Final Report

GULFMET.M.M.K4 "Key Comparison of 1 kg Stainless Steel Mass Standards"

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ABSTRACT

This report summarizes the results of the key comparison (KC) carried out among eight National Metrology Institutes (NMIs) and an Accredited Calibration Laboratory, six of which are member countries of Gulf Association for Metrology (GULFMET). The KC of two 1 kg stainless steel knob weights 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-K4 via INRIM (Italy), METAS (Switzerland), KRISS (Republic of Korea). 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-K4 within their expanded uncertainties with the coverage factor of $k = 2$.

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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-K4 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-K4 [1] via INRIM (Italy), METAS (Switzerland), KRISS (Republic of Korea). The protocol was 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 detail. Travelling mass standards of two 1 kg knob weights were used. Nine laboratories measured the two travelling standards between September 2017 and March 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]. As DCL is not a CIPM-MRA signatory, their results are presented in the Appendix A.

2. PARTICIPATING INSTITUTES

The number of participating institutes in this KC is 9 together with the pilot laboratory (UME) and three linking laboratories (INRIM, METAS and KRISS). The participating institutes are summarized in Table 1. In the 11^{th} meeting of GULFMET, DGSM (Oman) had also pronounced their intent for participating in the comparison. However, they have not returned the questionnaire to officially declare their participation. The participants are all CIPM-MRA signatories except DCL. This is why DCL is treated differently and their results are presented in Appendix A.

Table 1. Participating institutes of the comparison.

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
Korea Research Institute of Standards and Science	(KRISS) (Linking Lab)	Republic of Korea	Sungjun Lee
Emirates Metrology Institute	EMI/ QCC	United Arab Emirates	Christos Mitsas Asma Al Hosani
Qatar General Organization for Standards and Measurements	QGOSM	Qatar	Abeer I. Al-Qattan Yasser A. Abdelaziz
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
Dubai Central Laboratory Dubai,	(DCL)	United Arab Emirates[1]	Khalid Sadee Mahmoud Amal Gulam Shafi Niyas

[1] As DCL is not a CIPM-MRA signatory, their results are presented in the Appendix A.

3. DESCRIPTION OF THE TRAVELLING STANDARDS

The travelling standards of two 1 kg stainless steel knob weights were circulated among the participants. The weights are marked as K1 and K2 on their top surfaces as shown in Figure 1-(a).

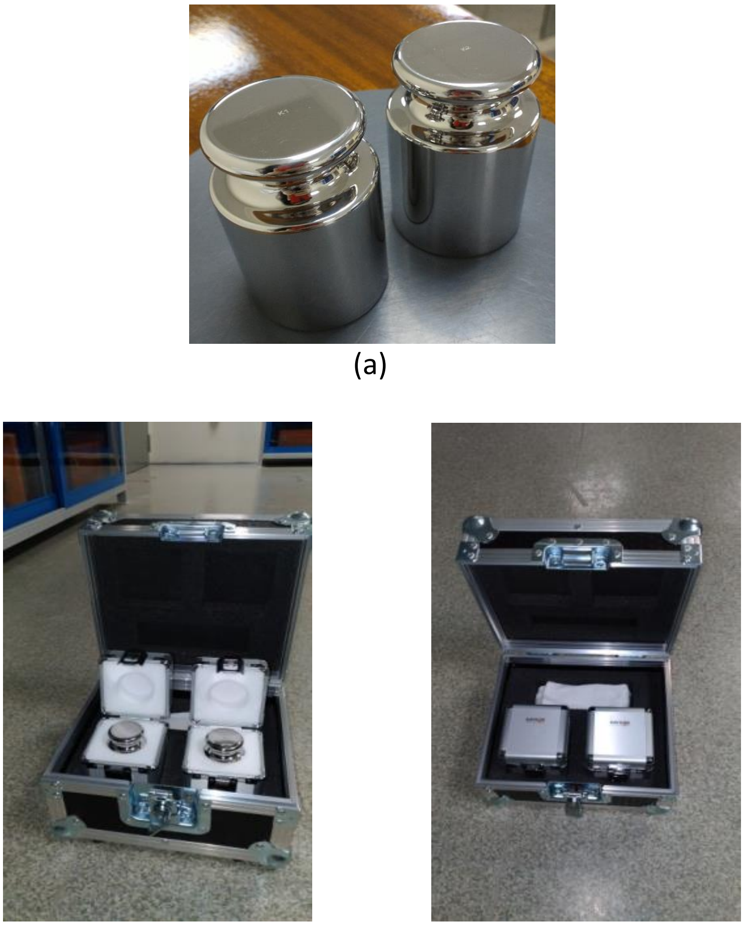
Table 2 summarizes the relevant technical data on density, volume, magnetic susceptibility, magnetization and the center of gravity values of the travelling standards together with their corresponding uncertainties, as determined at UME.

The transportation box for the transfer of the traveling standards is composed of an outer hard case with dimensions $24\ \text{cm} \times 27\ \text{cm} \times 20\ \text{cm}$ and two aluminum inner cases with dimensions $9\ \text{cm} \times 9\ \text{cm} \times 12\ \text{cm}$ as shown in Figure 1-(b) and Figure 1-(c). The two travelling standards (1kg-K1 and 1kg-K2) are placed in two separate boxes. The total weight of the transportation case together with the two 1 kg travelling standards is $\sim$6 kg in total. The appropriate gloves are provided within the transportation box.

Table 2. The technical data of the travelling standards.

	1 kg-K1	1 kg-K2
Density $\boldsymbol{\rho}\ (\boldsymbol{kg/m^3})$	8007.155	8010.583
Density Uncertainty $\boldsymbol{u_\rho}\ (\boldsymbol{kg/m^3})$	0.641	0.642
Volume $\boldsymbol{V}\ (\boldsymbol{cm^3})$	124.8884	124.8348
Volume Uncertainty $\boldsymbol{u_V}\ (\boldsymbol{cm^3})$	0.0100	0.0100
Magnetic Susceptibility $\boldsymbol{\chi}$	0.00328	0.00333
Magnetic Susceptibility Uncertainty $\boldsymbol{u_\chi}$	0.00200	0.00200
Magnetization $\boldsymbol{M}\ (\boldsymbol{\mu T})$	0.08	0.04
Magnetization Uncertainty $\boldsymbol{u_M}\ (\boldsymbol{\mu T})$	0.25	0.25
Center of Gravity $\boldsymbol{Z}\ (\boldsymbol{mm})$	35.8	35.8

Figure 1. The transfer standards and the transportation case.



(a)

(b) (c)

4. 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	-	02/10/2017	30/10/2017
	METAS	06/10/2017	06/11/2017	15/12/2017
	INRIM	24/11/2017	11/12/2017	29/12/2017
	KRISS	19/12/2017	18/01/2018	16/01/2018
Loop 1	UME	23/01/2018	21/02/2018	19/03/2018
	EMI/ QCC	05/03/2018	22/03/2018	19/04/2018
	DCL	22/03/2018	12/04/2018	10/05/2018
	QGOSM	29/04/2018	11/07/2018	18/09/2018
Loop 2	UME	04/09/2018	26/10/2018	23/11/2018
	SASO	14/11/2018	10/12/2018	13/12/2018
	PAI	12/12/2018	06/01/2019	16/01/2019

	UME	16/01/2019	-	08/04/2019

5. 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
1 kg	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	1 001.5 g	0.1 μg
	KRISS	Mettler-Toledo	M-one	1 001.5 g	0.1 μg
	EMI/ QCC	Mettler-Toledo	a1000	1 109 g	10 μg
	DCL	Mettler-Toledo	a1000	1 109 g	10 μg
	QGOSM	Mettler-Toledo	AX 2005	2 109 g	10 μg
	SASO	Mettler-Toledo	M-one	1 001.5 g	0.1 μg
	PAI	Mettler-Toledo	AX10005	10 011 g	10 μg

6. 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 $i = 1, \cdots, 9$ represents UME, METAS, INRIM, KRISS, EMI, QGOSM, SASO, PAI, DCL, respectively. The measurement number $p = 1, \cdots, 4$ for the pilot laboratory UME, while $p = 1$ for any other participating laboratory. The deviation of the true mass value $m_j(L_i)_p$ of the j^{th} travelling standard, where $j = 1, 2$ represents the travelling standards of 1 kg-K1 and 1 kg-K2, 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-K4 and the corresponding standard uncertainties with the coverage factor of $k = 1$ 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.

	1 kg –K1		1 kg – K2	
$(L_i)_p$	$m_1(L_i)_p - m_0$	u_1	$m_2(L_i)_p - m_0$	u_2
UME	0.785	0.023	-0.439	0.023
METAS	0.7756	0.0145	-0.4729	0.0145
INRIM	0.7700	0.0140	-0.4770	0.0140
KRISS	0.7510	0.0146	-0.4910	0.0146
UME	0.805	0.023	-0.444	0.023
EMI	0.77	0.04	-0.44	0.04
DCL	0.72	0.06	-0.57	0.06
QGOSM	1.03	0.10	-0.11	0.10
UME	0.800	0.023	-0.430	0.023
SASO	0.8305	0.0148	-0.3693	0.0148
PAI	1.05	0.12	-0.07	0.10
UME	0.882	0.023	-0.357	0.023

Table 6. The deviation of the linking laboratories from KCRV of CCM.M-K4 and their corresponding standard uncertainties with the coverage factor of $k = 1$. All units are given in mg.

L_i	$m_c - K$	u_c
METAS	-0.0100	0.0132
INRIM	0.0015	0.0078
KRISS	-0.0117	0.0145

BIPM amendments to certificates of the national prototypes of kilogram for the linking laboratories are given in the Table 7. The amendments are taken into account in the reports submitted by the linking laboratories.

Table 7. BIPM amendments to certificates of the national prototypes of kilogram for the linking laboratories. All units are given in mg.

L_i	No. Prototype	Old Mass – 1 kg	New mass – 1 kg	Difference
METAS	38	0.256	0.251	-0.005
INRIM	76	0.170	0.156	-0.014
KRISS	72	0.485	0.449	-0.036

It is important to note that the mean value of the differences in the three linking laboratories of GULFMET.M.M-K4 is -18 µg which is very close to the mean value of the amendments assigned by BIPM to all national prototypes of kilogram and that of the linking laboratory INRIM. As this value is also exceptionally close to the mean value of the BIPM amendments to the laboratories participating in CCM.M-K4, they are not taken into account for linking of GULFMET.M.M-K4 to the CCM.M-K4. Thus, a robust link is provided by the three linking NMIs which is not very sensitive to the way the linking is calculated and the results should be shifted by -18 µg in case the amendments are considered.

7. THE ANALYSIS OF THE RESULTS

The comparison results given in Table 5 are analyzed and linked to the CCM.M-K4 key comparison via Generalized Least-Squares (GLS) estimation [4]. Degree of equivalence of each participating laboratory relative to the CCM.M-K4 Key Comparison Reference Value (KCRV) is calculated. The model function for the comparison reads

$$\boldsymbol{y} = \boldsymbol{X}\,\boldsymbol{\beta} + \boldsymbol{e}, \qquad (1)$$

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 both travelling standard by n participating institutes and $h = n + 5$ represents the total number of unknowns obtained by travelling standards with nominal mass value of m_0 such that

$$\boldsymbol{\beta} = (\Delta_1, \cdots, \Delta_n, m_0 - m_1, m_0 - m_2, a_1, a_2, K - m_c)^T, \qquad (2)$$

where Δ_i^*, $i = 1, \cdots, n$ is the bias of i^{th} laboratory from the KCRV, m_j^+ is the obtained mass value of the j^{th} travelling standard at the time of GULFMET.M.M-K4 comparison, K represents the KCRV obtained in CCM.M-K4, m_c is the determined mass value for the travelling standard at the time of CIPM comparison and a_j appears if m_j changes linearly in time such that

$$m_j(t) = m_j' + \ a_j t. \qquad (3)$$

It is important to note that the model function is formed by the equations describing the measurement of the current comparison GULFMET.M.M-K4

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

and the that of the CIPM comparison CCM.M-K4

$$m_c(L_i)_p - K = \Delta_i - (K - m_c) + e_{c,i,p}, \qquad (5)$$

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 $m_c(L_i)_p - K$ and the value of $K - m_c$. We choose $K - m_c = 0$ as constraint so that the expected deviation of the i^{th} Laboratory from K is simply Δ_i.

The GLS solution to (1) is given by

$$\boldsymbol{\beta} = \boldsymbol{C}\boldsymbol{X}^{\boldsymbol{T}}\Phi^{-\mathbf{1}}\boldsymbol{y}, \qquad (6)$$

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

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

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* $\Delta_1 = \Delta_{\mathrm{UME}}$, $\Delta_2 = \Delta_{\mathrm{METAS}}$, $\Delta_3 = \Delta_{\mathrm{INRIM}}$, $\Delta_4 = \Delta_{\mathrm{KRISS}}$, $\Delta_5 = \Delta_{\mathrm{EMI}}$, $\Delta_6 = \Delta_{\mathrm{QATAR}}$, $\Delta_7 = \Delta_{\mathrm{SASO}}$, $\Delta_8 = \Delta_{\mathrm{PAI}}$.

\+ $m_1 = 1$ kg-K1, $m_2 = 1$ kg-K2.

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 $E[e_i e_j] = \Phi_{ij}$. 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 the each measurement result and off-diagonal entries are simply the covariances [4]. The correlations among the measurements are given in Table 8.

Table 8. Correlated standard uncertainties. All units are given in mg.

	Intra-laboratory	Intra-laboratory CCM-GULFMET
UME	0.015	
METAS		0.00885
INRIM		0.0059
KRISS		0.00146
EMI		
QGOSM		
SASO		
PAI		

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-K4 and CCM.M-K4 comparisons. The short term stability 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 goodness-of-fit of the model (1) is obtained by comparing the observed chi-squared values by

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

with the expected one $E(\chi^2_\nu)$ where ν is the degrees of freedom in the comparison. There are 10 unknowns (8 Laboratory biases and mass values of the 2 travelling standards) plus one constraint parameter and 25 known parameters (22 GULFMET.M.M-K4 measurement results, 3 CCM.M-K4 results of the linking laboratories) yielding $\nu = 14$.

The degree of equivalence between any two participating laboratory is obtained by

$$\Delta_{ij} = \Delta_i - \Delta_j, \tag{12}$$

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

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

The results of the analysis are summarized in Table 9 to Table 12. Table 9 represents the deviation of the participating institutes in GULFMET.M.M-K4 comparison from the KCRV of the CCM.M-K4 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 deviations of linking laboratories in GULFMET.M.M-K4 agree well with the ones in CCM.M-K4 within the expanded uncertainties for the coverage factor of $k = 2$.

Table 9. Deviation from the KCRV of CCM.M-K4 and associated expanded uncertainty ($k = 2$) for each participating laboratory.

L_i	Δ_i (mg)	U_i (mg)	d_i
UME	0.0375	0.0530	0.71
METAS	0.0118	0.0313	0.38
INRIM	-0.0010	0.0239	0.04
KRISS	0.0039	0.0313	0.13
EMI	0.0120	0.0762	0.16
QGOSM	0.2965	0.1511	1.96
SASO	0.0463	0.0665	0.70
PAI	0.3093	0.1669	1.85

Table 10. 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}).

	$m_0 - m'_j$ (mg)	U'_j (mg)	a_j (mg/day)	U_{a_j} (mg/day)
1 kg - K1	-0.7487	0.0375	0.00012	0.00015
1 kg - K2	0.4941	0.0338	0.00017	0.00014

Table 11-a. The degree of equivalence between any two participating laboratory in calibrating 1 kg mass standard. All units are given in mg.

L_i	UME	METAS	INRIM	KRISS	EMI	QGOSM	SASO	PAI
UME		0.0258	0.0386	0.0336	0.0256	-0.2589	-0.0088	-0.2717
METAS	-0.0258		0.0128	0.0078	-0.0002	-0.2847	-0.0346	-0.2975
INRIM	-0.0386	-0.0128		-0.0049	-0.0130	-0.2975	-0.0473	-0.3103
KRISS	-0.0336	-0.0078	0.0049		-0.0080	-0.2925	-0.0424	-0.3053
EMI	-0.0256	0.0002	0.0130	0.0080		-0.2845	-0.0344	-0.2973
QGOSM	0.2589	0.2847	0.2975	0.2925	0.2845		0.2501	-0.0128
SASO	0.0088	0.0346	0.0473	0.0424	0.0344	-0.2501		-0.2629
PAI	0.2717	0.2975	0.3103	0.3053	0.2973	0.0128	0.2629	

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	KRISS	EMI	QGOSM	SASO	PAI
UME		0.0506	0.0480	0.0481	0.0757	0.1499	0.0571	0.1630
METAS	0.0506		0.0233	0.0297	0.0744	0.1503	0.0648	0.1663
INRIM	0.0480	0.0233		0.0231	0.0728	0.1494	0.0625	0.1654
KRISS	0.0481	0.0297	0.0231		0.0730	0.1495	0.0622	0.1652
EMI	0.0757	0.0744	0.0728	0.0730		0.1605	0.0826	0.1737
QGOSM	0.1499	0.1503	0.1494	0.1495	0.1605		0.1528	0.2160
SASO	0.0571	0.0648	0.0625	0.0622	0.0826	0.1528		0.1628
PAI	0.1630	0.1663	0.1654	0.1652	0.1737	0.2160	0.1628	

Table 12. The observed chi-squared value and the expected value of chi-squared together with its standard deviation. The observed value agrees with the expected one within the standard deviation for $k = 2$.

χ^2	$E(\chi_\nu^2) = \nu$	$\sigma(\chi_\nu^2) = \sqrt{2\nu}$
7	14	5

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 10. Table 11-a gives the degrees of equivalence between the pairs of participating laboratories (Δ_{ij}) and their corresponding expanded uncertainties for $k = 2$ (U_{ij}) are given in Table 11-b. The observed chi-squared value and expected value of chi-squared $E(\chi_\nu^2)$ together with its standard deviation $\sigma(\chi_\nu^2)$ are given in Table 12. The results are also depicted in Fig. 2 to Fig. 4 where Fig. 2 and Fig. 3 represent the measurement results declared by participating institutes with their corresponding expanded uncertainties for $k = 2$ and Fig. 4 shows 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-K4 comparison. The majority of the results are consistent with each other and with KCRV of the CCM.M-K4.

Figure 2: Deviation of true mass values from nominal mass value of 1 kg-K1 transfer standard with expanded uncertainties at $k = 2$.

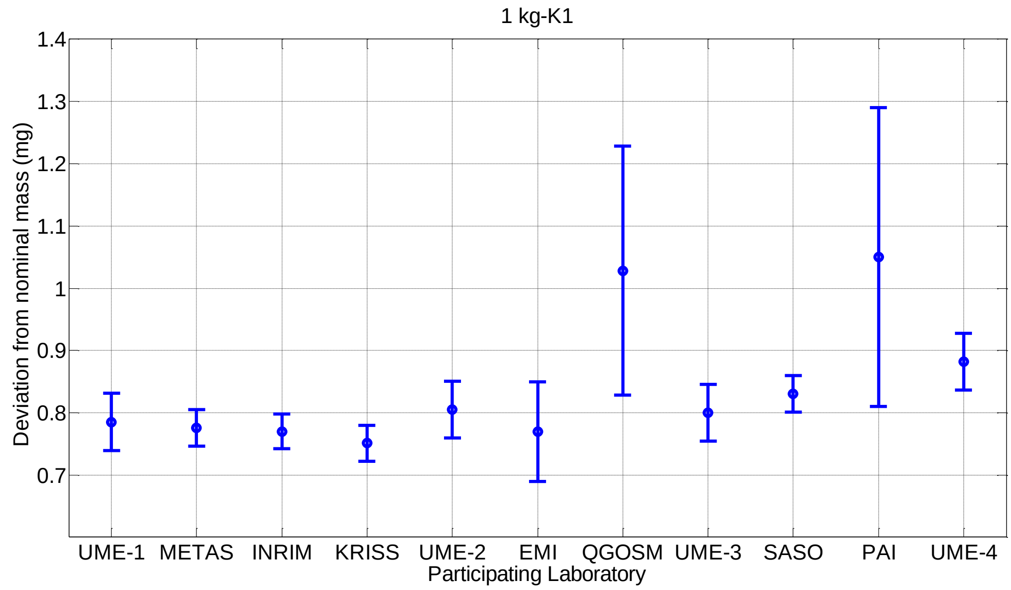


Figure 3: Deviation of true mass values from nominal mass value of 1 kg-K2 transfer standard with expanded uncertainties at $k = 2$.

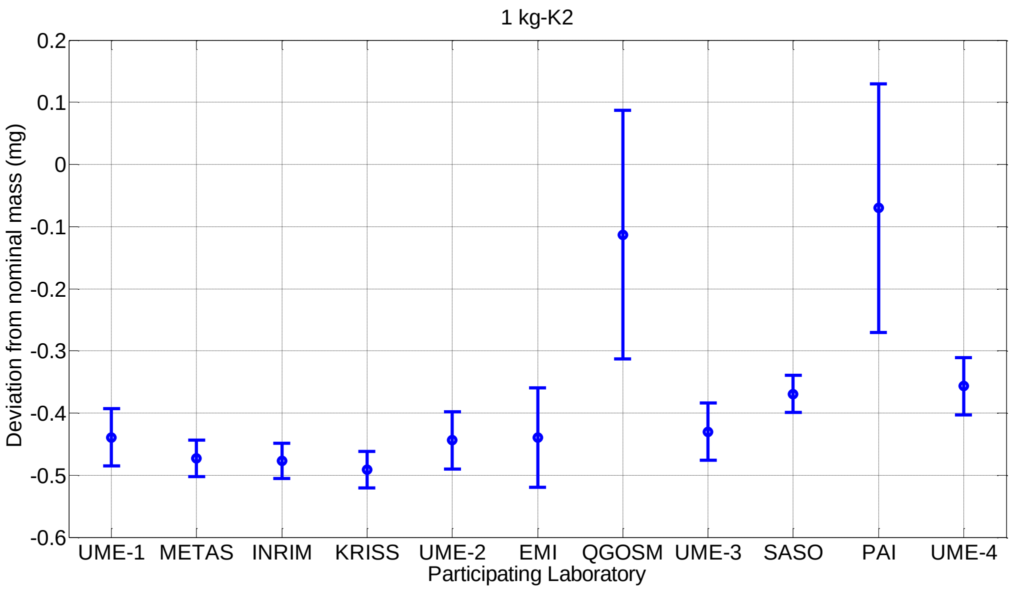
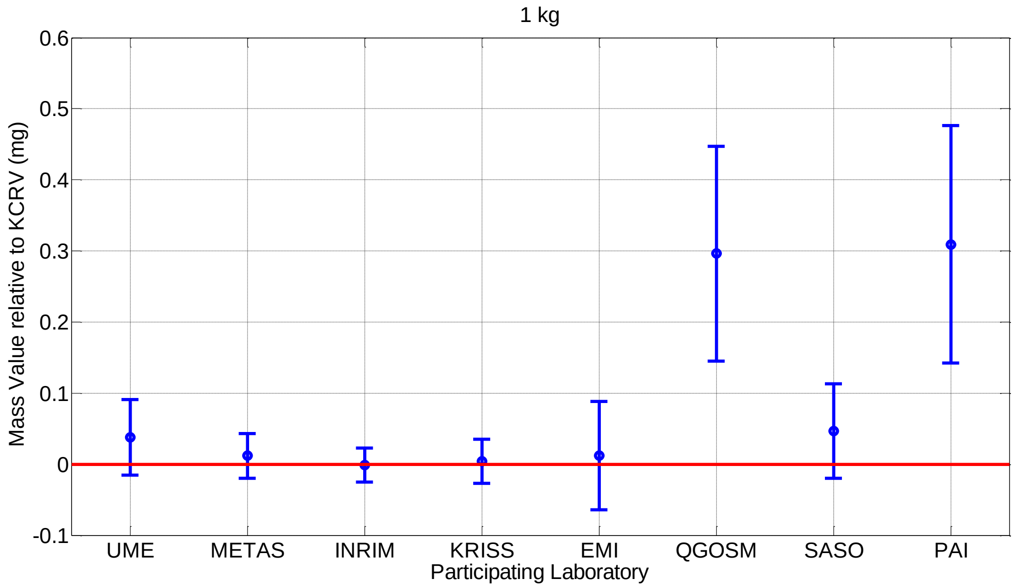


Figure 4: Deviation from the KCRV of CCM.M-K4 and associated expanded uncertainty at $k = 2$ for each participating laboratory. Zero line in red corresponds to the KCRV of the CCM.M-K4 comparison.



8. SUMMARY AND CONCLUSIONS

1. The GULFMET key comparison of two 1 kg stainless steel mass standards is linked to CCM.M-K4. Five GULFMET members participated in the comparison. Three linking laboratories were METAS, INRIM and KRISS.

2. GLS estimation is used for the analysis of the results. The majority of the participant results in GULFMET.M.M-K4 are consistent with each other and with KCRV of CCM.M-K4 within their expanded uncertainties of $k = 2$. The results have been reviewed by the participants with respect to their published CMCs. The results of the comparison have no impact on the published CMCs.

3. The results of the linking laboratories in GULFMET.M.M-K4 agree well with the ones in CCM.M-K4 within the expanded uncertainties at $k = 2$.

4. The results of the two laboratories in GULFMET.M.M-K4 differ significantly from KCRV of CCM.M-K4.

5. The delays in circulation of travelling standards mainly resulted due to a breakdown of weighing instrument in QGOSM and 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 were apparent linear drifts in the masses of both travelling standards.

7. It is important to note that CCM.M-K4 was conducted prior to the 2014 extraordinary calibration campaign with IPK at BIPM. As the BIPM working standards are found to be shifted unexpectedly by 35 µg over 22 years during this calibration campaign,

CCM recommended that all mass calibrations of national mass standards issued by BIPM during 2003 - 2013 are required to be amended in line with this value. The mean value of the amendments assigned by BIPM to the national prototypes of kilogram participating in CCM.M-K4 comparison is found to be ~18 µg. BIPM amendments are readily reflected in the GULFMET.M.M-K4 reports of linking laboratories since it is conducted after 2014 extraordinary calibration campaign. However, the final report of CCM.M-K4 is not corrected accordingly. Therefore, one has to find an appropriate method for linking with the CCM.M-K4 comparison. BIPM amendments to certificates of the national prototypes of kilogram for the linking laboratories of GULFMET.M.M-K4 are given in the Table 7. The mean value of the BIPM amendments to certificates of the national prototypes of GULFMET.M.M-K4 linking laboratories is around 18 µg. Moreover, the BIPM amendment to national prototype of INRIM is 14 µg. These results reflect very close coincidence with mean value of the amendments assigned by BIPM to the national prototypes of kilogram of CCM.M-K4 participants. Thanks to this coincidence, no further action is taken during the linking of GULFMET.M.M-K4 with CCM.M-K4. A robust link is provided by the three linking NMIs since the mean value of their amendments are exceptionally close to the mean value of the BIPM amendments to the laboratories participating in CCM.M-K4. The results presented in the GULFMET.M.M-K4 report should be shifted by 18 µg in case the amendments to CCM.M-K4 are taken into account.

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APPENDIX A

The comparison is performed between 9 participating institutes. However, as DCL is not a CIPM-MRA signatory, their results are presented in this section.

Table 13. Deviation from the KCRV of CCM.M-K4 and associated expanded uncertainty ($k = 2$) for each participating laboratory.

L_i	Δ_i (mg)	U_i (mg)	d_i
DCL	-0.0824	0.0994	0.83

Table 14-a. The degree of equivalence between the participating laboratories and DCL in calibrating 1 kg mass standard. All units are given in mg.

L_i	UME	METAS	INRIM	KRISS	EMI	QGOSM	SASO	PAI
DCL	-0.1199	-0.0942	-0.0814	-0.0863	-0.0944	-0.3789	-0.1287	-0.3917

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	KRISS	EMI	QGOSM	SASO	PAI
DCL	0.0984	0.0980	0.0968	0.0969	0.1137	0.1725	0.1037	0.1846

Figure 5: Deviation of true mass values from nominal mass value of 1 kg-K1 transfer standard with expanded uncertainties at $k = 2$.

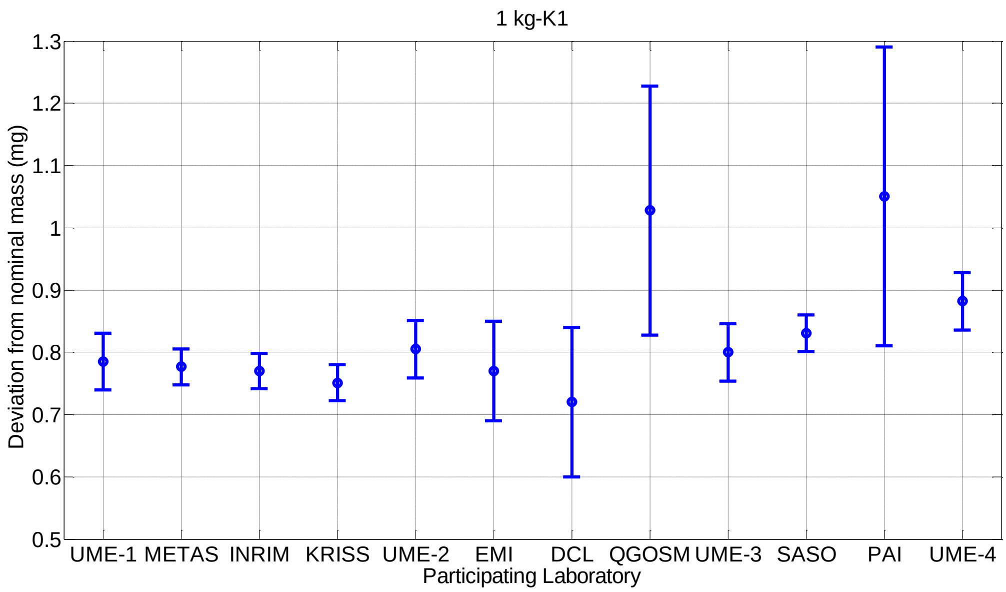

Figure 6: Deviation of true mass values from nominal mass value of 1 kg-K2 transfer standard with expanded uncertainties at $k = 2$.

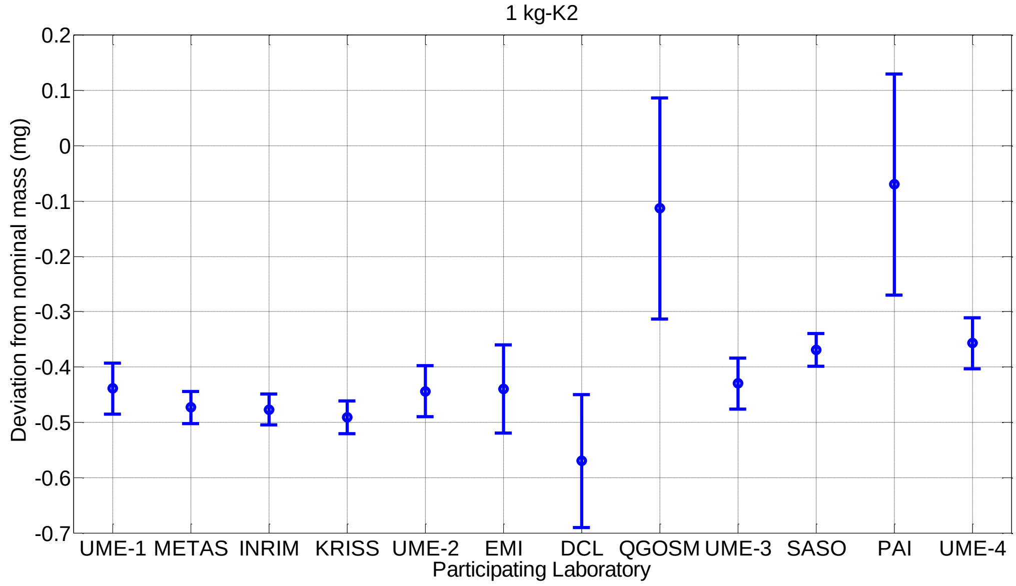

Figure 7: Deviation from the KCRV of CCM.M-K4 and associated expanded uncertainty at $k = 2$ for each participating laboratory. Zero line in red corresponds to the KCRV of the CCM.M-K4 comparison.