Final report
CCM key comparison of kilogram realizations
CCM.M-K8.2021

17 January 2023

M. Stock[1], P. Conceição[1], H. Fang[1], F. Bielsa[1], A. Kiss[1], L. Nielsen[2], F. Beaudoux[3], P. Espel[3], M. Thomas[3], D. Ziane[3], H. Baumann[4], A. Eichenberger[4], K. Marti[4], Y. Bai[5], M. Hu[5], Z. Li[5], Y. Lu[5], C. Peng[5], J. Wang[5], Y. Wang[5], D. Wu[5], P. Abbott[6], D. Haddad[6], Z. Kubarych[6], E. Mulhern[6], D. Newell[6], S. Schlamminger[6], K. Fujita[7], H. Inaba[7], Y. Kano[7], N. Kuramoto[7], S. Mizushima[7], S. Okubo[7], Y. Ota[7], L. Zhang[7], S. Davidson[8], R.G. Green[9], J.O. Liard[9], N.F. Murnaghan[9], B.M. Wood[9], M. Borys[10], D. Eppers[10], D. Knopf[10], E. Kuhn[10], M. Hämpke[10], M. Müller[10], A. Nicolaus[10], F. Scholz[10], M. Spoors[10], H. Ahmedov[11]

[1] BIPM
[2] DFM, Denmark
[3] LNE, France
[4] METAS, Switzerland
[5] NIM, China
[6] NIST, USA
[7] NMIJ, Japan
[8] NPL, UK
[9] NRC, Canada
[10] PTB, Germany
[11] UME, Türkiye

Bureau
International des
Poids et
Mesures

Table of Contents

Abstract

This report describes the second CCM key comparison of realizations of the kilogram definition based on the fixed numerical value of the Planck constant, which came into force on 20 May 2019. The objectives were to determine the level of agreement between realizations of the kilogram using Kibble and joule balances and the X-ray crystal density (XRCD) method and to provide input for the calculation of the second "consensus value" of the kilogram. The consensus value serves as the basis for an internationally coordinated dissemination of the kilogram and is updated after each new key comparison. Its use will continue until satisfactory agreement between realization experiments has been achieved. Another objective was the determination of the reproducibility of the realization experiments by comparing the new results with those of the first key comparison of kilogram realizations, CCM.M-K8.2019.

The comparison was organized by the BIPM and had nine participants. The BIPM, LNE, METAS, NIST, NRC and UME operated Kibble balances, the NIM used a joule balance and the NMIJ and the PTB participated using ^{28}Si spheres, the masses of which were determined with the XRCD method. These realization methods were used to calibrate 1 kg mass standards under vacuum or in air. The standards were sent (in containers filled with air) to the BIPM where they were compared with each other (in the same environment as at the participants' laboratories) and with BIPM Pt-Ir working standards. The latter were calibrated traceable to the International Prototype of the Kilogram (IPK), the mass of which served as the definition of the kilogram until 20 May 2019.

The results of the weighings at the BIPM together with the measurement results communicated by the participants allowed comparison of the values attributed to 1 kg mass standards using the realization experiments of the participants. The level of agreement between mass determinations with the realization experiments and the BIPM as-maintained mass unit, traceable to the Planck constant through the mass of the International Prototype of the Kilogram, could also be deduced.

1 Introduction

On 20 May 2019, a revision of the International System of Units, the SI, came into force [1]. Since then, the kilogram has been defined based on a fixed numerical value of the Planck constant [2]. This leads to the fundamentally new situation in mass metrology whereby the mass unit can, in principle, be realized individually by any National Metrology Institute (NMI) which is capable of developing an experiment allowing the realization of the new definition. At present, the *mise en pratique* of the kilogram [3] recognizes two independent primary methods that are capable of realizing the kilogram with relative uncertainties of a few parts in 10^8, corresponding to a few tens of micrograms: the Kibble balance [4] (a special realization of which has been described as a joule balance [5]) and the XRCD method [6].

In 2017, the numerical values of the defining constants for the four new SI definitions were determined by a least squares adjustment of all available data by the CODATA Task Group on Fundamental Constants [7]. The set of eight results for the Planck constant was not statistically consistent. The Consultative Committee for Mass and Related Quantities (CCM) discussed this situation at its meeting in 2017. It decided that until the dispersion between values became compatible with the individual realization uncertainties, NMIs should base their dissemination on an agreed "consensus value". The details of this international coordination of the kilogram dissemination are described in the "CCM detailed note on the dissemination process after the redefinition of the kilogram" [8]. The consensus value was calculated for the first time in

December 2020 after the completion of the first key comparison of kilogram realization, CCM.M-K8.2019 [9].

Following the completion of the present comparison, a new consensus value will be calculated. It will be calculated as the arithmetic mean of the following three sets of data:

- data from the CCM Pilot Study of realization experiments, carried out in 2016 [10], and corrected for the shift of 17 parts in 10^9 in h (corresponding to 17 µg) introduced by the CODATA 2017 adjustment, with respect to the CODATA 2014 value, which was used as the reference in the Pilot Study, and for a retrospective correction of the mass of the BIPM working standards of 4 µg, yielding a total correction of 13 µg;
- the key comparison reference value (KCRV) of the first key comparison of kilogram realizations, CCM.M-K8.2019;
- the KCRV of the present, second key comparison of kilogram realizations, CCM.M-K8.2021.

The reference values of the first two comparisons are maintained by the BIPM working standards. The three data sets from 2016, 2019 and 2021 can be tied together through the quantifiable stability of the BIPM working standards.

This comparison has the following three objectives: (1) to study the present level of agreement between realization experiments, (2) to provide input for the calculation of the second consensus value and (3) to determine the reproducibility of the realization experiments by comparing the results of the 2019 and 2021 comparisons.

The new consensus value will be determined by the *CCM Task Group on the Phases for the Dissemination of the kilogram following redefinition* (TGPfD-kg). The result will be published in a CCM document.

It is planned to repeat the key comparison every two years. After each comparison, the consensus value will be calculated as the arithmetic mean of the three most recent data sets, to reduce temporal changes in the consensus value.

2 Organization of the key comparison

The comparison followed a similar scheme as the first key comparison of kilogram realizations, CCM.M-K8.2019 [11]. It was organized in the form of a star-comparison, in which each participating institute was requested to send one or two of its own 1 kg mass standards to the BIPM, which acted as the pilot laboratory. Contrary to the first comparison, the use of Pt-Ir prototypes was not mandatory, to facilitate the transport of the travelling standards to the BIPM. The participants could choose between Pt-Ir prototypes, stainless steel standards, Si-spheres or any other standards of their choice. The standards should be well characterized with regard to their mass stability, in particular under repeated air-to-vacuum transfers.

The participants determined the mass of their travelling standards under vacuum or in air, using their realization experiment, before sending them to the BIPM. The mass values attributed to the standards were calculated using the numerical value of the Planck constant that is now fixed in the SI:

$$h = 6.626\,070\,15 \times 10^{-34}\ \mathrm{J\ s}.$$

While at the BIPM, the travelling standards were all compared under the same environment as in the participant's laboratory, to BIPM working standards which served as reference mass standards. The comparison of the mass standards at the BIPM, together with the mass values attributed by the participants, allowed a determination of the differences between the participants' realizations of the kilogram. The BIPM reference mass standards are traceable to the International Prototype of the Kilogram (IPK) but also effectively maintain the reference value of the CCM Pilot Study in 2016 and the KCRV of the 2019 key comparison.

The participants were asked to verify the mass stability of their travelling standards over the period of the comparison by comparing them before and after the measurements at the BIPM with another, stable mass standard, either in air or in vacuum. These measurements were to be made with the lowest possible uncertainty, in particular by avoiding large air buoyancy corrections.

3 Participants and travelling standards

All NMIs working on realization experiments had been invited to participate in this comparison, under the following conditions:

- standard uncertainty of the mass of the 1 kg travelling standards under vacuum (or in air if measurements under vacuum were not possible) based on the realization experiment < 200 µg, that is 200 parts in 10^9;
- a peer reviewed publication of the realization experiment, including a detailed uncertainty budget for a combined uncertainty close to the one claimed in the comparison, and some evidence of the reproducibility of the results over time;
- availability to perform the required measurements within the schedule of the comparison.

Nine institutes participated (table 1): the BIPM, LNE (France), METAS (Switzerland), NIST (USA), NRC (Canada) and UME (Türkiye) used Kibble balances, the NIM (China) used a joule balance and the NMIJ (Japan) and the PTB (Germany) used the XRCD method as the basis for their mass determinations.

Table 2 lists the travelling standards sent by the participants.

Table 1: Comparison coordinator, support group members and contact persons of the participating institutes.

Comparison coordinator		
Institute	**Contact person**	
BIPM	Michael Stock	
Support group		
Institute	**Contact person**	
DFM	Lars Nielsen	
NPL	Stuart Davidson	
Participants		
Institute	**Contact person(s)**	**Realization method**
BIPM	Hao Fang	Kibble balance
LNE	Matthieu Thomas	Kibble balance
METAS	Henri Baumann	Kibble balance
NIM	Zhengkun Li Jian Wang	Joule balance
NIST	Darine Haddad Patrick Abbott	NIST-4 Kibble balance
NMIJ	Naoki Kuramoto	XRCD method
NRC	Richard Green	Kibble balance
PTB	Dorothea Knopf Michael Borys	XRCD method
UME	Haci Ahmedov	Kibble balance

Table 2: Travelling standards and their properties, as communicated by the participants

Institute	**Identification of standard**	**Manufacturer**	**Type (dia x ht)/mm**	**Estimated air-vacuum surface sorption / μg**	**Magnetic susceptibility**	**Magnetic polarization / μT**
BIPM	100	BIPM	Pt-Ir prototype (39 x 39)	4	24×10^{-5}	<0.02
LNE	JM15	Johnson-Matthey and CNAM	Pt-Ir standard (39 x 39)	6.5	24×10^{-5}	0
METAS	H1-3-1kg	Häfner	Stainless steel cylindrical (54 x 54)	6	<0.02	<2.5
	H1-7-1kg	Häfner	Stainless steel cylindrical (54 x 54)	9	<0.02	<2.5
NIM	6600	Changzhou Accurate Weight Co.	stainless steel cylindrical (50.2 x 64.2)	5.5	5.16×10^{-4}	0.01
	8911	Changshu Goldengoat Weight Instr.	stainless steel cylindrical (54.2 x 54.5)	5.4	5.51×10^{-4}	0.01
NIST	85	BIPM	Pt-Ir prototype (39 x 39)	10	24×10^{-5}	<0.02
	104	BIPM	Pt-Ir prototype (39 x 39)	5	24×10^{-5}	<0.02
NMIJ	S1_2	Chyo balance	Stainless steel cylindrical (54 x 54)	8.9(3.1)	3.2×10^{-3}	< 0.07
	S2_1	Chyo balance	Stainless steel cylindrical (54 x 54)	8.1(3.1)	3.3×10^{-3}	< 0.07
NRC	S38	Troemner	Stainless steel cylindrical (54 x 54)	14.3	4.5×10^{-3}	0.02
	NC1000W1	NRC	Tungsten cylinder (38 x 47)	14.8	$< 1 \times 10^{-4}$	<0.1
PTB	109	BIPM	Pt-Ir prototype (39 x 39)	2	< 0.001	< 0.1
	Si14-02	PTB	Si sphere (diam. 93.6)	20	-2.6×10^{-7}	0
UME	2950120	Häfner	Stainless steel cylinder (54 x 54)	The travelling standards from UME were weighed in air	1.05×10^{-3}	0.04
	E0 02	Häfner	Stainless steel cylinder (54 x 54)		3.27×10^{-3}	0.03

4 Measurements made by the participants

The following are short summaries of the measurement reports provided by the participants. The reports, including the detailed uncertainty budgets, are available as an annex to this report.

4.1 BIPM

The details of the BIPM Kibble balance are described in [12]. The BIPM Kibble balance operates in the one-mode-two-phases scheme, in which the same current flows across one of the two windings of a bifilar coil in the weighing and the velocity phase.

The mass of the travelling standard was directly measured under vacuum in the Kibble balance. The measurements were carried out in the period of 22 October to 8 November 2021.

4.2 LNE

The details of the LNE Kibble balance are described in [13]. The paper describes the operation of the LNE Kibble balance in air. The measurements for the present comparison were made in vacuum.

The determination of the mass of JM15 under vacuum was made in three steps. At first, the mass of a 500 g iridium mass standard was determined using the LNE Kibble balance. This mass was then used to calibrate a second 500 g iridium mass in an M_one mass comparator. The travelling standard JM15 was then compared against the two 500 g masses together in the M_one mass comparator. The measurements were carried out during the period November 2021 to February 2022.

4.3 METAS

The value given for the mass H1-7-1kg is a primary realization with the METAS Kibble balance. The measurement campaign lasted from end of October to the middle of November 2021.

The mass value given for H1-3-1kg is based on a comparison with the primary realization in the METAS M_one mass comparator.

The METAS Kibble balance is described in [14].

4.4 NIM

Two travelling standards with the numbers 6600 and 8911 were measured under vacuum in the NIM-2 joule balance in December 2021. A PJVS system is used as the reference in the joule balance system for the electrical measurement. A standard resistor was used in the system for the current measurement and this resistor has been calibrated by the QHR standard system periodically. The length measurement was traced to the length primary standard of NIM. The absolute gravity is measured by the gravity group of the NIM.

The NIM joule balance is described in detail in [15]. Since then, the alignment has been improved as described in [16], which has led to a reduction of the uncertainty from 52 µg to 35 µg.

4.5 NIST

NIST measured two Pt-Ir masses K85 and K104 directly on the primary realization, the fourth generation Kibble Balance, NIST-4. Each mass was brought under vacuum to NIST-4. The mass was determined on NIST-4, and then transferred under vacuum to a vacuum balance to transfer the values to secondary masses and to check the stability of the masses. Two series of primary realizations for each mass were done from early July to early August 2021.

The NIST Kibble balance NIST-4 is described in [17].

4.6 NMIJ

The reproducibility of the realization of the kilogram with the XRCD method at the NMIJ is described in [18]. The NMIJ submitted a very comprehensive description of their application of the XRCD method which can be found in the annex to this report.

For the primary realization of the kilogram, the ^{28}Si-enriched crystal sphere AVO28-S5c was used. The values of its lattice constant, the relative atomic mass of Si and the influence of point defects on the core mass were already determined by the IAC project. There is no known mechanism that changes the values of these properties of Si crystals with respect to time. The mass of the sphere was therefore redetermined from the value of the Planck constant by measuring the volume of the core and the mass of the surface layers. The mass of the travelling standards was determined based on the mass of the sphere AVO28-S5c using a mass comparator.

4.7 NRC

Masses of different chemistry and surface area were used to track stability of the mass standard used in the Kibble balance over the course of the realization. AuCuB which is a 500 g gold plated copper mass was compared in an M_one vacuum comparator to an ensemble of witness masses comprised of 2 stainless steel, 1 tungsten, 1 doped silicon single crystal, and a second gold plated copper mass called AuCuA. AuCuB was brought to air through the M_one load-lock and placed in the Kibble balance. The Kibble balance was subsequently brought to vacuum to perform the realization measurements.

After the realization measurements, the Kibble balance was vented and AuCuB was transferred in air to the M_one vacuum comparator through the load-lock and compared in vacuum to the same 500 g ensemble which had remained under vacuum over the course of the realization. The change in mass of AuCuB with respect to the ensemble was included in the measurement uncertainty. The mass of AuCuB under vacuum in the M_one is given as the realization value plus half the difference in the change of mass of AuCuB over the course of the realization relative to the ensemble. For comparison at the 1 kg level, the vacuum balance was vented to air and AuCuB was stacked onto AuCuA. The stack of AuCuA+AuCuB was compared to traveling standards NC1000W1 and S38 in vacuum. Air to vacuum cycling stability of the AuCu stack, NC1000W1, S38 were evaluated and are included in the reported measurement uncertainty. All weighings were made during the period March-April 2022, after receiving the travelling standards back from the BIPM. A correction for the stability of the travelling standards made by subtracting half the measured mass change was included in the reported results.

The travelling masses were selected as non-precious metal types so they could be shipped by commercial courier. Traveling standards NC1000W1 and S38 were each packed in air within a sealed high purity enclosure for transfer between NRC and the BIPM. The changes in mass over the return trip of the traveling standards to the BIPM were measured in both air and vacuum with respect to several masses. Only the vacuum measurements are reported, though the air measurements were found to agree with the vacuum measurements within their uncertainty. The latest publication on the NRC Kibble balance is [19].

4.8 PTB

The PTB used two spheres made from isotopically enriched ^{28}Si as references: AVO28-S8c from the earlier work of the IAC and the more recently made sphere Si28kg01a. The travelling standards were calibrated against these references in a CCL1007 mass comparator during the period from September to December 2021. The measurement report showed the masses with respect to each of the two references and the weighted mean. The most recent relevant publications are [20] and [21].

4.9 UME

In the UME KB-3 the travelling standards with a nominal value of 1 kg are measured under ambient air conditions. The load cell (Mettler Toledo AX5006) is used for the comparative measurements of the vertical Lorentz force on the coil pair and the gravitational force acting on the travelling standard. The mass m of the travelling standard is assigned via

$$m = \frac{F_z - \Delta F}{g(1-\rho_{air}/\rho)}$$

where F_z is the vertical Lorentz force, ΔF is the difference between the load cell readings for the downward and upward Lorentz forces, g is the gravitational acceleration in the center of mass of the travelling standard, ρ_{air} is the air density and ρ is the density of the travelling standard.

The vertical Lorentz force is given by

$$F_z = \frac{I\,\Phi}{z}(1 + Q_{al} + Q_{aux} + Q_{nu})$$

by means of the joule balance principle which is the integral form of the watt balance principle. I is the electrical current passing through the coil, Φ is the magnetic flux passing through the coil pair induced by the motion of magnet assembly, z is the displacement of the magnet assembly, Q_{al}, Q_{aux} and Q_{nu} describe the effects due to the non-vertical motion of the magnet assembly, auxiliary magnetic field and non-uniformity, respectively. The link between the mass and Planck constant appears in the measurement of the $I\Phi$-term by using the Josephson effect and the quantum Hall effect.

Two stainless steel mass standards were used as the travelling standards. The calibration period in UME KB-3 for the first standard is 29/11/2021-26/12/2021 and for the second one 27/12/2021-23/01/2022. The stability checks are performed in an M_one mass comparator against the national kilogram prototype No. 54. The UME Kibble balance is described in [22].

5 Measurements at the BIPM

The objective of the weighings at the BIPM was to determine the mass differences between the participants' travelling standards and to compare them with BIPM working standards. The masses of the latter are traceable to the mass of the IPK from measurements made in 2014 [23] and maintain the reference values of the CCM Pilot Study of 2016 [10] and of CCM.M-K8.2019 [11].

All measurements were made with the M_one mass comparator, equipped with a six-place mass exchanger. The influence of the mass handler position is determined once a year, for the last time in September 2021. It has always been found to be close to the statistical uncertainty. No correction is applied, but an uncertainty of 0.001 mg is taken into account. The sensitivity of the mass comparator is determined at the beginning and at the end of each weighing set using a stainless steel sensitivity weight of 95 mg, which was recalibrated in September 2019. Since the masses of all travelling standards are within a range of 13 mg, the uncertainty contribution of the sensitivity is negligible. The residual pressure during the vacuum weighings was between 5×10^{-4} Pa and 8×10^{-4} Pa.

The masses of the BIPM, LNE, METAS, NIM, NIST, NMIJ, NRC and PTB were weighed under vacuum. The masses of UME were weighed in air, as in the UME laboratory. The mass comparator stayed under vacuum during the whole duration of the vacuum weighings. The cylindrical 1 kg Pt-Ir standard A0 of the BIPM stayed inside the comparator under vacuum during the whole duration and served as the reference with which all travelling standards were compared. Before and after all the vacuum weighings of the comparison, A0 was compared under vacuum against Pt-Ir prototype 101, which had been stored in air during the comparison. The stability of prototype 101 was verified in air with respect to prototype 99. According to these verifications, the mass of A0 had increased by 0.0015 mg during the vacuum measurements with an uncertainty of 0.002 mg. The BIPM stack A18, made of eight Pt-Ir disks, separated from one another by three small bent Pt-wires, also stayed under vacuum during the whole comparison. Its mass stability was verified in the same way as that of A0. Its mass has increased by 0.0060 mg during the vacuum weighings. Together with A0 it forms a pair of sorption standards, having very similar mass and volume, but very different surface areas. The surface area of A18 is 3.6 times larger than that of A0. From the measured mass differences between A18 and A0 in air and in vacuum and the calculated surface areas, the mass of the adsorbed water layers in air can be calculated. This allows the calculation of the mass of A0 under vacuum, based on its calibration in air. Following a series of four air-vacuum-air cycles to stabilize the sorption standards, the mass of the adsorbed water layer on A0 in air was determined as 0.0025 mg, corresponding to 35 ng/cm^2, with an uncertainty of 0.002 mg. This is consistent with previous determinations.

The mass of A0 was determined in air directly before and after the period of the vacuum weighings with reference to two Pt-Ir working standards for regular use, Nos. 42' and 103. Both of these were calibrated in September 2021 against the three working standards for limited use, 9, 31 and 650, which are only used once per year, and which had been calibrated using the IPK in 2014. The mass of A0 determined in air before the period of vacuum weighings, 1 kg + 0.8619 mg, corrected by the sorption correction of 0.0025 mg, served as the reference value for the vacuum weighings, 1 kg + 0.8594 mg.

Seven weighing sets were carried out under vacuum. Each of the sets contained the BIPM standards A0 and A18 and four of the travelling standards. The sets were formed as follows:

Set 1 (02-03/02/2022):	A0	A18	H1-3-1kg (METAS)	H1-7-1kg (METAS)	85 (NIST)	104 (NIST)
Set 2 (06/02/2022):	A0	A18	85 (NIST)	104 (NIST)	S1_2 (NMIJ)	S2_1 (NMIJ)
Set 3 (24-25/02/2022):	A0	A18	S1_2 (NMIJ)	S2_1 (NMIJ)	6600 (NIM)	8911 (NIM)
Set 4 (02-03/03/2022):	A0	A18	6600 (NIM)	8911 (NIM)	109 (PTB)	Si14-02 (PTB)
Set 5 (09-10/03/2022):	A0	A18	109 (PTB)	Si14-02 (PTB)	S38 (NRC)	NC1000W1 (NRC)
Set 6 (13-14/03/2022):	A0	A18	S38 (NRC)	NC1000W1 (NRC)	100 (BIPM)	JM15 (LNE)
Set 7 (17-18/03/2022):	A0	A18	100 (BIPM)	JM15 (LNE)	109 (PTB)	Si14-02 (PTB)

Standards which were included in two consecutive weighing sets stayed under vacuum in-between. The Si sphere Si14-02 was cleaned before each weighing, as requested by the PTB, by applying the recommended procedure [24] and using the cleaning products provided by the PTB. To investigate the reproducibility of the cleaning, the sphere was cleaned and weighed three times. The three results agreed within 0.002 mg. None of the other mass standards were cleaned, only dust was removed with a soft brush and by gently blowing some air.

For each set, four full weighing schemes were carried out. In each weighing scheme all 15 pairwise mass-differences between the six standards were determined. This led to 60 mass differences for each set and to 420 mass differences for the whole comparison. Each individual mass difference was obtained from an A-B-A-B-A-B-A scheme.

All 420 mass differences measured in vacuum were used to carry out a generalized least-squares adjustment to obtain the masses of the travelling standards. The vacuum mass of A0 served as the constraint in the adjustment. The mass increase of A18 of 0.006 mg was taken into account in the adjustment. The statistical uncertainty of the adjusted masses was 0.0004 mg.

The travelling standards from UME were compared in air against A0, A18 and two working standards:

Set 8 (25-26/03/2022):	A0	A18	42’	103	2950120 (UME)	E0 02 (UME)

The uncertainty budget for the vacuum weighings is shown in table 3. The table shows the combined standard uncertainties of the masses of the travelling standards with respect to two different references:

- with respect to the mass of A0 under vacuum:	0.0023 mg
- with respect to the Planck constant (via the IPK):	0.0120 mg

The uncertainty of the first part of the table, 0.0023 mg, representing the uncertainty of the mass of the travelling standards with respect to the mass of A0 in vacuum is considered to be uncorrelated for all travelling standards. The uncertainty contributions of the second part of the table, representing the uncertainty of the vacuum mass of A0 with respect to the Planck constant, are completely correlated for all travelling standards.

The uncertainty of the masses of the UME standards in air with respect to the *vacuum* mass of A0 (which served as the reference for all other travelling standards) is 0.0030 mg

Table 3: Uncertainty budget for the mass of the travelling standards with respect to the vacuum mass of the reference A0 and with respect to the Planck constant (via the IPK). The uncertainties of the second part of the table are totally correlated for all travelling standards.

Source of uncertainty	Uncertainty	Sensitivity coefficient	Unc. contribution / mg
position error of M_one	0.001 mg	1	0.001
centre of gravity of standards	0.5 mm	0.0003 mg/mm	0.0002
statistical uncertainty	0.0004 mg	1	0.0004
mass stability of A0 during vacuum weighings	0.002 mg	1	0.002
Standard uncertainty of mass of travelling standards with respect to mass of A0 in vacuum			**0.0023**
air to vacuum transfer of A0	0.002 mg	1	0.002
mass of A0 in air with respect to IPK	0.006 mg	1	0.006
mass of IPK with respect to Planck constant	0.010 mg	1	0.010
Standard uncertainty of mass of travelling standards with respect to Planck constant			**0.0120**

6 Results of the comparison

6.1 Mass stability of the travelling standards

Each participant determined the masses of the travelling standards against another mass standard or a set of mass standards before and after the weighings at the BIPM, to verify the mass stability:

$m_{\text{before},i,j}^{\text{NMI}}$: The mass of the travelling standard *j* (*j*=1,2) determined by participant *i* (*i*=1,..,9) against a stable reference mass before sending it to the BIPM.

$m_{\text{after},i,j}^{\text{NMI}}$: The mass of the travelling standard *j* (*j*=1,2) determined by participant *i* (*i*=1,..,9) against the same stable reference mass after the return from the BIPM.

Some participants made these measurements in air (BIPM, LNE, METAS, NIST, PTB, UME), others in vacuum (NIM, NMIJ, NRC). Only the Si-sphere Si14-02 was cleaned before these weighings at the PTB. The observed mass difference $\Delta m_{i,j}^{\text{NMI}} = m_{\text{after},i,j}^{\text{NMI}} - m_{\text{before},i,j}^{\text{NMI}}$ and its uncertainty $u(\Delta m_{i,j}^{\text{NMI}})$ were communicated to the BIPM. Table 4 and Figure 1 show the results of these measurements.

Table 4: Changes of the mass of the travelling standards during the comparison $\Delta m_{i,j}^{\mathrm{NMI}}$, and related uncertainty $u\left(\Delta m_{i,j}^{\mathrm{NMI}}\right)$, as determined by the participants. Also shown are the corrections $\delta m_{\mathrm{stab},i,j}^{NMI}$ for the mass changes, applied by the BIPM to the masses of the travelling standards determined with the NMIs realization experiments, and their uncertainties $u_{\mathrm{stab},ij}^{\mathrm{NMI}}$.

NMI	mass standard	mass change $\Delta m_{i,j}^{\mathrm{NMI}}$/ mg	uncertainty of mass change $u\left(\Delta m_{i,j}^{\mathrm{NMI}}\right)$/ mg	correction for mass change $\delta m_{\mathrm{stab},i,j}^{\mathrm{NMI}}$ / mg	uncertainty of correction $u_{\mathrm{stab},i,j}^{\mathrm{NMI}}$ / mg
BIPM	100	+0.006	0.002	+0.003	0.0026
LNE	JM15	+0.0009	0.005	+0.0005	0.0050
METAS	H1-3-1kg	+0.0054	0.010	+0.0027	0.0101
	H1-7-1kg	-0.0478	0.010	discarded from comparison	
NIM	6600	-0.0053	0.0165	-0.0027	0.0166
	8911	-0.0185	0.0165	discarded from comparison	
NMIJ	S1_2	+0.0071	0.0049	+0.0036	0.0053
	S2_1	+0.0073	0.0049	+0.0037	0.0053
NIST	85	-0.0048	0.0030	-0.0024	0.0033
	104	-0.0047	0.0022	-0.0024	0.0026
NRC	NC1000W1	-0.0013	0.0027	-0.0007(1)	0.0027
	S38	+0.0012	0.0031	+0.0006(1)	0.0031
PTB	109	+0.0003	0.0019	+0.0002	0.0019
	Si14-02	-0.0006	0.0048	-0.0003	0.0048
UME	E0 02	-0.011	0.035	-0.0055	0.0351
	2950120	+0.010	0.035	+0.0050	0.0351

(1) NRC applied this correction already in the reported mass values.

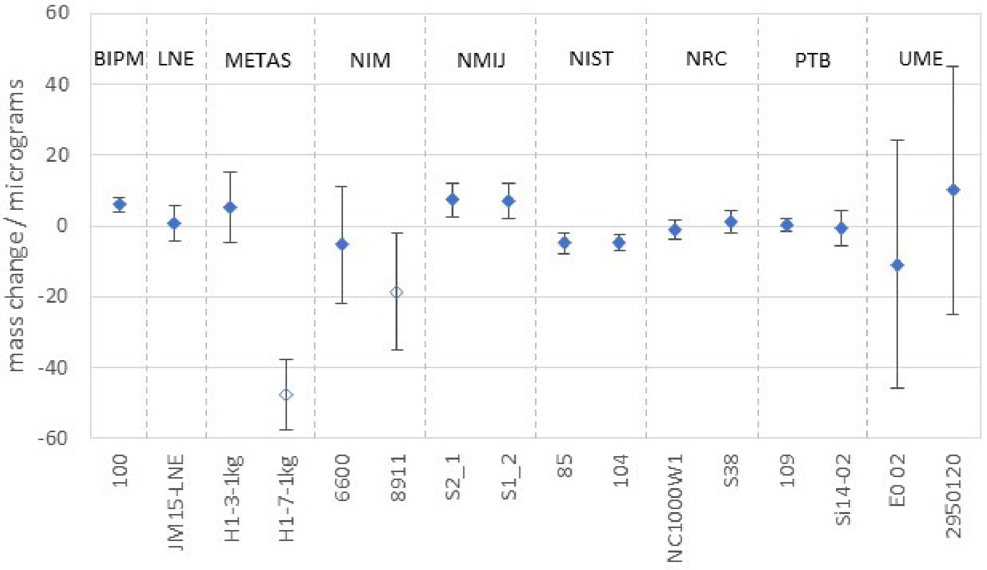

Fig. 1: Changes of the mass of the travelling standards during the comparison, $\Delta m_{ij}^{\mathrm{NMI}}$, as determined by the participants. The standards shown with open symbols were discarded from the comparison.

The two masses sent by METAS, H1-3-1kg and H1-7-1kg showed inconsistent results when their mass values determined by METAS were compared to those determined by BIPM. After their return to METAS, a mass change of -0.0478 mg was observed for H1-7-1kg. The reason for this mass loss is unknown. It was decided to discard this mass from the comparison.

The two masses sent by NIM, 6600 and 8911, also showed inconsistent results when the mass values determined by NIM were compared to those determined by BIPM. The stability check at the NIM showed a mass change of -0.0185 mg for standards 8911, however a second calibration against the joule balance resulted in a value 0.085 mg *higher* than the first calibration against the joule balance. A possible explanation might be that the mass was contaminated between the first joule balance measurement and the initial NIM measurement for the stability check. It was decided to discard this mass from the comparison.

The masses of the travelling standards determined by the participants using their realization experiments were corrected by the BIPM for the observed mass changes, to represent the masses of the standards while at the BIPM. In the absence of detailed knowledge about when and how the mass changes occurred (before or/and after the comparison at the BIPM, stepwise or continuously, …), the best estimate for the correction is half of the mass change observed by the participants:

$\delta m^{\mathrm{NMI}}_{\mathrm{stab},i,j} = \frac{1}{2}\Delta m^{\mathrm{NMI}}_{i,j}$: correction to be added to the mass of travelling standard *j* (*j*=1,2) determined by participant *i* (*i*=1,..,9), to predict the mass of the standard while at the BIPM.

In the case of the NRC, the correction needs to be subtracted from the realization with the NRC Kibble balance because the realization was made after the return of the travelling standards from the BIPM. The correction was already included in the reported results.

The uncertainty of the stability correction $u^{\mathrm{NMI}}_{\mathrm{stab},i,j}$ has two components. The first is the uncertainty of the determination of the mass change made by the participant $u\left(\Delta m^{\mathrm{NMI}}_{i,j}\right)$, shown in table 4. The second component is related to the choice of the value chosen for the correction. Assuming that the mass while at the BIPM lies between the NMI stability measurements, a rectangular probability distribution, centered at half of the observed change (used for the correction), and with width of half the observed change can be assumed. Adding both components quadratically leads to:

$$\left(u^{\mathrm{NMI}}_{\mathrm{stab},i,j}\right)^2 = u\left(\Delta m^{\mathrm{NMI}}_{i,j}\right)^2 + \left(\frac{1}{2\sqrt{3}}\Delta m^{\mathrm{NMI}}_{i,j}\right)^2$$

The corrections for mass stability and their uncertainties are shown in the two rightmost columns of table 4.

6.2 Results of the mass determinations by the participants and by the BIPM

The results of the mass determinations by the participants using their realization experiments and the BIPM, based on the mass unit maintained on the BIPM working standards, are shown in Table 5. The columns have the following meaning:

$m_{i,j}^{\mathrm{NMI}}$: the mass of the travelling standard *j* (*j*=1,2) determined by participant *i* (*i* = 1,..,9) using its realization experiment, presented as the deviation from 1 kg.

$u_{i,j}^{\mathrm{NMI}}$: the standard uncertainty associated with the mass value $m_{i,j}^{\mathrm{NMI}}$, as communicated by the NMI.

$m_{\mathrm{corr},i,j}^{\mathrm{NMI}}$: the predicted mass of the travelling standard *j* of participant *i* while at the BIPM, obtained by applying the correction for mass change (table 4) to the $m_{i,j}^{\mathrm{NMI}}$, presented as the deviation from 1 kg:

$$m_{\mathrm{corr},i,j}^{\mathrm{NMI}} = m_{i,j}^{\mathrm{NMI}} + \delta m_{\mathrm{stab},ij}^{\mathrm{NMI}} \text{ and}$$

$$m_{\mathrm{corr},i,j}^{\mathrm{NMI}} = m_{i,j}^{\mathrm{NMI}} - \delta m_{\mathrm{stab},ij}^{\mathrm{NMI}} \text{ (only for NRC)}$$

$u_{\mathrm{total},i,j}^{\mathrm{NMI}}$: uncertainty communicated by the participant, increased by the contribution for the mass stability correction (table 4):

$$\left(u_{\mathrm{total},i,j}^{\mathrm{NMI}}\right)^2 = \left(u_{i,j}^{\mathrm{NMI}}\right)^2 + \left(u_{\mathrm{stab},i,j}^{\mathrm{NMI}}\right)^2$$

After discussion with the contact persons from PTB, for the sphere Si14-02 an additional uncertainty of 0.004 mg for the potentially different cleaning efficiency at the PTB and the BIPM was included, as in the previous comparison CCM.M-K8.2019.

$m_{i,j}^{\mathrm{BIPM}}$: The mass value obtained by the BIPM for travelling standard *j* of NMI *i*, based on the mass unit maintained on the BIPM working standard (traceable to the IPK), presented as deviation from 1 kg.

$u_{i,j}^{\mathrm{BIPM}}$: The standard uncertainty associated with the BIPM results. Only the uncertainty components which are uncorrelated amongst the travelling standards are included (see table 3).

$\Delta m_{i,j}$: The difference between the mass values obtained by the NMI, corrected for the mass change, and the BIPM:

$$\Delta m_{i,j} = m_{\mathrm{corr},i,j}^{\mathrm{NMI}} - m_{i,j}^{\mathrm{BIPM}}$$

$u_{i,j}$: The standard uncertainty associated with the mass difference:

$$u_{i,j}^2 = \left(u_{i,j}^{\mathrm{BIPM}}\right)^2 + \left(u_{\mathrm{total},i,j}^{\mathrm{NMI}}\right)^2$$

r_j : correlation coefficient between the results obtained for two standards of an NMI, calculated from the detailed uncertainty budgets submitted by the participants, after including $u_{\mathrm{stab},i,j}^{\mathrm{NMI}}$, $u_{i,j}^{\mathrm{BIPM}}$ and the additional uncertainty of 0.004 mg for sphere Si14-02. The correlation coefficient is required for the calculation of the mean value of the results for both standards.

Table 5: Masses (deviations from 1 kg) and standard uncertainties of the travelling standards determined by the NMIs using their realization experiments and by the BIPM using its working standards (traceable to the IPK). On the right, the mass differences $\Delta m_{i,j} = m^{\mathrm{NMI}}_{\mathrm{corr},i,j}$ - $m^{\mathrm{BIPM}}_{i,j}$ are shown.

		NMI realization results				**BIPM results**		**Mass difference, NMI-BIPM**		
Institute	**Identification of standard**	$\boldsymbol{m^{\mathrm{NMI}}_{i,j}}$ **/ mg**	$\boldsymbol{u^{\mathrm{NMI}}_{i,j}}$**/ mg**	$\boldsymbol{m^{\mathrm{NMI}}_{\mathrm{corr},i,j}}$**/ mg**	$\boldsymbol{u^{\mathrm{NMI}}_{\mathrm{total},i,j}}$ **/ mg**	$\boldsymbol{m^{\mathrm{BIPM}}_{i,j}}$ **/ mg**	$\boldsymbol{u^{\mathrm{BIPM}}_{i,j}}$ **/ mg**	$\boldsymbol{\Delta m_{i,j}}$ **/ mg**	$\boldsymbol{u_{i,j}}$ **/ mg**	**corr. coeff.** $\boldsymbol{r_i}$
BIPM(1)	100	-0.115	0.041	-0.1120	0.0411	-0.0729	0.0023	-0.0391	0.0412	NA
LNE	JM15	-0.724	0.108	-0.7236	0.1081	-0.7713	0.0023	0.0477	0.1081	NA
METAS	H1-3-1kg	0.2877	0.047	0.2904	0.0481	0.3319	0.0023	-0.0415	0.0481	NA
NIM	6600	0.603	0.037	0.6004	0.0405	0.5983	0.0023	0.0020	0.0406	NA
NIST	85	-0.7726	0.0271	-0.7750	0.0273	-0.7603	0.0023	-0.0147	0.0274	0.88
	104	0.401	0.0273	0.3987	0.0274	0.4156	0.0023	-0.0169	0.0275	
NMIJ	S1_2	-1.3071	0.0232	-1.3036	0.0238	-1.2959	0.0023	-0.0077	0.0239	0.91
	S2_1	0.3986	0.0232	0.4023	0.0238	0.4118	0.0023	-0.0095	0.0239	
NRC	NC1000W1	8.5532	0.0111	8.5532(3)	0.0114	8.5485	0.0023	0.0047	0.0117	0.84
	S38	-0.1488	0.0110	-0.1488(3)	0.0114	-0.1517	0.0023	0.0029	0.0117	
PTB	109	0.139	0.014	0.1392	0.0141	0.1827	0.0023	-0.0436	0.0143	0.87
	Si14-02	-4.257	0.014	-4.2573	0.0153(2)	-4.1994	0.0023	-0.0579	0.0155	
UME	E0 02	-0.346	0.054	-0.3515	0.0644	-0.3334	0.0030	-0.0181	0.0645	0.65
	2950120	0.031	0.054	0.0360	0.0644	0.0484	0.0030	-0.0124	0.0645	

(1) For the BIPM, the "NMI result" is the mass of standard 100 obtained with the BIPM Kibble balance, and the "BIPM result" is its mass based on the BIPM working standards.

(2) For the sphere Si14-02 an additional uncertainty of 0.004 mg for the reproducibility of the washing between the PTB and the BIPM is included.

(3) The correction for the mass change was already applied in the mass values reported by the NRC.

The differences $\Delta m_{i,j}$ between the mass values attributed by the NMIs, corrected for the mass changes, and the BIPM and their uncertainties $u_{i,j}$ are shown in Figure 2.

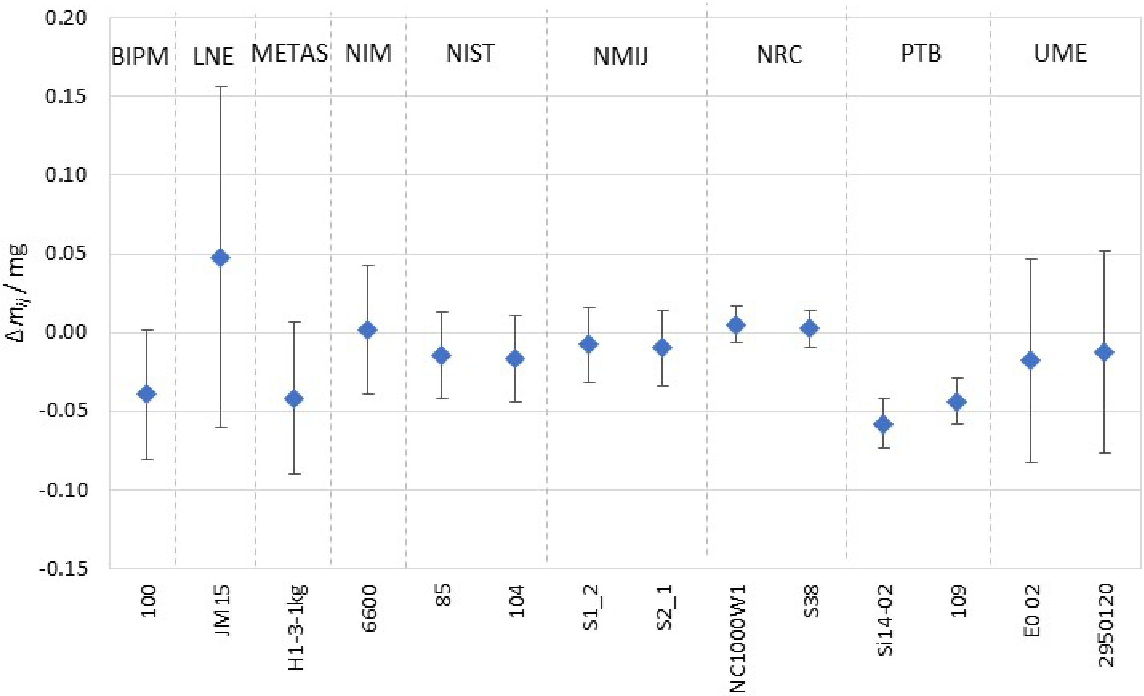

Fig. 2: Differences $\Delta m_{i,j} = m^{\mathrm{NMI}}_{\mathrm{corr},i,j}$ - $m^{\mathrm{BIPM}}_{i,j}$ between the mass determinations of each travelling standard with the NMI's realization experiment and the BIPM working standards and associated standard uncertainties $u_{i,j}$.

At the present stage of the data analysis, the BIPM working standards serve only as a common reference for the comparison. Therefore the BIPM comparison uncertainty $u^{\mathrm{BIPM}}_{i,j}$ of 0.0023 mg shown in table 5 includes only the uncertainty components of the first part of the uncertainty budget in table 3, which are uncorrelated between the travelling standards. It does not include the last three components of table 3 which are related to the uncertainty of the vacuum mass of A0 with respect to the Planck constant. These components are totally correlated for the travelling standards and can be omitted here, because for the purpose of the comparison of the realization experiments with each other, the BIPM mass unit has to be stable, but not accurate.

Ideally, for NMI *i* participating with two travelling standards, the differences between the NMI and the BIPM results for both standards, $\Delta m_{i,1}$ and $\Delta m_{i,2}$, should be the same. In practice they can differ due to the uncertainty contributions which are uncorrelated between the two results. Uncertainty contributions which are correlated between the results for the two standards have no influence on the consistency of the results. It was verified that for each NMI *i* which participated with two standards, the two results $\Delta m_{i,1}$ and $\Delta m_{i,2}$ agreed within the expanded uncertainty (*k*=2) of $\Delta m_{i,1}$ - $\Delta m_{i,2}$. This uncertainty was calculated from those components of the uncertainty budgets which where uncorrelated between the two standards.

It should however be noted that the mass difference between the travelling standards sent by the PTB measured at the BIPM differs from the mass difference measured at PTB by 0.014(8) mg. This leads to the difference between the results for Si14-02 and 109, as shown in Fig. 2. Attempts are planned for a further reduction of this difference. The difference between mass values assigned by the PTB to one travelling standard (Pt109 or Si14-02) by the two realizations (with the AVO28-S8c and the Si28kg01a sphere) amounts to 0.005(15) mg.

To obtain one single result, representative for each NMI, the results for the two travelling standards were averaged. The correlation coefficients *r* between the results of the two standards, shown in table 5, were taken into account. The weighted mean Δm_i of the two results $\Delta m_{i,1}$ and $\Delta m_{i,2}$ with uncertainties $u_{i,1}$ and $u_{i,2}$ and covariance $u_{i,12} = r_1 u_{i,1} u_{i,2}$ and its variance were calculated as [25]:

$$\Delta m_i = \frac{(u_{i,1}^2 - u_{i,12})(u_{i,2}^2 - u_{i,12})}{u_{i,1}^2 + u_{i,2}^2 - 2u_{i,12}} \left(\frac{\Delta m_{i,1}}{u_{i,1}^2 - u_{i,12}} + \frac{\Delta m_{i,2}}{u_{i,2}^2 - u_{i,12}} \right) \qquad \text{(eq. 1)}$$

$$\mathrm{var}\,(\Delta m_i) = \frac{u_{i,1}^2 u_{i,2}^2 - u_{i,12}^2}{u_{i,1}^2 + u_{i,2}^2 - 2u_{i,12}} \qquad \text{(eq. 2)}$$

This corresponds to the weighted mean in which only the uncorrelated uncertainty is used in the determination of the weights. Table 6 shows the averaged results Δm_i for all participants and figure 3 shows the results in graphical form.

Table 6: Differences Δm_i between mass values attributed to 1 kg mass standards using the realization experiment of the participants and by the working standards of the BIPM, and associated standard uncertainty.

Institute	Δm_i / mg	$u(\Delta m_i)$ / mg
BIPM	-0.0391	0.0412
LNE	0.0477	0.1081
METAS	-0.0415	0.0481
NIM	0.0020	0.0406
NIST	-0.0158	0.0266
NMIJ	-0.0086	0.0234
NRC	0.0038	0.0112
PTB	-0.0463	0.0142
UME	-0.0152	0.0585

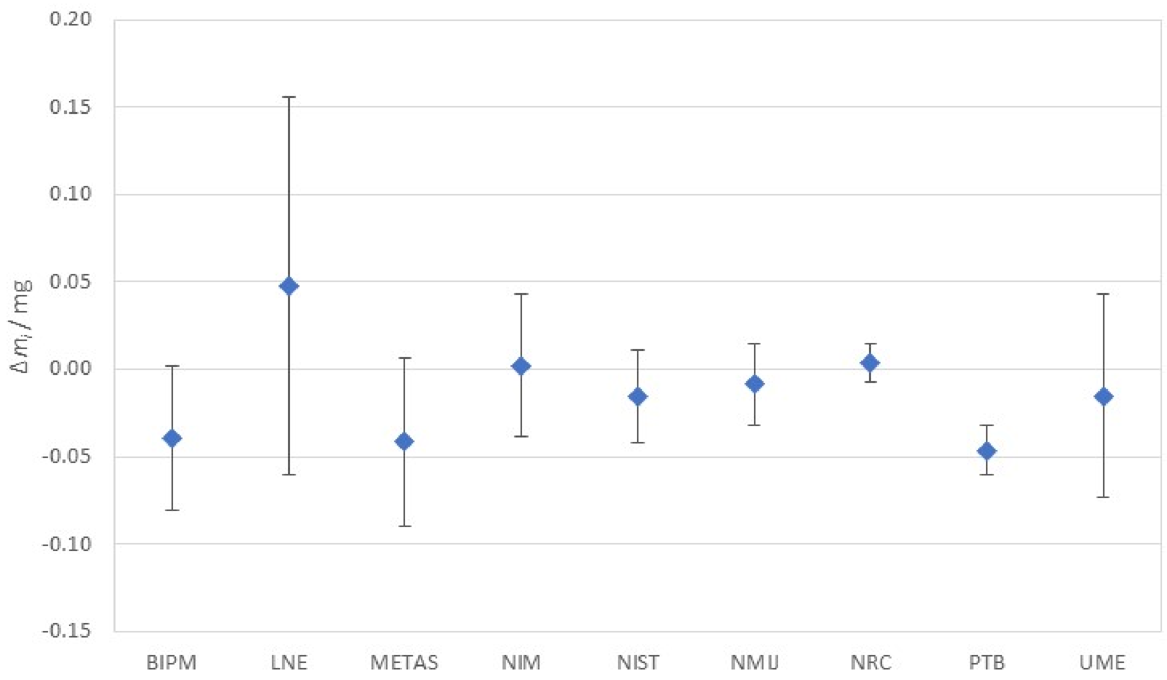

Fig. 3: Differences Δm_i between mass values attributed to 1 kg mass standards using the realization experiment of the participants and by the working standards of the BIPM, and associated standard uncertainty.

6.3 Calculation of the Key Comparison Reference Value

The key comparison reference value (KCRV) is calculated as the inverse-variance-weighted mean of the Δm_i $(i = 1, \dots, 9)$ of the realization experiments:

$$\overline{\Delta m} = \frac{\sum_i w_i \Delta m_i}{\sum_i w_i} \quad \text{with} \quad w_i = \frac{1}{u(\Delta m_i)^2} \quad \text{and} \qquad \text{(eq. 3)}$$

$$u(\overline{\Delta m}) = \sqrt{(\sum w_i)^{-1}} \qquad \text{(eq. 4)}$$

The result is $\overline{\Delta m}$ = -0.0152 mg with a standard uncertainty of 0.0074 mg. The largest statistical weights are attributed to the NRC and the PTB with 44 % and 27 %, respectively. This value of the KCRV (with respect to the mass unit maintained on the BIPM working standards) will be the input of this comparison to the calculation of the second consensus value.

In the last step of the analysis we calculate the deviation of the participants' results from the key comparison reference value $\overline{\Delta m}$:

$$\Delta m_i' = \Delta m_i - \overline{\Delta m} \qquad \text{(eq.5)}$$

For the participants that contributed to the calculation of the KCRV, the uncertainty is calculated as

$$u(\Delta m_i') = \sqrt{u(\Delta m_i)^2 - u(\overline{\Delta m}\,)^2} \qquad \text{(eq.6)}$$

These deviations and their uncertainties are shown in table 7 and figures 4 and 5. The BIPM working standards are traceable to the Planck constant through its known relationship with the IPK. The difference between mass values based on the BIPM as-maintained mass unit and the KCRV can be determined as:

$$\Delta m'_{h(IPK)} = \Delta m_{h(IPK)} - \overline{\Delta m} = -\overline{\Delta m} \qquad \text{(eq.7)}$$

$\Delta m_{h(IPK)} = 0$ because the BIPM working standards (traceable to the IPK) served as the reference for the comparison. Since the BIPM as-maintained mass unit was not used in the calculation of the KCRV, the uncertainty is calculated as:

$$u\left(\Delta m'_{h(IPK)}\right) = \sqrt{u\left(\Delta m_{h(IPK)}\right)^2 + u(\overline{\Delta m}\,)^2} \qquad \text{(eq.8)}$$

The uncertainty $u\left(\Delta m_{h(IPK)}\right)$ includes all uncertainty components of table 3 and is dominated by the uncertainty of the mass of the IPK in terms of the Planck constant, 0.010 mg.

Table 7: Deviations $\Delta m_i'$ of the NMIs' results from the KCRV, related standard uncertainties $u(\Delta m_i')$ and expanded uncertainties for *k* = 2, $U(\Delta m_i')$. The difference between mass values based on the BIPM working standards, traceable to the Planck constant through the IPK, and those based on the reference value is also shown.

Institute	**Deviation from KCRV** $\boldsymbol{\Delta m_i'}$ **/ mg**	$\boldsymbol{u(\Delta m_i')}$ **/ mg**	$\boldsymbol{U(\Delta m_i')}$ **/ mg**
BIPM	-0.0239	0.0405	0.0810
LNE	0.0629	0.1079	0.2158
METAS	-0.0264	0.0476	0.0951
NIM	0.0172	0.0399	0.0799
NIST	-0.0006	0.0256	0.0511
NMIJ	0.0066	0.0222	0.0443
NRC	0.0190	0.0084	0.0167
PTB	-0.0311	0.0122	0.0243
UME	0.0000	0.0581	0.1161
BIPM (*h*(IPK))	0.0152	0.0141	0.0282

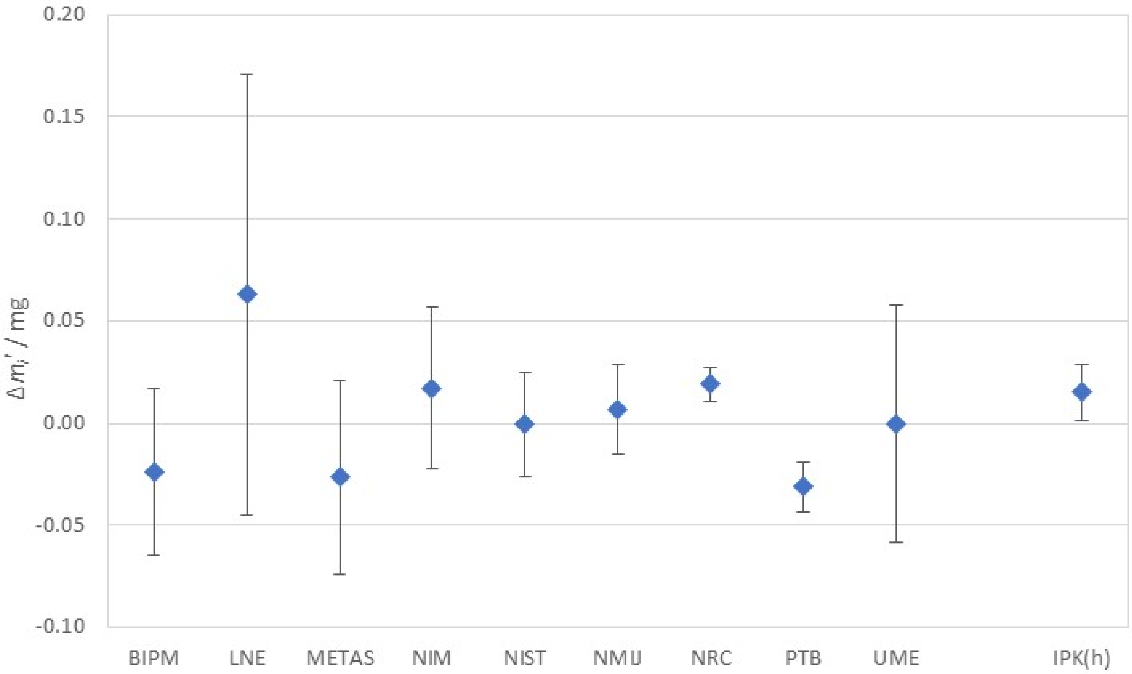

Fig 4: Differences $\Delta m_i'$ between mass values attributed to 1 kg mass standards using the realization experiment of the participants and the KCRV, and associated standard uncertainty. The difference between mass values based on the BIPM working standards, traceable to the Planck constant through the IPK, and those based on the reference value is also indicated.

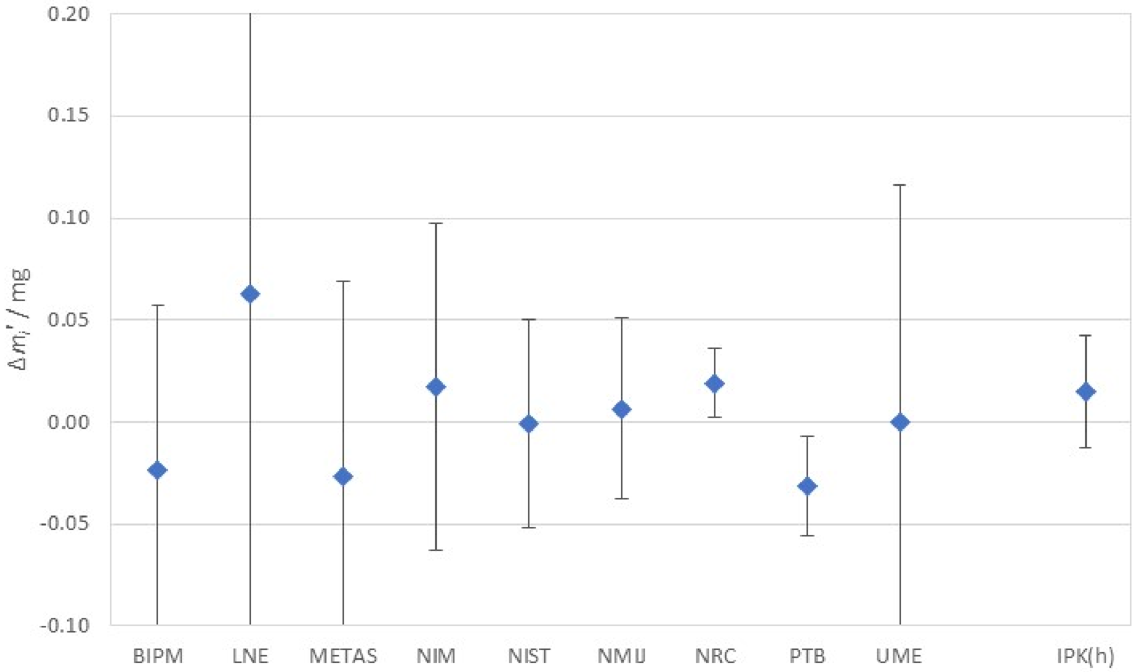

Fig 5: Same as figure 4, with uncertainty bars showing the expanded standard uncertainty for *k*=2.

To test the consistency of the data set, the chi-squared value of the data set was calculated from the data in table 7 according to

$$\chi^2_{obs} = \sum_{i=1}^{9} \frac{\Delta m_i'^2}{u^2(\Delta m_i)} \qquad \text{(eq. 9)}$$

The experimental chi-squared value is 8.9. The chi-squared value for eight degrees of freedom at the 95 % cut-off of the distribution is 15.5. A more conservative criterion is to require that the observed chi-squared lies within the expectation value of the chi-squared distribution plus its standard deviation. For ν degrees of freedom this value is $\nu + \sqrt{2\,\nu}$, for 8 degrees of freedom one obtains 12. Both tests are passed.

The difference between the NRC and PTB results is 0.050 mg, which is nearly three times the combined uncertainty of the result (0.018 mg). In the previous comparison, CCM.M-K8.2019, the difference was 0.037 mg with an uncertainty of 0.017 mg and in the data set used by the CODATA Task Group on Fundamental Constants in 2017 it was 4.1×10^{-8} in terms of h with a relative uncertainty of 1.5×10^{-8} (corresponding to 0.041 mg with an uncertainty of 0.015 mg). It is problematic that the KCRV is dominated by these two discrepant results.

6.4 Comparison with the results of previous comparisons

The CCM has established a list of criteria for a decision on the transition from the dissemination from the consensus value to dissemination from local, independent realizations. One of these criteria requires that at least five realization experiments demonstrate stability by producing consistent results for two consecutive key comparisons. It is therefore interesting to compare the results obtained in the present comparison with those obtained in CCM.M-K8.2019 and in the pilot study in 2016. Such a comparison is made possible by the quantified stability of the BIPM mass unit, as maintained by the BIPM Pt-Ir standards, and the link of this mass unit to the different comparison reference values.

Figure 6 shows the differences Δm_i between mass values attributed to 1 kg mass standards using the realization experiment of the participants and by the working standards of the BIPM, for the three comparisons. The results of the pilot study were corrected by +0.013 mg to account for the difference between the value of the Planck constant used for this study and the value fixed in 2019 for the new definition of the kilogram, and for a retrospective correction of the mass values of the BIPM working standards.

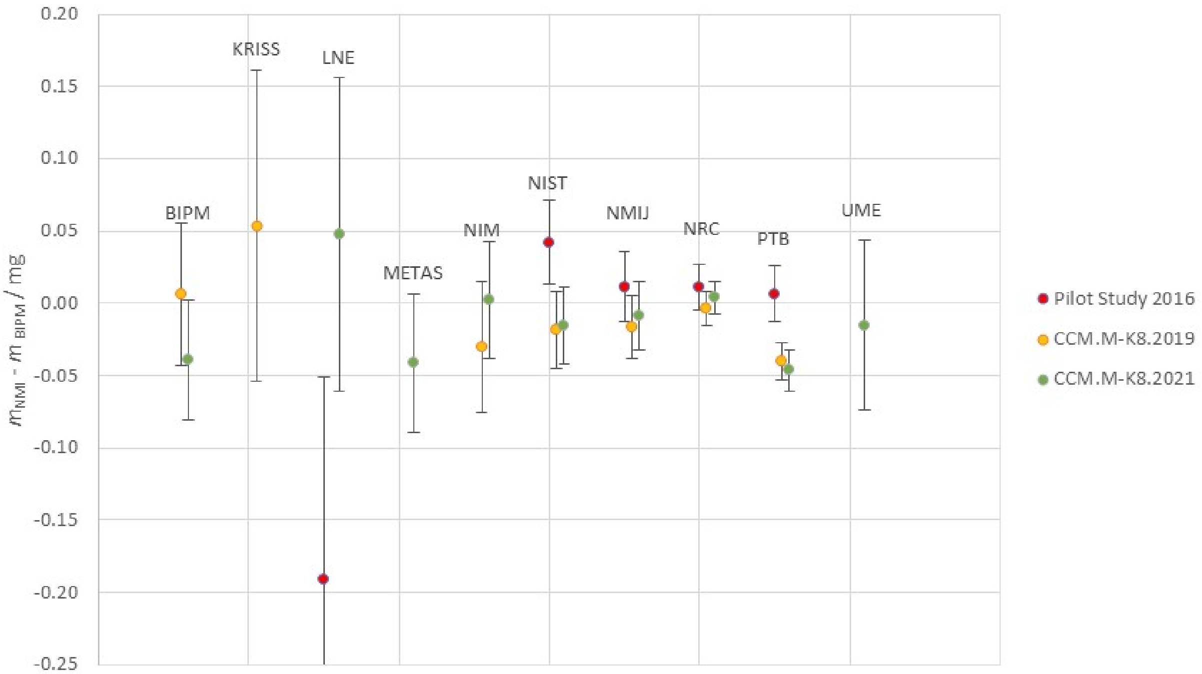

Fig. 6: Differences Δm_i between mass values attributed to 1 kg mass standards using the realization experiment of the participants and by the working standards of the BIPM (traceable to the IPK), for three comparisons and associated standard uncertainties (k=1).

7 Summary

This key comparison had the objective of comparing realizations of the kilogram based on six Kibble balances, a joule balance and two applications of the XRCD method. The participants determined the mass of one or two 1 kg mass standards traceable to their primary methods and sent them to the BIPM for comparison. At the BIPM all these travelling standards were compared with each other in a vacuum mass comparator using a BIPM mass standard as the reference.

Four types of travelling standards were used: 5 Pt-Ir standards, 9 stainless steel standards, a tungsten weight and a Si-sphere. With the exception of two standards which had shown very large mass changes and which were discarded from the comparison, all other travelling standards showed good stability. In most cases the observed mass changes were within the uncertainty of measurement.

The key comparison reference value is calculated as the weighted mean of the results. It has a deviation of -0.0152 mg with respect to the mass unit maintained by the BIPM working standards, with a standard uncertainty of 0.0074 mg. The chi-squared test for consistency using the 95 % cut-off criterion is passed, although the two results with the smallest uncertainty are not in agreement with each other. The key comparison reference value is dominated by these two results. This reference value will be the contribution of the present comparison to the calculation of the next CCM consensus value.

References

[1] M. Stock, R. Davis, E. de Mirandés, M. Milton, ”The revision of the SI – the result of three decades of progress in metrology”, *Metrologia* **56** (2019) 022001 and Corrigendum in *Metrologia* **56** (2019) 049502

[2] 9th edition of the SI Brochure, available on the BIPM web site: www.bipm.org

[3] *Mise en pratique* for the definition of the kilogram in the SI, available in Appendix 2 of the 9th edition of the SI brochure on the BIPM web site: www.bipm.org

[4] I. A. Robinson, S. Schlamminger, “The watt or Kibble balance: a technique for implementing the new SI definition of the unit of mass”, *Metrologia* **53** (2016) A46

[5] Z. Li et al., “The first determination of the Planck constant with the joule balance NIM-2”, *Metrologia* **54** (2017) 763

[6] K. Fujii et al., “Realization of the kilogram by the XRCD method”, *Metrologia* **53** (2016) A19

[7] D. B. Newell et al., “The CODATA 2017 values for h, e, k, and N_A for the revision of the SI”, *Metrologia* **55** (2018) L13

[8] CCM, 2019, “CCM detailed note on the dissemination process after the redefinition of the kilogram”, available on the BIPM web site: www.bipm.org

[9] S. Davidson, M. Stock, “Beginning of a new phase of the dissemination of the kilogram”, *Metrologia* **58** (2021) 033002

[10] M. Stock et al., “Comparison of future realizations of the kilogram”, *Metrologia* **55** (2018) T1

[11] M. Stock et al., “Report on the CCM key comparison of kilogram realizations CCM.M-K8.2019”, *Metrologia* **57** (2020) 07030

[12] H. Fang et al., “The BIPM Kibble balance for realizing the kilogram definition”, *Metrologia* **57** (2020) 045009

[13] M. Thomas et al., “A determination of the Planck constant using the LNE Kibble balance in air”, *Metrologia* **54** (2017) 468

[14] A. Eichenberger et al., “First realisation of the kilogram with the METAS Kibble balance”, *Metrologia* **59** (2022) 025008

[15] Z. Li et al., “The upgrade of NIM-2 joule balance since 2017”, *Metrologia* **57** (2020) 055007

[16] Y. Bai et al., “Automatic alignment technique for the suspended coil in the joule balance”, *Metrologia* **58** (2021) 065005

[17] D. Haddad et al., “Measurement of the Planck constant at the National Institute of Standards and Technology from 2015 to 2017”, *Metrologia* **54** (2017) 633

[18] N. Kuramoto et al., “Reproducibility of the Realization of the Kilogram Based on the Planck Constant by the XRCD Method at NMIJ”, *IEEE Trans. Instr. Meas*. **70** (2021) 1005609

[19] B. Wood et al., “A summary of the Planck constant determinations using the NRC Kibble balance”, *Metrologia* **54** (2017) 399

[20] G. Bartl et al., “A new ^{28}Si single crystal: counting the atoms for the new kilogram definition”, *Metrologia* **54** (2017) 693

[21] K. Fujii et al., “Avogadro constant measurements using enriched ^{28}Si monocrystals”, *Metrologia* **55** (2018) L1

[22] submitted for publication to *Metrologia*

[23] M. Stock *et al*., “Calibration campaign against the international prototype of the kilogram in anticipation of the redefinition of the kilogram part I: comparison of the international prototype with its official copies”, *Metrologia* **52** (2015) 310

[24] J. W. Chung, V. Görlitz, M. Vogtmann, E. Beyer, F. Härtig, “The PTB Cleaning Procedure for Silicon Spheres”, 2016, https://www.ptb.de/cms/fileadmin/internet/presse_aktuelles/messen_events/si-kg_workshop/Documents/PTB_Si_bestPracticeCleaningProcedure_PTB.pdf

[25] M. Cox, C. Eiø, G. Mana, F. Pennecchi, “The generalized weighted mean of correlated quantities” *Metrologia* **43** (2006) S268