Publishable Summary for 15RPT01 RFMicrowave
Development of RF and microwave metrology capability

Overview

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). This project aimed to develop research and measurement capacities as well as expertise for emerging EURAMET countries in RF&MW. It was achieved by transferring theoretical and practical know-how between the project partners and by combining their skills to focus on microwave and electromagnetic compatibility (EMC) measurements. The outcomes of this project have been vital for reducing the gap between the European countries in terms of metrological capabilities in radio frequency (100 kHz – 300 MHz) and microwave frequency (300 MHz – 300 GHz).

Need

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 has brought 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 characterisation and modelling of RF&MW components are 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 characterisation and modelling approach that is currently used for RF&MW components is inadequate.

Most 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 less developed NMIs in this project previously ignored the effect of higher harmonics in low-power measurements and they were not able to characterise power sensors for low-power. There was also a problem with RF&MW high-power measurements ($P \geq 1$ W) used in long-distance communication, broadcasting radar applications and other applications.

The characterisation of high-power measurement equipment such as wattmeters was 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 were needed to increase the quality of EMC test/calibration and measurements, in particular, advanced verification methods using vector network analysers (VNAs). Prior to the start of this project, knowledge transfer between EMC and RF&MW laboratories was 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 was growing constantly and prior to this project this situation was 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 needed to be transferred to those NMIs with less experience.

Objectives

The overall objective of this project was to improve the European measurement and research capability for RF&MW metrology and to establish a basis for future cooperation between European NMIs. This enabled less developed European NMIs to build necessary research capacity, as well as improving their calibration and measurement capabilities (CMCs) and reducing the increasing technological gap between NMIs. The specific objectives of the project were to:

1. **Improve 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 level to be able to adequately support the needs of their stakeholders. The primary traceability and uncertainty budget for the S-parameter measurements were established through calculable calibration standards with the use of specialised software tools.
2. **Improve 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 with the ability to measure and determine output reflection coefficients of signal generators via knowledge transfer.
3. **Investigate advanced calibration methods and established test procedures for EMC** with use of RF&MW metrology. EMC calibration methods were improved for traceability of loop antennas and pulse generators and existing verification methods also were improved for EMC immunity/emissions by using advanced RF&MW metrology methods and VNAs. Therefore, an efficient knowledge link was established between EMC and RF&MW experts across Europe.
4. **Develop an individual strategy for each partner for long-term operation of capacity development**, including regulatory support, research collaborations, quality schemes and accreditation. Each partner also developed a strategy to offer calibration services in their own country and in neighbouring countries. The individual strategies were discussed within the consortium and with other EURAMET NMIs/DIs to ensure that a coordinated and optimised approach to the development of traceability in RF&MW metrology was developed for Europe as a whole.
5. **Identify key industrial and scientific needs for stakeholders in RF&MW metrology**. At the beginning of this project, a survey on stakeholders' needs was conducted for these purposes. The results of this survey were instrumental to maximise the impact of this project within the European community of NMIs and industrial end-users via knowledge transfer, training and dissemination for this purpose, meetings, hands-on training sessions, technical papers and best practice guides were prepared.

Progress beyond the state of the art

This project 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 prepared the path to this more consistent approach that the project used, and provided better agreement with internationally accepted guidelines. METAS transferred their knowledge and experience to the partners TUBITAK, CMI, SIQ, INTA, RISE, NIS, GUM and NQIS, as part of a training course and workshops on characterisation calculable primary calibration standards and specialised software tools (VNA Tools II). The partners gained knowledge to characterise calculable calibration standards and to improve S-parameter measurement. TUBITAK, CMI, SIQ, INTA, RISE, NIS, GUM, METAS and NQIS performed comparisons on calculable primary calibration standards and S-parameter measurements for one-, two- and three- port devices with the help of VNA Tools II.

The project also focused on the traceability with respect to the calibration of power sensors for low-power at partners GUM, SIQ, NQIS, NIS and INTA. Characterised adapters and attenuators were used and the traceability approach was based on the experience of TUBITAK and CMI. So far, TUBITAK and CMI have established their own measurement setups and performed preliminary measurements regarding the characterisation of diode sensors used for low power measurements. In addition to this, SIQ, INTA and CMI produced and exchanged information about their proposed measurement setups and measurement techniques for the characterisation of 'attenuator and power sensor' combinations in small- as well as under large-signal conditions. Moreover, SIQ, INTA, NIS, TUBITAK and CMI 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 (1) the calibration of diode type power sensors, (2) the output VRC of a microwave generator and (3) the characterisation of a high power attenuator were organised for the implementation and enhancement of the gained information.

RF&MW and VNA metrology was used by this project to increase the quality of EMC test/calibration and measurements, e.g., 'just-before-test' verification methods using VNAs were developed in the project. Such 'just-before-test' verification methods were 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) were expanded to low-frequency immunity testing by means of the Fast Fourier Transform (FFT)-based time-domain methodology, which had never been done before. Furthermore, the extensive investigation of the three loop-antenna calibration method was experimentally finalised by performing standard SAE-ARP950&IEEE calibration methods and comparing the results with the three antenna method. The project also transferred knowledge and helped to fill existing knowledge gaps with the joint research effort of TUBITAK, RISE, UPC and SIQ.

Results

Objective 1 - Improve S-parameter measurements with lower uncertainty and to develop/enhance impedance and S-parameters traceability across Europe

Training activity and two workshops were organised, in which, the partners CMI, INTA, SIQ, RISE, NIS, NQIS, GUM and TUBITAK learned from METAS how to use specialised software tools (VNA Tools II) to evaluate reliable VNA measurement uncertainties and applied their S-parameter measurement system. The partners have gained the ability to model calibration standards for S-parameters and calculating rigorous uncertainty propagation through a measurement model and new software capabilities. To demonstrate new abilities of the partners, two inter-laboratory comparisons on S-parameter measurements of one-port, two-port and three-port standards and calculable primary calibration standards were completed. The comparison on S-parameter measurements was also registered as a EURAMET EM-1426 comparison project.

With the gained knowledge, CMI and TUBITAK are now able to perform the primary characterisation of their own calculable impedance standards and consequently parameter optimisation using the VNA Tools II. This has allowed CMI and TUBITAK to achieve a set of traceable standards with lower measurement uncertainty. In addition, SIQ has extended the frequency range for S -parameters measurement from 3 GHz up to 26.5 GHz.

Objective 2 - Improve the reliability and precision of RF power measurements under low and high-power conditions

A workshop on the Monte Carlo (MC) method and training on characterising of diode-type power sensor was held, during which the partners INTA, NQIS, GUM and NIS gained experience in characterising of diode-type power sensor using direct comparison technique and established own measurement setup. Technical protocols for 3 inter-laboratory comparisons were developed between partners on; (i) power sensor measurements for low-power (diode type power sensor), (ii) measurement of output VRC of a microwave generator and (iii) characterisation of a high power attenuator. These comparisons have been completed and the results showed good agreement. A comparison on the measurement of output VRC of a microwave generator was also registered as a EURAMET EM-1461 comparison project.

The partners INTA, NQIS, GUM and NIS now have the capability to accurately calibrate diode-type power sensor including vector correction as well as the capability to measure of output VRC of a microwave generator. SIQ, INTA and CMI have also gained experience of characterising a high-power attenuator in its operating conditions (elevated temperature) and its effect on the measurement uncertainty of calibration of high-power attenuators and sensors.

A report about harmonics effects on power measurements using diode type power sensors was produced by the project and equivalent circuits for diode-type power sensors were identified based on the findings from this report. NIS and TUBITAK have established known harmonics generating system and characterised their diode type power sensors with the help of CMI. Moreover, CMI, TUBITAK and NIS have gained knowledge to evaluate the measurement error caused by the presence of higher harmonics when using diode type power sensors. This knowledge has helped the partners to perform more reliable and accurate power measurement.

Objective 3 - Investigate advanced calibration methods and established test procedures for EMC

This project has successfully integrated the strength of RF&MW metrology, specifically the use of VNAs, into EMC tests and calibrations. It has established a link between the areas of RF&MW and EMC, which has not only embraced the integration of RF&MW metrology into the EMC field but has also promoted an efficient knowledge transfer/exchange between the two fields.

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 have also contributed to the improvement of the EMC test and measurement capability of the project partners.

The influences of a variety of support materials; (e.g. styrofoam, moulding polyamide, wood) in actual EMC tests were investigated using loop impedance measurements with a VNA. The results showed the effects of the support materials on the test results together with a significant link to the injected current, the loop impedance and the susceptibility of the equipment under test (EUT). In addition to this, S-parameters of the same support material samples at a high frequency, 2 GHz, were measured by using a WR 430 waveguide.

New and effective just-before-test verification methods that use a VNA were developed in order to be able to detect issues, particularly the most insidious ones, with conducted emission and immunity test setups just before tests. This just-before-test verification research has been expanded to low-frequency immunity tests to verify an entire low-frequency immunity test system. In this context, the project has integrated an 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. This has been done by using 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.

The project consortium also successfully evaluated the new CISPR25 chamber validation method and demonstrated effective applicability of the method along with the active role of network analysers in chamber validation measurements. Finally, the three antenna calibration method for loop antennas was successfully compared with the standard methods as per IEEE291, SAE-ARP958. Based on the results of the comparison measurements, the advantages of the three antenna method have been demonstrated in terms of lower uncertainty (< 1 dB) and ease of use in comparison to standard methods.

Objective 4 - Develop an individual strategy for each partner for long-term operation of capacity development

An individual strategy for each partner for long-term operation of capacity development, including regulatory support, research collaborations, quality schemes and accreditation has been produced. Partners also produced their own short and long term strategic reports to offer calibration services in their own country and in neighbouring countries. The prepared individual strategies have been discussed during the EURAMET TC-EM SC-RF&MW experts meeting (including EMC) in April 2019. The participants from other EURAMET countries at the meeting appreciated the improved measurement capabilities of the project partners. They indicated that the long-term strategies of some of the partners could be a good starting point for future cooperation in more demanding mutual research projects, especially in the area of power and S-parameters measurements.

Objective 5 - Identify key industrial and scientific needs for stakeholders in RF&MW metrology

A questionnaire to identify the RF&MW and EMC capabilities and needs of emerging metrology institutes who were not part of this consortium, partners and stakeholders' was undertaken. The results showed that training on power, S-parameters and EMC measurements was required. Therefore, a training course and two workshops on power, S-parameters and EMC measurements were held for such NMIs, stakeholders and customers. In total 73 participants attended the training courses and workshops and these events were hosted at TUBITAK. Examples of those who attended are Trescal - Denmark, SMD - Belgium, MBM -

Montenegro, Metronet - Romania, GEOSTM - Georgia, Vestel –Turkey, Esim – Turkey, Arçelik – Turkey.

5 training sessions and 4 workshops were also organised by the consortium for NMI partners to improve their knowledge on RFMW and EMC topics such as (i) MC methods, (ii) S-parameters traceability, (iii) traceable characterisation of pulse generators, (iv) characterisation of calculable primary standard, (v) advanced modelling and rigorous uncertainty calculation using specialised software, (vi) the calibration of diode type power sensors respectively, (vii) RF&MW calibrations of EMC devices, (viii) use of EMC components in EMC testing and (ix) probability pass or fail test.

Impact

The results of this project have been disseminated to the end-users in industry, calibration laboratories, academia and metrology community via training course, workshops, and publications at trade journals, well-known peer-reviewed journals and conferences. These are given below.

- 14 international/national scientific conference papers in proceedings of EMC Europe 2017 and 2018 conference, APEMC 2017 and 2018, I2MTC 2017, CPEM 2017, IEEE EMC SIPI Symposium, 6th Congreso Español de Metrología and ESA Workshop on Aerospace EMC.
- A total of 12 open access publications of which, 3 scientific journal papers were in IEEE Transactions on Instrumentation and Measurement and IEEE Transactions on Electromagnetic Compatibility.
- 3 trade journal papers in Signal Integrity Journal, CalLab Magazine and the IEEE Electromagnetic Compatibility Magazine.
- Totally 13 training courses and workshops including practical laboratory application on S-parameters, power and EMC measurements were organised for the project partners, non-consortium NMIs and stakeholders.

The outputs of the project have been also shared using the project website (http://rfmw.cmi.cz), ResearchGate, LinkedIn and Twitter.

Impact on industrial and other user communities

At the end of this project, participating NMIs have 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 was tailored to their stakeholders’ needs. In addition, an individual strategy for each partner for long-term operation of capacity development, including regulatory support, research collaborations, quality schemes and accreditation was produced.

Project partners have gained knowledge on the characterisation of calculable impedance standards including connector effects. For example TUBITAK has measured calculable impedance standards for the first time using dimensional and electrical parameters, which it can now provide to its customers. SIQ has also extended their frequency range for S -parameters measurements from 3 GHz up to 26.5 GHz and can offer this service to stakeholders.

In addition, the new just-before-test low-frequency immunity verification & testing methods, developed by the project, have been put into service at TUBITAK and are currently being used in EMC tests. The three loop-antenna calibration method (successfully investigated in the project) is also being used in loop antenna calibrations for customers at TUBITAK.

Impact on the metrology and scientific communities

The project identified the RF&MW and EMC capability needs of partners and emerging metrology institutes who were not part of consortium through a questionnaire. Based on the results two workshops and a training course for project partners, stakeholders and emerging NMIs (outside of the consortium) were held at TUBITAK.

The project successfully completed 6 comparisons to disseminate knowledge and to establish and enhance the metrological performance of project partners. The comparisons were on (i) calculable primary calibration standards (TUBITAK, CMI and METAS), (ii) S-parameter measurements (SIQ, INTA, CMI, NQIS, NIS, RISE, GUM, TUBITAK and METAS), (iii) power sensor measurement for low-power (INTA, SIQ, NQIS, CMI, NIS, TUBITAK and GUM), (iv) measurement of output VRC of a microwave generator (INTA, SIQ, GUM, NQIS, TUBITAK, NIS and METAS), (v) characterisation of a high power attenuator (SIQ, INTA and CMI) and (vi) traceable characterisation of pulse generator (SIQ, RISE, NQIS, TUBITAK, UPC and CMI).

The project also produced four best practice guides for stakeholders and end users, which are available on the project website. Three of the best practice guides related to power measurements on the calibration of power sensor for low-power measurements, high-power measurements and the harmonic effect on low-power measurements, and the fourth guide is on the traceability of pulse measurement in EMC.

Impact on relevant standards

At the EURAMET TC-EM RFMW meeting in April 2017 and 2019, TUBITAK and UPC presented the project outline and the calibrations and comparisons requested by EMC laboratories were discussed during the. At the EURAMET TC-EM RFMW meeting in April 2019 project partners presented the project's long-term strategy reports and the results of the project's registered EURAMET comparisons s EM-1426 and EM-1461.

Moreover, the project's outputs have been shared with the European metrology community via national standards organisations such as the TSE (Turkish Standards Institution) working group MTC 036 EMC, the UNMZ (Czech office for standards) committee TNK 47 Electromagnetic compatibility, AEN/CTN 208-Aenor Spanish Committee on Electromagnetic Compatibility, the Slovenian SIST/ Technical Committee for Electromagnetic compatibility, the SEK (Swedish; Svensk Elstandard) group TK EMC and the Polish Committee for Standardization (Polski Komitet Normalizacyjny – PKN) group KT 104 Electromagnetic compatibility.

Longer-term economic, social and environmental impacts

The project's results have an indirect social impact through the improved quality and safety of electronic devices. Everyday sources of RF electromagnetic fields are telecommunication devices, broadcasting antennas, microwave ovens and other white goods. High-frequency electromagnetic waves affect the human body in different ways, therefore this project will enhance consumer protection with more reliably calibrated devices. The electromagnetic spectrum is also a limited natural resource which has been progressively occupied by rapidly developing wireless applications. The spectrum is currently too crowded and for this reason; electromagnetic interference is a serious issue in terms of economic and social aspects. Further to this, electromagnetic interference (EMI) radiated from incompatible devices can be considered as environmental pollution and can have environmental consequences.

By enabling European Laboratories to perform regular checks and to control the EMC performance of products more precisely and reliably (with the power of RF&MW and VNAs), the outputs of this project will support the prevention of incorrect testing of devices, thereby making a positive financial impact on the European economy.

List of publications

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[8]. K. Dražil, J. Grajciar, T. Pavlíček, M. Celep and M. Hudlička, "Harmonics Effects on Microwave Power Measurement Using Diode Sensors," in *IEEE Transactions on Instrumentation and Measurement*, vol. 68, no. 6, pp. 1852-1859, June 2019. DOI: 10.1109/TIM.2019.2905885

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<table>
<tr><td colspan="2">Project start date and duration:</td><td>01 June 2016, 36 months</td></tr>
<tr><td colspan="3">Coordinator:
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Project website address: www.rfmw.cmi.cz</td></tr>
<tr><td>Internal Funded Partners:
1 TUBITAK, Turkey
2 CMI, Czech Republic
3 GUM, Poland
4 INTA, Spain
5 RISE Sweden
6 SIQ, Slovenia</td><td>External Funded Partners:
7 NIS, Egypt
8 NQIS, Greece
9 UPC, Spain</td><td>Unfunded Partners:
10 METAS, Switzerland</td></tr>
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