Publishable Summary for 20NRM01 MetTLM
Metrology for temporal light modulation

Overview

LED-based lighting contributes to energy saving and the reduction of the environmental impact of lighting. However, LED lamps can show fluctuations in the light output known as temporal light modulation (TLM) which could, above certain limits and under certain conditions, impact the health, well-being and safety of people. Pursuant to the EU Directives 2009/125/EC, on Ecodesign requirements, Commission Regulation (EU) 2019/2020 sets limitations on TLM of light sources. The overall aim of this project was to create the metrology infrastructure for the measurement of TLM in LED lighting and the visual effects induced by TLM, known as temporal light artefacts (TLAs). This project developed and validated measurement methods for quantitative measurement of TLAs, such as flicker and the stroboscopic effect, and advanced the development of a metric for the phantom array effect. The project results underpinned the development of standardisation on TLM and provided the lighting industry, instrument manufacturers and market surveillance authorities with undisputable results of their TLM measurements. Following the guidance provided by the project, end users can now be rely on traceable TLM measurement, and as a result, they have more trust in market surveillance.

Need

LED-based lighting is ever increasing, and the market is estimated to be worth more than 70 € billion in 2022. The ongoing transition to LED lighting is an important step in achieving the European goals on improved energy efficiency. However, LED lighting may show temporal variation of the light output, covering a large range of waveform shapes and frequencies. This temporal variation can often be perceived by humans. And as stated by the International Commission on Illumination (CIE) in TN 006:2016: "can lead to a decrease in performance, increased fatigue as well as acute health problems like epileptic seizures and migraine episodes". Also, distorted perception of moving objects could give rise to safety concerns, for instance, in traffic or work environments.

The three types of TLAs, caused by variations in light output, as defined in the TN 006:2016 by the CIE, are: i) flicker, which is the direct perception of temporal changes of the light output; ii) stroboscopic effect, which is observed as a discretised motion of moving objects resulting from illumination by a temporally modulated source; and iii) phantom array effect (or ghosting), which corresponds to a change in perceived shape or spatial position induced by saccadic eye movements across a temporally modulated light source. While metrics for flicker and the stroboscopic effect have been recommended by CIE, the metric for the phantom array effect is still missing due to a lack of the required research.

The need for worldwide harmonised TLM measurements has been recognised by the CIE. The European Commission has explicitly required the development of standards for the measurement of flicker and stroboscopic effect (Mandate M/519, Ares(2013)205169), and in 2021 the Commission Regulation (EU) 2019/2020 has entered into force. In view of public health and safety, the regulation has introduced limits on the allowed modulation of light sources for flicker and the stroboscopic effect. To demonstrate compliance with the regulation, lighting industry, measurement instrument manufacturers and market surveillance authorities need to be able to perform reliable, mutually comparable measurements of these TLAs. However, the metrology infrastructure to provide validated and SI-traceable measurements of TLM and TLAs is currently not available and international agreed standards do not exist.

Real scenes and life environments, such as offices and tunnels, are often illuminated with a combination of multiple light sources and daylight presenting an effective luminance pattern of high contrast and an inhomogeneous distribution of TLM parameters. Mapping the TLM of such environment would require multiple measurements with a single spot TLM measurement device. Such measurement procedures are inefficient and do not provide a full assessment regarding TLA perception. Multispectral cameras could map the spatially distributed TLM as seen from an observer's position. This provides a promising approach to map spatially resolved TLM and thereby to judge about the perception of TLAs in illuminated scenes. Although commercial state-of-the art image sensors, used in industrial cameras and imaging luminance measurement devices (ILMDs), already contain fast modes that provide the needed temporal resolution, methods for the evaluation of spatially resolved TLM are not yet available. Also, light sources comprised of multiple temporally modulated coloured LEDs potentially induce temporal colour modulation, often leading to the perception of colour-breakup in the phantom array effect. Although spectroradiometers have become widely available for spectral measurements, a framework for spectrally resolved TLM measurements is missing.

Objectives

The overall aim of this project was to create the metrology infrastructure required for the measurement of TLM and to contribute to the development of standardisation on the measurement of TLM. The specific objectives of the project were:

1. To establish methods for traceable TLM measurement of individual light sources and luminaires with a focus on flicker and stroboscopic effect. These would be based on IEC TR 61547-1 and IEC TR63158 and include: (i) methods for generating and measuring optical waveforms in the time-domain and power spectra in the frequency-domain, (ii) calibration and characterisation of TLM measurement devices and the evaluation of uncertainty budgets, (iii) quality metrics (e.g. frequency response, dynamic range of signal) for the classification of TLM measurement instruments.
2. To validate the traceable TLM measurement methods, developed in Objective 1, through an interlaboratory comparison between metrology institutes and industry, whilst ensuring compliance with the new EU Ecodesign 2019/2020 regulation. To develop a recommendation on associated standardised measurement conditions.
3. To develop novel methods for measuring TLM of the illuminated environment in extended scenes (e.g. offices, roads or tunnels) and for multispectral TLM measurement of light sources.
4. To develop a model for the visibility of the phantom array effect based on perception experiments that measure the visibility threshold for various lighting conditions (e.g. modulation frequency, amplitude, shape of the modulation and light level). This model would be shared with CIE TC 1-83 or its successor in a suitable format that enables its use in a future metric for the phantom array.
5. To facilitate the take up of methods, technology and measurement infrastructure developed in the project by the standards developing organisations (e.g. CIE) and end-users (e.g. regulatory bodies, lighting industry and instrument manufacturers). This should include providing input to CIE TC 2-89 and CIE TC 1-83 (or its successor) and support for a new CIE TC for addressing the measurement of spatially resolved TLM and colour TLM.

Progress beyond the state of the art

At the start of this project standardised and validated methods for traceable measurement of TLM were not available and measurement conditions had not yet been defined. Methods for testing equipment for flicker and the stroboscopic effect have been developed (IEC TR 63158:2018 and IEC TR 61547-1:2020), but these do not consider SI traceability or the measurement uncertainty for these quantities. In the MetTLM project, national metrology institutes (NMIs) have provided SI traceability to TLM measurements cover the TLA metrics for short-term flicker severity (PstLM) and stroboscopic visibility measure (SVM) used in the EU Ecodesign regulation.

This project has delivered validated methods and measurement conditions for traceable measurement of temporal light modulation for flicker and the stroboscopic effect, and has supported the development of standardisation on TLM measurement. It has contributed to the development of TLM measurement capability at NMI level. The developed TLM calibration methods have been validated by an interlaboratory comparison, that overall shows good consistency. The project outcomes have been summarised in a publicly available good practice guide (GPG), which will support CIE in the development of standardisation of TLM measurement via CIE TC 2-89 'Measurement of Temporal Light Modulation of Light Sources and Lighting Systems'. The overall goal of providing stakeholders with reliable measurement results and well-underpinned measurement uncertainties for their TLM measurements was achieved.

At the start of the project only single dimensional TLM measurement devices were available to measure TLM locally. However, for the phantom array effect, the spatial luminance pattern is important and imaging techniques are nowadays widely used to characterise lighting situations regarding its time-averaged luminance distribution. This project has investigated high-speed imaging as a new approach to measure the TLM distribution of structured luminaires and in extended scenes. Thus going beyond state-of-the-art at the time of this research.

With Red, Green, Blue (RGB) modulated displays and multispectral Red, Green, Blue, White (RGBW) or tuneable white luminaires temporal colour modulation is also gaining attention. Measurement methods to quantify colour (or spectral) TLM and temporal colour modulations have been developed. In this project, methods to assess colour- and (multi)spectral TLM have been investigated and demonstrated.

A metric for the phantom array effect has currently not yet been defined. Although several studies on the human perception of the phantom array effect have been executed, there is currently insufficient scientific evidence available to serve as a base for a definition of the phantom array effect. Within the MetTLM project representative perception experiments measuring the visibility threshold for various lighting conditions have been performed, aimed at the development of a model for the visibility of the phantom array effect. This model should contribute to the definition of a suitable metric for the phantom array effect.

Results

Methods for traceable and validated measurement of temporal light modulation (Objectives 1 and 2)

Based on the models given in IEC TR 63158:2018 and IEC TR 61547-1:2020, uncertainty components, which affect TLM quantities for flicker and the stroboscopic effect, have been identified. To propagate uncertainties, from the time domain to PstLM and SVM, models have been built. Using these models, sensitivity coefficients for uncertainty propagation have been determined for various waveforms. This uncertainty analysis has been used for the calibration of TLM measurement devices. Further investigation into the models revealed shortcomings of the current definitions as well as of reference implementations of TLA metrics. These issues have been solved and validated by comparison of multiple model implementations. In addition, the improved models have been implemented in a luminous flux measurement setup which has been used to measure a large number of light sources for TLM.

For validation of implementations of TLM models a dataset, containing discretised mathematically generated waveforms, named "MetTLM TLM waveform set 1", has been generated and validated. The dataset is accompanied by a report guiding and exemplifying how the dataset can be used by laboratories to achieve measurement uncertainties below 0.05 on PstLM and SVM. The dataset and report have been released to the MetTLM community on Zenodo, an open access repository.

Typical performance of measurement devices can be expressed in quality indices, which characterise how a physical effect influences the instrument's reading. For TLM measurement devices, quality indices have been defined for frequency response and dynamic range of signal. An LED-based facility has been built with the aim of characterising TLM measurement devices, have been used to assess dynamic range. A laser-based facility has been realised, and procedures to measure the frequency response of TLM measurement devices have been tested. The frequency response of various commercially available TLM measurement devices has been characterised and compared against the developed TLM models, for flicker and the stroboscopic effect. An approach for a quality index for frequency response has been tested and further developed.

To validate the traceable TLM measurement methods developed in Objective 1, an interlaboratory comparison has been carried out. Artefacts (four waveforms of a TLA box and 7 lamps, of which 4 are also measured in the IEA 4E SSL Annex comparison) were selected and aged prior to the comparison. The eight participants measured the artefacts using their facilities, and data was analysed according to the "Guidelines for CCPR Key Comparison Report Preparation". These results show that overall the participants are in consensus about lamps entering the EU market, regardless the differences in measured value. The results of the TLA box are consistent between participants, likely due to elimination of the effect of external power supplies, making this kind of source ideal for validation of measurements against the Ecodesign regulations.

The objective of developing traceable TLM measurement capabilities and to validate them in an interlaboratory comparison, has been achieved.

Novel methods for TLM measurement (Objective 3)

To probe individual light sources inside complex field scenes a luminance TLM meter based on a fast photocurrent flicker-meter, including an anti-aliasing filter, and a luminance photometer head was set up. This meter has been verified in the laboratory and thereafter used in field measurements. To enable a multi-channel TLM meter with synchronized acquisition a trigger extension for this fast photocurrent meter was initiated in this project. The advantages of parallel TLM measurements have been demonstrated. Both, the luminance TLM meter and the multi-channel TLM meter are now available as commercial products.

In laboratory-based measurements, a set of three TLM luminance sources with patterned transmissive filters have been used to generate luminance contrast patterns which are then measured with cameras. Doing so, limitations identified regarding the sampling theorem, resulting from the charge accumulating principle used in most pixel-based detectors, have been addressed. The linearity of the TLM luminance source in constant luminance mode and during transient operation was investigated, revealing issues regarding modulation depth and deviations resulting from time constants of the electrical circuit of the TLM luminance source. This information is a prerequisite for facilitating these sources in a characterization of TLM measurement devices.

An accurate method for the measurement of temporal colour modulation has been developed based on a 4-channel tristimulus detector head and four of the fast photocurrent meters, with a common trigger signal. This creates a unique meter that allows high-speed measurement of the tristimulus waveforms and temporal evaluation of colour coordinates. An experimental study, in as scene with smart lighting products revealed the operation principle of tuneable white LED-based lamps. The study underlined the need to evaluate TLM by (multi-)spectral and spatially resolved measurements and needs regarding spectral mismatch of flicker meters.

A commercial high-speed RGB camera was used for multi-spectral TLM imaging measurements in lab-based and field scenes using real time sampling and equivalent time sampling. For multi- and hyper-spectral TLM measurement, a hyperspectral camera was used to measure LED luminaires in office scenes. Measurements taken with an imaging luminance measurement device (ILMD), on different lamps and luminaires, demonstrated the feasibility of TLM measurements with such devices. Also, monochrome and RGB industrial cameras were used to implement and demonstrate also an Equivalent-Time-Sampling (ETS) mode for spatially resolved TLM measurements. The main issue that limits the TLM measurement by cameras is the low dynamic range compared to conventional traditional single spot TLM meters. Using the ETS mode with an industrial RGB camera also the measurement of temporal colour modulation from smart lighting products was successfully demonstrated.

Also, the impact of TLM on ILMD measurements of the average luminance and measurements of spectral irradiance by array-spectroradiometers was demonstrated. In addition, the possibility to use conventional cameras that provide a high frame rate mode of up to 1000 Hz, were investigated. In contrast to these, photos obtained with a long integration time of i.e. 0.05 s or 0.1 s captured during a camera pan can give visual evidence for the phantom array effect. As such cameras are widely used, this is expected to increase the uptake of results.

The objective of development of novel methods for measuring TLM of the illuminated environment in extended scenes and for multispectral TLM measurement of light sources has thus been achieved.

Model for the visibility of the phantom array effect (Objective 4)

Based on an initial literature review, five psychophysical experiments were designed to study the effect of temporal frequency, colour of the light source, saccade amplitude and velocity, and ambient illumination on the visibility of the phantom array effect. All of the five experiments used a two-interval forced-choice (2IFC) task for the observers, in which observers need to indicate in which of the two sequentially presented stimuli the phantom array effect is visible to them. Changing the modulation depth in the pair of stimuli in combination with the QUEST+ method (a Bayesian adaptive psychometric testing method), enables adaptive collection of data, thus reducing the number of perceptual experiments needed. By doing so, the visibility threshold of the phantom array effect could be determined for the various lighting conditions.

Experiment 1 focused on the effect of temporal frequency and the chromaticity of the light source on the visibility of the phantom array effect. The results of Experiment 1 show an inverted U-shaped bandpass sensitivity function for the phantom array effect as a function of temporal frequency for the three chromaticities used, i.e., red, green, and warm white. The 3rd order polynomial fit indicates a peak sensitivity at a temporal modulation of 600 Hz in all three cases, in line with earlier results in literature. However, the experimental peak differs from the provisional model presented in CIE 249:2022, in which the sensitivity peaks around 1000 Hz for an averaged luminance of 1000 cd/m^2. In our study, the luminance is 50 cd/m^2, which might partially explain the discrepancy. Substantial individual differences in sensitivity to the phantom array effect have been observed. Analyses of the result shows a significant effect of both colour and frequency as well as a significant interaction between them.

In experiments 2, 3 and 4, a narrow slit white light source was used. Experiment 2 focused on modelling the temporal contrast sensitivity function to the phantom array effect. In this experiment 22 participants were included, and 10 different frequencies were tested. The resulting sensitivity as a function of frequency, averaged over all participants shows that the sensitivity is clearly higher at the medium frequencies, with the maximum at 600 Hz and the sensitivities are substantially lower at the two far ends of the measured frequency range. Experiments 3 and 4 focuses on the effect of saccade amplitude and velocity as well as the effect of ambient illumination. In summary, results show that the sensitivity is frequency dependent, and that the ambient light level has a substantial effect on the visibility of the Phantom Array effect. It is much more difficult to observe when the contrast is lower.

In experiment 5 the results of the previous experiments were verified in real-life context, among 20 participants. One of the most common situations when the Phantom Array effect is reported is when viewing temporally modulated taillights of a car in low-light conditions. Therefore, a setup was constructed in the laboratory simulating viewing conditions closely resembling the real-life situation when driving behind a car with modulated taillights. Results showed individual variations in the threshold values for the visibility of the phantom array effect, but the frequency dependence was consistent among most participants. A psychometric function was used to fit the data across all included frequencies. Based on the visibility threshold determined at each frequency, a visibility threshold curve could be obtained showing the similar band pass shape as the more controlled experiments 1-3, albeit with a slightly higher peak frequency and a flatter appearance. With increased knowledge, more informed decisions about limit values in different settings can be made, thereby improving the safety, comfort, and overall quality of LED-based lighting systems.

The objective of developing a model for the visibility of the phantom array effect based on perception experiments that measure the visibility threshold for various lighting conditions e.g. modulation frequency, amplitude, shape of the modulation and light level, has been achieved.

Impact

The first results of the project, related to calibration of TLM measurement devices, were presented at the CIE Midterm Meeting hosted by MyCIE, the Malaysian CIE committee, in 2021. The project contributed to the CIE Expert Tutorial on the Measurement of Temporal Light Modulation in Athens, Greece, October 2022. The attendees were trained in measurement of TLM, estimation of measurement uncertainties and uncertainties in calculation of predictors of TLAs. The tutorial was followed by a project stakeholder meeting, which was attended by about fifty participants. After the presentations, the consortium and stakeholders engaged in open discussion. Stakeholders endorsed the need for guidance on implementation of TLM models as well as on the propagation of uncertainties. In addition, stakeholders endorsed the need for spectrally resolved TLM measurements, referring to colour-breakup perceived in light sources comprised of multiple temporally modulated coloured LEDs. At the CIE quadrennial session, held in Ljubljana, Slovenia, in September 2023, results of the MetTLM project have been presented by four members of the consortium in a dedicated session on temporal light modulation. Linked to this event, in a meeting of the CIE research forum on matters relating to temporal light modulation, project results have been presented and discussed. In conjunction with the final project meeting at PTB in April 2024 a training session was held, focusing on measurements, measurement uncertainty as well as verification and validation. Using an RGB-based smart lighting product also technical aspects of handheld flicker-meters that cover a huge price range, namely sampling rate and duration, aliasing, signal ringing at steep slopes, offset, and time constants and their dependence on the measurement range as well as digital low-pass filtering, had been demonstrated in the training.

A project website was regularly updated: https://www.mettlm.eu/. All told, 74 people registered on the website to receive periodic project updates via email. Registrants included EU Member State representatives, government experts, test organisations, manufacturers of measurement instruments, NGOs and other associations. As a result of direct engagement with stakeholders, 7 stakeholders confirmed the need for standardized measurement methods for TLM. Results have been presented at meetings of CIE, DIN, IEA SSL

Annex and EURAMET TC-PR, Which generated further awareness of the project. A YouTube video has been released aimed at explaining definitions related to TLM to the general public, as well as a longer video on the subject of TLM contains an interview with a prominent researcher.

Impact on industrial and other user communities

The availability of reliable TLM measurements and related temporal light artefacts is important for the lighting industry, because the Ecodesign Commission Regulation (EU) 2019/2020 sets limits for flicker and the stroboscopic effect of the light sources and luminaires they bring to the market. The project outcomes have supported the lighting industry in its efforts to demonstrate compliance of lighting products with the regulation. Similarly, market surveillance authorities have benefited from the availability of metrological methods and calibrated TLM measurement instruments, which is required for them to fulfil their role to enforce compliance with the regulation.

The project provided novel methods using multispectral imaging measurement devices to measure TLM of extended scenes or large area luminaires and displays. The findings have already initiated an improvement of the TLM measurement mode implemented in a commercial imaging luminance measurement device (ILMD). The initiated luminance, multichannel, and tristimulus TLM meters were demonstrated regarding their advantages compared to illuminance TLM meters. These results are especially relevant to end users who want to measure the quality of lighting in field installations e.g., in an office space under mixed lighting conditions or on a building façade. The research on the visibility of the phantom array effect of car taillights could provide the automotive industry and lighting manufacturers with a quantitative measure for the visibility of this effect. This could enable them to improve lighting products such that the visibility threshold for the phantom array effect is not exceeded, enhancing the safety and consumer appreciation of their products.

To promote the uptake of the project's outcomes by the lighting industry and instrument manufacturers, the consortium invited stakeholders from these sectors to participate in the interlaboratory comparison. To increase the number of participants the comparison was joined with the IEA 4E SSL Annex comparison.

The consortium built up LED- and laser-based facilities to characterise and calibrate TLM measurement devices. The first commercially available TLM measurement devices have been tested against the facilities. Further characterisation and calibration of TLM measurement devices supports regulatory compliance assessments. Preliminary tests were conducted on several (commercially available) TLM sources, using a variety of imaging devices, demonstrating the benefit of imaging TLM measurement modes.

In collaboration with stakeholder LightingEurope the project conducted at webinar on "Measurement of lighting with temporal light modulation and EcoDesign". The webinar was attended by at least 150 participants, with 300 signing up beforehand. A LinkedIn announcement of the webinar gained more than 1000 impressions on the platform.

Impact on the metrology and scientific communities

The project has strengthened the knowledge and measurement capabilities of national metrology institutes on the characterisation and calibration of TLM measurement devices and TLM sources. This has enabled NMIs to establish calibration services of TLM measurement devices and/or reference sources for their stakeholders. The project has published a set of representative computer-generated and real-life waveforms and the corresponding values and measurement uncertainties for flicker and the stroboscopic effect. This has allowed scientists and metrologists involved in TLM measurement to validate their models and uncertainty calculations. Within the project, novel techniques for measuring temporal light modulation of complete scenes have been investigated, based on high-resolution time-resolved and spatially resolved imaging. The development of metrology for this type of measurement, was new and challenging and has not only impacted the field of TLM measurement, but also the wider field of metrology for time and spatially resolved photometry. The project has impacted the research field of human perception of TLM. In particular, it has progressed scientific knowledge on the phantom array effect with the work on the development of a metric for this TLA. More generally, the developed metrology on TLM measurement supported ongoing research on health, performance and safety effects of TLM.

To promote the uptake of the project results by the metrology community, two presentations have been given at the CIE midterm meeting (2021). In the first presentation, a laser-based TLM calibration facility was evaluated for characterisation of TLM measurement devices, in relation to the Ecodesign Commission Regulation (EU) 2019/2020. In the second presentation, the findings of sensitivity analyses of TLM measurements to noise and sampling frequency have been shown. The findings of both presentations have been taken into account in the technical report on measurement of TLM, by CIE 2-89.

At the CIE Expert Symposium on the Measurement of Temporal Light Modulation in Athens, Greece, October 2022, the setup to determine the visibility of the phantom array effect was presented. The first results have been presented as well as an outline of methods that will be used to evaluate the data.

At Lux junior 2023 in Dörnfeld bei Ilmenau, Germany, June 2023, arranged by LitTG and Technische Universität Ilmenau two presentations were given on the characterization of TLM in scenes using imaging devices.

The results of the first phantom array sensitivity experiments, uncertainty propagation and the camera based TLM methods have been presented at the CIE 2023 conference in Ljubljana, Slovenia, September 2023. The results of the 5th phantom array sensitivity experiment will be presented at the IES conference in New York, USA, August 2024.

To facilitate impact a Zenodo community has been established: mettlm20nrm01, where data items related to TLM in general and MetTLM specifically will be curated and collected. So far, the dataset posted there has been viewed 320 times and downloaded 120 times.

Impact on relevant standards

The project has contributed to the work of the technical committee under the CIE, TC 2-89 “Measurement of Temporal Light Modulation of Light Sources and Lighting Systems”. One of the project deliverables is a GPG on metrological methods, instrumentation and conditions for calibration of TLM measurement devices, which has contributed to an international CIE standard on TLM measurement. CIE was the Chief Stakeholder of the project and the involvement of TC 2-89 in the stakeholder board of the project ensured that the needs of CIE were met and that project results were taken up effectively. Since CIE and CEN have a formal agreement on technical cooperation, it is expected that CEN will adapt the CIE standard once available. This will help CEN to respond to the mandate issued by the European Commission (Ares(2013)205169), requiring the development of standardisation on LED lighting and the development of standards for flicker and the stroboscopic effect. This project delivered a significant contribution to scientific data on the sensitivity for the phantom array effect and the development of a metric for this TLA. This will contribute to the work of CIE continuing work with visual aspects of time-modulated lighting systems. Other standards and guidelines that are likely to be impacted by this work are IEC TR 63158:2018 and 61547-1:2020.

Over the 36 months duration of the project, the consortium was actively involved in the following international standardisation committees: CIE TC 2-89, CIE TC 2-96, CIE TC 2-97, CIE RF-02, CEN TC 169, ISO TC 274 JWG1, and the national standardisation committees DIN- NA058-00-03AA, IEA 4E SSL Annex and DS-061. On behalf of the consortium direct input has been provided to the draft technical report of CIE TC 2-89, to ISO/CIE 19476:2024 "Characterisation of the performance of illuminance meters and luminance meters", which should be published in 2024 and falls under the responsibility of CIE TC 2-96, and to CIE S 025/E:2015 Test Method for LED Lamps, LED Luminaires and LED Modules, which should be published in 2024 and is being prepared by CIE TC 2-97.

Longer-term economic, social and environmental impacts

The project outcomes have supported the execution of the EU Ecodesign Commission Regulation (EU) 2019/2020, which protects EU citizens against potentially negative health, performance and safety effects resulting from modulated light sources like LED lighting. Having only compliant light sources on the market protects people against these potentially negative effects like decrease of performance, fatigue, eye strain or more severe effects like migraine episodes or epileptic seizures.

This EU regulation currently focuses on light sources that produce flicker and/or the stroboscopic effect and will be revised in 2024. Requirements on dimmable light sources, known for exhibiting TLM, will probably also be included in the revision.

The project indirectly contributed to energy saving and reduction of the environmental impact of lighting by supporting regulations that put limits on the allowed TLM of light sources. The ability to enforce compliance with regulations, based on appropriate standardisation, supported the adaption of LED lighting by the public and the phase-out of incandescent lighting. This supports European and international goals on energy saving and reduction of the emission of greenhouse gasses. End users such as building owners and governmental organisations benefited from the outcomes of the project, since it supports them in their efforts to save energy and cost by using efficient lighting.

List of publications

- Dekker, P.R., van Bloois, A.L. (2023) 'Facility for calibration of photometers for measurement of temporal light modulation', *Lighting Research & Technology* p. 1.4771535231e+14. Available at https://doi.org/10.1177/14771535231159289
- Ikonen, E. et al (2023) 'Digital implementations for determination of temporal light artefacts of LED luminaires', *Lighting Research & Technology*(0) p. 0-12. Available at https://doi.org/10.1177/14771535231212404
- Nordlund, R. (2022) 'Validation for measurement of Temporal Light Artefacts on LED light sources', Aalto University. School of Electrical Engineering. Available at https://aaltodoc.aalto.fi/handle/123456789/113709
- Stein, A., Wiswesser, P., Ledig, J. (2023) 'Auswertung der zeitliche Lichtmodulation unter Verwendung von bildauflösenden Messgeräten', *Lux Junior*, 2023 p. 10.22032/dbt.55787. Available at https://www.db-thueringen.de/receive/dbt_mods_00058613

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

<table>
<tr><td colspan="2">Project start date and duration:</td><td>1 May 2021, 36 months</td></tr>
<tr><td colspan="3">Coordinator: Paul Dekker, VSL   Tel: +31 15269 1500   E-mail: pdekker@vsl.nl
Project website address: https://www.mettlm.eu/</td></tr>
<tr><td colspan="2">Chief Stakeholder Organisation: CIE</td><td>Chief Stakeholder Contact: Dong-Hoon Lee</td></tr>
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2. Aalto, Finland
3. PTB, Germany
4. RISE, Sweden</td><td>External Funded Partners:
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