Progress Report on Electrical Metrology at METAS from 2021 to 2023

Report prepared for the 33rd meeting of the Consultative Committee for Electricity and Magnetism (CCEM)

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1. Electrical Quantum Standards & DC/LF Metrology

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1.1 Dual Josephson Impedance Bridge

The Dual Josephson Impedance Bridge (DJIB) is the result of a joint development with NIST. It consists of using the sampling bridge technique with two independent voltage sources based on Josephson Arbitrary Waveform Generator Synthesizers (JAWS). JAWS display quantum-accurate distortion-free voltage waveforms over frequencies between a few hertz and 1 MHz. Thanks to the independence of the sources, a single bridge can compare any impedance in the complex plane as arbitrary voltage ratios or phase shifts can be generated. The DJIB has been optimised and is now fully functional in the 1 kHz to 80 kHz frequency range. It displays remarkable agreement with a classical calibration chain, with uncertainties ranging between 0.01 ppm and 0.23 ppm (k = 1) for impedance ratio 1:1, and 0.04 ppm and 0.35°ppm for the 1:10 ratio [1-3].

The current development aims at using graphene for the impedance standard of the bridge, whereby the DJIB relies on three quantum references. This work is being carried out in the framework of the EMPIR GIQS project [4] and measurements of a 10 nF capacitor at 1233 Hz are under way.

1.2 Computational traceability

Simulations have been used in several collaborations with the industry in order to establish traceability for impedances [5]. The approach has been applied to a broad range of fields, such as contactless measurements using eddy-current techniques, calculations of resistive and capacitive standards for impedance analysers measuring up to 500 MHz. These new skills are particularly useful for complex geometries and to connect traceable measurements across the RF-LF gap, typically between 100 kHz and 500 MHz, where traceability using classical artefacts is not achievable. In particular, the physics of a Haddad-type resistor standard has been investigated taking into account the EM-field propagation and the effect of connectors, which dominate above 30 MHz.

New four-terminal pair coaxial resistive standards of 100 Ω and 1 kΩ have been designed and prototyped. Measurement results have been confronted with calculated values taking into account connector effects by means of FEM simulations and mathematical modelling. The major

finding is that deviations are solely to be ascribed to connectors. The uncertainties are better than those achieved using a VNA at frequencies below 200 MHz for the magnitude, and below 25 MHz for the time constant [6].

1.3 Electrochemical impedance spectroscopy for Li-ion cells

Following the extension of the METAS impedance simulator to the low impedance and frequency ranges, new CMCs have been published. The trigger for this development was the EMPIR LibForSecUse project [7]. The enhanced impedance simulator has also been successfully used in the Horizon 2020 Nanobat project for an interlaboratory comparison of batteries assessed by means of electrochemical impedances spectroscopy (EIS).

The setup for the EIS measurement of cylindrical cells (type 18650 Li-ion battey) is now fully operational.

1.4 Realisation of the kilogram

METAS has further improved its Kibble Balance experiment by implementing a series of optimisation steps. The experimental setup was thoroughly tested and each component, procedure, alignment and possible source of systematic errors were carefully investigated and validated. Thanks to its stability and reliability, high precision measurements can now routinely be performed under vacuum following two measurement campaigns in 2021 with 1 kg stainless steel test masses. The result differed from the value deduced from the calibration following the dissemination process after the redefinition of the kilogram by 6 µg with a total standard uncertainty of 43 µg (k = 1). The type A component to the uncertainty budget was evaluated using an Allan deviation analysis for each data set. A specific uncertainty was evaluated as a type B component for the polynomial fit in the dynamic phase of the experiment [8,9].

Following this project completion, the METAS Kibble balance is now fully operated by the mass laboratory and is participating in the activities led by the BIPM to determine the consensus value of unit mass.

2. Power and Energy

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2.1 Capabilities for flicker measurements

To support its power quality measurement capabilities, METAS has developed a primary standard for flicker applying the procedure described in the IEC 61000-4-15 standard. The device is able to measure the instantaneous flicker severity (P_{inst}) and the short-term flicker severity (P_{st}) in both square and sine wave modulations for the test cases at 120 V / 60 Hz and 230 V / 50 Hz described in the standard. METAS submitted CMCs for this measurement capability in March 2022. The CMCs were approved and published in January 2023.

2.2 Capabilities for high voltage measurements at 16.7 Hz

METAS has a long tradition performing traceable calibration of current transformers, instrument transformer comparators and instrument transformer burdens. METAS is now also able to perform traceable calibration in the field of high voltage at 16.7 Hz, whereby the needs of railway industry in Germany, Austria, Sweden, Norway and Switzerland can be satisfied. With this last puzzle piece, METAS is now able to cover the whole package from high voltage and high current power lines to the energy meter at 16.7 Hz.

3. RF & Microwave

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3.1 Impedance and Network Analysis

The VNA metrology software *VNA Tools* (www.metas.ch/vnatools) has been further developed and enhanced. Many bug fixes, small and larger extensions, convenience features and driver updates have been added. The support of non-linear measurements is partly realised and currently being extended. The software has continued to broaden its user base. So far there are more than 2000 registered licensees of *VNA Tools* and more than 300 persons have visited the three-day introductory course, which is provided by METAS. The courses are to an increasing degree being hosted by measurement device manufacturers, such as e.g. National Instruments (Austin, TX), and Tektronix (Portland, OR) in 2022. This demonstrates the interest in the software by key players in the field. The VNA Tools Real Time Interface (RTI), a stable high-level interface for integration of VNA Tools functionality into an existing software environment, has been licensed for two commercial applications: Option K50 of the Rohde&Schwarz ZNA allows real-time measurement uncertainties to be displayed on the VNA screen using VNA Tools functionality. The VNA software *Insight* by Maury Microwave also uses *VNA Tools* in the background through the RTI.

Developments of data cables are pushing to higher frequencies to support higher data rates. The laboratory works on extending the upper frequency limit of cable testing systems from a few GHz to 30 GHz. For this purpose, a calculable adapter is under development in cooperation with a Swiss company.

A new method was also evaluated to determine the receiver linearity in a vector network analyser [10].

3.2 RF power and Noise

The consortium for the development of a novel primary power standard based on the electro-optical effect consists of METAS (RF&MW lab and Photonics, Time & Frequency lab), the University of Otago in Dunedin, NZ, and a Swiss company. The project proposal has been submitted to Innosuisse (Swiss Innovation Agency) and is currently being evaluated.

The measurement software for power and noise measurements has been further modernised. The old LabView code has been continuously replaced with C# code, which allows direct implementation of the uncertainty evaluation based on *METAS UncLib* and the use of software components developed for *VNA Tools*. About 80% of the code has been ported so far.

3.3 Scanning Microwave Microscope (SMM)

Within the last two years, the METAS SMM has been developed further and has been used in various projects. The Horizon 2020 Nanobat project started in 2020 and will end soon. The project is about industry related research on lithium-ion batteries. The SMM with shielded tip has been set up in a glove box, which was specifically built and put into operation for the project, to enable measurements of the solid electrolyte interface of battery half cells under controlled atmosphere. In addition, a prototype of a robust multi-tip sensor has been developed, which should enable scanning probe measurements in rough industrial production environments. The two EMPIR projects FutureCom and Elena started in 2021. The main goals in these projects are the development of an on-wafer prober with very small pitch size based on the pulling technology developed for the coaxially shielded scanning tip (FutureCom) and the development of impedance standards that can be used with the shielded tip (ELENA) [11].

3.4 Terahertz metrology

From 2018 until 2022 the RF&MW laboratory has conducted an internal THz-Met project and an EMPIR project (TEMMT), both in cooperation with the Photonics, Time & Frequency laboratory, to address terahertz metrology both from the electronics and the optics perspective. The RF&MW laboratory has set up material and power measurements in the 500 to 750 GHz band (WR1.5 metallic waveguide band) [12]. Due to limitations in resources, the THz activity has now been reduced to opportunity based collaborative efforts with university partners with a long-term perspective towards some form of optical broadband THz VNA.

4. EMC and Antenna

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4.1 Measuring method for 5G New Radio

The METAS measurement method for 5G base stations has been published as a chapter in the book "Metrology for 5G and Emerging Wireless Technologies" [13,14]. METAS will pursue its efforts to characterise the 5G radiation of a base station, with a focus on the traffic beams. The EMPIR projet MEWS focussing on these issues has started in 2022.

A comparison between accredited laboratories of Switzerland will take place in 2023.

4.2 Round robin test device for EMC testing

METAS has been continuously expanding its capabilities in proficiency testing. A device for burst-immunity testing has been developed for testing according to IEC 61000-4-4. This device will be evaluated in a national comparison between accredited testing laboratories. METAS has now a full set of devices available for proficiency testing: conducted emission, radiated emission (comb generator with antenna), radiated emission (EUT with cabling), conducted immunity according to IEC 61000-4-6, surge immunity according to 61000-4-5, and radiated immunity according to 61000-4-3 [15,16].

METAS now provides proficiency testing for accredited laboratories in Europe (www.metas.ch/emc).

5. Participation in Comparisons

Comparisons completed since the 2021 CCEM meeting

- EURAMET.EM.RF-S45: Comparison Calibration of RF Current Monitoring Probe; coordinated by UME with final report published 28/06/2021,
- EURAMET.EM-S44: Comparison for Ultra-low DC Current Sources; coordinated by UME with final report published 02/01/2023.

6. Publication List

Articles published since the 2021 CCEM meeting

[1] Overney, F., Bauer, S., Jeanneret, B., Eichenberger, A. L. & Pimsut, Y. "Performances of Dual Josephson Impedance Bridges". 2022 Conference on Precision Electromagnetic Measurements (CPEM) (Wellington, 2022).

[2] Overney, F., Jeanneret, B. & Eichenberger, A. L. "A New Bridge for Measuring the Longitudinal Impedance of a Quantum Hall Effect Device". 2022 Conference on Precision Electromagnetic Measurements (CPEM) (Wellington, 2022).

[3] Jeanneret, B., Overney, F., Pimsut, Y., Bauer, S., Kieler, O. & Behr, R. "Load compensation bridge for Josephson arbitrary waveform synthesizers". International Metrology Congress (Lyon, 2021).

[4] Overney, F., Jeanneret, B., Eichenberger, A. L., Kruskopf, M., Yin, Y., Bauer, S. & Pierz, K. "Towards a fully automated , four-terminal pair , graphene impedance standard". IMEKO TC-4 Symp. Proc. (Brescia, 2022).

[5] Agustoni, M. & Overney, F. Impedance Metrology: "Bridging the LF–RF Gap". *IEEE Transactions on Instrumentation and Measurement* 70, 1–8. issn: 0018-9456. doi:10.1109/TIM.2020. 3036062 (2021).

[6] Agustoni, M., Overney, F. & de Préville, S. "Simulation of Resistor Standards in LF-RF Range". *2022 Conference on Precision Electromagnetic Measurements (CPEM)* (Wellington, 2022).

[7] Mašláň, S., Hinds, G., Ouameur, M. & Overney, F. Project LiBforSecUse : "Quality Assessment of Electric Vehicle Lithium Ion Batteries for Second Use Applications". Cal Lab, *The International Journal of Metrology* Apr-May-Ju, 22–31 (2022).

[8] Eichenberger, A. L., Baumann, H., Mortara, A., Tommasini, D., Reber, D., Klingelé, E., Jeanneret, B. & Jeckelmann, B. "First realisation of the kilogram with the METAS Kibble balance". *Metrologia* 59. issn: 16817575. doi:10.1088/1681-7575/ac566f (2022).

[9] Eichenberger, A. L., Baumann, H., Mortara, A., Tommasini, D., Reber, D., Klingelé, E., Jeanneret, B. & Jeckelmann, B. "Results of the METAS Kibble balance". 2022 Conference on Precision Electromagnetic Measurements (CPEM) (Wellington, 2022).

[10] J. Hoffmann, M. Wollensack, D. Stalder, P. Huerlimann, J. Ruefenacht, M. Zeier. "Measuring the Linearity of Receivers in a Vector Network Analyzer". *CPEM 2022, Conference Digest*, 2022.

[11] Johannes Hoffmann, Sophie de Preville, Bruno Eckmann, Benedikt Herzog, Kamel Haddadi, Georg Gramse, Damien Richert, Francois Piquemal. "Comparison of Impedance Matching Networks for Scanning Microwave Microscopy". CPEM 2022, *Conference Digest*, 2022

[12] Alireza Kazemipour, Johannes Hoffmann, Michael Wollensack, Martin Hudlicka, Jürg Ruefenacht, Daniel Stalder, Djamel Allal, Gregory Gäumann, Markus Zeier. "Standard Load Method: A new calibration technique for material characterization at Terahertz frequencies." *IEEE Trans. on Instr. and Meas*., Vol 70, 2021.

[13] Frédéric Pythoud. "Measurement of 5G new radio-base stations". *Metrology for 5G and Emerging Wireless Technologies*. Edited by Tian Hong Loh, Stevenage, United Kingdom, February 2022.

[14] Frédéric Pythoud. "Die Konformitätsbewertung komplexer Systeme am Beispiel der Strahlung einer 5G-Basisstation. Conformity assessment of complex systems on the example of radiation from a 5G base station." *tm - Technisches Messen*. Oldenbourg Wissenschaftsverlag July 20, 2022. doi: 10.1515/teme-2022-0014

[15] Emrah Tas. "Lessons learned from Proficiency testing". *Internationale Fachmesse und Kongress für Elektromagnetische Verträgli*chkeit, Köln, 12 –14.07.2022.

[16] Emrah Tas, Frédéric Pythoud. "An Interlaboratory Comparison on Radiated Immunity IEC 61000-4-3". *EMC Europe 2022,* September 5-8 Gothenburg Sweden. doi: 10.1109/EMCEurope51680.2022.9901300

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