Progress Report on Electrical Metrology at METAS 2015 to 2017

Report prepared for the 30th meeting of the Consultative Committee for Electricity and Magnetism (CCEM)

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This report gives a brief outline of the main research and development activities in the field of electricity at the Federal Institute of Metrology (METAS).

1. Electrical Quantum Standards

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1.1 GraphOhm

The goal of the EMRP project GraphOhm [1], completed in June 2016, was to implement graphene devices as a new, simpler and more robust quantized Hall resistance standards. The METAS task in the project was focused on the AC transport properties of graphene. To this end a new digitally assisted bridge [9] was built and characterized. This instrument allows a fully automated characterization of the Hall resistance of graphene devices. A systematic investigation of the AC properties of graphene devices grown on SiC has revealed a negative frequency dependence of the Hall resistance RH, in strong contrast with the positive frequency dependence observed with GaAs samples [1,5]. This behaviour was explained by a model taking into account the influence of capacitive losses affecting the ac QHE. According to this model, positive and negative contributions to the measured ac RH depend on the device geometry. This geometrical dependence opens the way to design graphene Hall bars with vanishing frequency dependence of RH making the practical realization of an impedance standard based on graphene superior to the existing GaAs standards.

1.2 CVD Graphene

The goal of this project, started in 2013 in collaboration with the Physics Department of Basel University, is to develop a research activity in the graphene area which complements and goes beyond our participation in the GraphOhm EMRP project to investigate the full potential of CVD graphene material in electrical metrology. The expertise at the physics department in Basel in the growth of CVD graphene samples combined with the METAS expertise in high precision measurement is dedicated towards the realization of a new quantum standard of resistance based on CVD graphene. The main effort in this investigation was on the devices fabrication were the film growth and its transfer to the Si substrate represents the main difficulties. The progresses made in the last two years were achieved by a combination of surface analysis method like Raman spectroscopy, LEEM, optical microscopy and transport measurements. Our best result to date was a device which achieved a quantization of the Hall resistance within 50 ppb of the von Klitzing constant over a range of gate voltage of a few volts. The project is continuing until this fall. The preliminary results are published in [3,5].

1.3 Q-Waves

The aim of the EMRP project Q-waves, completed in June 2016, was to provide direct and efficient traceability for precision devices generating or measuring arbitrary waves at frequencies up to 10 MHz. The demand for these significant improvements of high-precision voltage measurements is caused among other things by the rapid progress of semiconductor industry offering analogue-to-digital converters (ADC) and digital-to-analogue converters (DAC) with higher and higher sampling rates and accuracy.

The contribution of METAS, was to extend the characterization of ADCs up to 10 kHz in the time and frequency domain using a programmable Josephson voltage standard. Using an equivalent time sampling approach (see standard IEEE 1241-2000), an oversampling method was implemented to perform a waveform reconstruction that is extending the measurement bandwidth. The data analysis includes the evaluation of the integral non-linearity, of the Allen variance of the raw and the reconstructed waveform and of the amplitude of the harmonics of the Fourier spectrum which provides information in the frequency domain. The results of the project were published in [4] and in an EMRP Good Practice Guide.

1.4 Quantum ADC (QuADC)

The aim of this EMPIR project, which started in June 2016, is to develop measurement systems centred on Josephson AC-voltage quantum devices which will both operate at the highest level of accuracy and be simple enough for exploitation outside the national metrology institutes. In this JRP, innovative use of Josephson junctions is proposed for measurements of arbitrary signals in terms of fundamental constants referenced to the volt in the new SI. The need for this development is clearly driven by developments in the application fields. Sensing and measurement are increasingly dependent on fast analogue-to-digital conversion and emerging measurement applications in high end equipment are placing new demands on the traceability for dynamic quantities, which cannot be satisfied by the existing approaches.

As the frequency of the output signal increase towards the MHz-region, the cables connecting the Josephson arrays to the outside environment becomes crucial. Standing waves and capacitive leakage become dominant at such frequencies, which is directly correlated with the length of the cables. In order to have a quantum device operating under these restrictions, an impedance matching between the room temperature load and the JJ arrays will be developed. At METAS, a bridge will be constructed that will take into account the impedance and the leakage admittance of the leads and the DUT. The technology of this digital bridge will be based on the NI4461 ADCs and DACs, limiting its bandwidth to 100 kHz. A great advantage of this method is that it can compensate the effect of the cables without any need for external calibration, like AC-DC measurements for example. Preliminary measurements are underway.

1.5 Digital Josephson Impedance Bridge (DJIB)

The goal of this project is to develop an impedance bridge that combines a dual 1 V pulse driven Josephson standard (ACJVS) from NIST and the new Digitally Assisted Bridge (DAB) from METAS. This new Digital Josephson Impedance Bridge (DJIB) represents an important advance in impedance metrology in terms of automation and calibration range. It will surely replace many of the existing impedance bridges in the coming years as the technology involved progresses. This is a major step forward in electrical metrology.

One of the main advantages of the DJIB is the possibility to adjust the phase between the two AC sources to any value [8], meaning that any impedance in the complex plane can be calibrated with this bridge. This represents a tremendous simplification of operation compared to the quadrature bridge technique currently used to realise the capacitance from the resistance. The results of a comparison between capacitors, inductors and resistors obtained during a visit at NIST in August 2015 have shown that the measurement uncertainties are already below a ppm over the entire complex plane [7,9]. The project is under way and further improvements are expected in the near future.

2. DC/LF Metrology

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2.1 AIM-QuTE

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The EMRP project AIM-QuTE, completed in June 2016, had the goal to improve impedance metrology at the lowest uncertainties by making the transition from measurements performed at predefined values and relative phase angles for selected frequencies to any ratio over the complete audio frequency range (20 Hz to 20 kHz). This can achieved with two different types of impedance bridges: Josephson bridges and digital bridges. Within the project, METAS developed the impedance simulator (iSimulator), a fully automated impedance simulator [7] capable to simulate impedances ranging from 1 Ω to 10 MΩ, at arbitrary phase angle, over a large frequency range (from 100 Hz to 20 kHz). The validation of the instrument was performed by calibrating a commercial LCR meter up to 20 kHz along the axis of the complex plane. The results of the iSimulator calibration were in good agreement with measurements carried out using the classical artefact-based method. This validation clearly demonstrated the unique capabilities of the iSimulator, based on its flexibility, broad impedance and frequency range, full coverage of the complex plane and its full automation. In the near future, impedance simulators will definitely play a privileged role in the entire impedance calibration field both in National Metrology Institutes and in industrial calibration laboratories.

2.2 New capabilities for the calibration of lock-in amplifiers

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Lock-in amplifiers are very sensitive and low noise instruments which are well known in metrology. In particular, they are often used as null detectors in most AC bridges. In this case, the amplitude of the signal is close to zero and the non-linearity of the instrument can be neglected. However, in the sensor area for example, lock-in amplifiers are used as AC voltmeters and their linearity must be properly calibrated. To this end, a measurement system was developed at METAS [10] to calibrate lock-in amplifiers over a voltage range from 1 µV to 1 mV with a relative uncertainty of less than 100 ppm. This corresponds to the resolution of the best instruments on the market. The calibration method is based on inductive voltage dividers (IVD). Although a single IVD can produce an output voltage down to 1 µV or less, the uncertainty on the output voltage will be too high for high precision calibration. In the implemented system, several IVDs are connected in cascade. Using a 4-divider cascade, it is possible to reach a division ratio of 1/100’000 with an uncertainty of 10 ppm on the output voltage.

This new system is able to generate an AC voltage from 1 mV down to 1 µV, for frequencies ranging between 40 Hz and 1 kHz with an uncertainty of 100 ppm at maximum. In this way, the linearity of various lock-in amplifiers can be calibrated within their specifications for these amplitudes and frequencies.

3. Watt Balance

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3.1 The METAS watt balance Mark II experiment

The METAS Mark II experiment (BWM II) is fully assembled and aligned [12,13]. The operation of the balance is very stable and different experimental tests and simulations are now conducted to identify the origin of a systematic effect responsible for a shift on *h* at the ppm level.

The different partners active in this project are Mettler-Toledo (Greifensee, Switzerland) for the development of the new load cell, the laboratory of robotics of the Federal Institute of Technology, Lausanne (LSRO-EPFL, Lausanne, Switzerland) for mechanical developments (translation and driving stages, mass handler), the magnets and superconductors group of the European Organization for Nuclear Research (CERN, Geneva, Switzerland) for the design of the magnetic circuit and Maxon motors for the actuators used in the mass exchanger.

4. Power and Energy

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4.1 Calibration of instrument transformer test sets

Instrument transformer test sets are used to calibrate instrument transformers. Traditionally, commercial and reference transformers were very similar in design. The test sets for the calibration of those transformers were using bridge techniques. While the design of reference transformers has not changed, non-conventional commercial transformers have very different output signals. The rated output amplitude is much smaller than before and sometimes, the transformation ratio is not a dimensionless quantity – a current transformer might, e.g., have a voltage output. Usually, modern instrument transformers test sets use sampling techniques. Their full range of input values cannot be covered by traditional bridge-based calibrators. METAS has designed and characterised a new calibrator for test sets for both traditional and non-conventional analogue instrument transformers [14].

4.2 FutureGrid

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The aim of the EMRP project FutureGrid, which started in June 2014, is to support the wider application of novel voltage and current sensor technologies in future power networks (non-conventional sensors, usually based on magneto-optical or electro-optical properties). The specific task for METAS in this project is to develop a platform enabling new calibration services for non-conventional sensors both with analogue output and with digital output following the IEC 61850-9-2 standard.

The metrological infrastructure necessary to calibrate IEC 61950-9-2 instruments has been developed and tested [15,16]. Two different types of devices are considered: Stand Alone Merging Units (SAMUs) used to retrofit conventional transformers in power network substations and commercial test sets suited for non-conventional voltage and current sensor calibration in the field. A SAMU is essentially an analog-to-digital converter delivering its results in the IEC61850-9-2 format. The evaluated functionalities of the test set are the analog signal generation (voltage and current) and their synchronous IEC 61850-9-2 representation.

4.3 Metrology for Smart Grids

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As part of the EMRP project “Measurement Tools for Smart Grid Stability and Supply Quality Management”, the design of the calibrator for Phasor Measurement Units (PMU), developed in a previous EMRP project, is now being upgraded so that it will be capable to calibrate PMUs used in advanced distribution networks. These networks are characterised by much smaller phase angle variations although at faster rate. Another particularity of distribution networks is the presence of higher level of power quality disturbances. These two characteristics call for PMUs that are much more accurate and robust [20,21].

As a result, calibration system for such PMUs must also be much more accurate and capable to measuring TVEs around 0.01 %. Achieving this performance requires simultaneously better timing accuracy as well as improved magnitude and phase resolution. The ongoing activities are presently focusing on achieving these objectives.

METAS is working closely with the DESL (Distributed Electrical Systems Laboratory) laboratory from EPFL who is developing a demonstration smart grid controlled by advanced PMUs. This combination of metrological and power engineering expertise will ensure that an appropriate metrological infrastructure will be available to the industry at large when such advance distribution systems will become the norm.

5. RF & Microwave

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5.1 Impedance and Network Analysis

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METAS has recently established SI traceability in 50 Ω S-parameter measurements in the 1.0 mm coaxial connector system up to 116.5 GHz [25,26]. Crucial ingredients in this work were a custom-built calibration kit and an optimized measurement setup. The 1.0 mm offset short calibration kit had been developed in cooperation with an industry partner with an emphasis on the stability of the components and with a design suitable for modelling. Temperature control [27], mechanical improvements [28] and close cooperation with the vendors of commercial components [29] led to a stable and unique measurement system. This work signifies the completion of a development that started about ten years ago and has led to major improvements of accuracy and consistency in coaxial S-parameter measurements. METAS provides now SI traceability for all major metrology-grade coaxial connectors, Type-N, 3.5 mm, 2.92 mm, 2.4 mm, 1.85 mm and 1.0 mm, following the improved methodology that takes connector effects into account. METAS will be the first NMI to have a CMC entry in the KCDB of the BIPM for coaxial S-parameter measurements in the 1.0 mm connector interface.

Part of the activity happened within the EMRP project HF-Circuits (www.hfcircuits.org), which finished 2016. Other major contributions of METAS in this project were:

- A comprehensive study of connector effects for all metrology grade coaxial connectors. A report with the results was submitted to the standards committee IEEE P287. It will become part of the revised IEEE standard on coaxial connector interfaces.
- Revision of EURAMET guide cg-12 (VNA guide) promoting a contemporary way to evaluate VNA measurement uncertainties [30]. A complete draft of the guide has been submitted to the TCEM SC-RF&MW for further review.
- A study of connector effects in the TRL calibration algorithm [31].
- Investigation of VNA verification concepts [32].
- An S-parameter measurement comparison in 1.85mm [33].

Demand for the traceability of non-standard connector systems is increasing. It is however not always feasible or economically reasonable to establish the traceability chain based on calculable standards as it is being done for the metrology grade connectors mentioned above. METAS has developed a method for such cases, which is based on calculable adapters and subsequent de-embedding. The method has been applied to the 4.3-10 connector, which has been introduced recently for mobile communication applications up to 12 GHz. A CMC entry has been submitted.

Purchase of a 4-port 50 GHz VNA has led to a systematic study of different ways to characterize 3-port devices. The findings have been summarized in a paper [34].

The VNA metrology software VNA Tools (www.metas.ch/vnatools) has been developed further. Support for waveguide measurements and on-wafer measurements (as part of the EMPIR project PlanarCal, www.planarcal.ptb.de) have been implemented and extended the capabilities of the software beyond the coaxial world. So far there are more than 470 licensees of *VNA Tools* and more than 125 persons have visited the three-day introductory course, which is provided by METAS.

In 2016 a new EMPIR RPOT project RFMicrowave (rfmw.cmi.cz/) started in which METAS is disseminating knowledge in establishing SI traceability for S-parameters and evaluating VNA measurement uncertainties to other NMIs.

5.2 RF power

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The project 110 GHz Power to extend coaxial measurement capabilities in RF power from currently 67 GHz to 110 GHz is making progress. This project is conducted with an industry partner. To limit investments it uses 110 GHz VNA system for power measurements. The work is, thus, closely related to the activities in network analysis described above. As a side result, the lab will be able to measure RF power and S-parameters in the waveguide band WR10 (75 to 110 GHz).

Major advances in the project are:

- Development of a new power measurement software (PMS II), using components of VNA Tools. The software is designed for power measurements on the VNA and uses METAS UncLib (www.metas.ch/unclib) for proper uncertainty evaluation.
- Purchase, tests and characterization of various components (sensors, adapters, …)

5.3 Scanning Microwave Microscope (SMM)

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Within the last two years the METAS SMM [35] has undergone various improvements. The SMM has now a dedicated 50 GHz VNA. The software has been cleaned up and gradually improved. The experimental setup has been enhanced with various features, most notably with a vibration damping system and an acoustic chamber to reduce ambient influences.

The METAS SMM is currently used in three EMRP/EMPIR projects:

- The EMRP project SolCell (projects.npl.co.uk/solcell) started in 2014 and addresses the characterization of III-V materials based multi junction solar cells. The SMM is used to measure charge carrier densities and dopant profiles of these highly efficient solar cells.
- In the EMPIR project PlanarCal (www.planarcal.ptb.de) the SMM is used to characterize nano devices.
- The EMPIR project 3D-Stack (empir.npl.co.uk/3dstack/) is related to three dimensional integrated circuits. The SMM is used to characterize physical properties of so-called "Through Silicon Vias", the vertical electrical connections that are essential to successfully build stacked packages of silicon wafers.

Within the 2016 EMPIR call two further projects (ADVENT and HyMet) with participation of the METAS SMM have been approved. Contract negotiations are underway.

6. EMC and Antenna

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6.1 Round robin test device for EMC testing

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METAS successfully realized a round robin test for conducted immunity. METAS is working at increasing the library of test devices for round robin testing [39,45,46]. At the moment different standards are considered: IEC 61000-4-3, IEC 61000-4-5, conducted and radiated emission.

The goal is to provide proficiency testing for accredited labs in Europe, as a follow-up to the successful EMRP project EMC industry (www.emc-industry.com).

6.2 EA comparison among European accredited calibration labs

For the European Accreditation, METAS is leading one of the most important comparisons among accredited calibration labs in Europe. The scope of the comparison is the measurement of the ESD gun parameters: DC voltage, maximum current, rise time, amplitude and 30 ns and 60 ns. The comparison started January 2016 and includes 20 labs in Europe. The evaluation of the results is planned for the second quarter of 2017.

6.3 Power metrology of Long Term Evolution

Traceable measurements of mobile base-stations are important for protection against non-ionizing radiation. Within this project, a setup for measuring Long Term Evoluation (LTE) signals has been realized and algorithms have been developed to determine the power of LTE reference signals in a way that it is traceable to the International System of Units (SI) [38,42-44]. Experimental results have shown that the uncertainty of the LTE reference signal measurements is 0.05 dB (k=2). Moreover, the robustness of the power measurements has been demonstrated with a fading simulator.

This calibration capability is now available at METAS and the first certificates for calibration of LTE receivers have been issued. Reports and best practice guides are available for download from the project's website (projects.npl.co.uk/emrp-ind51-morse).

6.4 Protection against non-ionising radiation: scanning method

The measurement of non-ionizing radiation is an important subject in Switzerland [41] since it has, based on the precaution principle, stronger limits that the ICNIRP limits. However, the measurement uncertainty of the field measurement is typically 3 dB, which expressed in percent gives about 45%. This seems to be quite high for the general public. Therefore, METAS tries to improve the measurement methods and also the measurand in order to decrease the measurement uncertainty.

The idea to improve the uncertainty is to scan the field and to identify an averaging method in order to remove the uncertainties due to interference. METAS is at the moment at an early stage of experimenting using the Kinect Sensor by Microsoft.

6.5 EMC testing and calibration

METAS extended emission testing measurements up to 26 GHz. Moreover, METAS has improved calibration quality for a very large portfolio of calibration services: antenna, loop antenna, rod antenna, CDN, current clamp, EM-clamp, MDS clamp, common mode S-Parameters, electric and magnetic field probe, high power generator, LTE receiver.

7. Participation in Comparisons

Comparisons piloted by METAS, reports published since the CCEM meeting in 2015

- EA Comparison: Comparison for ESD pulse measurement (2016-2017).

Measurements carried out since the CCEM meeting in 2015

- EURAMET supplementary comparison EM-S31: Comparison of capacitance and capacitance ratio (2015); piloted by PTB.
- EURAMET comparison project 1367: Measurement Comparison in S-parameters up to 65 GHz in Coaxial 1.85 mm Line (June/July 2015); piloted by NPL.
- CCEM.RF-K26: Attenuation at 18 GHz, 26.5 GHz and 40 GHz using a step attenuator (July/August 2015); piloted by NMIJ.

8. List of Publications

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[2] F. Overney and B. Jeanneret, “A State-of-the-art impedance simulator”, METinfo, Vol 23, No. 2, 2016, p. 26-31

[3] K. Thodkar, M. El Abbassi, F. Lüönd, F. Overney, Ch. Schönenberger, B. Jeanneret and M. Calame, “Comparative study of single and multi domain CVD graphene using large-area Raman mapping and electrical transport characterization”, Phys. Status Solidi RRL, 1–5, 2016

[4] B. Jeanneret, F. Overney, Ch. Scherly and G. Schaller, “Josephson-Based Characterization of Analog-to-Digital Converters Using an Equivalent Time Sampling Method”, 2016 Conference on Precision electromagnetic Measurements, 2016

[5] K. Thodkar, Ch. Schönenberger, M. Calame, F. Lüönd, F. Overney, B. Jeanneret, “Characterization of HMDS Treated CVD Graphene”, 2016 Conference on Precision electromagnetic Measurements, 2016

[6] F. Overney, N. E. Flowers-Jacobs, B. Jeanneret, A. Rüfenacht, A. E. Fox, J. M. Underwood, A. D. Koffman and S. P. Benz, “Josephson-Based Full Digital Bridge for High-Accuracy Impedance Comparisons”, 2016 Conference on Precision electromagnetic Measurements, 2016

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[13] H. Baumann, A. Eichenberger, “Wie die Watt-Waage funktioniert/ Comment la balance du watt fonctionne”, METinfo, Vol 23, No. 1, 2016, p. 16-19

[14] C. Mester, S. Siegenthaler, “A computer-controlled calibrator for instrument transformer test sets”, Conference on precision electromagnetic measurements, 2016

[15] M. Agustoni, A. Mortara, “A Calibration Setup for IEC 61850-9-2 Test Sets”, 2016 Conference on Precision Electromagnetic Measurements, 2016

[16] M. Agustoni, “Sensoren digitalisieren Stromnetzdaten”, METinfo, Vol 23, No. 1, 2016, p. 13-15

[17] J.-P. Braun, “The metrological characterisation of PMUs”, IEEE Italy Section school on future energy systems

[18] J.-P. Braun, “The calibration of static and dynamic performances of PMUs”, International congress of metrology CIM, 2015

[19] J.-P. Braun, “Metrological characterisation of PMUs”, Workshop on PMU metrological requirement, Quality infrastructure for renewable energy sources & energy efficiency in Latin America and the Caribbean, Bento Goncalvez, Rio Grande do Sul, Brasil

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[36] Frédéric Pythoud, “Introduction to EMC”, SwissT.net, EMV-Fachtagung, Kloten, 21.01.2015

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