Report on the work programme of the BIPM electricity laboratories

CCEM meeting
24 March 2017
# Physical Metrology Department, since October 2015

<table>
<thead>
<tr>
<th>Role</th>
<th>Name</th>
<th>Position</th>
</tr>
</thead>
<tbody>
<tr>
<td>Impedance Principal Physicist</td>
<td>Dr Pierre GOURNAY</td>
<td>Principal Physicist</td>
</tr>
<tr>
<td></td>
<td>Nick FLETCHER</td>
<td>Physicist</td>
</tr>
<tr>
<td></td>
<td>Benjamin ROLLAND</td>
<td>Assistant</td>
</tr>
<tr>
<td>Voltage Principal Physicist</td>
<td>Dr Stéphane SOLVE</td>
<td>Principal Physicist</td>
</tr>
<tr>
<td></td>
<td>Régis CHAVRAMY</td>
<td>Technician (also imped.)</td>
</tr>
<tr>
<td>Watt balance Principal Physicist</td>
<td>Dr Hao FANG</td>
<td>Principal Physicist (CCM)</td>
</tr>
<tr>
<td></td>
<td>Dr Franck BIELSA</td>
<td>Physicist</td>
</tr>
<tr>
<td></td>
<td>Dr Shisong LI</td>
<td>Res. fellow</td>
</tr>
<tr>
<td></td>
<td>Adrien KISS</td>
<td>Assistant</td>
</tr>
<tr>
<td>ERMS Principal Physicist</td>
<td>Dr Estefania de MIRANDES</td>
<td>Principal physicist (CCU, 80%)</td>
</tr>
<tr>
<td></td>
<td>Faraz IDREES</td>
<td>Technician (also pressure, 50%)</td>
</tr>
<tr>
<td>Mass calibr. Assistant</td>
<td>Pauline BARAT</td>
<td>Assistant (also ERMS)</td>
</tr>
<tr>
<td></td>
<td>Damien BAUTISTA</td>
<td>Technician (also QMS)</td>
</tr>
</tbody>
</table>
BIPM comparisons

Organized by BIPM

BIPM.EM-K10.a/b  JVS on-site comparison, 1.018 V and 10 V
BIPM.EM-K11.a/b  Zener voltage, 1.018 V and 10 V
BIPM.EM-K12     QHR on-site comparison, $R_h(2)/100 \, \Omega$, $100 \, \Omega/1 \, \Omega$, $100 \, \Omega/10 \, k\Omega$
BIPM.EM-K13.a/b  resistance, 1 \, \Omega and 10 \, k\Omega
BIPM.EM-K14.a/b  capacitance, 10 pF and 100 pF at 1592 Hz and/or 1000 Hz
CCEM-K4.2017      capacitance, 10 pF at 1592 Hz (optional 100 pF, 1233 Hz)

Future acJVS comparison

BIPM participation

EURAMET.EM-S31   capacitance and capacitance ratio
GULFMET.EM.BIPM-K11 Zener voltage at 1.018 V and 10 V
BIPM.EM-K10: on-site Josephson comparison (1.018 V and 10 V)

- On average 2 comparisons / year
- Technical expertise and improvements leading to better results for 85% of the comparisons
- Typical uncertainty: a few nV, parts in $10^{10}$
BIPM.EM-K10.b: on-site Josephson comparison (10 V)

► June 2015: DMDM-Serbia, 10 V:

\[
\frac{(U_{\text{DMDM}} - U_{\text{BIPM}})}{U_{\text{BIPM}}} = -0.1 \times 10^{-10} \quad u_r = 1.5 \times 10^{-10}
\]

► November 2015: NIMT-Thailand, 10 V:

\[
\frac{(U_{\text{NIMT}} - U_{\text{BIPM}})}{U_{\text{BIPM}}} = -1.0 \times 10^{-10} \quad u_r = 2.6 \times 10^{-10}
\]

► June 2016: JV-Norway:

No satisfactory result could be obtained, due to instability of JV standard

No K10-comparisons planned for 2017, to concentrate on ac measurements
BIPM.EM-K10.b: on-site Josephson comparison (10 V)
First trial of an ac Josephson voltage comparison, at CENAM

\[ U_{\text{CENAM}} - U_{\text{BIPM}} = (0.7 \pm 0.3) \text{ ppm at 7 V rms, 50 Hz} \]

\[ U_{\text{CENAM}} - U_{\text{BIPM}} = (0.2 \pm 0.3) \text{ ppm at 0.7 V rms, 50 Hz} \]
First trial of an ac Josephson voltage comparison, at CENAM

- Stepwise approx. sinewave at 50 Hz
- Differential sampling with a continuous sinewave

Frequency reference

PJVS CENAM

PJVS BIPM

AC source (multifunction cal.)

Sampling DVM

In 2017 comparisons with NPL and PTB, in framework of EMPIR project ACQ-PRO

Secondment from KRISS being planned to develop this further
Start: September 2017
New RMO provisionally accepted by CIPM for participation in MRA

- Attend JCRB meetings (without voting right)
- Be invited to CC WG meetings
- Minimum waiting period for full membership of 1 year (technical competence essential, eg. comparisons)

4 SCs started

First KC:
GULFMET.EM.BIPM-K11 (SCL, SASO, EMI, KRISS, BIPM)
GULFMET.EM.BIPM-11, Zener voltage

Pilot lab: SCL Hong Kong (Steven Yang)

Participants
• BIPM
• KRISS, Rep. of Korea
• QCC EMI, UAE
• SASO, Saudi Arabia

BIPM contribution
• member of support group
• 2 measurement periods
• determination of sens. coeff. of Zeners ($T$, $p$)
• Steven Yang on secondment at BIPM for 2 months

1. Example of CB&KT project in PMD
Re-determination of Zener temperature coefficients

- 2 zeners in the enclosure
- 4 coefficients measured
- 10 V reference: 732A Fluke Zener
- 1 V reference: Weston cell
Measurement setup

- Nanovoltmeters
- P,T
- Switching unit
- Switching relays
- 10 V reference
- 732B under invest.
- Standard Cell

Equation:

\[ BIPM \]

Transportable

JVS:

\[ LRG = 10 \Omega \]

\[ = 100 \text{G} \]

P,T Standard Cell

732B under invest.
Zener temperature coefficients for 10 V output

The uncertainty on all temperature coefficients has been reduced considerably (better temp. stability of chamber).
Zener thermistor reference value (at 23°C RT)

- Normal operating range between 36.5 kΩ and 42.5 Ω
- Should not change by more than 900 Ω/year (manufacturer)

Most of the reference thermistor resistance values increased, indicating a lower oven temperature.
Conclusion


NSAI- BIPM bilateral Zener comparison – 2016

- the change of $T_c$ and $R_{\text{ref}}$ has negligible effect: 20 nV ($2 \times 10^{-9}$)
Bilateral resistance comparisons, BIPM.EM-K13.a/b, 1 Ω and 10 kΩ

► 2013/2014: BIM-Bulgaria
published in 2017

► 2013/2014: NPL-India
Draft B under review

► 2014: NSAI-Ireland
published in 2017

► 2015: NIMT-Thailand
published in 2017

► 2015: CMI-Czech Republic
published in 2017

► 2016/17: SMD-Belgium
Draft A under preparation

► 2017: NMISA-South Africa
measurements under way at NMISA
Bilateral resistance comparisons, BIPM.EM-K13.a/b, 1 Ω and 10 kΩ
On-site quantum Hall resistance key comparison (BIPM.EM-K12)

- To verify international coherence of primary resistance standards by comparing quantum Hall effect based standards of the NMIs with that of the BIPM
- Five such comparisons have already been carried out in the period 1993 to 1999. This comparison has been resumed in 2013 at the request of the CCEM
- A first comparison has been carried out with the PTB in Nov 2013
- 15 new comparisons are expected for the coming years
On-site quantum Hall resistance key comparisons (BIPM.EM-K12)

October 2015: comparison at VSL
• unexpected behavior of VSL equipment
• no publishable result

December 2016: comparison at METAS
• Resistors brought to METAS in September
• Postponed by METAS until unknown date

Next try: CMI in April 2017
Behaviour of 1 Ω resistors

Typical frequency dependence for 1 Ω and 100 Ω standard resistors

Value of 1 Ω res. increases with cycle time

Origin: Peltier effect

Magnitude of effect resistor dependent

Which is “true” (dc) value?

Metrologia 52 (2015) 509-513
Some evidence from resistance comparisons (BIPM.EM-K13)

CMI investigated the effect and applied a correction (24s, 340 s)
Investigations towards a compact next-generation QHR reference

Graphene QHR samples

- lower field (5 T)
- Higher temperature (4-5 K)

Carrier density of new G-SiC devices usually too high, needs to be adjusted

Investigation of techniques for \( n_e \) adjustment:

- UV light
- electrost. discharge
- NH\(_3\) gas

Poster at CPEM 2016 (with PTB, MIKES, Aalto Univ.)

LFCC bridge at room temperature

- cryogen free
- operating \(< 1\text{Hz}, \text{small ac-dc correction}\)

Investigation of LFCC operating below 1 Hz, based on new high permeability materials (nanocrystalline mat.);

Comparison between two new LFCCs and the 1 Hz BIPM LFCC

Poster at CPEM 2016 (with PTB, MIKES)
Bilateral capacitance comparisons, BIPM.EM-K14.a/b

- 2016: **NIS-Egypt**, 10 pF and 100 pF
  Draft B under review

- 2016: **NMISA-South Africa**, 10 pF and 100 pF
  Draft B under review

- 2016: **NSAI-Ireland**, 100 pF
  Final Report, to be published soon
CCEM-K4: capacitance, 10 pF at 1592 Hz (opt. 100 pF, 1233 Hz)

Comparison scheme:
→ star scheme, $N$ bilateral comparisons carried out simultaneously
→ advantage to shorten considerably the time duration of the comparison

BIPM meas.: May-June 2017
Draft A: December 2017

1- Each NMI measure its own standards
   → measurements carried out simultaneously in all NMIs

2- All NMIs send their standards to BIPM
   → measurement by BIPM of all standards simultaneously

3- Again, each NMI measure its own standards
   → measurements carried out simultaneously in all NMIs
Comparisons in capacitance: EURAMET-S31

• EURAMET.EM-S31 comparison of 10 pF and 100 pF standards for measurements traceable QHR – piloted by PTB, participation of LNE, METAS, VSL and BIPM. Circulation of standards 2010-2011.

• First round revealed significant frequency-dependent discrepancies.

• A supplementary circulation of ac-dc resistors in 2013 gave excellent results and eliminated one suspected cause of errors.

• Some participants discovered systematic bridge errors and submitted corrections.

• A new circulation of capacitance standards has started end 2014, this time to include calculable capacitor traceability from NMIA.

• Draft A: All results found in agreement.

➢ “...the ac measuring technique is prone to delicate systematic effects and a comparison is a proper instrument to rectify the ac measuring bridges of the participants. “
Calibrations

voltage: Zeners at 1.018 V, 10 V 2-3 per year
resistance: 1 Ω, 100 Ω, 10 kΩ 25-30 per year
capacitance: 1 pF, 10 pF, 100 pF 25-30 per year
Determining $R_K$ with a calculable capacitor with best unc. ever

Capacitance $\quad$ Quadrature bridge $\quad$ Resistance

$\omega^2 C_1 C_2 R_1 R_2 = 1$

Classical $\quad$ Quantum

Calculable capacitor

$$\Delta C = \frac{\varepsilon_0 \log e}{\pi} \Delta l$$

For $\Delta l \approx 0.2$ m, $\Delta C \approx 0.4$ pF

To compare $C$ to $R$, we also have to chose a frequency, $f$

(in our case, $f \approx 1$ kHz)

Quantum Hall effect

(2-d electron gas, $B \approx 10$ tesla, $T < 1$ K)

$$R_{\text{hall}} = R_K / i \quad (i = 1, 2, 4...$$

$$R_K = h / e^2 \approx 25.8 \text{ k}\Omega$$

for $i = 2$ plateau: $R \approx 13$ k\Omega

Target uncertainty for $R_K$: $1 \times 10^{-8}$
First measurements with calculable capacitor

Estimated uncertainty $0.31 \text{ ppm in } 1\sigma$

Repeatability $0.01 \text{ ppm}$

New iodine-stabilized laser source

Offset of $0.26 \text{ ppm}$ due to imperfect electrode alignment
Status of calculable capacitor

- New stabilized laser source has been built to fix the laser frequency instabilities detected during measurements

- The CC has been disassembled, relocated in a new room offering a floor of much better stability and, then, realigned with geometrical error of the order of $3 \times 10^{-9}$ (sub-μm accuracy)

- Better alignment thanks to new precision alignment probe, for residual skew and diagonal spacing of main electrode bars

- The completion of the reassembling and the start of new series of measurements are planned for the coming months

- Target uncertainty: $1 \times 10^8$

mobile clean room cabin
Watt balance: Major achievements during 2014-2016

- precision alignment of the magnetic circuit, publ. in *Metrologia*
- assembly of the improved apparatus on a new open support structure
- integrated mass exchanger
- re-arrangement of control and measurement units; electrical, optical links and vacuum feedthroughs
- completion and integration of the new interferometer
- new control and acquisition programs using FPGA & data synchronization scheme
- compact and vacuum compatible mechanical mounts for optics
- detailed study of effect of current on magnetic field profile (reluctance force), submitted to *Metrologia*
Assembly of the improved apparatus completed

mass exchanger

interferometer
New interferometer

Objective: minimize periodic non-linearity observed previously

- Heterodyne frequency of about 3 MHz
- Spatially separated beams
- Non-polarizing elements
- Differential output
  - noise level: 1/6000 fringe
  - S/N level improved by factor of 5
Last measurements, early 2016

$m = 100 \, g$

$v = 0,2 \, mm/s$

Main uncertainty components:
- alignment: $2 \times 10^{-6}$
- statistics: $3 \times 10^{-6}$ (one night measurement)
Outlook

1 July 2017

- bifilar coil
- better alignment
- possibly 1 kg
- PJVs
- noise reduction in force meas.
- vacuum

**target uncertainty**

\[ u_r(h) = 1 \times 10^{-7} \]

closing date for new data

design of a new suspension (motor & alignment mechanism) to further improve alignment & operation
Outlook in to the future

- Maintain travelling quantum standards which eliminates need for some CCEM comparisons

- Development of more versatile and more efficient quantum standards
  - acJVS for comparison of ac voltages
  - Table-top QHR system using graphene samples and new LFCCs at room temperature
  - acQHR as impedance standard

- Calibration service for ac/dc transfer standards using acJVS?

- Replace 1 Ω comparisons and calibrations by higher values (> 10 kΩ)? Which values (1 MΩ)?