Publishable Summary for 22IEM05 NEWSTAND
New calibration standards and methods for radiometry and photometry after phaseout of incandescent lamps

Overview

It is important to have an accurate understanding of the spectral irradiance of the optical radiation produced by light sources in a multitude of applications. Therefore, the SI traceability of spectroradiometric measurements needs to be ensured. For decades, the calibration of spectroradiometric measurement instruments has been realised using incandescent lamp-based transfer standards. However, their availability is diminishing due to a production phaseout of incandescent lighting products. This project aims to provide adequate and affordable replacement transfer standard light sources and alternative procedures for the detector-based transfer of the spectral irradiance unit in the ultraviolet-visible-near infrared (UV-VIS-NIR) spectral range. It also aims to establish an integrated European metrology infrastructure around this key radiometric unit.

Need

Accurate knowledge of the spectral irradiance of the optical radiation emitted by artificial and natural light sources is essential in various fields of industrial (UV-curing, disinfection, photovoltaic equipment, general and horticultural lighting, etc.), environmental (solar radiation, essential climate variables, etc.), medical (sun beds, photobiological treatment, etc.) or scientific (analytical spectroscopy, plasma, etc.) applications. The range of applications requiring spectral irradiance measurements has grown dramatically in the last couple of decades due to the introduction of affordable new technology spectroradiometers, based on array detectors, and the introduction of digital capabilities for the *in situ* processing of the spectral data. The routine availability of data on the spectral characteristics of optical radiation sources is seen as one of the technological enablers for producing higher-quality products, information and services.

Traceable spectral measurements of optical radiation are also required for the enforcement of many European regulations, directives and standards aimed at protecting the population against deleterious factors and sustainable energy use (DIRECTIVE 2006/25/EC, “on the minimum health and safety requirements regarding the exposure of workers to risks arising from physical agents (artificial optical radiation) (19th individual Directive within the meaning of Article 16(1) of Directive 89/391/EEC)”, Commission Regulation (EU) 2019/2020 "EcoDesign for light sources and separate control gears", EN 12464-1 "Light and lighting — Lighting of work places — Part 1: Indoor work places", EN 14255-1 to EN 14255-4 "Measurement and assessment of personal exposures to incoherent optical radiation", and EN 60335-2-27 “Household and similar electrical appliances - Safety - Part 2-27”).

Incandescent lamp-based transfer standards have been used for decades for the calibration of spectroradiometers. Certain selected types of quartz-tungsten-halogen (QTH) lamps have been applied to disseminate the spectral irradiance unit in the spectral range from 250 nm to 2500 nm. However, the market availability of such lamps, and their applicability for this metrological purpose, is diminishing due to their production being phased out following the ban on incandescent lighting by the European Commission in 2009 [DIRECTIVE 2009/125/EC OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 21 October 2009, “Establishing a framework for the setting of ecodesign requirements for energy-related products,” OJ L285, 10–35 (2009)] and by a technology change to solid-state-lighting (SSL) products. Therefore, there is an urgent need to develop alternative transfer standards using new-technology light sources, preferably with smooth

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European Partnership Co-funded by the European Union

The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

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spectra over the entire UV-VIS-NIR spectral range (Objective 1). Detector-based dissemination methods are also urgently needed as an alternative to source-based methods (objective 2). The need for new standards and traceability methods, triggered by the transition to solid-state lighting, has been expressed in research strategy papers by the European Association of National Metrology Institutes (EURAMET) [EURAMET Strategic Research Agenda for Metrology in Europe, V1.0 (03/2016), https://www.euramet.org/publications-media-centre/documents/], by the International Commission on Illumination (CIE) [CIE Research Strategy 4: New Calibration Sources and Illuminants for Photometry, Colorimetry, and Radiometry, https://bit.ly/34gDee3], and by the Consultative Committee for Photometry and Radiometry (CCPR) of the International Committee for Weights and Measures (CIPM) [CCPR Strategy Document 2022-2032, available at https://www.bipm.org/en/committees/cc/ccpr]. The new source-based transfer standards and detector-based methods developed require sound metrological validation through intercomparisons at all levels of the metrological traceability pyramid in order to demonstrate their metrological applicability for dissemination of the spectral irradiance unit with transfer uncertainties as low as 1 % (k = 2) (objective 3). Good practice guides for using the new-technology transfer standard sources and calibration procedures (objective 4) are needed to facilitate their adoption by the end user communities from the measurement supply chain (calibration and testing laboratories), standards developing organisations (CIE Division 2), technical committees (EURAMET TC PR, CCPR) and end users (manufacturers and users of spectroradiometers) and to establish an integrated European metrology infrastructure (objective 5).

Objectives

The overall objective of this project is to assure the SI-traceable measurement of spectral irradiance from natural and artificial sources of optical radiation and to develop the metrological infrastructure required for these measurements. This is necessary because the incandescent lamps, which are currently used as transfer standards, are being phased out. The specific objectives of the project are:

1. To develop new transfer standard sources for spectral irradiance in the ultraviolet-visible-near infrared (UV-VIS-NIR) spectral ranges, built on new-technology products, such as narrowband and broadband LED sources, radiant dye-coated integrating spheres, laser-driven plasma light sources (LDLS) and white-light broadband lasers, to replace current transfer standards that are based on incandescent lamps. The specific requirements for the spectral irradiance of the new standard sources are: i) well-defined and fit-for-purpose spectral and geometric properties, ii) long-term stability, iii) reproducibility, iv) robustness, and v) compatibility with existing calibration facilities. As a new approach to creating transfer standard light sources, wavelength-tuneable narrowband light sources, with a sub-nanometre spectral bandwidth will be built as well. The new standard sources should allow dissemination of the spectral irradiance unit with transfer uncertainties as low as 0.5 % (k = 2).
2. To develop novel methods to enable the detector-based traceability of spectral irradiance measurements as an alternative to the incandescent lamp-based dissemination of the unit. This will involve i) the definition of the minimum requirements for the relevant properties of (array) spectroradiometers to be suitable as transfer standards and the selection of the instruments for the work within the project, ii) comprehensive characterisation of the selected instruments for all relevant properties and their calibration with respect to the spectral irradiance responsivity, iii) development of a versatile digital twin model of a transfer standard spectroradiometer that will enable the transfer of the instruments' characterisation and calibration results to the end users' applications and it will also enable the associated measurement uncertainties to be determined under changing measurement conditions, and iv) elaborating and documenting the concept needed for the transfer of the calibration results from one spectroradiometer instrument to another.
3. To demonstrate the metrological applicability of the new standard sources and methods, developed in objectives 1 and 2, in spectroradiometric applications involving spectral irradiance measurements in at least 3 end-user sites with total uncertainties as low as 1 % (k = 2). This will be performed via interlaboratory comparisons and a measurement comparison campaign involving end user applications (i.e. solar radiation measurements, actinic radiometry, photovoltaics, lighting, and colour).
4. To develop good practice guides for the use of the newly developed transfer standard light sources, for the selection of spectroradiometers as transfer standard instruments and the respective calibration procedures, and for the use of the digital twin of the calibrated array spectroradiometers. These good

practice guides will enable the measurement methods and devices developed by the project to be implemented.

5. To demonstrate the establishment of an integrated European metrology infrastructure and to facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (calibration and testing laboratories), standards developing organisations (CIE Division 2), technical committees (EURAMET TC-PR, CCPR) and end users (manufacturers and users of spectroradiometers).

Progress beyond the state of the art and results

Developing new standard sources for spectral irradiance

Current state-of-the-art transfer standards for spectral irradiance, in the spectral range from 250 nm to 2500 nm, are either based on 1000 W quartz-tungsten-halogen lamps or on other lower-power and lower-quality lamps.

This project will develop transfer standards for spectral irradiance using new-technology light sources and other approaches for calibrating spectroradiometers in the UV-VIS-NIR spectral range. This will enable dissemination of the spectral irradiance unit with transfer uncertainties as low as 0.5 % ($k = 2$). The new-technology-based candidates include devices such as narrow- and broadband LEDs, radiant dyes, laser-driven light sources, broadband lasers, and other commercially available products. Moreover, a narrowband spectrally tuneable light source will be developed as a transfer standard for the calibration of spectroradiometers throughout the UV-VIS-NIR spectral range.

Developing novel methods to enable the detector-based traceability of spectral irradiance measurements

Common traceability chains for spectral irradiance measurements are built on light sources, which are used to transfer a spectral irradiance calibration from the primary standards to end-user applications.

This project aims to establish an alternative approach that will use compact and portable array spectroradiometers as detector-based transfer standards. This concept is based on a novel method that will employ a digital twin of a transfer standard instrument. The digital twin combines the results from extensive characterisations and calibrations of the instrument with respect to all relevant instrumental properties and a digital model. This model will enable the user to account for all of the instrument's characteristics during the measurements in their end-user applications. This will depend on their respective boundary conditions, which differ from the boundary conditions in the calibration laboratory. To enable instrument-to-instrument transfer of the calibration, respective methods and quality assurance procedures will be developed. Finally, comprehensive user guides and software code will be developed and provided to the end-user community in order to facilitate the uptake of the methods and the proper use of the transfer standard instruments.

Demonstrating the metrological applicability of the new standards and methods

This project will demonstrate the metrological applicability of both the newly developed transfer standard light sources, and the detector-based transfer standards, in different end-user applications both at calibration laboratory level and in different end-user applications. To achieve this, measurement comparison campaigns will be arranged with the goal of demonstrating spectral irradiance measurements with total uncertainties as low as 1 % when using the newly developed transfer standards and methods. Measurement comparisons involving array spectroradiometers, as transfer standards for spectral irradiance, will be a first demonstration of, and a proof of principle for, the new methods.

Developing good practice guides to enable the use of the new standard sources and methods

Currently guides and documented procedures are only available for using incandescent lamp-based transfer standards. This project will produce good practice guides that will be tailored to the end users of the newly developed transfer standards, which will be based on new-technology light sources and also for end users of the new dissemination methods, which will be based on transfer standard spectroradiometers. The good practice guides will aim to support the implementation of the project's results in the integrated European metrology infrastructure.

Outcomes and impact

Outcomes for industrial and other user communities

This project will provide new calibration standards and procedures, together with the extensive good practice guides accompanying each of the project's outcomes, for the industrial and other end users that rely on spectral irradiance measurements in industrial, occupational health and safety, photovoltaic energy generation, efficient energy use, and climate and earth observation applications.

Industrial users that apply spectral irradiance measurements to control radiation-related technological processes, such as the curing of materials, or the disinfection of air, water and surfaces, will profit from the new transfer standards as they will enable measurements that are traceable to the spectral irradiance unit after the incandescent lamps, which are currently used as transfer standards, have been phased out. The new spectral irradiance calibration standards, procedures and calibration services will also promote the industrial development of new products (e.g. novel standard sources) around the new technologies.

End users, from occupational health and safety applications, will receive new spectral irradiance standards for use in the calibration of their spectroradiometers or radiometers. These are used for performing onsite spectral measurements and for the assessment of personal exposures to incoherent optical radiation at places of work, outdoors and in sunbeds.

This project will provide new standards and calibration methods, which are highly relevant for photovoltaic energy production. Spectral irradiance measurements are an essential part of the metrological support provided to the photovoltaic energy generation sector. The results of this project are also highly relevant to energy saving through the use of energy-efficient lighting. The production, planning and installation of energy saving lighting products is highly reliant on spectral information, for which the metrological dissemination of the spectral irradiance unit is mandatory.

The outcomes of this project will also be used by the earth observation communities. The applicability of the new transfer standards to calibrate the spectroradiometers, which are used for measuring terrestrial solar radiation, will be demonstrated during a measurement campaign. The participants will disseminate the outcomes of this project within the stakeholder community that is associated with the European Metrology Network on Climate and Ocean Observation.

Outcomes for the metrology and scientific communities

This project will deliver new transfer standards and dissemination methods to enable National Metrology Institutes (NMIs), Designated Institutes (DIs) and calibration laboratories to disseminate the unit of spectral irradiance to end-users that are affected by the phaseout of standard incandescent lamps. The top-level metrological application of the transfer standards will enable the NMIs, DIs and calibration laboratories to compare their measurement capabilities at the International Bureau of Weights and Measures (BIPM) and the European Regional Metrology Organisation (RMO), i.e. from the EURAMET level down to bilateral interlaboratory comparisons. The new standard sources and procedures for the detector-based dissemination of the spectral irradiance unit, developed by the project, will meet the needs of a wide community of end-users, from metrology and other science disciplines, that measure the spectral properties of emitted radiation (analytical spectroscopy, plasma, luminescence, etc.).

The well documented implementation of a digital twin of the transfer standard instruments in an open-source code provided by the project will help the end users to benefit from the data yielded by instrument characterisations and calibrations. This will enable GUM-conforming propagation of the uncertainties and correlations into their measurement applications.

End-user communities will be able to select spectroradiometers as transfer standard instruments using the project's user guide which defines the minimum mandatory specifications of an instrument. This guide will also help the NMIs and calibration laboratories to clarify the calibration needs of their customers.

Outcomes for relevant standards

This project will provide the metrological basis for many European Regulations, Directives and Standards that refer directly or indirectly to the spectral measurement of optical radiation. These are aimed at protecting the population against deleterious factors, sustainable energy use and the protection of the environment:

- DIRECTIVE 2006/25/EC, “on the minimum health and safety requirements regarding the exposure of workers to risks arising from physical agents (artificial optical radiation) (19th individual Directive within the meaning of Article 16(1) of Directive 89/391/EEC)”. This directive states that the risk assessment shall consider the level, wavelength range and duration of exposure to artificial sources of optical radiation.
- Commission Regulation (EU) 2019/2020 "EcoDesign for light sources and separate control gears". This regulation requires a minimal general colour rendering index (Ra). This quantity can only be evaluated using spectral measurements in the wavelength range from 360 nm to 830 nm.
- EN 12464-1 "Light and lighting — Lighting of work places — Part 1: Indoor work places". This standard requires that authenticated general colour rendering index (Ra) and correlated colour temperatures (CCT) data shall be provided for the light source in the scheme by the manufacturer of the light source. The light sources shall be checked against the design specifications. These quantities can only be evaluated using spectral measurements in the wavelength range from 360 nm to 830 nm.
- EN 14255-1 to EN 14255-4 "Measurement and assessment of personal exposures to incoherent optical radiation". These standards require onsite measurements in the spectral range from about 200 nm to 2000 nm. Some of the measurements, particularly in the UV, can only be performed using a spectroradiometer.
- EN 60335-2-27 “Household and similar electrical appliances - Safety - Part 2-27: Particular requirements for appliances for skin exposure to ultraviolet and infrared radiation”. It requires that individual sunbed sessions shall have a maximum UV output that corresponds to the mid-day Mediterranean sun (UV index of 12) to avoid any risk of burns and to reduce the likelihood of accidents due to long exposure.

Longer-term economic, social and environmental impacts

The metrological traceability of spectral irradiance measurements in diverse industrial, health, scientific and environmental applications is currently based on incandescent lamps that are gradually vanishing from the market. After their complete phaseout, in the mid to long term, the dissemination of the spectral irradiance unit will be endangered. This project will provide new-technology transfer standards and methods to enable traceable measurements of spectral irradiance from artificial and natural light sources in the long term by the end user communities. Reliable and high-accuracy spectral data from optical radiation sources, supported by the developments in this project, will be one of the technological enablers for high-quality products, information and services in different end user applications. The accurate assessment of terrestrial solar radiation, and the derived atmospheric parameters used as essential climatic variables, are mandatory for monitoring climate change and its effects on ecosystems, human health, agricultural production and food safety on a global scale.

List of publications

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

Project start date and duration:	1 June 2023, 36 months	
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Internal Beneficiaries: 1. PTB, Germany 2. Aalto, Finland 3. CMI, Czechia 4. CNAM, France 5. CSIC, Spain 6. IPQ, Portugal 7. LNE, France 8. Metrosert, Estonia 9. RISE, Sweden 10. TUBITAK, Türkiye 11. VSL, Netherlands	External Beneficiaries: 12. ISFH, Germany	Unfunded Beneficiaries: 13. GGO, Germany 14. IS, Germany
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