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

Overview

This project aimed 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. As a result of this project, measurement capability has now been put in place, across several European NMIs, for accurate and traceable measurements of these 3 parameters at the millimetre-wave and THz frequencies. The capability provides direct benefits to applications that utilize this part of the spectrum, including point-to-point backhaul for 5G communications and beyond, the Internet of Things (IoT), radar sensors for connected and autonomous vehicles (CAVs), space-borne radiometers for remote sensing of the Earth and security imaging. Outputs of this project enable end-users to have confidence in measurement and specifications and to offer assured products through measurement traceability chains.

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

Metrological traceability for electrical measurements in the frequency range from 50 GHz to 1.5 THz was poorly served by the global NMI community. This global lack of traceability at these frequencies was demonstrated by the fact that there were 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 the use of this part of the electromagnetic spectrum (particularly for communications and electronics applications), this situation represented a serious gap in the services provided by the NMI community to stakeholders i.e. end-users in industry and academia.

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 waveguides up to 170 GHz, representing the highest frequency in the BIPM database. This project has contributed to the advancement of the state of the art by providing measurement capability for waveguides up to 1.5 THz. This has complemented 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 has advanced the state of the art by establishing both dimensional traceability and electrical traceability for E-band connector measurements, allowing the industry to perform traceable measurements with known uncertainty.

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. The work carried out in this project continues the work done in 14IND02 PlanarCal, and significant progress has been made in the development of traceability and verification techniques for S-parameters up to 1.1 THz. This enables the industry to characterise integrated circuits with confidence at these very high frequencies.

Furthermore, machine learning algorithms for on-wafer measurements have been developed and integrated into the VNA measurement software FAME. These automate all necessary alignment procedures without operator interaction and demonstrate superior performance than their manual counterparts.

This project has put in place traceability for power measurement up to 750 GHz. Micro-calorimeter and transfer standards have been 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 have also been explored. In addition, an evaluation of the traceability of a commercial power meter has been carried out up to 750 GHz.

For materials measurement (i.e. complex permittivity), traceability services extended only to 110 GHz and this was only available at a few NMIs. In this project, traceability mechanisms have been established for establishing the quality of measurement of materials up to 750 GHz, and the number of NMIs providing these services has been increased. The application of dielectric materials in applications requiring an accurate understanding of their material properties, such as those related to space applications, is now possible due to this breakthrough.

Results

Traceable S-parameter measurements in waveguides to 1.5 THz and in E-band coaxial lines to 90 GHz (objective 1)

New measurement systems are now operational at several European NMIs (i.e. LNE, NPL and PTB) to enable both dimensional and electrical measurements of coaxial components in the 1.35 mm line size. The dimensional measurement capabilities enable the diameters of the centre and outer conductors of reference air lines to be measured and hence the characteristic impedance of these lines can be determined as primary reference standards. The electrical measurement capabilities provide S-parameter measurements of one- and two-port devices fitted with 1.35 mm coaxial connectors. These measurement systems have been validated through participation in inter-laboratory measurement comparison exercises.

The work on waveguide traceability has 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 enables traceable measurements to be made in these three bands. Uncertainty evaluation techniques have also been established. The new calibration and uncertainty evaluation techniques have been validated through participation in three measurement comparison exercises.

This objective has been successfully achieved.

Traceable planar S-parameter measurements to 1.1 THz (objective 2)

Significant progress has been made towards extending the traceability for on-wafer measurements to up to 1.1 THz. The successful development of the reference calibration substrate has enabled the first-of-a-kind interlaboratory comparison in on-wafer measurements covering frequencies from 110 GHz to 1.1 THz. The measurement campaign included the comparison of verification standards such as a mismatched transmission line, attenuator, and a range of one-port devices. Three European NMIs, two universities, and one leading RF equipment manufacturer participated in the comparison exercise.

A reference calibration substrate, based on 3-inch semi-insulating high resistivity Silicon (Si) wafer, has been manufactured with eight identical dies being produced. Each die included 34 calibration and verification standards for measurements up to 1.1 THz. The reference values and corresponding uncertainties for each CPW standard have been estimated using electromagnetic (EM) simulations. The measurement comparison provided useful information about the usage of such EM simulations for the assessment of CPW device uncertainties up to 1.1 THz.

On-wafer multiline TRL (mTRL) was identified as the best choice for calibrations of millimetre-wave and THz VNA measurement systems. Various calibration methods have been investigated, and it was found that off-wafer calibrations are generally problematic above 100 GHz. The measurement campaign validates the applicability of mTRL calibration up to 750 GHz, beyond which the calibration accuracy seems to degrade and requires future investigations. High-frequency on-wafer measurements are significantly affected by probing accuracy, and therefore automated probing techniques have been developed for reproducible and operator-insensitive measurements with low uncertainties. These methods have been embedded into dedicated software for automated on-wafer probing.

Sources of uncertainties in on-wafer measurements have been studied to assess measurement uncertainty up to 1.1 THz. Measurement and simulation-based methods have been investigated for quantifying uncertainty sources. This led to the combined uncertainty estimates up to 330 GHz using the comprehensive uncertainty budget with the improved CPW model and measurements-based assessment of uncertainty sources. The second method relies strongly on EM simulations for assessment of the uncertainty contributions up to 1.1 THz. The comparison results up to 330 GHz agree well with the estimated measurement uncertainties. At the same time, the measurement comparison results from 330 GHz to 1.1 THz show moderate agreement with the estimated uncertainties. The co-variance-based uncertainty propagation method has been embedded in software for on-wafer calibration and uncertainty calculations.

This objective has been successfully achieved.

Traceable power measurements to 750 GHz (objective 3)

Three different types of waveguide calorimeters have been developed, fabricated, and characterised by LNE, NPL and PTB at three different locations for use in the 110 GHz to 170 GHz band. Different calibration principles for each type have been investigated, and they are multiple offset-short method (PTB), flush-short method (NPL) and VNA method (LNE). To validate these methods, microcalorimeter measurements have been carried out using two different types of power sensors (thin film thermistor sensors and thermoelectric sensors).

The thin film bolometric power sensors and the thermoelectric sensors have been mainly designed and manufactured by the University of Birmingham (BHAM) and Rohde and Schwarz GmbH & Co. Kommanditgesellschaft (R&S), respectively. The designed sensor demonstrated reasonable performance with a return loss of better than 15 dB across the entire 110-170 GHz band and a rise and fall time better than 1.8 ms. High power linearity between −10 and +8 dBm has been achieved. The power sensor has been characterised in the microcalorimeter, to have an effective efficiency of over 90%. The measurement results confirmed that these sensors provide decent efficiencies. A journal paper describing the design, fabrication, and characterization of a D-band (110–170 GHz) bolometric power sensor, used for millimetre-wave metrology has been published in IEEE Transactions on Instrumentation and Measurement [21].

Seven prototypes of the thermoelectric power sensor have been designed, optimised, and delivered by R&S. Six of them were calibrated in the waveguide calorimeters, two at PTB, two at LNE and two at NPL. Measurement comparison of the seventh prototype has been performed. The three laboratories measured thermoelectric power sensors from 110 GHz to 170 GHz to demonstrate equivalence and the results showed good agreement (i.e. suitable for use as power transfer standards to establish traceability for end-users). The measured effective efficiencies using microcalorimeters were changing from 0.629 to 0.874 and the uncertainties were calculated to be from 1.2% to 9.5% depending on the measurement methods and transfer standards. The interlaboratory measurement comparison was presented at the IEEE International Microwave Symposium 2022 [22].

Free-space power measurement setups based on pyroelectric detectors have also been developed, fabricated, and characterised for use in the 110 GHz to 170 GHz band (by PTB) and 500 GHz to 750 GHz band (by METAS). Measurements using the pyroelectric power sensors have been performed at 110 GHz to 170 GHz band with the thermoelectric power sensor supplied by R&S. Analysis work has been performed and decent results have been obtained in terms of a good agreement in calibration factors.

Finally, a comparison of power measurements has been performed by NPL, WAT, GUM, LNE, TUBITAK using the transfer standard R&S 900014 calibrated by PTB for the frequency range from 110 GHz to 170 GHz and the commercially available Erikson power meter PM5 provided by VDI for the frequency range from 500 GHz to 750 GHz. Good agreement in results has been achieved by all participants.

This objective has been successfully achieved.

Traceable material measurements to 750 GHz (objective 4)

Three different material measurement techniques have been studied and they are VNA-based systems, optical-based systems (Time-Domain Spectrometer TDS and Frequency-Domain Spectrometer FDS), and resonator-based narrowband systems.

The VNA-based setups at NPL and METAS use novel commercially available material characterisation kits (MCKs) provided by SWISSto12. MCKs provide quasi-TEM mode in the air gap between two antennas where the MUT is inserted. The mode converters are very compact, and measurements are easy to perform. New calibration methods (e.g. TRL) and extraction of material parameters techniques have been developed and verified through a measurement comparison exercise. Uncertainty evaluation on the material parameters has been implemented.

Optical setups have been developed, characterised, and used for the measurement of specimens. At least one robust data extraction method has been implemented by each partner. Two methods to calibrate the frequency axis have been proposed and compared with each other. A calibration artefact was calibrated by the frequency traceable THz FDS at METAS. The linearity of the amplitude measurements for optical setups has been tested and quantified. The resonator-based setups have been installed at GUM and NPL, and methods for the extraction of material properties have been developed.

The comparison of material properties measured by the above three different systems and setups has been completed and published as the EURAMET Comparison #1514. A good agreement between different participants has been observed for most samples. More significant deviations have been observed from samples including doped silicon, thin high-resistivity silicon and UHMW. For these samples, better results could be achieved by utilising improved calibration methods and parameter extraction techniques.

This objective has been successfully achieved.

Impact

Considerable efforts have been made to maximise the impact of this project within the European community of stakeholders and industrial end-users, and to ensure dissemination to, and uptake by, industry, academia, European and non-European National Metrology Institutes (NMIs) and standardisation bodies.

A range of activities have been undertaken to create impact from this project, and some highlights are described below.

- This project has produced 29 open access peer-reviewed scientific papers and technical reports, of which 14 are published in high impact journals including *Metrologia, IEEE Transactions on Instrumentation and Measurement*, *IEEE Transactions on Terahertz Science and Technology*, *IEEE Microwave and Wireless Components Letters*, *Journal of Infrared Millimeter and Terahertz Waves, Applied Sciences*, and *Metrolog*y. Additionally, 5 peer-reviewed papers have been accepted for presentation in major international conferences (i.e. 4 by CPEM 2022 and 1 by 99th ARFTG), 1 paper has been accepted for publication in *Journal of Infrared Millimeter and Terahertz Waves*, and 3 papers have been drafted/submitted to prestigious IEEE journals. In summary, research undertaken in this project has led to 36 peer-reviewed scientific papers, and among them 11 are joint publications.
- This project has been presented 25 times at conferences such as Conference on Precision Electromagnetic Measurements (CPEM), Microwave Measurement Symposium/Conference (ARFTG), IEEE International Microwave Symposium (IMS), International Conference on Electromagnetic Metrology (ICEM), IEEE International Conference on Smart Instrumentation, Measurement and Applications (ICSIMA), International Conference on Infrared, Millimeter, and Terahertz Waves (IRMMW-THz), International Conference on Electromagnetics in Advanced Applications (ICEAA), Asia-Pacific Microwave Conference (APMC), IEEE Workshop on Signal and Power Integrity (SPI), etc.
- Three one-day workshops have been held as part of premier international conferences: (i) One is entitled “Measurements at mmWave and Terahertz Frequencies of Three Measurement Quantities: S-Parameters, Power, and Complex Permittivity of Dielectric Materials”, at the European Microwave Week (EuMW) 2020; (ii) One is entitled “Research in Power and S-parameters Measurement at mmWave and Terahertz Frequencies”, at the EuMW 2021; and (iii) One is entitled “Recent developments in millimetre-wave measurement: S-parameters and material properties”, at the EuMW 2022. All these three workshops were about the outputs of this project, and the speakers were from either the consortium or its Technical Advisory Group (TAG).
- The consortium has also organised two training courses, one in July 2021 and the other one in July 2022. The training courses were held online, and each course included seven technical presentations covering all the technical work carried out under this project. Both courses were very successful, e.g. the first one was attended by more than 110 participants globally.
- This project has created a website for end users at http://projects.lne.eu/jrp-temmt/. Useful information such as publications and training course presentation slides has been made available on the website, which will exist beyond the lifetime of this project.
- Four teleconferences with the TAG have been held every nine months during the lifetime of this project. TAG members are a group of 16 experts in the project’s scientific areas.
- An EURAMET pilot study entitled “Comparison on material parameter measurements in the THz spectral range with optical, resonant and VNA based setups” has been launched as part of this project. A comprehensive report has been produced based on this pilot study and published with open access on EURAMET’s website.
- This project has provided inputs to a range of international standards committees including IEEE MTT/SCC P287, P2822, P1785, P3136; IEC TC46 and SC46F.

Impact on industrial and other user communities

This project enables 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 the 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.

This project has also significantly extended 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 set up a Technical Advisory Group, formed of members from the 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, and 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 the M9 project meeting, in October 2020 alongside the M18 project meeting, in July 2021 alongside with the M27 project meeting, and in July 2022 alongside the M39 project meeting.

Impact on the metrology and scientific communities

No single NMI currently has the capability to deliver this project, therefore, this project involved eight of Europe's NMIs and will synergise their national research programmes. During the project, preparatory tasks have been 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 has also fostered 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 has been 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 involved four NMIs (i.e. GUM, LNE, METAS and NPL), and hence such activities have enhanced collaborations between these, and other, NMIs across Europe. The consortium has produced a proposal about a coordinated network of European NMIs that will provide comprehensive measurement capability at millimetre-wave and THz frequencies, developed a roadmap for the network, and submitted the report to EURAMET for consideration.

Impact on relevant standards

This project has so far provided inputs to seven standardisation bodies, i.e. **IEEE MTT/SCC P287** "Standard for Precision Coaxial Connectors (DC-110 GHz)"; **IEEE MTT/SCC P2822** "Recommended Practice for Microwave, Millimeter-wave and THz On-Wafer Calibrations, De-Embedding and Measurements"; **IEEE MTT/SCC P1785** "A New Standard for Waveguide Above 110 GHz"; **IEEE MTT/SCC P3136** "Universal Waveguide Interface for Frequencies of 60 GHz and Above"; **IEC/TC 46** "Cables, Wires, Waveguides, RF Connectors, RF and Microwave Passive Components and Accessories"; **IEC/SC 46F** "RF and Microwave Passive Components"; and **DKE/UK 412.4** "Passive RF and Microwave Components".

IEEE MTT/SCC P287 has recently published three standards, i.e. IEEE Std 287.1-2021, IEEE Std 287.2-2021, IEEE Std 287.3-2021, in which the E-band 1.35 mm coaxial connectors are included.

A EURAMET report document has also been produced regarding materials property measurements within the range of 110 GHz to 750 GHz. Additionally, the project results will be fed into other standardisation bodies such as the BIPM Key Comparison Database and the BIPM database of CMCs.

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 a 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.

Examples of user uptake

Outputs of this project have already been utilised by end-users in industry and academia, as shown below a few notable examples.

- 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. Other component manufacturers who are not part of the project consortium also benefit from the 1.35 mm E-band coaxial connector work in their designs of calibration standards.
- 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. Next, these NMIs will work towards adding these capabilities as Calibration and Measurement Capability (CMC) entries in the BIPM key comparison database to provide metrological traceability for this new coaxial line size.
- Based on the outputs of this project, NPL is now preparing to launch on-wafer S-parameter measurements as a new measurement service. There has been no such service before this project at NPL. PTB is now extending the existing on-wafer calibration and measurement service to frequencies above 110 GHz.
- NPL has developed the bespoke TRL calibration technique for the material characterisation kits (MCKs) with support from the manufacturer SWISSTO12. The manufacturer has been looking at including this new calibration method as one of the recommended default calibration methods.

List of publications

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<table>
<tr><td colspan="2">Project start date and duration:</td><td>01 May 2019, 39 months</td></tr>
<tr><td colspan="3">Coordinator: Xiaobang Shang, NPL Tel: 020 8943 6643 E-mail: xiaobang.shang@npl.co.uk
Project website address: http://projects.lne.eu/jrp-temmt/</td></tr>
<tr><td>Internal Funded Partners:
1. NPL, United Kingdom
2. CMI, Czech Republic
3. GUM, Poland
4. LNE, France
5. METAS, Switzerland
6. PTB, Germany
7. TUBITAK, Turkey
8. VSL, Netherlands</td><td>External Funded Partners:
9. BHAM, United Kingdom
10. Chalmers, Sweden
11. FVB, Germany (withdrawn from January 2021)
12. ULILLE, France
13. WAT, Poland
14. FBH, Germany (joined January 2021, follow-up for FVB)</td><td>Unfunded Partners:
15. Anritsu, United Kingdom
16. FormFactor, Germany
17. INTI, Argentina
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<tr><td colspan="3">RMG -</td></tr>
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