# Publishable Summary for 18SIB09 TEMMT
# Traceability for electrical measurements at millimetre-wave and terahertz frequencies for communications and electronics technologies

## Overview

This project aims to establish traceability to the SI for 3 electrical measurement quantities; (i) S-parameters, (ii) power and (iii) complex permittivity of dielectric materials, at millimetre-wave and terahertz (THz) frequencies. Such traceability is important for many emerging applications, exploiting communications and electronics technologies – e.g. 5th Generation mobile networks (5G), the Internet of Things (IoT), Connected and Autonomous Vehicles (CAVs), space-borne radiometers for Earth remote sensing, security imaging, etc. The goal of this project is to support such emerging applications and enable European NMIs to provide traceability to the SI for these 3 parameters in the millimetre-wave and THz part of the spectrum, which will be beneficial to end-users.

## Need

The rollout of 5G networks and large-scale deployments of cellular IoT will lead to fundamental changes to our society, impacting not only consumer services but also industries embarking on digital transformations. CAVs are progressing rapidly and are expected to improve traffic flow, safety and convenience significantly. Space deployed radiometers are used for passive remote sensing of atmospheric constituents which are related to climate change and play a critical role in environmental protection. All these applications require the use of the millimetre-wave and THz regions of the electromagnetic spectrum, and demand devices and integrated circuits operating at these high frequencies.

However, the development of devices and systems to underpin these applications is currently hampered by the lack of traceability for electrical measurements at millimetre-wave and THz frequencies. For example, although power meters working at frequencies up to at least 750 GHz are commercially available, there is no established calibration hierarchy, accessible to industrial and other end-users, to allow traceability to the SI for these measurements. In addition, current commercially available frequency extender heads and calibration kits for vector network analysers (VNAs) enable these systems to measure S-parameters at frequencies up to 1.5 THz. These VNA systems can also be adapted to measure materials properties (e.g. complex permittivity) using commercially available Material Characterisation Kits (MCK) at frequencies up to at least 750 GHz. However, again, there is no traceability to the SI to benchmark this measurement capability. NMI-level metrology research is therefore, urgently needed to address this lack of traceability so that the capabilities of these high frequency measurement systems can be fully exploited.

This is important to ensure product quality and end user confidence, and ultimately to improve the competitiveness of European Industry. The work in this project also aligns with broader European visions, as outlined in the Europe Commission Strategy i.e. “Digital Single Market”.

## Objectives

The overall objective of this project is to achieve accurate and traceable electrical measurements for users of the millimetre-wave and THz regions of the electromagnetic spectrum, particularly for electronics applications impacting future communications technologies – so-called 5G communications and beyond.

The specific objectives of the project are:

1. To develop metrological traceability and verification techniques for S-parameters (that measure the loss and phase change for transmitted and reflected signals) in both coaxial line (using the 1.35 mm E-band connector to 90 GHz) and rectangular metallic waveguide (using waveguides covering frequencies from 330 GHz to 1.5 THz). Three waveguide bands within this frequency range will be covered and these are 330 GHz to 500 GHz, 500 GHz to 750 GHz, and 1.1 THz to 1.5 THz.

2. To develop metrological traceability and verification techniques for S-parameter measurements on planar substrates from 110 GHz to 1.1 THz. Three waveguide bands within this frequency range will be covered and these are 110 GHz to 170 GHz, 500 GHz to 750 GHz, and 750 GHz to 1.1 THz.
3. To develop metrological traceability for power measurements in waveguide to 750 GHz. Two waveguide bands within this frequency range will be covered and these are 110 GHz to 170 GHz, and 500 GHz to 750 GHz.
4. To develop metrological traceability for complex permittivity of dielectric materials to 750 GHz. Two waveguide bands will be covered and these are 140 GHz to 220 GHz, and 500 GHz to 750 GHz.
5. To facilitate the take up of the technology and measurement infrastructure developed in the project by other NMIs with the view of forming a coordinated network of NMIs that provide a comprehensive measurement capability as well as by the measurement supply chain (research institutes, calibration laboratories), standards developing organisations (e.g. IEEE P287 and IEEE P1785) and end users (i.e. manufacturers of telecom equipment, measuring instruments, absorber materials, etc).

**Progress beyond the state of the art**

Currently, metrological traceability for electrical measurements in the frequency range from 50 GHz to 1.5 THz is poorly served by the global NMI community. This global lack of traceability at these frequencies is demonstrated by the fact that there are no Calibration and Measurement Capability (CMC) entries in the BIPM key comparison database at any frequency above 200 GHz. Given the current rapid increase in use of this part of the electromagnetic spectrum (particularly for communications and electronics applications), this situation represents a serious gap in the services provided by the NMI community to stakeholders i.e. end-users in industry and academia.

*Traceable S-parameter measurements in waveguides to 1.5 THz and in E-band coaxial lines to 90 GHz*

The current state of the art for metrological traceability for measurements in coaxial lines is up to 116.5 GHz within Europe. The NMI of Japan is capable of providing traceability in waveguide up to 170 GHz, representing the highest frequency in the BIPM database. This project is extending the state of the art by putting in place traceability in waveguides up to 1.5 THz. This will complement the work carried out in the previous EMRP project SIB62 HFCircuits that included a preliminary study on the steps needed to establish traceability for waveguides up to 1.1 THz.

The E-band 1.35 mm coaxial connector has been recently introduced to support applications like 5G and 77 GHz automotive radar sensors. However, there is currently no traceability established for E-band connector measurements. This project is going beyond the state of the art by establishing both dimensional traceability and electrical traceability for E-band connector measurements, allowing industry to perform traceable measurements with known uncertainty.

*Traceable planar S-parameter measurements to 1.1 THz*

Currently there is no traceability established for on-wafer S-parameter measurements above 110 GHz. Another EMPIR project 14IND02 PlanarCal established traceability up to 110 GHz. This project is continuing the work of 14IND02 and developing traceability and verification techniques for S-parameters to 1.1 THz. This will enable industry to characterise integrated circuits with confidence at these very high frequencies.

*Traceable power measurements to 750 GHz*

The current state of the art for power measurement is up to 110 GHz in waveguides. This project is putting in place traceability for power measurement up to 750 GHz. Micro-calorimeter and transfer standards are being developed for the 110 GHz to 170 GHz band and novel approaches using a combination of quasi-optical (pyroelectric detection) and guided wave power measurement are also being explored. In addition, evaluation of the traceability of a commercial power meter will be carried out up to 750 GHz.

*Traceable material measurements to 750 GHz*

For materials measurement (i.e. complex permittivity) existing traceability services extend only to 110 GHz and currently this is only available at a few NMIs. This project is putting in place traceability mechanisms to establish the quality of material measurements to 750 GHz and will expand the number of NMIs offering such services to those in this consortium. This will unlock the potential for using dielectric materials in applications demanding accurate knowledge of material properties, e.g. for space applications.

## Results

1. *To develop metrological traceability and verification techniques for S-parameters (that measure the loss and phase change for transmitted and reflected signals) in both coaxial line (using the 1.35 mm E-band connector to 90 GHz) and rectangular metallic waveguide (using waveguides covering frequencies from 330 GHz to 1.5 THz). Three waveguide bands within this frequency range will be covered and these are 330 GHz to 500 GHz, 500 GHz to 750 GHz, and 1.1 THz to 1.5 THz.*

New measurement systems are now in place at several European NMIs (i.e. LNE, NPL and PTB) to enable both dimensional and electrical measurements to be made of coaxial components in the 1.35 mm line size. The dimensional measurement capabilities enable the diameters of the center and outer conductors of reference air lines to be measured and hence the characteristic impedance of these lines can be determined. The electrical measurement capabilities provide S-parameter measurements of one- and two-port devices fitted with 1.35 mm coaxial connectors. These measurement systems are currently being assessed using the measurement comparison exercises that are scheduled as part of this project. Following successful completion of these measurement comparison exercises, these capabilities will be added as Calibration and Measurement Capability (CMC) entries in the BIPM key comparison to provide metrological traceability for this coaxial line size.

The work on waveguide traceability has now established new calibration techniques for each of the three waveguide bands in this project i.e. 330 GHz to 500 GHz, 500 GHz to 750 GHz, and 1.1 THz to 1.5 THz. A specialised form of Thru-Reflect-Line (TRL) calibration has been developed that will enable NMI level accuracy to be achieved in these bands. Uncertainty evaluation techniques have also been established. The new calibration and uncertainty evaluation techniques are currently being validated using the measurement comparison exercises scheduled as part of this project.

2. *To develop metrological traceability and verification techniques for S-parameter measurements on planar substrates from 110 GHz to 1.1 THz. Three waveguide bands within this frequency range will be covered and these are 110 GHz to 170 GHz, 500 GHz to 750 GHz, and 750 GHz to 1.1 THz.*

Reference substrates incorporating co-planar waveguide (CPW) calibration standards including matched and mismatched lines, shorts, offset shorts, opens and loads for S-parameter measurements up to 1.1 THz have been designed and fabricated. Electromagnetic wave (EM) simulations have been carried out to optimise the dimensions and the layout of the silicon-based calibration substrate. The EM simulations have also been used for the assessment of reference values and uncertainties of each CPW standard. Measured dimensions and material properties of the CPW standards were used in these EM simulations to accurately evaluate the expected S-parameters with uncertainties.

The development of verification and calibration methods for S-parameter measurements on planar substrates from 110 GHz to 1.1 THz is progressing well. Reliability studies have been conducted using both manual and automated probing techniques through repeated measurements of devices on commercial calibration substrates. The results have shown reasonable stability for both probe planarisation and device contacting. These results have then been used to provide input to the development of verification and calibration methods. Several different calibration techniques, including off-wafer multi-line TRL, Short-Open-Load-Thru (SOLT) and on-wafer multi-line TRL calibration have been investigated. The on-wafer multi-line TRL technique has been found to be the most accurate calibration technique for measurements up to 1.1 THz and will be used in future activities in this project.

Regarding measurement uncertainty, the comprehensive uncertainty budget developed in the preceding EMPIR project 14IND02 PlanarCal (for operation up to 110 GHz) has been reviewed, along with recently published state-of-the-art results. This information has been used to identify all relevant uncertainty sources for planar measurements up to THz frequencies. A comprehensive uncertainty budget, including instrumentation errors, repeatability and calibration standard uncertainties, has been established. A new, improved CPW model, including radiation effects, has been developed and implemented and is compatible with uncertainty estimation procedures using METAS's UncLib for uncertainty propagation. Additionally, this uncertainty calculation framework will be implemented in the recently developed VNA measurement software FAME.

3. *To develop metrological traceability for power measurements in waveguide to 750 GHz. Two waveguide bands within this frequency range will be covered and these are 110 GHz to 170 GHz, and 500 GHz to 750GHz.*

Different types of waveguide calorimeters have been developed by LNE, NPL and PTB for use in the 110 GHz to 170 GHz band. Three different types of calorimeter designs have been developed and produced. To characterise these different types of waveguide calorimeter, investigations of the calibration principles for each type are being carried out. These different methods include, multiple offset-short methods (PTB), flush-short methods (NPL) and VNA methods (LNE).

Two types of power sensors, one a thin film bolometric type and the other a thermoelectric type, have been designed, manufactured and characterised (S-parameters) to be used with the waveguide calorimeters. The first two prototypes of the bolometric power sensor have been manufactured and are currently being characterised. Three prototypes of the thermoelectric power sensors have been fabricated, one of them has been characterised (S-parameters) and calibrated in one of the waveguide calorimeters (at PTB). Preliminary results obtained for the thermoelectric sensor were found to be reasonable (i.e. suitable for use as power transfer standards to establish traceability for end-users).

Free-space power measurement setups based on pyroelectric detectors have also been developed and fabricated for use in the 110 GHz to 170 GHz band and 500 GHz to 750 GHz band and installed at METAS and PTB. Corrugated horn antennas have been fully characterised in terms of losses and matching. Scattering and standing waves models have been developed to characterise the 500 GHz to 750 GHz free-space power measurement setups, which will be done next in the project.

4. *To develop metrological traceability for complex permittivity of dielectric materials to 750 GHz. Two waveguide bands will be covered and these are 140 GHz to 220 GHz, and 500 GHz to 750 GHz.*

This work focused on three measurement methods: (i) VNA-based systems, (ii) optical systems based on Time-Domain Spectrometer (TDS) and Frequency-Domain Spectrometer (FDS), and (iii) resonator-based systems.

The VNA-based setups have been installed and tested at NPL and METAS. Various calibration techniques (i.e. time-gated Short-Thru, Thru-Reflect-Line, Thru-only, etc) have been applied to the measurement systems. Preliminary uncertainties have been calculated with both random and systematic error components being considered. For extraction of material properties from S-parameters, existing techniques have been reviewed, implemented and further improved to operate for all frequencies of interest and specimens with different thicknesses.

The optical systems have been installed, optimised and are operational in dry air environments. Test measurements were successfully carried out on a frequency axis calibration artefact (highly resistive silicon etalon). The THz attenuators, which are possible candidate calibration artefacts for the linearity of the amplitude, will be investigated further next.

The resonator-based setups have been installed at GUM and NPL, and methods for the extraction of material properties have been developed. Material blocks of fused silica and ultra-high-molecular-weight (UHMW) polyethylene were purchased and multiple specimens have been cut and machined for the measurement comparison.

The comparison of material properties measured by the above three different systems and setups has been registered as the EURAMET pilot study (registration number 1514). A set of nine specimens have been selected as reference materials. The set of specimens will be circulated according to a fixed schedule for the comparison and each partner will carry out the measurements independently. The thickness of each specimen will be measured and used by all partners to extract the material properties.

## Impact

The project has created a website for end users at http://projects.lne.eu/jrp-temmt/. It has produced nine open access peer-reviewed scientific papers, of which four are published in high impact journals including *IEEE Transactions on Instrumentation and Measurement*, *IEEE Transactions on Terahertz Science and Technology*, and *Journal of Infrared Millimeter and Terahertz Waves*. Another scientific paper has been accepted for publication in *Metrologia*, the leading international journal in metrology. The project has also been presented 13 times at conferences such as the 44$^{th}$ International Conference on Infrared, Millimeter, and Terahertz

Waves (IRMMW-THz), the 21$^{st}$ International Conference on Electromagnetics in Advanced Applications (ICEAA), the 2019 Asia-Pacific Microwave Conference (APMC), the 12$^{th}$ and 13$^{th}$ UK/Europe-China Workshop on Millimetre-Waves and Terahertz Technologies (UCMMT), the 2020 IEEE 24$^{th}$ Workshop on Signal and Power Integrity (SPI), and the 2020 Conference on Precision Electromagnetic Measurements (CPEM).

A proposal for a one-day workshop, entitled “Measurements at mmWave and Terahertz Frequencies of Three Measurement Quantities: S-Parameters, Power, and Complex Permittivity of Dielectric Materials”, for end users, has been accepted by the European Microwave Week 2020 (Europe's premier conference on microwave, millimetre-wave and terahertz devices, systems and technologies). The workshop was devoted to the outputs from the project, with all 11 confirmed speakers from the consortium plus a project collaborator (i.e. AIST, Japan).

*Impact on industrial and other user communities*

This project will enable accurate and traceable measurements of three key electrical quantities at millimetre-wave and THz frequencies. This will have a direct impact on communications and electronics industries exploiting this part of spectrum. Notable examples include point-to-point backhaul for 5G communications, the IoT, radar sensors for CAVs, space-borne radiometers for Earth monitoring, and security imaging. Improvement of measurement accuracy and establishment of measurement traceability will enable manufacturers to provide confidence in their measurements and specifications. For example, partner R&S has already implemented the new 1.35 mm E-band coaxial connector in two thermal power sensors, the R&S NRP90T and R&S NRP90TN. The work on establishing traceability for S-parameter measurements in E-band connectors has therefore become very relevant and timely. In addition, new measurement systems are now in place at several European NMIs (i.e. LNE, NPL and PTB) to enable both dimensional and electrical measurements to be made of coaxial components in the 1.35 mm line size.

This project will also significantly extend the measurement capabilities of the participating NMIs, to over 1 THz for S-parameter measurement and to 750 GHz for power and material measurement. This will lead to greatly improved access to, and dissemination of, measurement traceability for European accredited testing and calibration laboratories and manufacturers of test instrumentation. This will be beneficial for all end-users, including customers and suppliers of millimetre-wave and THz devices and systems.

The project has setup a Technical Advisory Group, formed of members from end-user industry and metrology communities. Such direct interaction with industry ensures the project aligns with industrial needs and fosters knowledge transfer. The Technical Advisory Group currently comprises 15 end-users from the electronic, instrumentation, semiconductor sectors and 3 NMIs outside of Europe (AIST, Japan; NIM, China; and KRISS, Korea). Teleconferences with the Technical Advisory Group members were held in January 2020 at LNE (France) alongside with the M9 project meeting and in October 2020 alongside with the M18 project meeting.

*Impact on the metrology and scientific communities*

No single NMI currently has the capability to deliver this project, therefore, this project involves eight of Europe’s NMIs and will synergise their national research programmes. During the project, preparatory tasks are being undertaken to subsequently establish a coordinated network of NMIs, including the NMI of Argentina (INTI), in order to provide a comprehensive measurement capability based on the outcomes of this project, and the previous EMRP project SIB62. This project will also foster the development of three relatively small NMIs (CMI, GUM and TUBITAK) whose metrology programmes are at an early stage of development in the field of electrical measurements. This will be done through their working collaborations with the five experienced European NMIs (i.e. METAS, LNE, NPL, PTB and VSL) in this consortium. For example, the EURAMET comparison of material properties measured using different methods and different measurement setups involves four NMIs (i.e. GUM, LNE, METAS and NPL), and hence such activities are enhancing collaborations between these, and other, NMIs across Europe.

*Impact on relevant standards*

This project has so far provided inputs to five standardisation bodies, i.e. IEEE MTT/SCC (Standards Coordinating Committee) P287 - Standard for Precision Coaxial Connectors (DC-110 GHZ) Sub-committee; IEEE MTT/SCC P2822 Recommended Practice for Microwave, Millimeter-wave and THz On-Wafer Calibrations, De-Embedding and Measurements; IEC/TC 46 Cables, wires, waveguides, RF connectors, RF and microwave passive components and accessories; IEC/ SC 46F RF and microwave passive components; DKE Subcommittee 412.4 Passive RF and Microwave components.

Additionally, this project expects to make contributions to other standardisation bodies including IEEE MTT/SCC P1785 - A new standard for waveguide above 110 GHz, the BIPM Key Comparison Database, the BIPM database of CMCs, and EURAMET guidance documents on power calibrations and measurements, materials properties measurements, in the range from 110 GHz to 750 GHz.

*Longer-term economic, social and environmental impacts*

The measurement science generated by this project will pave the way for the development of emerging applications including future telecommunications, autonomous vehicles, the IoT, and security imaging. This will enable European businesses to move into these areas and will support a strong competitive advantage. For established applications, e.g. measurement instruments and space radiometers, state of the art performance will ensure a commercial edge and allow European industry in these sectors to continue progress with key technologies and to attract business from global markets.

The social benefits of this project will be to retain a competitive advantage in Europe over worldwide competition on technology and thereby keep and grow expertise and much needed highly skilled electronic engineering and support staff jobs. This project also has wider social impact on quality of life enabled by greater data transport in mobile networks, medical diagnostics using THz imaging, easier and safer mobility using CAV and security scanning in public places such as airports.

Space radiometers play a key role in Earth monitoring, which provides information about global climate change and weather forecasting. This project will facilitate more accurate and traceable measurements at millimetre-wave and THz frequencies, yielding radiometers with better performance. Improved energy efficiency of components and systems will also be supported by more accurate measurements, which will in turn support a reduction in energy consumption and should lead to a more sustainable environment.

**List of publications**

[1] R. Judaschke, M. Kehrt, and A. Steiger, “Comparison of Waveguide and Free-Space Power Measurement in the Millimeter-Wave Range”, in *2019 44th International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz)*, Paris, France, 1-6 Sept. 2019, https://doi.org/10.1109/IRMMW-THz.2019.8874235

[2] A. Kazemipour, M. Wollensack, J. Hoffmann, S.K. Yee, J. Rufenacht, G. Gaumann, M. Hudlicka, M. Zeier, "Material Parameter Extraction in THz Domain, Simplifications and Sensitivity Analysis," in *2019 IEEE Asia-Pacific Microwave Conference (APMC)*, Singapore, Singapore, 10-13 Dec. 2019, pp. 276-278, https://doi.org/10.1109/APMC46564.2019.9038523

[3] G. N. Phung and U. Arz, "Parasitic Probe Effects in Measurements of Coplanar Waveguides with Narrow Ground Width," in *2020 IEEE 24th Workshop on Signal and Power Integrity (SPI)*, Cologne, Germany, 17-20 May 2020, pp. 1-4, https://doi.org/10.1109/SPI48784.2020.9218166

[4] A. Kazemipour, J. Hoffmann, M. Wollensack, D. Allal, M. Hudlicka, J. Ruefenacht, D. Stalder, M. Zeier, "VNA-Based Material Characterization in THz Domain without Classic Calibration and Time-Gating," in *2020 Conference on Precision Electromagnetic Measurements (CPEM)*, Denver (Aurora), CO, USA, 24-28 Aug. 2020, pp. 1-2, https://doi.org/10.1109/CPEM49742.2020.9191818

[5] F. Mubarak, C. D. Martino, R. Toskovic, G. Rietveld and M. Spirito, "Automated Contacting of On-Wafer Devices for RF Testing," in *2020 Conference on Precision Electromagnetic Measurements (CPEM)*, Denver (Aurora), CO, USA, 24-28 Aug. 2020, pp. 1-2, https://doi.org/10.1109/CPEM49742.2020.9191800

[6] Y. Wang, X. Shang, N. M. Ridler, T. Huang and W. Wu, "Characterization of Dielectric Materials at WR-15 Band (50–75 GHz) Using VNA-Based Technique," in *IEEE Transactions on Instrumentation and Measurement*, vol. 69, no. 7, pp. 4930-4939, July 2020, https://doi.org/10.1109/TIM.2019.2954010

[7] N. M. Ridler, S. Johny, X. Shang, W. Sun and A. Wilson, "Comparing Standardized and Manufacturers' Interfaces for Waveguides Used at Submillimeter Wavelengths," in *IEEE Transactions on Terahertz*

*Science and Technology*, vol. 10, no. 5, pp. 453-459, Sept. 2020, https://doi.org/10.1109/TTHZ.2020.3010122

[8] Y. Wang, X. Shang, N. Ridler, M. Naftaly, A. Dimitriadis, T. Huang, W. Wu, “Material Measurements Using VNA-based Material Characterization Kits Subject to Thru-Reflect-Line Calibration,” in *IEEE Transactions on Terahertz Science and Technology*, vol. 10, no. 5, pp. 466-473, Sept. 2020. https://doi.org/10.1109/TTHZ.2020.2999631

[9] A. Kazemipour, M. Wollensack, J. Hoffmann, M. Hudlička, S. K. Yee, J. Rüfenacht, D. Stalder, G. Gäumann, and M. Zeier, “Analytical Uncertainty Evaluation of Material Parameter Measurements at THz Frequencies”, in *Journal of Infrared Millimeter and Terahertz Waves*, 41, pp. 1199–1217, 2020, https://doi.org/10.1007/s10762-020-00723-0

<table>
<tr><td colspan="2">Project start date and duration:</td><td>01 May 2019, for 39 months</td></tr>
<tr><td colspan="3">Coordinator:<br>Xiaobang Shang, NPL    Tel: 020 8943 6643    E-mail: xiaobang.shang@npl.co.uk<br>Project website address: http://projects.lne.eu/jrp-temmt/</td></tr>
<tr><td>Internal Funded Partners:<br>1. NPL, United Kingdom<br>2. CMI, Czech Republic<br>3. GUM, Poland<br>4. LNE, France<br>5. METAS, Switzerland<br>6. PTB, Germany<br>7. TUBITAK, Turkey<br>8. VSL, Netherlands</td><td>External Funded Partners:<br>9. BHAM, United Kingdom<br>10. Chalmers, Sweden<br>11. FVB, Germany<br>12. ULILLE, France<br>13. WAT, Poland</td><td>Unfunded Partners:<br>14. Anritsu, United Kingdom<br>15. FormFactor, Germany<br>16. INTI, Argentina<br>17. Keysight BE, Belgium<br>18. R&S, Germany<br>19. VDI, United States</td></tr>
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