Director’s Report on the Activity and Management of the International Bureau of Weights and Measures
Supplement: Physical Metrology Department
(1 January 2015 – 31 December 2015)

April 2016

Bureau International des Poids et Mesures
BIPM Physical Metrology Department
Director: M. Stock
(1 January 2015 to 31 December 2015)

In October 2015 the staff and the activities of the Electricity and Mass Departments were merged into the new Physical Metrology Department. The work in the electricity laboratories is described in Section 1, that of the mass group in Section 2.

1. Electrical metrology

1.1 Electrical potential difference (voltage)

1.1.1 Compact NIST 10 V programmable Josephson voltage standard for ac voltage measurements (S. Solve, R. Chayramy)

During the secondment of Dr Solve to the NIST, from July 2012 to July 2013, a programmable Josephson Voltage Standard (PJVS) with compact electronics, which was designed to be transportable, was developed for the BIPM under a cooperative research and development agreement. This new system is intended to be used to develop a future comparison scheme for AC Josephson voltage standards. In 2015, it was used for the first time for an on-site comparison, mainly to test its suitability for transportation and use in another laboratory. The comparison was performed with the NMIJ, Japan, at 10 V DC against one of their programmable Josephson voltage standards. This was the first direct comparison of programmable primary voltage standards of different technologies; it led to an excellent agreement of a few parts in 10^{12}. The BIPM PJVS was found to be very stable in terms of the repeatability of its biasing parameters. It was also found to be robust against trapping of magnetic flux.

Based on the work of 2014 on the leakage resistance to ground during the comparison with the NMIJ, different grounding configurations of the measurement setup and their influence on the measurement noise were investigated. It could be demonstrated that the capacitors of the filters on the precision measurement leads can introduce a systematic error of up to a few parts in 10^{10} depending on where the leakage current flows. Precautions must be taken in the implementation of filters on PJVSs in order to limit the leakage resistance error.

The current version of the new BIPM transportable quantum voltage standard is not yet fully operational for the generation of AC stepwise approximated signals. The generation of such signals is already possible, but they cannot yet be synchronized in phase with an external AC signal.

1.1.2 Quantum voltage reference for the watt balance (S. Solve, R. Chayramy)

The measurement of the induced voltage in the BIPM watt balance will be carried out using a programmable Josephson voltage standard. If the watt balance is operated in the special one-phase mode, where the force and velocity modes are carried out simultaneously, a second Josephson system will be needed for the determination of the coil current, measured as the voltage drop over a calibrated resistor. The work on these systems is described in Section 2.4 on the watt balance.
1.1.3 Upgrade of the automatic Zener measurement system for measurements at 10 V (S. Solve, R. Chayramy)

Work continued on the implementation of the automated Zener measurement setup throughout the year. The final aim is to replace the conventional primary voltage standard based on underdamped Josephson junctions and its associated measurement setup. To test the correct functioning of the new automated system, the 12 BIPM Zener secondary voltage standards were successively calibrated against the two measurement setups several times. For most of the standards, the results obtained with the two different measurement systems were in good agreement, with differences varying from 5 nV to 90 nV for the 10 V output. However, the difference can reach up to 500 nV for the remaining standards, which is not acceptable.

Calibrations of the 1 V outputs of the same Zener standards did not show a similar difference. The assumption of a leakage error at the level of the 10 V output of the Zeners was investigated by changing the grounding configuration of the PTB-SNS array in the automatic system but no evidence of leakage could be identified. A number of other tests were carried out but could not explain the observed offset. The Josephson voltage standards used for the two calibration systems were directly compared and showed agreement within a few parts in $10^{11}$. The output voltages of the Zener standards are corrected for changes of their internal temperature. The correction coefficients had been determined more than 10 years ago and there is the possibility that they might have changed with time. A measurement setup to re-determine the temperature coefficients has been developed and a measurement campaign will be carried out in 2016. The results are also of importance for the comparison of Zener calibrations, BIPM.EM-K11, which the BIPM offers to NMIs and for which the Zener standards are used.

1.2 Electrical impedance (resistance and capacitance)

1.2.1 DC resistance and quantum Hall effect (N. Fletcher, P. Gournay, B. Rolland)

The quantum Hall resistance (QHR) was realized several times during 2015, as required to maintain traceability for resistance calibration and comparison services and also the link to capacitance. Continuing improvements have been made to the BIPM’s set of transportable equipment for on-site QHR comparisons. The last of a set of three transportable thermo-regulated resistance standards has been brought into service, and regular verifications of the critical 1 Hz-dc coefficients of these new standards have been undertaken to establish confidence in their use with the transportable 1 Hz bridge.

In collaboration with MIKES/VTT and PTB a new generation of low frequency current comparators have been investigated. The new comparators, built at MIKES, offer some improved characteristics over those presently used at the BIPM, and gave good results when substituted in our existing bridge electronics.

Some graphene QHR samples (developed in a collaboration between MIKES-VTT and Aalto University (Finland) using SiC wafer technology) were investigated at the BIPM, and demonstrated equivalence to the existing GaAs reference for calibration work. Further sample improvements are required to achieve an accurately quantized QHR plateau under simplified experimental conditions (e.g. 4.2 K temperature and 5 T magnetic field, as compared to the existing requirement of 1.5 K and 10 T). A commercial graphene sample that promises to meet these conditions has been obtained, and will be tested in early 2016. If successful, this could greatly simplify the logistics and cost of performing on-site QHR comparisons.

1.2.2 Calculable capacitor (P. Gournay, N. Fletcher, L. Robertsson)

A new stabilized laser source for the interferometer has been developed to replace the previous source which had shown instabilities. Unlike the previous source, this one has been fully developed at the BIPM and allows fine control of all tuning parameters, leading to a much better stability of the laser frequency. Moreover, a frequency
beat can now be carried out with the stabilized laser source of the watt balance by creating interference between beams derived from both sources. During capacitance measurements with the calculable capacitor this beat frequency is now recorded to identify eventual frequency jumps, which lead to step changes of the realized capacitance.

A new series of measurements carried out with the new laser source have confirmed its good functioning and have allowed the BIPM to perform the first tests of the voltage dependence of the calculable capacitor. The results are encouraging but not yet conclusive. The limit is currently our knowledge of the voltage coefficient of the standard capacitors implied in these measurements, which need to be determined more precisely.

As evidenced by the characterization measurements performed in 2014 and confirmed in 2015, the present alignment accuracy of the electrode bars and a few other minor problems (requiring disassembly of the calculable capacitor) limit the uncertainty of the determination of the von Klitzing constant to about 2 parts in $10^7$. The weak point of the aligning method has been identified and a new aligning tool, designed by the NMIA, Australia, has been constructed and calibrated during 2015 at the BIPM. It will be used in early 2016 to re-align the electrode bars. Before re-alignment, the calculable capacitor will be disassembled and moved into a new laboratory with a floor comprising a large concrete block. This should limit significantly the effect of ground vibrations currently seen on the bridge balance signal of the calculable capacitor bridge.

The expected improvements from this work should allow the BIPM to measure the von Klitzing constant to better than 5 parts in $10^8$ in 2016.

### 1.2.3 Maintenance of a reference of capacitance (P. Gournay, R. Chayramy, N. Fletcher)

The unit of capacitance is maintained at the BIPM by a group of four 10 pF standard capacitors. They are calibrated every six months against the dc-QHR through a quadrature transfer. During 2015 this transfer was carried out a third time in-between the two normal ones due to the participation of the BIPM in the EURAMET.EM-S31 comparison of capacitances at 10 pF and 100 pF. In effect, following the significant discrepancies found after the first circulation of the standards in 2011, this comparison is still ongoing and a second circulation started in 2015. This time it includes the NMIA in order to obtain at least one result traceable to a Thompson-Lampard capacitor. As the BIPM received the standards two months apart, before and after the measurements in Australia (to keep track of possible drift of the standards during transportation), the reference group of capacitors was calibrated once more against the QHR to achieve the best possible measurement uncertainty. This also required verification of the entire measurement chain from the QHR to the 10 pF reference standards, including in particular:

- the frequency corrections of the standard transformers at the operating frequencies (measurements were carried out at 1027 Hz, 1541 Hz and 3082 Hz),
- the frequency corrections of the ac-resistors of the quadrature bridge against a coaxial and calculable Haddad resistor,
- the drift of the 10 pF reference group of capacitors,
- the frequency dependence of the voltage injection devices.

The final results of this second circulation should be known in the first half of 2016.

As usual, the reference group of capacitors has also been used during 2015 for calibrations for NMIs (see Section 1.4) and for a bilateral comparison of capacitances at 10 pF and 100 pF (BIPM.EM-K14.a and BIPM.EM-K14.b) which started with NIS, Egypt, at the end of 2015 and should be finished in February 2016.
1.3 Comparisons of electrical standards

1.3.1 BIPM ongoing key comparisons in electricity (R. Chayramy, N. Fletcher, P. Gournay, B. Rolland, S. Solve, M. Stock)

The work programme in Electricity is focused on a comparison programme to validate national primary standards for fundamental electrical quantities: voltage, resistance and capacitance. To validate the high intrinsic accuracy of electrical quantum standards, the BIPM organizes on-site comparisons of Josephson voltage standards (BIPM.EM-K10) and of quantum Hall resistance standards (BIPM.EM-K12). For these comparisons, the BIPM quantum standards are transported to the laboratory of the participating NMI. BIPM staff and NMI staff then carry out a joint direct comparison of the BIPM and the NMI quantum standards.

The BIPM also organizes comparisons of voltage (BIPM.EM-K11), resistance (BIPM.EM-K13) and capacitance (BIPM.EM-K14) by sending secondary standards (Zener voltage standards, resistors, capacitors) to the participating NMI. In the case of voltage and resistance, the uncertainties in these comparisons are significantly higher than in the on-site comparisons which allow a direct comparison of the quantum standards.

On-site comparisons of Josephson voltage standards were carried out with the DMDM, Serbia, and the NIMT, Thailand. The report on the comparison with the PTB, Germany, in 2014 was published. As described in Section 1.1.1 a first comparison with the new programmable AC Josephson system was carried out with the NMIJ, Japan.

An on-site comparison of quantum Hall standards was organized with the VSL, the Netherlands. Unfortunately, the VSL system did not function properly during the comparison and no definitive result could be obtained.

Comparisons of Zener calibrations were organized for the NSAI NML, Ireland, and the JV, Norway. The reports for three comparisons undertaken during 2014 were published.

Bilateral comparisons of resistance measurements for 1 Ω and 10 kΩ were carried out with NSAI NML, Ireland, NIMT, Thailand, and CMI, Czech Republic. Reports are currently being written.

A bilateral comparison of capacitances at 10 pF and 100 pF has started with NIS, Egypt, at the end of 2015 and should be finished in February 2016.

1.3.2 CCEM-K4.2016 (P. Gournay, N. Fletcher, M. Stock)

The key comparison CCEM-K4 of capacitance at 10 pF was last carried out during 1996 to 1999. In 2012 a decision was made by the Working Group on Low-Frequency Quantities (WGLF) of the Consultative Committee for Electricity and Magnetism (CCEM) to repeat this comparison and the general principles were discussed and adopted at its meeting in June 2015.

The new CCEM-K4 comparison will be organized as a large-scale star comparison. It will consist of a large number of bilateral comparisons between the participating NMIs and a reference institute during the same time frame. The BIPM has been designated by the CCEM as the reference institute and also the pilot for the comparison.

In this comparison scheme, all the participating institutes will be asked to send their own standards to the BIPM where they will be compared during the same time period. Before and after this measurement period at the BIPM, each institute should calibrate their own standards, again, preferably during the same time period. Two or three 10 pF standards capacitors could be sent to the BIPM and also an optional 100 pF standard in order to address the question of the scaling process from 10 pF.

For comparability, the capacitance measurements should be reported using the SI unit farad. This means that institutes realizing their traceability from a quantized Hall resistor should use the value of the von Klitzing constant ($R_K$) from the latest CODATA fundamental constants adjustment and not its 1990 conventional value.
Capacitance measurements will be carried out under the usual ambient conditions (23 °C ± 1 °C and 50 % ± 10 % relative humidity) and preferably at 1592 Hz and 100 V\text{rms} (10 V\text{rms} for 100 pF capacitors).

Analysis of the results will be performed by the BIPM with the support of a group of experts from NMIs appointed by the CCEM. A statistical method that will allow, to address at best, the problems of drifts and step changes due to transportation of the standards will be developed and agreed before starting the comparison. The BIPM will fulfill the dual role of serving as reference laboratory (to compare all participants’ standards against a set of reference capacitors) and of participating in the comparison with its own primary reference. The key comparison reference value (KCRV) will be derived by statistical techniques using all the participants’ results and will not be taken as the BIPM result (contrary to the program of bilateral comparisons BIPM.EM-K14).

The first draft of the technical protocol of the new CCEM-K4 comparison has been developed in 2015. It will be submitted for review and approval by the support group in early 2016 and the comparison is expected to start in the second half of 2016.

1.4 Calibrations of electrical standards (R. Chayramy, N. Fletcher, P. Gournay, B. Rolland, S. Solve, M. Stock)

During the period from January to December 2015 the Electricity Department calibrated the following standards:

- 1 Ω, 100 Ω or 10 kΩ resistors were calibrated for: BEV (Austria), NMISA (South Africa), INMETRO (Brazil), MSL (New Zealand), SMD (Belgium), NMC (Singapore), BIM (Bulgaria), NIMT (Thailand), RSE KazInMetr (Kazakhstan). In total 43 certificates and two study notes were issued for nine NMIs.

- 1 pF, 10 pF and 100 pF capacitors were calibrated for: CEM (Spain), BEV (Austria), NIMT (Thailand), NMISA (South Africa), CMI (Czech Republic), SMD (Belgium), RSE KazInMetr (Kazakhstan), CENAM (Mexico) and INTI (Argentina). In total 33 certificates and two study notes were issued for nine NMIs.

- Three Zener voltage standards were calibrated for UTE (Uruguay) and KIM-LIPI (Indonesia).

As every three years, the measurement services of the Electricity Department have been subjected to an external peer audit in 2015. As has been the case previously, services provided to the Member States of the BIPM are in compliance with the BIPM Quality Management System, based on the requirements of ISO/IEC 17025.

2. Mass Metrology

2.1 Measurement Services in Mass

2.1.1 Calibrations

2.1.1.1 Extraordinary calibrations with respect to the IPK in anticipation of the redefinition of the kilogram (P. Barat, E. de Mirandés, M. Stock, M. Milton)

In 2014 an extraordinary campaign of calibrations was initiated at the BIPM to provide improved traceability to the international prototype of the kilogram (IPK) for those NMIs that are carrying out experimental determinations of the Planck constant to support the forthcoming redefinition of the kilogram. During the first phase of the calibration campaign the IPK was used to recalculate its six official copies and the BIPM working standards. This work was completed in 2014 and the results for the IPK and the official copies have been published [1]. In Phase two of the calibration campaign, mass standards of eight NMIs involved in measuring the Planck constant were calibrated against the BIPM working standards. The calibration certificates were sent to the NMIs in April 2015, providing them with improved traceability to the IPK, with an uncertainty of 3.5 μg.
During Phase one, in 2014, it had been observed that the BIPM as-maintained mass unit, traceable to the IPK and which had been measured previously during the 3rd Periodic Verification, 1988-1992, had drifted away from the IPK by 35 µg. It had also been observed that all working standards had lost mass since 1992, with losses ranging from 19 µg to 88 µg, which appeared to be correlated with the intensity of use. In the light of these experimental findings, the BIPM has conducted an analysis of all the available data from internal mass comparisons among the ten BIPM working standards since the 3rd Periodic Verification in order to understand the origin and evolution of this offset. A set of deterministic mathematical models for the mass evolution of the mass standards, capable of describing the experimental weighing data set has been developed. The model which describes the data best, suggests that a wear phenomenon, associated with one of the BIPM mass comparators, which was modified in-house, was responsible for a collective mass loss experienced by all the BIPM working standards, principally during the years 2004-2010. Since the IPK was not accessible between the 3rd Periodic Verification and 2014, a part of this collective mass loss went undetected, which explains the offset observed in 2014. This mass comparator was taken out of service in 2010. It is planned to re-activate the comparator to test the hypothesis that it was the origin of the mass losses.

As a consequence of the undetected mass changes, mass values attributed in mass calibrations since 2004 were generally overestimated, up to 35 µg in 2014. The mathematical model allows determination of the evolution of this mass offset over time. This has allowed the BIPM to calculate corrected mass values which have been provided to its calibration customers. Revised calibration certificates for Pt-Ir standards were sent in March 2015 and for stainless steel standards in May 2015. Institutes involved in precision measurements of the Planck constant and the Avogadro constant had already been informed of the revised mass values at the end of 2014, so that they could provide updated measurement results for the CODATA 2014 fundamental constants adjustment.

As a result of these findings, a new strategy for the use of the working standards was developed, with the objectives of limiting the potential mass loss of the standards and to provide the possibility to detect such changes, if they were to occur. This new approach is described in the following section.

2.1.1.2 Calibration of 1 kg Pt-Ir prototypes and stainless steel standards (P. Barat, M. Stock)

As described in section 2.1.1.1, during the calibration campaign using the IPK in 2014, it had been observed that the BIPM working standards had changed mass and that the full amount of mass change had not been detected. In order to ensure a stable BIPM mass unit in the future, two measures have been presented to the CCM during its meeting held in February 2015 (see Report of the Consultative Committee for Mass and Related Quantities, 15th meeting (2015), 2015, p.19): (1) that, henceforth the BIPM mass calibration service is no longer continuously available but restricted to two periods of the year and (2) that the working standards shall be used in a hierarchical approach, with different levels of usage.

Only two calibration periods are now open to the NMIs: March to May and September to November. At the beginning and the end of each period, the stability of the BIPM working standards will be checked. As a consequence, the calibration certificates are issued only after the end of each calibration period.
Furthermore, a new hierarchy has been established among the BIPM working standards. This new hierarchy is described in figure 1.

During 2015, 41 mass calibration certificates and one study note have been issued:

- Thirteen calibration certificates issued in the framework of the Extraordinary Calibrations using the IPK (see section 2.1.1.1).

- Sixteen certificates issued for the first calibration period from February to June 2015 (due to the Extraordinary Calibrations, the first calibration period for 2015 was extended from February to June) for the calibration of prototypes Nos. 35 (France), 44 (Australia), 46 (Indonesia), 56 (South Africa), 71 (Israel), 78 (Chinese Taipei), 89 (Switzerland), for 1 kg mass standard in platinum-iridium designated “A” (NPL, UK) and for 1 kg mass standards in stainless steel from the BIM (Bulgaria), the INPL (Israel), the KazInMetr (Kazakhstan), the LATU (Uruguay) and the VSL (the Netherlands).

- Ten certificates issued for the second calibration period from September to November 2015 for the calibration of prototypes Nos. 24 (Spain), 48 (Denmark), 64 (China), 76 (Italy), 80 (Thailand), for 1 kg mass standard in platinum-iridium designated “B” NPL (UK) and for 1 kg mass standards in stainless steel from the NIMT (Thailand), the NSAI NML (Ireland) and the VSL (the Netherlands).

- Two certificates and one study note issued for the calibration of new prototypes which have been provided to Member States: Prototypes Nos. 93 SASO (Saudi Arabia), 108 INM (Colombia) and 109 PTB (Germany).

2.1.1.3 Mass determinations of the AVO28 spheres (P. Barat, M. Stock)

In 2014 the BIPM contributed to the work of the of the Avogadro consortium by weighing the two isotopically pure Si-spheres AVO28-S5 and AVO28-S8. The result of the new determination of the Avogadro constant was published in March 2015 [2]. For the CODATA fundamental constants adjustment it is important to know by how much this new result is independent from the previous determination, published in 2011. Both
determinations have been made with the same spheres, however in-between they were etched and re-polished to eliminate metal contamination and to improve roundness.

To make both results usable for the least squares adjustment, the correlation between both results has been determined. Owing to the surface re-polishing and the upgrades of many of the measurement technologies, the correction is only 17%. This analysis was published in July 2015 [3].

2.1.1.4 **Volume calibrations of mass standards (D. Bautista)**

New software has been developed with a view to using silicon density standards in the hydrostatic apparatus. This should also simplify the use of the apparatus and allow the measurements to be carried out with minimum intervention. This work is now nearly finished and tests will follow in early 2016.

It has been observed that the hydrostatic balance leaves marks on the surface of the new prototypes under fabrication. This complicates the final polishing, as these marks need to be removed. Studies have been carried out to investigate the origin of this surface damage and to reduce it. To achieve this, the alignment of the weight exchangers and pans has been improved and a new system for the thermal treatment of the suspension wire has been designed.

The measurement capability for stacks of disks has been re-established, following measurements carried out on a stack for which the density was previously determined by the NPL. The difference between the results is consistent with the uncertainties, at the 95% level of confidence, and proves the validity of our new measurements.

2.1.1.5 **Pressure calibrations (F. Idrees)**

No internal pressure calibrations were carried out in 2015 because the pressure calibration facility was not operational. The piston-cylinder assembly of the pressure balance has been damaged and the manufacturer has been contacted to resolve the issue. The calibration campaigns have been postponed until the whole system is functional again.

2.1.2 CCM pilot study of primary realizations of the kilogram (M. Stock, P. Barat, S. Davidson (NPL, UK))

One of the preparatory steps of the joint CCM and CCU Roadmap towards the redefinition of the kilogram is a “Pilot Study” of primary realizations of the kilogram. This Pilot Study shall compare realizations of the unit of mass at the level of 1 kilogram obtained with primary realization experiments (watt/joule balances, XRCD experiment), which are capable of determining mass at an uncertainty level of better than 2 parts in 10^7, that is 200 µg at the level of 1 kg. The BIPM will act as the pilot laboratory.

The two main objectives of the Pilot Study are (1) to test the uniformity of kilogram realizations based on different primary realization experiments and (2) to test the continuity between the kilogram realized according to the future definition and according to the present definition. The technical protocol has been designed so that primary realizations of the kilogram obtained by different primary realization experiments may be compared as directly as possible.

The Pilot Study will be carried out by using two sets of 1 kg travelling standards (provided by each participant) to be calibrated by the participants as follows:

Set 1: One Pt-Ir standard and optionally one standard of the participant’s choice (e.g. Si-sphere, tungsten cylinder, second Pt-Ir standard), to be calibrated as directly as possible with the primary realization experiment (in general under vacuum);

Set 2: Two stainless steel standards, to be calibrated in air, traceable to the primary realization experiment.
Each participant shall calibrate its travelling standards assigning to each of them a mass and an uncertainty, based on an exact value of the Planck constant, stated in the comparison protocol. The BIPM will afterwards collect the travelling standards from all participants and carry out mass comparisons among all of them. Results from these comparisons will be compared with the mass and uncertainties claimed by the participants. This will assess the capability of future primary realizations to realize and disseminate a consistent unit of mass (uniformity) world-wide. The traceability of the BIPM working standards to the IPK, re-established in 2014 (see 2.1.1.1), will allow investigations of the agreement between kilogram realizations based on the future and the present definition of the kilogram (continuity). Following the measurements at the BIPM, the NMIs will recalibrate the standards to verify that their mass has not changed.

The measurements at the NMIs are planned for January - March 2016 and July - September 2016. The comparison measurements at the BIPM are foreseen for the period of April - June 2016. The Final Report is expected by March 2017.

2.1.3 Maintenance of the mass comparators and associated equipment (P. Barat, T. Lavergne)

The M_one 6V-LL mass comparator is now equipped with an Artefact Transfer Device (ATD) developed by Mettler-Toledo AG. The latter allows the transfer of artefacts, stored in inert gas or under vacuum, into the comparator without contact with the ambient laboratory air by means of an Artefact Storage and Transport Vessel (ASTV).

Henceforth, with two mass comparators equipped with transfer systems for mass artefacts, CCL1007 from Sartorius (with the Vacuum Transfer System – VTS) and M_one 6V-LL from Mettler Toledo (with the ATD), the BIPM is equipped with an important capability for the future work for the Ensemble of Reference Mass Standards.

A new device is being developed for the transfer of mass artefacts from the Automatic Loadable Container (ALC, Sartorius) to the Artefact Storage and Transport Vessel (ASTV, Mettler Toledo) and vice versa. This will allow determinations of the average mass of the Ensemble of Reference Mass Standards with both mass comparators, i.e. the CCL1007 and the M_one 6V-LL.

2.2 Manufacturing 1 kg artefacts in Pt-Ir for NMIs (F. Boyer - BIPM Workshop)

The manufacture of three new 1 kg mass prototypes has been completed in 2015: one for Pakistan (the one previously allocated to Pakistan has been re-allocated to Saudi Arabia), one for Colombia and one for the PTB (Germany).

2.3 Ensemble of Reference Mass Standards (E. de Mirandés, F. Idrees, P. Barat)

In 2015 progress was made on the inert gas storage network of the ensemble of mass standards. The containers were already maintained under nitrogen and mass holders designed for each material have been inserted in the containers through the glovebox facility. This has led to a higher humidity level in the containers. In order to reach a lower level, all metallic parts of the containers were heated in the oven connected to the glovebox. A second heat treatment is planned at a higher temperature to reduce the humidity level further and to get it closer to the level of a blank measurement. The flow rates and the pressure levels inside the containers were adjusted to achieve a more uniform flow distribution inside each line. Software for monitoring the system and for detecting anomalies has been developed.

It has been observed that the vacuum level was too high when all the containers of the vacuum network were connected. To solve this problem a new series of containers has been designed which are under fabrication.
2.4 Watt balance (H. Fang, F. Bielsa, A. Kiss, T. Lavergne, R. Chayramy, Y. Lu 1, E. de Mirandés, B. Rolland, L. Robertsson, S. Solve, M. Stock)

A watt balance is being developed at the BIPM as a means for the practical realization of the expected new definition of the kilogram in terms of the Planck constant. A new apparatus has been developed with the objective of reducing in particular the type B measurement uncertainties related to misalignment. Its assembly is being finalized at the end of 2015. In addition to the use of several new elements and measurements facilities, the new apparatus allows the application of various alignment techniques already developed earlier, but not easily implemented inside the previous apparatus.

The radial magnetic field produced by the magnetic circuit has been aligned horizontally using two experimental procedures [4]. The upper cover segments of the magnet structure are presently not yet in place, thereby allowing relatively unrestricted access to the air gap. Both techniques make use of a 3-axis Hall probe mounted eccentrically on a high precision rotation stage. The axis of the rotation stage serves as a vertical reference while the magnetic probe is used to locally sense the orientation of the magnetic field by measuring its vertical component (which disappears for horizontal alignment). The first technique can be applied to the present open circuit configuration where the Hall probe can be rotated continuously around the gap. The magnetic plane at the central position inside the gap was aligned to better than 10 μrad and a planarity better than 15 μrad has been observed. The alignment uncertainty was within 20 μrad, which was mainly limited by the instability of the tiltmeter used for vertical alignment of the rotation axis. Constancy of the magnetic plane inclination was verified at the 20 μrad level over a length of 40 mm in the vertical direction. This is particularly important for the BIPM watt balance where the electromagnetic force is exerted on the coil while the coil moves vertically through the magnetic gap. The geometry of the magnetic circuit was also characterized which confirms the suitability of the magnetic circuit for use in the BIPM watt balance at the 10⁻⁵ uncertainty level. Capacitive sensors were used to measure a decentring between the inner and outer poles of the yoke of 14 μm and a cylindricality of each pole surface better than 1 μm. A variation in the magnetic flux density of 0.6 mT in amplitude observed in the gap is well correlated with the variations of the measured gap width. For the centring of the coil, necessary for the watt balance operation, this variation in magnetic flux density corresponds to a coil decentring below 0.25 mm which is largely within the space available in the gap. A second alignment method, which had been developed in 2014, has been refined and can also be applied to the circuit in the future closed configuration, for which the first technique is not applicable. An uncertainty of the horizontality alignment of about 25 μrad was achieved using this technique. Regarding the technique developed for an open circuit, the dominant uncertainty source is the instability of the tiltmeter. The second most important source of uncertainty is the imperfect cancellation of the planar Hall effect of the magnetic probe at each location of the circuit. The two techniques yielded consistent results when applied to the present open configuration of the circuit. The accuracies of the two experimental procedures fulfil the requirements for the BIPM watt balance. They could easily be improved further by using a tiltmeter with higher precision, a Hall probe compensated for the planar Hall effect, and a stiffer mechanical support.

A new support structure was mounted to support the weighing cell and the whole suspension hanging from the weighing cell. The new structure has an open design allowing easy access to key components of the watt balance in order to facilitate their alignment. The suspension including the dynamic alignment mechanism and the inductive coil was assembled. The integration of a new mass loading device, mass exchanger and new interferometers is in progress. Electrical and optical connections have been totally remade. A lot of care has been taken to adequately shield the cables that supply high voltages and the measurement signals as well as to avoid ground loops. Special precautions have been taken with the induced voltage signal in order to minimize thermal electro-motive forces. Improvements have also been made to the current source to minimize current leakage and to improve its reliability. All the control and measurement units have been transferred to an adjacent laboratory. This laboratory also accommodates the new green YAG laser source for velocity measurement and the new red

1 Secondee from NIM, China until 30 January 2015.
diode laser source for position sensors. In total, twelve fibre-coupled optical feedthroughs have been installed to transport the laser beams into the watt balance apparatus enclosure located in the adjacent room. Servo-control of the vertical coil motion along the air gap is being optimized. New compact position sensors have been developed and implemented inside the apparatus to determine the linear and angular displacements of the coil along its travel. Work will start soon to align the electric plane of the moving coil and its centre with respect to the magnetic circuit.

The BIPM continued the development of two Josephson voltage standards (JVSs), one for the voltage and one for the current measurements. To improve the flexibility of the JVS used for the current measurement, a multi-channel bias source capable of independently biasing the 13 segments of the Josephson junction array is being developed. The bias source is designed to supply a current adjustable between −30 mA and +30 mA for each segment. Special precautions have been taken to minimize the electrical noise and to avoid ground loops. Fabrication of a prototype source is under way and it is expected to be finalized by the end of 2015. Its operation will be tested on the Josephson array before fabrication of the whole multi-channel source.

The JVS dedicated to the induced voltage measurement was tested on its own. A voltage ramp from 0.6 V to 0.7 V was realized with a resolution corresponding to one Josephson junction (38 µV). This corresponds to the succession of 2615 combinations of the biasing configuration of the 13 subarrays. After each voltage step, the polarity was reversed to extract the linear evolution of the thermal EMFs. This test is very demanding on the equipment and therefore allows identification of weaknesses in the measurement setup.

The original design of the bias source, powered from a set of batteries, needed to be changed. The original bias source, tested on an array of resistances was successful, but behaved unpredictably when used with the array of Josephson junctions. We suspect that the problems encountered are related to both the structure of the impedance presented by the array and the galvanic isolation of the source. The generation of the voltage ramp using linear power supplies instead of the batteries was challenging but successful. The experimental results were as expected but exhibited a high sensitivity to magnetic flux trapping.

Development of the new interferometer is quite advanced. The frequency stabilization of the 532 nm laser source was further improved by refining the servo-control loop to compensate frequency drift in time. The frequency stability was characterized by measuring a beat note against a second similar laser system used for the calculable capacitor. The short-term stability was a few parts in 10^{12} for an integration time of several seconds which is mainly limited by the frequency modulation applied to the laser for the servo-control. Laser mode-leakage was also evaluated. No extra longitudinal modes were observed above the detection noise which was 55 dB below the laser mode. This should lead to an error of less than 10 pm on position measurement. The interferometers were aligned and characterized on a test bench. The output signals exhibit a signal-to-noise ratio of about 70 dB in a 1 kHz bandwidth, and a rejection of the cross-talk at the level of 60 dB, which should lead to very low phase noise and extremely low non-linear error. The whole experimental set-up has been transferred to the watt balance laboratories, where alignment of the interferometers inside the watt balance apparatus will start soon.

3. Activities related to the work of Consultative Committees

M. Stock is the Executive Secretary of the Consultative Committee for Electricity and Magnetism (CCEM) and a member of several of its working groups.

N. Fletcher is a member of the CCEM working group on proposed modification to the SI (WGSI). The CCEM and its working groups met in March 2015 at the BIPM.

M. Stock is the Executive Secretary of the Consultative Committee for Photometry and Radiometry (CCPR) and a member of its working groups. The working groups on key comparisons (WG-KC) and on strategic planning (WG-SP) met in October 2015 at the NIM, in Beijing. A workshop on comparison analysis was held at the same time. The new mise en pratique for the definition of the candela and associated derived units for photometric and
radiometric quantities has been published on the BIPM web site in July 2015. On 1 January 2016, J. Viallon from the BIPM Chemistry Department will become the new Executive Secretary of the CCPR.

H. Fang has been the Executive Secretary of the Consultative Committee for Mass and Related Quantities (CCM) since 1 January 2015. She is a member of several working groups (WGs) and task groups (TGs) of the CCM. The CCM and its working groups met at the BIPM in February 2015.

E. de Mirandés is Executive Secretary of the Consultative Committee for Units (CCU) which will hold its next meeting in June 2016.

4. **Activities related to external organizations**

M. Stock is a member of the Executive Committee of the Conference on Precision Electromagnetic Measurements (CPEM). H. Fang, N. Fletcher, S. Solve and M. Stock are members of the Technical Committee of the CPEM 2016.

M. Stock is the contact person for the BIPM liaison with the International Commission on Illumination (CIE).

P. Gournay represented the BIPM on the Organizing Committee and the Scientific Committee of the International Congress of Metrology, CIM 2015, held in Paris.

The BIPM is an external collaborator on the EMRP projects “Quantum Resistance based on Graphene (GraphOhm)” and “Automated Impedance Metrology extending the Quantum Toolbox for Electricity (AIMQuTE)”. The BIPM is also an external collaborator of the project ACQ-PRO, part of Joint Research Project to the European Metrology Programme for Innovation and Research (EMPIR), for the years 2015 to 2019.

M. Stock acted as the BIPM liaison with the International Avogadro Coordination project, the EURAMET Technical Committee for Mass and Related Quantities (TC-M), the Technical Committee for Photometry and Radiometry (TC-PR) and the Technical Committee for Electricity and Magnetism (TC-EM), and for the European Metrology Research Programme (EMRP) joint research projects SIB-05 (NewKILO) and SIB-03 (kNOW).

E. de Mirandés is a member of the CODATA Task Group on Fundamental Constants.

5. **Publications**


**Comparison Reports**


21. Solve S., Chayramy R., Stock M., Sengebush F., Bilateral Comparison of 1 V and 10 V Standards between the JV (Norway) and the BIPM, January to February 2015 (part of the ongoing BIPM key comparison BIPM.EM-K11.a and b), *Metrologia, 2015, 52*, Tech. Suppl., 01022.


23. Solve S., Chayramy R., Stock M., Vlad D., Bilateral Comparison of 1 V and 10 V Standards between the SMD (Belgium) and the BIPM, October to December 2014 (part of the ongoing BIPM key comparison BIPM.EM-K11.a and b), *Metrologia, 2015, 52*, Tech. Suppl., 01020.

6. **Travel in 2015 (conferences, lectures and presentations, visits)**

M. Stock to:
- NPL, Teddington (UK), 16 January, to discuss possible collaborations in the field of mass metrology.
- Sarajevo (Bosnia-Herzegovina), 15-17 April, to attend the EURAMET TC-M meeting and the EMRP NewKILO meeting.
- PTB, Braunschweig (Germany), 28-29 May, to visit the mass laboratories.
- NIM, Beijing (China), 26-28 October, to attend CCPR working group meetings and the CCPR workshop on comparison analysis.

P. Gournay and N. Fletcher to:
- LNE, Paris, 4-5 March, for EURAMET workshop on capacitance traceability and bridges, presentations on the BIPM quadrature chain and calculable capacitor.

P. Gournay to:
- International Congress on Metrology, CIM 2015, Paris, 24 September, to give a presentation on the calculable capacitor.

S. Solve to:
- Ecole Supérieure de Métrologie, Douai (France), 24 April, to give a talk on “voltage metrology within the BIPM mission”.
- SP, Boras (Sweden), 19-20 May, to attend the EURAMET Electrical Power and Energy Expert meeting.
- METAS, Bern (Switzerland), 27-29 May, to attend the EURAMET Expert meeting DC & Quantum Metrology.
- La Défense, Paris (France) to attend three LabVIEW® software courses, May and September.

S. Solve and R. Chayramy to:
- DMDM, Belgrade (Serbia), 17-25 June, to carry out an on-site BIPM Josephson voltage standard comparison.
• NIMT, Klong Luang, Pathumthani (Thailand), 3-12 November, to carry out an on-site BIPM Josephson voltage standard comparison.

• NMJJ, Tsukuba (Japan), 2-12 December, to perform the first direct comparison between the new BIPM Programmable Voltage Standard and the NMJJ Programmable Voltage Standard.

N. Fletcher, P. Gourlay, B. Rolland to:

• VSL (the Netherlands), 2-9 October, to carry out an on-site comparison of quantum Hall resistance standards.

F. Bielsa, H. Fang, A. Kiss and T. Lavergne to:

• METAS, Bern (Switzerland), 8 July, to visit the watt balance and for technical discussions.

P. Barat, F. Idrees and E. de Mirandés to:

• PTB, Braunschweig and Berlin (Germany), 4-6 May, to visit the mass laboratories.

P. Barat to:

• Académie des Sciences de Paris, Paris (France), 7 July, to deliver prototype No. 34 which was calibrated during the Extraordinary Calibrations using the IPK.

7. Visitors in 2015

Electricity laboratories

• Dr Nabil Ben Hsouna and Dr Ghislain Boloma, students at ESM (France), to visit the voltage metrology laboratories, 11 February.

• Dr. Yang Yan and Dr Lu Huang (NIM), to visit the electricity laboratories, 6 March.

• Dr Ralf Behr and Dr Luis Palafax (PTB) to discuss the comparison report on the Josephson voltage standard comparison with PTB in October 2014, 9 March.

• Dr Ilya Budovsky (NMIA) and Dr Jon Pratt (NIST), to visit the voltage metrology laboratories, 9 March.

• Dr Yi-hua Tang (NIST), to visit the voltage metrology laboratories and to discuss future collaboration work, 10 March.

• H.E. Mr Nabil A. Molla, Omar S. Kanakrieh, GCC Standardisation Organization (GSO), Saudi Arabia, Mohamed Ahmed Al Mulla, GULFMET President, United Arab Emirates, to visit the calculable capacitor and the watt balance, 19 March.

• Amer Ali, Graphensic AB, Sweden, for discussions on graphene samples, 9 June.

• Dr Alexandre Satrapinski, MIKES/VTT, Finland, for investigations on low-frequency current comparators, 22-26 June.

• Dr Martin Götz, PTB, Germany, for investigations on low-frequency current comparators, 23 June.

• Group of 30 visitors from KASTO (Korean Association of Standards and Testing Organization), Republic of Korea, to visit the electricity and mass laboratories, 29 June.

• Dr Barry Wood (NRC), for an external audit of the electricity measurement services, 2-3 September.

• M. Mohamad Syahadi (KIM-LIPI) to bring a Zener voltage standard for calibration and visit the voltage laboratories, 7 September.
• Group of five scientists (KIM-LIPI), for a laboratory tour, including the electricity laboratories, 9 September.

• Dr Samuel Benz (NIST) to visit the voltage metrology laboratories and discuss future collaboration work, 10-11 September.

• Dr Chihiaru Urano (NMIJ) to visit the voltage metrology laboratories and discuss the technical details of the comparison of programmable Josephson voltage standards at NMIJ, 14 September.

• Dr Sophie Djorjevic (LNE) to discuss issues on the operation of programmable arrays of Josephson junctions, 23 September.

• Khosro Madanipour (President NMCI), Ahad Mohammadi Livari (Deputy), Omidali Masoudi (General Director Public and international relations), NMCI(ISIRI), Iran, for a laboratory tour including the mass and electricity laboratories, 23 October.

Mass laboratories including the watt balance
• Dr Stephan Schlamminger (NIST), to deliver the watt balance made from LEGO bricks, 24 February.

• Ms Sheila Preste (LATU), to visit the watt balance, 25 February.

• Dr Ilya Budovsky (NMIA), to visit the watt balance, 9 March.

• Dr Dae-im Kang and Won-gyu Lee (KRISS), to visit the watt balance, 12 March.

• P. Pinot, P. Otal and F. Beaudoux (LNE/Cnam), to visit the Mass laboratories and to collect prototype No. 35, 18 March.

• H.E. Mr Nabil A. Molla, Omar S. Kanakrieh, GCC Standardisation Organization (GSO), Saudi Arabia, Mohamed Ahmed Al Mulla, GULFMET President, United Arab Emirates, to visit the calculable capacitor and the watt balance, 19 March.

• L. Caglioni and M. Kliebenschädel, Mettler-Toledo, Greifensee (Switzerland), to install the Artefact Transfer Device, 20-22 April.

• Mr Fernando Ferrer Margaleff and Mr Angel Robles Carbonell (CEM), to discuss the outcome of the Extraordinary Calibrations and to visit the watt balance, 23 April.

• Dr Sergio Zagier and Ms Claudia Urruty (Zagier&Urruty publications, Argentina) to visit the watt balance, 24 April.

• Mr Leon Chan (NIST), to visit the watt balance, 17 June.

• J. Pereira, Mettler-Toledo, Viroflay (France), to visit the mass laboratories, 24 June.

• Group of 30 visitors from KASTO (Korean Association of Standards and Testing Organization), Republic of Korea, to visit the electricity and mass laboratories, 29 June.

• Dr Wynand Louw (NMISA), to visit the watt balance 15 July.

• Mr Seog Hwan Hong and Dr Jookeun Park (KRISS), to visit the watt balance, 20 July.

• Group of NMI Public Relations experts to visit the watt balance, 21 July.

• Mr Ilya Victorov (INPL), to visit the watt balance, 24 July.

• S. Cantelou, Mettler-Toledo, Viroflay (France), to visit the mass laboratories, 29 July.

• Working Group CCTF-WGTWSTFT, to visit the watt balance, 8 September.
• Group of five scientists (KIM-LIPI), for a laboratory tour including the fabrication of mass standards, 9 September.
• Dr Ricardo José De Carvalho and Msc Hamilce Simas Iozzi Coda Santos (ON/DSHO), to visit the watt balance, 14 September.
• Dr Chiharu Urano (NMIJ), to visit the watt balance, 17 September.
• Ms Chanqing Cai and Dr Jiang Wang (NIM), to visit the watt balance, 22 September.
• R. Farley, S. Wettstein, MBW, Wettingen (Switzerland) and E. Georgin, CETIAT, Lyon (France), to visit the mass laboratories, 23 September.
• Dr Paul Gale (Vatican Observatory), to visit the watt balance, 5 October.
• Khosro Madanipour (President NMCI), Ahad Mohammadi Livari (Deputy), Omidali Masoudi (General Director Public and international relations), NMCI(ISIRI), Iran, for a laboratory tour including the mass and electricity laboratories, 23 October.
• Mr Thomas Mautjana (NMISA), to visit the watt balance, 13 November.
• R. Sukhon (NIMT), to have a training session on mass metrology and to collect prototype No. 80 and one 1 kg mass standard in stainless steel, 1-2 December.
• Mr Sylvain Lucas and Mr Yann Moysan (SHOM), to carry out gravimetric measurements in the watt balance laboratory, 1-2 December.
• Dr Eran Tal, Univ. of Cambridge, to discuss the philosophical aspects of the redefinition of the kilogram, 7 December.
• Mr Alfredo Esparza (CENAM) and Mr Jorge Arturo Arzate Flores (National Autonomous University of Mexico, UNAM), to visit the watt balance, 14 December.
• 38 visitors to deliver and to collect mass standards, at the BIPM for calibration.