# Development of RF and Microwave Metrology Capability

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The radio frequency and microwave (RF&MW) field has undergone revolutionary changes in the last 40 years and today, RF&MW technology is more pervasive than ever. This is especially true for commercial markets, where modern applications include cellular and smart phones, wireless networking, direct broadcast satellite, television, global positioning systems, wideband radio and radar systems, and microwave remote sensing systems for environment, biomedical and healthcare applications (to name but a few). The research and development in RF and microwave technology still continue with ever-increasing demands from industry. New devices and instruments which bring new challenges to the underpinning metrology play a critical role for advancing technologies. S-parameter measurements, RF power measurements and electromagnetic compatibility (EMC) tests and calibrations are important areas in microwave metrology to ensure and increase product quality and to create end user confidence.

On the behalf of the European Metrology Program for Innovation and Research program supported by the European Commission, under the coordination of TÜBİTAK - Turkey, CMI - Czech Republic, GUM -Poland, INTA - Spain, SIQ - Slovenia, RISE - Sweden, NIS - Egypt, NQIS - Greece, UPC - Spain and METAS -Switzerland, together with "15RPT01 RF Microwave" coded and "Development of RF and microwave metrology capability" project is carried out [1]. This project aimed to develop research and measurement capacities as well as expertise for EURAMET countries in RF&MW. It has done this by transferring theoretical and practical know-how between the project partners and by combining their skills to focus on microwave and EMC measurements.

## Introduction

New technologies in the health, energy, security, environmental, industrial and communication sectors require novel RF&MW devices and measurement methods which currently are under research and development (R&D). However, this R&D brings new challenges to the underpinning metrology for RF&MW as it requires advanced technologies. Scattering parameter (S-parameter) measurements, RF power measurements, EMC tests and calibrations are important areas in RF&MW metrology. These are used to ensure and increase product quality and end user confidence. The reliability of S-parameter measurements depends on how well the characterization and modelling of RF&MW components is performed, therefore, the devices used for this need to be calibrated accurately and their measurement uncertainty must be calculated precisely. However, recent R&D has shown that the simplified characterization and modelling approach currently used for RF&MW components is inadequate [2].

Most of the high frequency electronic devices include short distance communication units which generate low-power ($P \leq 0.01$ mW). In order to obtain traceable and accurate measurements at low-power in RF&MW metrology, power sensors which are used for low-power measurements must be characterised accurately. Due to the difficulty of characterising harmonic effects, some national metrology institutes (NMIs) ignore the effect of higher harmonics in low-power measurements and are not able to characterise power sensors for low-power. There is also a problem with RF&MW high-power measurements ($P \geq 1$ W) used in long distance communication, broadcasting radar applications and other applications. Characterization of high-power measurement equipment such as wattmeters is generally performed using an 'attenuator and power sensor' combination in which both are calibrated at mid-power level ($0.01$ mW $< P < 1$ W). The characterisation parameters of the attenuator and power sensor should be at the same power levels, however, this assumption does not describe the actual situation.

EMC is the interaction of electrical and electronic equipment with the electromagnetic environment and other equipment. In order to avoid EMC related issues, electronic goods manufacturers must test their products that are electromagnetically compatible with relevant regulations. However, new verification methods are needed to increase the quality of EMC test/calibration and measurements, in particular advanced verification methods using vector network analysers (VNAs). Knowledge transfer between EMC and RF&MW laboratories is very weak, which reduces awareness in measurements/calibrations and, therefore the overall quality of both EMC and RF&MW measurements.

The gap between developed and currently developing countries is growing constantly and this situation is even

more pronounced for RF&MW metrology. In order to prevent further widening of this gap in RF&MW metrology, the knowledge and expertise of the more developed NMIs needs to be transferred to those NMIs with less experience.

## Development of Metrology Capability

The overall objective of the project has been to improve the European measurement and research capability for RF&MW metrology and to establish a basis for future cooperation between European NMIs. The specific objectives of the project have been summarized as given below:

a. Improvement of the S-parameter measurements with lower uncertainty and to develop/enhance impedance and S-parameters traceability across Europe by improving the measurement and research capacities of NMI partners and bringing them to a level to be able to adequately support the needs of their stakeholders.
b. Improvement of the reliability and precision of RF power measurements under low and high-power conditions, power sensor measurements for low-power, as well as to investigate the effects of higher harmonics in the response of power sensors to cover the stakeholder needs. Also, to provide the NMI partners the ability to measure and determine output reflection coefficients of signal generators via knowledge transfer.
c. Investigation of advanced calibration methods and establishment of test procedures for EMC with use of RF&MW metrology.
d. Development of an individual strategy for each partner for long-term operation of capacity development, including regulatory support, research collaborations, quality schemes and accreditation.
e. Identification of key industrial and scientific needs for stakeholders in RF&MW metrology.

This project has supported modelling of calibration standards for S-parameters and rigorous uncertainty propagation through a measurement model that represents the entire measurement process from the calibration of the VNA to the result of the device under test (DUT). Advances in modelling and new software capabilities (VNA Tools II developed by METAS) have paved the way to this more consistent approach so the project is used and in better agreement with internationally accepted guidelines. The partners were able to make comparisons on calculable primary calibration standards given in Figure 1 and S-parameter measurements for one-port, two-port and three-port devices with the help of VNA Tools II. The comparison on the S-parameter measurement has also been registered as a EURAMET EM-1426 comparison project.

This project has also addressed the traceability of power sensor calibration for low-power. The traceability approach has been based on the use of characterized adapters and attenuators. So far, TUBITAK and CMI have established their own measurement setups and performed preliminary measurements regarding characterization of diode sensors used for low power measurements. In addition, other partners (SIQ, INTA and CMI) have produced and exchanged information about their proposed measurement setups and measurement techniques for the characterization of 'attenuator and power sensor' combination under small and large-signal conditions. Moreover, SIQ, INTA, NIS, TUBITAK and CMI have produced and distributed information about harmonics effects on power measurements using low-power diode sensors and equivalent circuits. NQIS, INTA and TUBITAK have also established their own setups for the measurement of the output voltage reflection coefficient (VRC) of a microwave generator. Three comparisons on (i) the calibration of diode type power sensors, (ii) the output VRC of a microwave generator (registered as a EURAMET EM-1461 comparison project) and (iii) the characterization of a high power attenuator have been organized for the implementation and enhancement of the gained information.

The strength of RF&MW and VNA metrology is used to increase the quality of EMC test/calibration measurements; 'just-before-test' verification methods using VNAs have been already developed in the project. Such 'just-before-test' verification methods will be able to efficiently detect insidious issues just before conducting emission and immunity tests and thereby significantly increase the quality of EMC measurements. These new and effective just-before-test verification methods developed in the project have also been expanded to low frequency immunity testing by means of the fast Fourier transform (FFT)-based time domain methodology, which has been never done before. Furthermore, the extensive investigation

Figure 1. Calculable primary standards used for comparison.

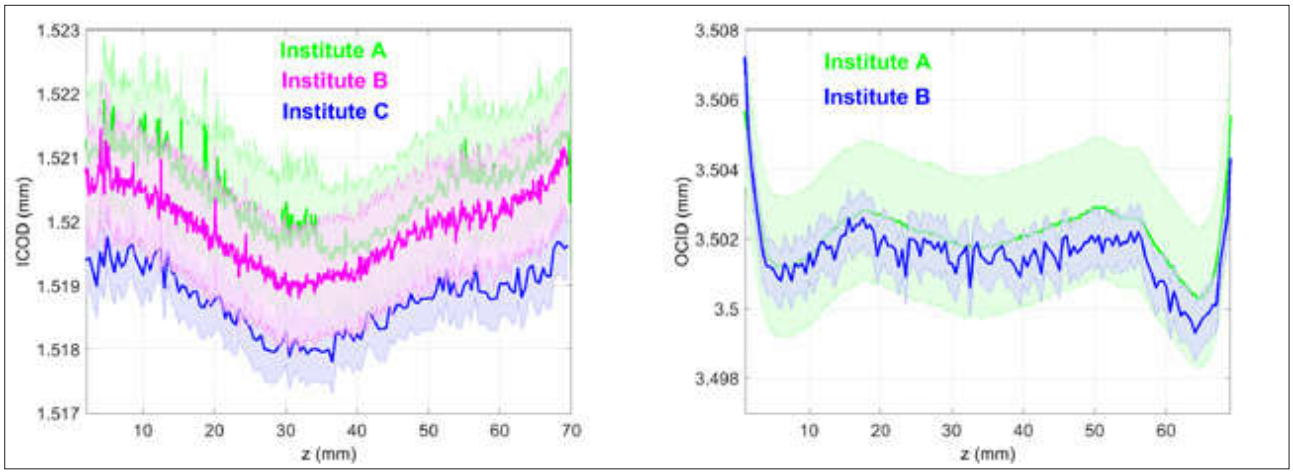



Figure 2. Measurement of the one-calculable standard.

of the three loop-antenna calibration method has been experimentally finalized by performing standard SAE-ARP950&IEEE calibration methods and comparing their results with the three antenna method. The project also transfers knowledge and awareness from the EMC field to the RF&MW field and vice-versa. Consequently, this knowledge link between the two fields will support an increase in the quality of metrology.

## Results

In order to increase S-parameter measurement accuracy among the project partners, primary traceability and uncertainty budget for the S-parameter measurements have been established through calculable calibration standards with use of specialized software tools. Training and workshops activities have been organized to evaluate reliable VNA measurement uncertainties and applied S-parameter measurement system. Partners gained the ability for modelling of calibration standards for S-parameters and calculating rigorous uncertainty propagation through a measurement model and new software capabilities. To prove the acquired ability of the partners, two inter-laboratory comparisons on S-parameter measurements of one-port, two-port and three-port standards [3] and calculable primary calibration standards were conducted. To characterize the calculable standards, partners measured mechanical parameters of the standards. Measurement result of an 'airline' standard for outer diameter of the inner conductor and inner diameter of outer conductor are given in Figure 2 [1].

To improve project partners' power measurement accuracy and capability on the characterization of power sensors for low power measurement, a workshop on the Monte Carlo (MC) method and training on characterizing of diode-type power sensor was organized. During the training, partners gained experience in characterizing of diode-type power sensors using direct comparison technique and establishing their own measurement setup. Technical protocols for three inter-laboratory comparisons have been circulated between partners and approved; (i) power sensor measurements for low-power (diode type power sensor), (ii) measurement of output VRC of a microwave generator [3] and (iii) characterization of a high power attenuator.

This project attempted to integrate the strength of RF&MW metrology, specifically the use of VNAs, into EMC tests and calibrations. It established a link between the areas of RF&MW and EMC that did not only embrace the integration of RF&MW metrology into the EMC field but

Figure 3. Participants of the workshop held at SIQ.

(a) (b) (c)

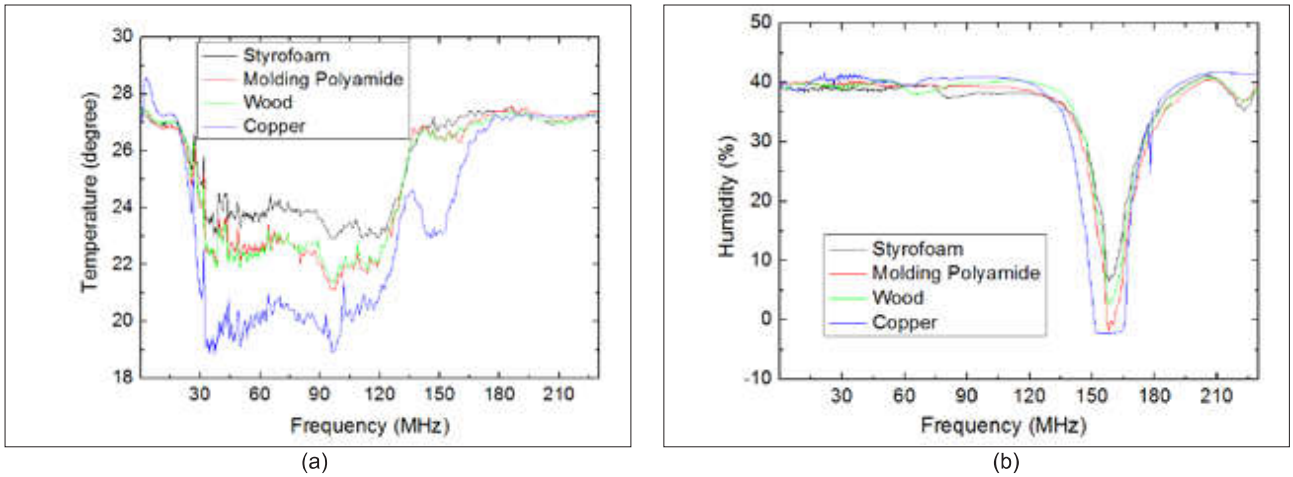
Figure 4. Conducted immunity test setups of the electronic thermometer, (a) used supports, (b) with CDN, (c) with mains without CDN [4].

also promoted an efficient knowledge transfer/exchange between the two fields. For this aim, a workshop was organized at SIQ for the project partners given in Figure 3.

Improved EMC test system verification using VNAs and just-before-tests, the effect of non-metallic objects on EMC test standards, and the traceable calibration of loop antenna using a VNA and pulse generator has also contributed in improving the EMC test and measurement capability of project partners.

The influences of a variety of support materials (styrofoam, moulding polyamide, and wood) in actual EMC tests have been investigated by means of loop impedance measurements with a VNA (Figure 4). Consequently, the effects of the support materials on the test results along with a good link to the injected current, the loop impedance and the susceptibility of the equipment under test (EUT) are shown (Figure 5). The research and results are reported in [4].

In addition to the investigation of the support material samples in actual EMC tests, S-parameters of the same samples at a high frequency, 2 GHz, have been measured by using a WR 430 waveguide. Furthermore, new and effective just-before-test verification methods that use a VNA have been developed in order to be able to detect all issues, including the most insidious ones, with conducted emission and immunity test setups just before tests. This just-before-test verification research has been also expanded to low-frequency immunity tests to verify an entire low-frequency immunity test system. In this context, the project consortium have jointly integrated a FFT-based time domain solution into just-before-test verification methods in order to easily separate low-frequency voltage ripples from the AC power frequency of the EUT by means of a simple oscilloscope and a piece of FFT-based software, which has significantly simplified low-frequency testing and just-before-test verifications and made them more accurate under the adverse AC power supply frequency in comparison with the hardware filtering solutions. Finally, the three antenna calibration method for loop antennas was successfully implemented and effectively compared with the standard methods performed as per international standards such as IEEE291, SAE-ARP958. After the comparison measurements, the advantages of the three antenna method have been clearly set out and demonstrated in terms of lower uncertainty less than 1 dB and ease of use in comparison to standard methods.




(a) (b)

Figure 5. Results of thermo-hygrometer and supports with CDN (a) temperature susceptibility level, (b) humidity susceptibility level [4].

## Conclusion

At the end of this project, participating NMIs gained the necessary knowledge and skills to provide 'new' or enhanced RF&MW measurements and services for their stakeholders. To ensure this, the participation of each partner in the project was designed according to their particular needs. To achieve the desired goal, four workshops and five training sessions have been completed on Monte Carlo methods, S-parameters traceability, traceable characterization of pulse generators, characterization of calculable primary standard, advanced modelling and rigorous uncertainty calculation using specialized software, the calibration of diode type power sensors, RF&MW calibrations of EMC devices, use of EMC components in EMC testing and probability pass or fail test, respectively. The new, just-before-test low-frequency immunity verification and testing methods, which were developed in the project, have been put into service at TUBITAK and are currently being used in actual EMC tests. Also, the three loop-antenna calibration method thoroughly investigated in the project has started to be used in loop antenna calibrations at TUBITAK.

The project partners have produced a peer-reviewed paper and 11 conference papers [4-10] presented in the prestigious metrology and EMC conferences such as 6th Congreso Español de Metrología, EMC Europe 2017/2018, APEMC 2017/2018, IEEE EMC SIPI 2018 and CPEM 2018 and can be found at [11].

## List of Publications

[1] http://rfmw.cmi.cz/

[2] K Wong, J Hoffmann, "Improve VNA Measurement Accuracy by Including Connector Effects in the Models of Calibration Standards," in *ARFTG Conference Digest*, number 82, 2013, pp. 1 – 7.

[3] https://www.euramet.org/technical-committees/tc-projects/

[4] O. Sen, S. Cakir, S. Acak, "More insight into conducted immunity tests and investigation of support influences," in Proc. of the *Asia-Pacific International Electromagnetic Compatibility (APEMC) Symposium*, Seoul, Korea, June 2017, pp. 124-126.

[5] O. Sen, S. Cakir, "Loop antenna calibrations with Inclusion of vector network analyser and comparison between calibration methods," 2017 *International Symposium on Electromagnetic Compatibility - EMC EUROPE*, Angers, France, 2017, pp. 1-6.

[6] M. Azpurua, J. Oliva, M. Pous, F. Silva, "Fast and automated verification of multi-channel full time-domain EMI measurement systems," in *Proc. of the 2017 IEEE International Instrumentation and Measurement Technology Conference (I2MTC 2017)*, Torino, Italy, 22-25 May 2017, pp. 785-790.

[7] M. A. Azpúrua, M. Pous, J. A. Oliva, B. Pinter, M. Hudlička and F. Silva, "Waveform Approach for Assessing Conformity of CISPR 16-1-1 Measuring Receivers," in *IEEE Transactions on Instrumentation and Measurement*, vol. 67, no. 5, May 2018, pp. 1187-1198.

[8] M. Pous, M. A. Azpúrua and F. Silva, "APD oudoors time-domain measurements for impulsive noise characterization," 2017 *International Symposium on Electromagnetic Compatibility - EMC EUROPE*, Angers, France, 2017, pp. 1-6.

[9] M. A. Azpúrua, J. A. Oliva, M. Pous and F. Silva, "Robust extreme value estimation for full time-domain EMI measurements," 2017 *International Symposium on Electromagnetic Compatibility - EMC EUROPE*, Angers, France, 2017, pp. 1-6.

[10] S. Cakir, M. Oztürk, B. Tektas, O. Şen, S. Acak, M. Pous, "FFT-Based Time Domain Solution to Power Frequency Issue of CS101 Testing for Military and Aerospace Equipment," in *Proc. of the 2018 IEEE International Symposium on Electromagnetic Compatibility and 2018 IEEE Asia-Pacific Symposium on Electromagnetic Compatibility (EMC/APEMC)*, May 2018, Singapore, pp. 177-182.

[11] http://rfmw.cmi.cz/index.php/publications.html

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