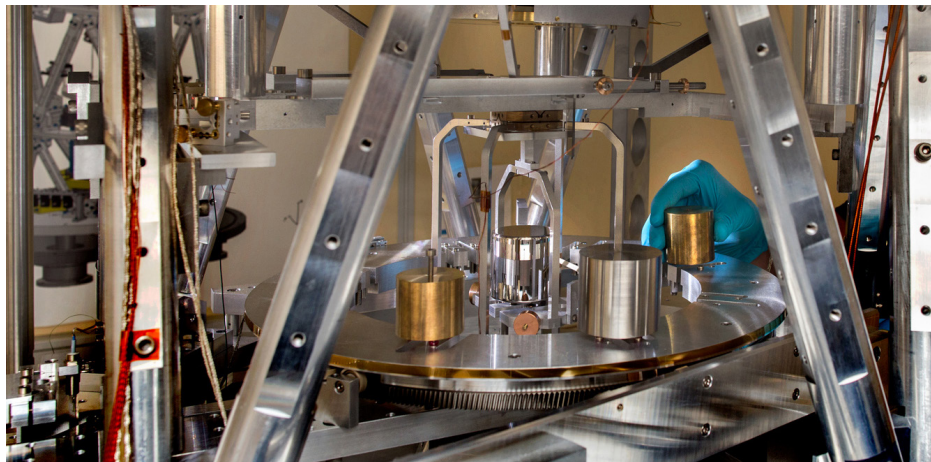




The BIPM

The BIPM is an intergovernmental organization established by the Metre Convention, through which Member States act together on matters related to measurement science and measurement standards.

THE VISION AND MISSION OF THE BIPM

Its **vision** is to be universally recognized as the world focus for the international system of measurement.

Its **mission** is to work with the NMIs of its Member States, the RMOs and strategic partners world-wide and to use its international and impartial status to promote and advance the global comparability of measurements for:

- Scientific discovery and innovation,
- Industrial manufacturing and international trade,
- Improving the quality of life and sustaining the global environment.

THE OBJECTIVES OF THE BIPM

- To represent the world-wide measurement community, aiming to maximize its uptake and impact.
- To be a centre for scientific and technical collaboration between Member States, providing capabilities for international measurement comparisons on a shared-cost basis.
- To be the coordinator of the world-wide measurement system, ensuring it gives comparable and internationally accepted measurement results.

Fulfilling the BIPM mission and objectives is complemented by its work in:

- Capacity building, which aims to achieve a global balance between the metrology capabilities in Member States,
- Knowledge transfer, which ensures that the work of the BIPM has the greatest impact.

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Director's introduction

I am delighted to report here on the highlights of 2018, which were particularly focused around the decisions taken by the Member States at the 26th meeting of the CGPM.

The decision that received most attention was Resolution 1 which agreed new definitions for the SI units. This resolution taken by the CGPM was the outcome of many years of work in NMIs around the world and much coordination activity carried out by BIPM staff. Additionally, the CGPM passed Resolution 3 which confirmed the objectives of the BIPM; these are summarized on the inside cover page of this report.

The CGPM also marked the retirement of six members of the CIPM including Dr Barry Inglis who has served as President of the CIPM for the last nine years. The 18 members of the CIPM elected at the meeting subsequently elected Dr Wynand Louw to serve as the President of the CIPM. (The full list of members of the CIPM is given on page 17 of this report)

There have been a number of highlights amongst the work in the BIPM laboratories during 2018 including:



The handover of one of the keys to the caveau from the outgoing CIPM President, Dr Barry Inglis (right) to the incoming President, Dr Wynand Louw (left).

Highlights in the BIPM laboratories during 2018:

- The first comparison of new capabilities developed by participants in the BIPM's Metrology for Safe Food and Feed Capacity Building has been completed, confirming the impact of the activities.
- The first series of BIPM's standard reference documents for quantitative NMR, have been published in collaboration with NMJ and other NMIs, to underpin the value assignment of organic primary reference materials at NMIs.
- The BIPM Kibble balance has been operating reliably under vacuum with an uncertainty of 8 parts in 10^8 , and participation in the first CCM key comparison of kilogram realizations is now confirmed.
- BIPM has completed the first key comparison in electrical metrology organized in the "star" configuration, which will serve as a model for future comparisons in the area.
- Results from a new Yb lattice clock at NIST have been used to steer the frequency of the International Atomic Time (TAI) scale. Optical frequency standards developed at SYRTE in France and NICT in Japan are now all contributing to TAI.
- The BIPM has contributed to work by the International Commission on Radiation Units and Measurements (ICRU) to revise the key data for ionizing radiation dosimetry which represent the biggest improvement in dosimetry standards in two decades.
- The BIPM has updated its comparison and calibration services to incorporate the new data and is working closely with the CCRI to promulgate the change world-wide.
- A joint Workshop was organized to review new technologies for low electrical current measurement in radionuclide metrology. A new Task Group has been formed that will work with BIPM staff and NMIs to validate methods for the next generation of instruments

This report includes summaries of the BIPM financial performance, and complements the Rapport Financier and the annual proceedings of the CIPM (both of which are available in French and English). All of these documents can be downloaded from our website.

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.^[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 XRCd 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.^[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*^[5]. The final report on the pilot comparison of future realizations of the kilogram has been published^[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 $1\ \Omega$, $100\ \Omega$ and $10\text{ k}\Omega$. The measurands are the value of the $100\ \Omega$ 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 10^9 . The observation made during previous comparisons that the value of the $1\ \Omega$ 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 NMIJ^[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 10^6 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 NMIs 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_K 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.

Time

Improvement and development of time transfer techniques

Most of the Time Department's research work in 2018 was devoted to the improvement and development of time transfer techniques in the computation of Coordinated Universal Time (UTC), its rapid approximation UTCr, and the contribution to the key comparison CCTF-K001.UTC. The introduction of clocks and frequency standards in UTC is based on the measures obtained by comparing clocks located in different laboratories, and these measures carry the most important uncertainty contribution.

GNSS activities

Global Navigation Satellite Systems (GNSS) activities were focused on testing the new Chinese Beidou and European Galileo systems. These activities have benefited from collaboration with NIM (China), which has installed Beidou receivers at the BIPM that will be used for testing^[9, 10]. As the Beidou constellation includes satellites in both geostationary and inclined geosynchronous orbit, a more refined data analysis is necessary, particularly for the benefit of the use, *a posteriori*, of precise orbits and clocks. The first results with the Galileo system have demonstrated very good stability, including with real-time broadcast parameters. The results were discussed at a dedicated workshop organized by the CCTF Working Group on GNSS Time Transfer (CCTF-WGGNSS) and will be presented at future international congresses.

Ongoing IPPP research

Research is continuing, in collaboration with the CNRS (France), on the use of Integer Precise Point Positioning (IPPP) as an improved treatment of the GNSS carrier phase measures to avoid cycle slips that degrade the stability of the time transfer solution^[11, 12].

GNSS calibration campaigns

The GNSS calibration campaigns, in collaboration with the RMOs, are progressing as expected; the aim is to visit G1 laboratories in each RMO every two years. Two new GNSS calibration campaigns have been carried out using the BIPM travelling apparatus, in the Russian Federation and another in Asia, visiting three different G1 laboratories. A calibration report will be published. Results of GNSS calibrations are available on the BIPM website.

Use of the SDR in TWSTFT

The department's work on Two-Way Satellite Time and Frequency Transfer (TWSTFT) has been devoted to the use of the Software Defined Radio (SDR) receiver, which has been evaluated in collaboration with the NMIs. The SDR receiving chain is now used as an "alternative" (back up) solution in the computation of UTC.^[13, 14] The results appear

on the link comparison, which is regularly published on the Time Department FTP server in collaboration with OP SYRTE (France). To support the further development of the SDR technique to allow, for example, calibration, transmission, and testing on other codes, the BIPM, in cooperation with the CCTF Working Group on TWSTFT, has created a platform running GitLab for collaborative open source code development. A task group has been created to validate the different versions of the software and to provide a convenient and secure method for its download to NMIs.

Future calibration of TWSTFT links

The Time Department is working, in collaboration with the OP SYRTE, on the preparation of a calibration travelling box, which aims to calibrate the TWSTFT links by means of GNSS receivers and a carefully designed measurement chain. The goal is to achieve a calibration uncertainty of the order of 1 ns, which could be used when the traditional TWSTFT mobile calibrating station is not available or is not suitable.

High-accuracy microwave link for use in UTC

The BIPM has started working with the Working Group for the exploitation of the Atomic Clock Ensemble in Space (ACES) experiment^[15] on the International Space Station (ISS) with the aim of studying a high-accuracy microwave link for possible future use in UTC.

The role of primary and secondary frequency standards in UTC

To ensure the accuracy of UTC the role of primary and secondary frequency standards is fundamental. The Department is observing the development in the NMIs and supporting the introduction of optical frequency measurements in UTC.^[16, 17, 18] Since November 2018 secondary representations of the second based on optical frequency standards have been used in steering the frequency of International Atomic Time (TAI). Optical secondary frequency standards developed at SYRTE (France) and NICT (Japan), based on a Sr lattice, have been providing data since 2017 and 2018, respectively. In 2018, NIST started contributing to the steering of TAI with its ytterbium lattice standard. In addition the Time Department is exploring the use of frequency standards for applications in geodesy and gravity field determination.^[19, 20] A workshop on relativistic geodesy was held at the BIPM in association with the International Association of Geodesy (IAG) on 10-11 October 2018.

Ionizing Radiation

Provision and development of comparison and calibration services

The work in the Ionizing Radiation Department in 2018 continued to focus on the provision and development of comparison and calibration services. These centralized services reduce the need for NMIs to pilot large-scale comparison exercises and also minimize the transport of hazardous materials or fragile instrumentation. The services form the basis of an established and robust measurement infrastructure in a field that impacts cancer therapy, medical imaging, safety of radiation workers, medical device sterilization, and environmental protection. Comparisons have continued for radiation dosimetry and radionuclide metrology, with six NMIs participating in a total of ten comparison exercises. Fifteen calibrations were also carried out for three NMIs in radiation dosimetry.

Updated data for dosimetry primary standards

All dosimetry primary standards require key physical data and correction factors that are based on published international recommendations. These data have recently been updated to incorporate recent studies and the adoption of these data is the biggest improvement in radiation dosimetry standards in two decades. The changes will affect the results from comparisons and calibrations and will also impact published CMCs. The BIPM has been working closely with the CCRI to promulgate the change world-wide; the changes to the BIPM's own standards have been published^[21] and came into effect on 1 January 2019.

Further development of the primary standards for the high-energy photon radiotherapy comparison service

A highlight for the department in 2018 has been the further development of the comparison service for primary standards for high-energy photon radiotherapy, based at the DOSEO research centre at Gif-sur-Yvette, France. Comparisons were completed for the KRISS (Republic of Korea) and METAS (Switzerland) and a procedure has been developed to reduce the measurement uncertainties due to small instabilities in the beam. In addition, a new project has started in collaboration with the LNHB (France) with help from a secondee from the NRC (Canada) to investigate the possible impact of variations on instrument calibration due to differences in photon spectrum between different models of accelerators.

Updating and replacement of facilities

The department's work has been affected by the increasingly stringent regulations on the use of sealed radioactive sources. The ^{137}Cs and ^{60}Co irradiators used for comparisons and calibrations for radiation protection standards have had to be closed; a project is under way to re-establish the former service in 2019 using the

^{137}Cs beam at the IAEA Laboratory in Austria. An older therapy-level ^{60}Co irradiator was also decommissioned and services were successfully transferred to a newer irradiator. For the same reason, a project has started with the IRA (Switzerland), the NPL (UK), the LNHB (France) and Triskem International to replace radium sources needed for radionuclide metrology; a suitable radionuclide ($^{166\text{m}}\text{Ho}$) has been identified and source preparation is under way.

The International Reference System (SIR)

The international system for radionuclide metrology relies on a set of stable and reproducible specialist instruments. The International Reference System (SIR) is used to compare activity standards of long-lived gamma-ray emitting radionuclides, and was used to compare standards of ^{223}Ra and ^{65}Zn during 2018. This instrument, which is not suitable for short-lived radionuclides, is complemented by a transportable version (the SIRTII) that is used on site at NMIs. It was agreed with the Key Comparisons Working Group (CCRI(II)-KCWG(III)) that the SIRTII instrument will now be calibrated at the BIPM for additional radionuclides (^{56}Mn , ^{153}Sm , ^{166}Ho , ^{123}I) to prepare for a more efficient approach to organizing comparisons. An international consortium of the LNHB (France), POLATOM (Poland), PTB (Germany) and NPL (UK) is working with the BIPM to develop a third instrument for comparing standards of pure beta-emitting radionuclides; a specialist instrument has been commissioned and studies are under way to establish the reproducibility of measurements.

Future-proofing the SIR

A long-term aim within the Ionizing Radiation Department is to future-proof the SIR by reducing the number of radium sources needed from five to one. Five are currently needed because the linearity of the measurements in ionizing chambers is not as precise as required. It is expected that this goal will be achieved by using new electrical current measurement technology.

Following discussions with NIST and members of the Consultative Committee for Electricity and Magnetism (CCEM), a preliminary workshop was held at NIST in September 2018 to discuss the options and to plan the next stages. Following the workshop, it was agreed that a project will start with the PTB (Germany) in 2019 to study the use of Ultra-stable Low Current Amplifiers.

It is hoped that this technology can be rolled-out to the NMIs if the project is successful.

Chemistry

Fifteen visiting scientists from NMIs participated in the Chemistry Department Programme in 2018. Six comparisons were run by the department in this period, involving eighty participations by NMIs in these studies. The Capacity Building and Knowledge Transfer (CBKT) programmes for “Metrology for Clean Air” and “Safe Food and Feed” continued, attracting seven of the fifteen visiting scientists from NMIs, who spent between three months and one year at the BIPM.

Launch of qNMR Internal Standard Reference Data

The BIPM has published a set of reference data to support laboratories world-wide that use quantitative Nuclear Magnetic Resonance (qNMR) for the purity assignment of organic compounds, thereby aiding the development of primary reference materials for SI traceable calibration hierarchies in organic analysis as well as Reference Standards and assays for pharmaceutical laboratories. The “qNMR Internal Standard Reference Data” documents were developed as part of a BIPM-NMIJ (Japan) collaboration together with visiting scientists from NIM (China), INMETRO (Brazil) and UME (Turkey) at the BIPM.

The publications cover a set of seven “universal calibrators” for qNMR, identified by the NMIJ and the BIPM as being able to serve as an ensemble of internal standards that would enable purity assignment measurements by proton qNMR of the vast majority of organic analyte/solvent combinations.

The seven standards that make up the qNMR universal calibrator set are:

- maleic acid
- dimethyl sulfone
- potassium hydrogen phthalate
- 3,5-bis(trifluoromethyl) benzoic acid
- dimethyl terephthalate
- 1,4-bis(trimethylsilyl)benzene
- 3-trimethylsilyl propanesulfonic acid sodium salt-d6

The development and publication of the documents were presented by the BIPM during an invited lecture on the “Role and Use of Reference Materials to underpin SI-Traceable measurements for qNMR” at the qNMR Summit 2018 in Tokyo on 29–30 January 2018.

Metrology for Clean Air

Three visiting scientists from the NPLI (India), NMISA (South Africa) and KazInMetr (Kazakhstan) undertook the Metrology for Clean Air Course on FTIR Measurements on Gas Standards (NO₂, HCHO, HNO₃, CO₂) in the BIPM laboratories. They received training in the use of B-FOS software for use with Fourier Transform Infrared (FTIR) in gas metrology applications; the software was made available later for use within the participating NMIs. Short training courses on the use of B-FOS FTIR software were also provided to visiting scientists from NMIJ (Japan) and PTB (Germany).

Metrology for Safe Food and Feed

The third meeting for the CBKT programme on “Metrology for Safe Food and Feed”, focusing on mycotoxin metrology and standards, was held at the BIPM in April 2018. The laboratory programme on mycotoxin standards was supported by three visiting scientists from NIM (China) working on related structure impurity analysis, calibration solution characterization, and qNMR for aflatoxin B1 and deoxynivalenol materials, as well as a visiting scientist from UME (Turkey) characterizing pure patulin material. In addition, two visiting scientists from UME and NMISA undertook three-month training secondments on non-related structure impurity quantification in mycotoxin pure materials. Stock solutions of zearalanone have been provided to all NMIs that have participated in the programme to date (KEBS, INTI, NMISA, NIMT, INMETRO, UME). The first key comparison (CCQM-K154.a) on mycotoxin calibration solutions was launched in the last quarter of 2018. NMI-prepared calibration solutions underwent comparison measurements at the BIPM in December 2018, with ten NMIs participating. A paper summarizing the mycotoxin standard preparation and validation was published.^[22]

Small organic primary calibrator programme

The final report of the CCQM-K55.d comparison on folic acid purity was published and the final report for the CCQM-K78.a comparison on multi-component amino acid calibration solutions was completed and circulated to the CCQM for approval in November 2018. Samples for the CCQM-K148.a comparison (bisphenol A calibrator purity) were distributed, with 20 NMIs participating, and results were submitted to the BIPM in February 2019.

Peptide and protein primary standard comparisons

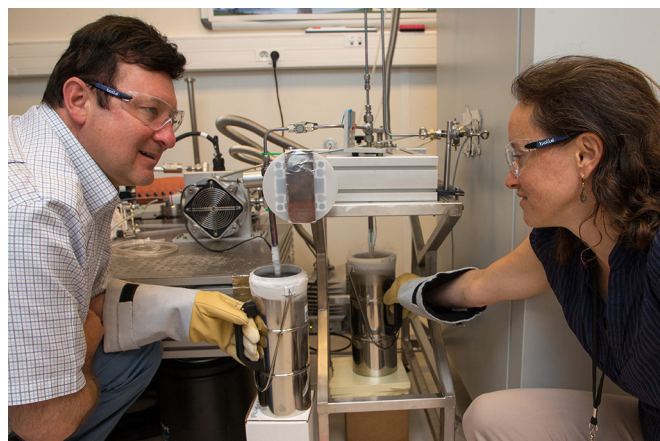
Support for the CCQM programme of peptide and protein primary standard comparisons continued. Preparative work for the comparison on oxytocin (CCQM-K155.b) was completed in collaboration with NIM (China) and with the secondment of a visiting scientist from NIM. Samples for the comparison have been distributed with results to be submitted to the BIPM by the end of December 2018. There are 12 participant NMIs in this comparison. Characterization work on pure hexapeptides of HbA1c for comparisons on the HbA1c glycated hexapeptide (GE), for CCQM-K115.c, and the non-glycated hexapeptide (VE), for CCQM-K115.2019, have continued with the support of a visiting scientist from NIMT (Thailand), and in collaboration with HSA (Singapore), LNE (France) and NIM. Methods developed for pure peptide characterization were published in *Analytical and Bioanalytical Chemistry*^[23] and an invited review paper.^[24]

Air quality measurement standards

In the area of air quality measurement standards, the BIPM continued to contribute to the CCQM Working Group on Gas Analysis (CCQM-GAWG) Ozone Cross Section Task Group. A paper summarizing the recommended best value and uncertainty for the ozone cross-section to be used in the key comparison BIPM.QM-K1 was submitted to *Metrologia*. Three NMIs: FMI (Finland), NILU (Norway) and NPLI (India) sent their ozone standards to the BIPM and participated in BIPM.QM-K1, with a report^[25] of the comparison being published. One calibration of an ozone standard was performed for NILU. Collaboration with the NIST (USA) on the upgrade of the electronic module for the Ozone Standard Reference Photometer (SRP) continued. The 2018 version of the prototype electronics module was successfully constructed and tested at the BIPM; the operating software is being developed by NIST. The Draft A report of CCQM-K137 (NO in N₂ at 30 µmol/mol and 70 µmol/mol) was completed and the key comparison reference value (KCRV) was agreed by the CCQM-GAWG in October 2018. Measurements at the BIPM for the comparison of NO₂ in N₂ standards at 10 µmol/mol (CCQM-K74.2018) and the pilot study of HNO₃ measurements in such standards (CCQM-P172) have started with 33 participating NMIs.

Greenhouse gas standards

In the area of greenhouse gas standards, the final report of the CO₂ in air standards comparison CCQM-K120 has been published. The comparison demonstrated a reduction in the reference value uncertainty by a factor of four compared to comparisons performed previously. In addition, it demonstrated the improvements in the accuracy of standards and comparison methods that can now be achieved. The BIPM's CO₂ PVT primary system, which is based on manometry, was compared in the pilot study CCQM-P188, which was performed in parallel to the key comparison. Good agreement was observed with this method at levels of uncertainty equivalent to those that can be achieved using gravimetric methods. The development and validation of a manometric system for CO₂ measurements, in support of a future planned ongoing comparison of CO₂ standards (BIPM.QM-K2), has progressed with a second secondment from the NIST. Development work will continue, with characterization of adsorption and trace gas effects as well as automation of the system planned. Preparation for a comparison on CO₂ isotope ratio standards, coordinated jointly by the BIPM and the International Atomic Energy Agency (IAEA) continued, with an isotope ratio infrared spectrometer (IRIS) system for isotope ratio measurements integrated into the SIRM-GEN facility. The first blending experiments for CO₂ gases have been carried out with support from visiting scientists from INRIM (Italy) and VNIIM (Russia). Samples prepared at the BIPM were sent and measured at the IAEA. The NMJ has donated highly-characterized pure CO₂ gas to the BIPM to support the validation work that is being carried out. A review paper summarizing standards activities for greenhouse and air quality gases has been published.^[26] In addition, a review of SI traceable versus scale approaches for metrological traceability for greenhouse gas monitoring has been published.^[27]



The BIPM's CO₂ PVT system

International Liaison and Communication

The BIPM staff continued to work with the Organisation for Economic Cooperation and Development (OECD). Collaboration in the OECD *“Partnership for effective international rule-making”* should help to ensure that the role of the world metrology system activities and structures are recognized as a critical part of the quality infrastructure (QI). Particular focus has been given to ensuring that metrology is seen as one of the key elements underpinning the so called ‘Rule-Based International System’. The BIPM is one of many international organizations that enables transnational issues to be effectively addressed.

2018 saw the re-launch and expansion of the DCMAS Network; it is now known as the International Network on Quality Infrastructure (INetQI). Its role is to bring together specialized organizations that operate at an international level and are active in promoting and implementing activities in metrology, accreditation, standardization and conformity assessment as tools for sustainable economic development. The BIPM, IAF, ILAC, IEC, ISO, ITC, ITU, OIML, UNECE and UNIDO† have been joined by the World Bank Group and World Trade Organization (WTO), and work has progressed on revising the terms of reference.

In the context of the above, the BIPM and others contributed to the UNIDO initiative and subsequent publication ‘*Quality Policy Guiding Principles*’, aimed at facilitating the effective implementation of QI in developing countries. Following the publication of ISO/IEC 17025:2017 in late 2017, and its referencing in that standard, the ‘*Joint BIPM, OIML, ILAC and ISO declaration on metrological traceability*’ was updated and re-signed by the four parties on the occasion of the 26th meeting of the CGPM (2018).

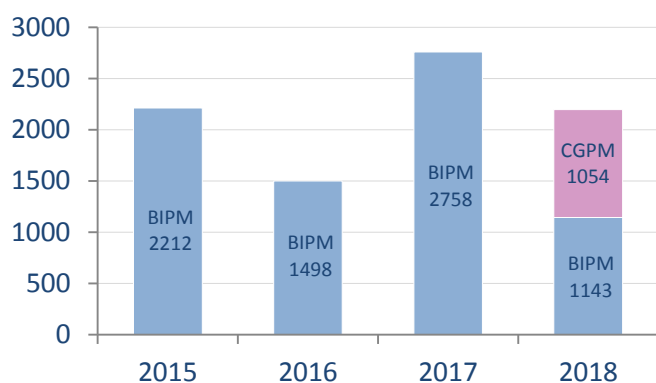
BIPM staff continue to alert the WTO of the importance to its mission of the world-wide metrology system and the comparability of measurements, by attending and delivering reports to the WTO Committee on Technical Barriers to trade, and associated meetings.

In anticipation of the revision of the SI at the 26th meeting of the CGPM in November 2018, the joint BIPM–OIML World Metrology Day 2018 focused on the expected changes from the SI revision and launched an international awareness campaign. In addition to World Metrology Day, BIPM staff work ever more closely with the OIML and the International Bureau of Legal Metrology (BIML) to ensure a consistent message is broadcast from the metrology community to the wider world.

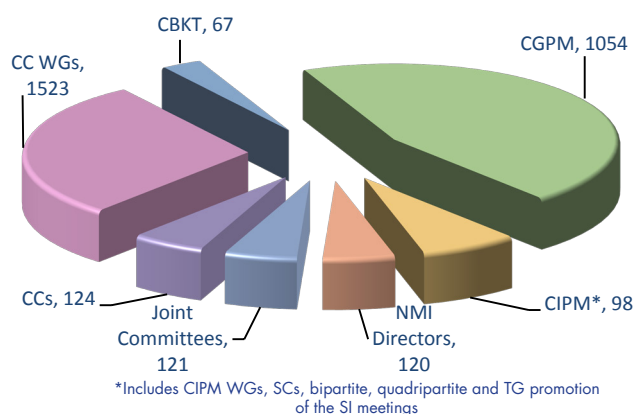
Early stage activities have been undertaken with the United Nations Educational, Scientific and Cultural Organization (UNESCO) to renew the relationship, which dates back to the 1949, but which has been dormant in recent years. A number of ideas for collaboration were explored, and will be progressed in 2019.

Meetings

Attendance at meetings hosted at the BIPM



Meeting attendance at the BIPM in 2018



†International Accreditation Forum (IAF), International Laboratory Accreditation Cooperation (ILAC), International Electrotechnical Commission (IEC), International Organisation for Standardisation (ISO), International Trade Centre (ITC), International Telecommunications Union (ITU), International Organization of Legal Metrology (OIML), United Nations Economic Commission for Europe (UNECE) and United Nations International Development Organisation (UNIDO).

Capacity Building and Knowledge Transfer

2018 proved to be another highly successful year for the CBKT programme. Following the 26th meeting of the CGPM, the programme is now partially funded from the BIPM dotation. The success of the CBKT programme can be demonstrated through a range of measurable outcomes. In particular, the target to increase the efficiency of the CIPM MRA, which resulted from the review of the MRA as well as being a goal for capacity building activities, has been achieved. Data on the delay in reviewing CMCs shows that there has been a 10 % increase in CMC review performance since the CBKT programme was launched.

Effective participation in Coordinated Universal Time (UTC)

13 to 14 February 2018 at the BIPM

Twenty-one participants from 21 countries completed the two-day course, which was sponsored by METAS (Switzerland). The course was designed to provide the necessary support to institutes to improve their contributions to the computation of UTC through participation to BIPM *Circular T* and the key comparison CCTF-K001.UTC. The main objective of the course was to instruct participants in the calibration of their GPS time transfer equipment, since this is the major source of uncertainty.

Sound beginning in the CIPM MRA

Two one-day "Sound beginning in the CIPM MRA" workshops were organized as part of the BIPM's ongoing series of joint initiatives with the Regional Metrology Organizations (RMOs). These workshops are aimed at staff from NMIs that have signed the CIPM MRA but have not yet submitted CMCs or are at an early stage in the process. The training is intended to help these NMIs achieve 'right first time' submissions into the CMC peer review system. This will help optimize NMI success rates and minimize the burden on the wider community that conducts reviews.

A one-day workshop was held in Bosnia and Herzegovina on 10 April 2018. The BIPM-COOMET "Sound beginning in the CIPM MRA" Workshop was hosted by IMBH (Bosnia and Herzegovina) and was attended by 27 participants from 14 countries.

A one-day workshop was also held during the 12th Intra-Africa Metrology System (AFRIMETS) General Assembly on 18 July 2018 in Enugu, Nigeria. The workshop was open to all members of AFRIMETS. Fifty-three participants from 14 African countries attended the workshop.

"Train the trainer": transitioning to ISO/IEC 17025:2017 in the CIPM MRA

23 to 24 May 2018 at the BIPM

This two-day course, organized by the BIPM and sponsored by METAS, was attended by 23 participants from 17 countries. It was taught by expert lecturers, who had been involved in the revision of the standard of the global quality infrastructure, particularly regarding the role of international organizations. The aim of the "Train the trainer" course was to assist RMOs in the implementation of ISO/IEC 17025:2017 and its application to the CIPM MRA.



The twenty-three "trainers" having completed the course.

The CIPM MRA

The CIPM Mutual Recognition Arrangement (CIPM MRA) is the framework through which NMIs demonstrate the international equivalence of their measurement standards and the calibration and measurement certificates they issue. The outcomes of the Arrangement are the internationally recognized (peer-reviewed and approved) Calibration and Measurement Capabilities (CMCs) of the participating institutes. Approved CMCs and supporting technical data are publicly available from the BIPM key comparison database (the KCDB). After almost two decades of successful operation, the CIPM MRA is being reviewed to ensure its sustainability for the future. Following a recommendation by the Working Group on the Implementation and Operation of the CIPM MRA that the KCDB be revised, work on the updated KCDB is well under way: a collaborative web platform for editing and reviewing CMCs as well as extended search facilities are being developed.

Key and supplementary comparisons

In December 2018, the key and supplementary comparisons database included 1 015 key comparisons and 560 supplementary comparisons. This represents an increase of 26 key comparisons on the previous year, while supplementary comparisons increased by 31. Around 70 comparisons were completed and published during 2018. Today, almost 90 % of the 89 ongoing BIPM key comparisons and around 70 % of all registered comparisons of the Consultative Committees and RMOs have results published in the KCDB. Almost all Associates participating in the CIPM MRA had at least one of their metrology institutes listed as a participant in a key or a supplementary comparison.

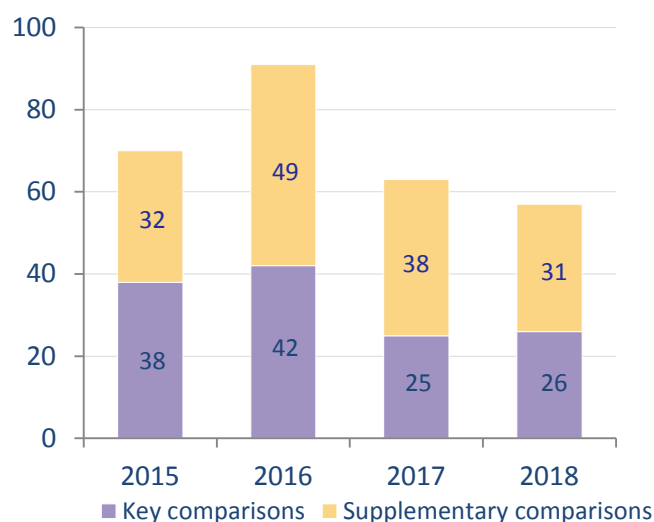
The KCDB currently includes a dozen examples where more than seven key comparisons are linked together.

Calibration and Measurement Capabilities

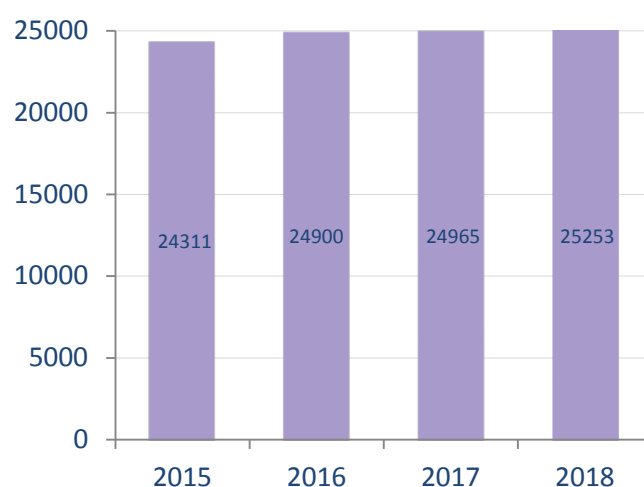
On 31 December 2018, there were 25 253 CMCs registered in the KCDB. Of these, 14 916 were in the field of general physics, 3 925 in ionizing radiation, and 6 412 in chemistry. The total number of CMCs increased by 288 during 2018. Twenty-three of the 42 Associates that participate in the CIPM MRA had CMCs published in the KCDB at the end of 2018.

It is possible to temporarily withdraw CMCs from the database by "greying out". At the end of 2018, 411 CMCs were "greyed out", a slight increase from 2017. However, only ten were definitively deleted from the KCDB during 2018, either as a result of a request from the corresponding NMI, or due to the lack of a QMS. This is a negligible number when compared to the total number of registered CMCs.

Number of new comparisons registered in the KCDB



Total number of CMCs registered at 31st December



Revised SI and the 26th CGPM meeting

26th meeting of the CGPM

The 26th meeting of the General Conference on Weights and Measures (CGPM) was held from 13 to 16 November 2018 in Versailles. Reports were given by the Presidents of the ten Consultative Committees of the CIPM and there was a full programme of presentations by invited speakers. The conference included an open session on the morning of Friday 16 November to coincide with the historic vote on the revision of the SI. The open session was attended by 700 people and was broadcast online to an audience of almost 27 000.



Four keynote lectures were given during the open session:

- **Prof. Klaus von Klitzing** (Nobel laureate) *"The quantum Hall effect and the revised SI"*
- **Dr Jean-Philippe Uzan** *"The role of the Planck constant in physics"*
- **Dr Jun Ye** *"Optical atomic clocks - opening new perspectives on the quantum world"*
- **Prof. William Phillips** (Nobel laureate) *"Measuring with fundamental constants; how the revised SI will work"*

Please see the BIPM website for the full text of the five resolutions that were adopted at the 26th meeting of the CGPM (2018)



The delegation from the Republic of Korea celebrate following the historic vote on Resolution 1.

Revision of the SI

In a historic decision, representatives from 54 Member States voted on 16 November 2018 to revise the International System of Units (SI), changing the definitions of the kilogram, the ampere, the kelvin and the mole.

The decision, made at the 26th meeting of the General Conference on Weights and Measures (CGPM) in Versailles, France, means that all SI base units are now defined in terms of constants that describe the natural world. This will assure the future stability of the SI and open the opportunity to use new technologies, including quantum technologies, to implement the definitions.

The changes came into force on 20 May 2019. They brought to an end the use of physical artefacts to define measurement units. The International Prototype of the Kilogram (IPK), which has been used as the definition of the kilogram for almost 130 years, has now been retired. It has been replaced by a definition based on the Planck constant – the fundamental constant of quantum physics. The stability of the IPK could only be confirmed by comparisons with artefact copies; the Planck constant can be used "for all times, for all peoples", and its invariability can be relied upon.

The new definitions impact four of the seven base units of the SI: the kilogram, ampere, kelvin and mole; and all units derived from them, such as the volt, ohm and joule.

- **The kilogram is defined by the Planck constant (h)**
- **The ampere is defined by the elementary electrical charge (e)**
- **The kelvin is defined by the Boltzmann constant (k)**
- **The mole is defined by the Avogadro constant (N_A)**

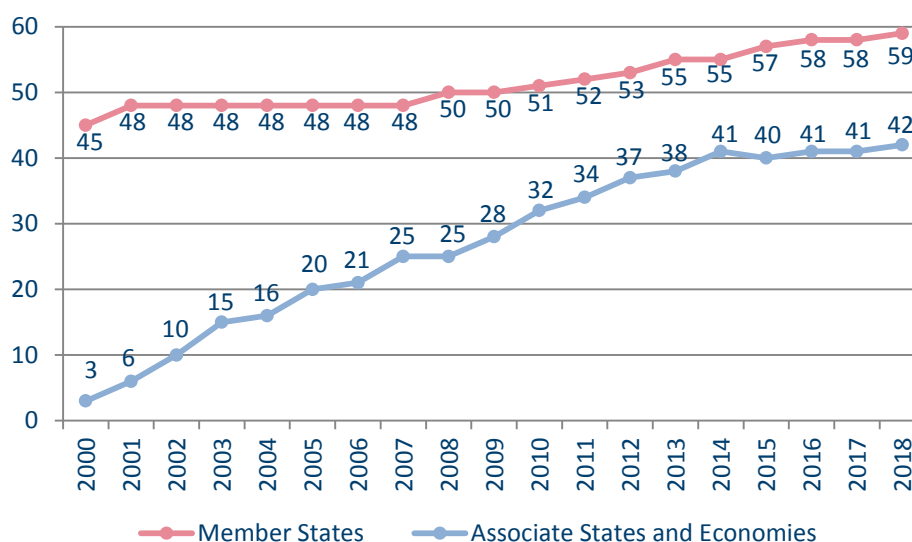
The revision of the SI was accompanied by an active promotional campaign. Hundreds of major articles were published in print, online, on the radio and television and it is estimated that the story reached a combined global audience of more than 2.1 billion people.

"The SI redefinition is a landmark moment in scientific progress. Using the fundamental constants we observe in nature as a foundation for important concepts such as mass and time means that we have a stable foundation from which to advance our scientific understanding, develop new technologies and address some of society's greatest challenges."

Dr Martin Milton, Director of the BIPM

Financial Summary

Growth in Member States and Associates (States and Economies) from 2000 to 2018



New Member States and Associates in 2018

New Member States:

Montenegro on 24 January (formerly an Associate since 2011)

Ukraine on 7 August (formerly an Associate since 2002)

New Associates of the CGPM:

The Federal Democratic Republic of Ethiopia on 1 January

United Republic of Tanzania on 1 January

The State of Kuwait on 23 March

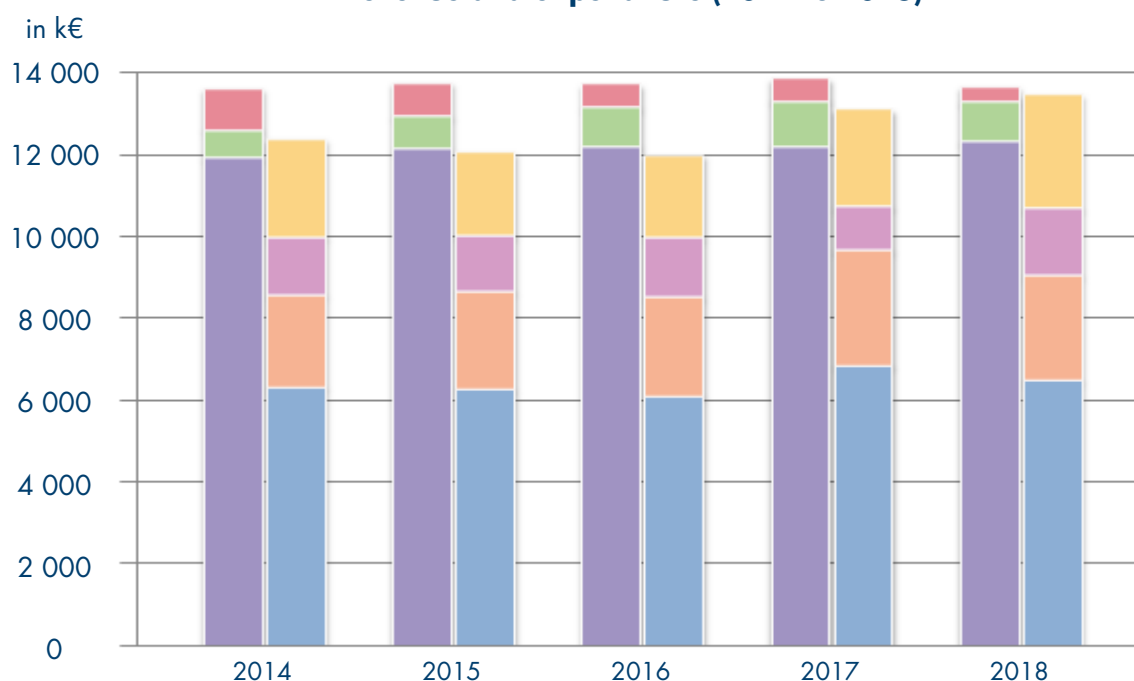
The Republic of Uzbekistan on 13 July

Key financial points

- Income from Member and Associate States followed forecast. During the year there was a significant reduction in outstanding contributions. In particular, just 56 687 € was outstanding for the preceding year (2017).
- Costs were controlled carefully; staff costs were down due to the continued careful management of salary costs which have now been decreased by 5.6 % since 2012.
- Operating costs increased by 411 k€ from 2017, notably because of the cost of the 26th meeting of the CGPM (176 k€).
- Capital spend was up by 580 k€ because of the start of two large IT projects and the arrival of a mass spectrometer for the chemistry department in 2018 that had been commissioned during 2017.
- The net result for the period was 901 k€ which is an increase of 156 k€ from that reported in 2017.

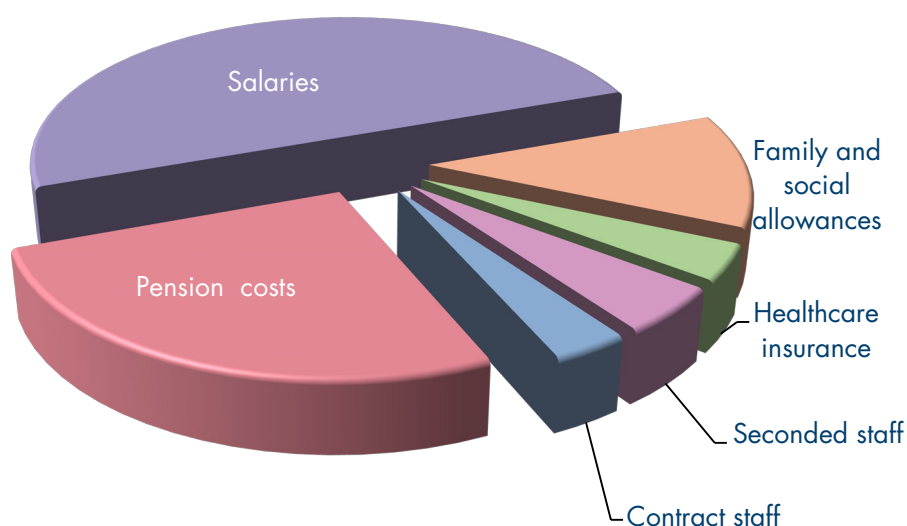
Financial Summary

Revenue and expenditure (2014 to 2018)



in k€	2014	2015	2016	2017	2018
Operating, laboratory and building expenditure	2 405	2 027	2 020	2 383	2 794
Capital spend	1 394	1 353	1 458	1 061	1 641
Contribution to the pension fund	2 251	2 400	2 400	2 800	2 550
Current staff cost	6 309	6 256	6 091	6 836	6 468
Other income	1 009	823	561	539	379
Subscriptions	702	790	955	1 116	967
Contributions	11 885	12 121	12 178	12 178	12 290

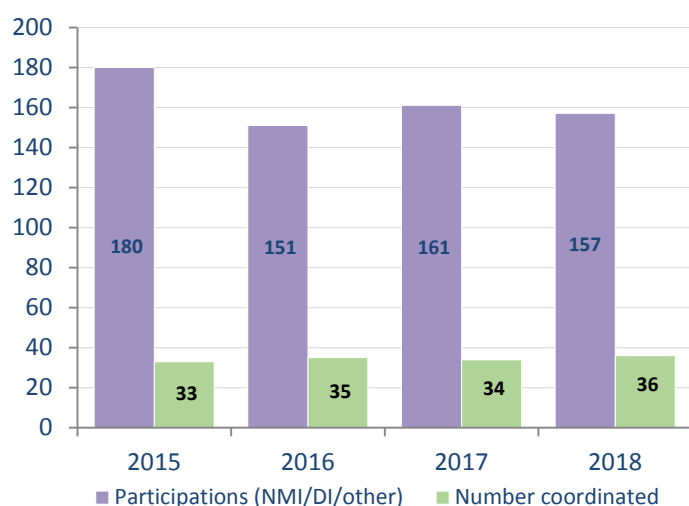
Staff and pension costs



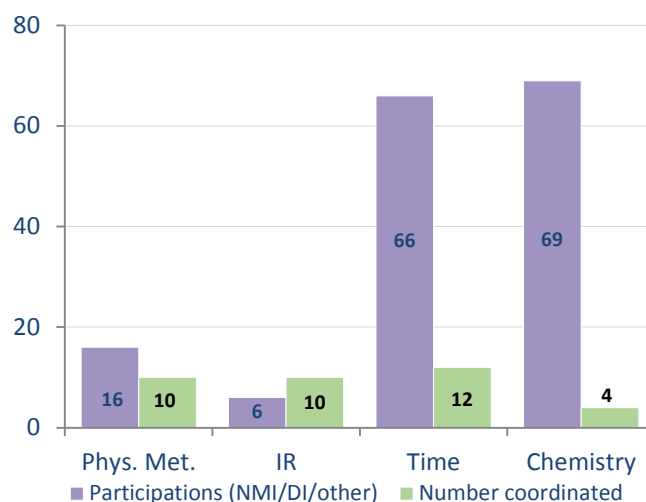
Full details of the financial and administrative situation of the BIPM are available in the “*Rapport Financier 2018*”:

Comparisons and Calibrations

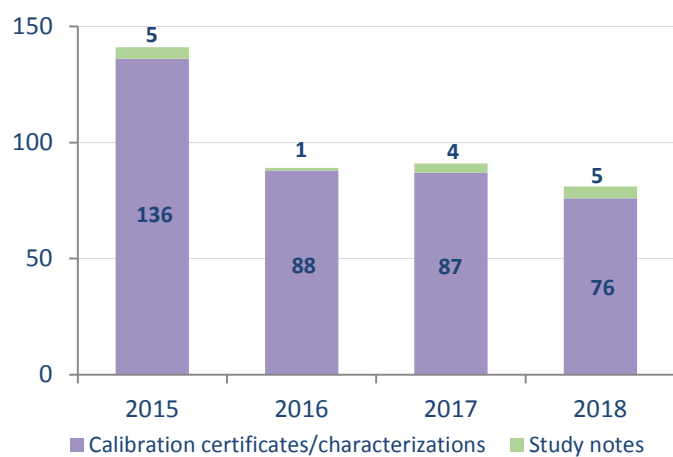
Comparisons coordinated by the BIPM laboratories



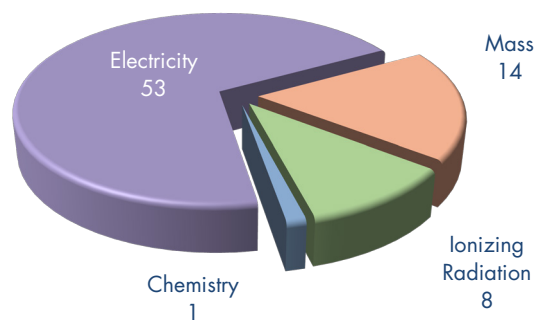
2018 – Breakdown by Department



Calibrations and Study Notes from the BIPM laboratories



2018 – Calibrations by metrology area



Organizational structure of the BIPM

The CIPM*

President

Dr W. Louw (South Africa)

Secretary

Dr T. Usuda (Japan)

Vice-Presidents

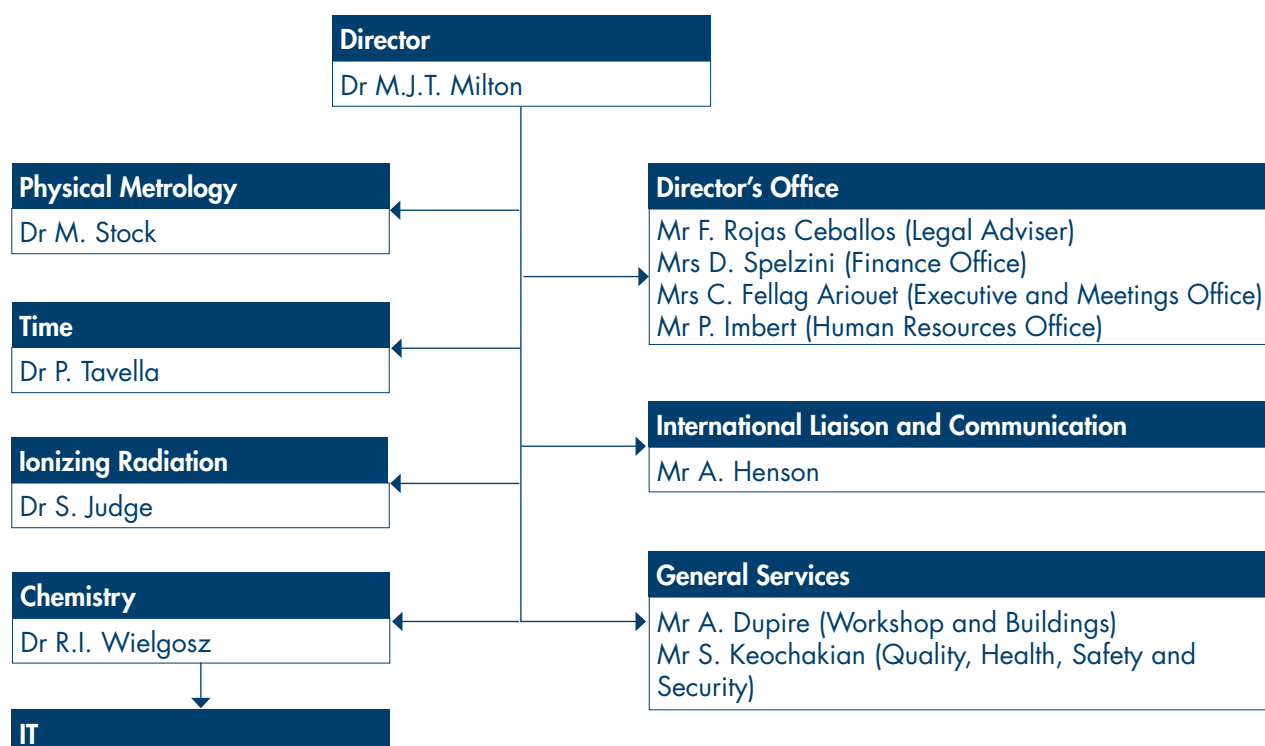
Dr J. Olthoff (United States of America)
Prof. J. Ullrich (Germany)

Other CIPM members

Dr F. Bulygin (Russian Federation)
Dr I. Castelazo (Mexico)
Dr D. del Campo Maldonado (Spain)
Dr Y. Duan (People's Republic of China)
Dr N. Dimarcq (France)
Dr H. Laiz (Argentina)
Dr T. Liew (Singapore)
Prof. P. Neyezhnikov (Ukraine)
Dr S.-R. Park (Republic of Korea)
Dr M.L. Rastello (Italy)
Dr P. Richard (Switzerland)
Dr G. Rietveld (Netherlands)
Dr M. Sené (United Kingdom)
Dr A. Steele (Canada)

*Elected on 16 November 2018

The BIPM staff



Publications

1. **Coil-current effect in Kibble balances: analysis, measurement, and optimization**
Metrologia, 2018, **55**(1), 75–83
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2. **Field analysis of a moving current-carrying coil in OMOP kibble balances**
Proc. 2018 International Applied Computational Electromagnetics Society Symposium (ACES), 2018
 Li S., Stock M., Bielsa F., Kiss A., Fang H.
3. **A new magnet design for future Kibble balances**
Metrologia, 2018, **55**(3), 319–325
 Li S., Stock M., Schlamminger S.
4. **On the proposed re-definition of the SI: “for all people for all time”**
Metrology: from Physics Fundamentals to Quality of Life, Eds. Tavella P., Milton M.J.T., Inguscio M., De Leo N.
 IOS Press, 187–201, ISBN 978-1-61499-817-4 (print) 978-1-61499-818-1 (online)
 Milton M.J.T.
5. **Maintaining and disseminating the kilogram following its redefinition**
Metrologia, 2017, **54**(6), S99–S107
 Stock M., Davidson S., Fang H., Milton M., de Mirandes E., Richard P., Sutton C.
6. **A comparison of future realizations of the kilogram**
Metrologia, 2018, **55**(1), T1–T7
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Metrologia, 2018, **55**(2), 302–313
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15. **Atomic clock ensemble in space (ACES) data analysis**
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Calibration
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