



## Progress Report on Electrical Metrology at METAS 2013 to 2015

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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. Watt Balance

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The watt balance effort at METAS is focused on two projects:

#### 1.1 The METAS watt balance Mark II experiment

The METAS Mark II experiment (BWM II) [1-3] is close to be fully assembled and the first characterization tests have started. In the dynamic phase, the field profile shows a curvature below 1 ppm/mm over a region larger than 15 mm. The field profile is measured at a velocity of 1.3 mm/s to produce an induced voltage of 1 V across the coil. This motion is measured with a Michelson interferometer where the moving optical element is placed at the geometrical center of the coil. The development of the mass handler is finished and the last parts are ready to be mounted. After a set of tests, the determination of the Planck constant will be performed in the second half of 2015.

The different partners active in this project are Mettler-Toledo (Greiffensee, 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.

#### 1.2 EMRP project kNOW

This project –carried out in the framework of the European Metrology Research Programme (EMRP) – is coordinated by INRIM and brings together PTB, LNE, INRIM, METAS and different other partners (<http://www.inrim.it/luc/know/>). The main goal is to combine the Avogadro (IAC) and watt balance (LNE and METAS) efforts and to contribute with independent determinations of  $h$ , at relative uncertainty of a few parts in  $10^8$ , to the redefinition of the mass unit. Part of the development and tests performed with the BWM II experiments are accomplished within the kNOW project.

## 2. Electrical Quantum Standards

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### 2.1 GraphOhm

The goal of the EMRP project GraphOhm [4], started in summer 2013, is to implement graphene devices as a new, simpler and more robust quantized Hall resistance standards. The METAS task in the project is to focus on the AC transport properties of graphene. To this end, a dedicated cryo-probe and a new digitally assisted bridge [5] were built. These instruments will allow a fully automated characterization of the Hall resistance of graphene devices. Lately, we have received graphene films grown on SiC at PTB that exhibit high quality DC QHE properties, making them good candidates for the first AC measurements.

### 2.2 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 will complement and go 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 will be combined with the METAS expertise in high precision measurement to work towards the realization of a new quantum standard of resistance based on CVD graphene. Preliminary measurements show encouraging results in view of the application of CVD graphene in electrical metrology [6].

### 2.3 Q-Waves

The aim of the EMRP project Q-waves [7] is 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.

Quantum voltage standards based on the Josephson effect currently ensure the traceability of DC and low-frequency AC voltage measurements. To increase the bandwidth, new measurements methods must be developed. At METAS, we are extending the characterization of ADCs up to 10 kHz in the time and frequency domain. Using an equivalent time sampling approach (see standard IEEE1241-2000), an oversampling method was implemented to perform a waveform reconstruction that will allow an extension of the measurement bandwidth. The main technical problem to solve was the synchronization of the Josephson source with sampling frequencies used by the ADC card. The development of the software that will be used for the characterization of the ADC is now complete. The modules for data analysis were recently completed. The 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. Precision measurements will start soon.

### 2.4 Josephson locked synthesizer (JoLoS)

The JoLoS was used to perform the calibration of thermal transfer standard of the type Fluke 792. The calibration range extends from 0.7 V to 60 mV (rms voltage) for frequencies ranging from 10 Hz to 1 kHz. The results are in good agreement with a calibration performed at BEV, Austria. The uncertainties obtained with the JoLoS represent an improvement of the METAS capabilities in the AC-DC transfer. Based on these results, new CMC entries, the first based on a programmable Josephson voltage standard, will be submitted.

### 3. DC/LF Metrology

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#### 3.1 Digitally Assisted Bridge (DAB)

A new ac coaxial bridge has been developed for the comparison of four terminal-pair impedance standards [5]. While the precise voltage ratio is still given by a “classical” transformer, all inductive voltage dividers, combining networks and detectors, needed to balance the bridge, are replaced by digital to analog and analog to digital converters. This makes the bridge completely computer-controlled and allows the automation of the balancing procedure. The validation of this new digitally assisted bridge (DAB) has been carried out comparing calculable resistors of different types (quadrifilars, Haddad) over a broad frequency range (50 Hz to 50 kHz). This bridge is presently in use for the investigation of the AC-QHE in graphene and will also be used to improve the accuracy of the impedance standards at METAS.

#### 3.2 AIM-QuTE

The EMRP project AIM-QuTE, started in summer 2013 [8], has 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 will be achieved with two different types of impedance bridges: Josephson bridges and digital bridges. Within the project, METAS will improve the accuracy of the sampling system by a factor of 10 and develop further the impedance simulator (iSimulator) [9]. The iSimulator is designed to automatically calibrate commercial LCR-bridges over the whole complex plane in the audio frequency range. For this purpose, we developed a new algorithm for the synchronization of the sampling frequency of the iSimulator with the internal oscillator of the LCR-bridge [10]. Finally, the impedance simulator will be used for the on-site demonstration at ESZ in Eichenau, Germany at the end 2015.

#### 3.3 FutureGrid

The aim of the EMRP project FutureGrid, 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.

Work on the subject has started in June 2014 and is proceeding swiftly. We are in a position to generate time-stamped streams of measured sampled values with a reference setup developed at METAS and compare them with sampled values from a commercial test set. We can also compare the electrical quantities generated by the test set with the corresponding digital values the test set transmits on the bus.

Next steps will involve development of the specific metrological infrastructure needed to calibrate non-conventional sensors as well as tests on actual sensors.

#### 3.4 New capabilities for the calibration of bridge standards

Strain gauge bridges are routinely used in mechanical measurements (force, weight, torque, pressure) and usually interfaced to high precision amplifiers. To ensure the traceability of the measurements, these amplifiers must also be calibrated. Dedicated bridge standards are commercially available for this purpose. One very popular model is a modified inductive voltage divider (IVD) that simulates a strain gauge bridge with the additional advantage of providing a voltage ratio with a greater accuracy and a better stability. A measurement system has been developed at METAS for the demanding calibration of this type of bridge standard.

The calibration of the bridge standard involves two main differences compared to the calibration of an IVD [11]. Firstly, the measurement of a strain gauge bridge is differential. Secondly, the required precision level is a challenge: 5 ppm for a signal of 2 mV / V which corresponds to 10 ppb of the input signal. These two issues were solved by developing a dedicated divider mounted in series with the reference divider.

All the signal generation and acquisition is done by using commercial digital boards. The balancing procedure of the bridge is automatic.

The new measurement capability enables calibration of a bridge standard (e.g. of type HBM-BN100) within its specifications for the three ratio decades. For example, for a ratio of 2 mV / V, the relative uncertainty is less than 5 ppm.

## 4. Power and Energy

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### 4.1 Metrology for Smart Grids

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 [12, 13], 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.

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 is the only NMI that provides calibration services in coaxial S-parameters that take into account the imperfections of the coaxial connector interface. Due to the project activities over the last years, a novel and unique process has been developed that is used in the characterization of primary coaxial measurement standards (offset shorts, flush shorts and airlines). Dimensional characterization, electrical measurements and material parameters of the standards are used with analytical calculations, numerical EM field simulation and an optimization algorithm to derive S-parameters of the primary standards. Including the connector interface in the model of the standards provides better accuracy and consistency [14]. In addition, a new way on how to determine propagation constants of offset shorts has been developed [15]. A recent publication [16] justifies the treatment of connector effects from a theoretical perspective and demonstrates the benefits for metrology and SI traceability. An important role plays the metrology software VNA Tools II ([www.metas.ch/vnatools](http://www.metas.ch/vnatools)) that has been developed by METAS. It

has been extended to support the process of primary characterization and it provides the possibility to propagate uncertainties from the mechanical characterization of the primary standards through the working standards that are used in daily calibrations, all the way to the DUT of the customer. A truly unbroken traceability chain has been established this way. As of now the improved calibration service is offered for the following connector types: PC-3.5mm, PC-2.92mm, PC-2.4mm and PC-1.85mm. Connector Type-N is currently in the works and should become available later this year. The extension to 110 GHz (PC-1mm) is as well currently pursued in two R&D projects: *ONE-mm* in cooperation with industrial partners and the EMRP project *HF-Circuits* ([www.hfcircuits.org](http://www.hfcircuits.org)).

*HF-Circuits* is as well dedicated to the investigation of the stability of electronic calibration units, a study that is being conducted in collaboration with SP and PTB. Some results have been presented at a conference [17]. Other important results within *HF-Circuits* that are largely based on work performed by METAS are the following:

- A comprehensive study of connector effects for all metrology grade coaxial connectors. The report with the results will be used by the standards committee IEEE P287 in the next version of the standard on coaxial connector interfaces.
- New data formats for S-parameter measurements

## 5.2 RF power

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In 2014 a project (*110 GHz Power*) has been started to extend the coaxial measurement capabilities from currently 67 GHz to 110 GHz. This project is conducted with an industry partner. To limit investments it aims at using the 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).

## 5.3 Scanning Microwave Microscope (SMM)

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METAS did the first steps with the SMM [18] within the EMRP project EMINDA ([projects.npl.co.uk/eminda/](http://projects.npl.co.uk/eminda/)). During the last two years, we have continued to do further work on new improved calibration algorithms [19, 20] for the SMM. The project finished in 2014.

During the project, METAS had access to a commercial device located at the institute of biophysics at the University of Linz in Austria. In parallel, METAS already started to build its own SMM. The aim was a simplified modular design that provides better control on the configuration of the electromagnetic fields in the vicinity of the measurement sample. We have even made attempts to build our own tips with the help of an electrochemical process. The home-built device is currently being used and improved in further research activities.

The EMRP project SolCell ([projects.npl.co.uk/solcell](http://projects.npl.co.uk/solcell)) [21] 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.

More recently, new projects were approved within EMPIR. One of them is related to on wafer measurements and the SMM will be used for the characterization of nano-devices. Another one is related to three dimensional integrated circuits (3d ICs), a hot topic within the semiconductor industry. The NFSMM will be 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.

## 6. EMC and Antenna

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### 6.1 Round robin test device for emc conducted immunity testing

Inter-laboratory comparisons can be an important tool to evaluate the capabilities of EMC test laboratories. However, today, accredited EMC test laboratories only rarely participate in inter-laboratory comparisons. The main reason is that there are simply no adequate EMC devices available for comparisons; especially in the field of immunity testing. METAS has, therefore, developed a new device which is able to assess the immunity test capabilities of a laboratory according to the IEC 61000-4-6 standard [22]. The device is intended to be tested as a normal EUT. It is equipped with appropriate detectors that record all important parameters associated with a chosen test set-up. This work was realized in the scope of the EMRP Project EMC Industry.

### 6.2 Protection against non-ionising radiation: method for measuring LTE base stations

In order to guarantee the traceability of measurements of non-ionising radiation, it is important to make traceable measurements of the LTE signals. In the scope of the EMRP Project MORSE, METAS has developed a method to measure the power of LTE reference signals. The measurement method consists of measuring the signal over the air, down converting it to lower frequencies, sampling it with a calibrated scope and finally demodulating it with decoding algorithms developed at METAS [23]. This development can be used to calibrate commercial LTE signal generators and LTE measuring receivers.

### 6.3 Protection against non-ionising radiation: a field comparison

In 2012, a method to measure the radiation of LTE base stations was presented. In order to validate this method as well as to assess the measurement capabilities of private accredited laboratories in Switzerland, METAS organised a comparison [24]. For this purpose, METAS set up two LTE base stations on the METAS area whose transmitted power was constantly recorded. The accredited laboratories had to measure the electric field strength in three rooms within the METAS building. Several scenarios have been played.

### 6.4 Improved current clamp calibration capabilities

Current clamps are used in the field of emc testing in the frequency range of 10 Hz to 400 MHz. METAS refined the calibration capabilities especially in the frequency range 10 kHz to 100 MHz. This improvement was possible by mixing measurements performed using scalar measurements (signal generators and power amplifiers), and by performing corrections using vector measurements based on VNA instruments.

## 7. Participation in Comparisons

*Comparisons piloted by METAS, reports published since the CCEM meeting in 2013*

- EURAMET.EM-K2.1: Comparison of resistance standards at 10 M $\Omega$  and 1 G $\Omega$  [25].
- EURAMET.EM-S32: Comparison of resistance standards at 1 T $\Omega$  and 100 T $\Omega$  [26].
- EURAMET.EM.RF-S27: Antenna factor for loop antennas [27].

*Measurements carried out since the CCEM meeting in 2013*

- EURAMET.EM-S35: Comparison of High-Current Ratio Standard (December 2013 and December 2014); comparison piloted by INRIM and co-piloted by METAS.
- CCEM-K2.2012: Comparison of resistance standards at 10 M $\Omega$  and 1 G $\Omega$  (May 2014).

## 8. List of Publications

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- [5] F. Overney, F. Lüönd and B. Jeanneret, “Digitally Assisted Coaxial Bridge for Automatic Quantum Hall Effect Measurements at Audio Frequencies”, 2014 Conference on Precision Electromagnetic Measurements, Conference digest pp. 226-227, 2014.
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- [12] G. Rietveld, J.-P. Braun , P. S. Wright, P. Clarkson, N. Zisky, “Smart grid metrology to support reliable electricity supply”, Conference on Precision Electromagnetic Measurements, Conference digest pp. 680-681, 2014.
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- [24] F. Pythoud et al., “Measurement of non-ionizing radiation from a LTE base station: Inter-laboratory comparison – November 2013”, METAS-Report Nr 154.1-2014.5218.904, 17. November 2014 ([www.metas.ch](http://www.metas.ch)).
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