Progress Report on Electrical Metrology at METAS from 2019 to 2021

Report prepared for the 32nd 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

METAS and NIST have collaborated for several years on the Dual Josephson Impedance Bridge (DJIB). The project consists of putting together the sampling bridge technique and two independent voltage sources based on Josephson Arbitrary Waveform Generator Synthesizers (JAWS). These sources 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. While the DJIB approaches the uncertainty levels of the best traditional bridges in the kilohertz range, its advantages include the flexibility which allows the comparison of arbitrary impedances, the wide frequency range, and the automated balancing procedure. Hence the maintenance of various impedance scales can be considerably simplified thanks to a single fully automated bridge covering the entire complex plane [1].

1.2 Computational traceability

Simulations have been used in several collaborations with the industry in order to establish traceability for impedances. 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. A new capacitor standard has also been designed by means of physical simulations. The use of this method has considerably improved the impedance model. Preliminary results have shown a good agreement and first estimations of the uncertainty are available [2].

1.3 Electrochemical impedance spectroscopy for Li-ion cells

A new version of the impedance simulator, covering the low impedance range which is of interest to electrochemical impedance spectroscopy (EIS) for Li-ion cells, is under development within the framework of the EMPIR LibForSecUse project [3]. The purpose of this simulator is the calibration of LCR meters in the impedance range from 1 mΩ to 10 Ω at low frequency and with an arbitrary phase angle.

Moreover, a new measuring setup for the EIS measurement of cylindrical cells (type 18650 Li-ion battey) is also under development.

1.4 Realisation of the kilogram

During the last years, METAS has further improved its Kibble Balance experiment. The main modifications that have been implemented are:

- Development of closed-circuit magnetic dampers for oscillation reduction in the suspension, essentially in the static mode.
- Complete redesign of the interferometer for noise reduction in the dynamic mode.
- Laser reference beam by means of a green laser from laboratory Length.
- Integration of three interferometers to determine the attitude of the coil in both phases of the experiment.

Based on these improvements, all parameters for the alignment of the experiment seem to be under control. During the last month of 2020 an extensive campaign under vacuum with the Josephson voltage standard has been undertaken. The results showed a type A uncertainty of some ppb.

During the coming months the experiment will be properly adjusted and run for a first realisation of the mass unit.

2. Power and Energy

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2.1 Primary power standard for f ≥ 0

A primary power standard working from DC to 9 kHz was developed. The trigger for this development were railway applications, in particular in the framework of the EMPIR MyRailS project [4]. In Switzerland, the dominant railway system operates at 16.7 Hz. This standard will also be used for the EMPIR projects WindEFCY and DC grids. At 400 Hz and below, the standard features uncertainties below 50 × 10-6 for voltages and currents below 700 V and 20 A respectively. The measurement of the voltage and current signals involved in the power computation is by means of type 3458A multimeters in DC mode with an external trigger signal. Different fitting algorithms are used to determine the RMS value and phase of the signal of interest. Comparison with power standards operating at 50 Hz have shown consistent results. The CMCs have been adapted to cover the extended voltage, current and frequency ranges. Due to the limitation of the AC power and energy category, the CMCs are limited to f > 0, excluding DC.

This standard was used in the power comparison EURAMET.EM-K5. Depending on the results, the CMCs will be revised to lower the uncertainties.

Furthermore, METAS is preparing legislation and verification equipment for electric vehicle charging for which a primary power standard operating at f ≥ 0 is essential.

2.2 Capabilities at 16.7 Hz

In the framework of the EMPIR project MyRailS, METAS have developed the primary power standard mentioned in § 2.1. The system has been adapted for the calibration of burdens as well as comparators for instrument transformers. The measuring systems can in principle be used in the same frequency range as the power standard. However, for both, there is limited demand for frequencies other than the power frequencies. For burdens requiring true power rather than phantom power, in addition, the source is limiting the frequency range to 16 Hz to 63 Hz. For current transformers, our existing set-up has been expanded such that through-hole transformers can be calibrated with superimposed high frequency components up to 9 kHz.

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 continuously developed further. Many bug fixes, small and larger extensions, convenience features and driver updates have been added. Currently *VNA Tools* is extended towards non-linear measurements and support for wave parameters is gradually being built in. For now this is limited to power calibrations, whereas frequency converting devices are not supported yet. The software has continued to extend its user base. So far there are more than 1300 registered licensees of *VNA Tools* and more than 200 persons have visited the three-day introductory course, which is provided by METAS. The VNA Tools Real Time Interface (RTI), a stable high level interface for integration of VNA functionality into an existing software environment, has been licensed for two commercial applications.

The RF&MW lab has a history in establishing S-parameter traceability for non-standard connectors. The latest addition is the NEX-10 connector, which has been specifically designed to handle compact 5G applications up to 20 GHz with low PIM (passive intermodulation) specifications. The connector system is dielectrically loaded, which required some refinements to the previously applied calculable adapter method [5]. The lab has updated its S-Parameter CMCs at the BIPM KCDB with this connector system.

3.2 RF power and Noise

The project 110 GHz Power to extend coaxial measurement capabilities in RF power from currently 67 GHz to 110 GHz has been completed and CMCs for this measurement service have been submitted for publication in the BIPM KCDB. An important outcome of this project is the new software *METAS PowerCal*, which can be used to calibrate power sensors on a VNA system. A project proposal for a novel primary power standard based on the electro-optical effect is currently being formulated. A collaboration with the University of Otago, New Zealand, for the development of the electro-optical sensor is pursued.

Because NPL has stopped (as the last lab in Europe) its primary noise service in 2018, METAS has built up its own primary realization of noise for the coaxial systems Type-N and 3.5 mm. The measurement systems are complemented by a new software *METAS NoiseCal*, which is using components of *VNA Tools* and which is based on *METAS UncLib* for proper uncertainty evaluation. The new service is now fully operational and worldwide customers are using it actively. CMCs at the BIPM KCDB have been updated accordingly.

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. A new laboratory room at METAS has been exclusively dedicated to the SMM activities. The EMPIR projects HyMet and ADVENT and the Horizon 2020 project MMAMAwere completed in the meantime. The main outcomes of these projects were the fabrication of impedance standards fabricated in a cleanroom using lithographic techniques [6] and the development of a coaxial scanning tip. A new Horizon 2020 project, NanoBat, has been started in 2020 with the aim to perform industry related research on lithium-ion batteries. The SMM with shielded tip is being set up in a glove box to enable measurements of the solid electrolyte interface of battery half cells under controlled atmosphere. In addition, a robust multi-tip sensor is being developed, which should enable scanning probe measurements in rough industrial production environments. Two new EMPIR projects, FutureCom and Elena, are currently in the contract signing phase and will start later this year.

3.4 Terahertz metrology

The RF&MW laboratory has pursued the THz-Met project in cooperation with the Photonics, Time & Frequency laboratory since 2018 to address terahertz metrology both from the electronics and the optics perspective. The RF&MW laboratory has made some progress in setting up material and power measurements in the 500 to 750 GHz band. Some of this work has synergies with activities in EMPIR project TEMMT, which started in 2019 [7].

4. EMC and Antenna

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4.1 Measuring method for 5G New Radio

METAS has developed a measurement method for 5G base stations. The method published in February 2020 [8] is currently in use in Switzerland. It takes into account the beam forming features of the standard, and it provides the value that the electric field would reach in the reference operating mode, defined as operation at maximum speech and data traffic at maximum transmission power. This method is, to the best of our knowledge, the first official method for 5G issued by a public authority. It covers frequencies below 6 GHz, i.e. mm-waves are not covered. These higher frequency bands will be addressed at a later stage.

4.2 Round robin test device for EMC testing

METAS has been continuously expanding its capabilities in proficiency testing. A device for surge-immunity testing has been developed for testing according to IEC 61000-4-5. This device has been evaluated in a national comparison between accredited testing laboratories. A device for testing according to IEC 61000-4-3 has also been developed and it is available for commercial rollout. Several devices are now 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, and surge immunity. A device for burst testing according to IEC 61000-4-4 is currently in development [9]–[11].

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

5. Participation in Comparisons

Comparisons completed since the 2019 CCEM meeting

- CCEM.K2.2012: Key comparison of resistance standards at 10 MΩ and 1 GΩ.; coordinated by NRC.
- EURAMET Project 1426: Comparison of S-parameter Measurements in N-type connector devices; coordinated by METAS.
- EURAMET project 1461: Comparison on Voltage Reflection Coefficient (VRC) of an RF source; coordinated by INTA.
- EURAMET.EM-S35: Comparison of high-current ratio standard; coordinated by INRIM.
- BIPM.EM-K12: On-site comparison of quantum Hall effect resistance standards; coordinated by BIPM.
- EURAMET Project 1466: Complex gain factor of a lock-in amplifier; coordinated by INRIM.

6. Publication List

Articles published since the 2019 CCEM meeting

[1] F. Overney *et al.*, “Dual Josephson impedance bridge: towards a universal bridge for impedance metrology,” *Metrologia*, vol. 57, no. 6, p. 65014, Oct. 2020, doi: 10.1088/1681-7575/ab948d.

[2] M. Agustoni and F. Overney, “Impedance Metrology: Bridging the LF-RF Gap,” *IEEE Transactions on Instrumentation and Measurement*, vol. 70, 2021, doi: 10.1109/TIM.2020.3036062.

[3] N. Meddings *et al.*, “Application of electrochemical impedance spectroscopy to commercial Li-ion cells: A review,” *Journal of Power Sources*, vol. 480, no. July, 2020, doi: 10.1016/j.jpowsour.2020.228742.

[4] C. Mester, “Sampling primary power standard from DC up to 9 kHz using commercial off-the-shelf components,” *2020 3rd International Colloquium on Intelligent Grid Metrology (SMAGRIMET)*, pp. 35–40, 2020.

[5] J. Hoffmann, P. Huerlimann, M. Wollensack, J. Ruefenacht, and M. Zeier, “S-Parameter Definition for Adapters with a Dielectrically Loaded Connector,” in *2019 93rd ARFTG Microwave Measurement Conference (ARFTG)*, 2019, pp. 1–4, doi: 10.1109/ARFTG.2019.8739159.

[6] T. le Quang, A. C. Gungor, D. Vasyukov, J. Hoffmann, J. Smajic, and M. Zeier, “Advanced calibration kit for scanning microwave microscope: Design, fabrication, and measurement,” *Review of Scientific Instruments*, vol. 92, no. 2, 2021, doi: 10.1063/5.0032129.

[7] A. Kazemipour *et al.*, “Analytical Uncertainty Evaluation of Material Parameter Measurements at THz Frequencies,” *Journal of Infrared, Millimeter, and Terahertz Waves*, vol. 41, no. 10, pp. 1199–1217, 2020, doi: 10.1007/s10762-020-00723-0.

[8] F. (METAS) Pythoud, “Technical Report : Measurement Method for 5G NR Base Stations up to 6 GHz,” 2020.

[9] E. Tas, F. Pythod, and D. Zhao, “The Consequences of Missing Specification for Coupling-Decoupling Networks,” 2019, pp. 598–602, doi: 10.1109/EMCEurope.2019.8872028.

[10] E. Tas and F. Pythoud, “Design, Implementation, and Evaluation of Proficiency Testing in EMC Surge Immunity,” *IEEE Transactions on Electromagnetic Compatibility*, vol. 62, no. 6, pp. 2368–2375, 2020, doi: 10.1109/TEMC.2020.2968107.

[11] E. Tas, F. Pythoud, and B. Muhlemann, “An Improved Reference Device for Radiated Immunity Interlaboratory Comparison,” pp. 1–6, 2020, doi: 10.1109/emceurope48519.2020.9245638.

[12] B. Jeckelmann and F. Piquemal, “The Elementary Charge for the Definition and Realization of the Ampere,” *Annalen der Physik*, vol. 531, no. 5, pp. 1–10, 2019, doi: 10.1002/andp.201800389.

[13] M. Götz, D. Drung, C. Krause, and M. A, “Calibration of ultrastable low-noise current amplifiers without direct use of a cryogenic current comparator,” *Metrologia*, vol. 57, no. 5, p. 55008, Sep. 2020, doi: 10.1088/1681-7575/ab8f7a.

[14] F. Overney, Y. Pimsut, S. Bauer, O. Kieler, R. Behr, and B. Jeanneret, “Load compensation bridge for Josephson arbitrary waveform synthesizers,” *Measurement Science and Technology*, vol. 31, no. 5, 2020, doi: 10.1088/1361-6501/ab62c7.

[15] Y. Seferi, S. M. Blair, C. Mester, and B. G. Stewart, “A Novel Arc Detection Method for DC Railway Systems,” pp. 1–22, 2020.

[16] Y. Seferi, S. M. Blair, C. Mester, and B. G. Stewart, “Power Quality Measurement and Active Harmonic Power in 25 kV 50 Hz AC Railway Systems,” *Energies*, vol. 13, no. 21, p. 5698, 2020, doi: 10.3390/en13215698.

[17] C. Cassiago and A. Mortara, “Supplementary comparison EURAMET.EM-S35: comparison of high-current ratio standard. Final report.,” *Metrologia*, vol. 57, no. 1A, p. 1004, Jan. 2020, doi: 10.1088/0026-1394/57/1a/01004.