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Beginning of a new phase of the dissemination of the kilogram

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Abstract
Following the completion of the first key comparison of realizations of the kilogram, CCM.M-K8.2019, the internationally coordinated dissemination of the kilogram has entered into a new phase on 1 February 2021. The traceability of the mass unit to the Planck constant will now be taken from the 'consensus value' of the kilogram. This letter provides the background on the phases of the dissemination of the kilogram and describes the determination of the consensus value and its consequences for mass traceability.

Keywords: kilogram, redefinition, SI units

1. Introduction

The new definition of the kilogram, based on the fixed numerical value of the Planck constant, came into force on 20 May 2019. It gives, in principle, any National Metrology Institute (NMI) the possibility to realize the kilogram [1]. At the time of writing of the present letter, it has been demonstrated that two techniques allow the realization of the kilogram from its definition sufficiently accurate to realize the unit of mass: the Kibble or joule balance [2, 3] and the x-ray crystal density (XRCD) technique [4]. The final numerical value of the Planck constant was determined in 2017 by a special fundamental constants adjustment of the CODATA Task Group on Fundamental Constants [5]. The individual eight data sets from Kibble balances and the XRCD method were not in agreement at the level of their respective standard uncertainties. By inference this means that realizations of the kilogram made by the various experiments would not be in agreement, with differences of up to 70 µg, meaning non-equivalence of global mass measurements based on these realizations. The Consultative Committee for Mass and Related Quantities (CCM) had therefore recommended at its 16th meeting in 2017 an internationally coordinated dissemination from the NMIs with realization experiments and the BIPM, instead of using their own, independent, realizations [6]. The dissemination should be based on the so-called 'consensus value' as a common basis to ensure the continuity, temporal stability and equivalence of the SI unit of mass. This arrangement would remain in place until the dispersion in values from realization experiments becomes compatible with their individual uncertainties. The use of the consensus value should facilitate the smooth transition from traceability derived from the International Prototype of the Kilogram (IPK) to the point where the use of individual realization experiments for realization and dissemination becomes viable. The details of this transition have been developed and published by a CCM task group [7]. The transition occurs in four phases:

- Phase 0: traceability to the IPK, $m_{\mathrm{IPK}} \equiv 1$ kg, before the revision of the SI on 20 May 2019;
- Phase 1: traceability to the Planck constant via its known relationship with the IPK, $m_{\mathrm{IPK}} = 1$ kg, $u(m_{\mathrm{IPK}}) = 10$ µg, from 20 May 2019 until the CCM approval of the consensus value resulting from the first key comparison of realization experiments;
- Phase 2: dissemination from the consensus value, until the CCM decides that dissemination from the consensus value is no longer necessary;
- Phase 3: dissemination by individual realizations.

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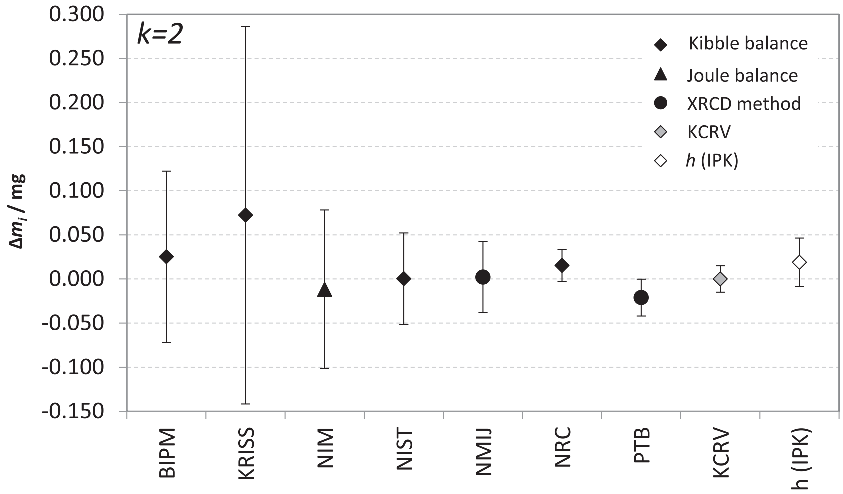

Figure 1. Differences Δm_i between mass values attributed to a 1 kg mass standard using the realization experiments of the participants and the key comparison reference value (KCRV), calculated as the weighted mean. The uncertainty bars represent the expanded uncertainty. h(IPK) represents the value based on the BIPM working standards, traceable to the Planck constant h through the IPK.

Table 1. Deviations Δm_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 the KCRV, shown as h(IPK) is also shown.

Institute	Deviation from KCRV Δm_i (mg)	$u\,(\Delta m_i)$ (mg)	$U\,(\Delta m_i)$ (mg)
BIPM	0.0252	0.0485	0.0970
KRISS	0.0724	0.1070	0.2140
NIM	−0.0117	0.0449	0.0899
NIST	0.0003	0.0259	0.0519
NMIJ	0.0022	0.0201	0.0401
NRC	0.0154	0.0091	0.0181
PTB	−0.0210	0.0104	0.0209
h(IPK)	0.0188	0.0138	0.0276

Following the completion of the first key comparison of realizations of the kilogram, the first consensus value has been calculated and implemented as we now describe, which marks the beginning of phase 2 of the dissemination of the kilogram.

2. The first key comparison of realizations of the kilogram, CCM.M-K8.2019

The first key comparison of realizations of the kilogram, CCM.M-K8.2019 has been completed and the results published [8]. The objectives of this comparison were to determine the level of agreement between kilogram realizations from different NMIs and to provide information for the calculation of the first CCM consensus value. The CCM started CCM.M-K8.2019 soon after the new definition of the kilogram came into force.

The BIPM was chosen as the pilot laboratory, as it had been for a similar CCM pilot study in 2016 [9]. Seven institutes, the BIPM, KRISS (Republic of Korea), NIM (China), NIST (USA), NMIJ (Japan), NRC (Canada) and PTB (Germany), participated using realizations based on Kibble balances, a joule balance and the XRCD-technique. Each participant determined the mass of one or two 1 kg standards under vacuum with their realization experiment. At the BIPM all mass standards were compared with a reference standard using a vacuum mass comparator. These weighings, together with the mass values determined by the participants, allowed a comparison of the consistency of the individual realizations. The chi-squared test for consistency using the 95% cut-off criterion was passed, although the two results with the smallest uncertainty were not in agreement with each other (figure 1 and table 1, [8]). The key comparison reference value (KCRV), calculated as the weighted mean of the participants' results, for a 1 kg mass standard deviates by −0.019 mg from the value based on the BIPM 'as-maintained' mass unit, which is traceable to the Planck constant through the IPK, shown as h(IPK) in figure 1.

Table 2. Values and uncertainties of the three contributions to the determination of the consensus value of 2020, expressed as deviations from the BIPM as-maintained mass unit. The reference value of the Pilot study 2016 was corrected as explained in the text.

Contribution to consensus value 2020	Deviation from BIPM as-maintained mass unit (μg)	Uncertainty (μg)
IPK 2014 [10]	0.0	11.7
Reference value of Pilot study 2016 [9]	12.4	11.4
KCRV of CCM.M-K8.2019 [8]	−18.8	7.5

3. Determination of the consensus value

As described in [7], the consensus value was calculated as the arithmetic mean of three sets of data (without taking into account any potential correlations between the data sets):

- Data directly traceable to the IPK, last used in 2014 [10];
- Extant data from the CCM Pilot study of realization experiments of 2016 [9] (corrected for the shift of 17 parts in 10^9 in h introduced by the CODATA 2017 adjustment [5] and for an adjustment of 4 μg in the as-maintained BIPM mass unit);
- The KCRV of the first CCM key comparison, CCM.M-K8.2019 [8].

The CCM had decided that the standard uncertainty of the consensus value is 20 μg. This value is based on the typical uncertainty of 'mature' realization experiments, the target uncertainty of newer realization experiments which are predicted for the next 10 years and for setting the expectations on future uncertainties from individual experiments [7].

All three data sets can be linked based on the assumption that the BIPM as-maintained mass unit has been stable (within some uncertainty) since 2014, because the BIPM working standards were involved in all three campaigns. The consensus value is determined as an offset from the BIPM as-maintained mass unit, which represents the mass of the IPK (equal to 1 kg during phases 0 and 1). It acts as an ersatz realization experiment and its uncertainty reflects a typical uncertainty for the pool of experiments.

The values and uncertainties of the three contributions to the determination of the consensus value are shown in table 2. The uncertainties are only shown for information since they are not used for the calculation of the arithmetic mean. The latter has been determined in December 2020 as −2 μg with respect to the BIPM as-maintained mass unit. This means that

- The mass of the IPK, based on the consensus value is 1 kg–2 μg and,
- The mass of every national mass standard, based on the consensus value, is 2 μg below its mass based on the IPK.

4. Actions required

The consensus value has come into force on 1 February 2021. Since the change between mass values based on the past traceability to the Planck constant, h, through its known relationship with the IPK (phase 1), and the new values, based on the consensus value (phase 2), is small in relation to the uncertainties, no adjustment to the international mass scale needs to be made. However, adjustments to the CMCs of NMIs may be necessary to take into account the uncertainty in the consensus value. Draft adjustments have been calculated by an ad-hoc task group of the CCM working group on mass and circulated to the affected NMIs for approval.

5. Next steps

Future determinations of the consensus value will be based on the latest three values from the key comparisons of realization experiments. These are scheduled to take place every two years and the consistency of the values will be reviewed according to this schedule. This method to determine the consensus value was adopted to provide temporal stability and it is expected that consecutive consensus values will not change by more than the uncertainty assigned to it, which is 20 μg. At such time that the CCM determines that the results from a sufficient number of individual realization experiments are consistent, taking into account the uncertainties of the results, individual realizations can then provide direct traceability to the SI unit of mass. The CMCs of these realizations will then be evaluated via the standard CIPM MRA process based on degrees of equivalence between the independent realizations and the KCRV. Criteria for the transition from internationally coordinated dissemination through the consensus value to dissemination from local realizations are described in [7].

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References

[1] Stock M, Davidson S, Fang H, Milton M, de Mirandés E, Richard P and Sutton C 2017 Maintaining and disseminating the kilogram following its redefinition *Metrologia* **54** S99–107
[2] Robinson I A and Schlamminger S 2016 The watt or Kibble balance: a technique for implementing the new SI definition of the unit of mass *Metrologia* **53** A46–74
[3] Li Z *et al* 2017 The first determination of the Planck constant with the joule balance NIM-2 *Metrologia* **54** 763–74
[4] Fujii K *et al* 2016 Realization of the kilogram by the XRCD method *Metrologia* **53** A19–45
[5] Newell D B *et al* 2018 The CODATA 2017 values of h, e, k, and N_A for the revision of the SI *Metrologia* **55** L13–16

[6] 2017 *Report of the 16th meeting of the CCM* Recommendation G1 (2017) for a new definition of the kilogram in 2018, available on the BIPM web site: www.bipm.org
[7] CCM 2019 Detailed note on the dissemination process after the redefinition of the kilogram CCM, available on the BIPM web site: www.bipm.org
[8] Stock M *et al* 2019 Report on the CCM key comparison of kilogram realizations CCM.M-K8.2019 *Metrologia* **57** 07030
[9] Stock M *et al* 2018 A comparison of future realizations of the kilogram *Metrologia* **55** T1–7
[10] Stock M, Barat P, Davis R S, Picard A and Milton M J T 2015 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** 310–16