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European Metrology Research Programme
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Glossary

ANAMET	RF and Microwave Metrology Forum
APC-7	7 mm precision coaxial connector
CMC	Calibration and Measurement Capabilities
DC	Direct Current (0 Hz frequency)
DUT	Device Under Test
ECU	Electronic Calibration Unit
EOS	Electro-Optic Sampling
EVM	Error Vector Magnitude
GSSG	Ground-Signal-Signal-Ground probe
IC	Integrated Circuit
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers (www.ieee.org)
IoT	Internet of Things
IPC	Association Connecting Electronics Industries (www.ipc.org)
LRL	Line-Reflect-Line calibration technique (calibration technique)
LSNA	Large Signal Network Analyser
MC	Monte Carlo
MCB	Mismatch Compensation Block
MTRL	Multi-mode TRL (calibration technique)
NVNA	Nonlinear Vector Network Analyser
PCB	Printed Circuit Board
QSOLT	'Quick' SOLT (calibration technique)
RF	Radio Frequency
SI	International System of units
SIG	Special Interest Group (of IEEE)
SRD	Step Recovery Diode
SOLT	Short-Offset short-Load-Thru (calibration technique)
SOL	Short-Open-Load (calibration technique)
SOLR	Short-Open-Load-Reciprocal (calibration technique)
TEM	Transverse Electro-Magnetic (wave)
TRL	Thru-Reflect-Line calibration technique
VNA	Vector Network Analyser

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1 Executive Summary

Overview

Industrial electronics that operate in the high-frequency range (radio frequency, microwave and millimetre-wave) require traceable measurements to support their development. The lack of measurement techniques and intsrumentation can prevent their use in a wide variety of applications such as next-generation communications, health-care monitoring, security and climate change monitoring. This project developed an extensive range of measuring services that have enabled electronics manufacturers and instrument manufacturers to demonstrate traceability to the SI for their measurements, and enabled them to justify and defend performance indicators such as product specifications. These outcomes have benefitted all sectors of the high-frequency electrical and electronics industries, and major contributions have also been made to a European guidance documents (e.g. EURAMET Calibration Guide cg-12, 2007) and international standards such as IEEE Std 287-2007, IEEE Std 1785.2-2016 and IEEE Std 1785.3-2016.

Need for the project

In recent years, high-frequency instrumentation has expanded in medical and security scanners, and transceivers (i.e. transmitters and/or receivers) for consumer electronics and environmental monitoring. It includes millimetre and submillimetre wave electronic components, high-speed digital printed circuit boards (PCBs), and waveguides and coaxial cables (used for connecting electronic components).

The requirements of these cutting-edge, high-frequency industrial electronics applications have driven test equipment manufacturers to develop new types of instrumentation. However, these new classes of instruments for measuring new properties or different aspects of existing properties, fell outside the traceability previously supported by European and other National Metrology Institutes (NMIs). As a result, end-user requirements for calibration and traceability to SI units are not being met. This has a detrimental effect on trading and the supply chain as they need to confirm the performance of the product against a specifiation anad give confidnece that it is performing as expected. To address this, new measurement methods with well characterised uncertainties are needed.

In addition, specialist calibration techniques are needed to achieve the necessary level of testing accuracy for component test set-ups including multiple simultaneous connections to electronic components (i.e. multi-port network analysers). There is also a lack of specialist measurement set-ups for the accurate characterisation of high power/large-signal devices, such as transistors used in communications transceivers (i.e. base stations), and new nano-electronic devices (based on carbon-nano-tubes).

Finally, the EURAMET Guide that impacts this sector of industry needed comprehensively revising in order to bring it up-to-date with current end-user requirements. This was driven by the need to improve uncertainties and to bring measurements in line with the “Guide to the Expression of Uncertainty in Measurement“ (GUM). Revised or new Institute of Electrical and Electronics Engineers (IEEE) standards for high-frequency (i.e. millimetre and submillimetre wavelength) waveguides and precision coaxial connectors were also needed.

Scientific and technical objectives

The project addressed the following scientific and technical objectives:

1. Traceability and verification for millimetre-wave and submillimetre-wave electronics and electromagnetics in coaxial line (to 110 GHz) and waveguide (to 1.1 THz);
2. Traceability and verification techniques for multi-port device configurations including the use of electronic calibration units (ECUs) for vector network analysers (VNAs);
3. Traceability and verification techniques for high-speed digital PCBs for Signal Integrity applications, including differential transmission lines;
4. Traceability and verification techniques for large-signal/non-linear device characterisation (e.g. high-power transistors and power amplifiers) and nano-scale devices (e.g. carbon-nano-tubes, graphene-related electronics and organic macromolecules);
5. Input to a revised version of the EURAMET Guide; the development of IEEE standard P1785; and the revision of IEEE standard P287. Input will also be made to a third IEEE standard-making activity (via a Special Interest Group), in the area of defining nonlinear measurement quantities.

Objectives 1 and 3 concentrated on the general requirements for high-frequencey electronics. Objective 2 was specifc to multiple simultaneous connections. Objective 4 concentrated on high power/large signal devices and nano devices. The final objective looked at the practicalities of how to carry out tests and ensure they are standardised. This included developing a revision of the EURAMET Guide cg-12 to bring these measurements in line with the GUM.

Results

Traceability and verification for millimetre-wave and submillimetre-wave electronics and electromagnetics in coaxial line (to 110 GHz) and waveguide (to 1.1 THz)

Significant extensions to high-frequency measurement traceability capabilities have been achieved:

- coaxial line traceability in the 1.85 mm connector type (that operates at frequencies up to at least 65 GHz)
- traceability in the 1 mm connector type (that operates at frequencies up to at least 110 GHz)
- traceable measurements on rectangular waveguides, in the 110 GHz to 170 GHz band
- traceable measurements in both the millimetre- and submillimetre-wave bands (140 GHz to 220 GHz, 220 GHz to 325 GHz, 750 GHz to 1.1 THz)

In both coaxial lines and waveguides, the measurements have been for one- and two-port devices, providing reflection and transmission coefficients. These are state-of-the-art capabilities that put Europe at the forefront of millimetre- and submillimetre-wave metrology and will ensure traceability for the new technologies being developed by instrument manufacturers, such as developments in 5G mobile communications. This is important because it will ensure reliable measurements are now available to underpin test specifications of products and services in this area of technology. These measurements were not previously available because the required test equipment and reference standards were not available. New products operating at these very high-frequencies can now be tested using traceable measurement systems. This will ensure that tests made by different companies can be demonstrated as equivalent. This ensures the integrity of product specifications in the supplier-customer chain.

Traceability and verification techniques for multi-port device configurations including the use of ECUs for VNAs

VNAs are widely used in industry for characterising the electrical performance of circuits and electronic components, and ECUs enable rapid, automatic and accurate calibration of these analysers. ECUs are used extensively by European calibration and test facilities for routine calibration of VNAs.

Multi-port devices include integrated circuits and microprocessors as used in the computer industry. These devices need to be accurately characterised prior to use in electronic circuits and therefore reliable multi-port VNA calibrations are vital for their accurate characterisation.

A series of comparisons were undertaken for multi-port network analyser calibration techniques between: (i) 4-port calibrations and multiple 2-port calibrations (i.e quick calibrations); and (ii) full 4-port calibrations. The so-called 'quick' calibrations are often used in industry to save time but they can potentially result in a loss of accuracy. The results showed that all types of calibration gave acceptable results for most end-user applications, however, for high accuracy work, the full 4-port calibration technique was the preferred and most accurate option. The choice of calibration routine is critical in achieving traceability for multi-port devices and so the project's comparisons have verified this traceability route.

Methods for monitoring the operational status of ECUs were developed and, using these, data was gathered for verifying the operational stability of ECUs over short time periods (minutes and hours), and, over long time periods (months and years). This data has been used to improve overall knowledge of the operational performance of ECUs for VNAs. This new knowledge will make a significant impact on the end-user community by informing them how often their ECUs need to be re-calibrated.

Traceability and verification techniques for high-speed digital PCBs for signal integrity applications, including differential transmission lines

Designs for a range of different types of calibration standards for high-speed digital PCBs were developed and the effects of different signal path lengths on electrical signals travelling simultaneously along PCB dual conductor lines were investigated. Asymmetries in signal path lengths can cause distortions in the transmitted signals.

A new reference standard PCB including striplines was designed and fabricated to provide a way for end- users to verify signal integrity applications, including the use of differential transmission lines. The reference PCBs have also enabled bespoke calibration techniques to be developed so that end-users can directly characterise components mounted on the surface of PCBs.

Traceability and verification techniques for large-signal / non-linear device characterisation (e.g. high-power transistors and power amplifiers) and nano-scale devices (e.g. carbon-nano-tubes, graphene-related electronics and organic macromolecules)

Large Signal Network Analysers (LSNA) and Nonlinear Vector Network Analysers (NVNA) are used for characterising transistors found in mobile phones and base stations. Two reference devices were developed, fabricated and tested for use by industry and academia for verifying their performance.The new large-signal reference device outperformed previous designs. Long term tests have also demonstrated good stability for the device over significant time periods of up to several weeks. This means that a characterisation of the large-signal reference device remains useable over these longer periods of time and therefore end-users do not need to spend time re-characterising the reference device, which is a time consuming process

Existing commercially available impedance standards are often not suitable for making measurements at the nano scale because the values of the impedances that need to be measured are often very different from the values of existing impedance standards. A range of extreme impedance standards suitable for both calibration and verification of nano-scale devices were designed, fabricated and characterised. These standards can be used to calibrate a measurement system (such as a network analyser) so that it is optimised for measurements of devices with intrinsic impedance values much greater than the usual reference impedance of 50 ohms. This is particularly relevant to carbon-based devices (e.g. devices containing carbon nano-tubes and/or graphene) that can be used in high-frequency electronics applications such as resistors, capacitors and transistors. The extreme impedance standards were subsequently tested using a conventional network analyser, which demonstrated the versatility of these extreme impedance standards over a wide range of operating conditions.

Input to European and International industry-level documentation

A report was submitted to the IEEE 287 standard Working Group, which summarised the investigations undertaken and findings of this project into performance characteristics of precision coaxial connectors. The report will be incorporated into the on-going revision that is taking place of the IEEE 287 standard, the global ‘industry’ reference for connectors of this type.

A document providing performance indications for waveguide devices operating to 1100 GHz was submitted to the IEEE P1785 standard Working Group. This has contributed to two of the three new IEEE standards that this Working Group has developed and published, i.e. IEEE Std 1785.2-2016 “Waveguide Interfaces” and IEEE Std 1785.3-2016 “Uncertainty Specifications”.

The “EURAMET Guidelines on the Evaluation of VNA” document Guide cg-12 has been fully revised by the project and submitted to EURAMET.

Actual and potential impact

The project successfully developed and introduced new, applied measurement traceability and assurance techniques to enable the exploitation of new instrumentation capabilities that have been developed by manufacturers of test equipment. This will support the new product development of European electronics companies by ensuring test equipment has been proven independently via the technical outcomes from this project. The project had a number of uptakes:

- New measurement services which extend the upper frequency range of NMI traceability in coaxial lines to 110 GHz and waveguides to 1.1 THz. These will ensure traceability for new technologies being developed by instrument manufacturers such as developments in communications e.g. 5G.

- Several NMIs have extended their calibration capabilities to include multi-port measurements and methods for using ECUs with VNAs.
- NPL is now evaluating whether a customer calibration service for users of ECUs should be introduced based on the work achieved in this project. At the present time, there are no other NMIs offering such a service.
- The project developed a reference PCB to act as a verification device for the end-user community and to enable bespoke calibration techniques so that users can directly characterise components mounted on the surface of the PCBs.
- LA Techniques Ltd, a UK SME, has been an early user of the project's work on PCBs, using it to verify their technique for establishing calibrations directly at the connection points for devices mounted on PCBs.
- A large-signal reference device has been developed for the verification of measurement systems, such as NVNAs and LSNAs, which are used for characterising transistors found in mobile phones and base stations. The project established measurement capability for nonlinear measurements and measurements that exceed the conventional reference impedance of 50 ohms – i.e. extreme impedance measurements.
- It is planned to use the large-signal reference device developed in the project in the follow-on EMPIR project 14IND10, MET5G and by measurement companies such as project partner Keysight BE). The device will be used as a travelling standard during a round robin measurement comparison exercise.
- Keysight BE and R&S had components and test equipment included in the investigations in the project. This has effectively benchmarked the performance of their systems, in particular their VNAs. This provides useful, independent, evaluation of these components and equipment within the context of this project.

Dissemination

In addition, dissemination activities by the project have ensured that links to the end-user community have been strengthened by providing:

- Three training courses, for end users, on: (i) "Good Practice with VNAs", at VSL, The Netherlands, in June 2014; (ii) "Multiport VNA Measurements", at METAS, Switzerland, in June 2015; (iii) "Revision of EURAMET VNA Guide cg-12', at NPL, UK, in June 2016. All three courses involved project's partners as instructors and each course was attended by approximately 40 participants.
- Three workshops, for end users, on: (i) "Electronic Calibration Units", (ii) "Plans and Considerations for the Upcoming Revision of the EURAMET VNA Calibration Guide" and (iii) "Uncertainties for VNA Measurements".
- Six European ANAMET technical seminars featuring presentations describing the technical outputs from the project were held concurrently with the training courses and workshops.
- 91 presentations at international scientific conferences and the publishing of 52 scientific papers, including contributing to a chapter in a new book on the subject of terahertz metrology.
- Regular six-monthly teleconferences with the project's Stakeholder Advisory Group (SAG); a group of 6 international experts in the project's scientific areas.
- A project web-site (www.hfcircuits.org) for end-users, and a LinkedIn Discussion Group.

Standards

Developing guides and standards has benefited electronics manufacturers and instrument makers by standardising equipment and methods used by the end-users. Two new international standards (IEEE Std 1785.2-2016 and IEEE Std 1785.3-2016) have been published which contain significant input from the project. These standards were developed in a timely manner and contain information which is useful to industry and the end-user community.

A Calibration Guide (EURAMET cg-12) has been submitted to EURAMET. The Euramet Guidelines are important because they provide a common method for evaluating the performance of VNAs that can be used by both end-users and international accreditation bodies.

Potential impact

The new measurement traceability and verification techniques that have been developed by the project will enable test equipment manufacturers and electronic component manufacturers to establish new products with much greater confidence. This includes verifying the credibility of new products and establishing protocols and procedures that can be universally understood and adopted.

2 Project context, rationale and objectives

The purpose of this project was to provide European organisations with reliable measurement capabilities for state-of-the-art high-frequency electronics applications. Electronics is an enabling technology that underpins a wide range of applications such as: (i) consumer electronics (laptops and smart phones, using microwave digital signals); (ii) security (airport security scanners using millimetre-waves); (iii) climate change monitoring (environmental sensing using millimetre-waves); (iv) medical diagnostics (RF scanners for breast cancer detection); (v) next generation electronics and telecommunications (using nano-technology and/or terahertz/submillimetre-waves).

Electronic components, circuits, sub-systems and systems are required in order to realise and enable all the above applications. However, for most applications, the electronics that is required pushes the state-of-the-art in terms of the necessary science, engineering and technology. This, in turn, pushes the state-of-the-art for the measurements that are required to validate and assure, through testing, the electronics that is used at component-level through to system-level architectures.

Over the past 10 years, suppliers of instruments used for high-frequency electromagnetic measurements have introduced entirely new ranges of products aimed at meeting the needs of today’s end-users. These new products/instruments have themselves introduced new measurement quantities and evolved existing measurement quantities to enable end-users to gain maximum insight into their target applications. However, the majority of the parameter space of these new instruments has not been backed-up by traceability mechanisms providing linkage to the SI. This need for new state-of-the-art measurement capabilities to address the issue was taken up by this project’s consortium of seven NMIs, four academic institutes and two unfunded industrial companies.

In the case of applications relating to security and climate change monitoring, this led to an objective within the project to establish traceability and verification for millimetre-wave and submillimetre-wave electronics and electromagnetics in coaxial line to 110 GHz and in waveguide to 1.1 THz. For applications relating to consumer electronics and medical diagnostics, an objective to establish traceability and verification techniques for high-speed digital PCBs for Signal Integrity applications, including differential transmission lines was included in the project.

Applications relating to next-generation electronics employing Radio Frequency (RF) nanotechnology led to an objective to establish traceability and verification techniques for nano-scale devices (e.g. carbon-nano-tubes, graphene-related electronics and organic macromolecules). Furthermore, an objective to establish traceability and verification techniques for large-signal/non-linear device characterisation (e.g. high-power transistors and power amplifiers) was included in the project for applications relating to next-generation telecommunications. In addition to this, an objective was included to establish traceability and verification techniques for multi-port device configurations including the use of ECUs for VNAs for the benefit of end users (including accredited calibration and testing laboratories), who require assured microwave measurements.

Finally, it was recognised that the project could make significant and timely contributions to European and International industry-level documentation as: (i) a comprehensive revision of “EURAMET Guidelines on the Evaluation of Vector Network Analysers”, Guide cg-12; (ii) development of the new IEEE 1785 standards for millimetre- and submillimetre-wave waveguides; (iii) revision of the IEEE 287 standard for precision coaxial connectors at RF, microwave and millimetre-wave frequencies; (iv) input to an IEEE Special Interest Group (SIG) that was reviewing the documentary standardisation needs in the area of defining nonlinear measurement quantities.

Leading to the following five objectives for the project:

1. Traceability and verification for millimetre-wave and submillimetre-wave electronics and electromagnetics in coaxial line (to 110 GHz) and waveguide (to 1.1 THz);
2. Traceability and verification techniques for multi-port device configurations including the use of ECUs for VNAs;
3. Traceability and verification techniques for high-speed digital PCBs for Signal Integrity applications, including differential transmission lines;

4. Traceability and verification techniques for large-signal/non-linear device characterisation (e.g. high-power transistors and power amplifiers) and nano-scale devices (e.g. carbon-nano-tubes, graphene-related electronics and organic macromolecules);
5. Input to European and International industry-level documentation:
   - Revision of “EURAMET Guidelines on the Evaluation of Vector Network Analysers”, Guide cg-12;
   - Development of the new IEEE 1785 standards for millimetre- and submillimetre-wave waveguides;
   - Revision of the IEEE 287 standard for precision coaxial connectors at RF, microwave and millimetre-wave frequencies;
   - Input to an IEEE SIG reviewing the documentary standardisation needs in the area of defining nonlinear measurement quantities.

3 Research results

3.1 Traceability and verification for millimetre-wave and submillimetre-wave electronics and electromagnetics in coaxial line (to 110 GHz) and waveguide (to 1.1 THz)

In order to establish traceability for reflection and transmission measurements in coaxial lines up to 110 GHz and in metallic waveguides up to 1.1 THz, several activities were undertaken by the project, covering modelling and characterising vector network analysers (VNA) as well as measurement practice for both coaxial and metallic waveguide measurements.

3.1.1 VNA modelling and characterisation for waveguide measurements

A procedure and test methods for the characterisation of VNA set-ups were developed by PTB and NPL enabling the determination of characteristic VNA parameters, including stability, noise, linearity, raw performance and cable movement effects. The results of these tests provided information to compare the performance of different VNAs and also to give input values for calculating the measurement uncertainty.

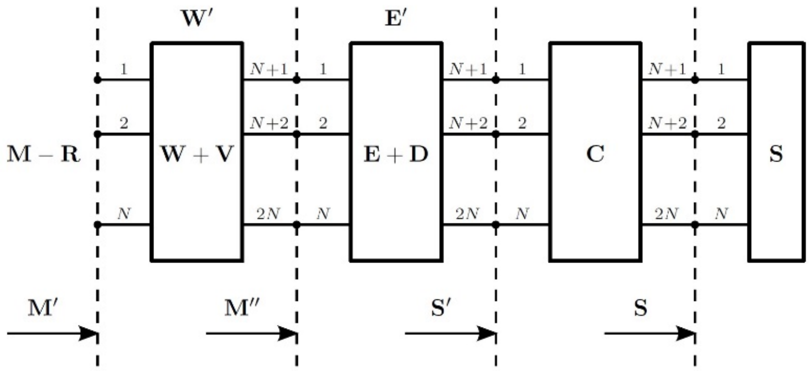

Fig. 1: VNA measurement model considering raw data (M), noise and linearity (R), switch terms (W), drift of the switch terms (V), calibration error terms (E), drift of the calibration error terms (D), cable stability and connector repeatability (C), and the standard (S)

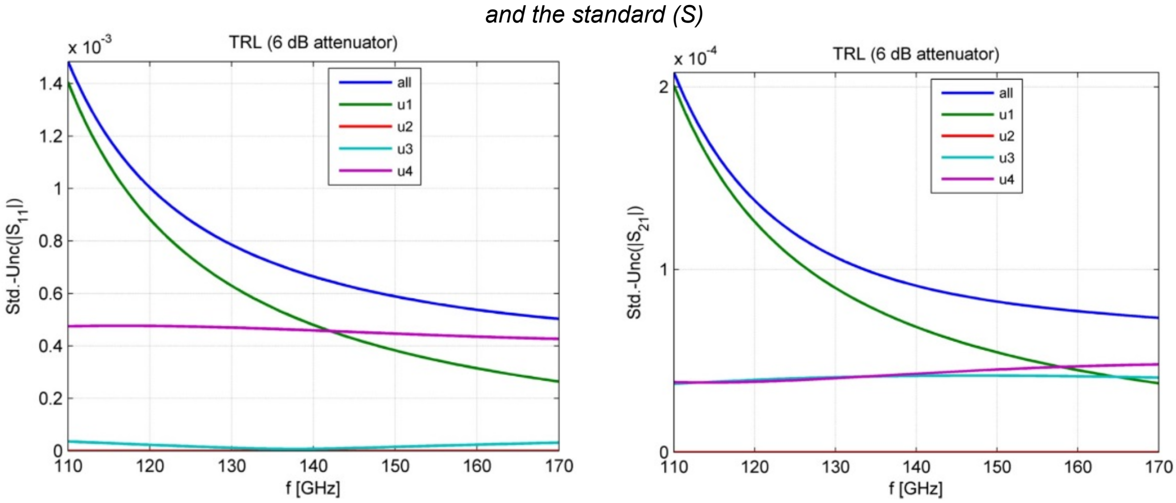

Fig. 2: Uncertainty budget for reflection and transmission S-parameters of a 6 dB attenuator, calibrated with TRL, considering dimensional tolerance of calibration standards (u1), conductivity tolerance of calibration standards (u2), drift, noise, non-linearity and connector effects (u3), cable movement (u4)

A comprehensive VNA measurement model (Figure 1) was established by METAS, PTB and NPL which consider all essential systematic and random influences such as connector effects or flange misalignment, calibration standard imperfections, and, VNA influences such as cable, drift, noise and linearity. The conductors' finite conductivity of the standards can be considered by the VNA measurement model as well as the surface properties (i.e. surface roughness).

Several calibration schemes including Thru-Reflect-Line (TRL), Line-Reflect-Line (LRL) and Short-Offset short-Load-Thru (SOLT) were investigated by NPL and a Researcher Excellence Grant (REG) at the University of Leeds (ULE). The calibration schemes were applied to a WR-05 (140 GHz to 220 GHz) waveguide measurement set-up and uncertainty budgets were established by PTB for two calibration schemes (TRL and LRL) applied to the WR-06 (110 GHz to 170 GHz) waveguide band (Figure 2).

3.1.2 Waveguide Measurements

The results from sub-section 3.1.1 were applied subsequently to waveguide measurements for different frequency bands in the designated frequency range up to 1.1 THz, depending on the necessary hardware available to each project partner (and REG). SI traceability was provided by a complete traceability chain (involving the VNA set-up as well as dimensionally characterised calibration standards) and validated by a comparison of measurements in the 140 GHz to 220 GHz waveguide band.

PTB performed traceable measurements for the waveguide frequency bands 110 GHz to 170 GHz, 140 GHz to 220 GHz and 220 GHz to 325 GHz applying TRL, LRL and SOLT (with sliding load) employing calibration kits supported by project partner Rohde & Schwarz (R&S). A comprehensive performance assessment of VNA calibration schemes for the 33 GHz to 50 GHz band, comparing old and new methods, was also performed by CMI (published in [45]). REG(ULE) and NPL established traceability for waveguide measurements in the waveguide frequency band 750 GHz to 1.1 THz (published in [32], [37] and [38]).

A measurement comparison involving NPL, REG(ULE), PTB and the collaborator the National Institute of Metrology (NIM) of China has validated traceable measurements in the 140 GHz to 220 GHz waveguide band (Figure 3). The results of the comparison have since been published.[1]

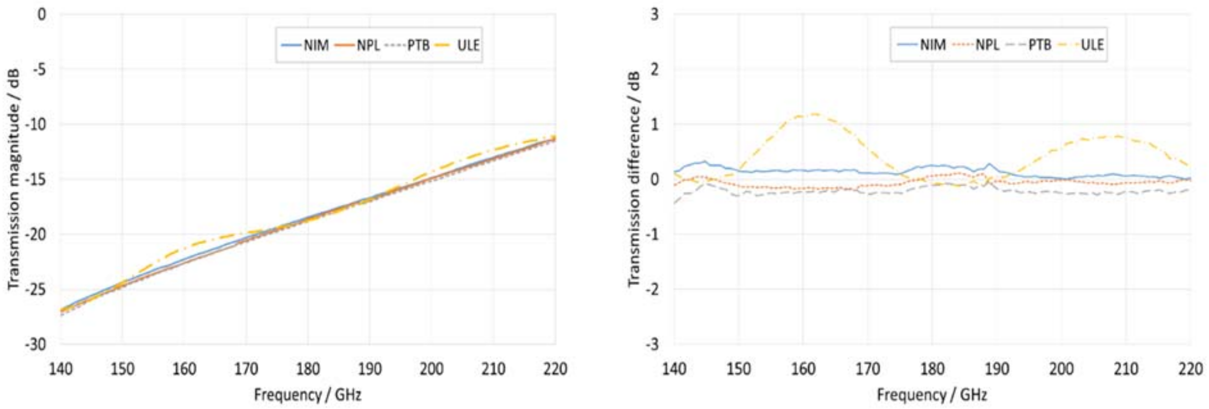

Fig. 3: Transmission magnitude (left) and difference (right) for a measured 0.62 mm cross-guide

3.1.3 VNA modelling and characterisation for coaxial measurements

VNA measurement set-ups for coaxial measurements are similar to those for metallic waveguide measurements except that instead of waveguide extension units the base VNA test-set (at low frequencies) or coaxial extension units (at high-frequencies) are used. Therefore, the procedure suggested in sub-section 3.1.1 was applied by LNE, METAS, PTB and VSL for the characterisation of their coaxial measurement set-ups. In addition, the VNA measurement model resembles that for waveguide measurements with the exception that repeatability and calibration accuracy are considerably dependent on an accurate modelling of coaxial connectors and lines with finite conductivity and surface roughness.

[1] R G Clarke, H Huang, N M Ridler and S Zinal, "Evaluation of cross-connected waveguides as transfer standards of transmission at high millimetre-wave frequencies", *Metrologia*, Vol 53, No 4, pp 1069-1078, August 2016.

METAS and PTB investigated the effects of finite conductivity and surface roughness (Figure 4) on the behaviour of coaxial air lines (employed in TRL and LRL calibration) and proposed models for the calculation of the attenuation and the propagation constant for material properties (published in [4], [12] and [40]).

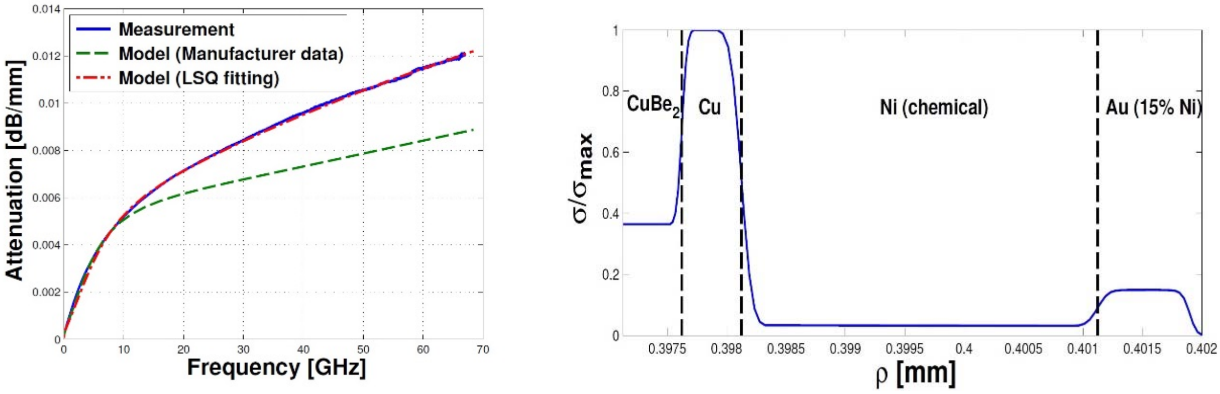

Fig. 4: Attenuation and conductivity profile of a multiple coated coaxial PC1.85 mm air line considering finite conductivities and surface roughness [12]

The influence of imperfect coaxial test ports and connectors (pin gap) was investigated by METAS and VSL (published in [11] and [29]). A comparison of different connector recession measurement methods (optical and tactile) was also performed by VSL. Based on these modelling results, LNE, NPL and PTB characterised a set of PC1.85 mm calibration standards to establish traceable coaxial measurements up to 67 GHz. Furthermore, LNE, METAS and PTB performed dimensional characterisation of PC1.0 mm calibration standards to establish traceable coaxial measurements up to 110 GHz.

3.1.4 Coaxial Measurements

The results obtained from sub-section 3.1.3 were applied to traceable coaxial measurements for PC1.85 mm (up to 67 GHz) and PC1.0 mm (up to 110 GHz) connector types. Traceability was provided by linking the electrical measurements to dimensional measurements of calibration standards. LNE, METAS and PTB electrically characterised their calibration standards for both PC1.85 mm and PC1.0 mm connector types.

The traceability was validated for PC1.85 mm measurements by performing a measurement comparison (Figure 5), involving LNE, METAS, NPL and PTB, applied to a set of test devices provided by R&S. The results of this comparison were published in [27].

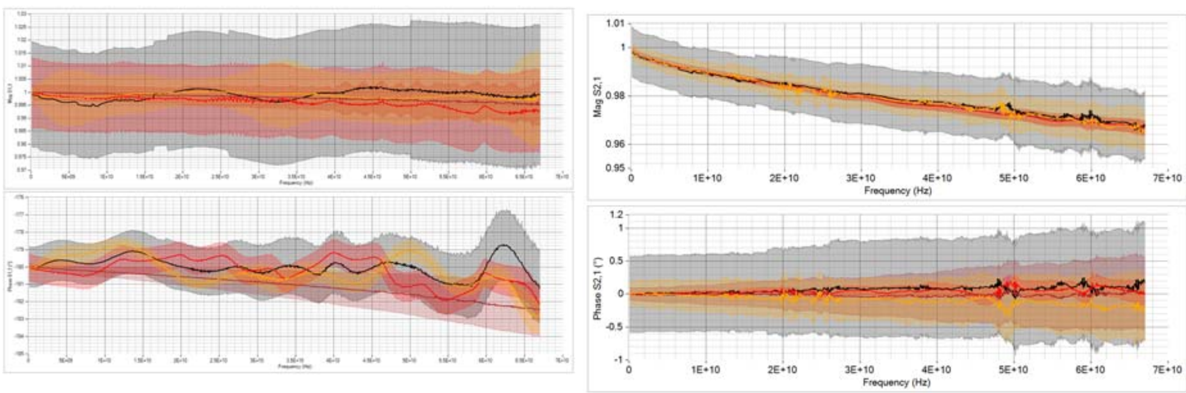

Fig. 5: Magnitude and phase of female flush-short reflection coefficient (left) and female-male adapter transmission coefficient (right). The black line represents LNE, the brown line METAS, the red line NPL and the orange line PTB [27]

Conclusions

In summary the project met Objective 1. Traceability and verification for millimetre-wave and submillimetre-wave electronics and electromagnetics in coaxial line (to 110 GHz) and waveguide (to 1.1 THz). Significant extensions to high-frequency measurement traceability capabilities have been achieved:

- coaxial line traceability in the 1.85 mm connector type (that operates at frequencies up to at least 65 GHz)
- traceability in the 1 mm connector type (that operates at frequencies up to at least 110 GHz)
- traceable measurements on rectangular waveguides, in the 110 GHz to 170 GHz band
- traceable measurements in both the millimetre- and submillimetre-wave bands (140 GHz to 220 GHz, 220 GHz to 325 GHz, 750 GHz to 1.1 THz)

In both coaxial lines and waveguides, the measurements have been for one- and two-port devices, providing reflection and transmission coefficients. These are state-of-the-art capabilities that put Europe at the forefront of millimetre- and submillimetre-wave metrology and will ensure traceability for the new technologies being developed by instrument manufacturers, such as developments in 5G mobile communications. This is important because it will ensure reliable measurements are now available to underpin test specifications of products and services in this area of technology. These measurements were not previously available because the required test equipment and reference standards were not available. New products operating at these very high-frequencies can now be tested using traceable measurement systems. This will ensure that tests made by different companies can be demonstrated as equivalent. This ensures the integrity of product specifications in the supplier-customer chain.

3.2 Traceability and verification techniques for multi-port device configurations including the use of ECUs for VNAs

The aim of this work was to develop traceability for multi-port measurements and electronic calibration units (ECUs). At the start of the project, no traceability existed for multi-port measurements. However, an increasing number of multi-port devices, particularly in industry, needed to be characterised (e.g. multiband mobile phone components, differential transmission lines) for analogue and digital applications and classical devices such as power splitters, etc.

At the same time, the ECU was becoming the most important calibration method in industry for traditional one- and two-port VNAs, and especially for multi-port VNAs. ECUs simplify the calibration of all VNAs significantly by reducing the number of connections necessary to complete a calibration. However, traceability when using these ECUs was not as well established as it was using mechanical calibration kits.

NPL led the work for multi-port VNAs up to 65 GHz (sub-section 3.2.1). RISE led the work to establish ECU traceability that is compatible with the traditional residual error method (sub-section 3.2.2), and METAS led the work to evaluate stability of ECUs over multiple timescales (sub-section 3.2.3).

3.2.1 Multi-port up to 65 GHz

The aim of this work was to investigate uncertainties for various multiport (3-port and 4-port) VNA calibration schemes and to provide traceability for multiport *S*-parameter measurements in coaxial line to 65 GHz using precision 1.85 mm connectors.

The error mechanisms influencing the measurement of multiport *S*-parameters were enumerated and methods for their quantification were proposed. A 4-port VNA was loaned to the project by R&S and was used, in addition to the 4-port VNAs already owned by some of the project partners, to investigate methods for the measurement of multiport *S*-parameters.

Table 1 lists methods used for measuring multiport *S*-parameters. These measurement methods were compared using a Marki Microwave 10 dB 4-port directional coupler (see Figure 6) as a Device Under Test (DUT). The coupler was fitted with female 1.85 mm connectors and had an operating frequency range of 6 GHz to 67 GHz.

The multiport measurement methods included two methods using a 2-port VNA (methods 1 and 2)[2], two methods involving a full calibrations of a 4-port VNA (methods 3 and 7)[3], and three methods involving ‘quick’ calibrations of a 4-port VNA in which the short, open and load (SOL) standards were only connected to a subset of the VNA ports (methods 4, 5 and 6)[4]. It was found that methods 1, 2, 3 and 7 gave broadly equivalent *S*-parameter results whilst the “Quick” methods (methods 4, 5 and 6) give less accurate results for those reflection coefficients measured on the VNA ports to which the SOL standards were not connected directly during calibration.

[2] J C Tippet and R A Speciale, "A rigorous technique for measuring the scattering matrix of a multiport device with a 2-port network analyzer", IEEE Trans MTT-30 (5): 661-666, May 1982.
H Dropkin, "Comments on 'A rigorous technique for measuring the scattering matrix of a multiport device with a 2-port network analyzer'", IEEE Trans MTT-31 (1): 79-81, January 1983.

[3] A Ferrero and U Pisani, “Two-port network analyser calibration using an unknown thru”, IEEE Microwave and guided wave letters, Vol 2, No 12, pp 505-507, December 1992.

[4] A Ferrero and U Pisani, “QSOLT: A new fast calibration algorithm for two port S parameter measurements”, 38th ARFTG Conference Digest, Winter 1991, pp. 15 24.
H J Eul and B Schiek, “Reducing the number of calibration standards for network analyser calibration”, IEEE Trans IM-40 (4): 732-735, August 1991.

Fig. 6: Marki Microwave 10 dB 4-port directional coupler used to compare different multiport measurement methods to 67 GHz

Table 1: Some methods for measuring multiport S-parameters

Method	Method description
1	**2-port SOLR without mismatch correction for terminating loads** Measurement of the DUT using a 2-port VNA with no correction applied for the mismatch of the terminating loads used to terminate unused ports of the DUT. The VNA was calibrated using a 2-port unknown reciprocal thru (SOLR) method.
2	**2-port SOLR with mismatch correction for terminating loads** Measurement of the DUT using a 2-port VNA with a correction applied for the mismatch of the terminating loads used to terminate unused ports of the DUT using a matrix renormalisation technique. The VNA was calibrated using a 2-port unknown reciprocal thru (SOLR) method.
3	**4-port SOLR** Measurement of the DUT using a 4-port VNA. The VNA was calibrated using a 4-port unknown reciprocal thru (SOLR) method.
4	**4-port QSOLT P1** Measurement of the DUT using a 4-port VNA. The VNA was calibrated using a Quick SOLT method with the short, open and load (SOL) standards connected to port 1 only (QSOLT P1) with the calibration being ‘transferred’ to the other ports (ports 2, 3 and 4) by means of measurement of a known thru connected between port 1 and each of the other ports in turn.
5	**4-port QSOLT P12** Measurement of the DUT using a 4-port VNA. The VNA was calibrated using a Quick SOLT method with the SOL standards connected to ports 1 and 2 (QSOLT P12) with the calibration being ‘transferred’ to the other ports (ports 3 and 4) by means of a known thru.
6	**4-port QSOLT P123** Measurement of the DUT using a 4-port VNA. The VNA was calibrated using a Quick SOLT method with the SOL standards connected to ports 1, 2 and 3 (QSOLT P123) with the calibration being ‘transferred’ to the other port (port 4) by means of a known thru.
7	**4-port SOLT (i.e. 4-port QSOLT P1234)** Measurement of the DUT using a 4-port VNA. The VNA was calibrated using a full SOLT method (SOLT i.e. QSOLT P1234)[5].

An inter-laboratory comparison of multiport *S*-parameter measurements was conducted amongst PTB, LNE and NPL [24]. The DUT in the measurement comparison was a 3-port Anritsu power splitter fitted with one male and two female 1.85 mm connectors and with an operating frequency range of 0-65 GHz; as shown in Figure 7. LNE and NPL used 3-port SOLR ‘port-to-port’ calibrations whilst PTB used a 3-port SOLT ‘port-to-

[5] D Rytting, “An analysis of vector measurement accuracy enhancement techniques”, RF & Microwave Measurement Symposium and Exhibition, Hewlett Packard, March 1982.

port' calibration as well as a least squares multiport method[6]. The measurements in the inter-laboratory comparison showed good agreement between the different methods and the different laboratories.

Fig. 7: Anritsu RF power splitter used as the device under test in an inter-laboratory comparison of multiport S-parameter measurements to 65 GHz

3.2.2 Uncertainty in two-port electronic calibration units

The aim of this work was to develop an uncertainty evaluation technique for ECUs without the need to access individual states or internal functions, which is usually proprietary information. ECUs are not compatible between manufacturers so the required approach needed to be independent of the manufacturers' implementations.

The most fundamental approach was to develop a residual error model that is compatible with existing models used in VNAs and calibration items. RISE and NPL proposed a residual error model that used an uncertain two-port associated with each connector in a calibration kit [39]. For a conventional mechanical calibration kit, this means associating an uncertain two-port with each connector sex, but for an ECU, it means associating an uncertain two-port with each port of the ECU. The approach and residual error model of NPL and RISE is similar to an earlier approach described elsewhere[7] but the difference is that the place of the true and model reference planes have been exchanged. An advantage of this new way of placing the reference planes is that it aligns better with the 'Guide to the expression of Uncertainty in Measurement' (GUM)[8] where the true value is usually said to equal the estimated value along with an associated uncertainty.

The calibration procedure by RISE and NPL was applied by transferring known uncertainties from a master mechanical calibration kit to an ECU under test that had been characterised without uncertainties. The procedure started with two calibrations of a VNA resulting in two estimated sets of calibration coefficients: one for the master kit and one for the ECU under test. These calibration sets were then de-embedded from one another to provide an estimate of the difference between the calibration sets.

This calibration procedure by RISE and NPL gave values and uncertainties for three parameters i.e. Directivity; Match; and Tracking; which can be associated with the residual errors used with traditional uncertainty

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[6] A Gronefeld, "Fehlermodelle und selbstkalibriermethoden fuer vektorielle netzwerkanalysatoren," Ph.D. dissertation, Ruhr-University, Bochum, Germany, 1998.
[7] J Stenarson and K Yhland, "Residual error models for the SOLT and SOLR VNA calibration algorithms," Proc. 69th ARFTG Microwave Measurement Conference, Honolulu Hawaii, 2007.
J Stenarson and K Yhland, "A new assessment method for the residual errors in SOLT and SOLR calibrated VNAs," Proc. in 69th ARFTG Microwave Measurement Conference, Honolulu Hawaii, 2007.
[8] "Evaluation of measurement data - Guide to the expression of uncertainty in measurement," JCGM-100:2008.

evaluation of VNAs as described in the EURAMET Guide[9]. The calibration procedure and its uncertainty model was verified using existing two-port ripple techniques.

The second part to this work related to checking the operational status of ECUs, as anecdotal evidence from industrial end users suggested that ECUs often fall out of specification between calibrations. It was expected that the calibration procedure of RISE and NPL could also be used for checking the operational status of ECUs so an uncertainty budget was developed. When performing an operational status check, it is not the actual values of the residual errors but rather the change in those values between the current test and a previous known good test that is needed. Therefore this means that only the drift part in the uncertainty of the residual errors from the master calibration kit needs to be included; and the systematic/constant term can be ignored. If the same VNA (i.e. the same settings) is used with the same cables and adapters for both measurements (i.e. the current test and a previous known good test) then it might also make sense to use a smaller value for linearity uncertainty or at least only include it once. Isolation can also be ignored since the transfer calibration is performed on one port at a time.

Four methods were highlighted as candidates for monitoring the operational stability of the ECU:

1. Comparison against mechanical standards, another ECU or itself (as described above);
2. Comparison of calibration states using a cross-ratio method[10];
3. Individual state measurement;
4. Verification item following ECU calibration.

Each method required at least one separate verification item unless the ECU under test contained a state that may be used only for verification purposes.

3.2.3 Stability in electronic calibration units

The main aim of this work was to study the stability of ECUs in a calibration laboratory and was carried out in the following three stages:

***Stage 1*:** A common method of measurement and analysis was developed to enable the stability of ECUs over different time scales. This common method included investigating the influence of temperature gradients, between the VNA test port and the ECU, on the calibration results. In addition, a workshop was organised and delivered (at RISE, Sweden, in December 2013) that described the common method. The workshop was attended by end-users of ECUs and was an opportunity to gain feedback on the developed method. Generally, the feedback received on the proposed common method was favourable and indicated that the method should be used, in the first instance by the project partners, to gather data on ECUs used in the project. This activity was done in Stage 2.

Tests on ECUs by the project partners, following the common method, produced a series of measured S-parameters or error correction terms, either as a function of time or as a function of ambient temperature change. To illustrate the analysis technique here, one S-parameter, S_{11}, is used, measured at different times, t_1, t_2, t_3. For all other cases the analysis remains, in principle, the same.

For the measured series of S_{11}, $S_{11}(t_1)$, $S_{11}(t_2)$, $S_{11}(t_3)$, calculate the vector differences with respect to the reference measurement:

$$\Delta S_i = S_{11}(t_i) - S_{11}(t_1)$$

A graphical representation can be given by reducing the two-dimensional (i.e. complex-valued) quantity to a scalar quantity by calculating the magnitude, $|\Delta S_i|$.

The measurement uncertainty is a reasonable criterion to distinguish between variations coming from the stability effects of the ECUs and variations coming from other measurement errors. Uncertainty propagation was used to determine the (standard) uncertainty covariance matrix, **V**, of the complex-valued ΔS_i. This matrix can be expanded by a factor $(2.45)^2$ to provide a 95 % coverage region. If the elliptical region defined by the

[9] "Guidelines on the evaluation of vector network analysers (VNA)," EURAMET cg-12, version 2.0, March 2011.
[10] U Stumper, "Extended cross-ratio reflection correction at microwave frequencies using waveguide air-lines," IEEE Trans IM-50, No 2, pp 364-367, April 2001.

expanded uncertainty does not contain the origin of the coordinate system, the deviation can be attributed to ECU effects.

For magnitude $|\Delta S_i|$, linear uncertainty propagation could provide an incorrect result due to the nonlinear relationship between $|\Delta S_i|$ and ΔS_i. Monte Carlo uncertainty propagation only produces positive values - i.e. the distribution will not contain zero and so was therefore unsuitable to make the above-mentioned assessment. Instead, a more heuristic uncertainty was calculated based on a graphical interpretation of the elliptical region defined by **V**.[11]

$$u(|\Delta S_i|) = \sqrt{(\Delta S_i' \, V^{-1} \Delta S_i)^{-1} \chi^2_{2,1-p}} |\Delta S_i|, |\Delta S_i| \neq 0$$

where ΔS_i represents a row vector of length two, containing the real and imaginary parts; $\chi^2_{2,1-p}$ denotes the chi-square factor for a coverage probability. $\chi^2_{2,1-p}$ = $(2.45)^2$ for p = 0.95.

Stage 2**:** Experimental data was gathered by the project partners of ECUs operating under various conditions: (i) over short timescales (of minutes and hours); (ii) over long timescales (of months and years); (iii) under the influence of temperature gradient effects between the VNA test port and the ECUs on calibration results. Part of this work was published in a scientific paper [5].

Stage 3**:** A Good Practice Guide (GPG) was produced giving recommendations for the recalibration (procedures and intervals) of ECUs. These recommendations were based on the outcomes from the investigations in Stage 2 and they revealed that ECUs show different behaviour, depending on the manufacturer and model/type of the ECU. Thus is was found that recommendations for recalibration intervals cannot be generalised for all kinds of ECU. Instead, the GPG outlined an approach to firstly determine the important characteristics of ECUs and then secondly their recalibration. For all stability tests, it was important to follow the manufacturer's instructions for the ECU (e.g. regarding warm-up time, etc).

The GPG concluded that in order to apply an ECU for VNA measurements in testing or calibration laboratories (or wherever a statement concerning measurement uncertainty in needed) an investigation of the individual unit is generally required. In addition, it would be beneficial for manufacturers of ECUs to provide thermal and long-term stability data along with recommendations for recalibration intervals.

Conclusions

In summary the project met Objective 2 Traceability and verification techniques for multi-port device configurations including the use of ECUs for VNAs. VNAs are widely used in industry for characterising the electrical performance of circuits and electronic components, and ECUs enable rapid, automatic and accurate calibration of these analysers. ECUs are used extensively by European calibration and test facilities for routine calibration of VNAs.

Multi-port devices include integrated circuits and microprocessors as used in the computer industry. These devices need to be accurately characterised prior to use in electronic circuits and therefore reliable multi-port VNA calibrations are vital for their accurate characterisation.

A series of comparisons were undertaken for multi-port network analyser calibration techniques between: (i) 4-port calibrations and multiple 2-port calibrations (i.e quick calibrations); and (ii) full 4-port calibrations. The so-called 'quick' calibrations are often used in industry to save time but they can potentially result in a loss of accuracy. The results showed that all types of calibration gave acceptable results for most end-user applications, however, for high accuracy work, the full 4-port calibration technique was the preferred and most accurate option. The choice of calibration routine is critical in achieving traceability for multi-port devices and so the project's comparisons have verified this traceability route.

Methods for monitoring the operational status of ECUs were developed and, using these, data was gathered for verifying the operational stability of ECUs over short time periods (minutes and hours), and, over long time periods (months and years). This data has been used to improve overall knowledge of the operational

[11] M Zeier, Proc CPEM, pp 458-459, 2006.

performance of ECUs for VNAs. This new knowledge will make a significant impact on the end-user community by informing them how often their ECUs need to be re-calibrated.

3.3 Traceability and verification techniques for high-speed digital PCBs for Signal Integrity applications, including differential transmission lines

The aim of this work was to develop traceability and verification techniques for high-speed digital PCBs for Signal Integrity applications, including differential transmission lines; which are needed for applications relating to consumer electronics and medical diagnostics.

3.3.1 Standards and calibration techniques

A literature survey was conducted relating to mixed-mode *S*-parameter modelling and measurement for differential circuits and the evaluation of the uncertainty for such measurements. Methods for measuring the mixed-mode S-parameters of a 2-port differential circuit include:

1. Measurement of 16 single-ended *S*-parameters using a 4-port VNA followed by a mathematical transformation to 16 mixed-mode *S*-parameters[12];
2. Measurement using a 2-port VNA and a pair of baluns (this method only measured the differential mode *S*-parameters)[13];
3. Multimode Thru-Reflect-Line (TRL) calibration of a 4-port VNA using a differential thru, a differential line and a differential reflect as calibration standards[14]; and
4. True differential mode and common mode excitation using a 4-port VNA with two signal sources[15].

Mixed-mode *S*-parameter measurements were made in the frequency range 1 to 10 GHz on a 180 degree hybrid coupler and on a differential amplifier operating in its linear range (input port power -10 dBm) using measurement methods 1 and 4. The 4-port VNA used for these measurements was loaned to the project by partner Rhode & Schwarz (R&S). For the passive device (180 degree hybrid coupler) the two methods (i.e. 1 and 4) showed good agreement. For the active device only the true differential mode stimulus method (i.e. 4) was used but in this case it was found that in order to accurately establish the differential and common mode excitations it was necessary to compensate for the reflection coefficients of the DUT.

Using the results of the S-parameter measurements, a range of balanced and unbalanced VNA calibration standards were designed on a polyimide printed circuit board (PCB) substrate as listed in Table 2.

[12] D E Bockelman and W R Eisenstadt, “Pure-mode network analyzer for on-wafer measurements of mixed-mode S-parameters of differential circuits,” *IEEE Trans. Microw. Theory Tech.,* vol. 45, no. 7, pp. 1071–1077, Jul. 1997.

[13] K Jung, R L Campbell, L A Hayden, W R Eisenstadt and R M Fox, “Evaluation of Measurement Uncertainties Caused by Common and Cross Modes in Differential Measurements Using Baluns”, *IEEE Transactions on Microw. Theory Tech.*, vol. 56, no. 6, June 2008, pp. 1485-1492.

[14] M Wojnowski, V Issakov, G Sommer, and R Weigel, "Multimode TRL Calibration Technique for Characterization of Differential Devices" *IEEE Trans. Microw. Theory Tech.*, vol. 60, no. 7, July 2012, pp. 2220-2247.

[15] J Dunsmore, “New methods & non-linear measurements for active differential devices”, *Microwave Symposium Digest, 2003 IEEE MTT-S International*, FL, Jun. 2003, pp. 1655–1658.

Table 2: Balanced and unbalanced VNA calibration standards

Transmission line type	Calibration standards	1-port or 2-port
Balanced microstrip	Uniform transmission lines	2-port
	Short-circuit termination	1-port
	Open-circuit termination	1-port
	Differential-short-common-open termination	1-port
	Mode converter termination (converts between differential and common modes)	1-port
Balanced stripline	Uniform transmission lines	2-port
	Short-circuit termination	1-port
	Open-circuit termination	1-port
	Differential-short-common-open termination	1-port
	Mode converter termination (converts between differential and common modes)	1-port
Unbalanced microstrip	Uniform transmission lines	2-port
	Offset short-circuit termination	1-port
Unbalanced stripline	Uniform transmission lines	2-port
	Offset short-circuit termination	1-port

The designs of the range of balanced and unbalanced VNA calibration standards were made with the aid of the electromagnetic simulation software CST Microwave Studio and were subsequently incorporated into the design of the reference PCB. In addition, balanced and unbalanced Beatty lines were designed for use as VNA verification standards, e.g. Figure 8 shows the geometry of a Beatty line for differential stripline and Figure 9 shows the simulated differential mode transmission and reflection coefficients.

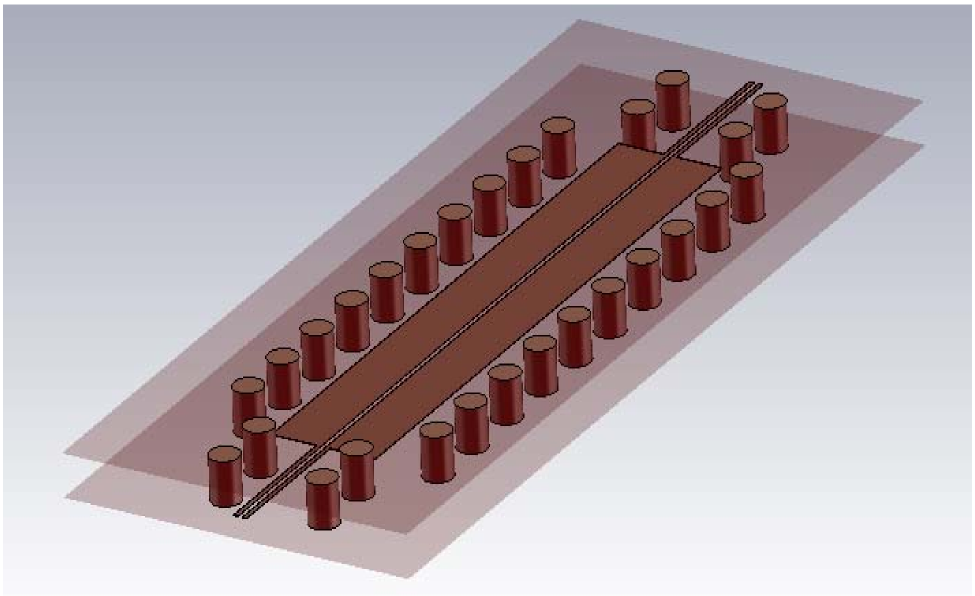


Fig. 8: Beatty line for differential stripline. Note that, for clarity, the dielectric substrate is not shown and the top and bottom ground planes are shown as transparent

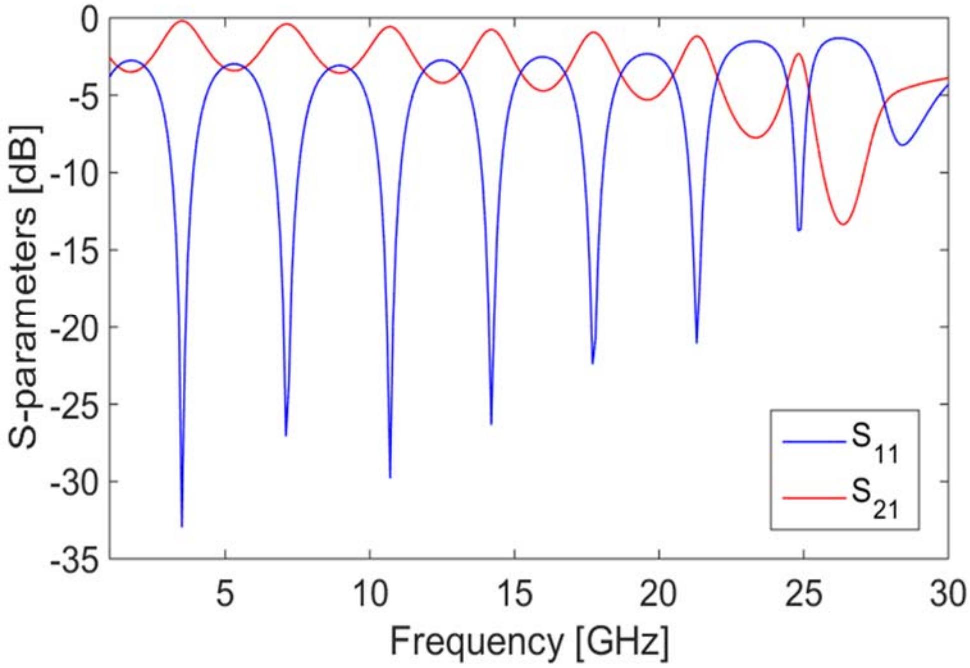


Fig. 9: Magnitude (dB) of the differential mode reflection and transmission coefficients (S11 and S21) for the differential stripline Beatty line predicted by electromagnetic simulation

An investigation on the effects of asymmetry in the cross-section of differential microstrip and differential stripline transmission lines on key transmission line properties was carried out, using the electromagnetic simulation software HFSS. The key transmission line properties investigated were the differential mode characteristic impedance Z_{diff} and the mode-conversion transmission coefficient S_{dd21}. Starting from symmetric designs of differential microstrip and differential stripline, the following parameters were varied:

- The gap between the two traces;
- The width of the second trace (resulting in asymmetry); and
- The gap between the two traces and the width of the second trace (resulting in asymmetry).

It was found that, in terms of S_{dd21}, differential stripline transmission lines exhibit a greater robustness against asymmetry compared to differential microstrip. Figure 10 shows the impact on the mode conversion transmission coefficient of varying the width of the second trace in a differential microstrip transmission line.

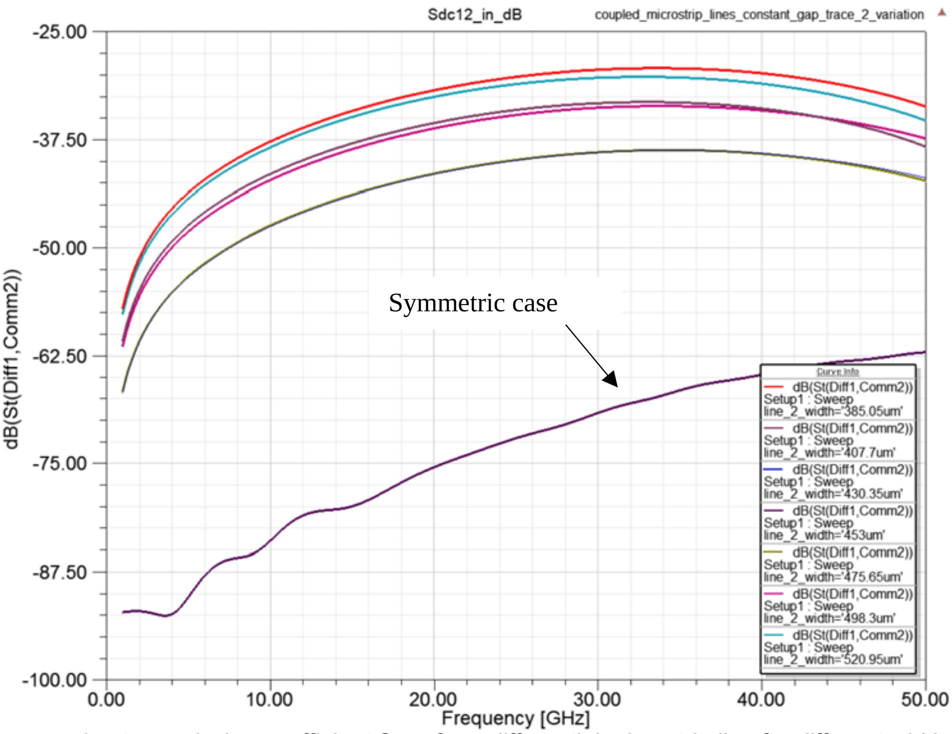


Fig. 10: Mode conversion transmission coefficient S_{dc21} for a differential microstrip line for different widths of the second trace

3.3.2 Interconnects and signal integrity in both time and frequency domains

Measurements of single ended and mixed-mode *S*-parameters were made on a range of transmission lines using a prototype reference PCB in the frequency range 100 MHz to 30 GHz. The transmission lines were either balanced or unbalanced, microstrip or stipline and probed or connectorised. The setup measured the mixed mode S-parameters of a balanced transmission line using Ground-Signal-Signal-Ground (GSSG) probes as shown in Figure 11. The measurements were used, together with electromagnetic simulations, to improve the design of the prototype reference PCB with more efficient fixtures.

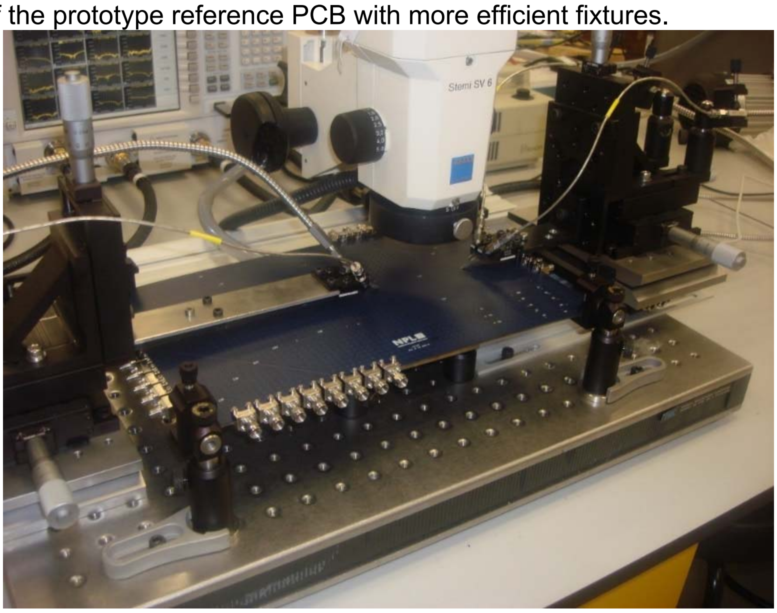


Fig. 11: Setup for measurement of mixed mode S-parameters showing the 4-port VNA, PCB probe station, GSSG probes and the prototype reference PCB under test

Using the improved the design for the reference PCB, a new reference PCB was designed and fabricated, that contained both coaxial end-launch connectors and on wafer landing pads[16]. The reference PCB included VNA calibration and verification standards and was designed to operate over the frequency range 500 MHz to 25 GHz. A summary of the contents of the reference PCB is given in Table 3; it has four copper layers separated by three 600 µm thick dielectric layers. The PCB dielectric base material is polyimide and photographs of the fabricated reference PCBs are shown in Figure 12 (only the probed version is shown).

Table 3: Contents of reference PCB

Unbalanced microstrip & Unbalanced stripline	Balanced microstrip & Balanced stripline
• Thru • 4 lines of different length • Beatty line • 7 Short-circuits of different offset length	• Thru • 4 lines of different length • Beatty line • Mode blocker (reflects differential mode, transmits common mode) • 4 terminations (short-circuit, open-circuit, differential-short-common-open and asymmetric mode converter)

The balanced calibration standards on the reference PCB (balanced thru, balanced lines and balanced reflects) allowed the following TRL calibrations to be performed:

- A multimode TRL (MTRL) calibration which deals with both the differential mode and the common mode simultaneously;
- A single mode TRL calibration which deals only with the differential mode; and
- A single mode TRL calibration which deals only with the common mode.

As an example, Figure 13 compares the magnitude of S_{dd21} for the balanced microstrip Beatty line on the reference PCB corrected using a partial MTRL calibration (using only the thru and the lines but not the reflect) with that corrected using a differential mode TRL calibration. The propagation constants of the differential and common modes for the balanced microstrip and are estimated during the MTRL calibration from the eigenvalues of a 4 X 4 matrix derived from the calibration measurements on the thru and the lines.

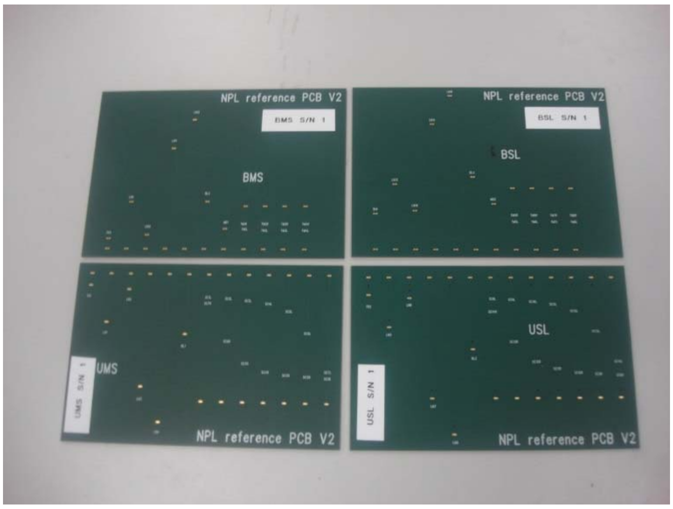


Fig. 12: Fabricated reference PCB with on-wafer landing pads. The two boards at the top of the picture contain balanced transmission lines (balanced microstrip and balanced stripline) whilst the two boards at the bottom contain unbalanced transmission lines (unbalanced microstrip and unbalanced stripline)

[16] M Salter, N Ridler, Y-P Hong, D Allal, F Ziade, M Hudlicka and T Pavlicek, "A reference printed circuit board (PCB) for validating microwave measurements on PCBs and a differential calibration kit for traceable measurements", Workshop, WS09 Microwave measurements and electromagnetic simulations of printed circuit boards (PCBs) for high speed digital and radio frequency (RF) applications, EuMW 2015, Paris, September 6-11, 2015.

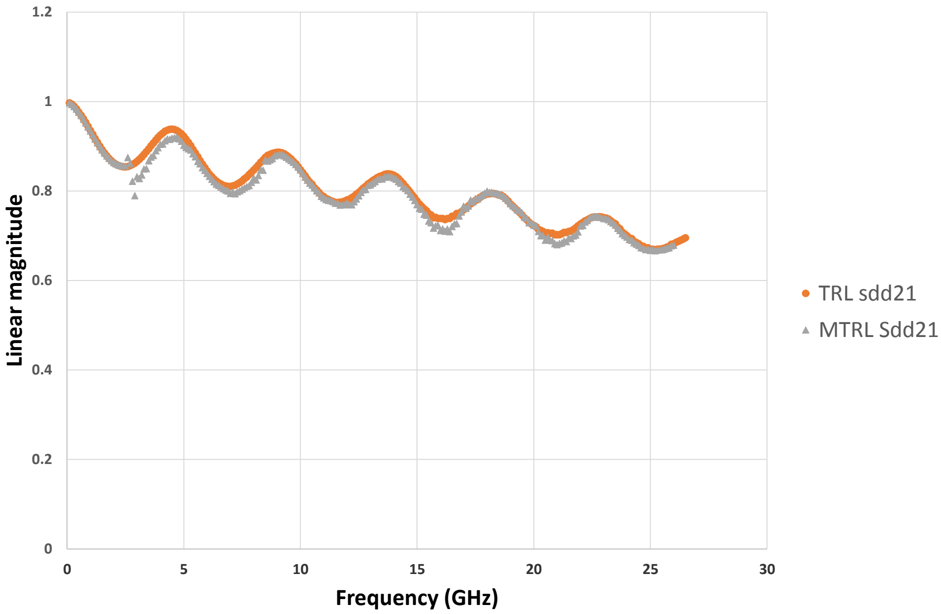


Fig. 13: Partial MTRL calibration vs. differential mode TRL calibration for S_{dd21} of the balanced microstrip Beatty line on the reference PCB

3.3.3 Modelling and measurement uncertainty

Two differential calibration kits were designed on a Nelco N7000-2 V0 substrate (which is similar to polyimide) for use over the frequency range 1 GHz to 25 GHz: one differential calibration kit in differential microstrip and one in differential stripline. The two calibration kits each consisted of a differential thru, three differential lines and four differential reflects (i.e. OOO, SSO, OSO and OOS). The mixed-mode *S*-parameters of the calibration standards were computed using the electromagnetic simulation software CST Microwave Studio. The geometry of the stripline thru is shown in Figure 14 and that of the stripline reflects is shown in Figure 15. The electromagnetic models of the calibration standards were used to derive uncertainties in the *S*-parameters of the standards which were then propagated through the TRL calibration algorithm to uncertainties in the *S*-parameters of a DUT consisting of a mismatched line as shown in Figure 16 [26].

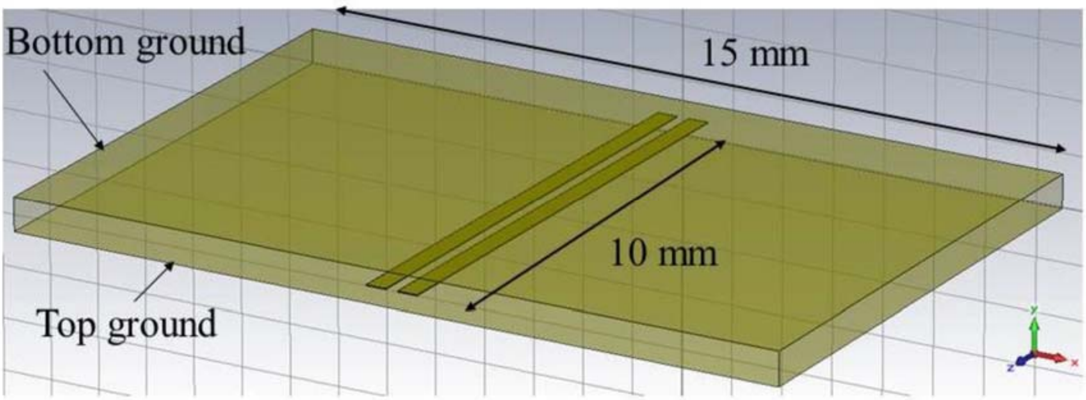


Fig. 14: Geometry of the balanced stripline thru standard

	Z1	Z2	Z12	Matrice Nodal	Matrice Modal
OOO	Open	Open	Open	$\begin{bmatrix}1 & 0\\0 & 1\end{bmatrix}$	$\begin{bmatrix}1 & 0\\0 & 1\end{bmatrix}$
SSO	Short	Short	Open	$\begin{bmatrix}-1 & 0\\0 & -1\end{bmatrix}$	$\begin{bmatrix}-1 & 0\\0 & -1\end{bmatrix}$
OSO	Open	Short	Open	$\begin{bmatrix}1 & 0\\0 & -1\end{bmatrix}$	$\begin{bmatrix}0 & -1\\-1 & 0\end{bmatrix}$
OOS	Open	Open	Short	$\begin{bmatrix}0 & 1\\1 & 0\end{bmatrix}$	$\begin{bmatrix}-1 & 0\\0 & 1\end{bmatrix}$

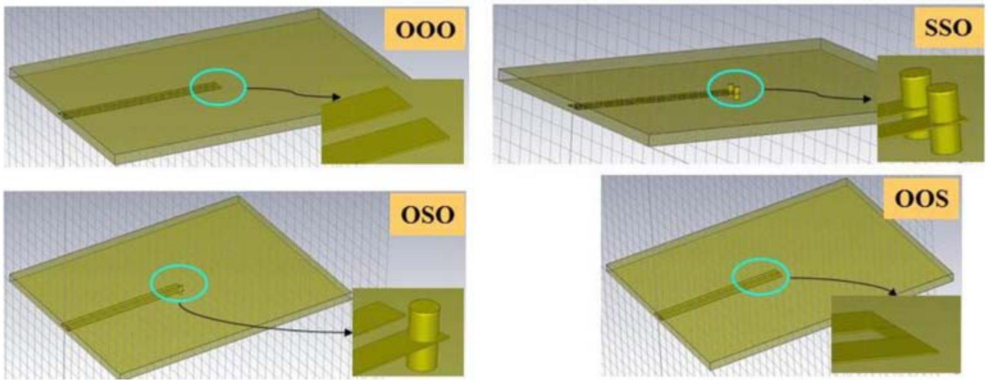


Fig. 15: Geometry of the balanced stripline reflect standards

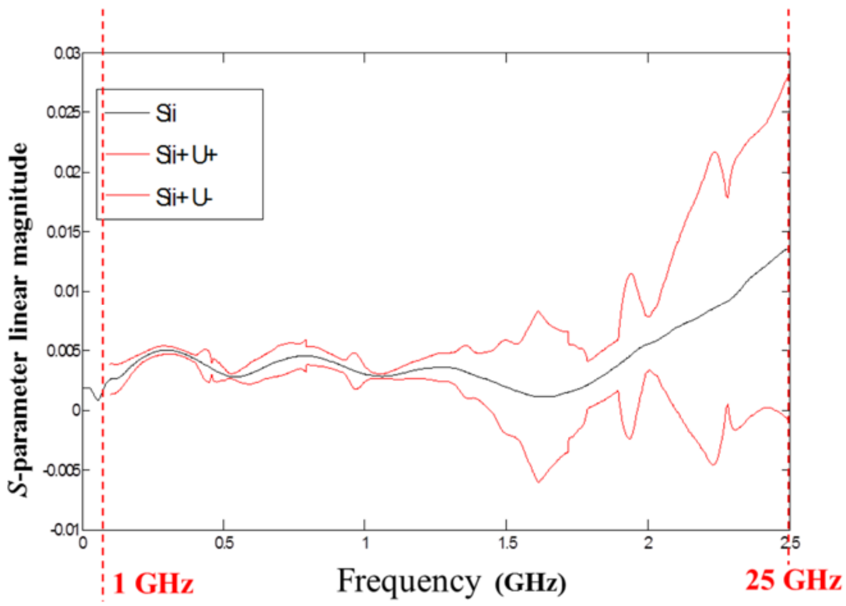


Fig. 16: Differential reflection coefficients Siid (S11d and S22d) of DUT consisting of a mismatched line together with the associated expanded uncertainty (k = 2)

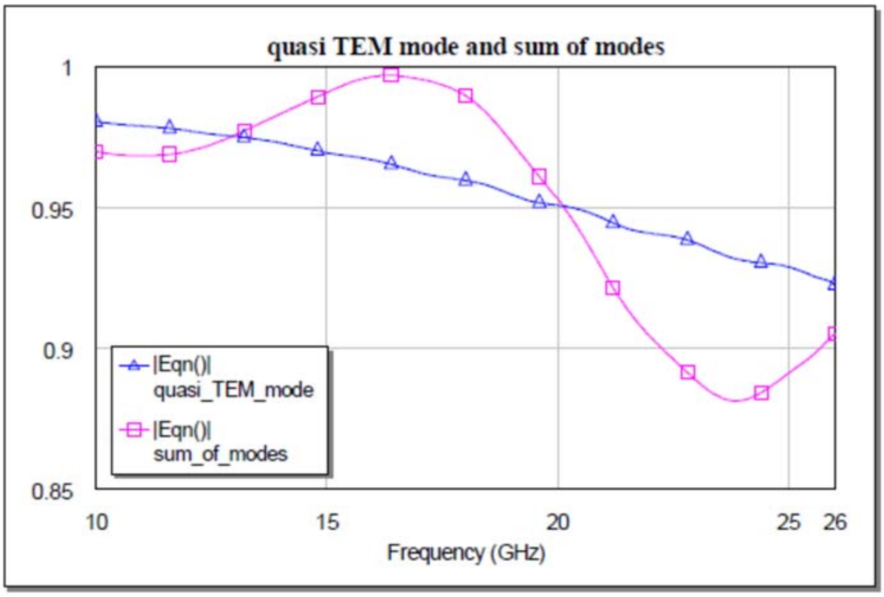


Fig. 17: Reflection coefficient of a 60 mm long open-circuited microstrip line with only the quasi-TEM microstrip mode considered and with the microstrip mode and two higher order modes considered

In microstrip open-circuits, which are frequently used as VNA calibration standards, radiation occurs from the coaxial to microstrip launcher as well as from the open end of the microstrip track. The wave radiated by the open end of the track reaches the launcher which then couples it back into the microstrip in the form of higher order modes which interfere with the quasi TEM microstrip mode reflected from the open end of the track. This modifies the observed reflection coefficient of the open-circuit and the effect was analysed at frequencies up to 26 GHz, using the electromagnetic simulation software CST Microwave Studio[17,18]. In the CST simulator, the launcher was replaced by a waveguide port for simplicity. As an example, Figure 17 shows the input reflection coefficient of a 60 mm length of microstrip line open-circuited at the far end and in the case when only the quasi-TEM microstrip mode is considered as well as in the cases of two higher order modes. The influence of the radiated field (corresponding to the higher order modes) and can change the reflection coefficient of the standard at the waveguide port by more than 0.05 in amplitude. Similar analysis, involving mixed-mode *S*-parameters, was carried out for balanced microstrip open-circuits and in this case the differential line was optimised in order to reduce unwanted radiation effects.

3.3.4 Electromagnetic modelling to improve measurements using differential transmission lines

The routing of differential lines (differential microstrip and differential stripline) was investigated using electromagnetic simulation and CST Microwave Studio software; on a PCB substrate with similar properties to the reference PCB (polyimide base material and 600 µm layer thickness) at frequencies up to 30 GHz.[19] As a result of the investigations, the following design rules were derived:

- For differential lines with bends there is a trade-off between mode coupling and loss: the line dimensions (trace width and gap between traces chosen to give the required characteristic impedance) should be small enough to reduce unwanted mode coupling but large enough to keep the losses small;

[17] M Haase, K Hoffmann, Z Skvor, "Microstrip Open - Problematic Calibration Standard", 85th ARFTG Microwave Measurement Conference, Measurements and Techniques for 5G Applications, May 22, 2015 Hyatt Regency Phoenix, Arizona, pp. 104-107.
[18] K Hoffmann, "Radiation of Microstrip Edge Mounted Transitions – Measurement Problems", Workshop, WS09 Microwave measurements and electromagnetic simulations of printed circuit boards (PCBs) for high speed digital and radio frequency (RF) applications, EuMW 2015, Paris, September 6-11, 2015.
[19] S Sinha, F-J Schmueckle, R Doerner, and A Rumiantsev, "Microstrip and stripline configurations for printed circuit board (PCB) applications and selected measurement issues", Workshop, WS09 Microwave measurements and electromagnetic simulations of printed circuit boards (PCBs) for high speed digital and radio frequency (RF) applications, EuMW 2015, Paris, September 6-11, 2015.

- The radius of a bend does not have a large influence on the properties of the odd mode (but any bend does produce some coupling from even to odd mode);
- De-routing is best done by a direct succession of two bends without a section of line between the bends; and
- Coupling is sufficiently avoided when the distance between the differential line and any other element is greater than 500 µm.

Using the design rules an optimised ground-signal-signal-ground (GSSG) probe (see Figure 18) was designed using electromagnetic simulation and CST Microwave Studio. Important design considerations include:

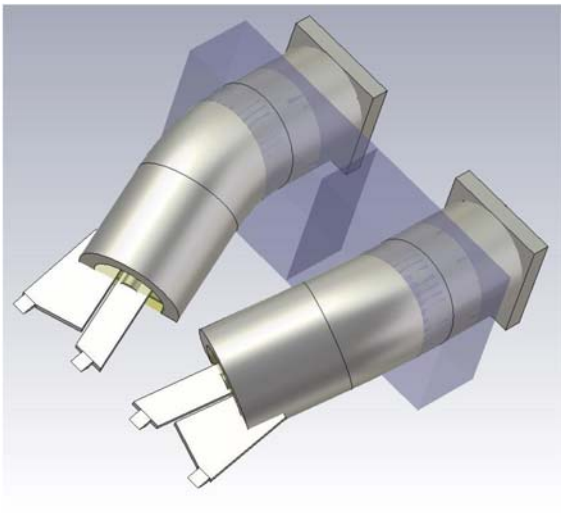


Fig. 18: Geometry of optimised GSSG probe

- Angle between the probe tips and the PCB – this has a strong effect on the performance of the probe, a smaller angle is better;
- Coaxial shielding – this has a moderate effect, the probe performance is improved when shielding is used;
- Width of the central signal sections – this has a strong effect and is optimised for impedance match;
- Probe pitch – a smaller pitch operates at higher frequencies;
- Absorber – this is needed to supress the twin wire line mode between the outer conductors of the two coaxial line feeds.

An optimal two stage strip-line transition was developed by again using electromagnetic simulation and CST Microwave Studio software. This optimal two stage strip-line transition was subsequently incorporated into the reference PCB.

Conclusions

In summary the project met Objective 3. Traceability and verification techniques for high-speed digital PCBs for Signal Integrity applications, including differential transmission lines. Designs for a range of different types of calibration standards for high-speed digital PCBs were developed and the effects of different signal path lengths on electrical signals travelling simultaneously along PCB dual conductor lines were investigated. Asymmetries in signal path lengths can cause distortions in the transmitted signals.

A new reference standard PCB including striplines was designed and fabricated to provide a way for end-users to verify signal integrity applications, including the use of differential transmission lines. The reference PCBs have also enabled bespoke calibration techniques to be developed so that end-users can directly characterise components mounted on the surface of PCBs.

3.4 Traceability and verification techniques for large-signal/non-linear device characterisation (e.g. high-power transistors and power amplifiers) and nano-scale devices (e.g. carbon-nano-tubes, graphene-related electronics and organic macromolecules)

This work was divided into two separate topics, i.e., (i) traceability for large-signal/non-linear device characterisation, and (ii) traceability for high impedance measurements, which are related to, for example, the characterisation of nano-scale devices.

3.4.1 Traceability for large-signal/non-linear measurements

In recent years the advent of novel active devices, has resulted in their characterisation using the traditional small-signal linear time-invariant system approach becoming insufficient. Measurement systems based on non-linear vector network analysers (NVNA) and large-signal network analysers (LSNA) are currently used, however the metrological traceability of such measurements has only been partly solved. It has also been difficult to ensure that different manufacturers' instruments are operating under the same conditions. Therefore a calibration standard or device able to calibrate the NVNA or LSNA in both their linear and non-linear regimes, i.e., traceability of the harmonic voltage and phase relationships is needed in addition to the impedance standards used in conventional VNAs. The requirements for such a calibration device are as follows:

- A two-port device;
- Operation in two modes – linear and nonlinear;
- In the linear mode, the linear calibration of the NVNA can be verified;
- In the non-linear mode, the power and phase calibrations of the NVNA can be verified;
- In the non-linear mode, the fundamental frequency is 2 GHz and the number of harmonics is five;
- The behaviour of the device in the non-linear mode should be insensitive to the small load harmonic mismatches of the instrument (i.e. linear reflection coefficient magnitudes of less than 0.1)

The project's initial design for a calibration device able to calibrate the NVNA or LSNA in both their linear and non-linear regimes was based on the idea of a circuit consisting of a nonlinear part (e.g., step-recovery diode (SRD) or a pulse generator) and a block (i.e. section) which made the output of the device less sensitive to mismatch (e.g., an attenuator or a circulator). The nonlinear device was first composed of a "general" SRD with an inductor but at a later stage, a special commercial integrated circuit was used. The integrated circuit can be used for more functions, depending on the bias voltage i.e. with DC bias, the output harmonics' spectrum amplitude was not sufficient; with AC bias, the device can be used as a mismatch compensator block. The diode circuit and mismatch compensator block were connected together and the resulting circuit is shown in Figure 19. The non-ideal load value was varied using a Monte Carlo (MC) simulation to enable the testing of a variety of possible scenarios.

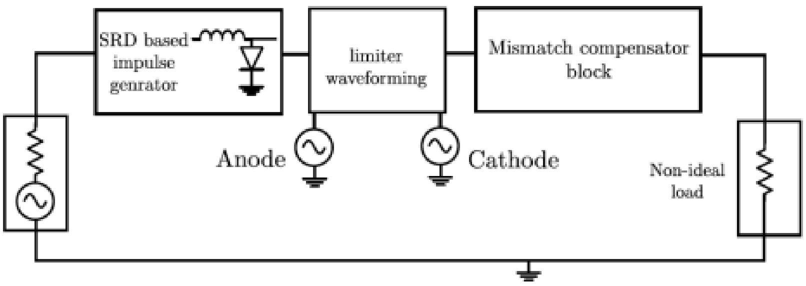


Fig. 19: SRD-based impulse generator and mismatch compensator block based on a commercial IC

The non-linear block could be realised as: (i) SRD-based, (ii) configurable, IC based, (iii) a combination of a SRD and IC, or (iv) a non-linear transmission line. The compensator mismatch block could be realised using: (i) an attenuator (lossy and broadband), (ii) a circulator (low loss, narrow-band), or (iii) a coupler.

The designed circuit needed to be as simple as possible, so it was decided to use a non-DC bias source. An SRD-based circuit was not considered a good idea as the verification device configuration needed to be different from the original phase calibration device configuration. As a figure of merit of the calibration device's performance, the Error Vector Magnitude (EVM) concept was adopted. The sensitivity of the circuit to the mismatch at the output was investigated and the load at five harmonics was changed randomly in each iteration of a MC simulation while constraining the magnitude of the reflection coefficient to be less than 0.1. The EVM is defined as follows:

$$\mathrm{EVM}_{\mathrm{RMS@freq\#}} = \left[\frac{\frac{1}{N}\sum_{r=1}^{N}\left|S_{ideal} - S_{meas,r}\right|^2}{\left|S_{ideal}\right|^2} \right]^{1/2} \times 100$$

where $S = V \times I^*$ at one frequency (i.e. the voltage, V, multiplied by the complex conjugant of the current, I), N is the number of MC iterations, "ideal" means ideal load, "meas" means non-ideal load in each MC iteration.

Four different combinations of the circuit were simulated using MC: (i) a device without mismatch compensator block, (ii) a device with attenuator block, (iii) a device with circulator block, and (iv) a device with a coupler. The best results were achieved using a device with an infinite-bandwidth circulator, however, for practical use a device with a coupler-based solution also gave acceptable results. Choosing the nonlinear block depended on the wanted bandwidth or the number of harmonics. A commercial configurable IC-based device showed the best (lowest value) average EVM from 200 MHz to 6 GHz.

A coupler/attenuator set-up was also simulated, as this is a more realistic scenario, and the EVM showed similar results. The EVM is directly proportional to the standard deviation of the harmonics' impedance of the load. Thus by reducing the standard deviation of the load at the fundamental frequency, the EVM at the fundamental frequency was significantly decreased. The coupler was designed in a way that decreased the amplitude of the fundamental frequency and made the output power level of the five harmonics the same.

Finally two realistic models (including the transmission lines' physical layout, substrate properties, etc) of the calibration device were created in a circuit simulator. Again, MC simulations were used to assess the behaviour under different load and source impedance conditions.

***1st design* for a calibration device able to calibrate the NVNA or LSNA in both their linear and non-linear regimes**

In the first prototype, the mismatch compensation block (MCB) consisted of two cascaded coupled lines, see Figure 20.

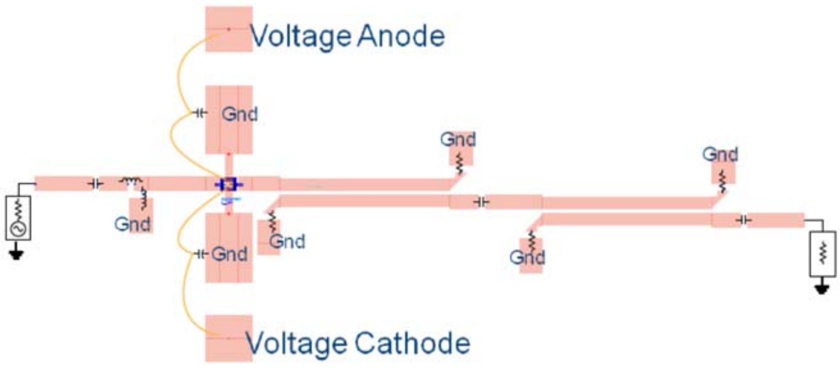


Fig. 20: First prototype of the verification device

The simulation results showed that the MCB significantly improved the circuit performance. The output spectrum of the circuit with and without the MCB is shown in Figure 21. The power of the signal at the fundamental frequency is less important for the evaluation than the power at higher harmonic frequencies and the figure of merit EVM is compared in Table 4, where it can be seen that the performance degrades quickly with increasing frequency and the highest usable frequency is approximately 6 GHz.

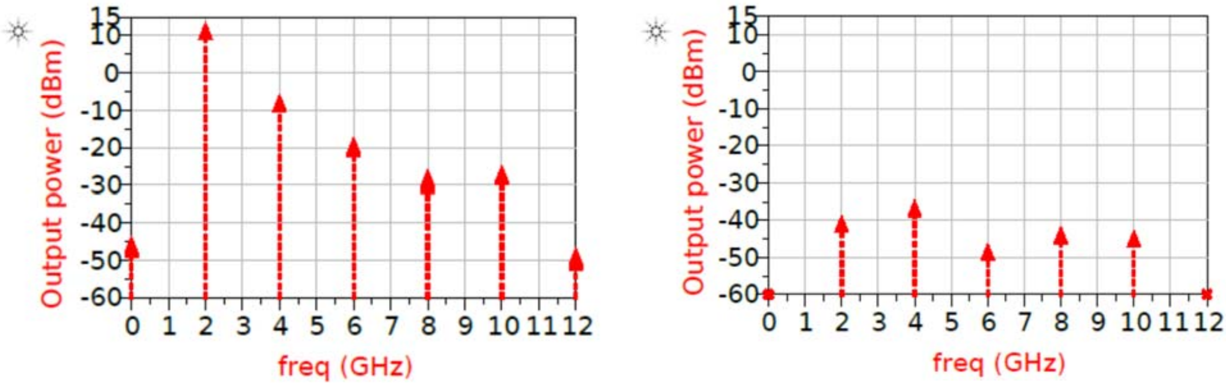


Fig. 21: Output spectrum of the circuit without (left) and with (right) the MCB

Table 4: Comparison of the EVM of the first design with/without the MCB, MC simulation

	2 GHz	4 GHz	6 GHz	8 GHz	10 GHz
Without MCB	0.51	6.51	7.18	18.18	16.97
Ideal lumped element	0.32	0.83	0.76	1.49	1.11
Foundry model	0.32	0.83	0.76	1.24	1.04

(a) Only the output impedances are varying

	2 GHz	4 GHz	6 GHz	8 GHz	10 GHz
Without MCB	2.16	9.27	7.99	26.62	24.46
Ideal lumped element	1.90	4.46	2.13	45.64	7.38
Foundry model	1.80	4.09	1.93	33.24	7.04

(b) Input and output impedances are varying

2nd design for a calibration device able to calibrate the NVNA or LSNA in both their linear and non-linear regimes

The main reason for creating a second design was to make the device insensitive to both input and output impedance mismatch. The dielectric substrate was changed, the number of lumped elements was lowered, a low-pass filter was added and a rat-race coupler was used as the MCB. The design is shown in Figure 22. The simulated figure of merit (EVM) of the second design is shown in Table 5, where "Ref." is used for the first design without MCB. It can be seen that the EVM is much better than that of the 1st design even at high-frequencies (>8 GHz). The small-signal S-parameters were also simulated.

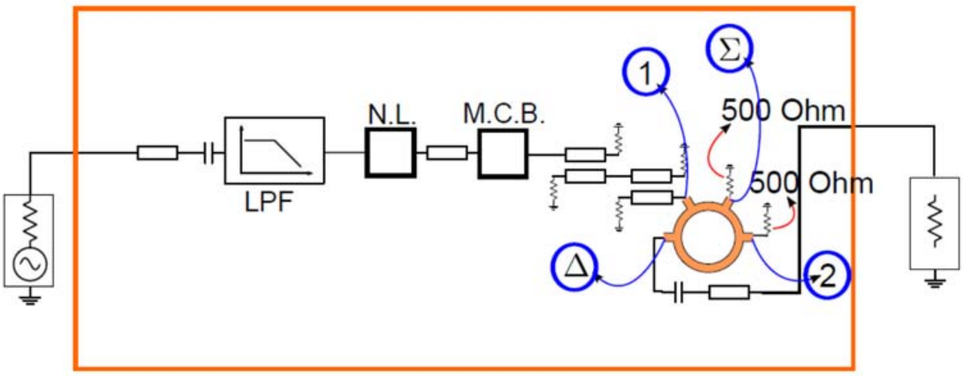


Fig. 22: Second design of verification device

Table 5: Simulated EVM of the second design

	2 GHz	4 GHz	6 GHz	8 GHz	10 GHz
Ref	0.51	6.51	7.18	18.18	16.97
Second design	0.44	1.08	0.52	1.19	0.47

(a) Only the output impedances are varying

	2 GHz	4 GHz	6 GHz	8 GHz	10 GHz
Ref	2.16	9.27	7.99	26.62	24.46
Second design	1.56	1.29	1.26	1.25	1.71

(b) Input and output impedances are varying

The second design from Figure 22 was fabricated and measured by NVNA. The output power spectrum for the second (more advanced) prototype was evaluated, and the EVM was measured (i) using attenuators and calibration standards, and (ii) using automated tuners. A large number of combinations were evaluated and good performance was observed with the EVM was low up to 16 GHz, which out-performs designs reported in the literature, based on active devices (amplifiers). The EVM of the second prototype is shown in Table 6.

Table 6: Simulated and measured EVM of the 2nd prototype

Frequency (GHz)	2	4	6	8	10	12	14	16
Simulation (With MCB)	0.35	0.42	0.30	0.41	0.29	0.98	0.17	1.66
Measurement	1.75	0.81	1.07	0.60	0.60	0.74	0.61	0.68

Traceability to the Electro-Optic Sampling (EOS) technique for the second prototype was provided using a special method; where a pulsed signal is measured using a high-speed sampling oscilloscope, which is traceable back to EOS. The oscilloscope’s timebase, impedance mismatch (essential for achieving low phase uncertainty) and residual parasitic harmonic content must be corrected. The time-domain waveforms from the verification device were the measurands in this case. This special method, however, is only applicable for high-bandwidth pulse generators (bandwidth of at least 10 GHz), as the current minimum achievable frequency step of the EOS is approximately 500 MHz. The traceability of power measurements can be achieved using a comparison with a calibrated power sensor or a measurement receiver. Therefore, as the output signal from the verification device contained higher harmonics with very similar power levels, a selective measurement method was used. Measurement of the waveform stability and also the stability of particular higher harmonic components was studied using the Allan variance and the second prototype device showed very good time stability over tens of hours’ time epoch.

The second prototype device (i.e. a calibration device able to calibrate the NVNA or LSNA in both their linear and non-linear regimes) met the required specification. The device was a two-port device and operated in both linear and non-linear modes. In the linear mode, linear calibration can be verified; and in the non-linear mode, the aim was to verify the power and phase calibration. The device is only composed of passive elements which supports its suitability as a verification tool for both the linear and nonlinear regimes of an NVNA or an LSNA. The device also out-performs earlier designs, based on active circuits (i.e. amplifiers). The work would not have be possible without collaborations between partners, REG(KU Leuven), Keysight BE, and NPL together with the independent evaluation of the designs by CMI.

3.4.2 Traceability and verification techniques for nano-scale devices

The increasing interest in extreme impedance measurement in the millimetre- and submillimetre-wave frequency region has driven the need for precision calibration standards. The ‘extreme impedances’ are here referred to as impedances substantially lower or greater than 50 Ω. The increasing interest has mainly been driven by novel applications of nano-structured devices, e.g., carbon nano-tubes, graphene transistors and others. Several measurement methods for improving the insufficient sensitivity of VNAs for nano-scale devices were proposed before the start of this project, however, suitable calibration standards were not available.

As all practical measurements suffer from systematic errors, a calibration process always needs to be performed. Moreover, the higher or lower the values of impedance to be measured, the greater the requirements the standards have to meet in terms of their characterisation, precision and connection repeatability. A system for measurement of extreme impedances was proposed by a REG at the Czech Technical University (CTU), shown in Figure 23. Instead of reflection coefficient, an amplified difference of two signals (reflected from a reference and the measured impedance) is measured which results in significantly improved accuracy of impedance measurement.

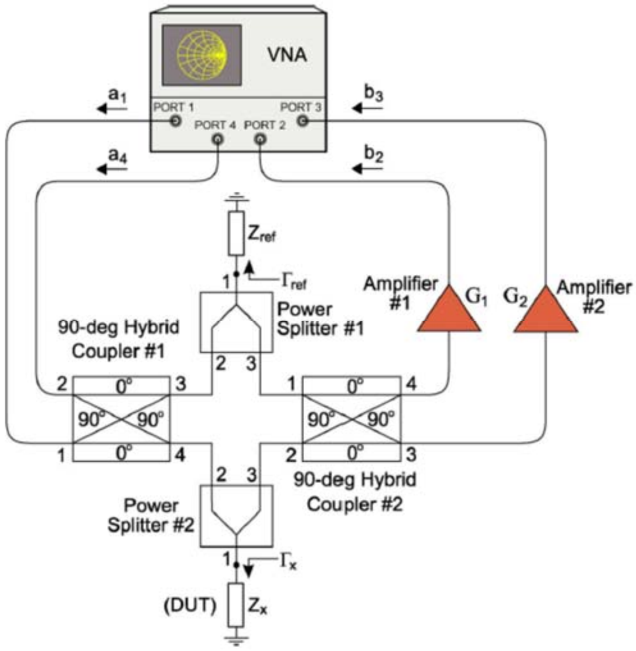


Fig. 23: Idealised arrangement of the measurement system

Design of calibration/verification standards for nano-scale devices

A closed coaxial structure compatible with APC-7 connectors was chosen in order to eliminate any radiation problems and to get good mounting reproducibility. Another advantage of the APC-7 connector is its good mechanical properties and suitable dimensions. The connector can also be easily dis-assembled and some new parts can be added to create a new calibration standard, which minimises requirements for the calibration standard fabrication. However, the connector dimensions, result in a relatively low upper operating frequency.

To begin with, extensive electromagnetic simulations were performed to prove the concept for the verification standards for nano-scale devices. The design criterion for a near identical electromagnetic field distribution around the calibration standards and the DUT was taken into account, as well as the requirements for simple fabrication and good mechanical properties. Thus, the use of fused silica (FS) as a dielectric and a carrier for CrNi resistive material was considered, as FS has low permittivity (of approximately 3.8), high homogeneity, and, good mechanical and chemical properties compatible with CrNi thin layer technology. A schematic diagram of the verification standards is given in Figure 24.

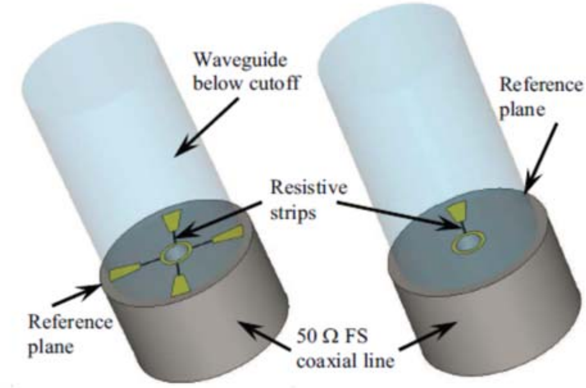


Fig. 24: Conceptual high-impedance structure, using four resistive strips (left) and one resistive strip (right)

The design of the verification standards for nano-scale devices was optimised to satisfy the following 3 requirements: (i) the structure of the standards should be suitable for the calibration and subsequent verification and measurement at the reference plane of the APC-7 connector (7 mm coaxial line); (ii) standards with extremely high impedances in the range from 5 kΩ to approximately 200 kΩ and an open-circuit; and (iii) to minimise the technological demands on fabrication, the structure of the standards should use the individual parts of the APC-7 connector effectively. The verification standards were comprised of resistive strips and so pure resistive behaviour was expected due to their dimensions and pre-supposed TEM field distribution at the reference plane. However, detailed simulations revealed frequency-dependent properties of the strips and the presence of higher-order modes. Therefore, the original assumption of pure resistive behaviour of the resistive strips was abandoned and the reference plane was moved to the plane of the APC-7 connector. The final design concept for the verification standards was comprised of resistive strips, fused silica coaxial line, and air coaxial line. This design proved to be correct, since these components were described by computed S-parameters and not by values of an ideal resistor.

A two-strip symmetrical structure was chosen as a compromise between the available technology and acceptable symmetry and the final structure of the verification standards is shown in Figure 25.

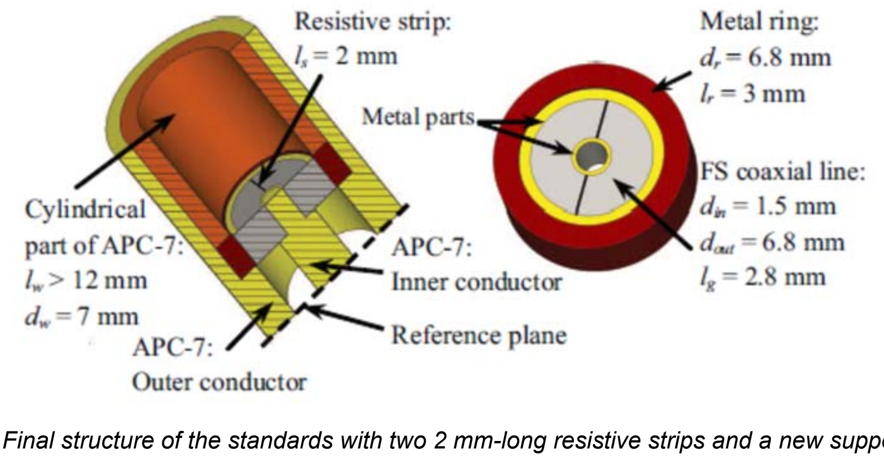


Fig. 25: Final structure of the standards with two 2 mm-long resistive strips and a new support bead

Practical realisation and experimental results

The strips made it possible to create verification standards for nano-scale devices with a range of impedance from 5 kΩ to 200 kΩ, depending on the width of the strip. Since the resistive strips are 2 mm long, the contact metal parts are far enough apart to minimise the fringing capacitance. The inner diameter d_r of the metal ring of the new support bead was adjusted to 6.8 mm, and the length l_r was set to 3 mm, see Figure 24. The structure without resistive strips forms the open-circuit standard. A fabricated sample of the FS coaxial line with deposited resistive strips and metal parts is shown in Figure 26 and several samples of new support beads with fixed inner conductor for an APC-7 connector are depicted in Figure 27.

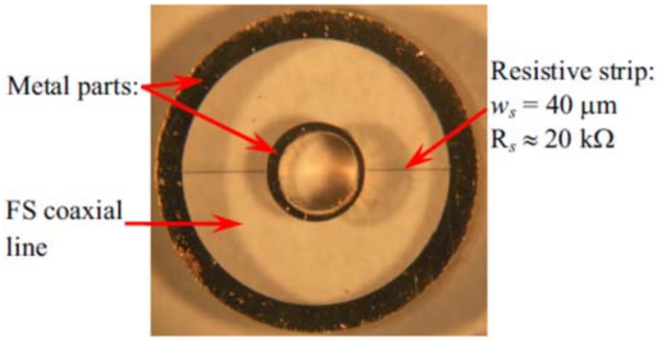


Fig. 26: An example of manufactured FS coaxial line with two deposited resistive strips, each of approximate value 20 kΩ, and metallic parts

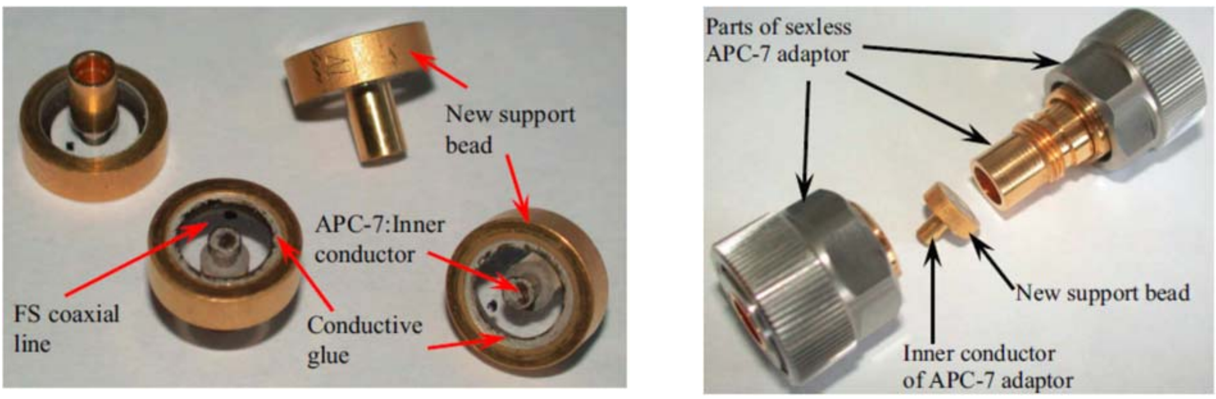


Fig. 27: An example of manufactured support beads with inner conductor of APC-7 connector (left) and dis-assembled APC-7 adaptor (right)

Fabricated calibration standards were also measured using a Keysight E8364A VNA in the frequency range 45 MHz to 18 GHz. A reflection coefficient measurement was performed in order to qualitatively verify the expected behaviour and reveal possible malfunctions, e.g., assembly and/or fabrication errors. A 7 mm precision mechanical calibration kit 85050C and TRL method was used for two-port VNA calibration and the measured reflection coefficients are depicted in Figure 28 (the same measurement was performed using two different VNA set-ups at REG(CTU) and NPL). In the reflection coefficients it can be clearly seen that a different behaviour of the amplitude of the reflection coefficient for different values of calibration standards was obtained, which demonstrates successful operation of the extreme impedance standards (i.e. verification standards for nano-scale devices).

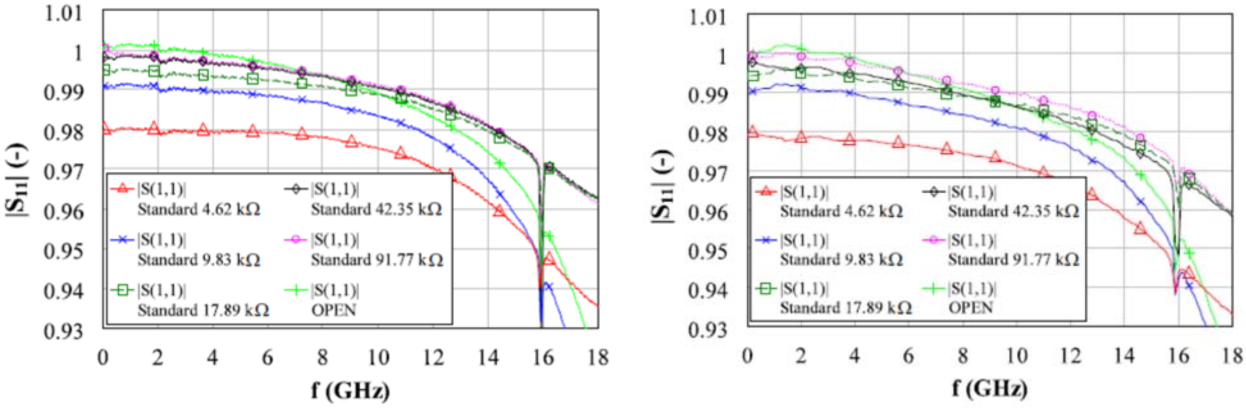


Fig. 28: Measurement of the calibration standards performed at CTU (left) and NPL (right)

In order to improve the uncertainty of standard characterisation methods a combination of characterisation techniques were studied by REG(CTU) in collaboration with CMI. Precise DC resistance measurement determines the reflection coefficient of the standard at the lowest frequency. Furthermore, the precise dimensional characterisation and determination of permittivity, ε_r, enables the creation of an electromagnetic model as accurately as possible. Since the conductive glue is effectively an undefined parameter, the combination of precise traceable measurement at 14 GHz, with a corresponding expanded uncertainty, and electromagnetic simulations was used. At this frequency the simulated S-parameters are still correct since there are no higher-order modes present and subsequently, the uncertainty at lower frequencies can be extrapolated from the two curves, see Figure 29. This leads to significantly smaller uncertainty in characterisation of a fabricated standard, compared with precise DC resistance measurements made at NPL. The resulting uncertainty for the 4.62 kΩ calibration standard was almost 10 times smaller at 6 GHz.

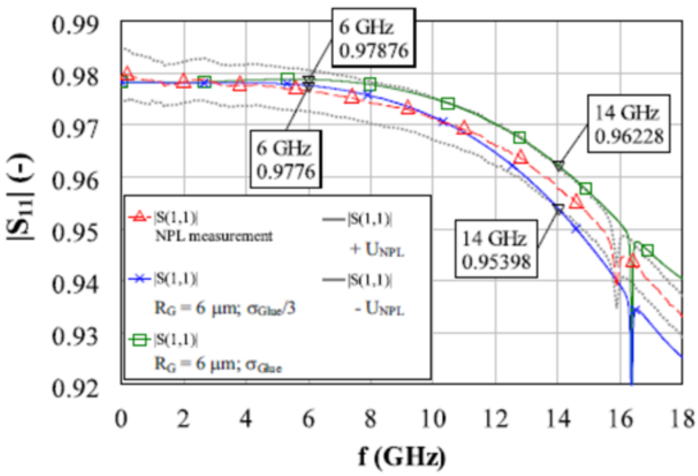


Fig. 29: The concept of reducing the characterisation uncertainty of 4.62 kΩ calibration standard at the frequency of 6 GHz

The project produced calibration/verification standards for nano-scale devices, applicable up to 14 GHz. Additionally, a new method, which substantially improved the characterisation uncertainty of fabricated extreme impedance standards, was developed, based on the combination of DC resistance measurement, precise dimensional characterisation, material characterisation, traceable microwave measurements and electromagnetic simulations. The new method reduced the uncertainty caused by fabrication technology and was used for characterisation of the calibration standards based on APC-7 connectors. In contrast to precise traceable measurement performed at NPL, the new method provides almost 10 times smaller uncertainty at around 6 GHz.

Conclusions

In summary the project met Objective 4. Traceability and verification techniques for large-signal/non-linear device characterisation and nano-scale devices. Large Signal Network Analysers (LSNA) and Nonlinear Vector Network Analysers (NVNA) are used for characterising transistors found in mobile phones and base stations. Two reference devices were developed, fabricated and tested for use by industry and academia for verifying their performance.The new large-signal reference device outperformed previous designs. Long term tests have also demonstrated good stability for the device over significant time periods of up to several weeks. This means that a characterisation of the large-signal reference device remains useable over these longer periods of time and therefore end-users do not need to spend time re-characterising the reference device, which is a time consuming process

Existing commercially available impedance standards are often not suitable for making measurements at the nano scale because the values of the impedances that need to be measured are often very different from the values of existing impedance standards. A range of extreme impedance standards suitable for both calibration and verification of nano-scale devices were designed, fabricated and characterised. These standards can be used to calibrate a measurement system (such as a network analyser) so that it is optimised for measurements of devices with intrinsic impedance values much greater than the usual reference impedance of 50 ohms. This is particularly relevant to carbon-based devices (e.g. devices containing carbon nano-tubes and/or graphene) that can be used in high-frequency electronics applications such as resistors, capacitors and transistors. The extreme impedance standards were subsequently tested using a conventional network analyser, which demonstrated the versatility of these extreme impedance standards over a wide range of operating conditions.

3.5 Input to European and International industry-level documentation

The aims of this work were:

1. To establish uncertainty evaluation and verification schemes for S-parameter measurements, suitable for high-frequencies. To do this, the limits of applicability of existing methods were examined so that the methods could be improved and extended, in order to provide methods that are better suited for requirements at high-frequencies (sub-sections 3.5.1 and 3.5.2)
2. To provide input to the development of two international standards (IEEE P1785 and IEEE P285). At the beginning of the project, IEEE P1785 (for metallic waveguides above 110 GHz) was a new standard that was under development. The standard was to be published in three parts: Part 1 – Frequency Bands and Waveguide Dimensions; Part 2 – Waveguide Interfaces; Part 3 – Recommendations for Performance and Uncertainty Specifications. IEEE P287 (for precision coaxial connectors at RF, microwave and millimetre-wave frequencies) was an existing standard that was being revised. Input from this project was also to be provided to an IEEE Special Interest Group that was being set up to investigate standardisation for nonlinear measurement quantities (sub-section 3.5.3). In addition, an updated version of the EURAMET Guidelines on the Evaluation of Vector Network Analysers (VNA)", Guide cg-12 (previously known as EA Guide 10/12) was to be produced by this project (sub-section 3.5.4).

3.5.1 Vector uncertainties

The aim of this work was to establish methods for VNA uncertainty evaluation in accordance with recently published international guidance. Older methods based on "residual errors" are often considered less suitable at higher frequencies and make assumptions that can be questionable. Therefore, methods needed to be improved and made compatible with international guidance (i.e. GUM Supplement 2). Methods based on a measurement model and on propagation of vector uncertainty from basic inputs taking correlations fully into account have become manageable through software that has recently become available. Therefore, comparison between the different methods was done by the project in order to help to validate them. The results have also contributed to the update of the EURAMET Guide (see sub-section 3.5.4). In addition, data formats were developed to store VNA measurement uncertainties without the loss of any uncertainty or correlation information. The specific problem of propagating uncertainties through a non-analytical measurement model (as is the case for some VNA calibration techniques) was also addressed and a solution involving the use of automatic uncertainty propagation techniques (developed previously by Blair Hall, at the Measurement Standards Laboratory of New Zealand) was presented in a conference paper [23].

3.5.2 Verification schemes

The aim of this work was to investigate verification schemes with respect to their applicability to VNA user requirements, and to develop new verification schemes well suited for higher frequencies and for measurements of high reflect standards. The results have also contributed to the update of the EURAMET Guide (see sub-section 3.5.4). The emphasis of this work was on the verification of measurements made in coaxial lines, fitted with precision coaxial connectors, at frequencies up to 110 GHz. However, consideration was also given to other transmission media – in particular, rectangular metallic waveguide working at frequencies up to at least 220 GHz. Different aspects of VNA verification techniques were investigated for different transmission line types (coaxial and waveguide) and the work ranged from plausibility studies based on fundamental physical considerations to the development of new types of calculable verification standards. It also included a proposal for an analytical pass-fail criterion for multivariate verification measurements and was summarised in a conference publication [30].

In the case of waveguide verification devices, a 'new' structure was evaluated at high millimetre-wave frequencies (i.e. above 110 GHz). The new structure was a cross-connected waveguide that provided a known value of attenuation at each frequency across the waveguide band. This known value was then used to assess the reliability of the measured value for a given length of cross-connected waveguide; published in [8, 36].

3.5.3 Input to IEEE standards

The aim of this work was to provide input to: (i) a new standard (P1785: "IEEE Standard for Rectangular Metallic Waveguides and their Interfaces for Frequencies of 110 GHz and Above"); (ii) a revision of an existing standard (P287: "IEEE Standard for Precision Coaxial Connectors at RF, Microwave and Millimeter-wave Frequencies"); and (iii) a IEEE Special Interest Group that was being set up to investigate standardisation for nonlinear measurement quantities (i.e. those quantities occurring in sub-section 3.4.2).

(i) P1785: "IEEE Standard for Rectangular Metallic Waveguides and their Interfaces for Frequencies of 110 GHz and Above"

The main activity that was undertaken was the evaluation of new types of waveguide interface that were being developed as part of the IEEEE P1785 standards making process. Part 2 of this series of standards contained designs of waveguide interface for use at frequencies above 110 GHz and Figure 30 shows the waveguide interface.

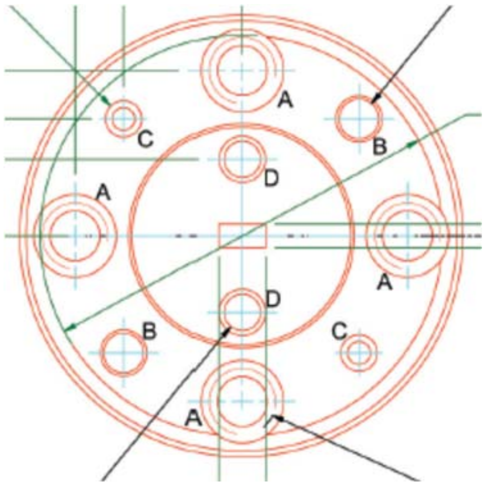


Fig. 30: diagram showing the generic features of the waveguide interface under investigation in this project. The dimensions for the holes A, B, C and D are given in the published standard (IEEE Std 1785.2-2016)

The project carried out a series of comparisons of these waveguide interfaces, which included experimental investigations by NPL and REG(ULE) at the current highest operating frequency for these waveguides (i.e. from 750 GHz to 1.1 THz) [32, 37, 38]. This showed that the designs featured in the new standard (IEEE Std 1785.2-2016) are likely to be suitable for metrology applications at all frequencies to at least 1.1 THz. In addition, data from these experimental investigations was used to validate the approach to uncertainty analysis being proposed in Part 3 of the new standard (IEEE Std 1785.3-2016). This information was reported to the IEEE P1785 Working Group at the time these standards were being developed (i.e. during 2014 and 2015).

(ii) Revision of an existing standard (P287: "IEEE Standard for Precision Coaxial Connectors at RF, Microwave and Millimetre-wave Frequencies")

The role of coaxial connectors has, for a long time, been under estimated in RF and microwave metrology and the SI traceability of VNA calibration standards has been established without taking the connector interface into account. Beadless air-dielectric lines have been considered as perfect 50 Ω devices, again neglecting the impact of the connector, which has led to incorrect definitions of measurement reference planes and consequently to inconsistencies between different calibration algorithms. The situation was improved when it was recognised that including the connector in the characterisation of standards gives much better and more consistent results. Therefore the project decided to make a substantial contribution to the revision of the IEEE P287 standard, which is a standard for precision coaxial connectors at RF, microwave and millimetre-wave frequencies. For this purpose a mechanical model for the coaxial metrology grade connector was established. Figures 31 and 32 show the mechanical models of the slotless and the slotted connector interfaces.

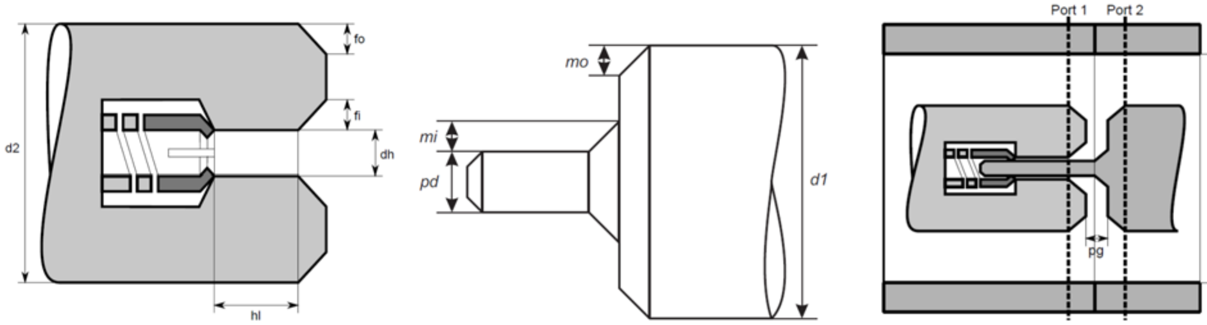


Fig. 31: Cross sections of mechanical models of the slotless coaxial connector. The three drawings show the female interface (left), the male interface (centre) and the assembled connector pair (right). All dimensions indicated by arrows have been considered in the calculations

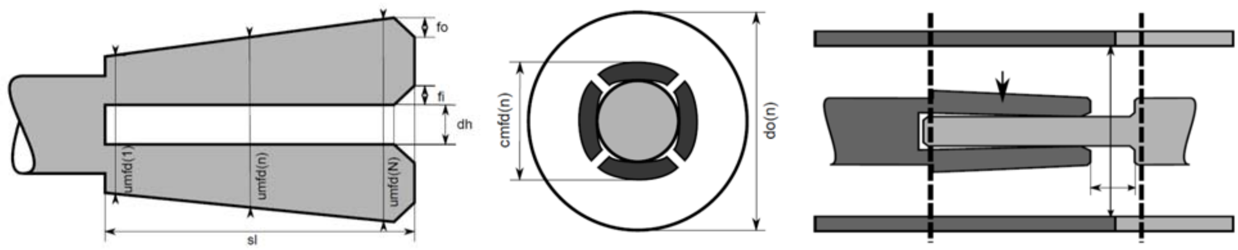


Fig. 32: Mechanical models of the slotted coaxial connector. The three drawings show the cross section of the female interface (left), a lateral cut of female interface (centre) and the assembled connector pair (right). The male connector interface is the same as for the slotless connector. All dimensions indicated by arrows were considered in the calculations

All the dimensions indicated by arrows in Figures 31 and 32, have an impact on the electrical performance of the connector interface. The mechanical model was then used to calculate reflection and transmission coefficients as a function of frequency for typical dimensions for all metrology grade connectors, i.e. Type-N, 3.5 mm, 2.92 mm, 2.4 mm, 1.85 mm and 1.00 mm. The calculations were performed using a combination of analytical equations and numerical field simulations. In the next step, sensitivity coefficients of the reflection and transmission coefficients with respect to the dimensions were calculated and finally minimal pin gap sizes were determined for each connector type to avoid near field effects when connectors are mated.

The project's results were summarised in an extended report, which was submitted to the IEEE P287 Working Group for inclusion in the next revision of the standard.

(iii) Input to IEEE Special Interest Group investigating standardisation for nonlinear measurement quantities

Meetings of this Special Interest Group (SIG) were held in June and December 2014, and in May 2015 and input to these meetings was provided by NPL. The SIG considered standardisation opportunites in areas impacting the measurement of nonlinear microwave quantities and concluded that two new IEEE standards should be developed, covering: (i) uncertainty in measurement of modulated signals for wireless communications; and (ii) terminology for large-signal vector network analysis.

Working Groups tasked with developing both these standards have since been set up by IEEE and regular meetings of both Working Groups are now being held. Input to these meetings is being provided by the EMPIR 14IND01 MET5G project (http://empir.npl.co.uk/met5g/), which was set up with similar activities that would enable the work from this project to be continued within the EMPIR.

3.5.4 Re-write of EURAMET Guide

The aim of this work was to write an updated version of the EURAMET Guidelines on the Evaluation of Vector Network Analysers (VNA)", Guide cg-12 (previously known as EA Guide 10/12). The updated version would take into account developments in VNA metrology, the trend to higher frequencies and technological advances of the VNAs. The updated version was submitted to EURAMET by the project with a recommendation that it is published as a new edition of the Guide.

The old EURAMET Guide cg-12 has become a de facto standard for the assessment of accredited calibration laboratories and the procedures therein are also applied by many national metrology institutes. The main difficulties with the evaluation of VNA measurement uncertainties are threefold:

1. The measurement quantity is multivariate. Scattering parameters (S-parameters) are measured in polar coordinates with amplitude and phase or in Cartesian coordinates with real and imaginary components. This requires the application of multivariate methods and the proper treatment of correlations.
2. The VNA measurement process consists of the measurement of reference standards to determine the error coefficients of the VNA (VNA calibration) and the subsequent correction of the measurement of the DUT (VNA error correction). The two-stage measurement process leads to a fairly large measurement model with long equations.
3. S-parameters and their associated measurement uncertainties might show fairly pronounced frequency dependence. It is not unusual that several hundred frequency points are measured over an extended frequency range.

It is not surprising that in the past simplifications were sought to overcome the difficulties mentioned above. The old EURAMET Guide cg-12 guide promoted a method, the so-called Ripple Method, which experimentally determined the residual errors after VNA calibration. Hence modelling of the entire measurement process is avoided. However, in this method the phase is neglected and the evaluations are reduced to scalar calculations, which leads to a measurement uncertainty evaluation that can principally be done on a spreadsheet.

The major shortcomings of this ripple method in the old EURAMET Guide cg-12 are:

- The beadless air-dielectric coaxial lines, which are used for the determination of the residual errors are difficult to handle. With higher frequencies the mechanical cross section of the components becomes smaller and the handling becomes even more difficult. Furthermore, nowadays, there is a trend towards higher frequencies to satisfy higher data rates in communication technology.
- A key assumption in the Ripple Method is that beadless air-dielectric lines act as perfect phase shifters, i.e. that they show no reflection and no loss. It is now known that this assumption does not hold and the connectors of the air-dielectric lines cause significant reflections. The longitudinal position of the centre conductor of the air-dielectric line is also not fixed which leads to instable behaviour and both can lead to an over- or under-estimation of the residual errors. Again an effect that becomes more pronounced with higher frequencies.
- The Ripple method is unable to determine all residual errors. The residual tracking remains undetermined, which leads to an uncertainty budget that is not complete.
- Correlations are either neglected or worst case assumptions are made and uncertainties can only be evaluated for the magnitude. The uncertainty associated with the phase remains undetermined.

The project completed a rewrite of the EURAMET Guide cg-12. The new guide underwent two review rounds and was submitted to EURAMET at the end of the project. It should become publicly available in 2017 after it has passed the review process within EURAMET. The new guide consists of more than 90 pages and is thus considerably longer than the old guide, which had less than 20 pages. The new guide also has a main section of about 25 pages with practical and applied information, which is intended to be of direct use for end users performing VNA measurements.

In addition the new guide provides advice on the choice of VNA calibration algorithms and verification techniques. The characterisation of measurement errors, which are affecting the VNA measurement, and the subsequent assignment of measurement uncertainties are explained in detail. The principles on how to derive a complete measurement model are also shown. Performing VNA measurements is demanding with many pitfalls. Therefore, an extended section on best measurement practice gives practical hints and tips on how to avoid common mistakes and to improve the quality of the measurements.

A major part of the new guide is dedicated to the evaluation of VNA measurement uncertainties. The new guide promotes a method, which is in agreement with GUM Supplement 2 (GUM-S2). GUM-S2 describes the measurement uncertainty evaluation of multivariate measurement quantities. It was published in 2011 and is thus an authoritative guideline for the evaluation of measurement uncertainties of S-parameters. The method is based on a full measurement model, which covers the entire VNA measurement process. The measurement model is used to propagate basic uncertainty contributions originating from the calibration standards, the VNA device parameters, cables, connectors and user actions to the S-parameters of the DUT. The uncertainty propagation cannot be done by hand or in a spreadsheet because the equations are long, but nowadays software is available, to support this tedious task. However, following this rigorous approach has several advantages.

- The method can be widely applied and works at higher frequencies and for other transmission media.
- The method avoids the use of unstable and difficult to handle components, such as air-dielectric coaxial lines.
- The measurement uncertainty is evaluated in a multivariate way taking correlations fully into account. Correlations are not only accounted for between the two components of a single S-parameter as correlations between different S-parameters and possibly even cross-frequency correlations can be calculated as well. This becomes important if S-parameters are further processed to derive secondary quantities.
- The method provides a clear and transparent relationship between the influences, which are affecting the measurement process and the S-parameters of the DUT. This way it is easy to provide an uncertainty budget and to identify the major contributors to the overall measurement uncertainty, which is vital for improving the accuracy of the measurements.

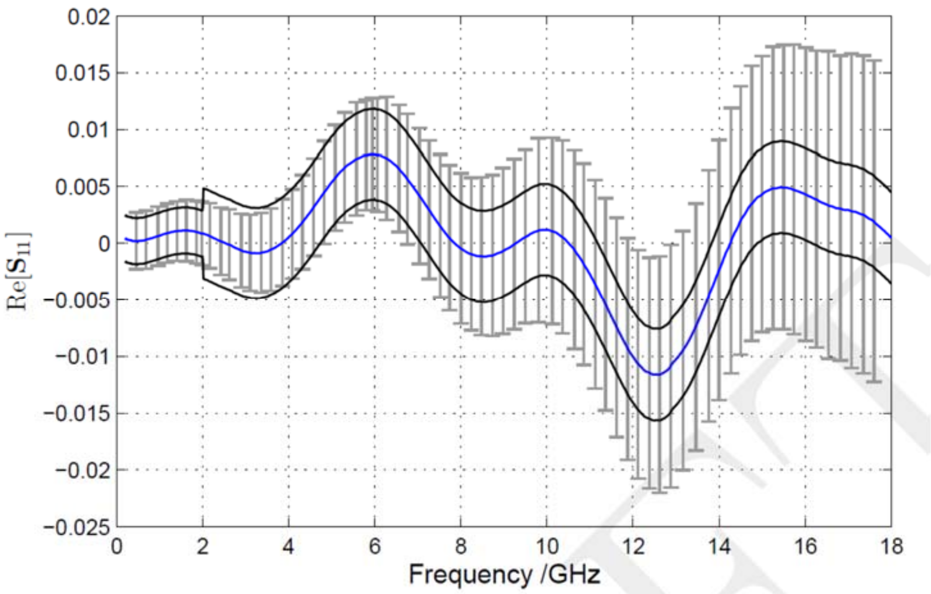


Fig. 33: Real component of the reflection coefficient of a matched Type-N load with associated standard uncertainties. The solid lines indicate the error corrected measurement data (blue center line) bounded by the interval of one standard uncertainty calculated with the rigorous method. The vertical bars indicate standard uncertainties evaluated with the modified (updated) Ripple Method

The Ripple Method was kept in modified form in the new guide for backward compatibility. This acknowledges the fact that many laboratories are equipped for the Ripple Method an the modifications suggested by the project aim at eliminating the most severe disadvantages of the Ripple Method. The experimental part remains the same, only the analysis of the data needs to be adjusted. Worst case safe guards have also been built in to the new guide avoid under-estimation of the measurement uncertainty, due to the problems with the air-dielectric lines (mentioned previously). The measurement model is more complete in the sense that it also includes uncertainty contributions, which are important in some situations, e.g. cable movements. A procedure to determine the residual tracking is also given in the new guide and the uncertainty associated with the phase is dealt with. Due to the worst case safe guards the uncertainties of the modified Ripple Method are larger than for the rigorous uncertainty evaluation as is shown in Figure 33.

Conclusions

In summary the project met Objective 5. Input to European and International industry-level documentation by:

- A report was submitted to the IEEE 287 standard Working Group, which summarised the investigations undertaken and findings of this project into performance characteristics of precision coaxial connectors. The report will be incorporated into the on-going revision that is taking place of the IEEE 287 standard, the global 'industry' reference for connectors of this type.
- A document providing performance indications for waveguide devices operating to 1100 GHz was submitted to the IEEE P1785 standard Working Group. This has contributed to two of the three new IEEE standards that this Working Group has developed and published, i.e. IEEE Std 1785.2-2016 "Waveguide Interfaces" and IEEE Std 1785.3-2016 "Uncertainty Specifications".
- The "EURAMET Guidelines on the Evaluation of VNA" document Guide cg-12 has been fully revised by the project and submitted to EURAMET.

4 Actual and potential impact

The project successfully developed and introduced new, applied measurement traceability and assurance techniques to enable the exploitation of new instrumentation capabilities that have been developed by manufacturers of test equipment. This will support the new product development of European electronics companies by ensuring test equipment has been proven independently via the technical outcomes from this project.

The project had a number of uptakes:

- New measurement services which extend the upper frequency range of NMI traceability in coaxial lines to 110 GHz and waveguides to 1.1 THz. These will ensure traceability for new technologies being developed by instrument manufacturers such as developments in communications e.g. 5G.
- Several NMIs have extended their calibration capabilities to include multi-port measurements and methods for using ECUs with VNAs.
- NPL is now evaluating whether a customer calibration service for users of ECUs should be introduced based on the work achieved in this project. At the present time, there are no other NMIs offering such a service.
- The project developed a reference PCB to act as a verification device for the end-user community and to enable bespoke calibration techniques so that users can directly characterise components mounted on the surface of the PCBs.
- LA Techniques Ltd, a UK SME, has been an early user of the project's work on PCBs, using it to verify their technique for establishing calibrations directly at the connection points for devices mounted on PCBs.
- A large-signal reference device has been developed for the verification of measurement systems, such as NVNAs and LSNAs, which are used for characterising transistors found in mobile phones and base stations. The project established measurement capability for nonlinear measurements and measurements that exceed the conventional reference impedance of 50 ohms – i.e. extreme impedance measurements.
- It is planned to use the large-signal reference device developed in the project in the follow-on EMPIR project 14IND10, MET5G and by measurement companies such as project partner Keysight BE). The device will be used as a travelling standard during a round robin measurement comparison exercise.
- Keysight BE and R&S had components and test equipment included in the investigations in the project. This has effectively benchmarked the performance of their systems, in particular their VNAs. This provides useful, independent, evaluation of these components and equipment within the context of this project.

4.1 Dissemination activities

A series of public events i.e. seminars, workshops and training activities, were organised by the project partners, throughout the lifetime of the project. Every six months, a European ANAMET[20] seminar was hosted by one of the project partners. These seminars gave the opportunity for the project partners to give technical presentations on the very latest research activities from the project. In addition, on some occasions, external speakers were also invited to contribute additional specialist knowledge, where appropriate. Each ANAMET seminar attracted approximately 40 attendees.

Further to this, a series of workshops and training activites were also held alongside each of the ANAMET seminars. The details of all these public events are shown in Table 7, below. These workshops and training activities were designed to disseminate the knowledge from the outputs of the project that were of direct relevance and use to end-users. For example, the first workshop concentrated on sharing with end-users the practicial knowledge gained within the project on using ECUs. The first training course gave specific good practice advice on how to improve measurements with VNAs. One workshop and one training course were devoted to the on-going project activity of revising the EURAMET VNA Guide which is used by a large number

[20] The term 'ANAMET' was used for these seminars as the events were similar to, and followed on naturally from, an earlier series of meetings called ANAMET, that were held from 1993 to 2011 at various locations in the UK. See www.npl.co.uk/anamet for more details.

of European calibration and test houses. These activities meant that the end-user community were kept up-to-date with the revision process and were also able to contribute thoughts and suggestions on how best to carry out the revision. Finally, a workshop and training course were each devoted to multi-port VNAs, and VNA uncertainty.

Table 7: workshops, training activities and ANAMET seminars held during the project

Date	Venue	Workshop	Training event
December 2013	RISE, Sweden	"Electronic Calibration Units"	
June 2014	VSL, Netherlands		"Good Practice with VNAs"
December 2014	PTB, Germany	"Revising the EURAMET VNA Guide"	
June 2015	METAS, Switzerland		"Multiport VNA Measurements"
December 2015	LNE, France	"VNA Uncertainty"	
June 2016	NPL, UK		"Revision of EURAMET VNA Guide"

In addition to the above public events, the project partners were very active in disseminatiing the new knowledge that was generated by the project via participation in international scientific conferences and publication of results in peer-reviewed scientific journals.

The project partners participated in, and presented papers at, all six ARFTG (Automatic RF Techniques Group) Microwave Measurement conferences that took place during the lifetime of the project. These were: 82nd conference, Columbus, Ohio, in November 2013; 83rd conference (alongside IMS 2014), Tampa, Florida, in June 2014; 84th conference, Boulder, Colorado, in December 2014; 85th conference (alongside IMS 2015), Phoenix, Arizona, in May 2015; 86th conference, Atlanta, Georgia, in December 2015; 87th conference (alongside IMS 2016), in San Francisco, California, in May 2016.

The project partners also particiapted in, and presented papers at, two CPEM (Conference on Precision Electromagnetic Measurements) conferences that took place during the lifetime of the project. These were: CPEM 2014, Rio De Janeiro, Brazil, August 2014; CPEM 2016, Ottowa, Canada, in July 2016.

In addition, the project partners particiapted in, and presented papers at three EuMW (European Microwave Week) events: EuMW 2013, Nuremberg, Germany, in October 2013; EuMW 2014, Rome, Italy, in October 2014; EuMW 2015, Paris, France, in September 2015.

Presentations by the project partners were also given at the following events: 1st Keysight Millimetre-wave and Terahertz Users Meeting, October 2013, UK; 2nd Keysight Millimetre-wave and Terahertz Users Meeting, October 2014, UK; Conference – Guide to the Expression of Uncertainty in Measurement – Past, Present and Future; November 2013, UK; IET Colloquium on Millimetre-wave and Terahertz Engineering & Technology, March 2014, UK; 2nd IET Colloquium on Millimetre-wave and Terahertz Engineering and Technology, March 2015, UK; 40th meeting of the Czech electrotechnical society, subgroup Microwave technique, May 2014, Czech Republic; 44th meeting of the Czech electrotechnical society, subgroup Microwave technique, May 2016, Czech Republic; CFM Technical day, October 2014, France; Keysight Metrology Workshop, April 2015, Turkey; 1st URSI Atlantic Radio Science Conference, May 2015, Spain; VDI Fachtagung Messunsicherheit, November 2015, Germany; 21st International Conference on Microwave, Radar and Wireless Communications (MIKON), May 2016, Poland; 17th International Congress of Metrology, September 2015, France; PTB Seminar, May 2016, Germany.

The project partners also published 51 scientific papers in peer-reviewed journals and published one chapter in a text book ("Terahertz Metrology", Editor M Naftaly).

The project also set up and operated a Stakeholder Advisory Group (SAG) consisting of key international experts in the fields of metrology covered by this project. This SAG met every six months and gave an opportunity for a two way flow of information: (i) knowledge generated by the project partners from work in the project was passed directly to the members of the SAG thus making them directly aware on the latest research in this area; (ii) the members of the SAG advised the project partners of the further development of the work taking place in the project.

Finally, the project set up a web-site (http://projects.npl.co.uk/hf-circuits) and a LinkedIn discussion Group (www.linkedin.com/groups/6542407) to facilitiate knoweldge dissemination via the internet.

4.2 Early impacts

4.2.1 International Standards

Early impact from this project was provided by contributions made to several international standards making groups. These were mostly IEEE but also the Association Connecting Electronics Industries (IPC).

In the case of IEEE, there was strong interaction with three standards making activities:

1. P1785 Working Group – Waveguides for Millimeter and Sub-Millimeter Wavelengths;
2. P287 Working Group – Precision Coaxial Connectors for RF, Microwave and Millimeter Waves;
3. Special Interest Group (SIG) on Standards for Nonlinear Measurements.

Project partners provided membership of both the P1785 and P287 Working Groups. In particular: for P1785, the role of Chair was provided by NPL and membership was provided by PTB and RISE; for P287, the roles of Vice Chair and Secretary were provided by NPL; membership was provided by PTB, RISE and METAS. Table 8, below, shows the participation in meetings of the IEEE P287 and P1785 Working Groups by participants in this project.

Table 8: Participation in IEEE standards meetings

Date	Venue	P287	P1785
November 2013	Columbus, OH	✓	✓
June 2014	Tampa, FL	✓	✓
December 2014	Boulder, CO	✓	✓
May 2015	Phoenix, AZ	✓	✓
December 2015	Atlanta, GA	✓	
May 2016	San Francisco, CA	✓	

The P1785 Working Group stopped meeting after May 2015 as the technical work on drafting the standards (IEEE Std 1785.2 and IEEE Std 1785.3) had been completed. The time between May 2015 and the dates of publication of these two standards (August 2016 and October 2016, respectively) was taken up with the IEEE authorisation process, type-setting the standard in the IEEE house style, and the public balloting process (which included several rounds of voting before the standard was finally approved).

For the IEEE SIG on Nonlinear Measurement, the role of Chair was shared jointly by NPL and NIST (USA). Meetings of this SIG were held in: June 2014 in Tampa, Florida; December 2014, in Boulder, Colorado; and May 2015, in Phoenix, Arizona. The outcome from the SIG meetings was that is was decided to initiate the development of two new IEEE standards: P1765 “Recommended practice for estimating the uncertainty in measurements of modulated signals for wireless communications with application to error vector magnitude and other system-level distortion metrics“; and P1770 “Recommended practice for the usage of terms commonly employed in the field of large-signal vector network analysis“. Both these Working Groups have since been formed and are now holding regular meetings and input to these meetings is being provided by the follow-on EMPIR 14IND10 MET5G project.

In the case of IPC, initial interaction helped steer the development of a standard test method produced by the D-24b Propagation Loss Test Method Task Group, within IPC-TM-650. However, once this test method was published, the D-24b Task Group became inactive. Involvement was therefore transferred to a related group: D-24c High-Frequency Test Methods Task Group: “Frequency-Domain Methods”, also within IPC-TM-650.

This task group is determining the needs of the microelectronics industry for high-frequency dielectric test methods. NPL is now a member of the D-24c Task Group and continues to participate in meetings.

4.2.2 Verification Devices

Two verification devices were designed, fabricated and tested for use beyond the lifetime of the project as described in sub-sections 3.3 and 3.4. In the case of sub-section 3.3, the device was a reference PCB that could be used by any laboratory for testing and verifying the performance of their measurement system. Work on the reference PCB was completed towards the end of the project (in line with the project plan). However, since completing the project, there has been much interest in using the reference PCB by several end-users. These include: (i) University College London (UCL), (ii) PacketMicro, Inc, (iii) the Korean National Metrology Institute, KRISS. Workers at UCL are using PCBs to build microwave measuring instruments for sensing the thickness of the ice cap covering Antarctica. This is part of a global initiative towards environmental climate change monitoring. The measuring instruments rely on accurate characterisation of the PCBs. The reference PCB from this project has been used by UCL to verifiy the performance of the measurement system used for testing the PCBs.

PacketMicro manufacture probing systems for making measurements on PCBs. This includes probes and calibration substrates that are sold to electronics companies around the world. PacketMicro are using the reference PCB from this project to cross-check measurements against their own test systems. This is work being done in conjunction with NPL and will provide a link for the project to the US electronics community.

Finally, KRISS are making measurements on PCBs to help support the global electronics industry which has a substantial footprint in East Asia. Plans are in place for KRISS to access the reference PCB and compare their measurements against measurements made at NPL. This will provide a link for the project to the Asian electronics community.

In the case of sub-section 3.4, the device was a reference nonlinear circuit that can be used for verifying the performance of nonlniear measurement systems (such as NVNAs and LSNAs, etc). Work on the nonlinear device was completed towards the end of the project and the device is going to be used as part of a round robin measurement comparison exercise in the follow-on project 14IND10 MET5G. This demonstrates take-up of technology from one EMPR project by a subsequent EMPIR project. The round robin comparison will involve partners from SIB62 HF-Circuits as well as additional partners that are involved in the 14IND10 MET5G project.

4.2.3 Consultancy

The research output from sub-section 3.3 has also enabled some consultancy services to be provided based on PCB measurements being made in industry. LA Techniques Ltd (a UK SME) has benefitted directly from the work on PCBs by verifying a technique they have developed for establishing calibrations directly at the connection points for devices mounted on PCBs. This work was undertaken in conjunction with NPL and was published in [3].

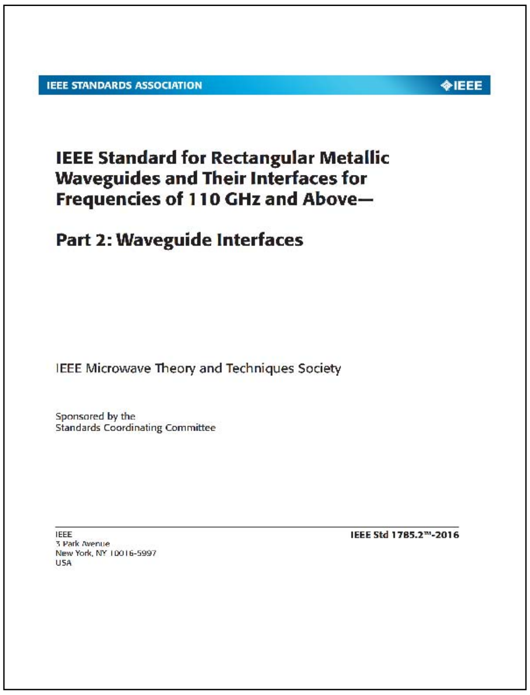
4.3 Longer-term impacts

The new measurement traceability and verification techniques that have been developed by the project will enable test equipment manufacturers and electronic component manufacturers to establish new products with much greater confidence. This includes verifying the credibility of new products and establishing protocols and procedures that can be universally understood and adopted.

A major long-term impact has been made by this project by the publication of documents that will have a profound, wide-ranging, impact on the international measurement and testing communites and the technologies they underpin, for many years to come.

In the first instance, this relates to two new international standards that have been published very soon after the completion of the project. These standards are shown in Figure 34 and are:

1. IEEE Std 1785.2™-2016, “IEEE Standard for Rectangular Metallic Waveguides and Their Interfaces for Frequencies of 110 GHz and Above—Part 2: Waveguide Interfaces“
2. IEEE Std 1785.3™-2016, “IEEE Recommended Practice for Rectangular Metallic Waveguides and Their Interfaces for Frequencies of 110 GHz and Above—Part 3: Recommendations for Performance and Uncertainty Specifications“


IEEE STANDARDS ASSOCIATION ◆IEEE

IEEE Standard for Rectangular Metallic Waveguides and Their Interfaces for Frequencies of 110 GHz and Above—

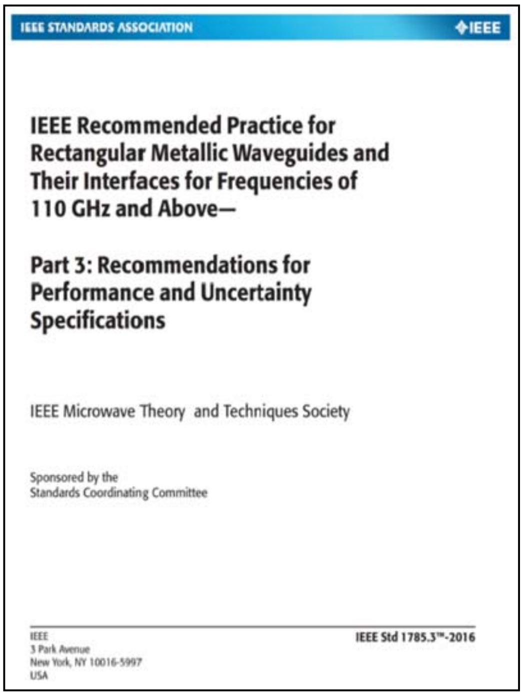
Part 2: Waveguide Interfaces

IEEE Microwave Theory and Techniques Society

Sponsored by the
Standards Coordinating Committee

IEEE
3 Park Avenue
New York, NY 10016-5997
USA

IEEE Std 1785.2™-2016


IEEE STANDARDS ASSOCIATION ◆IEEE

IEEE Recommended Practice for Rectangular Metallic Waveguides and Their Interfaces for Frequencies of 110 GHz and Above—

Part 3: Recommendations for Performance and Uncertainty Specifications

IEEE Microwave Theory and Techniques Society

Sponsored by the
Standards Coordinating Committee

IEEE
3 Park Avenue
New York, NY 10016-5997
USA

IEEE Std 1785.3™-2016

Fig. 34: Front covers of the two international standards that have been produced with significant input from the HF-Circuits project: IEEE Std 1785.2-2016 (left); IEEE Std 1785.3-2016 (right)

The project made a major contribution to the publication of both these standards i.e. the standards could not have been produced without the input.

One consequence of the development of these standards was a re-vitalisation of the equivalent IEC standard working group (TC-46) activities. This has since resulted in the updating of the equivalent standards published by IEC:

- IEC 60153-1:2016, “Hollow metallic waveguides. Part 1: General requirements and measuring methods“
- IEC 60153-2:2016: “Hollow metallic waveguides. Part 2: Relevant specifications for ordinary rectangular waveguides“
- IEC 60154-1:2016: “Flanges for waveguides. Part 1: General requirements“
- IEC 60154-2:2016: “Flanges for waveguides. Part 2: Relevant specifications for flanges for ordinary rectangular waveguides“

There was linkage between the IEEE P1785 Working Group and the IEC TC46 Technical Committee thus ensuring the compatibility of designs used in both series of standards. The linkage comprised several individuals who were members of both the IEEE Working Group and the IEC technical commitee. This included membership from the project partners NPL and PTB.

Another document that will have a major impact on the RF, microwave and millimetre-wave community for many years to come will be the revised IEEE Standard 287 (for precision coaxial connectors at RF, microwave and millimetre-wave frequencies). This standard is undergoing a major revision – the current published version is a single standard whereas the revised standard will be published as three separate standards, i.e. the standard will be in three parts. These will be:

1. “Standard for Precision Coaxial Connectors at RF, Microwave and Millimeter-wave Frequencies. Part 1: General Requirements, Definitions, and Detailed Specifications”
2. “Recommended Practice Standard for Precision Coaxial Connectors at RF, Microwave and Millimeter-wave Frequencies. Part 2: Recommended Test Procedures”
3. “Recommended Practice Standard for Precision Coaxial Connectors at RF, Microwave and Millimeter-wave Frequencies. Part 3: Connector Effects, Uncertainty Specifications and Recommendations for Performance”

The scope of the standards is being widened considerably to include new connectors (e.g. the 0.8 mm connector which has an operational bandwidth extending well above 100 GHz) and existing connectors that are now being used in the telecommunications industry (e.g. the 7-16 and 4.3-10 connectors). In addition, methods used for testing and evaluating connectors are being brought up-to-date to reflect the latest test equipment that is used for this purpose. This project has made a major contribution to the revision process, particularly through the research described in sub-sections 3.1 and 3.5. It is expected to be a very long time before the P287 and P1785 standards receive any subsequent revision. Therefore the contributions made by this project will have a very long-lasting impact on this user community.

The above series of standards (IEEE 1785 and IEEE 287) relate directly to the use of high-frequencies in technologies such as telecommunications. These standards will therefore have a direct impact on the rollout of next generation telecommunications (via 5G and the Internet of Things). This further extends the impact and outreach achieved by the SIB62 HF-Circuits project in this area. Other technologies impacted by these standardisation activities include security and climate change monitoring, where the standardisation of interfaces used at millimetre and submillimetre wavelengths will facilitate product development and systems' inter-operability.

Another area where the project will make a lasting impact is in measurement quality and integrity, via accreditation and traceability to the SI. Two outputs from the project will make a major contribution in this area: (i) the provision of new measurement services resulting from the project (as described in sub-section 3.1); and (ii) the revision of the EURAMET Guide for VNAs (as described in sub-section 3.5).

New measurement services are now available in selected waveguide sizes, extending measurement traceability to 1.1 THz. This reflects the current state-of-the-art for waveguide measurement capability throughout the world. In addition, coaxial measurement services are now available to 110 GHz in the 1 mm coaxial connector size. One NMI (METAS) has provided an updated Calibration and Measurement Capability (CMC), managed by the BIPM, for their measurement capability in the 1 mm coaxial line size.

A revised version of the EURAMET Calibration Guide for VNAs cg-12 was a significant output from this project. This document is now undergoing review by EURAMET before it is published as the new Guide for this area. Once published, the Guide will have a profound impact on all accredited laboratories using VNAs to provide accreditated calibrations and measurements (e.g. against standards such as ISO 17025).

Since measurement accreditation is an underpinning discipline affecting all products and services that use these capabilities, the work on traceability in the project will impact user sectors such as consumer electronics (mobile phones, computers, internet, etc), defence and security, climate change monitoring, medical and next generation electronics.

5 Website address and contact details

The public web-site for this project is at: www.hfcircuits.org

The contact person for general enquiries is Prof Nick Ridler, NPL (nick.ridler@npl.co.uk).

6 List of project publications

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