

Report related to the CCM activities of the French metrology at LNE, Cnam and OBSParis (2019-2020)

1 Main research and development activities

1.1 Mass

1.1.1 Dissemination of the kilogram

The dissemination of sub-multiples of the kilogram up to 1 mg was carried out following phase 1 of the implementation of kilogram redefinition. Uncertainties have been recalculated.

1.1.2 Kibble balance

The Kibble balance experiment developed at LNE in collaboration with the CNAM and the LNE-SYRTE has obtained a value of the Planck constant with a relative standard uncertainty of 5.7 parts in 10⁸ in 2017. From this result, obtained in air at atmospheric pressure, LNE has decided to continue the developments on the KB to realise the kilogram with an aimed uncertainty of a few parts in 10⁸. Improvements of different parts of the set-up are ongoing, mainly to improve the Type A uncertainty of the experiment, and to be able to work under vacuum (and thus improving Type B uncertainty).

Significant mechanical modifications around the concrete slab, which supports the apparatus, but also of the bearing structure of the apparatus (“V-shaped feet” to “pillar feet”), allow to increase the immunity of the experiment to nearby activity but also lead to a significant improvement of the noise rejection in dynamic phase.

Mechanical stability of the structure, of the coil and its suspension, but also of optics in vacuum, was confirmed with an uncertainty of some tens of microradians.

Dynamic phases have been carried out in vacuum, as well as static phases: kilogram determinations will be the next step (mid-2021).

1.1.3 Electrostatic balance

A new project aiming to realize the unit of mass in the milligram range using an electrostatic force balance in the revised SI started in 2020. The balance is still in the design phase, the first elements will be manufactured in the first half of 2021. A new laboratory has been set up to accommodate the balance.

1.2 Force and torque

1.2.1 500 N m Torque lever and deadweight machine

The metrological qualification of the new LNE 500 N m torque standard machine has been completed. A comparison was carried out with CEM. Results were satisfactory and the study has been published. Uncertainties of this new 500 N.m reference torque machine is equal to :
(3 mN m + $5 \cdot 10^{-5} \cdot T$) ($k=2$) , for an applied torque (T) from 10 N m to 500 N m.

1.2.2 Force deadweight machine 500 kN and 5 kN

New method for re-calibration of the mass of those machines, letting them inside the machine, have been study. It have been applied with satisfactory results for firsts mass. Calibration will be made for the other masses of force standard machines 500 and 5 kN.

1.3 Pressure and vacuum

1.3.1 Vacuum

A new method for determining volumes with complex shapes has been developed. The method is based on pressure rise measurements performed with a constant-volume flowmeter set-up. This method exhibits a standard relative uncertainty between 0.03 % and 2 % for volumes ranging from 1 to 3000 cm³, which is only about one order of magnitude higher than capabilities of the gravimetric volume calibration. An accreditation has been obtained from COFRAC.

1.3.2 High pressure references

The high-pressure gas standards cover a pressure range from 1 MPa up to 50 MPa. These standards are composed of three reference piston-cylinder assemblies and three working assemblies. Cross comparisons as well as comparisons with the 1MPa primary references allowed us to redefine the effective sections at zero pressure of these standards and the distortion coefficients. The consistency of the new effective areas values show deviations of less than 5 ppm from those recorded in our database of more than 20 years of history.

1.4 Gravimetry

Gravimetry activities are carried out by LNE-SYRTE. Activities cover:

- Absolute gravimetry, with the realization of a Cold Atom Gravimeter (CAG) in the frame of the LNE watt balance project
- Relative gravimetry, with the operation of a Scintrex spring gravimeter for the transfer of the value of g, and an iGrav superconducting gravimeter, for the monitoring of long term gravity variations

These activities contribute to the National Service of Observation in Gravimetry (http://igets.u-strasbg.fr/SG_france.php) and to the International Geodynamics and Earth Tide Service (IGETS) (<http://isdc.gfz-potsdam.de/igets-data-base/>)

1.4.1 Characterization of the CAG

- Study of the impact of direct-digital-synthesizer finite resolution on the phase of atom gravimeters
- Improved determination of systematic effects related to light shifts

1.4.2 Characterization of the iGrav

- Continuous measurements with the iGrav : monitoring of gravity fluctuations, monitoring of the drift of the iGrav, delivery of continuous calibrated gravity measurements to the watt balance
- Regular calibrations of the iGrav scale factor. Evaluation of the uncertainty in the determination of the scale factor.

1.4.3 Ties and vertical gravity gradients (vgg) in the laboratories

Some ties and vgg are regularly determined on the gravimetry pillar. A new complete mapping on the Watt balance pillar has been performed in summer 2019.

1.4.4 g determination for LNE Kibble Balance

1.4.5 Other activities

- Development of a cold atom gradiometer : realization of gravity gradient measurements with laser beamsplitters based on Bragg transitions
- Study of cold atom gradiometry and accelerometry for space geodesy applications
- Test and validation of a prototype industrial laser systems for space applications

1.5 Participation in research projects

1.5.1 EURAMET (EMRP)

- JRP 18SIB04: Towards quantum-based realizations of the pascal

The project started in 2019. The overall objective is to develop two new primary pressure standards based on a quantum approach directly traceable to the SI, and to improve absolute pressure uncertainties especially in the range 1 Pa to 10 kPa.

The new standards developed by LNE-CNAM will be based on a Fabry-Perot cavity refractometer and a micro-wave cavity.

Three departments are involved in this project: pressure, length and temperature.

The project is ongoing, it will end in 2022.

- JRP 16NRM05 : Towards a documentary standard for an ionisation vacuum gauge

The overall objective was to determine and specify all relevant parameters to enable an ISO standard for an ionisation gauge so that this gauge is accurate, robust and long-term stable. The project has allowed strengthening the metrological and technological basis of the ISO NP TS 20175 and 20177, which required a reliable ionization gauge. LNE was mainly involved in WP1 (Fundamental physics for the design of ionization gauges) and WP3 (Testing ionization gauges).

The project ended in 2020

2 Participation in relevant comparisons

2.1 Euramet Comparisons

- EURAMET M.M- K4. The scope was calibration of 1 kg stainless steel mass standards against the secondary stainless steel mass standards of the participants. The results obtained by the LNE confirm the CMC.

- EURAMET 1452 The aim of this project is to compare the results of the calibrations of a 20, a 50 and a 250 L proving tank. Measurements are completed. Draft A is in progress.

- EURAMET M.F K3 : Force comparison at 1 MN
PTB pilots this comparison. Measurements at LNE were carried out in 2014. Sixteen laboratories participate. Draft A is in progress.

- EURAMET M.T-S4 (Project 1304) : Torque comparison from 0.1 up to 50 N m
Measurements with PTB have been performed in 2017. Uncertainties claimed by LNE, lower than CMCs, were not supported. But LNE registered CMCs were supported. The final report is underway.

- EURAMET M.T-S5 (Project 1428) : Torque comparison up to 5000 N m.
In order to verify the validity of the protocol, a preliminary study comparison was carry out with CEM and NMIJ. Results are satisfactory. The official comparison with PTB have been registred. Measurements will started in 2021.

- EURAMET M.T-Sx : Torque comparison up to 5 N m.
A preliminary study comparison was carried out with NMIJ to validate the protocol. Results were not satisfactory (instability on NMIJ measurements), a new preparatory comparison will be planned, with PTB.

- EURAMET M.T-Sx : Torque comparison up to 50 N m.
In order to validate of the protocol, a preliminary study comparison was carried out with CEM. The results are satisfactory and confirm the new uncertainties of the LNE reference. The official comparison could be now registered.

- EURAMET M.T-Sx : Torque comparison up to 500 N m.
A preliminary study comparison was carried out with CEM to validate the protocol. Results were satisfactory and the study has been published. The official comparison with PTB could be now registered.

2.2 CIPM comparisons

- Key comparison in the field of R-134a refrigerant leaks.

During the CCM pressure meeting in February 2014, LNE proposed to pilot a key comparison for leaks flowing to the atmosphere (R-134a gas, for leak rates around 3 grams per year (g / a)). This comparison has been initiated in 2020, the characterization of the transfer standard is currently under study.

- CCM.MF K3 : Force comparison at 500 kN

PTB pilots this comparison. Measurements at LNE were carried out in 2007. This key comparison is approved for equivalence and results have been published in 2019 in Metrologia. Uncertainty LNE claims are supported (all $E_n < 1$).

- EURAMET M.F K23 : Force comparison at 200 and 500 N

METAS pilots this comparison. LNE reference transducers are used. Thermal characteristics of these references have been improved. Measurements should start at the beginning of 2021.

2.3 Other comparisons

Comparisons with atomic and corner-cube absolute gravimeters: A10-043 (IGN), A10-014 (IGN, IRD et IPGP), AQG-A01 (OMP) and AQG-B01 (RESIF)

3 List of relevant publications of the French metrology

- Djilali Bentouati, Pierre Otal et Marc Plimmer, « Development of calibration methods for differential pressure measurements with line pressures up to 10 MPa », CIM 2019, 19th congrès international de Métrologie, Paris
- K.Jousten, F. Boineau, N. Bundaleski, C. Illgen, J. Setina, O. Teodoro, M. Vicar, M. Wüest , “A review on hot cathode ionisation gauges with focus on a suitable design formeasurement accuracy and stability”, Vacuum [Volume 179](#), September 2020, 109545
- Otal P. - Yardin C, “Modelling methods for pressure balance calibration”, Measurement Science and Technology ; vol 31 ; n°3 ; 034004 (2020)
- Boineau F.; Elkatmis A.; Kangi R.; Becker U.; Jousten K, “Time stability characterization of quadrupole mass spectrometers”, Measurement ; Volume 165 ; 1 December ; 108143; 14 (2020)
- Silvestri Z., Bentouati D., Otal P., Wallerand J-P “Towards an improved helium-based refractometer for pressure measurement”; Acta Imeko ; Volume 9, Number 5, december ; p305-309 ; 5p ; ISSN: 2221-870X (2020)
- Boineau F., Plimmer M.D., Mahe E, « Volume calibration using a comparison method with a transfer leak flow rate”, Acta Imeko ; Volume 9, Number 5, december ; p343-348 ; 6p ; ISSN: 2221-870X (2020)
- M. Thomas, P. Espel, D. Ziane, P. Pinot, and F. Piquemal, « La redéfinition du kilogramme et la balance de Kibble », Les reflets de la mesure, n°62, p18-21 (2019)
- M. Thomas, “ Kilogram and new SI definitions”, High Temperatures - High Pressures, 48(3), p193-205

- Patrick Espel, Djamel Ziane, Florian Beaudoux, Kamel Dougdag and Matthieu Thomas, "LNE Kibble balance progress report: modifications for vacuum operation", CPEM2020
- F. Beaudoux, P. Espel, P. Pinot, F. Piquemal, M. Thomas, D. Ziane; "News from LNE Kibble balance", Kibble balance technical meeting, Teddington, octobre 2019
- R. Caldani, K. Weng, S. Merlet, F. Pereira dos Santos, "Simultaneous accurate determination of both gravity and its vertical gradient", *Phys. Rev. A* 99, 033601 (2019)
- Trimeche, B. Battelier, D. Becker, A. Bertoldi, P. Bouyer, C. Braxmaier, E. Charron, R. Corgier, M. Cornelius, K. Douch, N. Gaaloul, S. Herrmann, J. Müller, E. Rasel, C. Schubert, H. Wu, F. Pereira dos Santos, "Concept study and preliminary design of a cold atom interferometer for space gravity gradiometry", *Classical and Quantum Gravity* 36, 215004 (2019)
- R. Caldani, S. Merlet, F. Pereira dos Santos, G. Stern, A.-S. Martin, B. Desruelle, V. Ménoret, "A prototype industrial laser system for cold atom inertial sensing in space", *Eur. Phys. J. D* 73, 248 (2019)
- R. Karcher, F. Pereira dos Santos, S. Merlet, "Impact of direct-digital-synthesizer finite resolution on atom gravimeters", *Phys. Rev. A* 101, 043622 (2020)
- R. Geiger, A. Landragin, S. Merlet, F. Pereira dos Santos, "High-accuracy inertial measurements with cold-atom sensors", *AVS Quantum Sci.* 2, 024702 (2020)
- R. Kumme, P. Averlant, T. Bartel, A. Germak, A. Knott, J. Man, N. Medina, A. Ostrivnoy, You-Kyu Park, D. Röske "Final report on the force key comparison CCM.F-K3" *Metrologia*, vol 56, 07001 (2019)
- P. Averlant and C. Duflon, "Development and metrological characterisation of the new LNE 500 N.m deaweight torque standard machine", *Acta IMEKO Vol 9, No 5*, 168-172, Dec. 2020