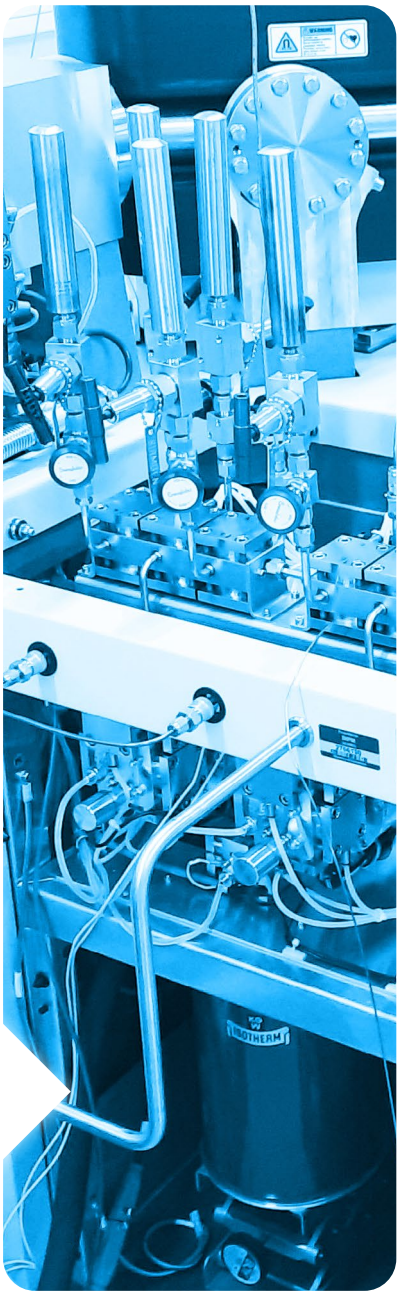
Bureau International des Poids et Mesures

Annual Review **2021/2022**



www.bipm.org

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.

Contents

Director's introduction

I am pleased to bring you the highlights of the BIPM laboratory, liaison and coordination work during 2021. A theme that now runs through the work of all our departments is the use of new digital methods to enhance our knowledge transfer and to provide new opportunities for coordination. These first steps towards a digital transformation of our work were triggered by the initiatives taken by the CIPM to develop an SI digital framework. This work was discussed and promoted at an on-line workshop on the "The International System of Units in FAIR digital data" (see p15).

The launch of our e-learning platform during the year has opened new opportunities for our capacity building and knowledge transfer activities (see p12). Already we are using this as a tool to share technical information and to complement the capacity building work in the laboratories (see p9). We have now opened the use of the e-learning platform to the RMOs for their own materials and courses.

Another new development in our collaboration activities during the year has been the development of a new collaborative model to share joint technical projects with NMIs. These projects are an effective way to build collaboration at a time when the secondee programme has been reduced because of travel restrictions.

I also want to highlight the launch of our first new digital service providing machine-readable access to our data bases. The first such service provides access to the CMC data in the KCDB (see p13). I hope it will be the trigger for our stakeholders to find new ways to use this data, for example, by underpinning future Digital Calibration Certificates (DCCs). We are already working on similar interfaces for the data used by the Consultative Committees to underpin the realization of the base units.

Throughout the year we have adapted our activities to work within the confinement measures imposed in France to control the global pandemic. Despite this we have been able to deliver the planned work programme with greatly increased participation in our meetings (see page 11) and in some of our technical activities such as the monthly calculation of UTC (see page 10).

Our financial performance in 2021 was again very sound as shown by the summary financial information in this report. (The full audited Financial Report is available on-line)[†]. Finally, I would like to thank all Member States and Associate States/Economies for your support at a time of growing financial uncertainty and I look forward to meeting you at the 27th meeting of the CGPM in November this year (please visit our website for full details).

Martin Milton
BIPM Director

[†]This report includes summaries of the BIPM financial performance, and complements the Financial Report and the Proceedings of the CIPM, which are available in French and English.

Physical Metrology

Mass

CCM consensus value

The first Consultative Committee for Mass and Related Quantities (CCM) consensus value was determined following the completion of the first key comparison of realizations of the new definition of the kilogram in 2020. It serves as the basis for an internationally coordinated dissemination of the kilogram. The CCM decided in its meeting in 2017 that until kilogram realizations made with different realization experiments (Kibble balances, X-ray-crystal-density (XRCD) experiments) agree within their respective uncertainties, the consensus value should serve as a common basis for the dissemination of the kilogram. It can be interpreted as an 'international mean kilogram' and is calculated from three sets of data: the key comparison reference value of the first key comparison, the reference value of the CCM pilot comparison in 2016 and data from the latest use of the International Prototype of the Kilogram (IPK) in 2014. The mass of the IPK, which was exactly 1 kg before the revision of the SI, is 1 kg – 2 µg based on the consensus value, with an uncertainty of 20 µg[1]. Since the difference between mass values based on the consensus value and those based on the previous reference are so small, no changes need to be made to the mass scales of the National Metrology Institutes (NMIs). However, the Calibration and Measurement Capabilities (CMCs) of some NMIs had to be adjusted to account for the uncertainty of the consensus value. The consensus value came into force on 1 February 2021.

Second key comparison of kilogram realizations

The second key comparison of kilogram realizations was agreed by the CCM in May 2021. It will follow a very similar scheme as the first key comparison. The travelling standards, which were calibrated through the realization experiments of the participating NMIs, are expected to be at the BIPM for mutual comparison from January to March 2022. The final report is expected in September 2022. The result will contribute to the calculation of a new consensus value.

Calibrations of mass standards

The BIPM continues to provide calibrations of 1 kg Pt-Ir prototypes and stainless steel mass standards for the NMIs of its Member States. During 2021, four Pt-Ir prototypes and five stainless steel standards were calibrated. Traceability to the new definition was achieved via the CCM consensus value. The calibration uncertainty was 21 µg, dominated by the uncertainty of the consensus value. A new Pt-Ir prototype, n° 114, has been fabricated in the BIPM workshop and will be attributed to the NIM (China). Quotations have been requested for three more prototypes and a stack of eight Pt-Ir disks.

Kibble balance improvements

The BIPM continued its efforts to improve the operation of its Kibble balance[2]. Investigations have been pursued to minimize current leakage during voltage measurements, which is the second largest uncertainty contribution. An unexpected effect attributable to the nanovoltmeter, which is part of the programmable Josephson Voltage Standard (PJVS) system, on two PJVS arrays was observed. A new switch box was integrated into the apparatus, which allowed the disconnection of the nanovoltmeter from the measurement circuit during voltage measurement and simplification of electrical connections. Preparations are under way for participating in the second key comparison of kilogram realizations. The apparatus has been completely realigned.

'Mark II' BIPM Kibble balance

The design of a balance prototype as well as associated actuators and sensors for the 'Mark II' version of the BIPM Kibble balance was completed. The objective is to reduce the largest uncertainty component due to misalignment by replacing the upper suspension and the commercial force sensor of the present apparatus. The balance beam has a symmetrical design using flexure hinges. The beam and the flexure hinges were machined from the same metal block in the BIPM mechanical workshop. The ensemble is being assembled on an independent bench and will be characterized soon.

Electricity

Calculable capacitor

Assembly of the calculable capacitor has resumed. Assembly of the apparatus was temporarily stopped during the alignment phase of the main electrodes in 2017 due to other priorities. A first step in the resumption of the work consisted of measuring the alignment state of the electrodes. The alignment defects, which should ideally be below 100 nm, were found to be within a few hundreds of nanometres, which is insufficient for reaching the target uncertainty of a few nF/F on the capacitance provided by the calculable capacitor. This initial characterization was followed by an improvement of the alignment method, which required better characterization of the specific capacitive probes required for this task. In addition, the frequency stabilization electronics of the laser, which is used for interferometric measurements of the guard electrode displacement, were improved and it is now more reliable.

Realization of the ohm

The ohm was realized two times, six months apart, in 2021 using the quantum Hall resistance (QHR), as required to maintain traceability for resistance calibration and comparison services. Traceability for the capacitance services was performed at the same time by linking

the capacitance reference base to the QHR by using a quadrature bridge at two different frequencies. This work was completed by the calibration of all the working transfer standards required for the services. Thanks to this periodic activity, the uncertainty of the relative capacitance change with frequency of the standard capacitors was significantly reduced: 25 % less for 1 pF capacitors and 40 % less for 10 pF and 100 pF capacitors. This leads to a significant reduction of the uncertainty of the frequency coefficients of the standard resistors sent to the BIPM for calibration.

Cryogenic current comparator

Fabrication of a new cryogenic current comparator (CCC) used for resistance metrology has started. The multi-winding superconducting coil has been wound in collaboration with the LNE and the design of the cryogenic probe, including the superconducting quantum interference device (SQUID), will be carried out soon. A new room temperature low-frequency current comparator (LFCC) is under construction. This new LFCC will equip a new low-frequency precision bridge for comparison of resistance standards.

1 Ω resistance standards

A study of the stability and low-frequency dependence of 1 Ω resistance standards started in collaboration with the NMIJ-AIST (Japan) and the PTB (Germany). The frequency dependence of these resistors is the main uncertainty component in their measurement during on-site comparisons of QHR-standards, BIPM.EM-K12. The standards under test are new resistance standard prototypes developed by the NMIJ-AIST and the company Alpha Electronics. Characterization measurements carried out collaboratively by the BIPM and the PTB are ongoing. It is expected that the frequency dependence of these new standards is low enough (or even negligible) to be used for BIPM.EM-K12 comparisons. Final conclusions of this study are expected in 2022.

Programmable Josephson Voltage Standards

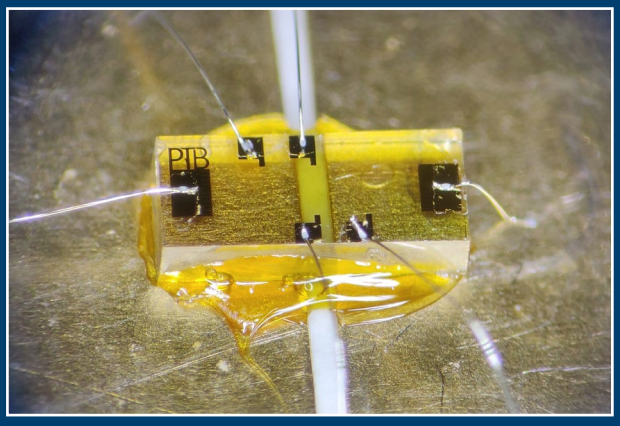
Work continued on establishing a protocol for a future on-site comparison of programmable Josephson Voltage Standards (pJVSs) used at ac. The measurand will be the RMS value of the voltage of a low-frequency sine wave. The characteristics of a new sampler (Fluke 8588A), to be used in the differential sampling measurement technique, have been investigated and compared to those of the previously used sampler (HP 3458A). The influence of the low-pass input filter and the analogue to digital conversion error were investigated. It is expected that reliable differential sampling of ac voltages with frequencies of the order of several kilohertz can be achieved by using this sampler. A task group gathering 15 metrology experts from NMIs around the world will support the BIPM in the further development of the technical protocol. A first version of the protocol has been circulated to the members of the group.

Calibrations

In the field of impedance, a total of 67 calibrations have been provided for 19 NMIs: 24 certificates for capacitance and 43 for resistance. In addition, two BIPM.EM-K13 resistance comparisons with the NSAI-NML (Ireland)[3] and INMETRO (Brazil) have been completed and another with NPLI (India) is under way. In the field of voltage metrology, the request for calibrations was significantly higher than usual. Due to the pandemic, some NMIs could not operate their primary references and therefore requested a calibration from the BIPM. A total of ten Zener voltage standards were calibrated for five NMIs. Comparisons of Zener voltage standards are under way with NPLI (India), SMD (Belgium) and NSAI-NML (Ireland). A number of reports on comparisons carried out in earlier years have been published[4-8].

Preparing for the transition from GaAs to graphene-based quantum Hall resistance references at the BIPM

Tests of new graphene samples from two different sources (PTB and a commercial source, based on a NIST development) were performed in 2021. Differences as low as 1 to a few nΩ/Ω were measured between GaAs samples operated at 1.4 K and 10 T, and graphene-based samples at 4.2 K and 4 T. These results as well as the ease and relaxed conditions of use of the graphene-based samples are encouraging. The experience gained through these tests will help in the design of a new QHR system based on graphene, which is expected to be operational in a few years time at the BIPM. This new system represents a significant advance in terms of simplifying the implementation and reducing operating costs. This will be of particular benefit to the on-site QHR comparison programme.



Ionizing Radiation

Radionuclide metrology

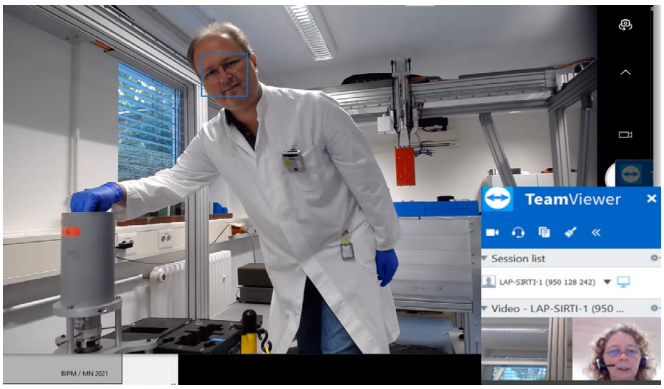
The International Reference System (SIR)

Comparisons of national activity standards of gamma-ray emitting radionuclides rely on the SIR. SIR participations in 2021 focused on radionuclides that have applications in nuclear medicine (^{68}Ge, ^{123}I, ^{223}Ra and ^{225}Ac) as well as on ^{60}Co (see ESIR section below). This second 2021 participation for ^{225}Ac[11] will allow the definition of a first Key Comparison Reference Value (KCRV) for this important nuclide used in targeted alpha therapy. The new software written to automate the calculation of comparison results, of KCRVs and the generation of comparison reports enabled the department to publish nine SIR reports in 2021[12-20].

The SIR relies on two highly stable re-entrant ionization chambers dating from the 1970s. However, only about 50 ampoules have been measured in the second chamber, compared to almost 1000 ampoules for the original chamber, on which all the KCRVs are defined. A project has been setup with the NPL (UK) and Prof. M. Cox to find a mathematical method which will enable the transfer of the KCRVs from the first chamber to the second. Three possible methods have been proposed and will be tested using software to be developed.

The SIR transfer instrument (SIRTI)

The SIRTI enables comparisons of many short-lived radionuclides used in nuclear medicine to be carried out on site at a metrology institute, avoiding shipping delays. As a result of the Covid-19 pandemic, the SIRTI has been adapted so that the instrument can be used by staff from a metrology institute with remote oversight by a BIPM scientist. The first 'remote' SIRTI comparison took place at the PTB (Germany) in the second half of 2021.



The first remote SIRTI comparison at the PTB

In 2019, the link between the SIRTI to the SIR was measured for ^{123}I and ^{153}Sm, however these measurements were significantly influenced by impurities present in the radioactive solutions available. In 2021, Monte-Carlo simulations of the impurities in the SIRTI were carried out using the Penelope2018 package thanks to a collaboration with the nuclear data group at the LNE-LNHB (France). This collaboration enabled improved impurity corrections. Further measurements of these links were carried out by measuring samples of the same ^{123}I solution in the remote SIRTI at the PTB, and in the SIR. The same process will be undertaken for ^{153}Sm in early 2022 enabling the first SIRTI ^{123}I and ^{153}Sm comparisons to be carried out at KRISS (Republic of Korea), ANSTO (Australia) and LNMRI/IRD (Brazil) in the next two years.

APMP and SIM contacted the BIPM to discuss the development of a travelling activity comparator for short-lived radionuclides in their regions. RMO SIRTI comparisons would enable comparisons to be carried out at the NMIs/DIs that the BIPM SIRTI could not yet visit. APMP and SIM agreed that setting-up copies of the BIPM SIRTI would be more efficient, with the technical support of the BIPM. Preliminary contact with EURAMET has taken place.

The extended version of the SIR (ESIR)

The radionuclide metrology community has to address new radiopharmaceuticals used in emerging cancer treatments: targeted (Alpha or Beta)-particle therapies. Molecules are tagged with beta-emitting radionuclides (^{32}P, ^{89}Sr, ^{90}Sr/^{90}Y, …) or alpha-emitting radionuclides (^{225}Ac, ^{211}At, ^{212}Bi, …) for which the SIR and SIRTI have some limitations due to the detector entry windows and the impact of the solution density. Thus, development of an international comparator based on liquid scintillation to help NMIs/DIs evaluate their international equivalence for these isotopes is a major concern. To that end, a new instrument (the ESIR) has been developed. In 2021, a paper on the estimation of measurement uncertainties was published[21], and another is in preparation to demonstrate the good measurement reproducibility highlighted by the quality control. A pilot study is under way to validate the ESIR against the reference SIR with the use of Co-60 solutions standardized by eleven participating NMIs/DIs. This study is close to completion and further investigations are required to better understand the results and to make available the ESIR as a BIPM comparison service. Enhancement of the system to address alpha-particle emitting radionuclides is an important step, which is under active development.

CCRI ^{109}Cd key comparison

The ^{109}Cd radionuclide provides a low-energy calibration point for high-resolution gamma-ray spectrometers that are used not only in NMIs but also in the nuclear industry and in environmental monitoring laboratories. As the last ^{109}Cd key comparison was carried out in 1986, the Consultative Committee for Ionizing Radiation (CCRI) decided to repeat the exercise with the BIPM and LNE-LNHB as pilot laboratories. Ampoules of ^{109}Cd have been sent to twenty participants and measurements are in progress.

Radiation dosimetry metrology

Key comparisons and calibrations at the BIPM

The BIPM provides the KCRV for air kerma and absorbed dose to water in a number of key radiation fields, critical for traceability in radiotherapy. Comparisons in the BIPM reference fields allow NMIs to validate their primary standards, while calibrations are provided for NMIs that hold national secondary standards. These services continued through 2021, although the pandemic resulted in a reorganization of the planning to accommodate restrictions at the NMIs and difficulties in the transportation of equipment. A total of eight comparisons were carried out, for Hungary (five comparisons), China (one) and Poland (two). Three calibrations were made, for Argentina (one) and Spain (two). Quality control checks continued to ensure that the BIPM standards and radiation beams remain stable.

In total, thirteen comparison reports for Australia (three), Austria (two), Japan (one), Poland (three), Russia (one) and Canada (three), were completed and ten were published in the *Metrologia* Technical Supplement[22-31]. The production of calibration certificates was incorporated into the data analysis software (Excel) so that certificates can now be produced automatically. This speeds up certificate production and simplifies the process of validating calibration certificates.

Key comparisons and offsite calibrations

High-energy x-ray beams are used increasingly for radiotherapy world-wide, combined with advanced technologies for better targeting of the tumour. The provision of key comparisons for these beams continued at the DOSEO facility, one comparison with Germany being carried out in 2021 and the report of one previous comparison with France published in the *Metrologia* Technical Supplement[32]. To meet the traceability needs of the NMIs and DIs that do not maintain a primary standard, a BIPM calibration service was developed based on the direct comparison of an NMI secondary standard with BIPM reference chambers. When combined with the BIPM external beam monitoring system, calibrations can be made with a reproducibility approaching 0.02 %. This facility was used for the calibration of three instruments for Denmark as well as for measurements of k_Q factors for several chamber types.

The quality procedures associated with the new service were developed and incorporated into the BIPM Quality System. As an additional quality assurance check, DOSEO measurements are supplemented by supporting calibrations in the BIPM Co-60 facility; three such measurements were made for Germany and two for the International Atomic Energy Agency (IAEA).

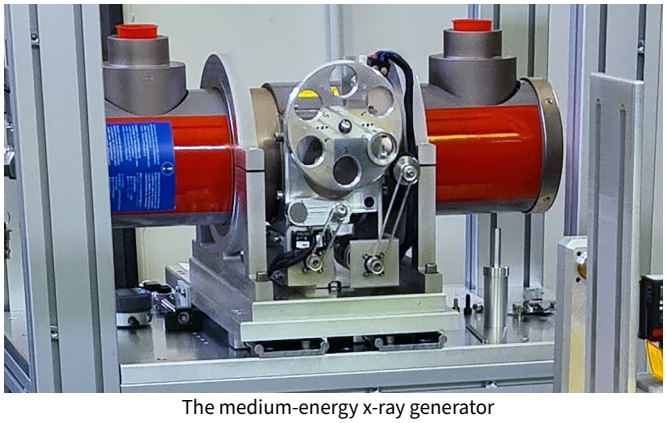
To improve the robustness of the primary standard, a second graphite core was developed and tested. When fully characterized, this will serve as a replacement core in the event of failure.

The plan to restart the BIPM comparison and calibration services for Cs-137 using the IAEA facility had to be postponed until the second half of 2022. This is because the new Cs-137 source was not delivered to the IAEA as scheduled as a result of the Covid-19 pandemic.

Upgrade of the medium energy x-ray facility

The change of generator on the existing medium-energy x-ray facility had an unexpected effect on the standard for absorbed dose to water, necessitating extensive measurements to re-establish the conversion coefficient from air kerma to absorbed dose. This work was described in the report "*Impact of a high-voltage generator replacement on the BIPM standards for K_{air} and D_w in medium-energy x-rays*", which was presented to the meeting of the CCRI(I) in June 2021 (CCRI(I)/2021-12).

Work continued to renew the medium-energy facility. The x-ray tube purchased in 2020 was installed together with a new support system incorporating beam collimation, beam shutter and an automated filter-wheel for the different radiation qualities. Automated control of the filter wheel allows the high-voltage generators to remain in operation while the radiation quality is changed, which increases beam stability and reduces the time required to change the quality. The new measurement bench for air kerma and absorbed dose to water comparisons and calibrations was constructed, incorporating mechanical and optical devices for instrument positioning. On completion of the software, this new arrangement for the positioning and interchange of the BIPM standards and the instruments under test will be controlled remotely, with consequent reductions in time and staff intervention. Initial measurements are under way to complete the beam alignment and fine-tune the collimation, after which the new reference radiation qualities will be characterized.



The medium-energy x-ray generator

Design of a new primary chamber for medium energy x-rays

Design of the new primary standard instrument for these beams has started, including the simulation of the chamber using a finite-element analysis software package to study the electric-field homogeneity under various design scenarios; this will help to define mechanical tolerances for the construction of the standard.

Chemistry

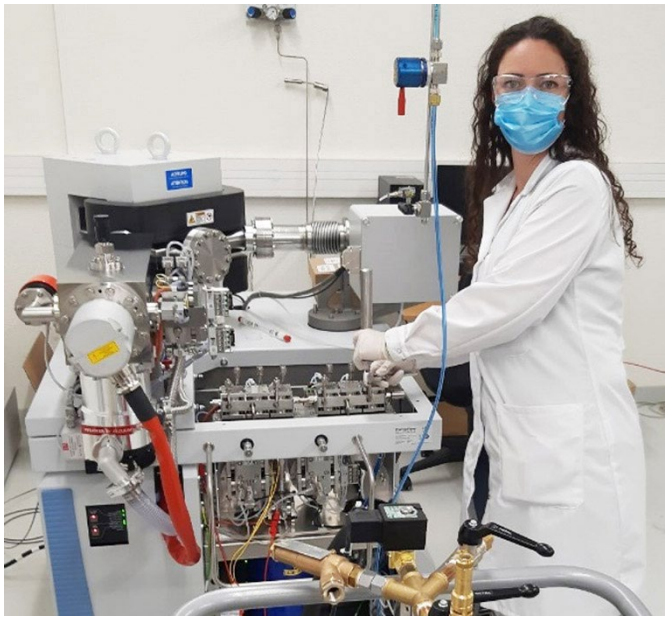
The Chemistry Department progressed 12 interlaboratory comparisons in 2021. Two knowledge transfer programmes were reconfigured and transferred to the BIPM e-learning platform, one on organic pure calibrator characterization for Metrology for Food Safety and the other on the application of Fourier Transform Infrared Spectroscopy (FTIR) for Gas Standards for Metrology for Clean Air. Over one hundred NMI scientists registered to follow these programmes on-line. The department produced ten publications including four comparison reports and three papers in peer reviewed journals.

The department hosted 70 on-line meetings, for eleven Consultative Committee for Amount of Substance: Metrology in Chemistry and Biology (CCQM) working groups and the Joint Committee for Traceability in Laboratory Medicine (JCTLM) throughout 2021. The department ran a webinar on the '*Reliability of measurements in response to the Covid-19 pandemic*', an on-line CCQM workshop on a roadmap for metrology of infectious disease and future pandemic readiness, and a joint JCTLM-International Consortium for Harmonization of Clinical Laboratory Results (ICHCLR)-International Federation of Clinical Chemistry and Laboratory Medicine (IFCC) workshop on overcoming challenges to global standardization of clinical laboratory testing: reference materials and regulations. In support of the *Measurement for Health* theme of World Metrology Day, a series of videos explaining the impact and benefits of metrology in laboratory medicine were released in association with the JCTLM.

Gas Metrology Activities: Greenhouse gases

The comparison of CO_2 isotope ratio measurements (CCQM-P204) on pure CO_2 samples, coordinated jointly by the BIPM and the International Atomic Energy Agency (IAEA), has continued with 120 cylinders filled at the BIPM with four gases of differing isotope ratios. An isotope ratio mass spectrometry (IRMS) method was developed and validated, with the support of an external expert, Dr Colin Allison. The BIPM's internal calibration hierarchy of CO_2 isotope ratio standards, was established with traceability to the Vienna Peedee Belemnite (VPDB) scale, realized with the IAEA-603 reference material and calibration measurements of the IAEA. Of the 120 comparison samples, 80 were sent to participants, 12 to the IAEA as co-coordinator of the comparison, and 28 maintained at the BIPM. Homogeneity and stability measurements were performed at the BIPM. A cryogenic extraction line for CO_2 in air isotope measurements was designed and built for the IRMS. Collaboration with the laboratory of M. Daëron at LSCE (France) continued, with a one-month training programme for a BIPM staff member in the LSCE laboratory. A carbonate line for the IRMS at the BIPM has been designed. The department is supporting the steering committee of the BIPM-World Meteorological Organization (WMO) workshop on *Metrology for Climate Action*.

Final measurements were made by participants for the nitrous oxide (N_2O) in air standard comparison (CCQM-K68.2019) in February 2021. The Draft A report was circulated in April and three on-line meetings have been held in to discuss the results and possible reference values. Collaborative work was undertaken with the NIST (USA), who developed an additional variance approach for treating the comparison results. A final meeting is planned for the start of 2022 to finalize agreement on the comparison reference value.



Newly established isotope ratio mass spectrometer facility supporting comparison of CO_2 and CO_2 in air isotope ratio standards, CCQM-P204 and future planned on-demand comparisons BIPM.QM-K3 and BIPM.QM-K4

Improvements to the BIPM's primary manometric system for CO_2 measurements, in support of a future planned ongoing comparison of CO_2 standards (BIPM.QM-K2), have allowed standard deviations of 0.02 µmol/mol to be achieved for the measurement of CO_2 in air standards in the range 380 µmol/mol to 800 µmol/mol. A study of the pressure dependency of measured amount fractions has been completed to characterize potential biases due to adsorption and variable volume effects.

Gas Metrology Activities: Air quality gases

Projects in support of air quality measurement standards continued to focus on ozone and nitrogen oxides during 2021. The ozone standard comparison, BIPM.QM-K1, was re-established in September 2021, following an upgrade of the electronic systems of BIPM's ozone photometers. A comparison with CHMI (Czech Republic) was completed, demonstrating the same level of performance as with the last comparison in February 2021 with ISCIII (Spain), which was carried out before the service was suspended. One comparison report for BIPM.QM-K1 with METAS (Switzerland) was published[33]. The BIPM supported the newly established CCQM GAWG Task Group for Ozone Cross-Section (CCQM-GAWG-OZONE-TG) and developed a document on the values of the absorption cross section when expressed in different units and related quantities to assist in the global effort to update documentary standards in the field.

The BIPM finalized, approved, and published the final report for the comparison of NO_2 in N_2 standards at 10 µmol/mol (CCQM-K74.2018)[34]. A 5-month study on the stability of four NO_2 in N_2 standards was completed as a follow on to the comparisons and demonstrated the impact of trace impurities on the stability of the standards. The Draft A report of the HNO_3 in NO_2/N_2 standards study (CCQM-P172) was completed and discussed by participants in June.

The Metrology for Clean Air Course on '*FTIR Measurements on Gas Standards*' (NO_2, NO, HNO_3, CO_2) was made available on-line via the BIPM e-learning platform on 1 September 2021, with scientists from NIMT (Thailand) and NMISA (South Africa) enrolled to follow the on-line intensive 6-month course, with remote support from the BIPM. The development of a knowledge transfer project of dynamically generated NO_2 standards was initiated with the completion of a first series of measurements comparing the METAS ReGas and BIPM systems.

Metrology for Health

In its programmes related to Metrology for Health, the BIPM worked with NIM (China), NRC (Canada) and the pilot group for the CCQM pilot study on SARS-CoV-2 antibody quantification (CCQM-P216) to finalize the protocol for the second part of the comparison that focused on monoclonal antibody quantification. The BIPM completed its measurement on amino acid analysis and tryptic peptides quantification and submitted these, which contributed to the reference value, with the comparison report to be published. Measurements for the second part of the study, focusing on size exclusion chromatography, were completed with publication of the study report planned for 2022. A paper describing the qNMR analysis of peptide calibrators for the SARS-CoV-2 IgG was presented at the International Metrology Congress (CIM 2021) in September and published in *Measurement Science and Technology*[35]. A paper on the Metrological framework to support accurate, reliable, and reproducible nucleic acid measurements developed with support from the BIPM, was published in *Analytical and Bioanalytical Chemistry*[36].

Draft A reports for comparisons on hexapeptide calibrators for the HbA1c glycated hexapeptide (GE) (CCQM-K115.c and CCQM-P55.2.c), and the non-glycated hexapeptide (VE), (CCQM-K115.2018 and CCQM-P55.2.2018), were developed and discussed at on-line meetings of the CCQM Working Group on Protein Analysis (CCQM-PAWG). Additional measurements were performed at the BIPM to confirm the presence and amounts of depsipeptides within the materials. A paper describing methods of impurity quantification in oxytocin standards was published in *Analytical and Bioanalytical Chemistry*[37], following on from the key comparison completed in 2020.

The Chemistry Department continued to support the Joint Committee for Traceability in Laboratory Medicine (JCTLM), by providing the secretariat for the committee and hosting the JCTLM Database of Reference Materials, Methods and Services. The secretariat's workload in 2021 included: preparation of 180 nominations for JCTLM database entry review; and publication of 33 new entries in the JCTLM database from 2020 nominations. Activities to update the JCTLM database to a new operating system was progressed with an outside contractor. A new version of the database is expected to be operational in 2022 and will include an Application Programming Interface (API).

Metrology for Safe Food and Feed

In its programmes related to Metrology for Safe Food and Feed, the Chemistry Department completed the drafting of the final report of the comparison of Aflatoxin B1 calibration solutions (CCQM-K154.b), which was submitted to the CCQM chairs for approval. The characterization of comparison materials, including homogeneity and stability studies, of standard solutions containing trifluralin and methoxychlor (270 units), was completed for use in the comparison on pesticide calibration solutions, CCQM-K78.b, (multi-component, non-polar compounds). The final report of the CCQM-K148.a comparison (bisphenol A calibrator purity) was approved and published in the KCDB[38]. The sixth meeting of the CBKT programme on '*Metrology for Safe Food and Feed*', coordinated by the Chemistry Department, was organized as an on-line meeting in March 2021, focusing on mycotoxins, veterinary drug residues and pesticide standards. An additional Purity Evaluation Guideline for aflatoxin B1 and a Calibrant Assessment Guideline for deoxynivalenol were published as *BIPM Rapport 2021/01* and *2021/02*, respectively[39,40]. A 6-month on-line training course on '*Impurity Content Quantification in Organic Pure Materials*' was launched on the BIPM e-learning platform in May 2021. Participants from nine NMIs enrolled in the full on-line course, consisting of six modules, with activities on all six modules completed. The recorded lectures and learning material available through the BIPM e-learning portal have been accessed by more than 100 NMI scientists from 22 countries. An overview of the application of NMR and qNMR applications in organic analysis was published[41].

The BIPM laboratory programme on mycotoxin standards continued with the call for participation and protocol for the CCQM-K154.c comparison on deoxynivalenol calibration solution being distributed to participants, and stock solution being distributed to NMIs that had participated in the CBKT programme. The stock solution for the next comparison on patulin (CCQM-K154.d) has been distributed to CBKT course participants. The collaborative project on veterinary drugs with UME (Turkey) continued with tetracycline material being distributed to 14 participants in a knowledge transfer study. Characterization of the CCQM-K148.b material (oxytetracycline) has continued with completed quantitative NMR (qNMR) and liquid chromatography/ultraviolet spectroscopy (LC-UV), water, ion chromatography and homogeneity measurements. A joint technical project was initiated with NIM (China), as a collaborative project to provide pure pesticide and pesticide calibration solutions for future knowledge transfer activities and comparisons.

Time

Advances with PSFS

In 2021 the Time Department contributed to the development and use of a new estimation technique for the evaluation of the reference frequency values of Primary and Secondary Frequency Standards (PSFS), based on graph theory, and their correlation in support of the Joint CCL-CCTF Working Group on Frequency Standards (CCL-CCTF-WGFS).

Production of UTC

The regular production of UTC, rapid UTC (UTCr), and the key comparison CCTF-K001.UTC was ensured in 2021 despite difficulties in several time laboratories due to the sanitary restrictions resulting from the Covid-19 pandemic. The support of the world time laboratories during this difficult period is kindly acknowledged. Data were provided regularly and rapid interventions, in the case of anomalies, were ensured in almost all laboratories. This support allowed the regular publication of the UTC results with the usual metrological quality. New secondary realizations of the second were mature enough for contribution to UTC. A plot showing the PSFS contributing to UTC is updated every month and is available on the department's webpages.

Record number of frequency standards contribute to International Atomic Time

International Atomic Time (TAI) achieves its stability from more than 450 atomic clocks world-wide and its accuracy from a small number of primary and secondary frequency standards, which aim at realizing the SI second with the smallest uncertainty. Each month the BIPM publishes, in section 3 of *Circular T*, an estimation of the TAI frequency accuracy as measured by those individual frequency standards, as well as an ensemble average computed by the BIPM. In November 2021, sixteen different frequency standards operated in eleven laboratories contributed to this estimation, including ten Cs fountains, one Rb fountain, one Sr optical lattice and two Yb optical lattice clocks, in addition to the two legacy Cs beams operated by the PTB. This constitutes a record level of participation, both in terms of the number of different standards and the number of different laboratories.

The feasibility of inserting redundant optical fibre links that measure Primary and Secondary Frequency Standards (PSFS) into UTC computation was analysed[42]. A statistical analysis on the predictability of several families of H-Masers was undertaken with the aim of improving the long-term stability of UTC[43].

Work is in progress to update *Circular T* section 4 on the GNSS dissemination of UTC, which is to be extended to Beidou and Galileo systems. The impact of multiple information in GNSS navigation messages has been studied[44].

Comparing clocks with IPPP

The capacity to compare clocks by the Integer Precise Point Positioning (IPPP) technique, based on the software developed by the French Space Agency, was developed leading to regular publication of some IPPP links on the BIPM web pages[45]. The computation of IPPP links by the BIPM is used to validate other very precise time and frequency transfer methods[46].

Time transfer calibrations

The new mobile calibration box (B4TS) has been tested and is almost ready for the first calibration exercise[47]. The mobile calibration box is designed to perform calibrations of Two-Way Satellite Time and Frequency Transfer (TWSTFT) links when other techniques are not available. Work continued on the absolute delay measurement of GNSS receivers, in collaboration with the CCTF Working Group on GNSS Time Transfer (CCTF-WGGNSS). The absolute calibration of delays for the Beidou BDS3 signals has been carried out by European Space Technology and Research Centre (ESTEC) for one BIPM receiver (BP27). As a result, all BIPM receivers that are able to track the four GNSS systems can now be traced to an absolute calibration measurement.

The results of the Group 1 visit to EURAMET G1 laboratories (OP, PTB, ROA) and to SIM G1 laboratories (NIST, USNO) in 2020 are available and have been published in the department's database. A visit to COOMET G1 (SU) is in preparation. The calibration guidelines were updated to version 4.0. The reports of fifteen Group 2 calibrations were validated and the results are available in the database.

TWSTFT

Support to two-way satellite time and frequency transfer (TWSTFT) is ongoing by following the tests on the new satellite for the Asia Pacific network and by ensuring the continuity of all EU-USA links with a transfer of calibration and revaluation of all the calibration delays when the satellite and, successively, the transmission frequencies were changed. A new participating station began transmitting in September 2021.

IT systems update

The update of the Time Department's IT systems is in progress, with a gradual migration towards a virtual machine system. The GNSS calibration database has been updated to include the calibration of Galileo signals, which have become available since the last calibration campaigns.

Application Programming Interface

A test Application Programming Interface (API) was developed, which gives access to machine readable data regarding UTC and rapid UTC. The API was developed in the framework of further digitalization and to increase availability of machine-readable products within the department.

International Liaison and Communication

A Practical Arrangement between the BIPM and the Preparatory Commission for the Comprehensive Nuclear-Test-Ban Treaty Organization (CTBTO) on collaboration on the metrological traceability of measurements of infrasound, seismic activity and radioactivity was signed in June 2021.

A Memorandum of Understanding between the BIPM and the Committee on Data (CODATA) of the International Science Council (ISC) was signed in October 2021. The BIPM hosts the CODATA-TGFC portal on the BIPM website. The CODATA-TGFC assists the BIPM in the development of the SI and promotes the consistent use of the SI, in particular by expressing the recommended values of the adjusted constants in SI units. The BIPM promotes consistent use of the latest CODATA recommended values of the basic constants.

The Organisation for Economic Co-operation and Development (OECD) established the *Partnership of effective rulemaking* (IO Partnership) as a voluntary platform of international organizations (IOs), academics and OECD Regulatory Policy Committee delegates to exchange good practices and promote greater quality, effectiveness, and impact in international rulemaking. As part of the 8th Annual Meeting of International Organisations within the context of the IO Partnership, Dr Martin Milton, Director of the BIPM, participated in the OECD virtual event held on 13 September 2021: *Rethinking and modernizing international rulemaking to design better policies for the 21st century*. Dr Milton emphasized the critical role of the organizations, in particular the role of members in underpinning effective international rulemaking.

The *Compendium of International Organisations' Practices: Working Towards More Effective International Instruments* was launched during the 8th Annual IO Meeting. The IO Compendium is the first common tool developed collaboratively by some 50 IOs to improve the quality of international rulemaking and lists BIPM practices such as World Metrology Day, CBKT Programme, CIPM MRA Review, JCGM, etc. in five core focus areas.

A Joint Task Group, established between the BIPM and the International Organization of Legal Metrology (OIML) to foster enhanced cooperation between the two organizations, met several times in 2021. It discussed joint representation for liaison activities, joint initiatives, and promotion of metrology and digital transformation. The Task Group will reflect on the opportunities to link the celebration of the 150th anniversary of the signing of the Metre Convention and the 70th anniversary of the OIML in 2025.

World Metrology Day (20 May) is a joint initiative between the BIPM and OIML to celebrate the day the Metre Convention was signed in 1875. The theme for 2021 was "*Measurement for health*", which was chosen to raise awareness of the importance of measurement in facilitating fair global trade by ensuring products meet standards and regulations and satisfy customer quality expectations. The 2021 poster was designed in collaboration with the GULFMET RMO and specifically with SASO (Saudi Arabia) and translated into more than 20 languages. The 2021 World Metrology Day Resource Website https://2021.worldmetrologyday.org listed a further 36 national celebratory events.

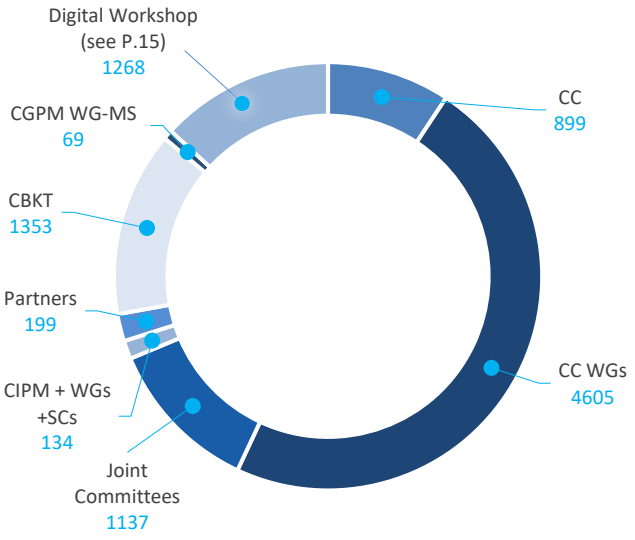
Ongoing work within the International Network on Quality Infrastructure (INetQI) is focusing on developing the concept of an INetQI "Single library" bringing together available resources for the QI community.

The BIPM contributed to the methodology included in the UNIDO sponsored publication *Quality Infrastructure for Sustainable Development (QI4SD)* Index specifically related to benchmarking of individual QI dimension (metrology), which allows for continual improvement and mutual learning. The focus of the BIPM contribution was to ensure the QI4SD team properly understood the CIPM MRA metrics, advising on data collection and validating indicators that the team developed. A dedicated tool will be made available on the UNIDO Knowledge Hub.

The BIPM and the World Trade Organization (WTO) cooperate to ensure effective dissemination of information on the importance of the quality infrastructure. A particular focus of this cooperation is metrology as one of the key components among trade regulators and international/ intergovernmental organizations that hold *ad hoc* observer status at the WTO Committee on Technical Barriers to Trade (WTO TBT Committee). BIPM staff submitted the BIPM statements and attended the virtual meetings of the WTO TBT Committee in February, June and November 2021.

The BIPM and the United Nations Educational, Scientific and Cultural Organization (UNESCO) cooperate to ensure effective dissemination of information on the importance of the quality infrastructure and particularly metrology in the scientific and wider context. BIPM staff attended (remotely) the 41st Session of the UNESCO General Conference in November 2021.

Meeting participations in 2021



CBKT and e-learning

Launch of the BIPM's e-learning platform

https://e-learning.bipm.org/

The covid-19 crisis accelerated the strategic plan to offer remote-learning opportunities for the NMI/DI and RMO communities. With remote-learning in the form of short courses and technical exchanges implemented in 2020, the BIPM took a further significant step in 2021 by working with an external contractor to develop a bespoke e-learning solution based on the Moodle - Open-Source software. The platform is accessible around the clock and is optimized for desktop and hand-held devices to provide learning support to metrologists as conveniently as possible.

The platform immediately attracted participation from NMI/DI staff of Member States and Associates around the world. Furthermore, the e-learning solution offers excellent opportunities to expand the portfolio in the future.

The following e-learning courses were made available in 2021:

CIPM MRA course

This course is made up six modules and is intended to give an overall understanding of the CIPM MRA processes.

Non structure-related impurity content in organic pure materials

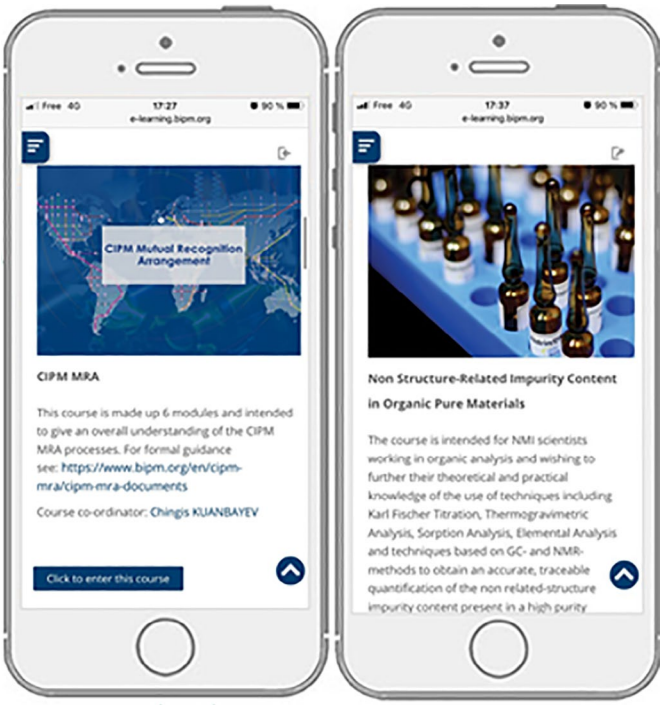
The course is for NMI scientists working in organic analysis and wishing to further their theoretical and practical knowledge of the use of techniques including Karl Fischer Titration, Thermogravimetric Analysis, Sorption Analysis, Elemental Analysis and techniques based on GC- and NMR-methods to obtain an accurate, traceable quantification of the non related-structure impurity content present in a high-purity organic material.

Metrology for clean air

The course is intended for NMI scientists working in gas metrology and wishing to further their theoretical and practical knowledge of the use of the FTIR technique to obtain an accurate, traceable quantification of infrared gas active species.

How to enter a CMC claim for ionizing radiation metrology

The aim of this course is to provide guidance on entering the information needed on the KCDB for claiming a CMC for radiation dosimetry, radioactivity or neutron metrology.



Other activities

BIPM-TÜBİTAK UME project placements

The placements of the fourth cycle of the "BIPM–TÜBİTAK UME project placements" started in September 2021 with nine participants from Albania, Bosnia and Herzegovina, Colombia, Kenya, the Philippines, Russia, Sudan, Thailand and Tunisia. A CIPM MRA webinar was organized to supplement the laboratory activities.

BIPM CBKT remote-learning

The BIPM CBKT Programme continued to deliver and expand the range of its "remote-learning" capabilities in 2021 with a series of on-line technical exchanges and short courses. These addressed various aspects of the CIPM MRA, delivered as short courses for wider CIPM MRA community and the technical exchanges which focused on particular topics. Many of these courses were delivered in partnership with individual RMOs. Technical exchanges were repeated in order to be convenient for the different time zones helping to ensure very high levels of participation, and feedback was excellent.

Collectively these courses and technical exchanges attracted some 700 participations in 2021.

Additionally, a joint BIPM-ILAC webinar "Mining KCDB 2.0 in the context of accreditation" welcomed more than 600 experts from Accreditation Bodies and Accredited Laboratories around the world.

The CIPM MRA

The KCDB 2.0 is a collaborative web platform that was launched in late 2019. The platform is now being used daily for submission of Calibration and Measurement Capabilities (CMCs), their review and publication, as well as for comparison registration and updates in all metrology areas. It provides statistics, which can be tailored to a targeted RMO, country or metrology area, and search capabilities. The search facilities covering CMCs were made available as an API in mid-2021 as a first step towards digitalization of the data.

Calibration and Measurement Capabilities

On 31 December 2021, there were 26 049 CMCs published in the KCDB. Of these, 15 617 were in the field of general physics, 3 873 in ionizing radiation, and 6 559 in chemistry. The total number of CMCs increased by 368 in 2021. Twenty-four of the 38 Associates that participate in the CIPM MRA had CMCs published in the KCDB at the end of 2021.

It is possible to temporarily withdraw CMCs from the database by "greying out". At the end of 2021, 464 CMCs were "greyed out", a decrease of 10 % since 2020.

The first review of CMCs issued from the Chemistry and Biology metrology area were made using the KCDB 2.0 platform in 2021; all metrology areas are now using this facility. A survey of the review delay shows that the duration of the JCRB review of a CMC has, on average, been halved by using the KCDB 2.0 platform.

Key and supplementary comparisons

On 31 December 2021, the key and supplementary comparisons database included 1 109 key comparisons and 648 supplementary comparisons. This represents an increase of 22 key comparisons on 2020, while supplementary comparisons increased by 14. Around 74 comparisons were completed and published during 2021. Today, 93 % of all the 94 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.

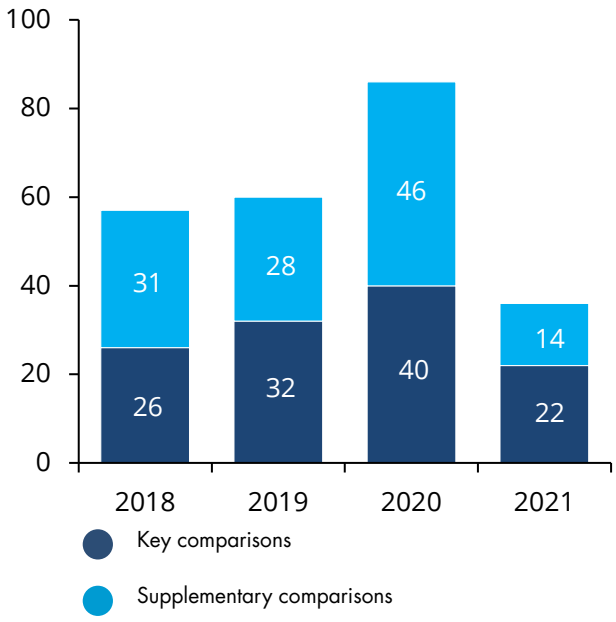
The KCDB currently includes a dozen examples of where more than seven key comparisons are linked together.

API KCDB

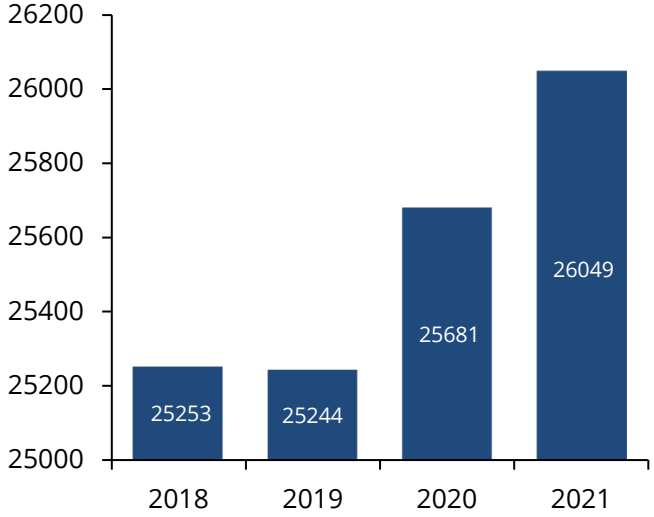
The BIPM launched an Application Programming Interface (API) for the KCDB in 2021, which allows automated searching for CMCs. The API KCDB provides data in response to search queries on CMCs. Although it may provide the basis for digital CMCs in the longer term, the API is presently used for searching for CMC data. The API KCDB provides search facilities on CMCs via advanced or quick search and is available at https://www.bipm.org/en/cipm-mra/kcdb-api

The API represents the first practical step on the road towards digital calibration certificates and lays the foundation for future developments, and ultimately new NMI digital services.

Number of new comparisons registered in the KCDB

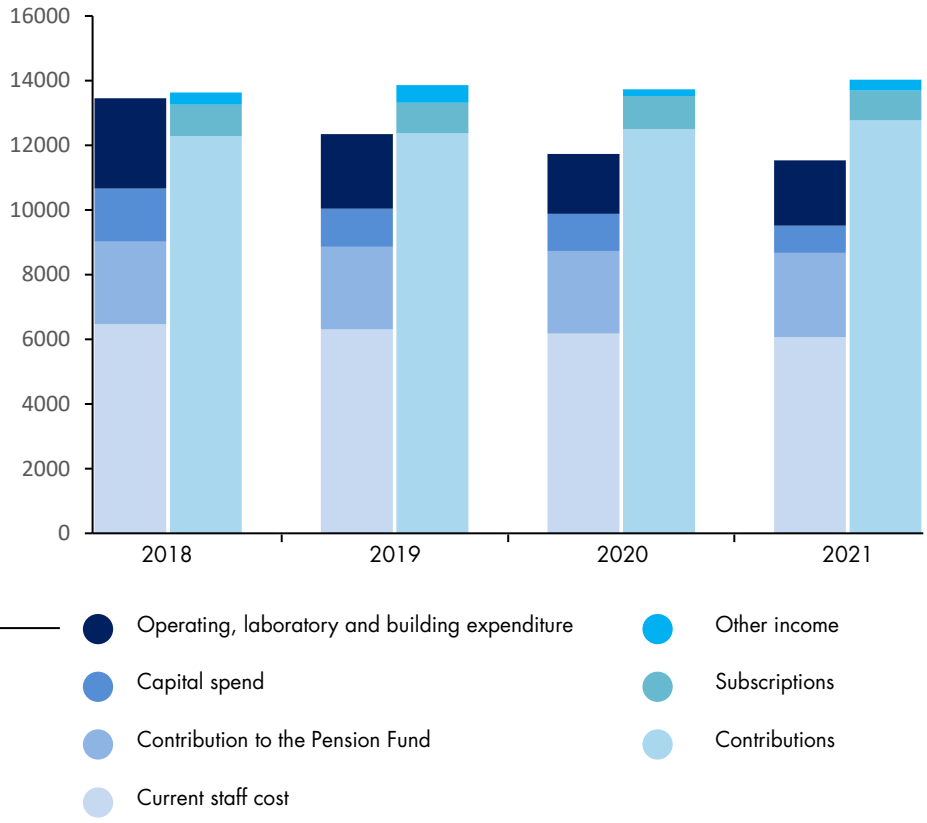


Total number of CMCs registered at 31st December



Financial Summary

Revenue and expenditure (2018 to 2021)



in k€	2018	2019	2020	2021
Operating, laboratory and building expenditure	2 794	2 302	1 848	2 020
Capital spend	1 641	1 184	1 153	844
Contribution to the Pension Fund	2 550	2 550	2 550	2 600
Current staff cost	6 468	6 310	6 180	6 072
Other income	379	547	209	336
Subscriptions	967	935	1 022	928
Contributions	12 290	12 379	12 503	12 767

Key financial points

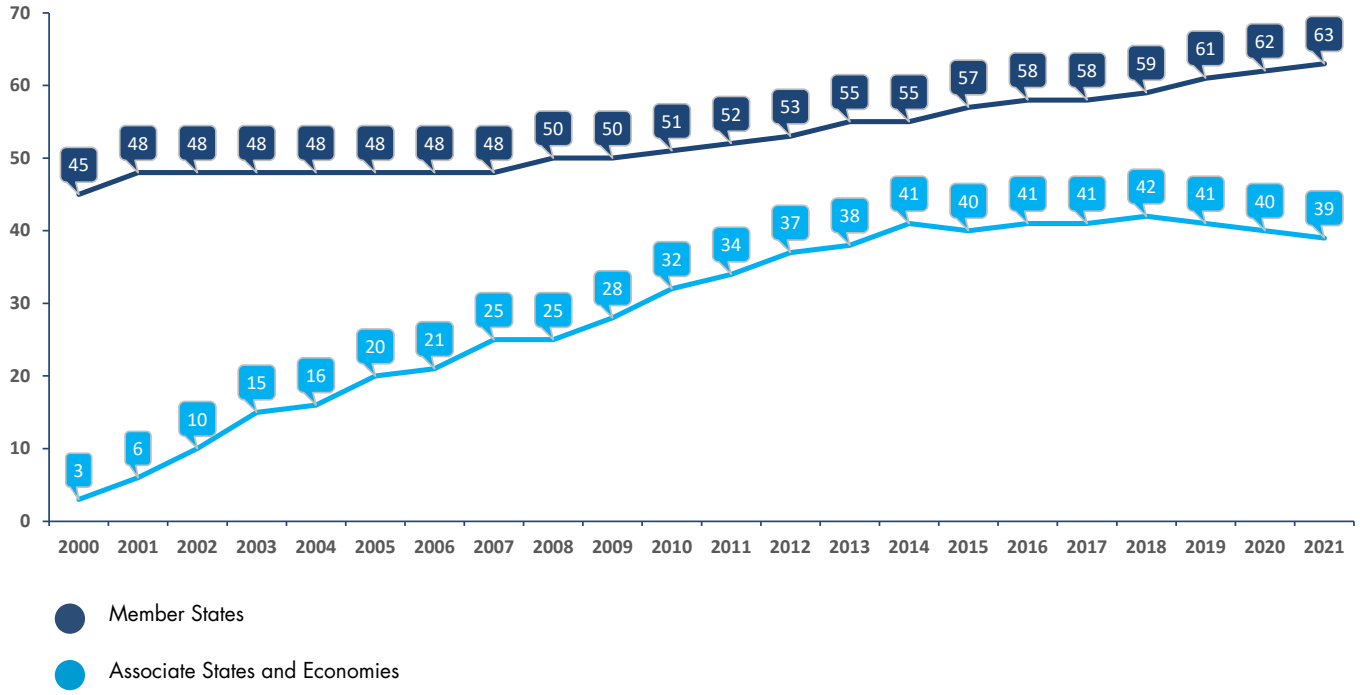
– These results are the consequence of careful control of spending in 2021 and the continued reduction of meeting activities and travel due to the global pandemic.

– Revenue followed forecast; staff costs continue to be stable and the spend on investment followed the agreed budget.

– The CIPM decided to transfer 3 000 thousand € from the BIPM reserves to the reserves of the BIPM Pension Fund.

Financial Summary

Growth in Member States and Associate States and Economies from 2000 to 2021



Full details of the financial and administrative situation of the BIPM are available in the "*Financial Report 2021*"

Bureau International des Poids et Mesures

The International System of Units (SI) in FAIR digital data.

FINDABLE ACCESSIBLE INTEROPERABLE REUSABLE

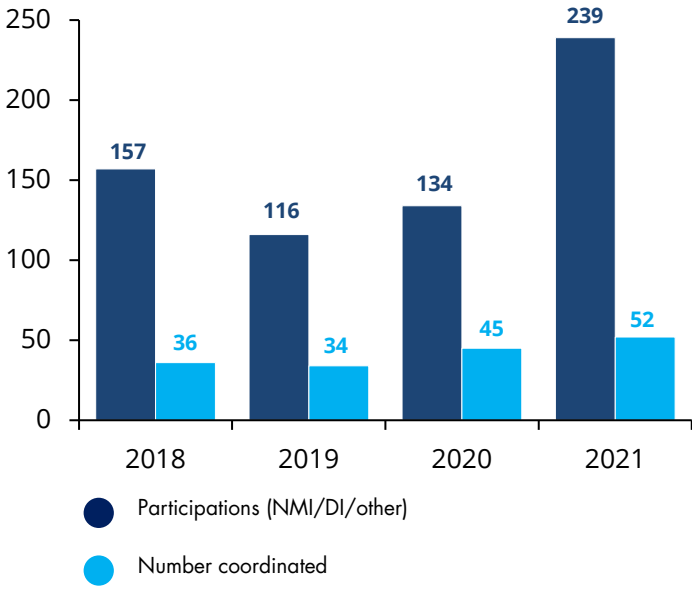
The BIPM hosted and contributed to a four-day virtual workshop in February 2021 on "The International System of Units (SI) in FAIR digital data." The workshop was organized under the auspices of the CIPM Task Group on the Digital SI (CIPM-TG-DSI). The virtual workshop brought 1268 participants together with leading experts and groups in digitalization related to metrology and data science to exchange ideas about the first steps to agree basic standards for a "Digital SI" framework and its propagation in compliance with FAIR (**F**indable, **A**ccessible, **I**nteroperable, **R**eusable) principles.

Plenary sessions set the scene and looked at the topic from the perspective of data science, quality infrastructure, RMOs and industrial digital infrastructure, concluding with the session on the digital representation of units. These sessions were complemented by parallel breakout topics addressing the SI core representation and services, interoperability; machine-actionable metadata and data, fairness of data; Digital Calibration Certificates (DCCs); readiness of data for Artificial Intelligence and Machine Learning.

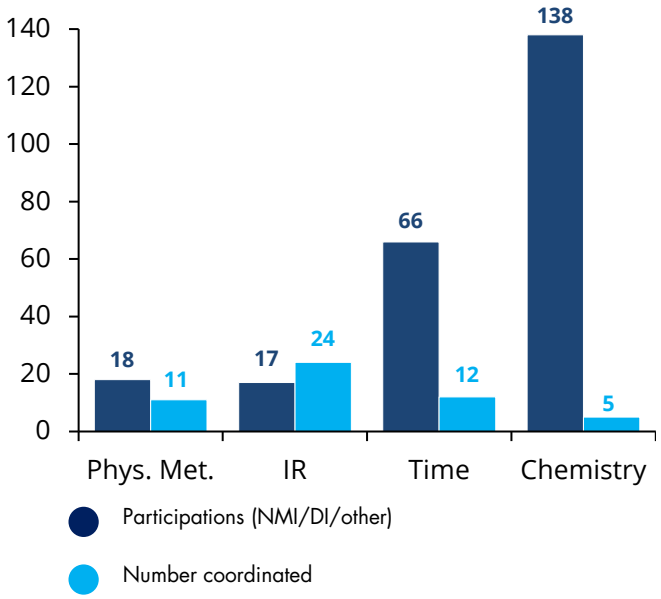
Comparisons and Calibrations

Comparisons

Comparisons coordinated by the BIPM laboratories

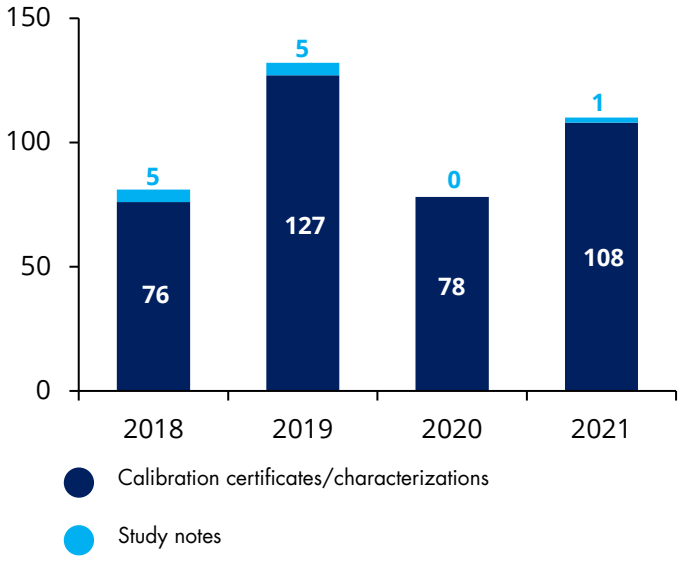


2021 - Breakdown by department

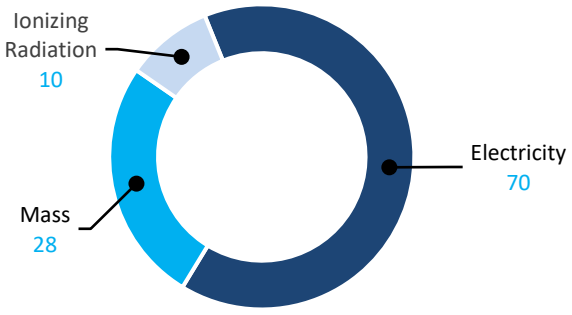


Calibrations and Study Notes

Calibrations and Study Notes from the BIPM laboratories



2021 - Calibrations by metrology area



Organizational structure

The CIPM

President

Dr W. Louw (South Africa)

Secretary

Dr T. Usuda (Japan)

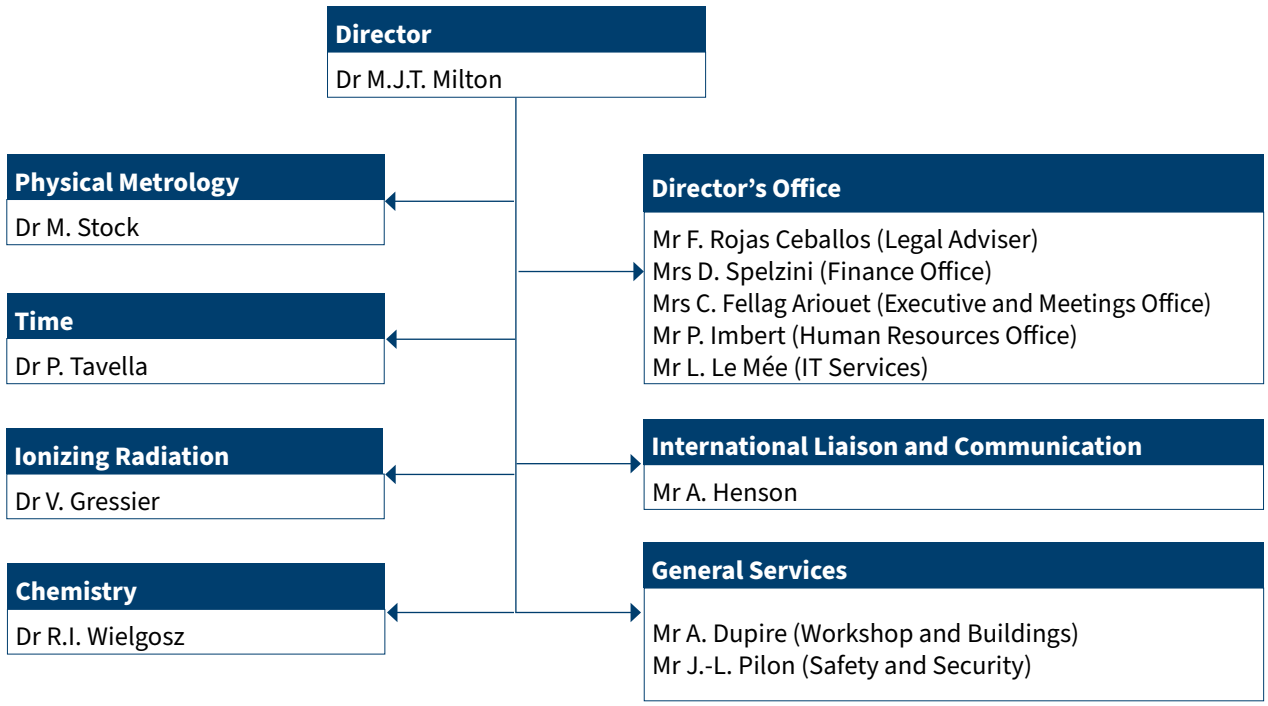
Vice-Presidents

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 N. Dimarcq (France)
Dr Y. Duan (People's Republic of China)
Dr H. Laiz (Argentina)
Dr T. Liew (Singapore)
Prof. P. Neyezhmakov (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)

Organigram of Headquarters Departments and Services



Publications

1. **Beginning of a new phase of the dissemination of the kilogram**
   Metrologia, 2021, **58**, 033002 https://doi.org/10.1088/1681-7575/abef9f
   Davidson S., Stock M.

2. **A new Interferometric System for the BIPM Kibble Balance**
   IEEE Trans. Instrum. Meas., 2021, **70**, 7002706 https://doi.org/10.1109/TIM.2021.3057930
   Bielsa F., Fang H., Kiss A., Stock M.

3. **Bilateral comparison of 1 Ω and 10 kΩ standards between the NSAI-NML (Ireland) and the BIPM**
   Metrologia, 2021, **58**, Tech. Suppl., 01008 https://doi.org/10.1088/0026-1394/58/1A/01008
   Rolland B., Stock M., Gournay P., Power O., Walsh R.

4. **Bilateral comparison of 10 V standards between the NSAI-NML (Ireland) and the BIPM**
   Metrologia, 2021, **58**, Tech. Suppl., 01006 https://doi.org/10.1088/0026-1394/58/1A/01006
   Solve S., Chayramy R., Stock M., Power O.

5. **Bilateral comparison of 1.018 V and 10 V standards between the BIM (Bulgaria) and the BIPM**
   Metrologia, 2021, **58**, Tech. Suppl., 01005 https://doi.org/10.1088/0026-1394/58/1A/01005
   Solve S., Chayramy R., Hadzhistoykova R., Marinov R., Stock M.

6. **Comparison of Josephson voltage standards of the MIKES and the BIPM**
   Metrologia, 2021, **58**, Tech. Suppl., 01007 https://doi.org/10.1088/0026-1394/58/1A/01007
   Solve S., Chayramy R., Immonen P., Nissilä J., Stock M.

7. **Bilateral comparison of 1 Ω and 10 kΩ standards between the EMI (United Arab Emirates) and the BIPM**
   Metrologia, 2021, **58**, Tech. Suppl., 01002 https://doi.org/10.1088/0026-1394/58/1A/01002
   Rolland B., Stock M., Gournay P., Bartholomew J., Al Kalbani W., Al Kayyoomi S.

8. **On-site comparison of Quantum Hall Effect resistance standards of the NMC A*STAR and the BIPM**
   Metrologia, 2021, **58**, Tech. Suppl., 01009 https://doi.org/10.1088/0026-1394/58/1A/01009
   Gournay P., Rolland B., Chua S.W., Lim K.H., Teck E.T.B.

9. **Comparison of the Josephson voltage standards of the MIKES and the BIPM**
   Metrologia, 2021, **58**, Tech. Suppl., 01007 https://doi.org/10.1088/0026-1394/58/1A/01007
   Solve S., Chayramy R., Immonen P., Nissilä J., Stock M., Manninen A.

10. **Characterization of the Frequency Dependence of the AC Resistors Used in the Quadrature Bridge of the BIPM**
    IEEE Trans. Instrum. Meas., 2021, **70**, 1003005 https://doi.org/10.1109/TIM.2020.3039303
    Angel Moreno J., Gournay P., Rolland B., Sakamoto N.

11. **New BIPM comparison BIPM.RI(II)-K1.Ac-225 of activity measurements of the radionuclide ^{225}Ac to include the 2019 result of the PTB (Germany)**
    Metrologia, 2021, **58**, Tech. Suppl., 06018 https://doi.org/10.1088/0026-1394/58/1A/06018
    Michotte C., Courte S., Nonis M., Coulon R., Judge S., Kossert K., Nähle O.

12. **New BIPM comparison BIPM.RI(II)-K1.Tb-161 of activity measurements of the radionuclide ^{161}Tb including the 2019 result of the IRA (Switzerland)**
    Metrologia, 2021, **58**, Tech. Suppl., 06009 https://doi.org/10.1088/0026-1394/58/1A/06009
    Michotte C., Courte S., Nonis M., Coulon R., Judge S., Juget F., Nedjadi Y., Durán M.T.

13. **Update of the BIPM comparison BIPM.RI(II)-K1.Co-60 of activity measurements of the radionuclide ^{60}Co to include the 2017 result of the PTB (Germany) and the 2018 result of the TAEK (Turkey)**
    Metrologia, 2021, **58**, Tech. Suppl., 06001 https://doi.org/10.1088/0026-1394/58/1A/06001
    Michotte C., Courte S., Nonis M., Coulon R., Judge S., Kossert K., Marganiec-Gałązka J., Nähle O., Yeltepe E., Dirican A.

14. **Update of the BIPM comparison BIPM.RI(II)-K1.Sr-85 of activity measurements of the radionuclide ^{85}Sr to include the 2018 result of the PTB (Germany)**
    Metrologia, 2021, **58**, Tech. Suppl., 06006 https://doi.org/10.1088/0026-1394/58/1A/06006
    Michotte C., Courte S., Nonis M., Coulon R., Judge S., Nälhle O., Takács M.

15. **Update of the BIPM comparison BIPM.RI(II)-K1.Ga-67 of activity measurements of the radionuclide ^{67}Ga to include the 2010 result of the PTB (Germany) and the 2010 result of the NIST (United States)**
    Metrologia, 2021, **58**, Tech. Suppl., 06017 https://doi.org/10.1088/0026-1394/58/1A/06017
    Michotte C., Courte S., Nonis M., Coulon R., Judge S., Ratel G., Fitzgerald R., Kossert K., Nähle O.

16. **New BIPM comparison BIPM.RI(II)-K1.Ra-223 of activity measurements of the radionuclide ^{223}Ra including the 2014 result of the NPL (United Kingdom), the 2014 result of the PTB (Germany) and the 2018 result of the LNE-LNHB (France)**
    Metrologia, 2021, **58**, Tech. Suppl., 06007 https://doi.org/10.1088/0026-1394/58/1A/06007
    Michotte C., Courte S., Nonis M., Coulon R., Judge S., Ratel G., Fréchou C., Cassette P., Keightley J., Kossert K., Nähle O.J.

17. **Update of the BIPM comparison BIPM.RI(II)-K1.Ag-110m of activity measurements of the radionuclide ^{110m}Ag to include the 2015 result of the PTB (Germany)**
    Metrologia, 2021, **58**, Tech. Suppl., 06002 https://doi.org/10.1088/0026-1394/58/1A/06002
    Michotte C., Courte S., Nonis M., Coulon R., Judge S., Ratel G., Kossert K., Nähle O.J.

18. **Update of the BIPM comparison BIPM.RI(II)-K1.Cd-109 of activity measurements of the radionuclide ^{109}Cd to include the 2012 result of the LNE-LNHB (France)**
    Metrologia, 2021, **58**, Tech. Suppl., 06026 https://doi.org/10.1088/0026-1394/58/1A/06026
    Michotte C., Courte S., Nonis M., Coulon R., Judge S., Ratel G., Fréchou C., Thiam C.

19. **Update of the BIPM comparison BIPM.RI(II)-K1.Gd-153 of activity measurements of the radionuclide ^{153}Gd to include the 2020 result of the NIST (United States)**
    Metrologia, 2021, **58**, Tech. Suppl., 06027 https://doi.org/10.1088/0026-1394/58/1A/06027
    Michotte C., Courte S., Nonis M., Coulon R., Judge S., Bergeron D.E., Cessna J.T., Fitzgerald R.P., Laureano-Perez L., Pibida L.

20. **Update of the BIPM comparison BIPM.RI(II)-K1.Co-60 of activity measurements of the radionuclide ^{60}Co to include the 2019 result of the VNIIM (Russian Federation)**
    Metrologia, 2021, **58**, Tech. Suppl., 06019 https://doi.org/10.1088/0026-1394/58/1A/06019
    Michotte C., Courte S., Nonis M., Coulon R., Judge S., Alekseev I.V., Zanevsky A.V., Zhukov G.V.

21. **The international reference system for pure beta-particle emitting radionuclides: an evaluation of the measurement uncertainties**
    Metrologia, 2021, **58**, 025007 https://doi.org/10.1088/1681-7575/abe355
    Coulon R., Judge S., Liu H., Michotte C.

22. **Key comparison BIPM.RI(I)-K3 of the air-kerma standards of the GUM, Poland, and the BIPM in medium-energy x-rays**
    Metrologia, 2021, **58**, Tech. Suppl., 06016 https://doi.org/10.1088/0026-1394/58/1A/06016
    Burns D., Kessler C., Michalik Ł.

23. **Key comparison BIPM.RI(I)-K3 of the air-kerma standards of the VNIIM, Russian Federation, and the BIPM in medium-energy x-rays**
    Metrologia, 2021, **58**, Tech. Suppl., 06003 https://doi.org/10.1088/0026-1394/58/1A/06003
    Burns D., Kessler C., Villevalde A.Y., Grishin D., Oborin A.V.

24. **Key comparison BIPM.RI(I)-K3 of the air-kerma standards of the ARPANSA, Australia, and the BIPM in medium-energy x-rays**
    Metrologia, 2021, **58**, Tech. Suppl., 06024 https://doi.org/10.1088/0026-1394/58/1A/06024
    Burns D., Kessler C., Hanlon M., Bailey T., Oliver C., Butler D.

25. **Key comparison BIPM.RI(I)-K1 of the air-kerma standards of the ARPANSA, Australia and the BIPM in ^{60}Co gamma radiation**
    Metrologia, 2021, **58**, Tech. Suppl., 06012 https://doi.org/10.1088/0026-1394/58/1A/06012
    Kessler C., Burns D., Oliver C., Bailey T., Butler D.

26. **Key comparison BIPM.RI(I)-K1 of the air-kerma standards of the BEV, Austria and the BIPM in ^{60}Co gamma radiation**
    Metrologia, 2021, **58**, Tech. Suppl., 06004 https://doi.org/10.1088/0026-1394/58/1A/06004
    Kessler C., Burns D., Steurer A., Tiefenboeck W., Merza V.

27. **Key comparison BIPM.RI(I)-K1 of the air-kerma standards of the GUM, Poland and the BIPM in ^{60}Co gamma radiation**
Metrologia, 2021, **58**, Tech. Suppl., 06011 https://doi.org/10.1088/0026-1394/58/1A/06011
Kessler C., Burns D., Knyziak A., Szymko M., Derlaciński M.

28. **Key comparison BIPM.RI(I)-K4 of the absorbed dose to water standards of the ARPANSA, Australia and the BIPM in ^{60}Co gamma radiation**
Metrologia, 2021, **58**, Tech. Suppl., 06013 https://doi.org/10.1088/0026-1394/58/1A/06013
Kessler C., Burns D., Oliver C., Bailey T., Harty P., Butler D.

29. **Key comparison BIPM.RI(I)-K4 of the absorbed dose to water standards of the BEV, Austria and the BIPM in ^{60}Co gamma radiation**
Metrologia, 2021, **58**, Tech. Suppl., 06008 https://doi.org/10.1088/0026-1394/58/1A/06008
Kessler C., Burns D., Steurer A., Tiefenboeck W., Merza V.

30. **Key comparison BIPM.RI(I)-K4 of the absorbed dose to water standards of the GUM, Poland and the BIPM in ^{60}Co gamma radiation**
Metrologia, 2021, **58**, Tech. Suppl., 06014 https://doi.org/10.1088/0026-1394/58/1A/06014
Kessler C., Burns D., Knyziak A., Szymko M., Derlaciński M.

31. **Key comparison BIPM.RI(I)-K7 of the air-kerma standards of the NMIJ, Japan and the BIPM in mammography x-rays**
Metrologia, 2021, **58**, Tech. Suppl., 06023 https://doi.org/10.1088/0026-1394/58/1A/06023
Kessler C., Burns D., Tanaka T., Kurosawa T.

32. **Comparison BIPM.RI(I)-K6 of the standards for absorbed dose to water of the LNE-LNHB, France and the BIPM in accelerator photon beams**
Metrologia, 2021, **58**, Tech. Suppl., 06005 https://doi.org/10.1088/0026-1394/58/1A/06005
Kessler C., Burns D., Roger P., Delaunay F., Donois M., Rapp B.

33. **Final report, on-going key comparison BIPM. QM-K1, ozone at ambient level, comparison with METAS, July 2020**
Metrologia, 2021, **58**, Tech. Suppl., 08012 https://doi.org/10.1088/0026-1394/58/1A/08012
Viallon J., Idrees F., Moussay P., Wielgosz R., Nierderhauser B.

34. **International comparison CCQM-K74. 2018: Nitrogen dioxide, 10 µmol mol^{-1}**
Metrologia, 2021, **58**, Tech. Suppl., 08018 https://doi.org/10.1088/0026-1394/58/1A/08018
Flores F., Viallon J., Idrees F., Moussay P., Wielgosz R., et al.

35. **qNMR characterization of potential peptide calibrators for isotope dilution LC–MS quantification of a SARS-CoV-2 IgG monoclonal antibody**
Meas. Sci. Technol., 2021, **33**(1), 014003 https://doi.org/10.1088/1361-6501/ac2fe9
Martos G., Westwood S., Bedu M., Josephs R.D., Wielgosz R.

36. **Metrological framework to support accurate, reliable, and reproducible nucleic acid measurements**
Anal. Bioanal. Chem., **414**, 2022, 791-806 https://doi.org/10.1007/s00216-021-03712-x
Milavec M., Cleveland M.H., Bae Y.-K., Wielgosz R.I., Vonsky M., Huggett J.F.

37. **Structurally related peptide impurity identification and accurate quantification for synthetic oxytocin by liquid chromatography–high-resolution mass spectrometry**
Anal. Bioanal. Chem., 2021, **413**, 1861-1870 https://doi.org/10.1007/s00216-021-03154-5
Li M., Josephs R.D., Daireaux A., Choteau T., Westwood S., Martos G., Wielgosz R. et al.

38. **Mass fraction assignment of Bisphenol-A high purity material**
Metrologia, 2021, **58**, Tech. Suppl., 08015 https://doi.org/10.1088/0026-1394/58/1A/08015
Westwood S., Martos G., Josephs R., Choteau T., Wielgosz R.

39. **Calibrant Assessment Guideline: DON, BIPM CAG-03**
Rapport BIPM-2021/02, 29pp
Josephs R.D., Li X., Bedu M., Daireaux A., Martos G., Li X., Guo Z., Li X., Gao Y., Choteau T., Westwood S., Li H., Wielgosz R.

40. **Purity Evaluation Guideline: AfB1**
Rapport BIPM-2021/01, 27pp
Westwood S., Josephs R., Martos G., Choteau T., Li Xiuqin, Li Xiaomin, Li Xianjiang, Guo X., Garrido B., Un I.

41. **Metrological Applications of NMR and qNMR in Organic Analysis**
Proc. of the International School of Physics "Enrico Fermi", 2021, **206**, 231-254 https://doi.org/10.3254/ENFI210028
Westwood S., Martos G., Stoppacher N., Wielgosz, R.

42. **Improving UTC with redundant time/frequency links**
Proc. IFCS-EFTF 2021, 7086
Petit G., Panfilo G.

43. **Statistical analysis of H-Masers to improve the long-term stability of UTC**
Proc. IFCS-EFTF 2021, 7114
Milton J., Panfilo G.

44. **Validation of the UTC information broadcast in the navigation messages by all GNSS**
Proc. IFCS-EFTF 2021, 7065
Defraigne P., Petit G., Pinat E.

45. **Sub-10^{-16} accuracy GNSS frequency transfer with IPPP**
GPS Solut., 2021, **25**, 22 https://doi.org/10.1007/s10291-020-01062-2
Petit G.

46. **A broadband VLBI system using transportable stations for geodesy and metrology - an alternative approach to the VGOS concept**
J. Geod., 2021, **95**, 41 https://doi.org/10.1007/s00190-021-01479-8
Sekido M., Leute J., Petit G., et al.

47. **Validation of a new BIPM calibration system based on GNSS receivers for TWSTFT links**
Proc. EFTF-IFCS 2021, 7174
Meynadier F., Petit G., Tisserand L., Rovera G.D., Achkar J., Uhrich P., Riedel F., Thai T., Sesia I., Courde C.

48. **Lasers and ultracold atoms for a changing Earth**
Eos, 2021, **102**, https://doi.org/10.1029/2021EO210673
Van Camp M., Pereira dos Santos F., Murböck M., Petit G., Müller J.

49. **Discontinuities in Coordinated Universal Time: advantages and perspectives**
Proc. URSI GASS 2021, Rome, Italy, 28 August - 4 September 2021
Levine J., Tavella P.

50. **BIPM Capacity Building and Knowledge Transfer programme on time scale realization**
Proc. URSI GASS 2021, Rome, Italy, 28 August - 4 September 2021
Tavella P., Hanado Y.

51. **Timekeeping and navigation systems**
Proc. of the International School of Physics "Enrico Fermi", 2021, **206**, 291-304 https://doi.org/10.3254/ENFI210031
Tavella P.

52. **Analysing and obtaining statistical information on time varying quantities**
Proc. of the International School of Physics "Enrico Fermi", 2021, **206**, 273-290 https://doi.org/10.3254/ENFI210030
Tavella P.

53. **GNSS-to-GNSS Time Offsets: Study on the broadcast of a common reference time**
GPS Solut., 2021, **25**, 61 https://doi.org/10.1007/s10291-020-01082-y
Sesia I., Signorile G., Thai T.T., Defraigne P., Tavella P.

54. **Statements from International Union of Radio Science (URSI) on the Need for a Continuous Reference Timescale**
URSI Radio Science Letters, 2021, **3**, 1-4 https://doi.org/10.46620/21-0047
Koyama Y., Tavella P., Levine J.

55. **An evolutionary algorithm for consensus building in inter-laboratory comparisons**
Metrologia, 2021, **58**, 065007 https://doi.org/10.1088/1681-7575/ac31c0
Coulon R., Judge S.

56. **News from the BIPM laboratories - 2020**
Metrologia, 2021, **58**, 015018 https://doi.org/10.1088/1681-7575/abcec7
Wielgosz R.I, Tavella P., Judge S., Stock M., Milton M.J.T.

57. **The metric system, the Metre Convention and the BIPM**
Proc. of the International School of Physics "Enrico Fermi", 2021, **206**, 155-174 https://doi.org/10.3254/ENFI210024
Milton M.J.T., Fellag Ariouet C.

58. **Metrological traceability: A global perspective**
Proc. of the International School of Physics "Enrico Fermi", 2021, **206**, 215-230 https://doi.org/10.3254/ENFI210027
Henson A.

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