Report from the BIPM mass laboratory

M. Stock
CCM
25-26 May 2023
### Staff of the Physical Metrology Department

#### Electricity
- **Impedance (Resistance, Capacitance)**
  - Dr Pierre GOURNAY, Principal Physicist
  - José Angel MORENO, Physicist
  - Benjamin ROLLAND, Assistant

#### Voltage
- Dr Stéphane SOLVE, Principal Physicist (CCT)
- Régis CHAYRAMY, Principal Technician
- Kazuaki FUJITA, Secondee (NMIJ)

#### Mass
- **Kibble balance**
  - Dr Hao FANG, Principal Physicist (CCM)
  - Dr Franck BIELSA, Principal Physicist
  - Adrien KISS, Assistant
- **Mass calibr.** (also pressure, density)
  - Pedro CONCEIÇÃO, Principal Technician

---

Dr Michael STOCK  
(CCEM, CCU)
Activities in Mass Laboratories

Traditional and ongoing tasks
- mass calibrations (Pt-Ir, stainless steel) for NMIs (incl. volume/density, centre of gravity)
- provision of 1 kg Pt-Ir prototypes to Member States

Support for the revised SI
- extraordinary calibrations with respect to the IPK (2014)
- CCM pilot study of kg realizations (2016)
- organization of 2-yearly key comparisons of realizations of the kilogram (2019, 2021, 2023, ...)
- contribution to the determination of the “Consensus Value” by CCM TGPFd-kg
- development of an “international” Kibble balance for realization of kilogram
- organization of key comparisons of calibrations of stainless steel standards (2012, 2024 ?)
Guiding principles to ensure a stable BIPM mass unit

• Stable mass unit needed to compare KCRVs of successive KCs of kg realizations and for calculation of Consensus Value
• BIPM working standards calibrated against IPK in 2014
• significant unexpected mass changes since 3rd PV in 1992, attributed to wear
• new hierarchical system of mass standards with 3 significantly different levels of usage introduced in 2015
• significant reduction of the total number of weighings
• regular reports of status to CCM and CIPM
Hierarchy of BIPM Pt-Ir working standards, introduced in 2015

- **IPK**
- **25 73 91**

1. **2014**: IPK
2. **2015**: 25
3. **2016**: 31
4. **2017**: 650
5. **2018**: 9
6. **2019**: 31

5 years (no use in-between)

**Extraordinary calibrations**

*Cleaned and washed*
<table>
<thead>
<tr>
<th>Source of uncertainty</th>
<th>uncertainty / µg</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Traceability of working standards for exceptional use, in 2019, wrt IPK 2014</strong></td>
<td></td>
</tr>
<tr>
<td>calibration of 25, 73, 91 against IPK in 2014</td>
<td>3.0</td>
</tr>
<tr>
<td>reproducibility of c/w (Pedro 2019 vs. Pauline 2014)</td>
<td>3.0</td>
</tr>
<tr>
<td>extrapolation of mass from 2 months after c/w to c/w</td>
<td>2.0</td>
</tr>
<tr>
<td><strong>Traceability of working standards for limited use wrt working standards of exc. use</strong></td>
<td></td>
</tr>
<tr>
<td>weighing uncertainty (incl. repeatability) in 2019</td>
<td>1.1</td>
</tr>
<tr>
<td>buoyancy correction (using CIPM-2007 formula)</td>
<td>0.5</td>
</tr>
<tr>
<td>stability of limited use standards 2019 - 2022 (from within group comp)</td>
<td>1.0</td>
</tr>
<tr>
<td>stability of limited use standards 2019 - 2022 (correlated contamination)</td>
<td>2.3</td>
</tr>
<tr>
<td><strong>Traceability of working standards for current use wrt working standards of limited use</strong></td>
<td></td>
</tr>
<tr>
<td>weighing uncertainty (incl. Repeatability) in 2022</td>
<td>1.1</td>
</tr>
<tr>
<td>buoyancy correction (using formula)</td>
<td>0.5</td>
</tr>
<tr>
<td>stability of 2 reference standards during campaign</td>
<td>0.5</td>
</tr>
<tr>
<td>stability of 2 reference standards 42 and 103 during campaign</td>
<td>0.8</td>
</tr>
<tr>
<td><strong>Calibration of NMI Pt-Ir standards</strong></td>
<td></td>
</tr>
<tr>
<td>weighing uncertainty (incl. repeatability)</td>
<td>1.1</td>
</tr>
<tr>
<td>buoyancy (using CIPM-2007 formula)</td>
<td>0.5</td>
</tr>
<tr>
<td><strong>Sum (traceability to IPK)</strong></td>
<td>5.8</td>
</tr>
<tr>
<td><strong>Uncertainty of consensus value wrt IPK (2014)</strong></td>
<td>20.0</td>
</tr>
<tr>
<td><strong>Sum (traceability to h)</strong></td>
<td>20.8</td>
</tr>
<tr>
<td>rounded up to</td>
<td>21</td>
</tr>
</tbody>
</table>
Number of calibrations of mass standards per year

On average per year: 5 Pt-Ir prototypes
10 stainless steel standards
Fabrication of new prototypes

2016: no. 110 for NIM, China
2017: no. 111 for KRISS, Rep. of Korea
2018: no. 107 for NPSL, Pakistan
2019: no. 112 for SNSU-BSN, Indonesia
2020: no. 113 reserved for a potential buyer
2022: nos. 114 & 115 for NIM, China
2023: request for a quotation received
CCM Recommendation G1 (2017) - For a new definition of the kilogram in 2018

Extract from CCM Recommendation G1 (2017):

**Considering**

- ...that most recent measurement results with relative standard uncertainty below $5 \times 10^{-8}$ 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,

**requests** those National Metrology Institutes having a realization of the kilogram to **avail themselves of the consensus value** (as determined from the ongoing comparison) when disseminating the unit of mass according to the new definition, until the dispersion in values becomes compatible with the individual realization uncertainties, thus preserving the international equivalence of calibration certificates and in accordance with the principles and agreed protocols of the CIPM Mutual Recognition Arrangement,

Internationally coordinated dissemination of kg, based on consensus value (‘international mean kilogram’)
The calculation of the Consensus Value and its uncertainty

**Determination**
- Key comparisons of the realization experiments take place every 2 years (piolated by BIPM)
- Consensus value (CV) is calculated as arithmetic mean of the last 3 key comparison reference values (this moving average will ensure temporal stability)
- Initial value will be based on IPK, Pilot study results (2016), reference value of first KC (2019)

**Dissemination**
- CV is maintained and disseminated by the BIPM using its Pt-Ir working standards

**Uncertainty**
- The uncertainty in the Consensus Value has been decided to be 20 μg:
  - This is the typical uncertainty of mature realization experiments
  - It sets the expectation on future uncertainties from realization experiments
CCM.M-K8.2019: Results of the first key comparison of kg realizations

Differences between mass values attributed to a 1 kg weight

- Pilot: BIPM
- 7 participants: 4 Kibble balances, 1 joule balance, 2 XRCD
- Mass of travelling standards of each participant: measured in vacuum
- Final Report published in Oct. 2020
- KCRV calculated as the weighted mean of the participants’ results with $u_R(x_R) = 7.5 \mu g$
Second key comparison of realizations of the kilogram: CCM.M-K8.2021

Objectives
- test the consistency of realizations based on different realization experiments (Kibble balances, joule balance, XRCD method)
- contribute to the second consensus value

Pilot laboratory
BIPM

Conditions
\( u(m) < 200 \, \mu g \) at 1 kg

for participation
peer reviewed publication incl. detailed uncertainty budget

Participants (9)
Kibble balances (6): BIPM, LNE, METAS, NIST, NRC, UME
Joule balance (1): NIM
XRCD method (2): NMIJ, PTB

Timeline
Technical protocol: September 2021
BIPM measurements: February-March 2022
last part. report: 25 June 2022
Draft A-1: 2 August 2022
Draft B: 3 January 2023
Final Report published: 26 January 2023
17 months in total
CCM.M-K8.2021: organization of comparison

- Each participant selected 1 or 2 travelling 1 kg standards:
  - Pt-Ir (5), stainless steel (9), tungsten (1), Si-sphere (1)
  for calibration based on realization experiment, under vacuum (UME in air)

  based on: \( h = 6.626 \, 070 \, 15 \times 10^{-34} \text{ Js} \)

- NMIs sent travelling standards to BIPM

- At BIPM, all travelling standards compared under vacuum (UME in air) with BIPM reference standard

- The mass of the reference standard under vacuum is known in terms of BIPM as-maintained mass unit (traceable to \( h \) via the IPK)
CCM.M-K8.2021, second key comparison of kilogram realizations

Comparison of the participants’ mass standards under vacuum at the BIPM

Calibration in vacuum

Vacuum mass comparator

BIPM Pt-Ir sorption standards (vacuum)

Vac.-air transfer

BIPM working standards (air)

IPK (last used in 2014)
CCM.M-K8.2021: Results

Differences between mass values attributed to a 1 kg weight (in mg)

<table>
<thead>
<tr>
<th>Method</th>
<th>Δm_i / mg</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kibble balance</td>
<td>50 μg</td>
</tr>
<tr>
<td>Joule balance</td>
<td></td>
</tr>
<tr>
<td>XRCD method</td>
<td></td>
</tr>
<tr>
<td>KCRV (IPK)</td>
<td></td>
</tr>
</tbody>
</table>
The mass of the IPK, based on the consensus value is 1 kg - 7 μg with $u = 20 \mu g$

Since 1. March 2023, basis for worldwide coordinated mass dissemination
Adjustment to the international mass scale of 7 μg needs to be made

No further adjustments of the CMCs is needed
The BIPM Kibble balance (started in 2005)

- magnetic flux density 0.47 T
- bifilar coil (each 26 layers & 1100 turns)
- current 10 mA for a 1 kg mass
- standard resistor 100 Ω
- voltage drop 1 V
- velocity 1 mm/s
- induced voltage 0.5 V
Measurement scheme

One-mode two-phase scheme

**Weighing phase**

\[ mg = BLI \]

**Moving phase**

\[ BL = \frac{U}{v} \]

\[ \frac{m}{h} = \frac{n_1 n_2 f_1 f_2}{4r g v} \]

- Constant Joule heating of the coil (60 mW) -> better temperature stability
- Same alignment for both phases
- Allows faster measurement sequence

\( n \): integer number
\( f \): frequency
\( r \): calibration factor
CCM.M-K8.2021: second key comparison of kilogram realizations

Differences between mass values attributed to a 1 kg weight

- **Pilot:** BIPM
- **9 participants:** 6 Kibble balances, 1 joule balance, 2 XRCD
- **Mass of travelling standards of each participant:** measured in vacuum
- **Comparison at BIPM during Feb./Mar. 2022**
- **Final Report published in Jan. 2023**
- **KCRV calculated as the weighted mean of the participants’ results with** \( u_R(x_R) = 7.4 \mu g \)

KB will be maintained for future comparisons
Main changes since 2\textsuperscript{nd} KC

- use of a cryo-cooler for cooling PJVS array (new 2 V PJVS array, kindly supplied by NIST)
- first characterization and comparison against 2\textsuperscript{nd} array last year
- comparison against PJVS system belonging to BIPM voltage metrology service under way
New beam mechanism

Design
- an equal-arm beam mechanism using flexure hinges for pivots
- serve as zero-force detector in force phase and as coil vertical displacement generator in velocity phase
- use of a translation stage for correcting coil horizontal displacement (due to beam arc-motion) in velocity phase

Objectives
- evaluate the performance improvement to the present set-up in order to reach a target uncertainty of 2 parts in $10^8$ at the 1 kg level
- develop a prototype apparatus that implements the beam mechanism design as the basis for a compact Kibble balance at masses of 500 g and below
Experimental test bench

Visit to the Kibble balance laboratory on Friday afternoon
Liquid helium shortage

- Since early 2022, the cost for liquid helium has more than doubled from 13 €/l to close to 30 €/l, which we expect to continue.
- In other countries the cost is already around 80 €/l.
- At the same time, the quantity available from our supplier has decreased significantly (about 40-50%).

PJVS of Kibble balance now operated inside a cryocooler, use of cold water of the air conditioning of the building for cooling down the compressor.

Comparison between PJVS in cryocooler and PJVS in dewar being carried out this week.
<table>
<thead>
<tr>
<th>Detailed strategy</th>
<th>Plans (2022-2023)</th>
<th>Long Term (2024-2029)</th>
</tr>
</thead>
</table>
| Support the comparison programme of the CCEM to demonstrate the capabilities of the NMIIs and for knowledge transfer through travelling scientists by providing on-site comparisons using dedicated travelling quantum standards. | – Operate a programme of on-site comparisons of electrical quantum standards:  
  – Josephson voltage standard  
  – Quantum Hall resistance standard  
  – Develop more efficient and versatile quantum standards to be used for on-site comparisons. | – Deliver a programme of on-site comparisons using a new generation of more efficient and versatile quantum standards to increase the impact of the service with NMIIs.  
  – Provide knowledge transfer services to NMIIs that are developing new quantum standards capabilities. |
| Support NMIIs that have no access to quantum standards by providing calibrations for electrical quantities and by knowledge transfer. | – Maintain the portfolio of highest-accuracy calibration services for the most fundamental electrical quantities that exploits past investments. | – Adapt the portfolio of calibration services to the NMIIs needs.  
  – Implement a digital calibration certificate system.  
  – Provide knowledge transfer on electrical quantum standards for emerging NMIIs. |
| Support the *mise en pratique* of the kilogram by coordinating CCEM key comparisons of primary realizations held by NMIIs. | – Organize 2-yearly key comparisons of realizations of the kilogram to support the internationally coordinated dissemination of the kilogram.  
  – Determine the CCEM consensus values for the dissemination of the kilogram.  
  – Contribute to the CCEM consensus value with the BIPM Kibble balance. | – Coordinate key comparisons of primary realizations of the kilogram and of secondary mass standards according to the *mise en pratique*.  
  – Maintain the BIPM Kibble balance for realizing the kilogram. |
| Support the dissemination of the kilogram by providing calibrations of mass standards to NMIIs that have no access to a primary realization. | – provide mass calibrations for NMIIs that do not have access to their own primary realization. | – Implement digital calibration certificates and provide knowledge transfer in the fields of the realization (Kibble balance) and dissemination of the kilogram. |
E-learning courses on realization and dissemination of the kilogram

- e-learning.bipm.org

- 66 participants
- 40 participants
Thank you for your attention!