Report on the Calculation of the CCM Consensus Value for the Kilogram 2023

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1 Introduction

In 2017 the Consultative Committee for Mass and Related Quantities (CCM) reviewed the available experimental data which served as input for the least squares adjustment of the numerical value of the Planck constant for the new definition of the kilogram [1]. The set of eight results for the Planck constant was not statistically consistent with differences between determinations as large as four standard uncertainties. The CCM therefore requested in its meeting in 2017 that NMIs with a realization of the kilogram should adopt an agreed consensus value [2]. A new consensus value would be calculated after each of a series of biennial key comparisons of realization experiments. This international coordination of the dissemination of the kilogram should be continued until the dispersion in values from individual realization becomes compatible with their individual determined uncertainties.

The details of this approach are described in the "CCM detailed note on the dissemination process after the redefinition of the kilogram" [3]. The second consensus value, following the completion of the second key comparison, CCM.M-K8.2021, will be determined based on the arithmetic mean of the reference values of the following three sets of data:

1. the reference value of the 2016 CCM Pilot Study of realization experiments (corrected for the shift of 17 parts in 10^9 in h introduced by the CODATA 2017 adjustment and for the retrospective correction of the mass of the BIPM working standards of 4 µg, yielding a total correction of 13 µg);
2. the KCRV of the first CCM Key Comparison CCM.M-K8.2019;
3. the KCRV of the second CCM Key Comparison CCM.M-K8.2021.

It was decided that the uncertainty of the consensus value should be 20 µg, unless a statistical analysis showed that this value should be increased. This uncertainty corresponds to the typical uncertainty of a "mature" realization experiment and sets the expectation on future uncertainties from individual realization experiments.

The BIPM Pt-Ir working standards were involved in all three comparisons. Therefore the three data sets can be linked together based on the assumption that the BIPM as-maintained mass unit has been stable, within some uncertainty. Contrary to its name, the consensus value is not an absolute value, but is expressed in terms of an offset from the BIPM as-maintained mass unit, which represents the mass of the IPK. The consensus value will be accessible to all NMIs having mass standards traceable to the BIPM, without the need of recalibration of mass standards.

2 The long-term stability of the BIPM working standards

For the combination of the results of the three data sets which contribute to the consensus value, it is necessary to have a common, stable reference which allows them to be linked. This reference is provided by the BIPM working standards which were used during all three campaigns. It is not necessary that the mass of the working standards is stable, what needs to remain stable is the mass unit maintained by the standards. If the mass of the standards changes, this change needs to be detected and the mass values attributed to the standards corrected accordingly. Since the stability of the BIPM as-maintained mass unit is essential for the calculation of the consensus value, we describe briefly the approach used by the BIPM.

Following the Extraordinary Calibrations using the IPK in 2014, the BIPM has put in place a new, hierarchical scheme of usage of its 12 Pt-Ir working standards. Three of them form the set of “standards for exceptional use”. They are only used once every five years and they are cleaned and washed before use, to re-establish the mass they had during the Extraordinary Calibration campaign. They have been used once since the Extraordinary Calibrations, in 2019. Three other standards form the set of “standards for limited use”. They are used once a year and they are recalibrated every five years (the last time in 2019) using the standards for exceptional use. Finally, six standards form the set of “standards for current use”. They are calibrated once a year using the standards for limited use and are used throughout the year to provide calibrations to NMIs. The different levels of usage allow the detection of mass changes which are caused by the manipulation of the standards during the measurement process.

The instability of the BIPM as-maintained mass unit has been estimated as 5 µg for the period from 2016 (when the pilot study was carried out) to 2021 and as 3 µg for the period from 2019 (when the first key comparison was made) to 2021. These uncertainties are significantly smaller than the ad-hoc uncertainty of the consensus value, which is 20 µg. Since the consensus value is calculated as the arithmetic mean of the three reference values mentioned in the introduction, the uncertainties do not enter into the calculation.

3 Data contributing to the consensus value of 2023

3.1 Reference value of the 2016 CCM Pilot Study of realization experiments

The CCM Pilot Study of future realizations of the kilogram [4] compared the realizations of the Kibble balances from LNE, NIST and NRC and the application of the XRCD method by NMIJ and PTB. The comparison consisted of two parts: one set of standards was calibrated under vacuum, another set in air. The results for both sets of standards were very similar. For the present analysis we consider only the results of the weighings in vacuum.

At the time of the Pilot Study, the latest CODATA value of the Planck constant dated from 2014:

$$h_{2014} = 6.626\,070\,040 \ \times 10^{-34}\ \mathrm{J\,s}$$

For CCM.M-K8.2019 and CCM.M-K8.2021 the 2017 CODATA value, which served for the redefinition of the kilogram, was used:

$$h_{2017} = 6.626\,070\,15 \ \times 10^{-34}\ \mathrm{J\,s}$$

The relative difference between the values is (h_{2017}/h_{2014} – 1) = 16.6 x 10^{-9}. Therefore to bring the results of all comparisons to a common basis, the NMIs’ results in the Pilot Study, expressed in terms of mass, have to be corrected by +16.6 µg.

The recalibration of the BIPM working standards in 2019 with respect to the working standards of exceptional use led to the conclusion of an annual contamination rate of about 1.8 µg, which had previously not been taken into account. Since the working standards had been calibrated using the IPK in 2014, the results of the Pilot Study in 2016 were corrected for a mass increase of the BIPM working standards of 3.6 µg, with an uncertainty of 2 µg, taken as 50 % of the correction.

Because of this mass increase of the standards, the results of the participants with respect to the BIPM as-maintained mass unit in the Pilot Study were increased by only (16.6 – 3.6) µg = 13 µg.

The differences between mass values attributed by the participants to a 1 kg mass standard and the values attributed using the BIPM working standards, corrected as explained above, are shown in table 1.

The difference between mass determinations of a 1 kg standard based on the reference value (the weighted mean of the five realizations) and on the BIPM as-maintained mass unit of 2016 is 12.4 µg with a standard uncertainty of 10.2 µg. Combined with the uncertainty of 5 µg for the stability of the as-maintained mass unit from 2016 to 2021, the uncertainty of the reference value, as maintained in 2021, is 11.4 µg.

Table 1: Differences between mass values attributed by the participants of the CCM Pilot Study in 2016 to a 1 kg mass standard and the values attributed using the BIPM working standards, and related standard uncertainty (Table 9 of [4]), corrected for the change from h_{2014} to h_{2017} and for the adjustment of the BIPM as-maintained mass unit of 3.6 µg in 2016, as described in the text.

Institute	$\boldsymbol{m_i^{\mathrm{NMI}} - m_i^{\mathrm{BIPM}}}$ **/ mg**	$\boldsymbol{u(\Delta m_i)}$ **/ mg**
LNE	-0.1913	0.1400
NIST	0.0420	0.0293
NMIJ	0.0113	0.0241
NRC	0.0109	0.0158
PTB	0.0064	0.0195
Reference value (Weighted mean)	0.0124	0.0102

3.2 The KCRV of the first CCM Key Comparison, CCM.M-K8.2019

This comparison compared the realizations of five Kibble balances from BIPM, KRISS, NIM, NIST and NRC and two applications of the XRCD method by NMIJ and PTB. The protocol of this comparison required determination of the mass of the travelling standards in vacuum.

The differences between mass values attributed by the participants of CCM.M-K8.2019 to a 1 kg mass standard and the values attributed using the BIPM working standards are shown in table 2.

Table 2: The differences between mass values attributed by the participants of CCM.M-K8.2019 to a 1 kg mass standard and the values attributed using the BIPM working standards, and related standard uncertainty (Table 7 of [5]).

Institute	$m_i^{\mathrm{NMI}} - m_i^{\mathrm{BIPM}}$ / mg	$u(\Delta m_i)$ / mg
BIPM	0.0064	0.0491
KRISS	0.0536	0.1072
NIM	-0.0305	0.0456
NIST	-0.0185	0.0270
NMIJ	-0.0166	0.0214
NRC	-0.0034	0.0118
PTB	-0.0399	0.0128
KCRV (Weighted mean)	-0.0188	0.0075

The difference between mass determinations for a 1 kg standard based on the key comparison reference value (weighted mean of the seven realizations) and on the BIPM as-maintained mass unit is -18.8 µg with a standard uncertainty of 7.5 µg. Combined with the uncertainty of 3 µg for the stability of the as-maintained mass unit from 2019 to 2021, the uncertainty of the KCRV, as maintained in 2021, is 8.1 µg.

3.3 The KCRV of the second CCM Key Comparison, CCM.M-K8.2021

This comparison compared the realizations of seven Kibble balances from BIPM, LNE, METAS, NIM, NIST, NRC and UME and two applications of the XRCD method by NMIJ and PTB. The protocol of this comparison required determination of the mass of the travelling standards in vacuum.

The differences between mass values attributed by the participants of CCM.M-K8.2021 to a 1 kg mass standard and the values attributed using the BIPM working standards are shown in table 3.

The difference between mass determinations for a 1 kg standard based on the key comparison reference value (weighted mean of the nine realizations) and on the BIPM as-maintained mass unit is -15.2 µg with a standard uncertainty of 7.4 µg.

Table 3: The differences between mass values attributed by the participants of CCM.M-K8.2021 to a 1 kg mass standard and the values attributed using the BIPM working standards, and related standard uncertainty (Table 6 of [6]).

Institute	$m_i^{\mathrm{NMI}} - m_i^{\mathrm{BIPM}}$ / 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
KCRV (Weighted mean)	-0.0152	0.0074

4 Calculation of the consensus value of 2023

Figure 1 shows the results of the 2016 Pilot Study (table 1), CCM.M-K8.2019 (table 2) and CCM.M-K8.2021 (table 3). The markers show the differences between mass values attributed by the participants of the comparisons to a 1 kg mass standard and the values attributed using the BIPM working standards. Figure 2 shows for each participant the evolution of its results for the comparisons in which it participated.

Whereas the results of several NMIs have changed from 2016 to 2019, in general there is good agreement between the results obtained in 2019 and 2021. This is also demonstrated by the good agreement between the KCRVs of 2019 (-18.8 µg) and 2021 (-15.2 µg).

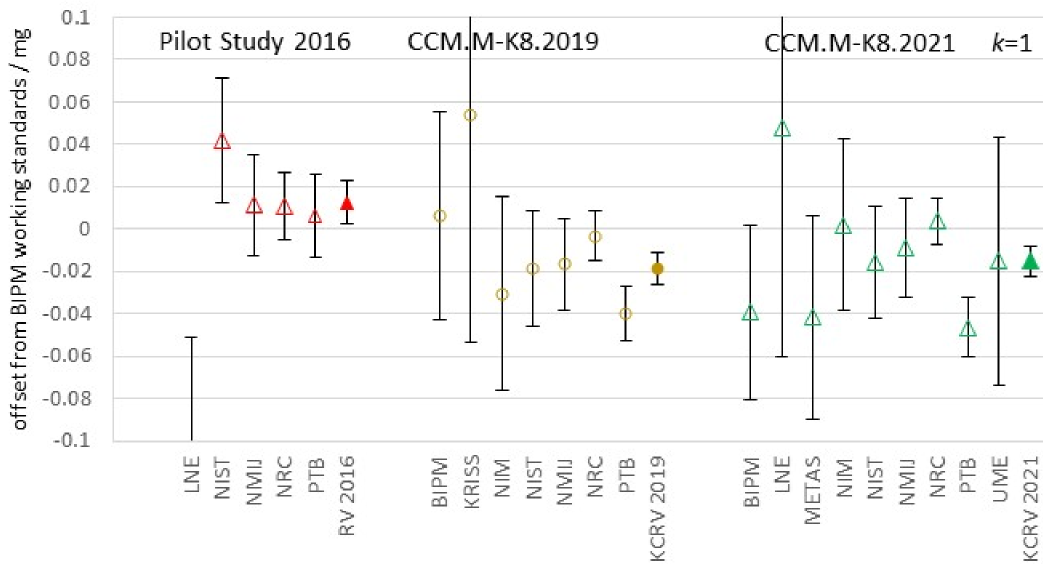

Fig 1.: Differences between kilogram realizations and the as-maintained BIPM mass unit in the three comparisons and related standard uncertainties. The reference values are shown with filled symbols.

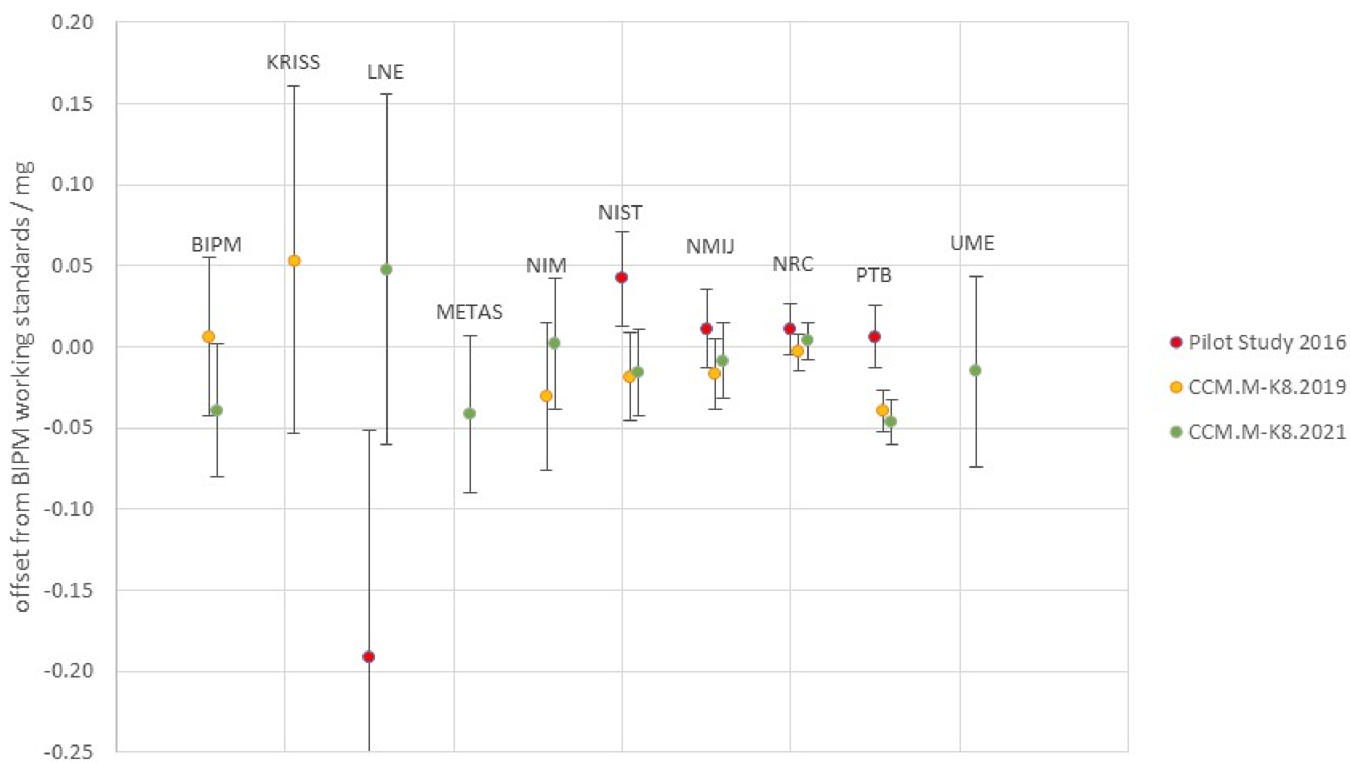

Fig 2.: Comparison of the results of the participants obtained in the 2016 Pilot Study, and the 2019 and 2021 Key Comparisons, and the associated standard uncertainties.

The three contributions to the consensus value of 2023 are shown in table 4 and on figure 3. The arithmetic mean of the three results is -7.2 µg with a standard uncertainty of 5.3 µg. The weighted mean of the three results is -11.4 µg with a standard uncertainty of 4.9 µg. These small numbers mask the problem that between 2016 and 2019 the weighted mean of the realization experiments has changed by -31 µg with respect to the BIPM as-maintained mass unit. Figure 2 shows how the results of the different NMIs contributed to this change. If the next comparison produces a similar result to CCM.M-K8.2021, the consensus value would change significantly from -7 µg to about -16 µg.

Table 4: Values and uncertainties of the three contributions to the determination of the consensus value of 2023. The uncertainties include the contribution from the instability of the BIPM working standards.

Contribution to consensus value 2023	deviation from BIPM as-maintained mass unit	unc. / µg
RV Pilot Study 2016	12.4	11.4
KCRV CCM.M-K8.2019	-18.8	8.1
KCRV CCM.M-K8.2021	-15.2	7.4

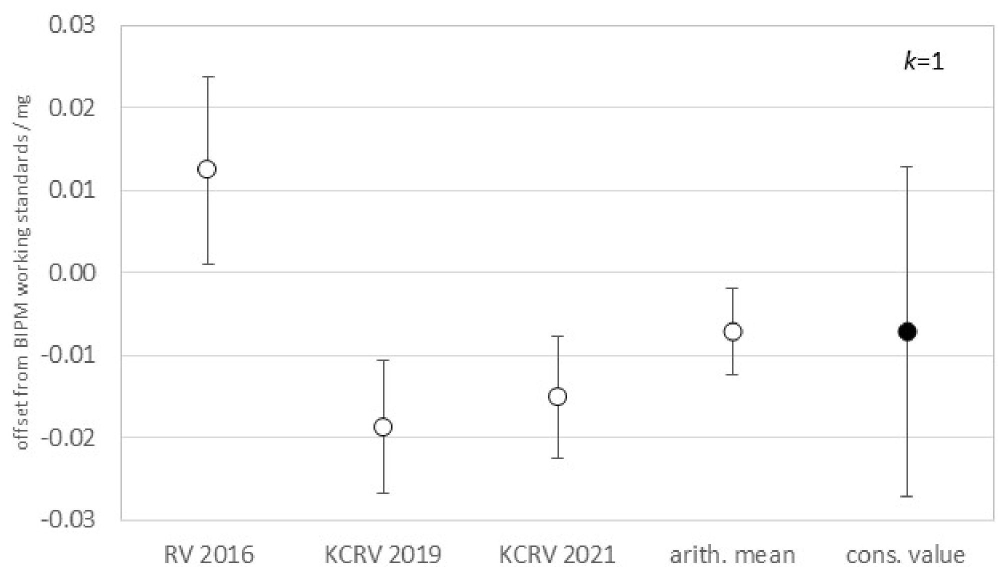

Fig 3.: The three values contributing to the consensus value of 2023 (second consensus value): reference value of the Pilot Study in 2016 and KCRVs of CCM.M-K8.2019 and CCM.M-K8.2021.

As decided by the CCM task group on the phases of the dissemination of the kilogram, the consensus value will be the arithmetic mean of the three contributions, -7 µg, with an uncertainty of 20 µg.

The mass values of 1 kg standards based on the consensus value of 2023 will be 7 µg lower than those based on the BIPM as-maintained mass unit. They will be 5 µg lower than those based on the consensus value implemented in 2021.

Traceability for the SI unit of mass will be taken from the 2023 consensus value of the kilogram commencing 1st March 2023.

To achieve consistency with the consensus value of 2023, all NMIs would need to reduce the mass value of their national as-maintained mass unit by 7 µg with respect to the mass value based on the IPK or by 5 µg with respect to the consensus value of 2021. The adoption of the consensus value of 2023 requires no further adjustment to the published CMCs of NMIs.

5 Phases of the dissemination of the kilogram since its redefinition

Table 5 gives an overview over the past and future basis for the dissemination of the kilogram. The consensus values of 2021 and 2023 are not absolute values but have to be expressed as an offset from a stable reference. This reference is the mass unit maintained by the BIPM, which represents the mass of the IPK.

Table 5: Past and future basis for the dissemination of the kilogram since its redefinition.

Date of implementation	**Basis for dissemination**	**Uncertainty**
20 May 2019	*m*(IPK) = 1 kg	10 µg
1 February 2021	Consensus value 2021 *m*(IPK) = 1 kg – 2 µg	20 µg
1 March 2023	Consensus value 2023 *m*(IPK) = 1 kg – 7 µg	20 µg

6 References

[1] P. J. Mohr *et al*., “Data and analysis for the CODATA 2017 special fundamental constants adjustment”, *Metrologia* **55** (2018) 125-146

[2] Report of the 16th meeting of the CCM, 2017, Recommendation G1 (2017) “For a new definition of the kilogram in 2018”, available on the BIPM web site www.bipm.org

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

[4] M. Stock *et al*., “Final report on CCM Pilot Study CCM.R-kg-P1 - Comparison of future realizations of the kilogram”, CCM working document CCM/17-03-7B2, available on the BIPM web site: www.bipm.org

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

[6] M. Stock *et al*., “Final report on the CCM key comparison of kilogram realizations CCM.M-K8.2021”, *Metrologia* **60** (2023) 07003

7 List of Acronyms

BIPM - Bureau International des Poids et Mesures (International Bureau of Weights and Measures)

CCM - Consultative Committee for Mass and Related Quantities

CODATA - Committee on Data for Science and Technology

IPK - International Prototype of the Kilogram

KC - Key Comparison

KCRV - Key Comparison Reference Value

KRISS - Korea Research Institute of Standards and Science (NMI of the Republic of Korea)

LNE – Laboratoire National de Métrologie et d’Essais (NMI of France)

METAS – Federal Institute of Metrology (NMI of Switzerland)

NIM - National Institute of Metrology (NMI of China)

NIST - National Institute of Standards and Technology (NMI of the United States of America)

NMI - National Measurement Institute

NMIJ - National Metrology Institute of Japan

NRC - National Research Council Canada (NMI of Canada)

PTB - Physikalisch-Technische Bundesanstalt (NMI of Germany)

RV - Reference value

UME - National Metrology Institute of Türkiye

XRCD - X-ray Crystal Density