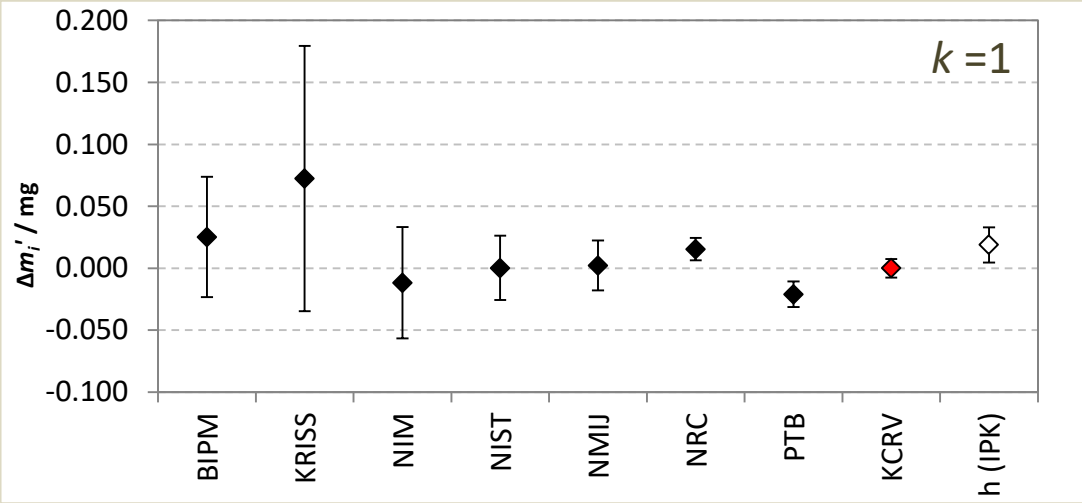
Summary of updates of realization & mass dissemination from NMIs

Richard Green

18th CCM meeting, 20-21 May 2021

Bureau International des Poids et Mesures

BIPM Kibble balance: measurement & improvement



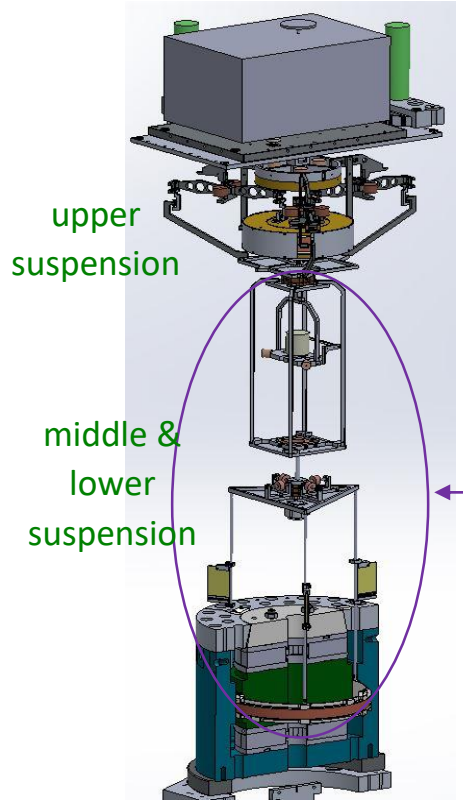
Measurements in 2019

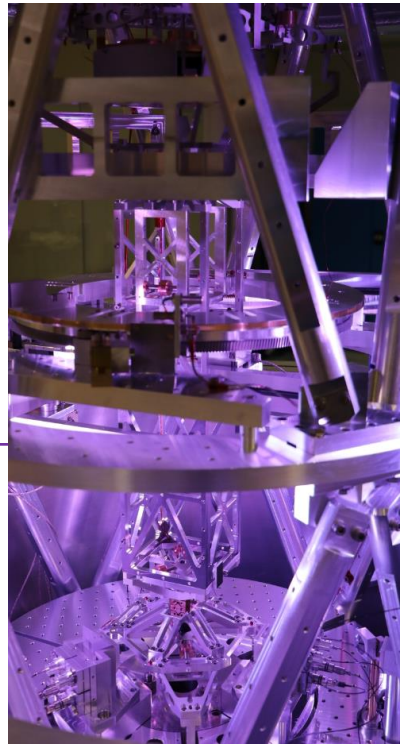
- participation in CCM.M-K8.2019
- *Metrologia* paper
- standard uncertainty 49 µg limited by parasitic coil motion & voltage measurement (electrical grounding)

Various improvements in 2020

- Upgrade of laser frequency servo-control and of various electronics for position sensors
- automation & refinement of data processing programs
- investigation & improvement of electrical circuit → further investigation is required

BIPM Kibble balance: towards Mark II apparatus

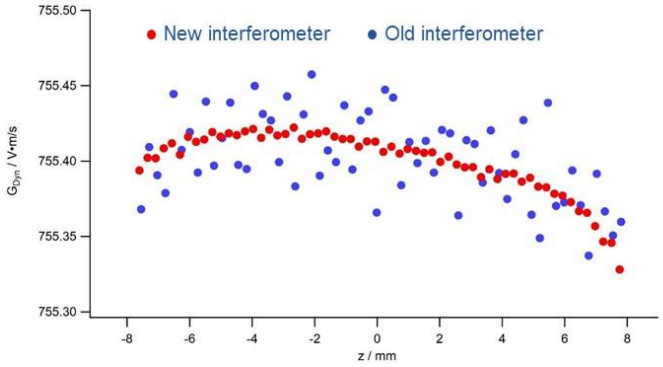




- STEP I: new middle & lower suspension
  - much stiffer and more easily adjustable mechanics
  - new bifilar coil having a larger wire length
  - operation in vacuum confirmed
- STEP II: replacing upper suspension (motor + 3 levers for generating the coil vertical motion) → minimize unwanted coil motion (reduce type B uncertainty)
  - replacing commercial weighing cell
  - a first beam balance prototype being fabricated

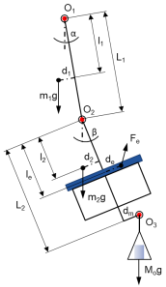
Main improvements

- Significant noise reduction in the dynamic phase

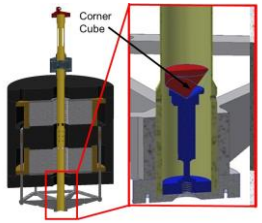


- Redesign of the interferometer physically attached to the magnet
- Mean of the fit residuals on one trajectory ~ 5 ppm

- Alignment stability / Abbe error



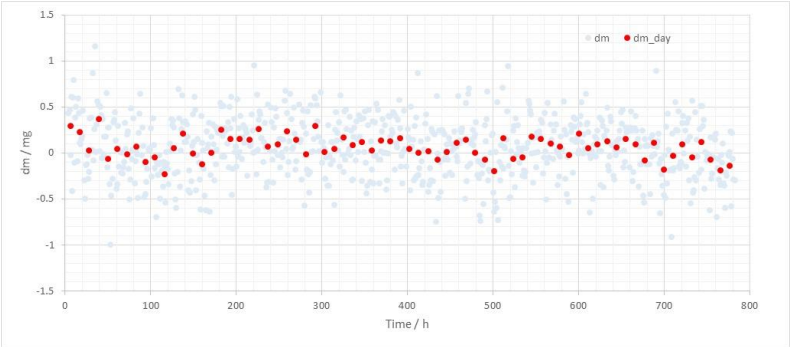
- $u_{Alignement}$ < 10 ppb



- u_{Abbe}< 10 ppb

Preliminary results / Next steps

- ~ 30 days measurement under vacuum

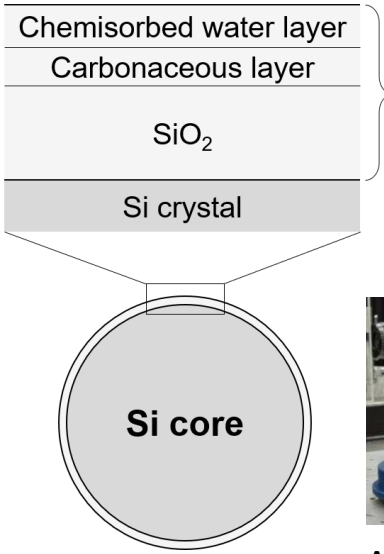


- dm = 60 ug
- std = 2 ug

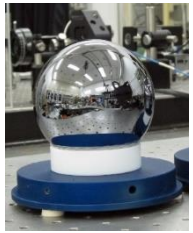
- Complete realignment of the whole experiment
- Two campaigns with two different masses
  - Stainless steel
  - Gold plated copper

Realization of the new kilogram at NMIJ by the XRCD method using AVO28-S5c

Principle of the XRCD method



Surface model of the sphere AVO28-S5c



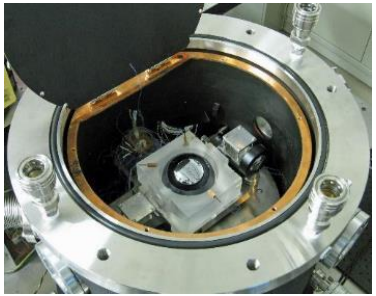
AVO28-S5c ^{28}Si-enriced

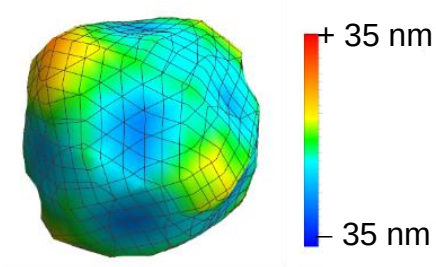
$$m_{\text{sphere}} = \underbrace{\frac{2hR_\infty}{c\alpha^2}\frac{A_r(\text{Si})}{A_r(\text{e})}\frac{8V_{\text{core}}}{a^3} - m_{\text{deficit}}}_{\text{Si core}} + \underbrace{m_{\text{SL}}}_{\text{Surface layer}}$$

- Parameters measured for CCM.M-K8.2019
  - Volume of Si core, V_{core}
  - Mass of surface layer, m_{SL}
- Parameters taken from the previous works
  - Lattice constant, a
  - Relative atomic mass of Si, A_r(Si)
  - Mass deficit due to impurities and vacancies, m_{deficit}

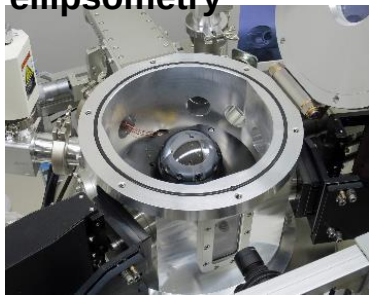
Volume measurement and surface characterization to realize the new kilogram

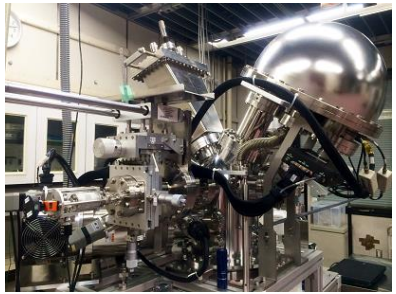
Volume measurement by optical interferometry





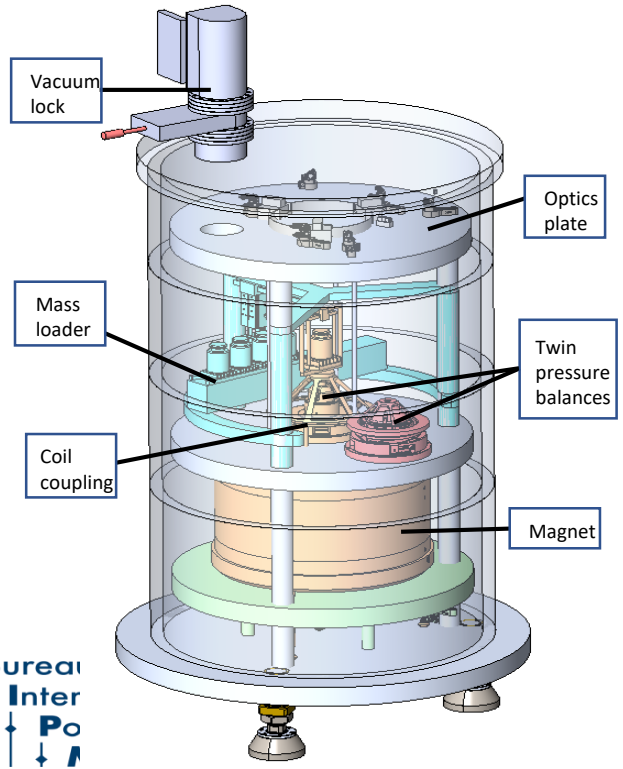
Surface characterization by X-ray photoelectron spectroscopy (XPS) and ellipsometry





- **$u_r(m_{sphere}) = 2.1 \times 10^{-8}$, 21 µg for 1 kg**
- **N. Kuramoto *et al.*, *IEEE Trans. Instrum. Meas.*, DOI: 10.1109/TIM.2021.3061805**

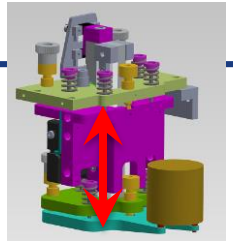
MSL Kibble balance updates



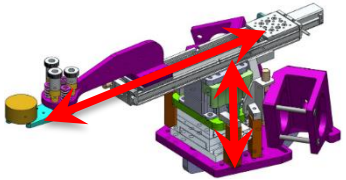
- Layout of modules has been decided, vacuum chamber being made.
- Measurement model under development.
- Still pursuing oscillatory moving mode.
- 3 experimental projects: pressure balances, interferometer, coil-magnet test.
- Pressure balances: rotating cylinder, syringe pump, repeatability of differential pressure transducer.
- Interferometer: voice coil, non-linearity error, AOM frequency shifting.
- Coil-magnet test: uniformity of field, parasitic forces, mass balance based KB.

LNE Kibble balance progress report

New mass lifters



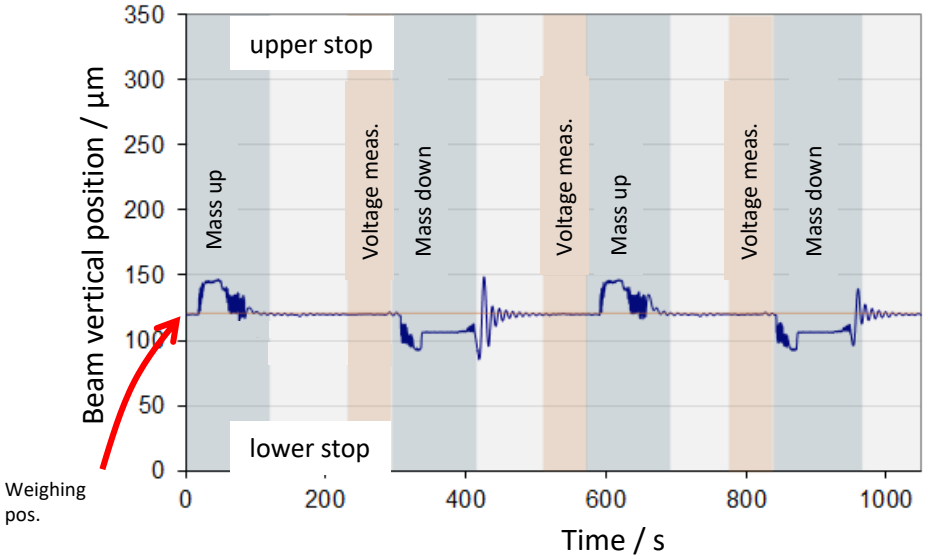
Lifter embedded in the translation stage:
double weighing at different vertical positions



2-axis lifter: bring in and out the mass standard in the mass pan

Altogether with servo control improvements:
double weighing with a vertical beam excursion of only +/- 60 µm

→ could reduce hysteresis in static phase



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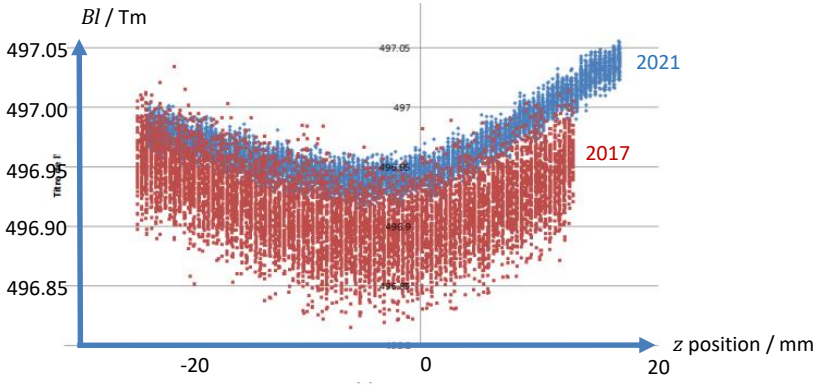
LNE Kibble balance progress report

Modification of the feet of the balance + modification around concrete slab

- Increase the **immunity of the experiment** to mechanical nearby activity
- Two-fold **improvement of the noise rejection** in dynamic phase

100 trajectories up and down, $Bl = U/v$



Works have been delayed some months due to the failure of the vacuum vessel lifter and of the current source

Dynamic phases have been carried out in vacuum, as well as static phases: kilogram determinations will be the next step (mid-2021).

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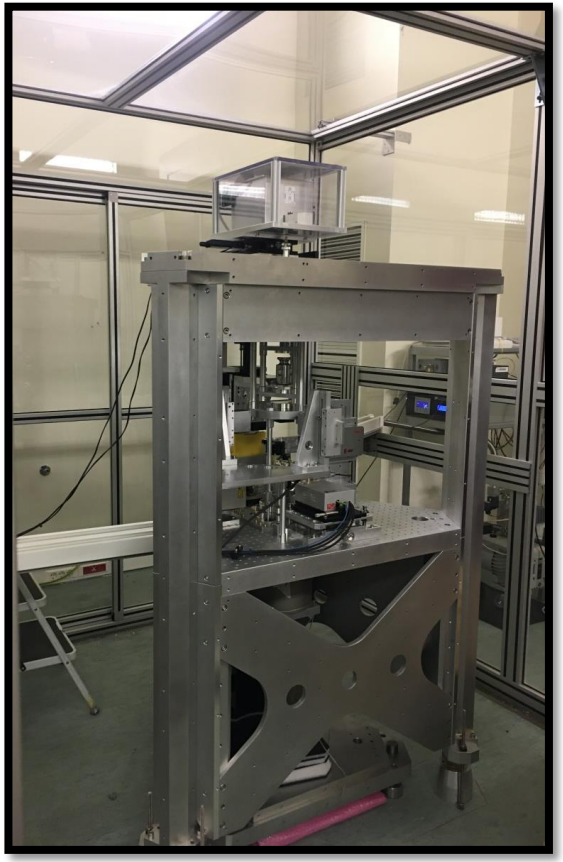
LNE KB team : K. Dougdag, P. Espel, M. Thomas, D. Ziane

UME-KB3

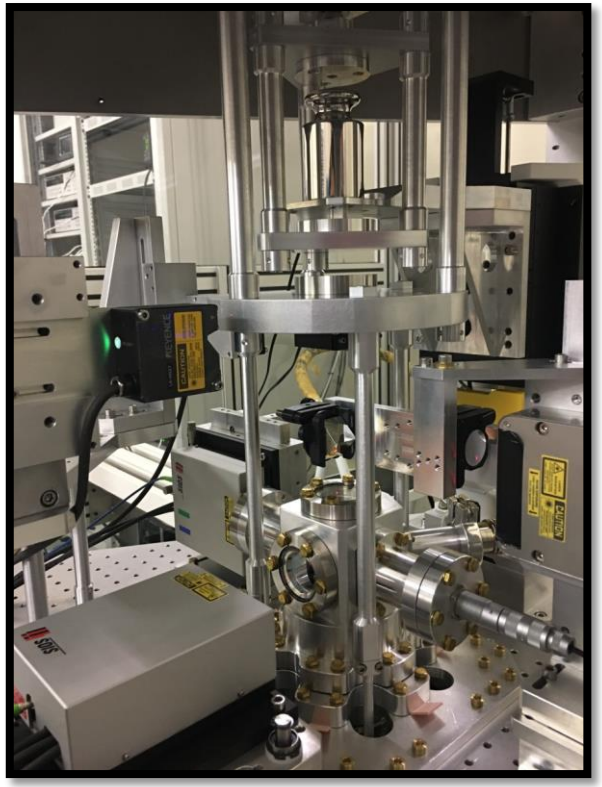


UME-KB3 was installed. Distinguishing aspects:

- Novel dynamical measurement procedure
- Local vacuum around the around the cubic mirror on the top of the moving magnet for determining the displacement of the magnetic circuit with respect to the coil
- Compact design including a moving magnetic circuit and a stationary coil
- Simultaneous testing of Faraday's Law of Induction and Ampere's Law of Force

TÜBİTAK UME

Current Status of UME-KB3



Local Vacuum & Interferometer Heads

Control Units & Instruments

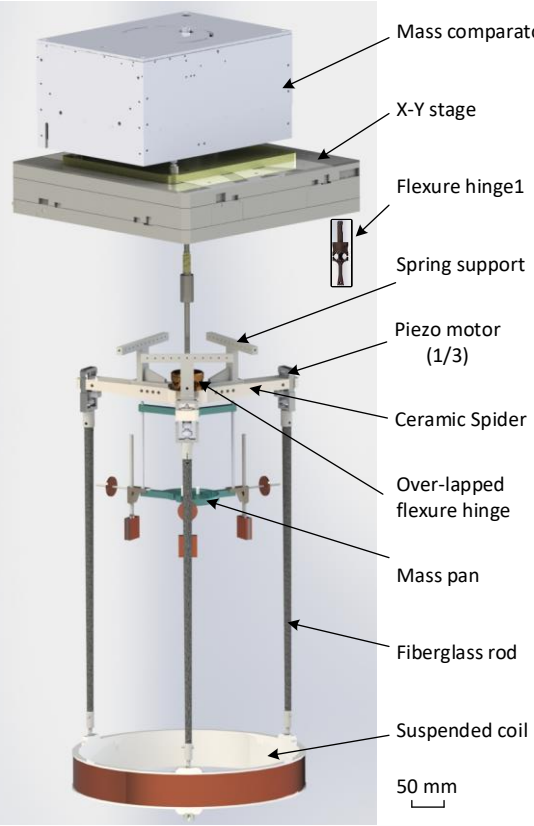
Preliminary Measurement Result

Uncertainty parameter	Relative Uncertainty (ppb)
Alignment	45
Resistance	45
Mass	38
Others	19
Total	77

TÜBİTAK UME

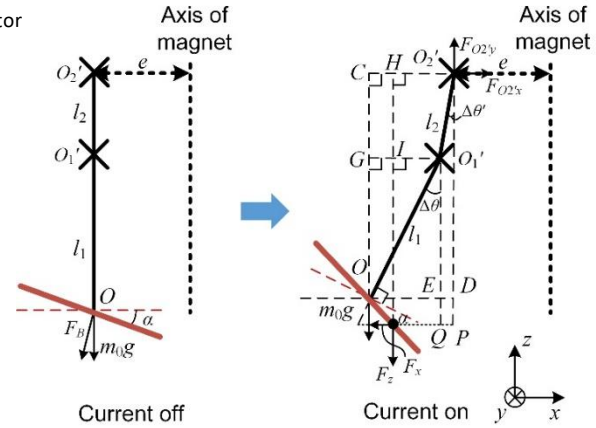
NIM - Current status of the Joule balance

1. An automatic alignment technic for suspended coil in the Joule balance



Suspended structure in joule balance

The principle of automatic alignment



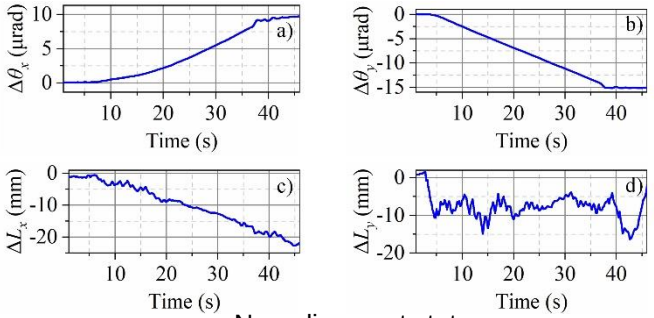
Linear Relationship

$$\begin{pmatrix} \alpha \\ e \end{pmatrix} \Leftrightarrow \begin{pmatrix} \Delta L \\ \Delta\theta \end{pmatrix}$$

Initial position /posture

Parasitic displacement

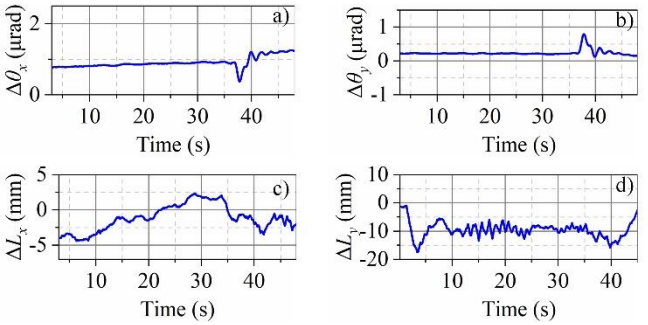
Automatic alignment Test（Current off/on）



Non-alignment status

Automatic adjustment

Within several minutes

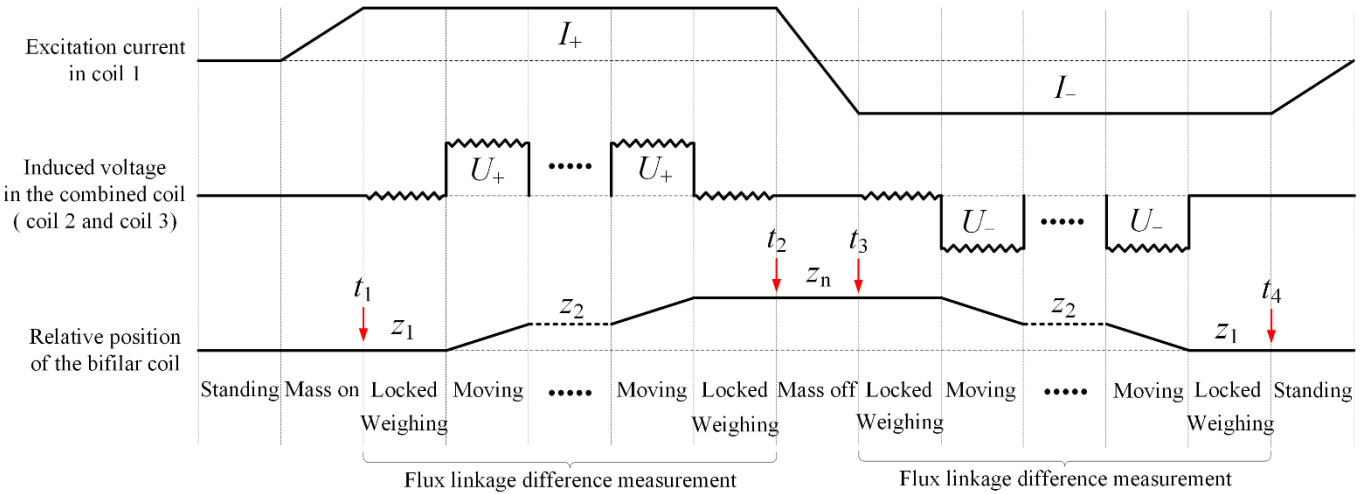


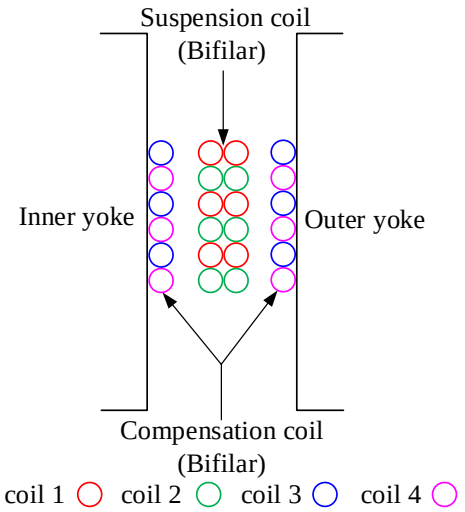
Alignment status

NIM - Current status of the Joule balance

2. The one-mode one measurement phase (OMOP) scheme in the Joule balance

1) Consistency of the two independent coils of the bifilar suspension coil: σ < 3E-9
2) Evaluation of the coil current effect, U_{rel}< 4.3E-9
3) A bifilar compensation coil is new wound to suppress the effect of the external magnetic field and the magnetization effect of the suspension system simultaneously.
4) The whole system is still under construction and testing.





[1] Fang H, et al. Status of the BIPM watt balance. IEEE Trans. Instrum. Meas., 2013, 62(6):1491-1498.
[2] Robinson I A. A simultaneous moving and weighing technique for a watt balance at room temperature. Metrologia, 2012, 49(1):108-112.
[3] Qian L S, et al. Preliminary Study on the OMOP Joule Balance. IEEE Trans. Instrum. Meas., 2020, 69(9):6478-6489.
[4] Qian L S, et al. The interaction between the magnetized coil-suspension system and the compensation coil in the joule balance. Metrologia, 2020, 57(4):045010.

Realisation with ^{28}Si spheres

Reference ^{28}Si sphere AVO28-S8c (primary mass standard):

Source of uncertainty	Standard uncertainty / µg
Molar Mass	5.4
Lattice parameter	6.5
Point defects	3.8
Surface layer mass	7.7
Mean Diameter	9.4
Combined standard uncertainty (k = 1), w.r.t. realisation of the definition of the kilogram	15.3

Reference ^{28}Si sphere Si28kg01a (primary mass standard):

Source of uncertainty	Standard uncertainty / µg
Molar Mass	1.5
Lattice parameter	6.3
Point defects	3.4
Surface layer mass	7.0
Mean diameter	8.7
Combined standard uncertainty (k = 1), w.r.t. realisation of the definition of the kilogram	13.4

- Realisation with two ^{28}Si spheres (AVO28-S8c and Si28kg01a) made from two different crystals
- Previous results of material properties were used
- Volume and surface layers were measured anew
- Agreement of two realisations based on two different silicon crystals within 1×10^{-8}

PTB activities for future realisation and dissemination

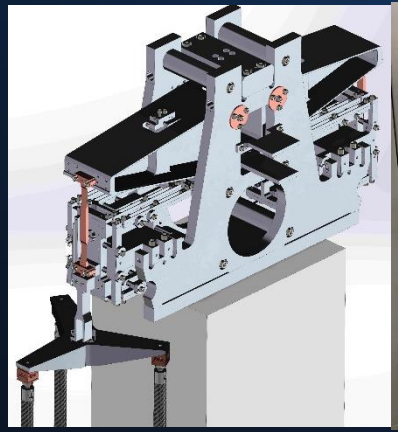
- New ^{28}Si material (two single crystal boules) for future realisation and dissemination received
- Manufacture of two new ^{28}Si spheres completed; another ^{28}Si sphere in progress
- Extended investigations of material parameters (lattice parameter, impurities and their distribution) in preparation
- Density comparisons show agreement with mass/volume results of different spheres
- Investigation of the repeatability of the cleaning method applied for silicon spheres at PTB by gravimetric measurements and by XRF/XPS analysis of the surface layers; results show that the repeatability can be characterised by a standard deviation in the order of two micrograms
- “Planck-Balance” – improvement in the determination and correction of Abbe error; application of an AC-Josephson standard

National Institute of Standards and Technology
U.S. Department of Commerce

NIST will have two primary realizations.

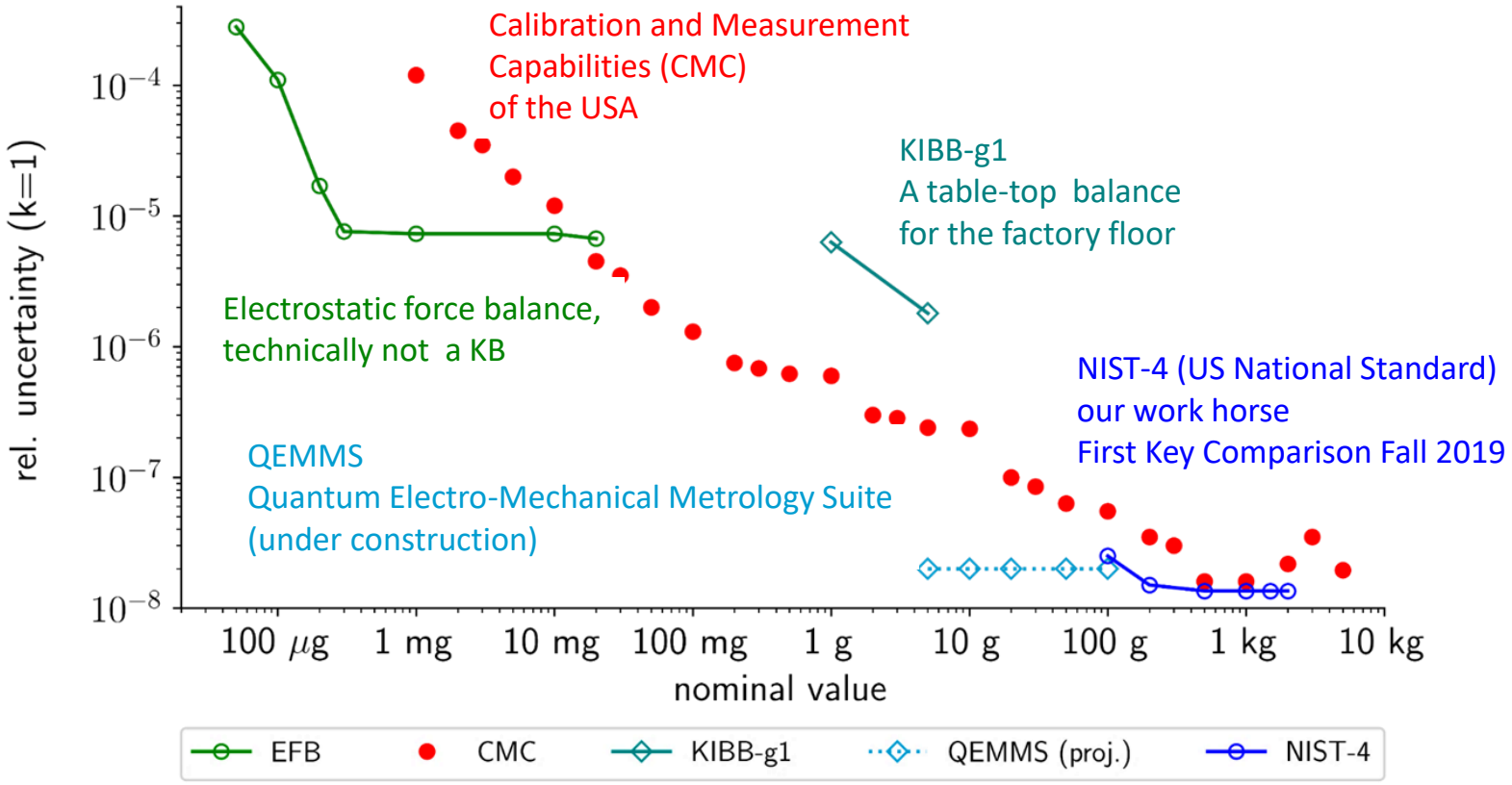
NIST-4, the current workhorse (50g-2kg)

- Realization of two primary masses at 100g and 50g level.
- Getting ready for the next key comparison.



QEMMS (10g-200g) Quantum Electro-Mechanical Metrology Suite (QEMMS) is composed of a Kibble balance, a Josephson voltage standard and a Quantum Hall resistance standard.

- Magnet/coil ready.
- Vacuum chamber to be delivered end of April 2021 .
- Cryogen Free PJVS ready.
- Cryogen Free Superconducting Magnet System for QHR in purchase.
- Flexure based mechanism for weighing and moving ready in few months.


Calibration and Measurement Capabilities (CMC) of the USA
KIBB-g1
A table-top balance for the factory floor
Electrostatic force balance, technically not a KB
NIST-4 (US National Standard)
our work horse
First Key Comparison Fall 2019
QEMMS
Quantum Electro-Mechanical Metrology Suite
(under construction)
rel. uncertainty (k=1)
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
100 μg
1 mg
10 mg
100 mg
1 g
10 g
100 g
1 kg
10 kg
nominal value
EFB
CMC
KIBB-g1
QEMMS (proj.)
NIST-4

National Institute of Standards and Technology
U.S. Department of Commerce

Pools of Artifacts for Mass Dissemination and SIM Kilogram Project

VACUUM POOL

- Artifacts: (3) Pt-Ir kilograms, cylindrical,
  (2) Stainless-Steel kilograms, cylindrical or OIML
- Designed to act as "flywheel" for NIST-4 KB realizations
- Traceability: Consensus value of kilogram
- Transfer of mass unit to AIR POOL using measured vac to air correction
- Stability: ~ 0.003 mg over past 18 months; << Unc. (.021 mg)

AIR POOL

- Artifacts: (3) Pt-Ir kilograms, cylindrical,
  (2) Stainless-Steel kilograms, cylindrical
- Designed to act as starting point of mass scale in air
- Stability: Pt-Ir: 0.001 to 0.003 mg over 18 months;
  Stainless-Steel: ~0.005 mg over 18 months

SIM Kilogram Project

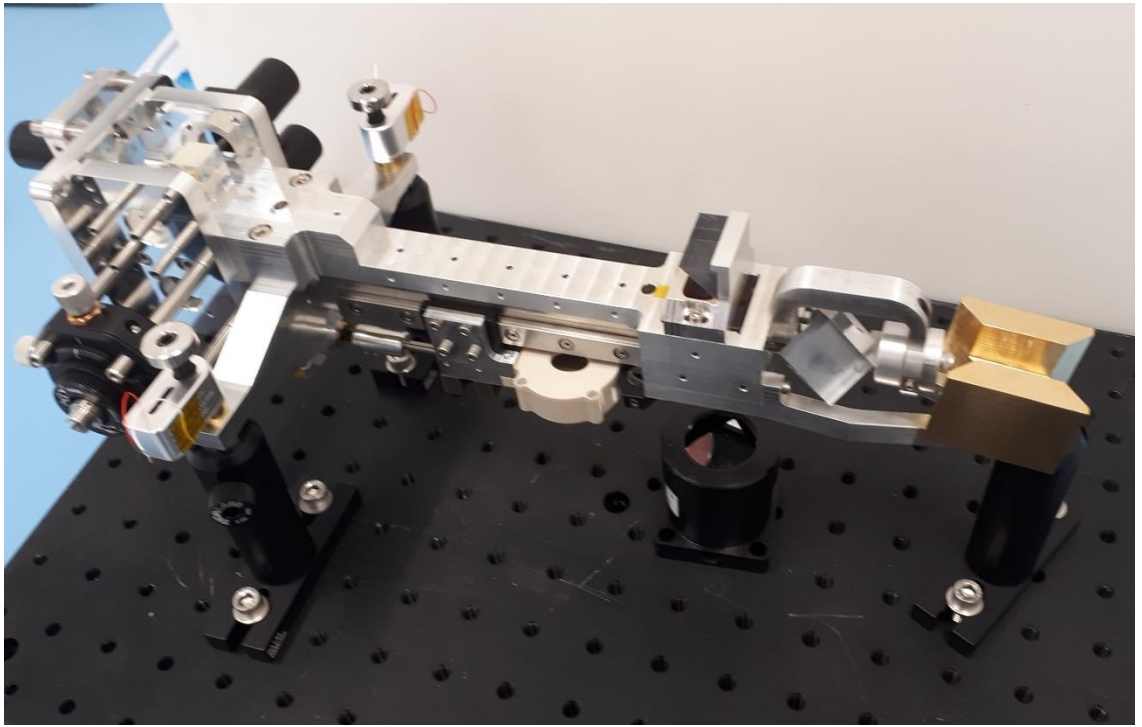
- **Piloted by NRC and NIST**
- **SS Kilograms calibrated at NRC/NIST and distributed to 32 countries within SIM RMO in October 2018**
- **Storage conditions monitored in host labs (T, P, Rh)**
- **Scheduled to return to NRC/NIST in June 2021 for recalibration**

NPL Kibble Balance developments

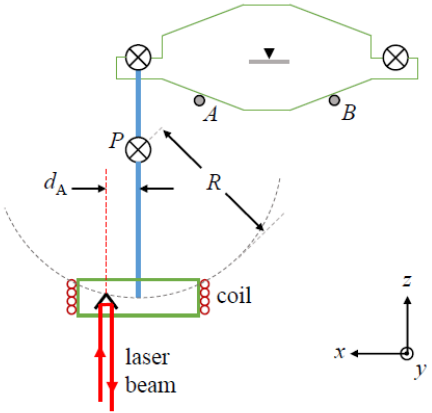
- We are starting the manufacture of the three Kibble balances required for the collaboration between NPL, NMISA (South Africa) and RISE (Sweden).
- The balances are based on a seismometer-like design and employ a bifilar wound main coil to allow single-mode two-phase operation.
- The balance is designed to be compact. Most of the electronic systems are built into hinged, shielded enclosures around its base and are isolated via the optical fibre ring.
- The balance will measure masses up to 250 g with an initial uncertainty of 1 part in 10^7, but with the ultimate aim of 2 parts in 10^8 or better.

NPL Kibble Balance developments

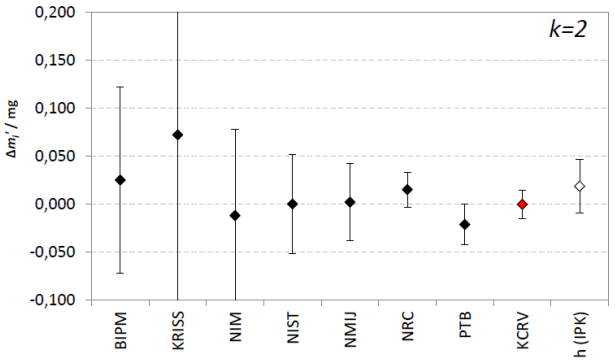
- The interferometer has been constructed and is intended to determine, and adjust, the verticality of the laser beam.
- We will be evaluating a small number of mechanisms for guiding the moving part of the balance.



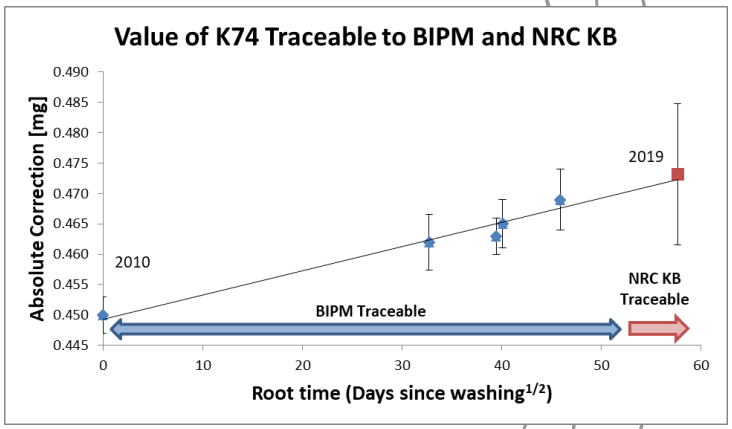
Update and Participation in CCM.M-K8.2019



C. A. Sanchez and B. M. Wood, "Abbe Offset Measurement in the NRC Kibble Balance," doi: 10.1109/CPEM49742.2020.919177



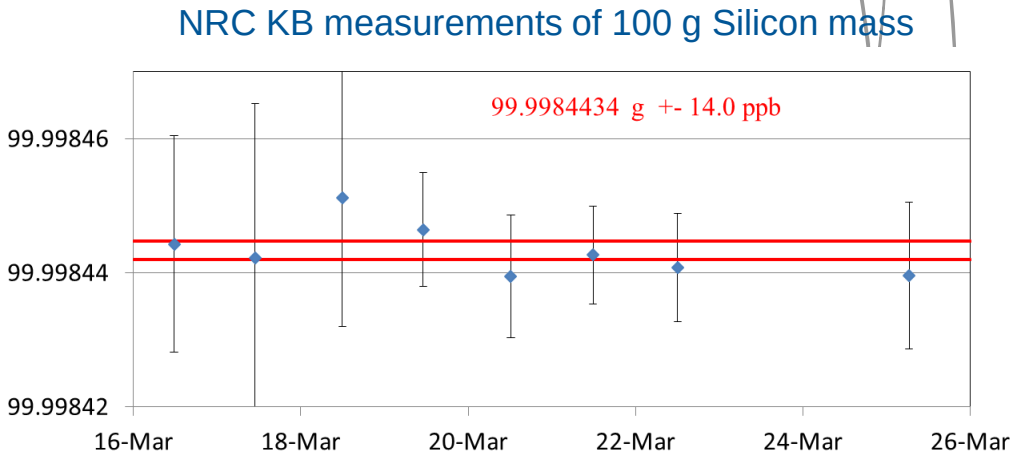
M Stock *et al* 2020 *Metrologia* **57** 07030



- Re-evaluation of Abbe offsets yielding an uncertainty of 3 ppb were included in result of CCM.M-K8.2019
- Realization measurements demonstrated good stability wrt. to BIPM working standards and NRC mass scale (< 3.5 ppb)

100 g realization comparison with NIST:
Interrupted by COVID

- Type A at 100 g was found to be 14 ppb in this study
- Type A at 500 g typically ~2.5 ppb
- Combined uncertainty at 100g expected to be between 20-25 ppb with type A and knife edge hysteresis the dominant components
- Slightly higher uncertainty than would be expected from subdividing from realizations at 500 g or 1 kg (~16 ppb)



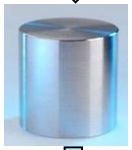
New kg realization via XRCD method at CMS/ITRI

Planck constant *h*

Primary mass standard **(vacuum)**

Vacuum to air transfer

Secondary kg standard **(air)**

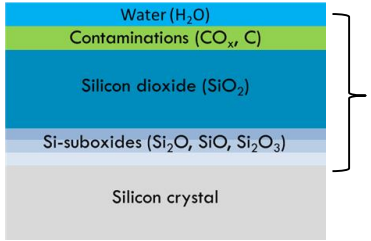


Dissemination

1 mg – 1000 kg

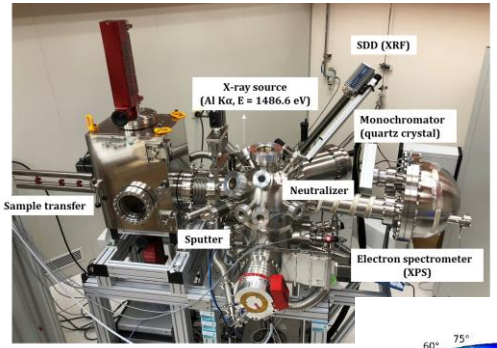
- Evaluate the mass of the Si-sphere *under vacuum*

$$m_{sphere} = \underbrace{\frac{8V_{core}}{a^3}\frac{\sum_i x(^i\mathrm{Si})A_r(^i\mathrm{Si})}{A_r(e)}\frac{2hR_\infty}{c\alpha^2}}_{m_{core}} - m_{defect} + m_{SL}$$

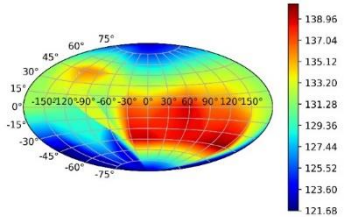


Surface layer model of Si-sphere

✓ XRF/XPS surface analysis system for the measurement of m_{SL}



Total mass deposition of oxygen: **36.68 ± 3.37 µg**



✓ Evaluate m_{sphere} *under vacuum* based on m_{SL} and other pre-determined parameters of m_{core}

X_i	x_i	$u(x_i)$	Unit	$c_i(y_i)$	$u_i(y_i)$
M_e	5.485799E-07	1.65E-16	kg· mol^{-1}		
Mu	1.000000E-03	3.00E-13	kg· mol^{-1}	1000	3.00E-10
$A_r(e)$	5.485799E-04	1.60E-14		1800	2.90E-11
h	6.626070E-34	0.00E+00	kg· m^2 · s^{-1}		
R_∞	1.097373E+07	2.10E-05	m^{-1}	9.10E-08	1.90E-12
c	2.997925E+08	0	m· s^{-1}		
α	7.297353E-03	1.10E-12		270	3.00E-10
M_{Si}	2.797694E-02	1.40E-10	kg· mol^{-1}	36	5.00E-09
V_{core}	4.310555E-04	5.06E-12	m^3	2300	2.20E-08
a	5.430996E-10	1.46E-18	m	5.50E+09	8.10E-09
$m_{deficit}$	1.740E-08	3.98E-09	kg	1	4.00E-09
m_{SL}	6.5840E-08	6.66E-09	kg	1	6.70E-09
m_{sphere}	1.0000783890	1.91E-8	kg		

New kg realization via XRCD method at CMS/ITRI

Planck constant *h*

Primary mass standard **(vacuum)**

Vacuum to air transfer

Secondary kg standard **(air)**

Dissemination

1 mg – 1000 kg

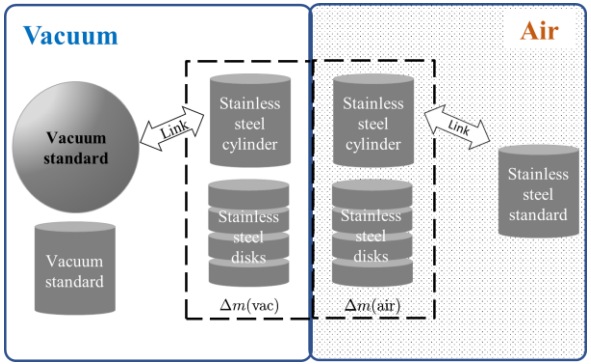
- Vacuum-air transfer the mass from the Si-sphere to the stainless steel kg standard

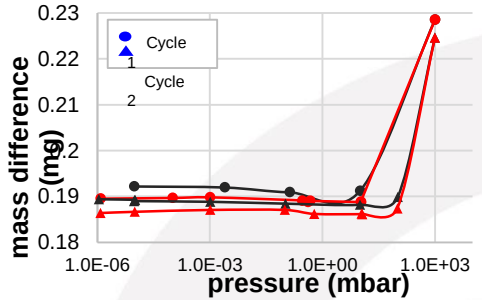
$$m_{ss,air} = m_{ss,vac} + A_{ss}\,s \quad \rightarrow \quad s = \frac{\Delta m_{vac} - \Delta m_{air}}{\Delta A}$$

✓ Sorption coefficient ***s*** estimated by measuring the mass difference of sorption artefacts in air and vacuum with vacuum mass comparator.

Vacuum mass comparator

Sorption artefacts



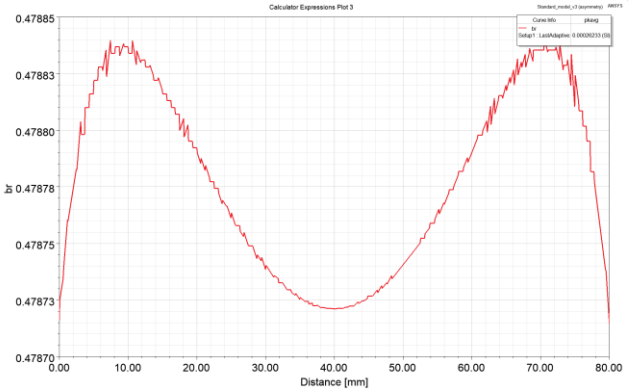


	Δm_{vac} (mg)	Δm_{air} (mg)	ΔA (cm²)	s (μg/cm²)
10 disks	-0.1865	-0.1717	434.4310	0.0342

KRISS Kibble balance

- Starting this year, a new project has been launched to build the second Kibble balance, the KRISS-2, to reduce the measurement uncertainty

- Magnet for the KRISS-2 are being designed
  - BIPM-type closed magnet structure
  - Magnet material is Sm_2Co_{17}
  - Target magnetic field uniformity is below 4×10^{-4}
  - Now, several parameters are being analyzed



Simulated magnetic field uniformity $\pm1.3\times10^{-4}$ @ 80 mm

- Heterodyne interferometer are being designed
  - Frequency-doubled Nd:YAG at 532 nm as an optical source for interferometer
  - Stabilization to $^{127}I_2$, a_{10} component of R(56) 32-0 transition

- Mechanical designs including weighing cell, guide, and vibration isolation are being studied

- D. Kim (PI), M. Kim, M. Seo, S. Cho, K.-C. Lee, J. Kim

SIM Kilogram Dissemination Project

- Collaboration Co-led by NIST and NRC

- **Objectives:**

1. To provide a practical artefact traceable to two Kibble balances in the region.
2. Develop a highly correlated set of masses for which characterization of a subset can be applied to the full set laying the foundation for studies correlating mass behavior with surface characteristics, handling and environment

29 SIM countries Participating

Select from maximum of two source rods

- Masses to be cut from no more than two source rods
- 10 disk stack cut from each rod
- Even numbered to Canada, Odd to USA

1 kg Bar Cutting and Numbering Schema

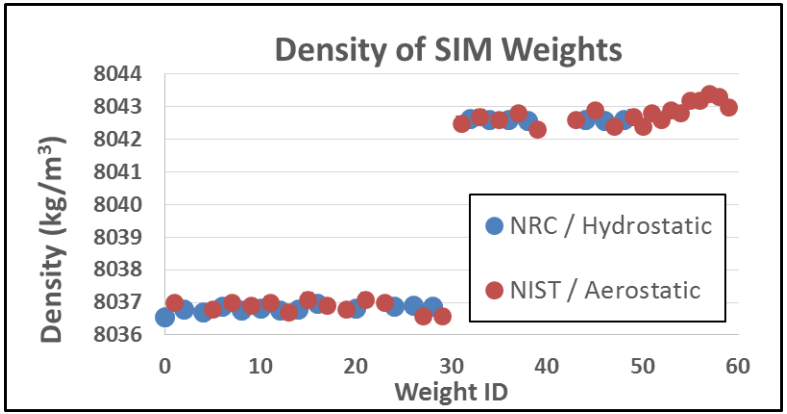
Bar 1

Disc	Disc	Disc	Disc	Disc	Disc	Disc	Disc	Disc	Disc	Disc	Disc	Disc	Disc	Disc	Disc	Disc	Disc	Disc	Disc	1 kg	1 kg	1 kg	1 kg	1 kg	1 kg	1 kg	1 kg	1 kg	1 kg	1 kg	1 kg	1 kg	1 kg	1 kg	1 kg	1 kg	1 kg	1 kg	1 kg	1 kg	1 kg	1 kg	1 kg	1 kg	1 kg	1 kg	1 kg	1 kg	1 kg
D 19	D 18	D 17	D 16	D 15	D 14	D 13	D 12	D 11	D 10	D 09	D 08	D 07	D 06	D 05	D 04	D 03	D 02	D 01	D 00	S 29	S 28	S 27	S 26	S 25	S 24	S 23	S 22	S 21	S 20	S 19	S 18	S 17	S 16	S 15	S 14	S 13	S 12	S 11	S 10	S 09	S 08	S 07	S 06	S 05	S 04	S 03	S 02	S 01	S 00

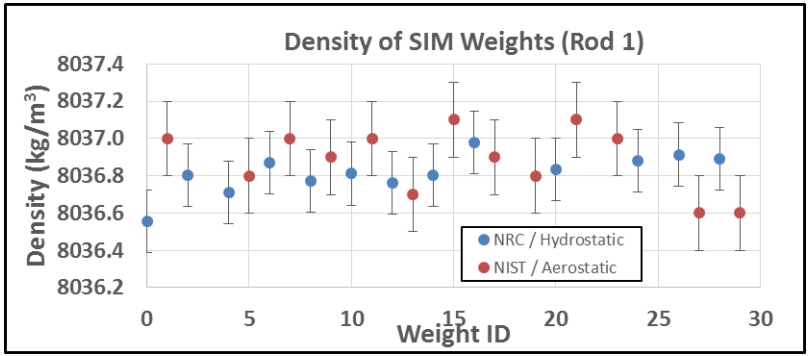
Bar 2

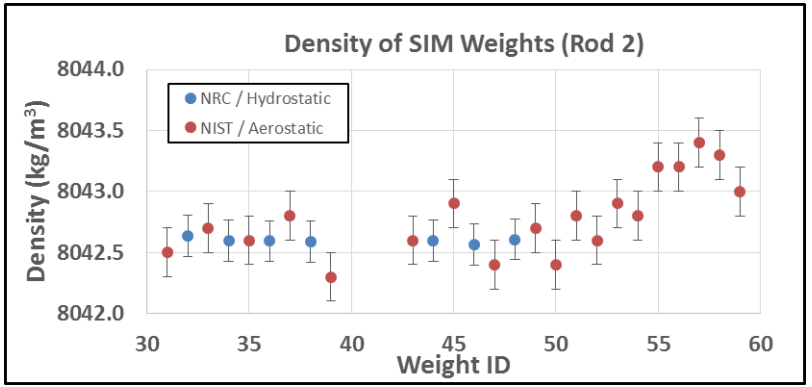
Disc	Disc	Disc	Disc	Disc	Disc	Disc	Disc	Disc	Disc	Disc	Disc	Disc	Disc	Disc	Disc	Disc	Disc	Disc	Disc	1 kg	1 kg	1 kg	1 kg	1 kg	1 kg	1 kg	1 kg	1 kg	1 kg	1 kg	1 kg	1 kg	1 kg	1 kg	1 kg	1 kg	1 kg	1 kg	1 kg	1 kg	1 kg	1 kg	1 kg	1 kg	1 kg	1 kg	1 kg	1 kg	1 kg
D 29	D 28	D 27	D 26	D 25	D 24	D 23	D 22	D 21	D 20	D 19	D 18	D 17	D 16	D 15	D 14	D 13	D 12	D 11	D 10	S 59	S 58	S 57	S 56	S 55	S 54	S 53	S 52	S 51	S 50	S 49	S 48	S 47	S 46	S 45	S 44	S 43	S 42	S 41	S 40	S 39	S 38	S 37	S 36	S 35	S 34	S 33	S 32	S 31	S 30

NRC-NIST Bilateral Comparison: No masses were exchanged



- $\rho_f \Delta V_{t-r}$ → 2 methods
- Aerostatic- ΔBuoyancy with air density
- Hydrostatic- ΔBuoyancy between fluids



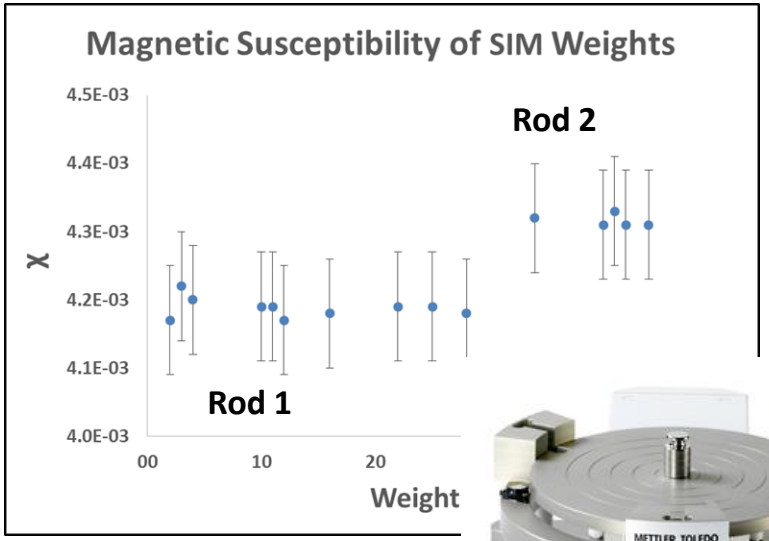


Present Status of Characterization: Magnetic properties

- Magnetic Susceptibility measurements complete
  - Full Susceptibility and permanent magnetization determined on subset of masses
  - All Masses checked to assure E1 class met
  - Average Susceptibility:

    0.00423 +/- 0.00007

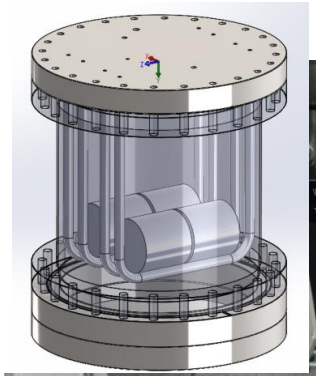
    All masses satisfy E1 class criteria



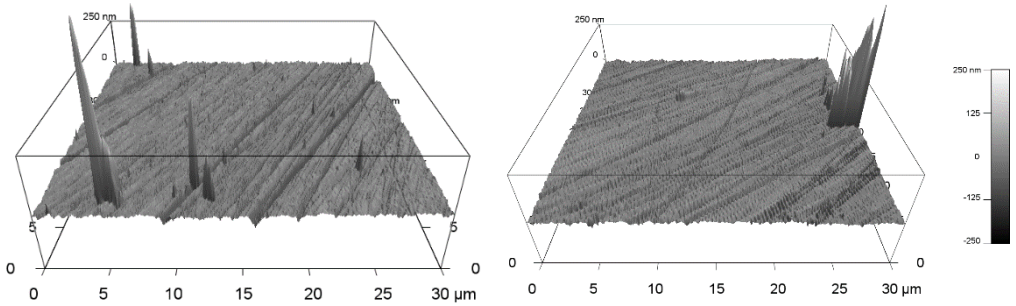
Cleaning post density determination (NRC)

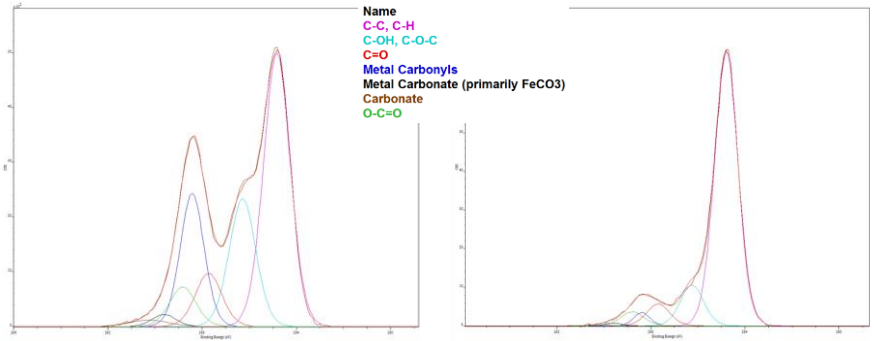
Step 1) Ethanol vapour degreaser

Step 2) Sonicate in cascade bath fed by ultrapure water (18.3 MΩ)



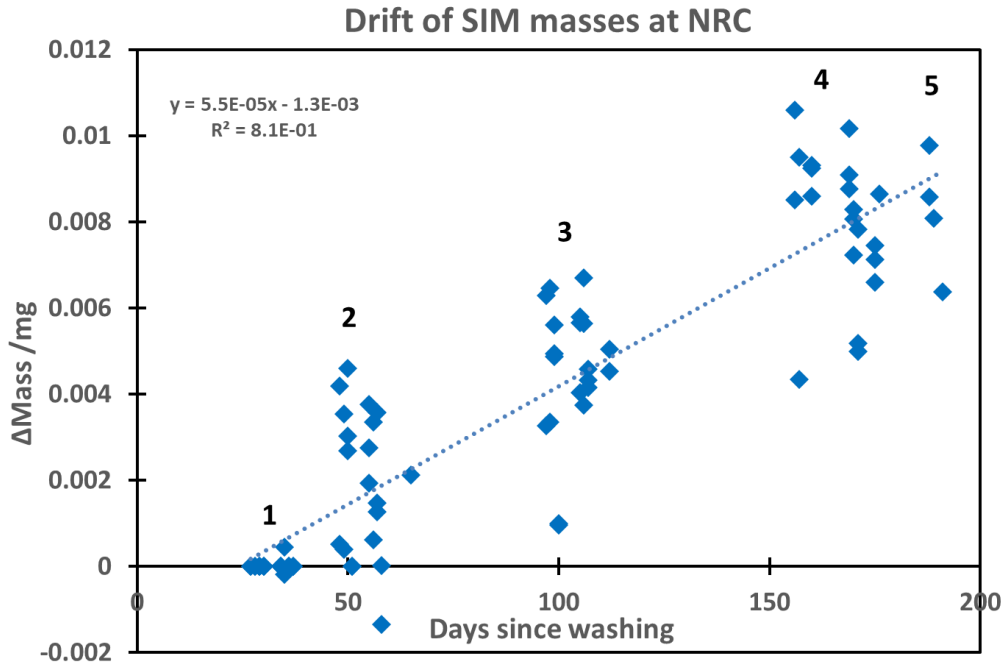
Mass and Surface analysis: Impact of cleaning



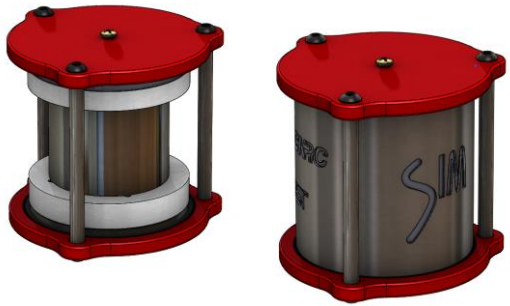


Mass Drift in Time

- **Mean drift approximately 56 +/- 10 ng/day after washing**



Transport Enclosure: Traveling case contents



Status

- Masses and kits distributed beginning October 2018
- Protocol and Data recording template complete translated and distributed to participants:
  - Frequency and number of stability of measurements recommended based on capability
  - Strategy to encourage participation through flexibility
  - High value even if no measurements are performed at assigned NMI
- First recalibration campaign delayed due to COVID-First round now planned for late June 2021
- First masses have been received at NRC
- Many NMIs have reported large disruption due to COVID impacting ability perform stability measurements but most have communicated intent to return mass for recalibration

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