Report on the meeting of the CCEM working group on electrical methods to monitor the stability of the kilogram – July 2018

This was an informal meeting of the working group, which was held on Friday 6th July 2018 at the time of CPEM 2018 at LNE in Paris. The meeting was held jointly with the CCM working group on the realisation of the kilogram (CCM-WGR-kg). The report also includes information gathered in March 2019 from the groups participating in the July 2018 meeting.

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Glossary

BIPM	Bureau International des Poids et Measures
BIPM	International Bureau of Weights and Measures
CCEM	Consultative Committee for Electricity and Magnetism
CCM	Consultative Committee for Mass and Related Quantities
CCM-WGG	CCM Working Group on Gravimetry
CCU	Consultative Committee for Units
CIPM	International Committee for Weights and Measures
CODATA	COmmittee on DATA for science and technology
CPEM	Conference on Precision Electromagnetic Measurements
FPGA	Field Programmable Gate Array
g	Acceleration due to gravity
h_{90}	A stable value of the Planck constant derived from K_{J-90} and R_{K-90}
IAC	International Avogadro Coodination
ICAG	International Comparison of Absolute Gravimeters
INRIM	Istituto Nazionale di Ricerca Metrologica - Italy
IPK	International Prototype of the Kilogram
KBTM	Kibble Balance Technical Meeting
K_{J-90}	Conventional value of the Josephson constant
KRISS	Korea Research Institute of Standards and Science – Korea
LN_2	Liquid Nitrogen
LNE	Laboratoire National de métrologie et d'Essais - France
METAS	Federal office of metrology – Switzerland
MSL	Measurement Standards Laboratory – New Zealand
NiFe	Nickel Iron Alloy
NIM	National Institute of Metrology - China
NIST	National Institute of Science and Technology – USA
NMI	National Measurement/Metrology Institute
NMIJ	National Metrology Institute of Japan – Japan
NPL	National Physical Laboratory - United Kingdom
NRC	National Research Council – Canada
PEEK	PolyEther Ether Ketone – thermoplastic polymer
PID	Proportional-Integral-Derivative – servo control
PJVS	Programmable Josephson Voltage Standard/Source
PSD	Position Sensitive Detector
PTB	Physikalisch-Technische Bundesanstalt – Germany
PtIr	Platinum-Iridium alloy
R_{K-90}	Conventional value of the von Klitzing constant
SmCo	Samarium Cobalt
SNS	Superconductor-Normal-Superconductor
SS	Stainless steel
UME	TÜBİTAK UME National Metrological Institute – Turkey
XPS	X-ray Photoelectron Spectroscopy
XRCD	X-Ray Crystal Density
XRF	X-Ray Fluorescence spectroscopy
Zerodur	A glass ceramic having a small coefficient of thermal expansion

In memoriam: Dr Chris Sutton , MSL, New Zealand.

In the time between the meeting of the group in July 2018 and the CCEM meeting in March 2019 Dr Chris Sutton passed away. Chris worked for MSL in New Zealand for 43 years and originated designs for a novel form of Kibble balance utilising two coupled pressure balances. He also proposed an oscillating moving mode for the apparatus and published the design of a magnet for the MSL apparatus. His contributions to the group will be missed. Our thoughts and condolences go out to his colleagues and family in New Zealand.

Redefinition and maintenance of the kilogram

CCM-WGR-kg

The meeting started with some general issues for the CCM-WGR-kg. To restrict the length of these notes the substance of this discussion can be found in the February 2019 report of the CCM-WGR-kg.

PTB: Mise en Pratique for the kilogram

Version No. 9 of the Mise en Pratique for the kilogram was provisionally accepted by the CCM in 2015 and Version 11.3 was distributed on the 20th July 2018. A Focus Issue of Metrologia has also been published on the new kilogram to provide background and guidance on the changes to the definition of the kilogram. Some open questions remain:

How will the BIPM ensemble of reference mass standards be used?
How can the technical protocol of the BIPM.M-K1 comparison be improved?
How often should NMIs participate in such comparisons to maintain their CMCs?
How to include Kibble balance measurements of small masses?

It is intended to run the first BIPM.M-K1 comparison immediately after the redefinition of the kilogram with a proposed 1 x 10^{-7} upper limit on uncertainty for participation. The detailed protocol for this comparison will be proposed at the CCM meeting in May 2019. The second comparison would be approximately 2 years after that. Further comparisons would be initiated approximately every 2-10 years assuming that the results of the previous comparisons are acceptable - considering the CCM recommendation G1 (2013) and G1 (2017). While the processes for deriving the mass unit from the definition are refined the CCM will maintain and disseminate a “Consensus Value” based on comparisons of realisations of the kilogram and the IPK.

BIPM: Ensemble of reference mass standards and the Consensus value

BIPM have built an ensemble of reference mass standards which they will use to maintain a stable mass reference which will help maintain the CCM “Consensus Value”. They have modified the way that they will configure and use it. They have established that PtIr contamination/wear rates can be less than 1 µg/yr and have established a hierarchy of reference masses. The ensemble has been placed in the hierarchy and is mainly in the once per year use category.

Realisation of the kilogram using the X-Ray Crystal Density (XRCD) method.

INRIM: silicon lattice spacing measurements

INRIM have been improving their lattice spacing measurements. They are applying diffraction corrections to their measurements and are checking temperature issues for distances between sensor and analyser above 1 cm by using both experimental measurements and a digital twin of the apparatus. They are looking into the effects of surface strains on the lattice constant. They estimate that they should be able to see the effects of stresses around 1 N/m. They have found scattered light problems that arise when the interferometer arm lengths are balanced. The scattered light gives significant errors but the effect can be reduced by limiting the size of the active area of the detector to close to the beam width. The effect is of the order of 25 x 10^{-9} for AVO 28 near zero optical path. They have published a paper on the problem in Metrologia: Forward scattering in a two beam laser interferometer.

INRIM: Neutron activation analysis and simulation

INRIM have been using neutron activation analysis to look for impurities, voids and vacancies in ^{28}Si crystals.

They have made a digital twin of the sphere supports of the NMIJ optical interferometer and have used it to predict the effects, on the volume measurement, of the distortions produced by gravity. They have published a paper in Metrologia: Self-weight effect in the measurement of the volume of silicon spheres.

NMIJ: X-Ray Crystal Density (XRCD) measurements.

NMIJ published an independent determination of the Avogadro constant with a relative standard uncertainty of 2.4 x 10^{-8} in 2017 for the redefinition of the kilogram. They have made diameter and volume measurements of the ^{28}Si spheres and have improved the temperature control of their interferometer by improving their radiation baffle. They have made further comparisons of silicon lattice spacing. They are using electron paramagnetic resonance techniques to look at impurity concentrations and check mass deficit corrections. They have improved their ellipsometry equipment for characterising the materials adsorbed on the surface of silicon spheres.

PTB: X-Ray Crystal Density (XRCD) measurements.

The IAC published a measurement of the Avogadro constant in 2017 with a relative standard uncertainty of 1.2 x 10^{-8}.

PTB have a number of new silicon crystals, each of which has yielded two spheres:

- Si28-23Pr11 with a mass of 5120 g and a purity of 99.9985% ^{28}Si.
- Si28-24Pr11 with a mass of 5637 g and a purity of 99.9993% ^{28}Si.
- Si28-31Pr11 with a mass of 5682 g and a purity of 99.998% ^{28}Si.

They have made progress with their molar mass determinations giving a contribution to the relative uncertainty of 2 x 10^{-9}. Their uncertainty on the sphere volume is 7 x 10^{-9}. They are working on direct measurements of the lattice parameter. Together with INRIM they have checked the temperature measurements needed to relate the lattice parameter measurements and the volume measurements. Only differences in temperature are important and their thermometers show differences less than 0.1 mK which corresponds to an uncertainty on the volume of less than 1 x 10^{-9}. To examine materials on the surface of the sphere they have an XRF/XPS apparatus which allows the spheres to be transferred under vacuum to the balance. They are investigating alternatives to the use of the extremely expensive ^{28}Si spheres.

Realisation of the kilogram using Kibble balance techniques.

BIPM: Kibble Balance measurements

The BIPM Kibble balance is operating in vacuum and they have adopted the 1 mode and 2 measurement phase operating scheme using a bifilar coil at room temperature. The measurement velocity has increased to 1 mm s^{-1}. They use a PJVS in direct opposition for the induced voltage and the current measurements. The improvements have resulted in a factor of 100 improvement in weighing noise and the repeatability of the apparatus is now a few parts in 10^7. Their alignment has improved but is not yet optimal.

They have investigated the effect of the weighing current on the field of the magnet and have published two papers in Metrologia.

They have been working on coil alignment by modelling their new alignment method, investigating the stiffness and stability of the mechanics and checking the operation of the double gimbal and aligning the centre of the middle structure using a loading device. They have looked at the effects of vertical torque on their suspension and have found some significant parasitic resonance peaks but the effect is estimated to be at the level of parts in 10^8. They align the verticality of the laser beams of their 3 interferometers in air and estimate the change in alignment under vacuum to be 200 µrad. (Since the meeting in July 2018 a new interferometer has been installed and the alignment accuracy is now about 30 µrad.)

They are now using their PJVS to directly oppose either the induced voltage in the coil or voltage drop across the standard resistor. They have validated the measurement chain and have found that errors due to leakage resistances are negligible.

Their original absolute gravimeter is no longer operational but, using results from ICAG comparisons, the BIPM site seems to be stable to within 1 µGal over 10 years and they have measurements taken in 2009. New measurements would be desirable and METAS has offered to help in this regard.

In the future they plan to make a number of changes. They will add more stable mechanical mounts for both their mass loading system and their interferometers and will add a 4^{th} interferometer for the servo-control of vertical velocity (These changes have been made since the meeting in July 2018). They will use a stiffer device to align the mass centre of the middle support of the coil. They plan to repeat their measurements and establish an uncertainty budget for a publication in 2019. In the longer term they will develop a new motor and a new guiding mechanism and make new coil formers to increase the BL product of the coil/magnet by increasing the length of wire in the coil.

KRISS: Kibble Balance measurements

The KRISS Kibble balance uses a commercial weighing cell of 5 kg capacity which is moved using a counterbalanced mechanism incorporating a piston/cylinder guide and flexure guide. The mass pan and mass exchanger are placed below the magnet. The balance has been working in vacuum since 2015 and presently both moving and weighing mode experiments are being conducted. They are aiming for an uncertainty of between 1-2 parts in 10^7 in 2019 improving to 5 parts in 10^8 by 2020 and are intending to contribute to the comparison BIPM.M-K1 in 2020.

Their current in weighing mode is 10.5 mA for a 1 kg mass with a 500 g tare offset. Their weighing repeatability is better than 6 parts in 10^8 for a single 1 hour run. Their magnet has a temperature coefficient of -130 ppm/K.

In moving mode they move the coil 14 mm at 1 mm/s with a stability of 7.3 parts in 10^4. They take 24 measurements in each direction and in 60 minutes perform 75 up/down cycles. They minimise the effects of Abbe offset by carefully combining the data from the three interferometers placed around the periphery of their coil. By this means they can align the centre of mass and the effective optical centre to better than 0.1 µm giving a contribution to the overall uncertainty of less than 1 part in 10^8. They have measured the horizontal and angular velocities of the coil to be less than 0.3 µm/s and 10 µrad/s for a coil velocity of 1 mm/s. Present repeatability of moving mode is 50 ppm at each data acquisition position. They are aiming to achieve 10 ppm by reducing the synchronization error between the voltage and velocity measurements. Recently, they have improved the alignment of their laser to the vertical to reduce the associated uncertainty to less than 5 parts in 10^8.

Future work is aimed at combining the results from the moving and weighing to give initial results at the 1-2 parts in 10^7 level. They are starting work on a micro Kibble balance for use in the range between 1 mg and 2 g.

LNE: Kibble Balance measurements

LNE produced a measurement of the Planck constant in 2017 with a relative standard uncertainty of 57 x 10^{-9}. They are now working on improving the uncertainties of the apparatus. The uncertainty components which dominated their 2017 result were the type A uncertainty and the uncertainty associated with the refractive index of air which would be eliminated by operating under vacuum. The original balance mounting feet moved 1 mm vertically on evacuation which disturbed the alignment of the apparatus. They have now installed new feet which reduce the motion to a common 1 µm vertical motion with less than 1 µm difference allowing vacuum operation.

Much of the existing type A uncertainty arises from environmental vibration. By removing sand, which was previously placed around the balance support slab, they have made a significant improvement to the isolation of the slab from mechanical shocks which may occur in the vicinity of the Kibble balance lab. They have also improved the isolation of the apparatus from the slab, by modifying the balance structure, further reducing the vibrational noise. Their next steps towards improving the weighing phase are to install a new elevator for the test mass and use monolithic flexures in the suspension. For the moving phase they will be testing a voice coil type actuator and a commercial triggering system for the data acquisition. The short term goal of the work is to contribute to the comparison BIPM.M-K1 with a relative standard uncertainty of below 50 x 10^{-9}. In the longer term they intend to realise the mass unit and work on a traceable method to measure small forces and masses.

METAS: Kibble Balance measurements

Work is in progress to improve the METAS Kibble Balance. For some time the balance had used a “crossed cone” system to maintain alignment of the mass pan, coil and the mass comparator whilst protecting the mass comparator from possibly damaging horizontal forces or a vertical torque. The cones were found to behave anelastically and are being replaced by flexures which will have better defined centre points but introduce the possibility of passing significant forces to the mass comparator. To achieve improved operation in vacuum they are also replacing the three motors in their mass exchanger for dc motors each incorporating an encoder and planetary gearhead. They have introduced a green laser with a higher power than their previous laser to improve both their velocity measurement and their direct measurement of x and y displacements using a PSD. They use two autocollimators to measure the angles of the upper and lower parts of the coil suspension during the moving phase. They have added a mechanism to align the working axis of the mass comparator with the gravitational vertical. They are about to test an adjustment mechanism for the x-y position of the central corner cube to eliminate the Abbe error.

The system is becoming operational, showing reproducible alignment and they will be able to perform measurements in vacuum. They intend to transfer the apparatus to their mass lab and participate in the comparison BIPM.M-K1.

MSL: Kibble Balance measurements

The MSL Kibble Balance uses two interconnected pressure balances for both the weighing and the moving parts of the experiment. The balances are modified so that the cylinder rotates and the piston carrying the coil is stationary.

Accurate operation of a pressure balance requires that the effective area of the piston remains constant. The piston and cylinder were modelled using a 2-d finite difference technique to determine the effect of tilt, eccentricity and geometric imperfections. Tilt and eccentricity are critical, but the modelled variations were less than 2 parts in 10^9. The modelled geometric imperfections produced insignificant changes to the results.

They have designed the magnet for the apparatus. It exhibits both axial and mirror symmetry and is shielded from external fields. The reversible temperature coefficient of magnetization of the permanent magnet material is less than 20 ppm/K which represents almost a factor of 20 improvement over samarium cobalt. It produces a 0.6 T flux density in the gap and is designed to produce a uniformity of better than ±20 ppm over a ±20 mm span. The magnet is designed to have no radial magnetic field in the permanent magnet material and uses non-magnetic spacers to reduce the magnetic field in the yoke to around 1.5 mT. One of the design aims is to ensure that the coil current does not act on the permanent magnet material to ensure that errors from this cause are negligible. They have built an assembler/splitter for the magnet system with the help of NIST and HTS-110 (a magnet company in New Zealand).

They have constructed a laboratory for the Kibble balance work and are designing the vacuum chamber to hold the balance. They will be using DHI pressure balances and have been characterising them: particularly with respect to the piston righting moment. They are working on the mass loading mechanism design.

They have modified and constructed a METAS design for a current source which can produce 6, 12 or 24 mA. With the help of NIST they have improved the triggering of their 3458 voltmeter.

They have a temperature controlled resistance network for the current measurement and have obtained new measurements of the acceleration due to gravity in the new Kibble balance laboratory. They are characterising the non-linearity in length measurements made with their heterodyne laser interferometer.

They intend to operate in air in 2021 with vacuum operation expected at a later stage. Their overall aim is to be able to participate in the key comparison: BIPM.M-K1.

NIM: Joule Balance measurements

The design and construction of the NIM-2 joule balance was started in 2013 and it is currently operating, fully automatically, in a vacuum of approximately 1 Pa. At the start of the work an electromagnet was used to generate a magnetic field with a flux density of 0.08 T. A six axis laser interferometer system is used for length measurement and control of the position of the suspended coil with a resolution of 10 nm. A commercial mass comparator with a capacity of 5 kg and a repeatability of 15 μg is used as the force measurement unit. To keep the mass comparator stable and guarantee its performance the magnet is moved, rather than the suspended coil, using a translation stage having a linearity of several μm over its 100 mm range. The balance uses active vibration control to avoid the effects of vibration from the environment.

In May 2017, they published the first measurement of the Planck constant by NIM-2 having a relative standard uncertainty of 2.4×10^{-7}. Since then, they have been making improvements to reduce this uncertainty towards several parts in 10^{8}. By the end of 2018, a shielded permanent magnet, with a factor of 6 improvement in flux density (0.49 T), had been constructed to replace their electromagnet. This has reduced the Type-B uncertainty arising from external magnetic fields to 1.4×10^{-8}. They have also improved the alignment of the balance by incorporating a new suspension system. By March 2019, the type-A uncertainty of the apparatus had been decreased to 3×10^{-8}. Further improvements are still in progress. At the same time, a mass exchanger, handling both spherical and cylindrical masses, is being tested and will be installed in the near future.

Their long term aim is to realise the redefined kilogram in vacuum and transfer it to the mass group of NIM.

NIST: Kibble Balance measurements

The NIST Kibble balance produced a measurement of the Planck constant in 2017 with a relative standard uncertainty of 13×10^{-9}. They then worked on improvements to the apparatus including coil rotation control using two independent sets of XY-detectors and an external autocollimator. They have made measurements using a 10V portable PJVS, they replaced the balance knife edge, realigned the coil motion and checked their sensitivity to various misalignments. They found the source of a small weighing position drift but unfortunately, during attempts to fix this, a flexure broke which dropped and nearly destroyed their coil. This, plus the unexpected flooding of part of their laboratory, has delayed work. They plan to measure masses from 100 g to 1 kg assuming a fixed value of h. If time permits they will measure down to 10 g. At the end of 2019 it is planned to vacate the existing laboratory, which will be repaired and refurbished over the following year.

Since 2016, they are slowly working on a low-cost table-top Kibble balance. The table-top instrument will cover nominal mass values ranging from 1 g to 10 g with relative uncertainties in the region of 10^{-6}. The table-top instrument uses a dual diameter wheel balance, a custom-made heterodyne interferometer and air bearing guides. The magnet is made using SmCo using a dual coil in series opposition. Electrical measurements are made using a Fluke resistor, a Keysight 3458A voltmeter and a custom 24-bit current source. Their aim is to produce a balance costing less than $50,000.

During the time that the laboratory is inaccessible, they will be producing an in-vacuum 100 g level Kibble balance with a range of 1 g - 100 g. Its vacuum chamber will be less than 1 m in height and diameter and it will use a laser interferometer, a 10 V PJVS and a resistor in the range from 1 kΩ – 10 kΩ. The detailed design is still in progress.

NPL: Kibble Balance measurements

NPL is building two new Kibble balances named TD1 and TD2, which are intended to support the design and production of a next generation Kibble Balance to work in the range from 100 g – 250 g. This balance is intended to be robust, relatively easy to manufacture and operate, and will provide an uncertainty suitable for the realisation of the mass unit. TD1 is based on a conventional beam balance and is designed to test the new ideas proposed for the balance and TD2 is designed to test critical technology such as flexures.

The mechanics of TD2 have been constructed and the Finite Element design of the flexures is proceeding. The FEM results will be compared with measurements of flexures that have been fabricated.

Three magnets have been manufactured for TD1 and TD2. They use a shielded open design with the magnetic material in the centre and provide two opposing field regions in a similar way to the original NPL Mk II design the symmetry of which has considerable advantages. The coil is made from two, identical, self-supporting, twisted-pair, coil elements connected in series opposition. The elements are spaced apart and connected to the balance using 6 mm diameter silica rods.

Six demonstration balances have been built to support publicity for the revision of the SI. This slowed work on TD1 but allowed the updating of the custom, low-noise, isolated, electronics used to control NPL Kibble balances. A modern, compact, real-time, computer has been made which interfaces properly to a new controller for the NPL optical fibre ring. The demonstration balance is controlled by four boards: two current sources, an interferometer controller and a balance controller all controlled via the optical fibre ring.

A common basis for constructing simple, precise mK/sub-mK temperature control systems has been developed. It is currently used for laboratory/apparatus temperature control and for constructing a portable, battery-powered, temperature controlled, resistance standard.

In 2019 work will resume on TD1 with the aim of sub ppm measurements by the end of 2019. This will involve the commissioning of a Josephson array voltage standard (provided by PTB), the construction of an improved version of the preamplifier constructed for the NPL Mk II balance and improvements to the quadrature beam splitter for the interferometer. Guest workers from NMISA will be working on a precise, isolated voltmeter and portable, temperature controlled resistance standards. Further work will be carried out on the design/construction of Kibble balances for small masses.

NRC: Kibble Balance measurements

The NRC Kibble balance produced a measurement of the Planck constant in 2017 with a relative standard uncertainty of 9.1 x 10^{-9}: the lowest uncertainty measurement to date. Their talk covered many of the critical techniques which were used in the apparatus. These consisted of some techniques which were developed at NPL and some produced by NRC.

The NPL originated techniques include:

- Digital Servos for both weighing and moving. Run on a real time computer at about 500 Hz, they are more than just simple PID based servos and allow smooth parameter changes to change the characteristics of the servo with minimum disturbance to the balance.
- The single interferometer has two isolated detection systems to separate the velocity measurement system from the electronics used to monitor the position and find the velocity/acceleration of the coil.
- A constant velocity drive using voice coil actuation and a look-forward digital control giving low velocity noise ~ 5 ppm. This reduces the need both for the matching of ac responses of interferometer and coil voltage and the precise synchronisation of the measurements.
- A custom-built nanovolt amplifier of composite construction having a wide bandwidth. Its input voltage must remain below ±10 mV but it exhibits low noise and high stability with no chopping noise. This eliminates the need for voltmeter autozero measurements.
- The tracking PJVS uses a PTB array and an NPL/LNE isolated bias source. The array dynamically tracks the moving voltage to within 1 mV during accelerated motion and 100 μV during measurement and removes the need for nV level switching between runs.
- Errors caused by the anelastic behaviour of the balance knives are reduced to ~ 1 x 10^{-9} by a precisely controlled, damped sinusoidal motion of the balance using the digital servo.
- An error due to residual magnetisation at the end of the weighing is eliminated by locking the beam and altering the coil current in a damped sinusoidal manner.

NRC originated procedures:

- The reference resistors have not been moved in 10 years and they are measured using an NRC designed portable Quantum Hall resistance and cryogenic current comparator.
- The interferometer is fed by a Zeeman stabilised laser which has a small (~ 300 kHz) separation of mode frequencies which reduces errors due to polarisation leakage to below 1 x 10^{-9}. The laser is calibrated in-situ using an optical fibre to the NRC frequency group.
- The NRC underground laboratory has thick walls and non-magnetic reinforcement. Isolated concrete pads for the apparatus and gravimeter were built, which extend to the bedrock, minimising the effects of transverse vibration.
- The construction of the laboratory simplifies thermal control. The casing of the apparatus is controlled to ~ 4 mK. The unoccupied laboratory produces magnet temperature changes of ~ 25 μK over a 90 minute run.
- The original programmed acceleration profile of the coil in moving mode has been further optimised to minimise induced sway.

They have investigated and characterised many possible sources of uncertainty. The drift in their measurements of h over 3.2 years is (-0.51 ± 2.3) x 10^{-9}/year.

Recently they have made progress in the measurement of gravity transfer in the presence of the magnet and preliminary results confirm their previous measurements and should allow a decrease in the associated uncertainty to 3 x 10^{-9}.

Future work includes: coil tilt adjustment in vacuum, refinements to mass pan position adjustments, relocation of the coil retroreflector to simplify Abbe adjustment and the refinement of the post weighing demagnetisation sequence.

UME: Kibble Balance measurements

UME have constructed a Kibble balance (UME KB-I) that oscillates the magnet while the coil carries a static current opposing the weight of the working mass. The oscillation of the magnet represents the moving phase of the measurement and induces a low frequency ac voltage in the coil which is measured using a phase coherent technique thus separating it from the voltage which arises from the weighing current flowing in the coil. Like the BIPM simultaneous moving and weighing technique this method is largely immune to temperature induced changes in the field of the magnet. They use a 50 Ω resistor to convert the 60 mA weighing current into a voltage. The moving magnet induces a 1 V p-p 0.5 Hz signal in the coil. They make a 6^{th} order fit to the variation of the magnetic field by varying the centre of oscillation of the coil with respect to the magnet centre in 0.1 mm steps. They are working on methods of aligning the coil and magnet and eliminating angular motions to eliminate alignment uncertainties. At present they have an overall uncertainty on the measurement of 6 ppm.

UME KB-II was constructed to provide a lower uncertainty than UME KB-1. They developed an optimization procedure for the determination of induced Faraday's voltage across the ends of the coil which eliminates the need for perfect alignment between the magnetic centre of the magnetic circuit and electric centre of the coil. The static parameters (horizontal force and torque) are treated as optimization parameters and are obtained by measuring the dynamical parameters (displacements and voltage). They achieved a repeatability of 0.3 ppm by following this procedure.

Dynamic calibration of 3458A Digital Multimeter with a PJVS indicated that the repeatability of the experiment is in agreement with the uncertainty due to the multimeter. Therefore, the alignment procedure results are constrained by the repeatability of the multimeter. They are expecting to achieve the desired accuracies for the maintenance of the redefined kilogram by integrating the PJVS into the measurement system. Differential measurements between the Josephson signal and coil output voltage will enhance the accuracy of the voltage measurements. The UME Oscillating Magnet Kibble Balance can be sensitive to any external magnetic field which causes an asymmetry between the Ampere's law of force and Faraday's law of induction. They are working on ways for eliminating the effects of such magnetic fields. Currently, UME KB-III is being designed where mechanical restrictions will be eliminated and the optical measurement system will be enhanced. The target uncertainty is 0.05 ppm within two years.

Related Topics

NMIJ: Small mass measurements

NMIJ are working on a voltage balance to provide traceability for measurements of small masses using the electrostatic force generated by the voltage difference between two cylindrical electrodes. A flexure balance is used for the measurement and a buckling spring device has been added to the balance to reduce the effective spring constant of the flexures. They have a relative standard uncertainty on the capacitance gradient of 1.9×10^{-4}. They have also built a MEMS based voltage balance to measure small masses and their work to measure small torques is proceeding well.

They also described force measurements using radiation pressure. The target range of the system was 10 nN to 10 pN using laser powers varying from 1.5W to 1.5 mW. The balance used for the measurement uses a Roberval mechanism. It incorporates cylindrical capacitive electrodes to allow comparison between electrostatic and radiation pressure measurements. Damping is provided via an aluminium plate and a magnet. At present they have found significant discrepancies between the two measurement methods and are investigating the cause.

Gravitation

The CCM-WGG are discussing the treatment of results from key comparisons in gravity. The uncertainties of Kibble balances are decreasing, and their influence in maintaining mass globally is going to increase. As all the balances require measurements of g the detailed mechanism of the application of the results of key comparisons of absolute gravimeters to the results produced by a particular Kibble balance will become of increasing importance. For example comparisons can produce discrepancies, and there are recognised methods of dealing with them, but it important that any guidelines do not produce unnecessary problems and can be applied uniformly. This is not an immediate issue, but it is important to ensure that a dialogue exists between the CCM-WGG and the working group charged with representing the Kibble balance groups around the world.

Future Kibble Balance technical meetings

The next Kibble Balance Technical Meeting (KBTM 2019), will be hosted by NPL in the UK. The meeting will be held on the 21st and 22nd October 2019 at NPL in Teddington. It is intended to hold the meeting in Bushy House – the birthplace of the Kibble Balance. Contact Ian Robinson for further details.

Closure of the CCEM working group on electrical methods to monitor the stability of the kilogram

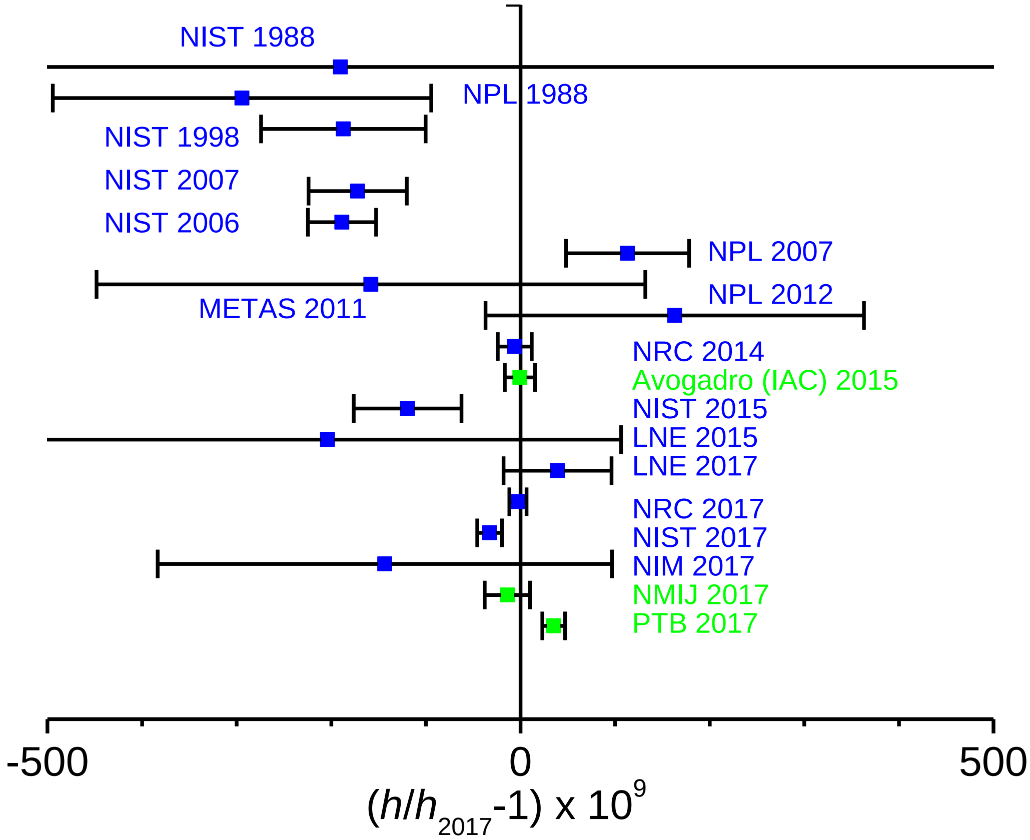

Figure 1 Selected measurements of the Planck constant

At their meeting in November 2018 the CGPM resolved to revise the SI and fix the numerical values of both the Planck constant and the elementary charge. This change will take place on the 20th May 2019. Once the SI has been so revised the electrical units will no longer depend on the kilogram. All the members of this group have encouraged and contributed to this change. Figure 1 shows selected historical measurements of the Planck constant and Figure 2 shows more recent data which led to the redefinition of the kilogram. This achievement, by its members, represents a successful conclusion to the work of the group and removes the need for the CCEM to maintain a working group on monitoring the stability of the kilogram; this task now falls squarely upon the CCM. An e-mail discussion between the chair of this working group and the President of the CCEM came to the conclusion that the group will be disbanded at the forthcoming CCEM meeting in March 2019. This does not mean that the activities supported by this group will stop, but will transfer to the appropriate working group of the CCM.

The NMIs operating Kibble Balances will still look to the CCEM to coordinate the improvement of relevant standards and techniques in the electrical area. For example:

- conventional resistors with improved robustness, stability and reduced temperature and power coefficients,
- compact QHR arrays,
- novel conventional voltage references / precise integrating voltmeters,
- novel quantum voltage references/voltmeters – preferably operating at LN_2 temperature.

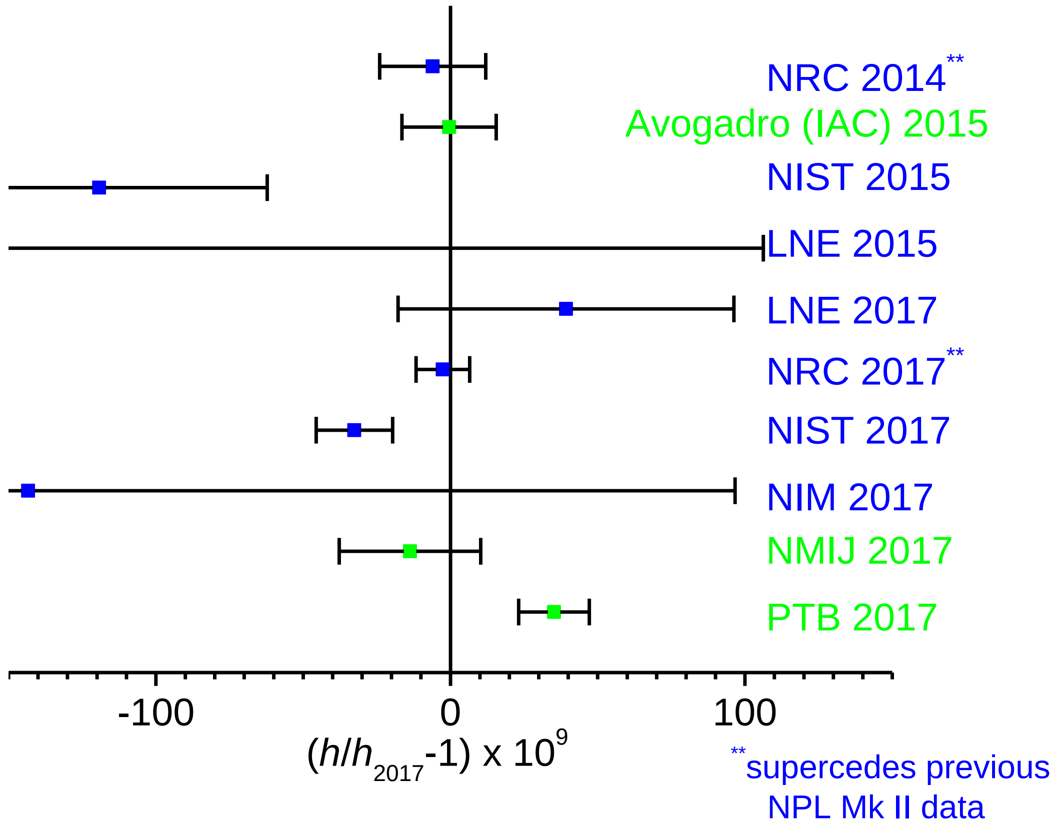

Figure 2 Recent measurements of the Planck constant

As the revision of the SI has encouraged novel applications of Kibble balances, over a range of uncertainties, some of these applications, especially in the industrial area, are critically dependent on the price, size and convenience-of-use of these devices. Whilst, for the provision of measurements of the highest quality, cryogenic quantum standards operating at liquid helium temperatures will be needed for the foreseeable future, the cost either in liquid helium or in electricity precludes their use in many other applications. This means that new developments should not be directed solely towards cryogenic quantum standards but should look at achieving major improvements to standards/instruments which operate close to room temperature.

On a personal note I would like to thank all the members of the group, both past and present, who have contributed to our work and its successful conclusion; it has been a privilege to work with you all. The group was started under the chairmanship of Bryan Kibble and I have been honoured to have been associated with it since its inauguration. Our discussions, and the actions of both the membership of the group and the CCEM, have helped steer and enable the process of redefinition over more than 20 years.

Electrical methods have been applied to the measurement of mechanical quantities such as mass, force and torque for some time, but the revision of the SI allows such techniques to achieve primary status and, in particular, the Kibble technique holds the promise of novel applications. I am proud to have chaired this group and I intend to continue to drive progress in this exciting field. Eventually I hope to see a world-wide mass scale maintained by an ensemble of independent Kibble Balances. In addition I would like to see this powerful technique applied to solve problems in a range of industrial applications.

Ian A Robinson
26th March 2019