Mass Calibration at NIST in the Revised SI

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Abstract

The unit of mass has been realized by the International Prototype Kilogram (IPK) for over 130 years. Beginning on May 19, 2019, all fundamental quantities of the International System of Units (SI) will be tied to natural constants. In this revision of the SI, mass will be tied to the Planck constant. For several years, the world has been engaged in measuring the Planck constant to very high precision, and with the recent CODATA adjustment in 2017, the value of the Planck constant has been fixed with no uncertainty. For the first year or two after redefinition, the world will use a consensus value for the kilogram realization rather than individual realizations from the Planck constant. This paper will describe the planned transition from consensus value to individual realizations that will take place during the next decade, and specifically discuss how NIST plans to disseminate mass during this period.

1. Introduction

On World Metrology Day, May 20, 2019, The SI will undergo a fundament revision that will realize the present seven SI base quantities (time, length, mass, electric current, thermodynamic temperature, amount of substance, and luminous intensity) using seven exact values of a set of defining constants: the ground-state hyperfine splitting of the cesium-133 atom $\Delta\nu(^{133}\mathrm{Cs})_{\mathrm{hfs}}$, the speed of light in vacuum c, the Planck constant h, the electron charge e, the Boltzmann constant k, the Avogadro constant N_A, and the luminous efficacy K_{cd}.[1] The unit of mass will be tied to the Planck constant, which has been measured to high precision in the past several years and recently fixed by a special CODATA[2] adjustment[3]. For the first time in the history of the SI, the unit of mass will not be realized with zero uncertainty by the IPK, but instead by experiments that relate mass to the Planck constant. This "frees the mass scale"[4] to be realized at values other than one kilogram with non-zero uncertainty[5]. Given a fixed value for the Planck constant and the revision of mass in the SI, it will be possible to realize the unit of mass in any laboratory that has an appropriate experiment, which revokes the geographical limitation of the IPK mass realization, which is only available at the Bureau International des Poids et Mesures (BIPM) in Sèvres, France (near Paris)[6]. To date, two major experiments have been used to measure the Planck constant using an IPK-traceable mass artifact as input: The Kibble balance[7] and the XRCD[8] experiments. Now that the Planck constant is fixed, these experiments can be "run in reverse" using the Planck constant as input to determine an unknown mass. However, recent determinations of the Planck constant have shown more variation than allowed by the criteria that was used to determine the consistency of the world's Planck constant measurements[9,10]. For this reason, the kilogram will not be realized independently by appropriate experiments throughout the world beginning on May 20, 2019; instead mass will be realized by a consensus value that will be implemented gradually over the next few years. This consensus value will be used until the dispersion in the world's mass realization experiments is reduced to a level below the uncertainties of the individual experiments. This paper will describe this process and the implications for dissemination of mass at NIST.

2. The 2017 CCM Meeting

The concept for changing the realization of the kilogram from a platinum-iridium artifact to a Planck constant-based measurement was first seriously proposed in 2005[11]. Eventually, the Consutlative Committee for Mass and Related Quantities (CCM) set forth four main conditions to be met before redefinition could occur; these are described in reference [9] and consist of the following[12]:

> **1. Consistency:**
> 'at least three independent experiments, including work from Watt (Kibble) balance and XRCD experiments, yield consistent values of the Planck constant with relative standard uncertainties not larger than 5 parts in 10^8',
>
> **2. Uncertainty**:
> 'at least one of these results should have a relative standard uncertainty not larger than 2 parts in 10^8',
>
> **3. Traceability:**
> 'the BIPM prototypes, the BIPM ensemble of reference mass standards, and the mass standards used in the watt balance and XRCD (x-ray crystal density) experiments have been compared as directly as possible with the international prototype of the kilogram',
>
> **4. Validation:**
> 'the procedures for the future realization and dissemination of the kilogram, as described in the *mise en pratique*, have been validated in accordance with the principles of the CIPM MRA (International Committee of Weights and Measures Mutual Recognition Arrangement)'.

All conditions for redefinition were met by the time of the 16th meeting of the CCM in May 2017, and this is reflected in the resulting recommendation submitted to the CIPM (reference [10]). However, the recommendation further notes:

“that the most recent measurement with relative standard uncertainty below 5×10^{-8} do not pass the standard chi-squared test of consistency, but it is expected that the CODATA value and uncertainty for the Planck constant will be suitable for even the most demanding applications”

This situation is shown in Figure 1, which corresponds to Figure 1 of reference [3]. Clearly the IAC[13]-15, NRC[14]-17, and NMIJ[15]-17 measurements fulfill the CCM criteria for redefinition.

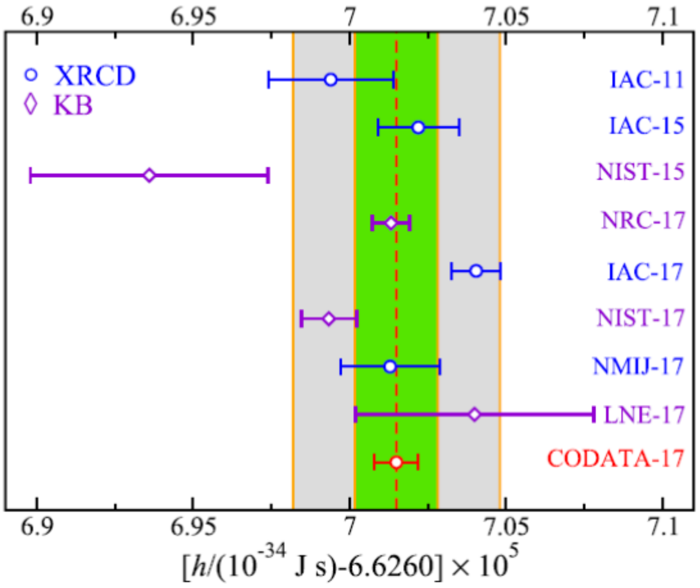

Figure 1. Values of the Planck constant h inferred from the input data in table 1 and the CODATA 2017 value in chronological order from top to bottom. The inner green band is ±20 parts in 10^9 and the outer grey band is ±50 parts in 10^9. KB: Kibble balance; XRCD: x-ray-crystal-density.

Figure 1 also shows that the values of the Planck constant obtained from the IAC-17 and the NIST-17 measurements differ by about 70 parts in 10^9 and do not agree within their respective standard uncertainties. These are the measurements that led to the failure of the chi-squared consistency test. Because of the poor consistency of these recent results for the Planck constant, there were some who felt that the redefinition should be delayed until more consistent results were obtained from the world’s realization experiments. Even so, it was believed by most attendees that the ensuing CODATA value and uncertainty would be sufficient for the most demanding mass metrology applications. As shown in Figure 1, the CODATA value has a relative uncertainty of 1 x 10^{-8}, which translates to ten micrograms on a mass of one kilogram. To deal with the systematic differences between the world's realization experiments, it was proposed that the world's National Measurement Institutes (NMI) disseminate the unit of mass from a consensus value derived from an on-going key comparison of primary realizations of the kilogram. This key comparison "will capture and maintain a table of the experimental degrees of equivalence, which can be used to create a formal procedure for applying corrections relative to the consensus value"[16] It was further agreed that dissemination from the consensus value would continue until the dispersion in the world's realization experiments becomes compatible with the individual realization uncertainties.

Practically, this decision by the CCM postpones the ability of laboratories having Planck-constant-based primary realizations of the kilogram to disseminate from these experiments. Instead, the world will use an ongoing pool of measurements to calculate a weighted average of these realizations, which is similar to what was done for fixing the Planck constant. In the subsequent months after the 16th CCM meeting, further guidance emerged detailing how this consensus value will be implemented.

3. The Consensus Value and NIST

It has been decided by a CCM Task group[17] that the dissemination of the kilogram will take place in three phases following the revision of the SI. These phases are meant to ensure the world-wide consistency of the unit of mass during the transition from the current IPK definition to the eventual dissemination of mass based on the Planck constant from the world's realization experiments. These phases are summarized below.

Phase 1 will go into effect on May 20, 2019, and maintains traceability to the IPK, but adds an uncertainty to the mass of the IPK for the first time in its history. Practically this means that the IPK will still realize mass for the world, but it will have an uncertainty of ±10 μg derived from the 1 x 10^{-8} uncertainty determined by the CODATA Planck constant adjustment. NIST is currently traceable to the IPK through BIPM calibrations of its national prototype kilograms K20, K4, K79, K92, and K102. These national prototypes will continue to serve as the foundation of NIST's mass scale during Phase 1, but an additional uncertainty of ±10 μg will be added in quadrature to the uncertainty stated on the BIPM certificates. For example, the most recent calibration certificate for K102 states a combined standard uncertainty of 3.5 μg. During Phase 1, this uncertainty, u, will be increased to:

$$u(\mathrm{K102}) = \sqrt{3.5^2 + 10^2} = 10.6\ \mu\mathrm{g}$$

This increased uncertainty will be propagated to the one-kilogram stainless-steel working standards and will increase their uncertainty to about 12 μg. The final combined standard uncertainty on one-kilogram customer calibrations at NIST will remain at about 20 μg, so the new uncertainty on the IPK will not affect the NIST mass scale.

Phase 1 will continue until a true world consensus value of the kilogram is determined from the ongoing international key comparison of primary standards. It is estimated to take about two years to complete the first round of the international comparison, which means the world will still define the unit of mass using the IPK (with an uncertainty) until sometime in 2021.

Phase 2 of the dissemination process of the new definition of the kilogram will use the Key Comparison Reference Value (KCRV) of the ongoing international key comparison of primary realizations of the kilogram. The format of the key comparison is not yet finalized, but will either be a parallel comparison between the BIPM and participating laboratories or a series of bilateral comparisons. In either case, participation in the key comparison will be limited to NMIs having published results having a relative standard uncertainty less than or equal to 5.0×10^{-7}. NIST will participate in the key comparison with its Kibble balance, dubbed NIST-4, whose performance has been well documented in the lead-up to the CODATA Planck constant adjustment[18]. The KCRV will be calculated using an established methodology, e.g., the mean value of participants' data weighed to reflect their reported uncertainties. The KCRV will initially be derived from the BIPM working standards that are currently traceable to IPK. As the key comparison of realizations progresses, the consensus value will be revised considering new values from the realization experiments, with appropriate statistical weighting. The consensus value should be stable to within the same 10 μg uncertainty that is attached to Phase 1, since this uncertainty is derived from the CODATA Planck constant adjustment. The Pilot Laboratory of the Key Comparison will be responsible for disseminating the consensus value to all NMIs.

During Phase 2, NIST will maintain an ensemble of mass standards containing both platinum-iridium and stainless-steel kilograms that are traceable to the KCRV as transmitted by the Pilot Laboratory. This ensemble will be used to create working standards that will be used for disseminating the mass scale to the US measurement system. The ensemble will be maintained in atmospheric pressure air and the masses composing the ensemble will be intercompared frequently to monitor and compensate for any mass drifts in the artifacts.

The duration of phase two will depend on the progress that is made on the world's dissemination experiments.

Phase 3 will begin when the dispersion of the results from individual realization experiments is compatible with the uncertainties of the individual realizations. This eliminates all systematic differences that may exist between the realization experiments so that the natural statistical variation of measurements is the dominant uncertainty. The scientific choice to start Phase 3 will be reviewed and approved by the CCM. In Phase 3 it will be statistically appropriate for the world to disseminate mass from individual realization experiments and to abandon the consensus value. This is the objective of the SI revision, and the implementation of Phase 3 will truly leverage the Planck constant-based kilogram. Figure 2 illustrates a possible timeline for the phase-in of the new definition.

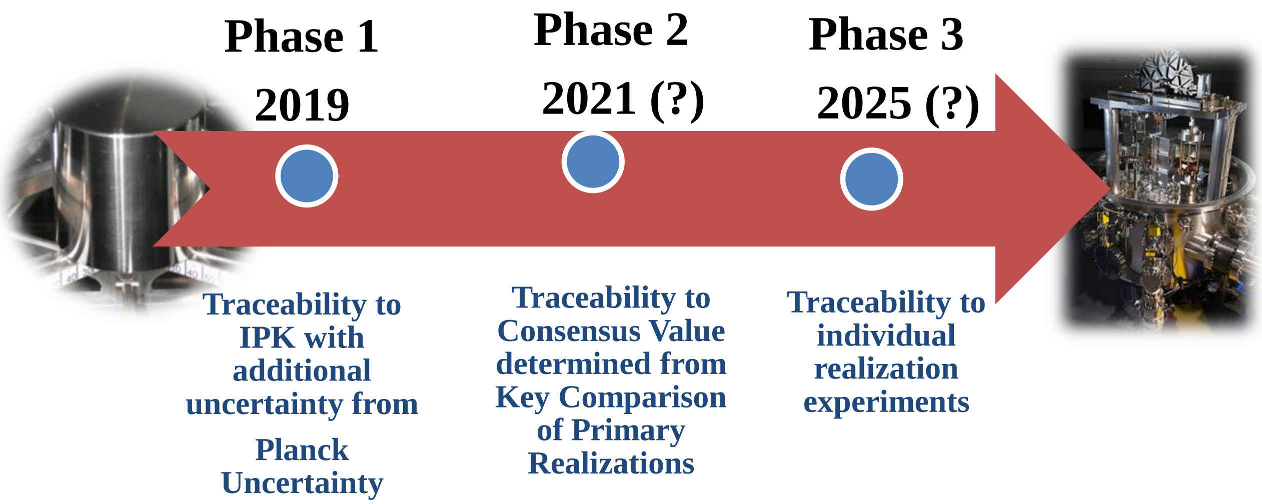

Figure 2. Phase-in to freedom: Possible timeline for the phase-in of the new definition of the kilogram. Traceability will go from the IPK plus uncertainty from the Planck constant (Phase 1 far left) to traceability to the SI Planck constant through individual realization experiments (Phase 3 far right).

The BIPM will maintain their own pool of artifacts that are tied to the KCRV and used to calibrate their working standards; these working standards, or the BIPM's own Kibble balance will be used to provide calibrations to NMIs that do not possess their own realization experiment. NIST will realize the kilogram using its Kibble balance. Two ensembles of artifacts in platinum-iridium and stainless-steel, traceable to the NIST-4 Kibble balance, will be maintained. One of these ensembles will be stored in a vacuum environment and the other in atmospheric pressure air. These ensembles will be the basis of the NIST mass scale, and like the NIST ensemble described in Phase 2 above, the composing masses will be intercompared frequently to monitor drift and to determine the frequency of performing a mass realization in the NIST Kibble balance.

4. Outlook and Conclusions

It is impossible to predict how long Phases 2 and 3 will last, but it is not unreasonable to expect a period of five years before the world is disseminating mass from individual experiments. The world is working to criteria that will ensure the equivalence of realizations. Meanwhile, more NMIs will develop primary experiments for mass dissemination and will have to tie in to the ongoing key comparison to establish equivalence with the KCRV. This will be done via the standard processes set up by the CIPM MRA for evaluating degrees of equivalence between independent realizations.

NIST will be a full participant in all three phases of the implementation of the kilogram redefinition. During Phase 1, NIST will realize mass with its Pt-Ir National Prototype kilograms. The uncertainty of each prototype will contain an additional 10 μg (added in quadrature) derived from the uncertainty of the 2017 CODATA adjustment of the Planck constant. During Phase 2, NIST will contribute to the KCRV of the ongoing key comparison of primary realizations through its NIST-4 Kibble balance. An ensemble of 1 kg mass artifacts will be established at NIST for dissemination of the unit of mass during Phase 2. The artifacts in this ensemble will be traceable to the KCRV that is disseminated by the pilot lab. When Phase 3 is implemented NIST will realize mass using the NIST-4 Kibble balance. It will disseminate through two ensembles of artifacts that are traceable to NIST-4. One of the ensembles will be maintained in atmospheric pressure air; these artifacts will be used for creating working standards for dissemination to the U.S. Measurement System. The second ensemble will be kept in a vacuum environment; these will serve as the starting point for the ensemble that is maintained in air. Both ensembles will be carefully monitored for any drift in the component masses. This information will be used to establish the frequency of primary realizations using the NIST-4 Kibble balance.

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