Publishable Summary for 19NRM02 RevStdLED
Revision and extension of standards for test methods for LED lamps, luminaires and modules

Overview

LED-based lighting products are the most rapidly evolving light sources on the market for general lighting in urban areas or domestic dwellings. Due to spectral and geometrical peculiarities, SI traceable measurements of LED-based light sources are much more difficult than those of traditional tungsten filament lamps or fluorescent light sources. This makes it difficult for test laboratories to evaluate application-relevant properties using existing measurement methods and standards developed for incandescent light sources. Standards for traceable test methods exist but important metrological aspects for their practical application had not yet been fully considered before this project. For example, the assessment of uncertainty, intensity distributions of luminaires as well as spectral measurements, had yet to be resolved. This project identified essential test parameters, develop validated procedures and good practice guidelines for test laboratories and helped to shape the upcoming revisions of CIE S 025/E:2015, ISO/CIE 19476:2014 and EN 13032-4 standards.

Need

Reliability and validity of product specifications are of great importance in the general lighting market, which is unsettled by unfulfilled performance promises of cheap lighting products. Trust can only be rebuilt if test laboratories can deliver reliable SI-traceable test results of photometric quantities, which meet the demands of industry and customers, for a large range of diverse LED-based light sources. Statements on uncertainty assessment to improve the evaluation of LED products became mandatory in the first worldwide accepted standards CIE S 025/E:2015 and EN 13032-4 on test procedures for LED based lamps, luminaires and modules published by the International Commission on Illumination (CIE) and the European Committee for Standardization (CEN). However, these standards are incomplete, as there was still no validated procedure available to assign measurement uncertainties, at test laboratory level, for some listed measurement quantities and metrological procedures.

Requirements and boundary conditions for precise image-based luminance measurements and concepts for evaluating the uncertainty of typically correlated spectral measurement data are of high importance for test laboratories to determine the real performance of LED-based sources. Although prerequisites for the application of the standards are well established, respective guidelines were not available. Moreover, a suitable harmonised metric including associated tolerances for a target/actual performance comparison of luminous intensity distributions of LED-modules or luminaires was also missing.

Photometers are ubiquitous metrological devices in lighting, being used by a wide range of lighting professionals from designers to electricians, for testing installations on performance, compliance and utility. But these meters typically include significant errors that cannot be neglected, namely in the measurement of LED-based lamps. To estimate the spectral mismatch of the response of the photometers (in relation to standardised efficiency of the human eye) within a measurement setup, the so called f_1' index defined in ISO/CIE 19476:2014 can be used according to EN 13032-4. However, the metric i.e., the mathematical equation for determining f_1' is deemed to be not the most appropriate for LED light sources. Therefore, for the revision of ISO/CIE 19476:2014, CIE S 025/E:2015 and EN 13032-4, it had to be clarified under which conditions the mismatch index can be used in the measurement of LED light sources in the future and how the newly defined LED reference spectrum can be integrated here.

The CIE identified these issues as being part of their research priorities.

Objectives

The overall goal of the project was to deliver metrics and procedures as well as guidance on metrology issues, and to made existing CIE and CEN test standards for LED-based light sources applicable to testing laboratories as a whole. The specific objectives were:

1. To develop a strategy for the evaluation, validation and traceability of spatially and angularly resolved luminance and luminous intensity distributions of LED-based lamps, luminaires, and modules. This should be based on measurements using imaging luminance measurement devices (ILMDs). Additionally, to develop guidelines on the determination of uncertainty and tolerance intervals required in the revision of CIE S 025/E:2015.
2. To develop guidelines on the estimation and uncertainty of i) the spectral mismatch of integral (filtered) measurements for sources emitting coloured light, and ii) integral quantities derived from spectral measurements. Additionally, to propose an extension of CIE S 025/E:2015 and EN 13032-4 for an alternative spectral mismatch quality index, based on the new LED reference spectrum published in CIE 15:2018 for white LEDs.
3. To propose a harmonised metric to compare luminous intensity distributions, including the definition of the associated tolerance intervals and uncertainties, with a focus on test methods that require the declaration of measurement uncertainties.
4. To contribute to the revision of CIE S 025:2015 / EN 13032-4 through CIE Division 2, CEN/TC 169 and IEC TC 34. Outputs should be in a form that can be incorporated into the standards at the earliest opportunity and communicated through a variety of media to the standards community and to end users. Additionally, to promote the take up of the results by end users e.g. manufacturers of LED-based sources.

Progress beyond the state of the art

The ability to indicate light distributions and tolerances based on reliable measurement uncertainties, is a prerequisite for the comparison of different lighting products with respect to their use in different applications. The strategy developed in this project for the evaluation, validation and traceability of spatially and angularly resolved luminance measurements with luminance cameras was based on an application-oriented separation between uncertainties based on user-accessible luminance data and system-related uncertainty contributions that must be claimed from manufacturers in order to provide generalised but application field-specific solutions for traceability.

The spectral mismatch of photometers often leads to unexpected errors when measuring LED sources. Using array spectroradiometers instead of photometers is an option, but this often fails due to unknown correlations in the measurement chain, when uncertainties of a few percent are required. To make the occurrence of correlations visible to users of reference instruments, participating laboratories started to identify correlations in their traceability chain, to provide this information to their customers with guidelines and methods for further use. A procedure was tested and made available to provide information about the most likely impact of (hidden) correlations on the uncertainty of integral quantities derived from spectral measurements even if no correlations are explicitly declared. The method is based on a Monte Carlo simulation in which orthogonal basis functions are added to the spectral distribution to be measured, weighted by the uncertainties of the spectral data. In this way, it is possible to provide estimates of the uncertainties of spectrally integrated quantities on the user side, even if the calibration laboratory does not provide an explicit correlation matrix.

For white light, it turned out that the idea of an alternative spectral mismatch quality index would be only of little use. Instead, the ability to use additional calibration reference spectra, e.g. based on the new LED reference spectrum L41, which has been published in the meantime by CIE in addition to Illuminant A, would extend the scope of application and enables the user to classify the performance of photometers used for measurements of non-tungsten-filament lamps.

This project developed a generic metric that describes the symmetry, envelope and size of the light distribution produced by LED lamps, modules and luminaires via a set of defined parameters. This project built open-access software tools that are available on GitHub to provide calibration laboratories with an easy entry into uncertainty assessment based on Monte Carlo methods. The latter are necessary to provide reliable and traceable measurement results for complex photometric and radiometric measurands.

Results

Evaluation, validation and traceability of spatially and angularly resolved luminance and luminous intensity distributions

A survey on the metrological requirements of luminance measurement using ILMDs was conducted amongst the partners to identify the metrological peculiarities in a variety of applications. A tabular list of more than thirty application entries was generated, including parameters relevant for characterisation and measurement uncertainty. From this table, a list of 11 main applications was generated and annexed to a Good practice Guide (GPG), which was written in the project and included examples of the evaluation region in exemplary luminance images. Information on these main applications included, where necessary, the quality indices to be considered according to the technical report CIE 244:2021 "Characterization of imaging luminance measurement devices (ILMDs)", published in May 2021, with members of the consortium as authors.

The partners developed an internal model of evaluation and implemented calibration procedures for ILMDs that parametrise this model including the handling of corrections for uncertainty components like non-linearity, shading and change of the focus distance. These experiments provide insights on non-linearity contributions originating in the interaction of the charge accumulation of the sensor and the I-V curve of the pixel diode itself and the spectral dependence of the charge generation profile inside the pixel. From these internal calibration procedures, critical measurement conditions could be derived, where for ILMDs that are used “as is” the largest residual uncertainty contributions can be expected, despite internal corrections implemented by the manufacturer. Another result was the insight that the determination and parametrisation functions that describe the residual error contributions and their application as second stage of corrections will be very error-prone to be done by the user of an ILMD without knowledge on device internals (“black-box” approach). Therefore, the decision was made to not correct for residual errors but determine their maximum error for specific contributions and handle them as uncertainty contributions covering the not corrected residual errors.

The most relevant contributions were selected and the methods for the estimation of their uncertainty contribution were collected in the first part of a GPG on handling of uncertainties of ILMD measurements that focuses on contributions coming from the ILMD itself. The application of these estimation methods is demonstrated on the examples of the application list. A second part of the GPG gives advice on extended aspects and handles uncertainty contributions that originate from the scene or the device under test.

The objective of providing methods for traceable spatially and angularly resolved luminance and luminous intensity distributions for the general user of ILMDs has been achieved from the general user's point of view, whereby the user is responsible for recording the influences of these deviations from the manufacturer's calibration conditions in the context of test measurements and adding them to the manufacturer's uncertainty budget as an uncertainty component.

Guidelines on the estimation and uncertainty of the spectral mismatch and integral quantities derived from spectral measurements.

The consideration of the (often complex) correlations within spectral measurement data in the calculation of integral quantities is essential. With the aim to harmonise the different approaches used by participating NMIs, reports and internal tutorials on the treatment of measurement uncertainties using Monte Carlo simulations, as well as software code for the consideration of correlations written in Python, were developed and shared within the consortium. These libraries and the software tools provided by the consortium for measurement data analysis have been continuously updated during the project and made available on the development platform GitHub (https://github.com/empir19nrm02). In order to share information stakeholders, a summary report on current and future calibration strategies of the NMIs and DIs involved in the survey was published to the download area of the project website and a guideline for the development and distribution of correlation matrices has been prepared. A GPG for calibration laboratories was developed. This includes the creation of models of evaluation, the minimum requirements for test setup and detailed working procedures as the basis for a sound uncertainty budget. To setup a strong link with the chief stakeholder, a member of the project consortium was selected to chair the new technical committee CIE TC 2-97, established in May 2022, to revise the CIE standard CIE S 025. Moreover, it was achieved that the revision of CEN standards EN 13032-4, which is based on the CIE S 025, is set on halt until the revision of the CIE S 025 is close to final. This is important to ensure that both the international CIE S 025 and the European EN 13032-4 remain harmonised. In the spring of 2022, a new working group was established at the CIE Division Management level, which includes CIE Division 2 Board, Consortium members of 19NRM02 RevStdLED, and the TC Chair who is responsible for CIE S 025. This group structures the work on the most significant questions on how to make uncertainty evaluation in CIE S 025 usable for end-users. In this context, it is planned to continue to constantly update the software code on the GitHub repository even after the end of the this project.

In order to compare the results of spectrally based photometric quantities measured in partner laboratories taking into account correlations, an interlaboratory comparison was performed with six LED-based standard lamps. The results of the chromaticity coordinates of the LED lamps and their uncertainties were determined for the first time not only according to the classical GUM (JCGM 100:2008) as independent coordinates, but correctly taken as multivariate quantities (JCGM 102:2011), to which an approach for determining the 2-dimensional degree of equivalence (DOE) was provided.

A document describing the rationale for a complementing spectral mismatch index for LED light sources, which also discusses the potential impact on existing applications and measurement uncertainty calculation, was published at the CIE midterm meeting 2021. The results of the work have been forwarded to the i) CIE reportership DR 2-89 on the "Definition of a complementary general $V(\lambda)$-mismatch index" and to ii) Technical Committee TC 2-96. These two committees are chaired by members of the project’s consortium and were both established within CIE Division 2 in early 2021.

The outcome of the investigations on the mismatch index are summarised in conference proceedings and peer reviewed journals. The most unexpected result is that there will be practically no benefit from redefining the metric of the general spectral mismatch index f_1', but it would make a large difference if the calibration source, which is currently defined as Illuminant A only, will be changed to Illuminant L41. All calculations are based on a large data set which also includes data from 15SIB07 PhotoLED (see: https://doi.org/10.11583/dtu.12783389.v1) and can be retraced using the freely accessible software and data via the EMPIR 19NRM02 GitHub project (https://github.com/empir19nrm02).

The objective of establishing guidelines for the estimation and uncertainty of spectral mismatches and integral quantities derived from spectral measurements has been achieved. It has been shown that the consideration of partial correlations (spectral as well as general) and the use of Monte Carlo methods are crucial for meaningful uncertainty determinations. Particular attention was paid to partial correlations, as their influence was completely underestimated in the past. A documented software code was also provided to promote the adoption of the guidelines.

The investigation of the spectral mismatch index revealed no need to define a complementary index for LEDs. The results were passed on to the standardisation committees. Harmonised metric for luminous intensity distribution

As a prerequisite to describe spatial distributions of light, a model for geometrical dependencies of a generic goniophotometer was developed and was presented at the NEWRAD (2020) meeting and at the CIE midterm meeting in 2021. In this model, the description of coordinate systems and relations between goniophotometer pose, source and detector are described by Denavit Hartenberg (DH) parameters. The propagation of the geometric uncertainties including correlations takes place by consecutive transformation of the coordinate systems of the source and receiver in relation to a device coordinate system.

The final results of the geometric analysis for the case of ILMD-based luminous intensity distribution (LID) measurements using Monte-Carlo simulations have been published as a peer reviewed paper in the conference series of the Journal of Physics (see: List of Publications, 1).

Based on the findings published in the article, further investigations were carried out on the influence of the centre of light on the uncertainty of the spatial luminous intensity distribution. For this purpose, the LID standards developed in the project were measured with their describable characteristic LIDs on different goniometer methods.

It turned out that the exact knowledge of the actual centre of light is necessary to apply the model for the propagation of the geometric uncertainties. However, this centre of light can only be traced back from the collected measurement data in case of near-field goniometers. This raises the problem that measurement uncertainties of the LID cannot be determined for far-field goniometers without in-depth knowledge about the LID itself. In order to make the model of geometric dependencies applicable to general goniometers, a tutorial was created within the EMPIR 19NRM02 GitHub project, which visualises the influence of the centre of gravity of light on a LID via an interactive Python-based notebook.

In summary, it can be said that a harmonised metric for light intensity distributions has been developed, but this can only be used without restriction for camera-based near-field goniophotometers. For classical far-field goniophotometers, the quality of the uncertainty analysis depends on the estimation of the centre of light.

Impact

To increase visibility, the project website (https://www.ptb.de/empir2020/revstdled) was created shortly after the start of the project.

As the dissemination of results to CIE as the chief stakeholder was of utmost importance, the project focused on the establishment of reporterships and technical committees in CIE under the leadership of partners and collaborators of this project. In addition, various members and collaborators of the consortium are also members of the relevant committees of the national standardising bodies and thus promote the dissemination of the project results to the corresponding bodies at ISO and CEN via national representatives.

The project participated in several national and international conferences, and the works were shared in a total of 21 presentations/posters. Targeted Conferences included Licht2021 and the CIE Mid-Term Conference 2021. A total of 12 posters and oral presentations were given at the latter, including a general overview of the project and two oral presentations at a CIE workshop on the revision of ISO/CIE 19476 and CIE S 025 led by the RevStdLED project coordinator. The status of the work in the project's work packages was presented at the first RevStdLED stakeholder meeting, which took place on 7 October 2021 with 11 stakeholders from UK, Belgium, Italy, Austria and Germany.

In addition to these dissemination activities, the project regularly informed other key stakeholders of the project, such as the chief stakeholder CIE Division 2, EURAMET TC-PR, DIN and CEN/TC 169/WG 7, through their contact persons and at their annual meetings. In this context, the mismatch index f1' (as described above) was discussed with stakeholders during the TC 2-96 Technical Committee meeting (responsible for the revision of ISO/CIE 19476) at the Division 2 Conference in Athene, Greece, in Oct. 2022. During the runtime of the project, posters and oral presentations were also submitted and accepted for the NEWRAD conference in Sept. 2023, and the 30th CIE Quadrennial meeting in Sept. 2023.

Additionally, 4 open-access peer-reviewed papers have already been published and 3 more have been approved and submitted for publication.

Impact on industrial and other user communities

Since tungsten filament lamps were banned, LED based lighting products are the general lighting market's most rapidly evolving light sources. Test laboratories are therefore faced with a wide variety of different LED based light sources, for which reliable test results based on SI traceable measurements of photometric quantities are required to meet the demands of industry and have not yet been comprehensively developed. Standards CIE S 025/E:2015 and EN 13032-4 pave the way to improve the quality of lighting products by introducing the concepts of measurement uncertainty declarations and acceptance intervals, as mandatory requirements in test standards for LED based light sources. However, procedures to determine uncertainties especially if spectral measurements take place were missing. This project filled the missing gap and provided the appropriate procedures and the distinctive guidance necessary for a full implementation of the standards on test laboratory level.

For testing laboratories, luminance is increasing in significance for instance in relation to glare. As the use of the LED becomes ubiquitous, considerations of luminance distribution increases in significance, for instance for arrays of bright LEDs. Traceability of luminance measurements is important to gain the confidence of the market. The developed techniques and procedures were shared with industry and test laboratories at stakeholder meetings and workshops organised within this project.

To promote uptake of the project's outputs by the industrial and other communities, the project delivered the following training activities:

i) May 23-24, 2023, at PTB Braunschweig, Germany: A two-day hands-on training course on measurement with and characterisation of ILMDs. The training was attended by 28 participants from industry, universities and NMIs.

ii) July 24, 2023: A one full day online training on uncertainty determination of spectrally integrated quantities. 10 presentations on measurement uncertainty, Monte Carlo simulation, Python and Matlab implementations, the use of the projects GitHub repository and information on Basis Function technique and 2-dimensional DOE were given. In total 60 participants from industry, university, NMIs and calibration laboratories registered for this training.

iii) August 22-23, 2023, at TUBITAK, Türkiye. A two-day hands-on training on spectral measurement methods for photometric quantities. The training was attended by 23 participants from industry and NMIs. The aim of this training was to deepen the techniques presented in the online training in practice.

Participation in the training courses was advertised via EURAMET, the project website and also via the LinkedIn entries of the project partners.

Impact on the metrology and scientific communities

Since the adoption of the Guide to the Expression of Uncertainty in Measurement (GUM), the reliable determination of uncertainties is a main aspect in scientific metrology. However, in the field of testing, the use of uncertainty calculations is mostly disregarded because it is expected that any uncertainties will be covered by appropriate allowed tolerances given to the measured quantities. In many cases, this is highly justified. But in cases where the influence of details in the measurement setups on the magnitude of quantities is high, the consideration of uncertainties even in testing environments are necessary. To address this, the consortium provided a special training course (listed above in ii) where test laboratories staff was invited to give participants a deep insight not only into measurement procedures and appropriate models for the evaluation of measurement uncertainty, but also in free available software tools to establish Monte Carlo techniques that can be used in routine testing environments.

The triumph of digital cameras used for 2D-photography also paved the way for metrological cameras, so called ILMDs, used to measure 2D-distributions of light from a source or illuminated objects. This project provided calibration procedures which are published on the project website and were forwarded to the CIE so that they can be incorporated into the technical committees dealing with the revision or introduction of measurement standards. They enable fully traceable measurements in selected applications, for the first time. Thus, it fosters the entry of this innovative measuring technology into precision metrology.

CIE 198-SP2:2018 provides an analytical background for further processing of spectral data taking into account correlation. However, the analytical approach detailed here is far too complex to be useful for testing laboratories. The methods provided by this project, based on Monte Carlo simulation, are more applicable and much easier to implement with the aid of the guidelines in practical metrology that take into account the handling of correlation and metadata in future digital calibration certificates. The methods were published on the project website and made available for CIE technical committees dealing with the revision or introduction of measurement standards In addition, a procedure was made available to metrologist in photometry and radiometry to provide information about most likely impact of (hidden) correlations on the uncertainty of integral quantities derived from spectral measurements, even if no correlations are explicitly declared, e.g. based on auxiliary measurements.

Impact on relevant standards

In order to feed the work of this project into the relevant technical committees of CIE Division 2, the reportership DR 2-89 "Complementary mismatch index" was set up under the leadership of a partner of the consortium. DR 2-89 officially fed information from this project into TC 2-96 "Revision of ISO/CIE 19476:2014 "Characterisation of the performance of illuminance meters and luminance meters", which was established in March 2021. TC 2-96 is chaired by the coordinator of this project, it currently consists of 22 members from 11 countries around the world, including 9 consortium members and 2 project collaborators. Since its establishment, 11 TC meetings were held.

In addition, another partner of this consortium, who also chaired CIE TC 2-93 on the revision of ISO 23539/CIE S 010 "Photometry- The CIE System of Physical Photometry", has also been appointed to chair the CIE TC 2-97 that works on the revision of CIE S 025. Since its establishment in April 2022, 9 TC meetings were held.

Members of the consortium and its collaborators are also involved in the following technical committees and reporterships of CIE, which deal at least in part with the topics of this project:

- CIE TC 2-93: Standard on the “Revision of ISO 23539:2005(E) / CIE S 010/E:2004 Photometry - The CIE system of physical photometry”.
- CIE TC 2-90: Report on “LED Reference Spectrum for Photometer Calibration”.
- CIE TC 2-95: Report on “Measurement of Obtrusive Light and Sky Glow”.
- CIE TC 2-62: Report on “Imaging photometer-based near-field goniophotometry”.
- CIE TC 2-86: Report on “Glare Measurement by Imaging Luminance Measurement Device (ILMD)”
- CIE TC 2-89: Report on: “Measurement of Temporal Light Modulation of Light sources and Lighting Systems”.

CIE TC 2-86: Report on Glare Measurement by Imaging Luminance Measurement Device (ILMD). As an example for ILMDs, project partners are involved in CIE TC 2-86 which is dealing with glare evaluation using ILMDs and in CIE TC 2-95 which is assembling an application list regarding measurement of obtrusive lightusing e.g. ILMDs.

As mentioned above, the international standard CIE S 025/E:2015 is up for its first revision and this project aims to increase its uptake by test laboratories by proposing revisions that will aid testing in routine test environments, thereby increasing its scope, to include commonly used methods and equipment, and improved guidance for the estimation of uncertainties for laboratories. As CEN/TC 169/WG 7 will postpone the revision of the European standard EN 13032-4, until the CIE S 025 is revised, there is a good chance that both standards will be harmonised again. Resulting from planned regular consultation and exchanges between the consortium and standards organisations CIE and CEN (via national representatives), most of the guidelines and procedures that have been developed in this project are suitable for direct use by the respective standardisation committees. In the meantime, CIE has formed TC 2-97 to revise the CIE S 025 standard, with this project specifically mentioned in the CIE Division 2 proposal as a stakeholder for TC 2-97. The chair of TC 2-97 was in turn an active member of this consortium, and other partners in the consortium have signed up for membership in the TC. In addition, the partners continued to seek memberships in other relevant technical committees established at CIE and CEN to support the publication of revised and new standards.

Some members of the American Illuminating Engineering Society (IES), responsible for the standard IES LM-79-19, are also members of the new CIE committee on the revision of the CIE S 025. So the outcomes of this project, which have been forwarded to CIE, will also have influence on the next revision of the IES LM-79.

By improving metrological transparency and trust, the project results support EU regulatory initiatives on lighting products, specifically the European Union's energy labelling and ecodesign requirements applied to lighting product, which came into force in September 2021.

Longer-term economic, social and environmental impacts

The confidence in the performance of lighting products relies on the reliability of test procedures provided by standards such as the CIE S 025/E:2015, which must cover the full spectra of product capabilities to provide reliable test results. Appropriate standards and test procedures will provide consumers and end-users with reliable information, so that they are able to choose and purchase products which best fit to their applications. Consumers will have better characterisation on which to base purchase decisions, thus helping avoid dissatisfaction and reducing unnecessary environmental waste and increasing product satisfaction in the longer term.

Using innovative instrumentation (such as ILMDs) supported by updated standards for characterisation and testing will allow more reliable and comprehensive product specifications, so that requirements for light installations due to current and future regulations can be more easily met. In the longer term, this will improve urban lighting and reduce unnecessary light emission also known as light pollution and obtrusive light.

List of publications

1. Kantona M., Trampert K., Schwnengel C., Krüger U., Neumann C. (2022); “Geometric system analysis of ILMD-based LID measurement systems using Monte-Carlo Simulation”; Journal of Physics: Conference series 2149; https://doi.org/10.1088/1742-6596/2149/1/012015
2. Ferrero, A., & Thorseth, A. (2021). IMPACT OF THE NORMALIZATION OF THE SPECTRAL RESPONSIVITY ON THE PERFORMANCE OF THE GENERAL V() MISMATCH INDEX, Proceedings of the Conference CIE 2021 CIE - International Commission on Illumination; https://orbit.dtu.dk/en/publications/impact-of-the-normalization-of-the-spectral-responsivity-on-the-p
3. Krüger, U., Ferrero, A., Mantela, V., Thorseth, A., Trampert, K., Pellegrino, O., & Sperling, A. (2022). Evaluation of different general V(λ) mismatch indices of photometers for LED-based light sources in general lighting applications. *Metrologia*, *59*(6), 065003. https://doi.org/10.1088/1681-7575/ac8f4d
4. Krüger, U., Ferrero, A., Thorseth, A., Mantela, V., & Sperling, A. (2023). General V(λ) mismatch index: History, current state and new ideas. *Lighting Research and Technology*, *55*(4-5), 420-432. https://doi.org/10.1177/14771535231158528

This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/

Project start date and duration:	1 September 2020, 36 months	
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Internal Funded Partners: 1. PTB, Germany 2. Aalto, Finland 3. CSIC, Spain 4. IPQ, Portugal 5. LNE, France 6. TUBITAK, Türkiye	External Funded Partners: 7. DTU, Denmark 8. KIT, Germany 9. NSC-IM, Ukraine	Unfunded Partners: 10. candelTec, Spain 11. JETI, Germany 12. NMISA, South Africa 13. TechnoTeam, Germany
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