protocol prior to the comparison where timetable, list of participating institutes, plan of the comparison, description of the travelling standards, transport and handling of the travelling standards, determination of mass and reporting are described in details. Travelling mass standards of 5 kg, 100 g, 10 g, 5 g stainless steel knob weights and 500 mg nickel silver flat pentagonal shaped weight were used. Seven laboratories measured the set of travelling standards between November 2017 and January 2019. The travelling standards were mainly delivered by courier companies between the participants. They were hand-carried between the participating institutes by their technical staffs whenever possible. The analysis of data is performed in MATLAB 7.8.0 (R2009a) according to the guidelines given in [3-6].

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3. PARTICIPATING INSTITUTES

The number of participating institutes in this KC is 7 together with the pilot laboratory (UME) and two linking laboratories (INRIM and METAS). The participating institutes, contact persons and co-workers are summarized in Table 1. In the 11th meeting of GULFMET, DCL (Dubai) and DGSM (Oman) had also pronounced their intent for participating in the comparison. However, DGSM has not returned the questionnaire to officially declare their participation and in the course of circulation of the travelling standards, DCL stated that they decided to withdraw from the comparison.

Table 1. Participating institutes, contact persons and co-workers of the comparison. The contact persons are listed in the first row for each institute.

Participating Institute	Acronym	Country	Contact Persons Co-workers
TÜBİTAK Ulusal Metroloji Enstitüsü	UME (Pilot Lab)	Turkey	Beste Korutlu Sevda Kaçmaz Lenara Kangı
Eidgenössisches Institut Für Metrologie	METAS (Linking Lab)	Switzerland	Christian Wüthrich Kilian Marti Stefan Russi
Istituto Nazionale di Ricerca Metrologica	INRiM (Linking Lab)	Italy	Andrea Malengo Davide Torchio
Emirates Metrology Institute	EMI/ QCC	United Arab Emirates	Christos Mitsas Asma Al Hosani
SASO - National Measurement and Calibration Center	SASO-NMCC	Kingdom of Saudi Arabia	Saud Alqarni Ahmed Aljuwyr
Public Authority for Industry	PAI	Kuwait	Aisha Al-Abdulhadi Mariam Khalaf Tahani AL-Rabah
Qatar General Organization for Standards and Measurements	QGOSM	Qatar	Abeer I. Al-Qattan Yasser A. Abdelaziz

4. DESCRIPTION OF THE TRAVELLING STANDARDS

The travelling standards of 5 kg, 100 g, 10 g, 5 g stainless steel knob weights and 500 mg nickel silver flat pentagonal shaped weight were circulated among the participants. The weights are marked as K1 on their top surfaces as shown in Figure 1-(a).

Table 2 summarizes the relevant technical data on density, volume, magnetic susceptibility, magnetization and the center of gravity values of the travelling standards together with their corresponding uncertainties as determined at UME.

The transportation box for the transfer of the traveling standards is composed of an outer hard case with dimensions $32\ \mathrm{cm} \times 53\ \mathrm{cm} \times 24\ \mathrm{cm}$ and an inner ABS case with dimensions $24\ \mathrm{cm} \times 38\ \mathrm{cm} \times 18\ \mathrm{cm}$ as shown in Figure 1-(b) and Figure 1-(c). Each travelling standard (5 kg, 100 g, 10 g, 5 g and 500 mg) is placed in the appropriate space provided inside the ABS case. There is an additional plastic box for 500 mg weight. The total weight of the transportation case together with the travelling standards is ~ 14.2 kg in total. The appropriate gloves are provided within the transportation box.

Table 2. The technical data of the travelling standards.

	5 kg	100 g	10 g	5 g	500 mg
Density $\rho\ (kg/m^3)$	7858.0	7988.0	8041.0	8004.2	8600[†]
Density Uncertainty $u_\rho\ (kg/m^3)$	0.3	1.1	3.9	6.4	215 (% 2.5)
Volume $V\ (cm^3)$	636.303	12.5188	1.2436	0.6246	0.058
Volume Uncertainty $u_V\ (cm^3)$	0.026	0.0018	0.0006	0.0005	0.001 (% 2.5)
Magnetic Susceptibility χ	0.00269	0.00373	0.00393	0.00491	-
Magnetic Susceptibility Uncertainty u_χ	0.00200	0.00200	0.00600	0.00600	-
Magnetization $M\ (\mu T)$	0.01	0.06	0.06	0.18	-
Magnetization Uncertainty $u_M\ (\mu T)$	0.25	0.25	0.25	0.25	-
Center of Gravity $Z\ (mm)$	64.0	17.0	8.2	-	-

Figure 1. The transfer standards and the transportation case.

(a)

(b)

[†]*Assumed density value.*

(c)

5. TIMETABLE FOR THE CIRCULATION OF THE TRAVELLING STANDARDS

Table 3 shows the timetable for the circulation of the travelling standards.

Table 3. Timetable for the circulation of standards

Loop	Participating Institute	Date of arrival	Date of departure	Date of sending the results
Loop 0	UME	-	20/11/2017	25/12/2017
	METAS*	30/11/2017	09/01/2017	09/01/2019
	INRIM	30/01/2018	19/02/2018	19/03/2018
Loop 1	UME	26/02/2018	12/04/2018	10/05/2018
	EMI/ QCC	18/04/2018	31/05/2018	27/08/2018
	SASO	23/06/2018	12/07/2018	12/08/2018
Loop 2	PAI	18/07/2018	08/08/2018	27/08/2018
	UME	13/08/2018	28/09/2018	01/10/2018
	QGOSM	04/10/2018	27/11/2018	25/12/2018
	UME	05/12/2018	-	05/02/2019

* The measurement period is extended two more weeks due to the pause in shipping during Christmas Holiday.

6. WEIGHING INSTRUMENTS USED BY PARTICIPANTS

The weighing instruments used by the participating laboratories are listed in Table 4 based on the information provided by the participants without any verification.

Table 4. Weighing instruments of the participating institutes.

Nominal	NMI	Manufacturer	Model	Capacity	Resolution
5 kg	UME	Sartorius	C10000S	10 050 g	100 µg
	METAS	Mettler-Toledo	AT10005	10 011 g	10 µg
	INRIM	Mettler-Toledo	AT10005	10 011 g	10 µg
	EMI/ QCC	Mettler-Toledo	AX10005	10 011 g	10 µg
	SASO	Mettler-Toledo	AX10005	10 011 g	10 µg
	PAI	Mettler-Toledo	AX10005	10 011 g	10 µg
	QGOSM	Mettler-Toledo	XP 26003 L	26 100 g	1 mg
100 g	UME	Sartorius	C1000S	1 000.5 g	1 µg
	METAS	Mettler-Toledo	M-one	1 001.5 g	0.1 µg
	INRIM	Mettler-Toledo	M-one	1 kg	0.1 µg
	EMI/ QCC	Mettler-Toledo	a100	111 g	1 µg
	SASO	Sartorius	CC1000S-L	1 000 g	1 µg
	PAI	Mettler-Toledo	AX106H	111g	1 µg
	QGOSM	Mettler-Toledo	AX 2005	2109 g	10 µg
10 g	UME	Sartorius	C 50S	50.5 g	1 µg
	METAS	Mettler-Toledo	AT106	111 g	1 µg
	INRIM	Mettler-Toledo	AT107	100 g	0.1 µg
	EMI/ QCC	Mettler-Toledo	a100	111 g	1 µg
	SASO	Sartorius	CCR10-1000	1 016 g	0.1 µg
	PAI	Mettler-Toledo	AX106H	111g	1 µg
	QGOSM	Mettler-Toledo	AX 2005	2109 g	10 µg
5 g	UME	Mettler-Toledo	AT21	22 g	1 µg
	METAS	Mettler-Toledo	A5	5.1 g	0.1 µg
	INRIM	Mettler-Toledo	UMX5	5 g	0.1 µg
	EMI/ QCC	Mettler-Toledo	a5	5.1 g	0.1 µg
	SASO	Sartorius	CCR10-1000	1 016 g	0.1 µg
	PAI	Mettler-Toledo	AX106H	111g	1 µg
	QGOSM	Mettler-Toledo	AX 2005	2109 g	10 µg
500 mg	UME	Sartorius	S4	4 g	0.1 µg
	METAS	Mettler-Toledo	A5	5.1 g	0.1 µg
	INRIM	Mettler-Toledo	UMX5	5 g	0.1 µg
	EMI/ QCC	Mettler-Toledo	a5	5.1 g	0.1 µg
	SASO	Sartorius	CCR10-1000	1 016 g	0.1 µg
	PAI	Mettler-Toledo	AX106H	111g	1 µg
	QGOSM	Mettler-Toledo	AX 2005	2109 g	10 µg

7. MESUREMENT RESULTS

The comparison results reported by each participant are presented in Table 5. The p^{th} measurement of participating NMI is denoted by $(L_i)_p$ where $i = 1,\cdots,7$ represents UME, METAS, INRIM, EMI, SASO, PAI, QGOSM, respectively. The measurement number $p = 1,\cdots,4$ for the pilot laboratory UME, while $p = 1$ for any other participating laboratory. In Table 6, the deviation of the true mass value $m_j(L_i)_p$ of the j^{th} travelling standard, where $j = 1,\cdots,5$ represents the travelling standards of 5 kg, 100 g, 10 g, 5 g and 500 mg, respectively, from the nominal mass value m_0 of the relevant travelling standard and the corresponding standard uncertainty u_j determined by each participating NMI are given. Table 6 summarizes the deviation of the linking laboratories from the Key Comparison Reference Value (KCRV) of CCM.M-K7 and the corresponding standard uncertainties for each travelling standard.

Table 5. The true mass values and their standard uncertainties with the coverage factor of $k = 1$ reported by each participant. All units are given in mg.

	$m_0 = 5$ kg		$m_0 = 100$ g		$m_0 = 10$ g		$m_0 = 5$ g		$m_0 = 500$ mg	
$(L_i)_p$	$m_1(L_i)_p - m_0$	u_1	$m_2(L_i)_p - m_0$	u_2	$m_3(L_i)_p - m_0$	u_3	$m_4(L_i)_p - m_0$	u_4	$m_5(L_i)_p - m_0$	u_5
UME	8.8	0.2	-0.018	0.008	-0.008	0.001	0.007	0.001	-0.0280	0.0015
METAS	8.69	0.14	-0.0171	0.0029	-0.0110	0.0014	0.0079	0.0010	-0.0297	0.0017
INRIM	8.84	0.08	-0.0190	0.0046	-0.0085	0.0018	0.0070	0.0013	-0.0297	0.0013
UME	8.6	0.2	-0.019	0.008	-0.008	0.001	0.008	0.001	-0.0320	0.0015
EMI	8.90	0.23	-0.037	0.008	-0.012	0.002	0.0058	0.0010	-0.0312	0.0017
SASO	8.76	0.26	-0.013	0.005	-0.0096	0.0022	0.0042	0.0018	-0.0325	0.0012
PAI	-4.81	0.40	-0.007	0.008	0.000	0.004	0.010	0.003	-0.009	0.002
UME	8.7	0.2	-0.021	0.008	-0.008	0.001	0.007	0.001	-0.0340	0.0015
QGOSM	-4	1	-0.03	0.05	0.03	0.05	0.00	0.03	-0.03	0.04
UME	8.6	0.2	-0.028	0.008	-0.006	0.001	0.007	0.001	-0.0350	0.0015

Table 6. The deviation of the linking laboratories from KCRV of CCM.M-K7 and their corresponding standard uncertainties with the coverage factor of $k = 1$. All units are given in mg.

	$m_0 = 5$ kg		$m_0 = 100$		$m_0 = 10$ g		$m_0 = 5$ g		$m_0 = 500$ mg	
L_i	$(m_c)_1 - K_1$	u_{c1}	$(m_c)_2 - K_2$	u_{c2}	$(m_c)_3 - K_3$	u_{c3}	$(m_c)_4 - K_4$	u_{c4}	$(m_c)_5 - K_5$	u_{c5}
METAS	0.157	0.148	0.0025	0.0042	-0.0026	0.0022	-0.0002	0.0015	0.0007	0.0008
INRIM	-0.009	0.091	0.0037	0.0041	0.0005	0.0019	-0.0004	0.0012	0.0000	0.0006

8. THE ANALYSIS OF THE RESULTS

The comparison results given in Table 5 are analyzed and linked to the CCM.M-K7 key comparison via Generalized Least-Squares (GLS) estimation [4]. Degree of equivalence of each participating laboratory relative to the CCM.M-K7 Key Comparison Reference Value (KCRV) is calculated. The model function for the comparison reads

$$\boldsymbol{y} = \boldsymbol{X}\,\boldsymbol{\beta} + \boldsymbol{e}, \tag{1}$$

where $\boldsymbol{y} = (y_1, \cdots, y_g)^{\boldsymbol{T}}$ is a $g \times 1$ column vector of measurement results, $\boldsymbol{X}$ is a $g \times h$ design matrix, $\boldsymbol{\beta} = (\beta_1, \cdots, \beta_h)^{\boldsymbol{T}}$ is a $h \times 1$ column vector of the unknowns and $\boldsymbol{e} = (e_1, \cdots, e_g)^{\boldsymbol{T}}$ is a $g \times 1$ column vector of random errors and disturbances associated with the measurement. Here, g represents the total number of measurements carried on the travelling standard by n participating institutes and $h = n + 3$ represents the total number of unknowns for one travelling standard with nominal mass value m_0 such that

$$\boldsymbol{\beta} = \left(\Delta_1, \cdots, \Delta_n, m_0 - m_j,\ a_j, K_j - m_c\right)^T, \tag{2}$$

where Δ_i^*, $i = 1, \cdots, n$ is the bias of i^{th} laboratory from the j^{th} KCRV, $m_j^\dagger$ is the obtained mass value of the j^{th} travelling standard at the time of GULFMET.M.M-K7 comparison, K_j represents the KCRV obtained in CCM.M-K7 for the mass with j^{th} nominal mass value, m_c is the determined mass value for the travelling standard with j^{th} nominal mass value at the time of CIPM comparison and a_j appears if m_j changes linearly in time such that

$$m_j(t) = m_j' + \ a_j t. \tag{3}$$

It is important to note that the model function is formed by the equations describing the measurements of the current comparison GULFMET.M.M-K7

$$m_j(L_i)_p - m_0 = \Delta_i - \left(m_0 - m_j\right) + e_{j,i,p}, \tag{4}$$

and that of the CIPM comparison CCM.M-K7

$$m_c(L_i)_p - K_j = \Delta_i - \left(K_j - m_c\right) + e_{c,i,p}, \tag{5}$$

where p represents the repeat measurement of the laboratories. The elements of vector $\boldsymbol{y}$ are the measurement results $m_j(L_i)_p - m_0$ and $m_c(L_i)_p - K_j$ and the value of $K_j - m_c$. We choose $K_j - m_c = 0$ as constraint so that the expected deviation of the i^{th} laboratory from K_j is simply Δ_i.

The GLS solution to (1) is given by

$$\boldsymbol{\beta} = \boldsymbol{C}\boldsymbol{X}^{\boldsymbol{T}}\Phi^{\,-\boldsymbol{1}}\boldsymbol{y}, \tag{6}$$

where $\boldsymbol{C}$ is the uncertainty matrix

$$\boldsymbol{C} = (\boldsymbol{X}^{\boldsymbol{T}}\Phi^{\,-\boldsymbol{1}}\boldsymbol{X})^{-\boldsymbol{1}}. \tag{7}$$

* $\Delta_1 = \Delta_{\mathrm{UME}}$, $\Delta_2 = \Delta_{\mathrm{METAS}}$, $\Delta_3 = \Delta_{\mathrm{INRIM}}$, $\Delta_4 = \Delta_{\mathrm{EMI}}$, $\Delta_5 = \Delta_{\mathrm{SASO}}$, $\Delta_6 = \Delta_{\mathrm{PAI}}$, $\Delta_7 = \Delta_{\mathrm{QATAR}}$.

† $m_1 = 5$ kg, $m_2 = 100$ g, $m_3 = 10$ g, $m_4 = 5$ g and $m_5 = 500$ mg.

The Φ matrix appearing in (6) and (7) is the $g \times g$ variance-covariance matrix formulated such that the expected value $E[e_i] = 0$ and $E\left[e_i e_j\right] = \Phi_{ij}$. The diagonal elements of Φ are the variances $u(y_i)^2$ (standard uncertainty squared declared by the i^{th} laboratory for $k = 1$) associated with each measurement result and off-diagonal entries are simply the covariances resulting from the correlations among the measurements as given in Table 7. Intra-laboratory correlations occur between the repeat measurements of the travelling standards by the pilot laboratory by virtue of the fact that the same reference standard has been used in calibrating the travelling standards and between the measurements of the travelling standards by linking laboratories as they have used the same reference standards in GULFMET.M.M-K7 and CCM.M-K7 comparisons. Another source of correlation is the traceability of one participating laboratory to another one. In GULFMET.M.M-K7, there is correlation between SASO-NMCC and UME as the reference standards of SASO-NMCC are traceable to the primary standards of UME. The short term stability (STS) of the travelling standards was calculated from the repeat measurements of the pilot laboratory and included in the diagonal elements Φ_{ii} as rectangular distribution

$$u_{STS} = \frac{m_j(L_{UME})_{p+1} - m_j(L_{UME})_p}{2\sqrt{3}}. \quad (8)$$

The storage during transport, handling, temperature changes, environmental factors and comparator characteristics might be the reasons for instability in the mass of the travelling standards.

The expanded uncertainty for the i^{th} bias for the each travelling standard is calculated by the square root of the i^{th} diagonal element of the relevant $\boldsymbol{C}$ matrix multiplied by the coverage factor k such that

$$U_i = k\sqrt{C_{ii}}. \quad (9)$$

The normalized deviation d_i reflecting degree of equivalence is calculated by

$$d_i = \frac{\Delta_i}{U_i}, \quad (10)$$

for each travelling standard. A measure of the goodness-of-fit of the model (1) is obtained by comparing the observed chi-squared values by

$$\chi^2 = (\boldsymbol{y} - \boldsymbol{X\beta})^T \Phi^{-1} (\boldsymbol{y} - \boldsymbol{X\beta}), \quad (11)$$

with the expected one $E(\chi_\nu^2)$ where ν is the degrees of freedom in the comparison. There are 8 unknowns (7 Laboratory biases and 1 mass of the travelling standard for each transfer standard) plus one constraint parameter and 12 known parameters (10 GULFMET.M.M-K7 measurement results, 2 CCM.M-K7 results of the linking laboratories) yielding $\nu = 4$.

The degree of equivalence between any two participating laboratory is obtained by the differences between the biases of the laboratories

$$\Delta_{ij} = \Delta_i - \Delta_j, \quad (12)$$

for $i, j = 1, \cdots, 7$ and the corresponding expanded uncertainty reads

$$U_{ij} = k\sqrt{C_{ii} + C_{jj} - 2C_{ij}}. \tag{13}$$

The results of the analysis are summarized in Table 8 to Table 15. Table 8 represents the deviation of the participating institute in GULFMET.M.M-K7 comparison from the KCRV of the CCM.M-K7 comparison (Δ_i) together with the expanded uncertainties for the coverage factor of $k = 2$ (U_i) and normalized deviation (d_i). Note that the deviation of linking laboratories in GULFMET.M.M-K7 agrees well with the ones in CCM.M-K7 within the expanded uncertainties for the coverage factor of $k = 2$. The deviation of true masses of the travelling standards from their nominal values, their corresponding expanded uncertainties for coverage factor of $k = 2$, the linear drifts in the masses of travelling standards and the expanded uncertainties for coverage factor of $k = 2$ in the linear drifts are given in Table 9. Table 10-a to Table 14-a give the degrees of equivalence between (Δ_{ij}) the pairs of participating laboratories and their corresponding expanded uncertainties for $k = 2$ (U_{ij}) are given in Table 10-b to Table 14-b for each travelling standard. The observed chi-squared values for each travelling standard and the expected value of chi-squared $E(\chi_v^2)$ together with its standard deviation $\sigma(\chi_v^2)$ are given in Table 15.

The results are also depicted in Fig. 2 to Fig. 11 where Fig. 2 to Fig. 6 represent the measurement results declared by participating institutes with their corresponding expanded uncertainties for $k = 2$ and Fig. 7 to Fig. 11 show the deviation of the laboratories from the KCRV value. Zero mass difference (given in red solid line) corresponds to the KCRV of the CCM.M-K7 comparison. The majority of the results are consistent with each other and with KCRV of the CCM.M-K7.

9. SUMMARY AND CONCLUSIONS

1. The GULFMET key comparison of 5 kg, 100 g, 10 g, 5 g and 500 mg is linked to CCM.M-K7. Five GULFMET members participated in the comparison. Two linking laboratories were METAS and INRIM.

2. GLS estimation is used for the analysis of the results. The majority of the participant results in GULFMET.M.M-K7 are consistent with each other and with KCRV of CCM.M-K7 within their expanded uncertainties of $k = 2$.

3. The results of the linking laboratories in GULFMET.M.M-K7 agree well with the ones in CCM.M-K7 within the expanded uncertainties of $k = 2$.

4. The results of two laboratories in GULFMET.M.M-K7 differ significantly from KCRV of 5 kg, and the result of one laboratory differs significantly from KCRV of 500 mg. However, none of these laboratories have published CMC values in the KCDB.

5. The delays in circulation of travelling standards mainly resulted during the custom clearance of travelling standards.

6. The stability of the travelling standards is monitored by the repeat measurements of the pilot lab. Linear drifts in the travelling standards are taken into account in the analysis of the results. There was an apparent linear drift in the mass of 500 mg travelling standard (see a_j in Table 9). This drift causes uncertainties of the

laboratories to get larger in the linking analysis compared to the ones declared by the participants in their reports.

7. The uncertainty associated with the volume of the 500 mg travelling standard was not adequate to demonstrate the CMCs of the pilot (UME) and linking laboratories (METAS and INRIM). In the same way, due to the volume uncertainty of the 100 g travelling standard, the results of the pilot (UME) and linking laboratory (INRIM) were slightly outside of the declared CMCs. However they are good enough to demonstrate all the CMCs of the GULFMET participants (which is the aim of this comparison).

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Table 7. Correlated standard uncertainties. All units are given in mg.

	Intra-laboratory					Intra-laboratory CCM-GULFMET					Inter-laboatory Tracable to another GULFMET laboratory				
	5 kg	100 g	10 g	5 g	500 mg	5 kg	100 g	10 g	5 g	500 mg	5 kg	100 g	10 g	5 g	500 mg
UME	0.1	0.0015	0.0005	0.0005	0.0002										
METAS						0.134	0.0021	0.0004	0.0004	0.0003					
INRIM						0.076	0.0040	0.0016	0.0011	0.0006					
EMI															
SASO											0.1 (UME)	0.0015 (UME)	0.0005 (UME)	0.0005 (UME)	0.0002 (UME)
PAI															
QGOSM															

Table 8. Deviation from the KCRV of CCM.M-K7 and associated expanded uncertainty ($k = 2$) for each participating laboratory.

	$m_0 = 5$ kg			$m_0 = 100$			$m_0 = 10$ g			$m_0 = 5$ g			$m_0 = 500$ mg		
L_i	Δ_i (mg)	U_i (mg)	d_i	Δ_i (mg)	U_i (mg)	d_i	Δ_i (mg)	U_i (mg)	d_i	Δ_i (mg)	U_i (mg)	d_i	Δ_i (mg)	U_i (mg)	d_i
UME	-0.116	0.342	0.34	-0.0036	0.0128	0.28	0.0012	0.0030	0.41	0.0006	0.0021	0.26	-0.0007	0.0048	0.14
METAS	-0.156	0.303	0.51	-0.0027	0.0076	0.36	-0.0002	0.0031	0.06	0.0008	0.0021	0.38	-0.0007	0.0016	0.45
INRIM	0.009	0.199	0.04	-0.0037	0.0084	0.44	0.0001	0.0037	0.03	0.0003	0.0024	0.14	0.0000	0.0012	0.00
EMI	0.099	0.507	0.20	-0.0198	0.0188	1.05	-0.0031	0.0049	0.64	-0.0009	0.0026	0.36	0.0001	0.0066	0.01
SASO	-0.018	0.581	0.03	0.0056	0.0155	0.36	-0.0010	0.0053	0.19	-0.0025	0.0040	0.62	-0.0003	0.0065	0.05
PAI	-13.580	0.848	16.02	0.0122	0.0206	0.59	0.0085	0.0086	0.99	0.0034	0.0063	0.54	0.0236	0.0074	3.19
QGOSM	-12.743	2.030	6.28	-0.0091	0.0101	0.09	0.0381	0.0100	0.38	-0.0066	0.0600	0.11	0.0039	0.0803	0.05

Table 9. The deviation of true masses of the travelling standards from their nominal values ($m_j' - m_0$), their corresponding expanded uncertainties (U_j') for coverage factor of $k = 2$, the linear drifts in the masses of travelling standards (a_j) and the expanded uncertainties for coverage factor of $k = 2$ in the linear drifts (U_{a_j}).

m_0	$m_j' - m_0$ (mg)	U_j' (mg)	a_j (mg/day)	U_{a_j} (mg/day)
5 kg	8.86	0.13	0.0003	0.0011
100 g	-0.0134	0.0072	0.00002	0.00005
10 g	-0.0097	0.0026	-0.000005	0.000007
5 g	0.0069	0.0016	0.000001	0.000006
500 mg	0.0282	0.0037	0.00002	0.00002

Table 10-a. The degree of equivalence between any two participating laboratory in calibrating 5 kg mass standard. All units are given in mg.

L_i	UME	METAS	INRIM	EMI	SASO	PAI	QGOSM
UME		0.040	-0.124	-0.215	-0.097	13.464	12.628
METAS	-0.040		-0.164	-0.255	-0.137	13.424	12.588
INRIM	0.124	0.164		-0.091	0.027	13.588	12.752
EMI	0.215	0.255	0.091		0.117	13.679	12.843
SASO	0.097	0.137	-0.027	-0.117		13.561	12.725
PAI	-13.464	-13.424	-13.588	-13.679	-13.561		-0.836
QGOSM	-12.628	-12.588	-12.752	-12.843	-12.725	0.836	

Table 10-b. The expanded uncertainties ($k = 2$) for the corresponding values in Table 10-a. All units are given in mg.

L_i	UME	METAS	INRIM	EMI	SASO	PAI	QGOSM
UME		0.426	0.353	0.543	0.524	0.852	2.026
METAS	0.426		0.326	0.566	0.636	0.886	2.048
INRIM	0.353	0.326		0.515	0.587	0.852	2.032
EMI	0.543	0.566	0.515		0.711	0.939	2.065
SASO	0.524	0.636	0.587	0.711		0.965	2.074
PAI	0.852	0.886	0.852	0.939	0.965		2.160
QGOSM	2.026	2.048	2.032	2.065	2.074	2.160	

Table 11-a. The degree of equivalence between any two participating laboratory in calibrating 100 g mass standard. All units are given in mg.

L_i	UME	METAS	INRIM	EMI	SASO	PAI	QGOSM
UME		-0.011	-0.010	0.005	-0.020	-0.027	-0.006
METAS	0.011		0.001	0.016	-0.009	-0.016	0.005
INRIM	0.010	-0.001		0.016	-0.010	-0.017	0.004
EMI	-0.005	-0.016	-0.016		-0.026	-0.032	-0.011
SASO	0.020	0.009	0.010	0.026		-0.007	0.014
PAI	0.027	0.016	0.017	0.032	0.007		0.021
QGOSM	0.006	-0.005	-0.004	0.011	-0.014	-0.021	

Table 11-b. The expanded uncertainties ($k = 2$) for the corresponding values in Table 11-a. All units are given in mg.

L_i	UME	METAS	INRIM	EMI	SASO	PAI	QGOSM
UME		0.015	0.016	0.021	0.016	0.021	0.101
METAS	0.015		0.011	0.021	0.019	0.023	0.102
INRIM	0.016	0.011		0.022	0.019	0.024	0.102
EMI	0.021	0.021	0.022		0.023	0.026	0.102
SASO	0.016	0.019	0.019	0.023	0.00	0.022	0.101
PAI	0.021	0.023	0.024	0.026	0.022		0.102
QGOSM	0.101	0.102	0.102	0.102	0.101	0.102	

Table 12-a. The degree of equivalence between any two participating laboratory in calibrating 10 g mass standard. All units are given in mg.

L_i	UME	METAS	INRIM	EMI	SASO	PAI	QGOSM
UME		0.001	0.001	0.004	0.002	-0.007	-0.037
METAS	-0.001		0	0.003	0.001	-0.009	-0.038
INRIM	-0.001	0		0.003	0.001	-0.008	-0.038
EMI	-0.004	-0.003	-0.003		-0.002	-0.012	-0.041
SASO	-0.002	-0.001	-0.001	0.002		-0.009	-0.039
PAI	0.007	0.009	0.008	0.012	0.009		-0.030
QGOSM	0.037	0.038	0.038	0.041	0.039	0.030	

Table 12-b. The expanded uncertainties ($k = 2$) for the corresponding values in Table 12-a. All units are given in mg.

L_i	UME	METAS	INRIM	EMI	SASO	PAI	QGOSM
UME		0.0032	0.0041	0.0044	0.0046	0.0082	0.1000
METAS	0.0032		0.0044	0.0050	0.0054	0.0086	0.1001
INRIM	0.0041	0.0044		0.0056	0.0060	0.0090	0.1001
EMI	0.0044	0.0050	0.0056		0.0062	0.0093	0.1001
SASO	0.0046	0.0054	0.0060	0.0062		0.0093	0.1001
PAI	0.0082	0.0086	0.0090	0.0091	0.0093		0.1001
QGOSM	0.1000	0.1001	0.1001	0.1001	0.1001	0.1003	

Table 13-a. The degree of equivalence between any two participating laboratory in calibrating 5 g mass standard. All units are given in mg.

L_i	UME	METAS	INRIM	EMI	SASO	PAI	QGOSM
UME		0	0	0.001	0.003	-0.003	0.007
METAS	0		0.001	0.002	0.003	-0.003	0.007
INRIM	0	0.001		0.001	0.003	-0.003	0.007
EMI	-0.001	-0.002	-0.001		0.002	-0.004	0.006
SASO	-0.003	-0.003	-0.003	-0.002		-0.006	0.004
PAI	0.003	0.003	0.003	0.004	0.006		0.010
QGOSM	-0.007	-0.007	-0.007	-0.006	-0.004	-0.010	

Table 13-b. The expanded uncertainties ($k = 2$) for the corresponding values in Table 13-a. All units are given in mg.

L_i	UME	METAS	INRIM	EMI	SASO	PAI	QGOSM
UME		0.0024	0.0029	0.0024	0.0036	0.0062	0.0600
METAS	0.0024		0.0030	0.0028	0.0042	0.0064	0.0600
INRIM	0.0029	0.0030		0.0033	0.0045	0.0066	0.0601
EMI	0.0024	0.0028	0.0033		0.0041	0.0063	0.0600
SASO	0.0036	0.0042	0.0045	0.0041		0.0070	0.0601
PAI	0.0062	0.0064	0.0066	0.0063	0.0070		0.0603
QGOSM	0.0600	0.0600	0.0601	0.0600	0.0601	0.0603	

Table 14-a. The degree of equivalence between any two participating laboratory in calibrating 500 mg mass standard. All units are given in mg.

L_i	UME	METAS	INRIM	EMI	SASO	PAI	QGOSM
UME		0	-0.001	-0.001	0	-0.024	-0.005
METAS	0		-0.001	-0.001	0	-0.024	-0.005
INRIM	0.001	0.001		0	0	-0.024	-0.004
EMI	0.001	0.001	0		0	-0.024	-0.004
SASO	0	0	0	0		-0.024	-0.004
PAI	0.024	0.024	0.024	0.024	0.024		0.020
QGOSM	0.005	0.005	0.004	0.004	0.004	-0.020	

Table 14-b. The expanded uncertainties ($k = 2$) for the corresponding values in Table 14-a. All units are given in mg.

L_i	UME	METAS	INRIM	EMI	SASO	PAI	QGOSM
UME		0.0049	0.0050	0.0059	0.0053	0.0063	0.0802
METAS	0.0049		0.0020	0.0066	0.0065	0.0074	0.0803
INRIM	0.0050	0.0020		0.0067	0.0066	0.0075	0.0803
EMI	0.0059	0.0066	0.0067		0.0071	0.0079	0.0803
SASO	0.0053	0.0065	0.0066	0.0071		0.0074	0.0803
PAI	0.0063	0.0074	0.0075	0.0079	0.0074		0.0803
QGOSM	0.0802	0.0803	0.0803	0.0803	0.0803	0.0803	

Table 15. The observed chi-squared values for each travelling standard and expected value of chi-squared together with its standard deviation.

m_0	χ^2	$E(\chi_\nu^2) = \nu$	$\sigma(\chi_\nu^2) = \sqrt{2\nu}$
5 kg	0.5	3	3
100 g	0.2		
10 g	4.4		
5 g	1.2		
500 mg	0.4		

Figure 2: Deviation of true mass values from nominal mass value of 5 kg transfer standard with expanded uncertainties at $k = 2$.

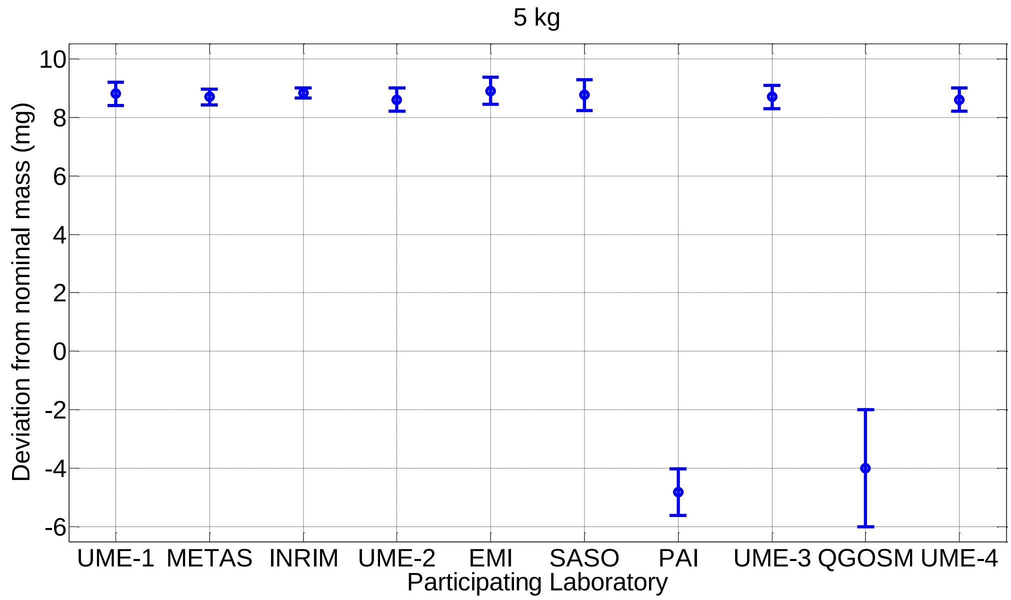

Figure 3: Deviation of true mass values from nominal mass value of 100 g transfer standard with expanded uncertainties at $k = 2$.

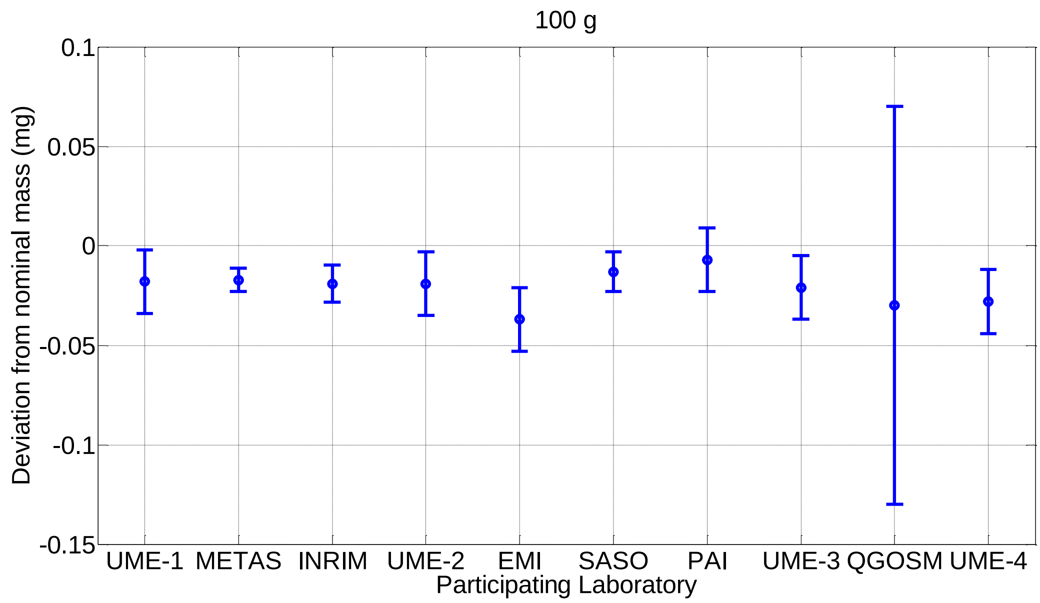

Figure 4: Deviation of true mass values from nominal mass value of 10 g transfer standard with expanded uncertainties at $k = 2$.

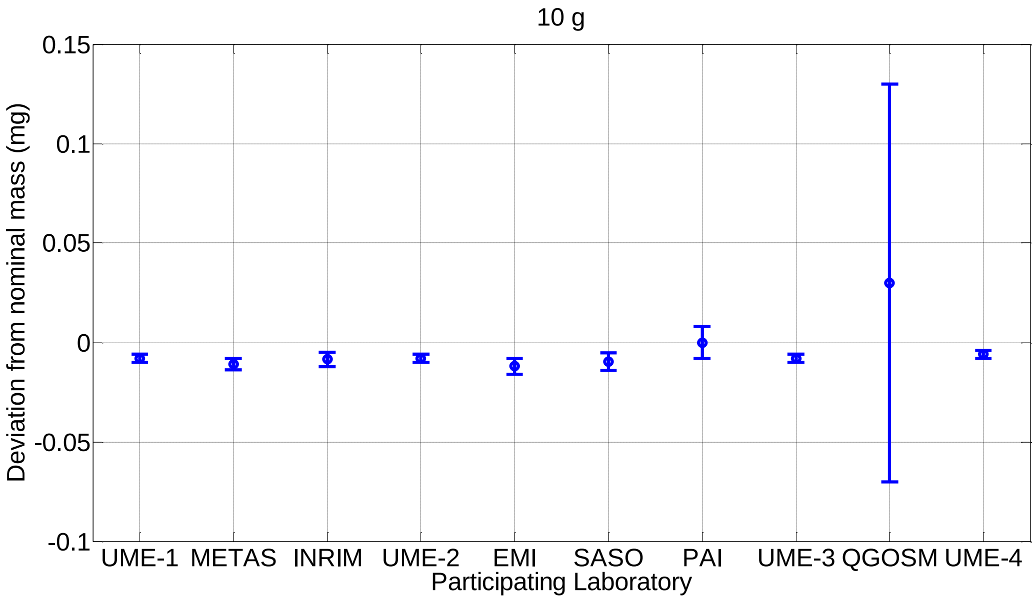

Figure 5: Deviation of true mass values from nominal mass value of 10 g transfer standard with expanded uncertainties at $k = 2$.

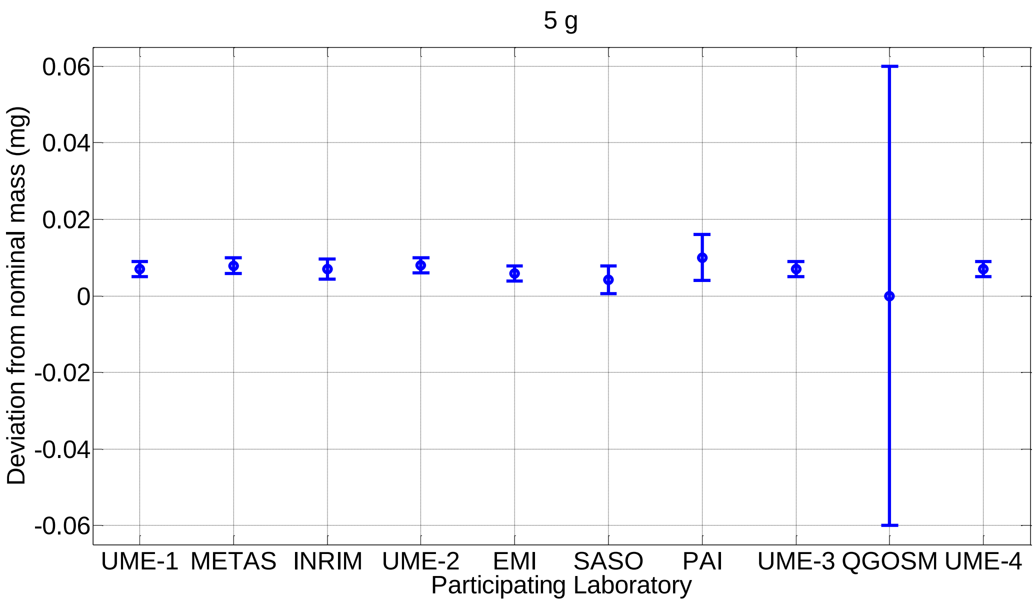

Figure 6: Deviation of true mass values from nominal mass value of 10 g transfer standard with expanded uncertainties at $k = 2$.

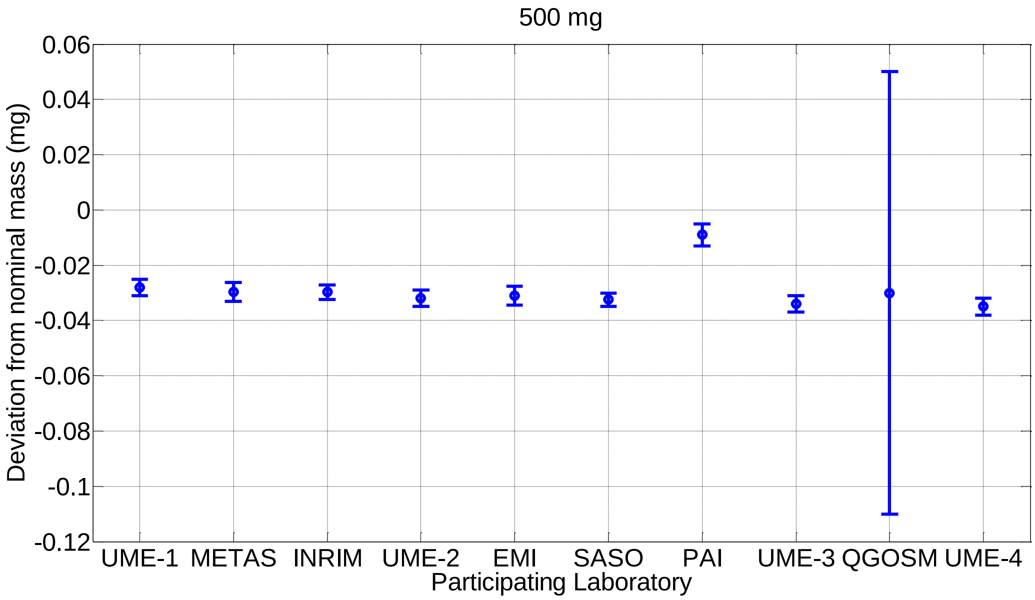

Figure 7: Deviation from the KCRV of 5 kg transfer standard in CCM.M-K7 and associated expanded uncertainty at $k = 2$ for each participating laboratory. Zero line in red corresponds to the KCRV of the CCM.M-K7 comparison.

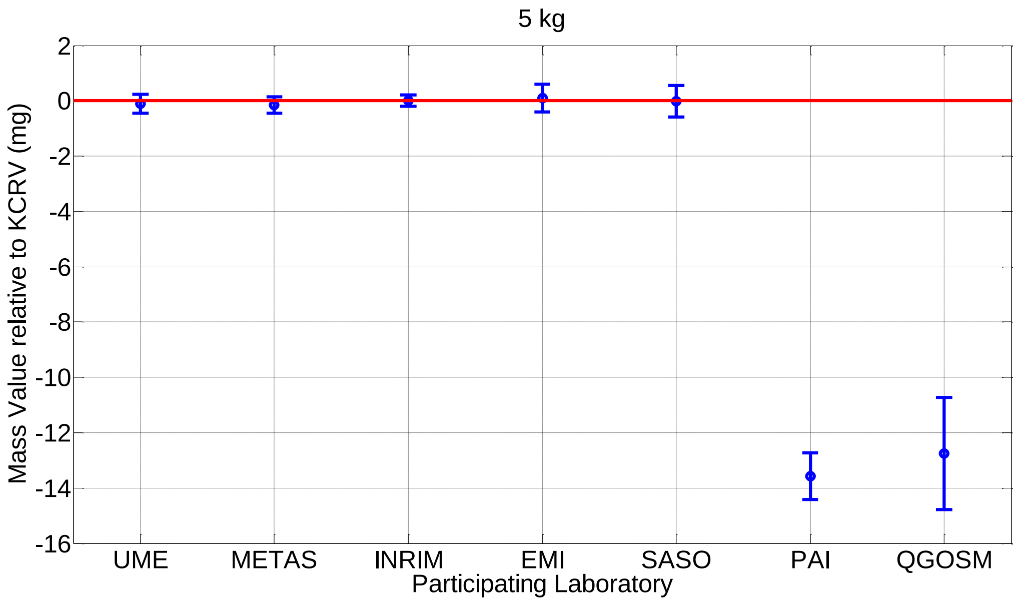

Figure 8: Deviation from the KCRV of 100 g transfer standard in CCM.M-K7 and associated expanded uncertainty at $k = 2$ for each participating laboratory. Zero line in red corresponds to the KCRV of the CCM.M-K7 comparison.

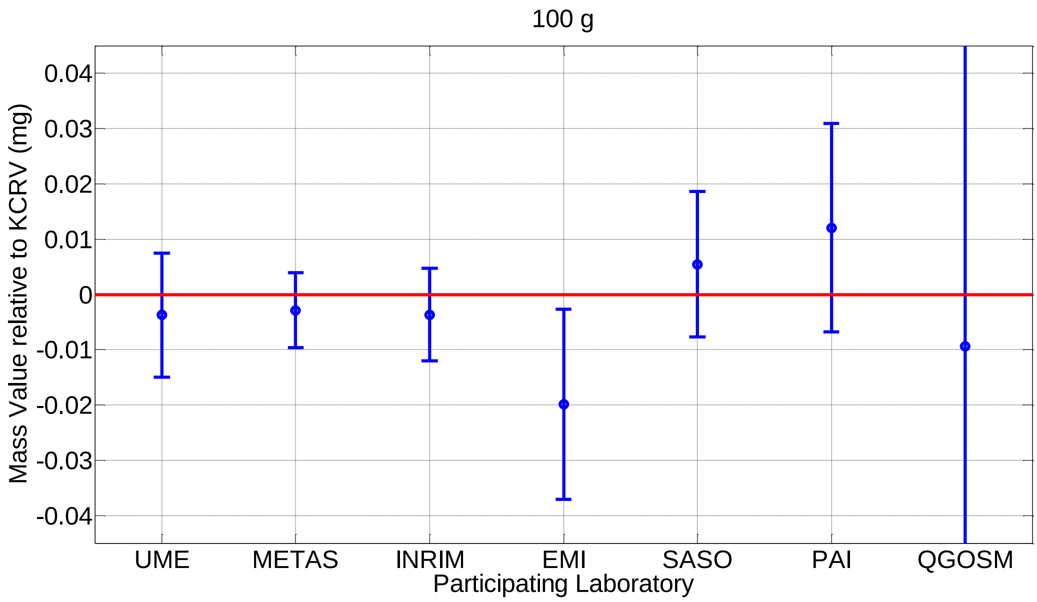

Figure 9: Deviation from the KCRV of 10 g transfer standard in CCM.M-K7 and associated expanded uncertainty at $k = 2$ for each participating laboratory. Zero line in red corresponds to the KCRV of the CCM.M-K7 comparison.

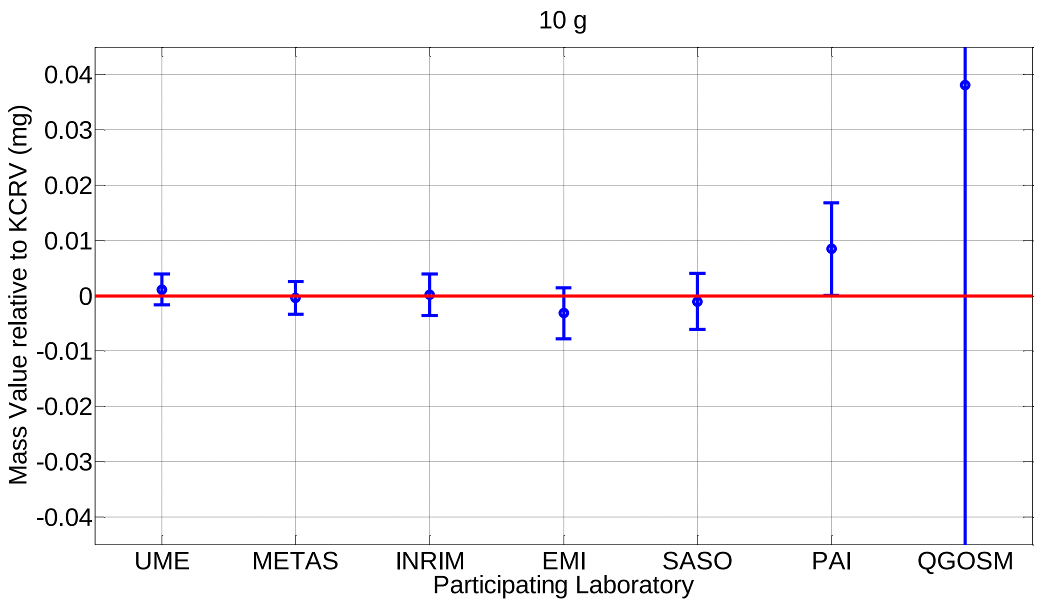

Figure 10: Deviation from the KCRV of 5 g transfer standard in CCM.M-K7 and associated expanded uncertainty at $k = 2$ for each participating laboratory. Zero line in red corresponds to the KCRV of the CCM.M-K7 comparison.

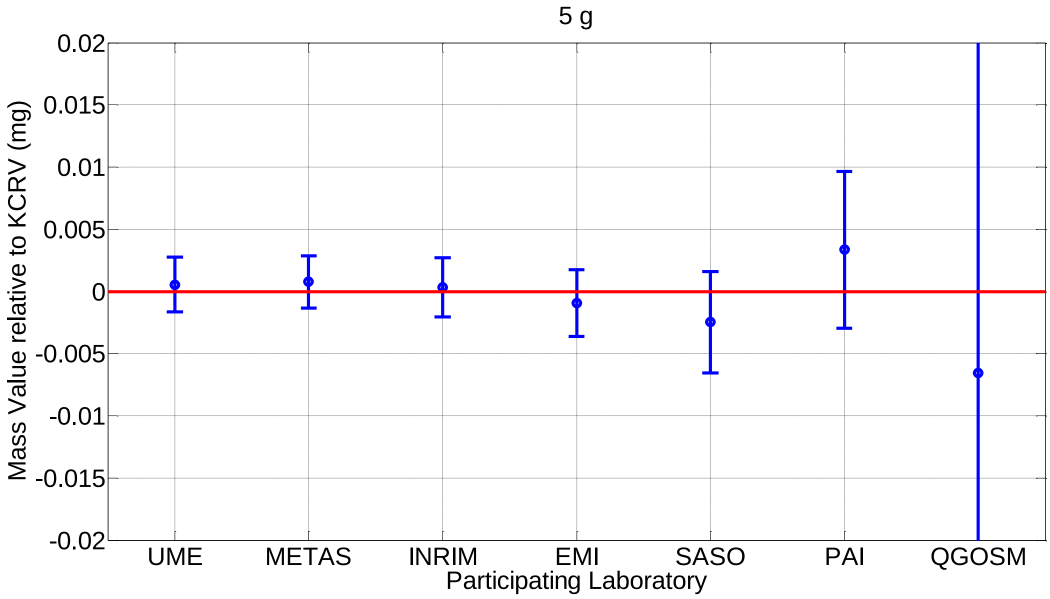

Figure 11: Deviation from the KCRV of 500 mg transfer standard in CCM.M-K7 and associated expanded uncertainty at $k = 2$ for each participating laboratory. Zero line in red corresponds to the KCRV of the CCM.M-K7 comparison.