Recent developments of tabletop Kibble-based technologies at NIST: a step towards commercialization

CCM
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Dr. Darine Haddad
**New SI mass scaling at NIST/PREME Team**

- **Calibration and Measurement Capabilities (CMC) of the USA**
- **KIBB-g1 and KIBB-g2**
- **A table-top balance for the factory floor**
- **QEMMS**
  - Quantum Electro-Mechanical Metrology Suite (under construction)
- **NIST-4 (US Primary Realization)**
  - our work horse

**Graph Details**

- **y-axis:** Relative uncertainty ($k=1$)
- **x-axis:** Nominal value in kilograms (100 μg to 10 kg)
- **Legend:**
  - **EFB**
  - **CMC**
  - **KIBB-g1**
  - **QEMMS (proj.)**
  - **NIST-4**
NIST-4 Kibble Balance

- NIST primary realization to parts in $10^8$ uncertainty
- Primary realization of masses from 50g to 2kg
- 2016 pilot study
- 2017 Planck constant publication
- 2019, 2021 Key comparison and future ones
The LEGO Kibble Balance (2014)

1000g
0.000001% uncertainty
10 % fun

1g - 10 g
1 % uncertainty
100 % fun

*Thanks Terry Quinn, BIPM*
LEGO Kibble Balance Outreach (2015)

Produced by Jenny Lee, PML, NIST
NIST’s path forward in modernizing commercial mass metrology:

- No vacuum required
- No need for quantum standards
- Tabletop-sized instrument & low complexity
- Compete with commercial OIML class E2 gram-level mass standards
- Uncertainty on the order of parts in $10^6$
- New area of research

Optimal point to begin endeavor:

- Difficulty vs. relative uncertainty graph
- Need for continuous g measurement
- Need for quantum standards
- $\times$ symbol indicates optimal point
Present state of Mass Dissemination

Subdivision from 1 kg to 1 g

- ~1 week to complete
- 44 weighings
- 1200 individual measurements
- Uncertainties now on the order of $10^{-6}$
Truncate the traceability chain

Given the Planck constant is now fixed, a 1-kg mass can be realized with uncertainties on the order of $1 \times 10^{-8}$ with a Kibble balance.

Subdivision from 1 kg to 1 g:
- ~1 week to complete
- 44 weighings
- 1200 individual measurements
- Uncertainties now on the order of $10^{-6}$

Mass Metrology Lab
Realize and Disseminate gram-level masses in the comfort of your own laboratory!

Tabletop Kibble Balance
Best Features:
- Too less complicated
- Too less expensive
- Too less big
- Too less difficult to operate
- Too less accurate

Freedom from NMI's
KIBB-g1 (2017-2019)

NIST first generation tabletop Kibble balance

Target:

(1) Nominal values: between 1 g–10 g
(2) Relative uncertainties: single digit ppm
(3) Form factor: 'tabletop' sized instrument
(4) Convenience: operates in air (no vacuum required)
(5) Cost: <50 000 USD.
The performance of the KIBB-g1 tabletop Kibble balance at NIST

Leon Chao, Frank Seifert, Darine Haddad, Jon Pratt, David Newell, and Stephan Schlamminger

National Institute of Standards and Technology, 100 Bureau Dr., Gaithersburg, MD 20899, United States of America
E-mail: leon.chao@nist.gov

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| COMPARISON OF $E_2$ MASS VS. KIBB-G1 MASS REALIZATION RELATIVE UNCERTAINTIES |
|----------------------------------|---|---|
| $\Delta m_{E_2} / m_{E_2} \times 10^6$ | 2 | 5 |
| $\Delta m / m \times 10^6$ | 1.8 | 6.3 |

TABLE I
KIBB-G1 UNCERTAINTY BUDGET. ALL UNCERTAINTIES ARE $\times 10^{-6}$

<table>
<thead>
<tr>
<th>Source</th>
<th>5 g measurement</th>
<th>1 g measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Item</td>
<td>Subtotal</td>
<td>Item</td>
</tr>
<tr>
<td>Laser Stability/Accuracy</td>
<td>0.0</td>
<td>0.0</td>
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<tr>
<td>Deadpath Error</td>
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<td>Optics Thermal Drift</td>
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<td>Electronics Error</td>
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<tr>
<td>Interferometer Readout</td>
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<tr>
<td>Abbe Error</td>
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<tr>
<td>Off Axis Motions</td>
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<tr>
<td>Cosine Error</td>
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<td>Wavelength Compensation Velocity</td>
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<tr>
<td>Field Gradient</td>
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<tr>
<td>Material Thermal Expansion Coil Z Position</td>
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<td>0.4</td>
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<tr>
<td>Statistical</td>
<td>0.7</td>
<td>2.8</td>
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<tr>
<td>BL Interpolation</td>
<td>0.2</td>
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<tr>
<td>Individual BL Profile</td>
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<td>0.7</td>
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<tr>
<td>Profile Fitting</td>
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<td>Resistor</td>
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<tr>
<td>DVM (Force Mode)</td>
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<td>0.4</td>
</tr>
<tr>
<td>DVM (Velocity Mode)</td>
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</tr>
<tr>
<td>Electrical</td>
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<td>0.8</td>
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<tr>
<td>Magnetic Susc. of Mass</td>
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</tr>
<tr>
<td>Balance Sensitivity</td>
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<tr>
<td>Buoyancy</td>
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<tr>
<td>Balance Mechanics</td>
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<td>1.0</td>
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<tr>
<td>Gravity</td>
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<tr>
<td>Magnet Nonlinearity</td>
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<td>Air Bearing Pressure</td>
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<tr>
<td>Forces on mass</td>
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<td>5.5</td>
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<tr>
<td>Total</td>
<td>1.8</td>
<td>6.3</td>
</tr>
</tbody>
</table>
KIBB-g1 inducted into the NOAC program (2020)

NIST On A Chip

Barbara Goldstein, Program Manager
barbara.goldstein@nist.gov

Jay Hendricks, Deputy Program Manager
jay.hendricks@nist.gov

* Not quite on a chip, but at least on a table
US Dept. of Defense Interest (summer 2020)

- Army USATA (Test, Measurement, Diagnostic Equipment Activity) SOW on KIBB-g2: 3 year funding for the development of the next generation tabletop Kibble balance with a focus on design for commercialization at OIML Class F2 uncertainties.

- AFMETCAL (Air Force Metrology and Calibration) SOW on torque realization: 3 year funding for the development of an absolute standard having a dynamic range of 0.1 – 142 in-ozf with 0.1% uncertainty.
Goal: Construct a second generation tabletop Kibble balance for directly realizing [500 mg – 20 g] masses with ASTM Class 3 accuracies (OIML Class F2)

- US Army Funded
- Flexure-based mechanics
- Commercial voice coils
- Commercial optical encoder
Kibble Principle for Torque

### Self-Calibration Mode

\[ V = B(\phi)Lr\dot{\phi} \]

*Spin Mode*

### Measurement Mode

\[ \tau = B(\phi)LrI \]

*Torque Mode*

\[ \tau = I \frac{V}{\dot{\phi}} \]
Electronic NIST Torque Realizer (ENTR)

Create an absolute small torque standard with range:

0.1 in ozf – 142 in ozf

(7 x 10^{-4} N m – 1 N m)

and uncertainty of:

0.1%

(7 x 10^{-7} N m)
Utilizing commercial components

- USB DAQ I/O
- 6.5 Digit Voltmeter
- Programmable Current Source
- Calibrated Resistor

Can produce holding torque up to:

$2 \times 10^{-2} \text{ N m} \quad (3 \text{ in-ozf})$

Torque tool under test

Dual read head encoder system

Disclaimer: Certain commercial equipment, instruments, and materials are identified in this presentation in order to specify the experimental procedure adequately. Such identification is not intended to imply recommendation or endorsement by the National Institute of Standards and Technology, nor is it intended to imply that the materials or equipment identified are necessarily the best available for the purpose.
QEMMS as an NMI in one lab

1. Kibble balance
2. Graphene quantum Hall array resistance standard
3. Programmable Josephson voltage system (PJVS)
4. Absolute gravimetre
5. Caesium clock time standard
6. Iodine stabilized HeNe-laser length standard

→ Quantum Electro-Mechanical Metrology Suite:
  time, length, mass, electric current, voltage, electric resistance

Laboratory $L \times W \times H$: 6.5 m x 4.5 m x 3.7 m
Vision for the QEMMS Kibble balance

- Balance smaller and more compact than NIST-4: makes parts structurally stiffer and allows for reduction of components/complexity

- Measuring mass between 10 g – 200 g with absolute uncertainty of 2 μg at 100 g

- Open-source hardware and software to replicate the balance

- Comparable in size to a commercial high precision vacuum 1 kg mass comparator

- Ability to measure multiple masses without breaking vacuum → in vacuum mass exchange and storage

- QEMMS will be ready end of 2025, and will be also another US primary realisation
# Direct Mass Realization Capabilities at NIST from 50 µg to 2 kg

<table>
<thead>
<tr>
<th>Measurement Range</th>
<th>Relative Uncertainty</th>
<th>Relative Cost</th>
<th>Target Users</th>
</tr>
</thead>
<tbody>
<tr>
<td>50 µg – 20 mg</td>
<td>1 \times 10^{-4} – 7 \times 10^{-6}</td>
<td>$$$</td>
<td>National Lab</td>
</tr>
<tr>
<td>500 mg – 20 g</td>
<td>5 \times 10^{-5} – 5 \times 10^{-6}</td>
<td>$</td>
<td>Calibrations Lab</td>
</tr>
<tr>
<td>10 g – 200 g</td>
<td>5 \times 10^{-8} – 2 \times 10^{-8}</td>
<td>$$</td>
<td>Calibrations/National Lab</td>
</tr>
<tr>
<td>50 g – 2 kg</td>
<td>3 \times 10^{-8} – 1 \times 10^{-8}</td>
<td>$$$$</td>
<td>National Lab</td>
</tr>
</tbody>
</table>