Physical Metrology

Kibble balance progress
Significant progress has been made on the development of the BIPM Kibble balance in 2018. The suspension was modified in order to align all of the components more easily and independently. This improvement allowed more accurate alignment of the coil with respect to the magnet, which had previously been the main contributor to type B uncertainty. The use of a programmable Josephson voltage standard (PJVS) for current and induced voltage determination has further improved the measurement accuracy. The apparatus has been operating reliably in vacuum since mid-2018. Measurements of the Planck constant were carried out using a 1 kg stainless steel and a 1 kg Pt-Ir mass standard. As a consequence of the improvements, the measurement uncertainty has been reduced to a level of 2 parts in $10^7$. This uncertainty is dominated by instability in the vertical alignment of the interferometer beams when going from air, where the alignment is made, to vacuum for measurement. A new interferometer of novel design, which is fixed on a more stable support, is to be integrated into the apparatus to further reduce the measurement uncertainty. A detailed study has been carried out to evaluate the effect of the coil-current on the magnetic field.\textsuperscript{[1, 2, 3]}

The BIPM will serve as the pilot laboratory for the first CCM key comparison of kilogram realizations, based on Kibble balances and XRCDD experiments. This comparison will closely follow the scheme of the CCM Pilot Study of future kilogram realizations, which was carried out in 2016 as a trial comparison. It is planned that measurements shall start around September 2019 and that a Final Report will be available around mid-2020. The BIPM Kibble balance will participate in this comparison.

Future calibrations of mass standards
The BIPM will continue to provide calibrations of mass standards for the NMIs of Member States following the redefinition of the kilogram, which came into force on 20 May 2019. This follows the revision of the International System of Units (SI) by a decision adopted by the 26th meeting of the General Conference on Weights and Measures (CGPM) in Versailles on 16 November 2018.\textsuperscript{[4]}

Immediately after the redefinition the BIPM calibrations will be traceable to the new definition – based on the fixed numerical value of the Planck constant - through its known relationship with the IPK. The calibration uncertainty will then be dominated by the uncertainty of 10 micrograms of the mass of the IPK with respect to the Planck constant. All BIPM calibration customers have been informed that BIPM calibration certificates issued before the redefinition will remain valid, but for use after 20 May 2019, this uncertainty needs to be added in quadrature to the uncertainty stated on the certificate. After the completion of the first key comparison of kilogram realizations, expected around mid-2020, the BIPM will disseminate the kilogram based on an international consensus value, until satisfactory agreement is reached between the NMIs’ realization methods.

The maintenance and dissemination of the kilogram following its redefinition is described in Metrologia\textsuperscript{[5]}. The final report on the pilot comparison of future realizations of the kilogram has been published\textsuperscript{[6]}. 
On-site QHR comparisons

The department’s electricity laboratories organized two further on-site comparisons of quantum Hall resistance (QHR) standards, with the NRC (Canada) and the NMIJ (Japan) and the report of a previous comparison with METAS was published. These comparisons require considerable logistics in transporting more than 1 tonne of equipment to the participating NMI: the main elements are the cryostat with magnet and QHR sample, a resistance bridge and thermo-regulated resistors of 1 Ω, 100 Ω and 10 kΩ. The measurands are the value of the 100 Ω resistor, measured using the BIPM and the NMI QHR standards and bridges, and the 1:100 ratios between the resistors, measured with the BIPM and NMI bridges. The comparison with the NRC has led to agreement at the level of 1 to 2 parts in 10^8. The observation made during previous comparisons that the value of the 1 Ω standard depends on the cycle time of the comparison bridge was confirmed. The results obtained at the NMIJ are being analysed. In addition to the on-site QHR comparisons, the department organizes bilateral resistance comparisons using resistance transfer standards.

New protocol to extend on-site comparison of quantum voltage Josephson standards from DC to AC voltages

The BIPM is developing a new protocol to extend its on-site comparison of quantum voltage Josephson standards from DC to AC voltages for frequencies below 1 kHz. A pilot study was carried out at the NPL (UK) in February 2018, following those previously undertaken with the NMU[7], the CENAM (Mexico) and the PTB (Germany).

The BIPM contributed to a comparison of two cryo-cooled programmable Josephson standards at the NIST.[7] The aim of these studies is to gain experience in the comparison of AC voltages and to investigate the metrological behaviour of different AC sources used as transfer standards. At the NPL, an agreement within a few parts in 10^8 could be achieved in measuring rms values of sinewaves at 1 V rms and 60 Hz, using the differential sampling method. The noise of the phase-locking process appeared to be the limiting factor. In addition, a comparison of AC signals was performed between the NMIA (Australia), using thermal converters, and the BIPM, using its programmable Josephson voltage standard (PJVS), with a voltmeter as a transfer standard. In this comparison the input filter of the voltmeter was identified as a potential source of error. In addition to the on-site comparison of Josephson voltage standards, the department organizes bilateral voltage comparisons using secondary Zener voltage standards as transfer standards.

In parallel, the influence of different types of samplers on the differential sampling technique was investigated with the support of a secondee from KRISS (Republic of Korea). The observed differences between samplers, which increased with frequency, have been attributed to the differences in the input bandwidths. Work on the determination of leakage resistance to ground on PJVS, performed in collaboration with NIST, continued. The sources of leakage to ground were investigated using a direct comparison setup between two NIST cryo-cooled systems.[8]

CCEM capacitance comparison completed using the ‘star scheme’

For the second time since the inauguration of the CIPM MRA, the CCEM organized a key comparison of electrical capacitance calibrations, CCEM-K4. The comparison was piloted by the BIPM and had seven NMI participants from four RMOs: METAS, NIM, NIST, NMIA, NPL, PTB and VNIIM. The BIPM participated in the comparison with its own realization of the capacitance unit, the farad.

This was the first CCEM comparison to adopt the ‘star scheme’, which consists of a set of parallel bilateral comparisons carried out between the participating NMIIs and the BIPM. Each participant provided a set of capacitance standards and the BIPM served as a common reference for the comparison. The measurands were the capacitance values at 10 pF and optionally at 100 pF. All participants carried out measurements at both values.

Four of the participants, which included the BIPM, took their traceability from the DC or AC quantum Hall effect, the other four from a calculable capacitor. The comparison results agreed within ± 5 parts in 10^8 at 10 pF and within ± 10 parts in 10^8 at 100 pF, consistent with the claimed uncertainties.

The comparison also allowed the evaluation of the difference between the value of the von Klitzing constant R_V measured by electrical means - based on the calculable capacitor - and the value recommended in the CODATA fundamental constants adjustment of 2014. The latter value is dominated by measurements of the anomalous magnetic moment of the electron and atomic recoil. A difference of (43 ± 23) parts in 10^9 (k=1) has been found.

The use of the star scheme was a great success. The comparison was completed and the results are excellent. The CCEM community will consider if this model can be applied to comparisons of other quantities.