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Contents

IMPACT OF SAMPLING RATE ON FLICKER METRIC CALCULATIONS

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Abstract

1. Motivation, specific objective

There are multiple metrics that have been proposed to assess the visibility of direct and indirect temporal light modulation (TLM), which is also referred to as “flicker.” In the course of other research, MATLAB® codes were found to yield some metric values with unexpected values. An investigation revealed metric values varied with sampling rate. Some recommendations about appropriate sampling rate will be proposed, based on the existing MATLAB® codes.

2. Methods

MATLAB® codes provided by multiple industrial standards and regulations were used to investigate how different flicker metrics vary with the sampling rate for a set of simulated waveforms. The waveform types included sinusoidal and rectangular, with frequencies from 5 Hz to 6000 Hz, modulation depth from 10% to 100%, and duty cycle (only for rectangular waveforms) from 10% to 90%. A sampling rate from 2 kS/s to 400 kS/s was applied. The metrics investigated include percent flicker, flicker index, physiological percent flicker, stroboscopic visibility measure (SVM), IEC/TR P_{st}^{LM}, ASSIST M_P, and Title 24 JA-10. For each of the waveforms, values of all metrics were calculated using the different sampling rates. A variation threshold of “(max - min) / max > 10%” was established to identify those metrics with considerable variation. For each metric, the study determined how its values varied with sampling rate, and identified a proper value of the sampling rate range in which the metric value is stable and reliable.

3. Results

Sampling rates that are too low could not restore the original shape of the waveform, and sampling rates that are too high would waste computing power and resources. Using the results of this investigation, rules are recommended for selecting sampling rates for calculations of each metric, so that the calculated results can remain stable, and thus, can be reliable when calculated in different meters and laboratories. The proposed rules balance fidelity and computing resources/measurement feasibility.

These recommendations are based on the existing MATLAB® codes from the standards and regulations, which are assumed to be widely used for flicker metric calculations. The robustness of the codes against the change of sampling rate will also be discussed. And the discussion is expected to trigger a review and improvement of the codes.

4. Conclusions

Some of the existing flicker metrics vary considerably with sampling rate. Based on extensive simulations of the characterization of theoretical waveforms, we propose recommendations on selecting sampling rate to guarantee reliable metric calculations from the existing MATLAB® codes, while avoiding the waste of computing power and resources. The robustness of the MATLAB® codes against the change of sampling rate will also be discussed.

ANTI-ALIASING FILTER EFFECTS ON SAMPLING FREQUENCY AND EFFECTS OF MATHEMATICAL IMPLEMENTATION

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Abstract

1. Motivation, specific objective

Temporal light modulation (TLM) and the resulting temporal light artefacts (TLA) of luminaires can lead to discomfort or health issues. The accurate measurement and evaluation of TLM and TLA is an important task in order to fulfil and guarantee the product safety in respect to e.g. the European Commission's Eco-design Regulation, which specifies limit values for SVM and P_{st}.

A guidance about the principle measurement and an overview of TLA and TLM is given in TN 012:2021. The accurate measurement of a product includes furthermore calibration and measurement uncertainty evaluations. Such a statement of the uncertainties is a rather challenging task due to many effects to be considered and a detailed measurement uncertainty modelling might be needed. Currently a technical committee and scientific projects works on this issue. For instance, the effect of noise, sampling and frequency has been investigated on the calculation of TLA metrics.

In this work we would like to show the effect of the anti-aliasing-filter transmission curve and the sampling frequency in this respect on TLA evaluations for different waveforms.

In addition, we would like to present some examples about the windowing effect on SVM implementation and about the P_{st} mathematical implementation.

2. Methods

We analyse P_{st} and SVM for different anti-aliasing filter transmission curves with different sampling frequencies for different waveforms. Specifically, the methods consist of:

- A set of mathematically calculated reference waveforms of various shapes and frequencies
- A set of different anti-aliasing filters (Butterworth-Filter, Bessel-Filter, different orders)
- Investigation of SVM and P_{st} with different sampling frequencies

In addition, we investigate the SVM of specific reference waveforms with the free available IEC MATLAB script and an own mathematical implementation by applying different analysing methods.

- A set of mathematically calculated reference waveforms of various shapes and frequencies
- Investigation of SVM with IEC MATLAB script and own implementation by applying different windowing and zero-padding functions on the signal and different methods for calculating the integral sum
- Evaluate the effect of different implementations, especially the windowing, for SVM

At last, we point out the advantages of calculating the P_{st} in frequency domain and verify if the measurement duration of 180 s can be reduced this way

- A set of mathematically calculated reference waveforms of various shapes and frequencies
- Calculation of P_{st} in time domain and in frequency domain by using different signal lengths
- Comparison of the results calculated in frequency and time domain and comparing it to the result with 180 s signal length.

3. Results

The data shows, that it is not sufficient to apply the Nyquist criterium to the cut-off frequency of an anti-aliasing-filter. The whole filter transmission curve has to be considered and depended on that the optimal sampling rate has to be chosen. Since the waveform of the examined signal usually isn't known, the anti-aliasing-filter and sampling frequency have to be optimized for all possible waveforms. Otherwise, aliasing effects can result in errors that exceed the real value of SVM and P_{st} by far.

The mathematical implementation of the P_{st} and especially SVM evaluation shows an uncertainty which needs to be considered during the measurement uncertainty evaluation. This is especially true since the mathematical application of especially the FFT (windowing, zero-padding, etc.) is not clearly described in documents yet.

We showed that the measurement time of the P_{st} can be at least reduced to a total time of 60 s by moving into the frequency domain for the signals analysed.

4. Conclusions

The anti-aliasing filter transmission curve, especially type and shape, has to be considered for determining the needed sampling frequency. Especially for P_{st}. The cut-off frequency of the anti-aliasing filter, which is sometimes defined at 3dB or 50%, is not sufficient for this consideration if the Nyquist criterium is applied.

The mathematical implementation of especially SVM represents also a measurement uncertainty contribution, which additionally depends on the waveform measured. This is no general problem; however, it needs to be considered and free available codes of the implementation are not generally correct for all signals. Ideally the calculation of SVM and especially the application of the FFT (windowing, zero padding, etc.) on the original signal have to be better specified in technical reports or standard, to guarantee comparable results.

By moving into the frequency domain, the filter transient (filter response time) for the P_{st} determination can be significantly reduced and shorter measurement times as 60 s in total are possible. This compared to 60 s + 60 s (CIE TN 012:2021) or 60 s + 120 s (IEC TR 61547-1:2020) recommendations where the first 60 s represent the filter settling time. The evaluation in the time domain seems to be a result of transferring the classical EMC tests of voltage signals and analogue filters into the light domain. The fact that we evaluate light signal in the digital world would allow to think about adapted approaches.

IMPLEMENTING LOCK-IN DETECTION IN PHOTOMETRY AND SPECTRORADIOMETRY USING TEMPORAL LIGHT MODULATION

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Abstract

1. Motivation, specific objective

Lock-in detection is a well-established technique to measure the amplitude and phase of a modulated signal in the presence of noise, background and parasitic signals. This technique is commonly used in many areas to extract small, modulated signals buried in noise that could not directly be measured otherwise.

In most lighting products, the observed temporal light modulation is usually a periodic change in the light output resulting from the power supply. Lock-in detection is inherently well-suited to the characterisation of these optical oscillations superimposed to a large luminous background.

The objective of this work is to present different methods of lock-in detection applicable to photometric and spectroradiometric measurements in the presence of temporal light modulation: electrical lock-in detection, digital lock-in detection and optical lock-in detection.

The practical implementations of these methods will be detailed, illustrated, and compared. Their respective advantages and drawbacks will be presented in the case of single photometric and radiometric measurements, and in the case of more complex measurements based on array spectrometers and imaging photometric instruments.

2. Methods

The implementation of any lock-in technique requires using a periodic reference signal whose frequency and phase are locked to the temporal light modulation waveform through an optical link to the light source or an electrical link to its power supply.

In electrical lock-in detection, the signal to measure is generated by an optical sensor, typically a photometer, having a voltage output. The electrical signal is routed towards two channels working in parallel. In the first channel, called the in-phase channel, the signal is multiplied by the reference signal. In the second channel, called the quadrature channel, the signal is multiplied by the same reference waveform but phase-shifted by 90°. Following the multiplier stages, both signals are sent to identical low pass filters. After the low pass filtering stage, the output of both channels are respectively the real and imaginary parts of the Fourier component of the signal at the frequency of the reference signal. The outputs of the in-phase and the quadrature channels can be combined to generate the amplitude and phase of the signal at the reference frequency. Lock-in detection can be seen as a very narrow phase-sensitive electrical bandpass filter centred on the reference frequency, rejecting the dc components and ac components at other frequencies.

The use of commercially available lock-in amplifiers is the most robust and widely used approach to perform these operations. However, most lock-in amplifiers are currently limited to 32 simultaneous measurements. This is the reason why spectroradiometric and image-based lock-in measurements are difficult to perform because a much higher number of individual signals need to be processed in parallel. This is typically the case with CCD and CMOS sensors used in array spectrometers and image-based photometric instruments. Such sensors have thousands or millions of pixels.

To overcome the limit in the number of simultaneous measurement channels needed with array sensors, a fully digital implementation of lock-in detection is possible. It requires fast sensors with read-out circuits and A/D converters to digitise the signals of all the pixels

simultaneously at very precise time intervals, at least three times per modulation cycle of the light source under test. A real-time data acquisition and processing algorithm is needed, with a computing power being directly proportional to at least the cube of the number of pixels. This approach has been successfully used in lock-in infrared thermography which operates at low modulation frequencies of typically a few Hz.

Optical lock-in detection is an emergent technique which is adapted to sensor arrays because it overcomes the requirements for fast sensors, fast digitising, and computing power. It relies on the principle of phase and quadrature demodulation applied to the optical signal itself using one or several optical modulators. Optical lock-in instruments have been designed in areas such as gravitational wave detection and imaging though scattering media.

3. Results

The implementation of optical lock-in detection has been successfully done in a standard sphere-spectroradiometer system used to measure the spectral radiant flux of lighting products. This communication will describe the specific equipment that was designed and built for this purpose.

The first key element is the optical link and the electronic circuit used to generate the reference signal with a frequency and phase locked to the temporal light modulation of the light source under test.

The second key element is a four-port optical modulator operating simultaneously in phase and in quadrature with sinusoidal transmission functions having 100% modulation depth at all wavelengths.

Spectroradiometric measurements of light sources using optical lock-in detection revealed features about light emission processes that were not observed using standard methods and will be discussed in this communication.

4. Conclusions

When performing photometric and spectroradiometric measurements of light sources exhibiting periodic temporal light modulation, the implementation of lock-in detection is a very efficient way to measure the amplitude and phase of the luminous and spectral fluctuations of the light output. It is particularly efficient to discriminate temporal light modulation against strong and unsteady background lights.

The electrical lock-in detection technique is the most used technique, applied with commercial lock-in amplifiers. It is well suited to measurements carried out with photometers and other types of single detectors. To extend lock-in detection to measurements based on array sensors such as spectrometers and image-based photometric instruments, it is possible to implement digital lock-in detection, but it requires fast sensors, fast data acquisition and intensive computing power.

Optical lock-in detection overcomes these requirements, as demonstrated with an experimental setup integrated in a standard sphere-spectroradiometer equipment. The lock-in spectroradiometric measurements of lighting products gave a new insight and useful information about light emission characteristics.

Taking advantage of temporal light modulation, the implementation of lock-in detection opens interesting opportunities to extend the application range of photometric and spectroradiometric measurements, both in the laboratory and in remote sensing applications.

CHARACTERIZATION OF KEY PERFORMANCE OF TLM MEASUREMENT INSTRUMENTS

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Abstract

1. Motivation, specific objective

The temporal light modulation (TLM) quantities, such as PF, SVM, P_{st}^{LM}, of light sources and lighting systems are acquired based on the measurement of the fast and time resolved photometric data. The measurement instrument for the waveform of luminous quantities plays key roles in TLM measurement. The measurement instrument is usually composed of input optics, photo sensor with $V(\lambda)$ correction filter(s) and necessary electronic circuits, in which the photo sensor can be single channel or array detectors. Except that the components should meet the relevant requirements, the overall performance of the measurement instrument is more important to be ensured so as to obtain accurate and reproducible TLM quantities.

ISO/CIE 19476 and CIE 244 have defined the indices and measurement procedures for the characterization of the performance of single-channel photometers and multi-channel luminance meters. For TLM sources, these instruments are intended to obtain the arithmetic mean values of the luminous quantities other than the transient waveform. General quality indices, such as spectral properties, UV response, IR response, directional response and fatigue, are applicable for the TLM measurement instrument, while some other important performances relevant to the speed transient sampling need to be characterized and evaluated.

2. Methods

The characterization of the linearity, frequency response and noise properties of the TLM measurement instrument was researched, which are main factors affecting the waveform acquisition and the measured TLM quantities. Traditionally, there are corresponding indices to characterize these performances of an instrument, but for the specific application for TLM measurement, the characterization needs to be reconsidered.

Unlike photometers for arithmetic mean value measurement, the instrument for fast and time resolved photometric data acquisition usually does not change range during one measurement sampling. In order to take the maximum and minimum readings, the linear dynamic range should be quite wide in one range. The method to characterize the linearity in a fixed measurement range was described in ISO/CIE 19476 and CIE 244. In this work, the linearity f_3 of several kinds of TLM measurements is measured and compared to verify the availability of this index. Furthermore, the measurement of dynamic range, i.e. the maximum and minimum measurable value in a range, is researched based on the differential responsivity method.

The frequency dependent knowledge of a measurement instrument is important when measuring modulated light signals. It is affected by the acquisition time of the detector, speed of the pre-amplifier and digitizer, as well as the anti-aliasing filter. In this work, a reference light source for frequency response measurement was developed to produce pure sinusoidal irradiation whose frequency is adjustable and can cover the frequency range of interest. The reference light source is realized by means of a single colour LED, whose luminous intensities are modulated sinusoidally using a suitable power supply. The output light of the LED can be easily and accurately modulated by a suitable input voltage V_{in} of the amplifier. And a reference detector whose frequency response is calibrated and covers the measurement frequency range is used for comparison.

The signal-to-noise ratio (SNR) of the measurement instrument needs to be large enough so that measurements of fluctuations in the signal are not significantly affected by noises. The noises in the TLM measurement cannot be easily reduced by time-averaging. For a TLM measurement instrument, noises may differ with the applied measurement range, sampling rate and low-pass filter if applicable. The measurement of baseline noise can be realized by taking the readings for a certain duration when the detector is covered. To characterize the noise of an instrument for TLM measurement, an index named noise-equivalent modulation is proposed in this work. And several kinds of TLM measurements are measured to verify the availability of this index.

3. Results

Through the experiments, the linearity index f_3 in current CIE published documents can be used to characterize a TLM measurement instrument, under the prerequisite that the lower limit of the range being determined. The results will be involved in the full paper.

To characterize the frequency response, the peak-to-peak amplitude of the instrument's output waveform of the measured sinusoidal light at different frequencies with constant modulation depth is measured and normalized with respect to a reference value, written as $A_{\mathrm{rel}}(f)$ (in percentage). When the frequency response extends down to DC, the chosen reference value typically has a frequency near 0 Hz, here 10 Hz value is taken. The $A_{\mathrm{rel}}(f)$ is the frequency response of the measurement instrument, and it can be illustrated in a figure. With the reference source and reference detector described above, several instruments have been measured, and the figures will be illustrated in the full paper.

The frequency bandwidth is the frequency range in which the measured waveform is proportional to that of the input light signal, and the upper limit is used to characterize the frequency bandwidth, f_{BW}. Generally, the frequency of -3dB point, i.e. the point where the $A_{\mathrm{rel}}(f)$ decreased to 0.707, is taken as the frequency bandwidth. However, for TLM measurement, the frequency bandwidth f_{BW} is better to be determined according to the acceptable measurement uncertainty. For example, f_{BW} is taken at the frequency where $A_{\mathrm{rel}}(f)$ falls to 95%.

The noise of a TLM measurement instrument can be characterized by noise-equivalent modulation, which means a noise is superimposed to the input light modulation of the detector equalling to the maximum fluctuations, for a stated measurement range and sampling rate of the measuring instrument.

In order to make it more universal and independent of a specific measurement, a series of practical measurements using different instruments have been conducted and analyzed, which will be listed in the full pap.

4. Conclusions

Measurements of TLM and their accuracy are influenced by various parameters, such as operational conditions, properties of light sources, as well as characteristics of the applied measurement instrument. The characteristics of these instruments alone do not allow the determination of the measurement uncertainty for a specific measurement task. Nevertheless, it is generally true that instruments with "better" characteristics in most cases produce smaller uncertainties than instruments with "worse" properties, which means that the instrument plays a key role in TLM measurement. So, it is important to characterize the TLM measurement instrument accurately. As the general quality indices which are applicable have been defined by other documents, this document mainly discusses the indices related to TLM measurement, giving clear and unambiguous definitions for these quality indices, defining measurement procedures and methods for numerical evaluation of these indices, and laying foundations for the subsequent work of TR.

FIELD MEASUREMENT OF TLM QUANTITIES IN LIGHTING SCENARIOS

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Abstract

A field measurement is considered to be any measurement that is not done under controlled laboratory conditions, e.g. a measurement in a classroom, an office or outdoors. However, the lighting in actual scenarios is what human visual perceived directly, and it is meaningful to evaluate the TLM quantities on field. With traceable TLM measurement equipment and proper assessment of the environmental conditions it should be possible to provide traceability to field measurements.

There are many factors influencing the TLM quantities of a specific lighting scenario. As stated in CIE TN012, when the field measurements are reported (or results discussed), the conditions under which the measurements were performed should be listed, as similar as possible to how laboratory measurements are reported. Although the field measurements results of TLM quantities may be different from laboratory measurements even with the same equipment, it is generally true that lighting equipments with “better” TLM performance can produce better lighting environment. To prove that and for further understanding of the TLM effect on the bases of lighting additive law, a series of TLM measurements and comparisons have been conducted, including:

1. TLM quantities measured in laboratories and on-site in classrooms located in different parts of China, using the same batch of luminaires;
2. TLM quantities measured at several locations of a room, with the same luminaire installation method but different luminaire types;
3. TLM quantities measured on-site under the limited controllable conditions when changing the power supply and outer environmental lighting levels;
4. TLM quantities measured on-site when changing the parameter setup of the measurement instrument, for example, sampling time, sampling frequency, cut-off frequency of the anti-aliasing filter, etc.

The illuminance measurement geometry is adopted in the field lighting measurement, and the measurement instrument is EVERFINE LFA-3000 which is traceable to NIM China. To ensure the accuracy, the sampling sampling detector is mounted in an anti-shake fixture to avoid shock and vibration during the field measurement. Except for item 3), other field measurements are conducted without outer environment light disturbance.

On the basis of the measurement comparison, the main factors affecting the field measurement of TLM quantities are further considered, and the measurement uncertainty in specific lighting scenarios is analyzed.

Detailed measurement results and the example of uncertainty budge for the field measurement of TLM quantities in a classroom will be illustrated in the full paper.

TOWARDS MODELLING THE VISIBILITY OF THE PHANTOM ARRAY EFFECT

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Abstract

The phantom array effect is the least studied temporal light artefact (TLA) among the three defined in TR 249:2022 by CIE Technical Committee 1-83 "Visual Aspects of Time-Modulated Lighting Systems." Models that predict the visibility of both flicker and the stroboscopic effect have been detailed by the CIE and the IEC.

When it comes to the phantom array effect, its visibility in real-life situations is most often described as 'in an otherwise dark environment', during 'night driving conditions', and from a 'backlight of a car at night'. Thus, almost all laboratory investigations on the phantom array effect adopted experimental conditions with bright light sources in a dark room (i.e., < 1 lx). Multiple psychophysical investigations have studied the phenomenon qualitatively or quantitatively. Variables that have been employed in these studies can be categorized as: 1) individually related characteristics: the age and gender of the observer, and maybe also the saccade speed (i.e., variations around the average speed determined by the size of the saccade amplitude); 2) characteristics of the light modulation: the time-averaged luminance/illuminance for direct/indirect viewing conditions, the temporal frequency, the modulation depth, the shape of the waveform, the duty cycle, and the chromaticity of the light source; and 3) characteristics of the viewing geometry: foveal or peripheral observance, the size of the light source (i.e., the subtended visual angle), the spatial distribution of the light source (i.e., with sharp or smooth edges), the saccade amplitude (which usually is fixed in an experimental setting), and the relative motion of the light source to the observer. Some of these studies measured the visibility of the phantom array effect, but others asked the observers to rate the noticeability and/or annoyance of the phantom array effect.

The results of all these investigations can be summarized as follows. The visibility of the artefact did not depend on the observer's gender, but did depend on the age; younger observers were reported to be more sensitive to the phantom array artefact. It was concluded that a higher luminance/illuminance, a higher modulation depth, and a smaller size of the light source resulted in higher visibility of the artefact. The shape of the waveform also played a role. The square waveform was more visible than the sinusoidal waveform for the same duty cycle, modulation depth, and temporal frequency. The visibility of the phantom array effect was also colour dependent, with blue light resulting in a lower sensitivity than red, green, and white light. Not all studies drew consistent conclusions regarding the effect of temporal frequency. Some studies concluded that the phantom array effect became less visible when the frequency increased, while others showed a band-pass-shaped curve, with a peak at around 600 Hz. Combining all these results would facilitate the determination of a visibility model, but not all studies measured visibility nor used the same protocol, and hence not all data can straightforwardly be combined.

In addition, substantial individual differences in visibility of the phantom array effect were found. These differences can be partly attributed to age, maybe partly to differences in executing the experimental task, and maybe also to individual differences in eye movements. In CIE TN 008:2017 (prepared by CIE Reportership 3-32 of Division 3 "Interior Environment and Lighting Design"), it was also pointed out that eye movements differ greatly in pattern and velocity. Since the phantom array effect is visible as a consequence of an interaction between an observer's eye movements and the temporal light modulation, measuring the actual eye movements while measuring the visibility of the artefact may show added value in explaining individual differences in seeing the phantom array effect. On the other hand, it is known from the literature that the average saccade speed is related to the saccade amplitude with a

maximum speed of about 500 deg·s^{-1}. So, how far small fluctuations around the average speed determine individual differences in viewing the artefact still has to be explored. Only a limited number of studies recorded the eye movements of the observers during the experiment, and thus there is a lack of in-depth analysis of the relationship between the visibility of the phantom array effect and variations in eye movements. Recording and reporting eye movement data using an eye-tracking device would facilitate understanding to what extent including eye movements in the visibility model of the phantom array effect is needed.

Some researchers discuss their findings in terms of contrast, i.e., the ratio between the target (the light source) and the background (the surrounding). Expressing the visibility of the phantom array effect in terms of the contrast of the average luminance of the light source with the background luminance does not allow them to conclude whether a change in sensitivity is due to a change in the absolute luminance level of the light source or in its contrast with the background. Thus, to disentangle these two effects, one needs to systematically change the luminance of the light source independently of the luminance of the background.

In summary, designing a visibility model for the phantom array effect requires more systematic data on the visibility threshold, measured in a consistent way, including its dependency on the modulation frequency. These measurements should disentangle the effect of the average luminance of the modulated light source and the luminance of the background. In addition, the effect of specific eye movements can be established. Therefore, we are currently designing a set of psychophysical experiments using a two-interval forced-choice (2IFC) procedure to determine at which modulation depth the phantom array effect becomes just visible. This visibility threshold will be measured systematically as a function of temporal frequency, and for different values of the luminance of the light source and luminance of the background. The eye movement data will be recorded simultaneously during these experiments. First results will be presented at the CIE Symposium on the Measurement of Temporal Light Modulation in October 2022.

MINIMISING THE UNCERTAINTIES IN THE CALCULATION OF STROBOSCOPIC EFFECT VISIBILITY MEASURE

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Abstract

1. Motivation, specific objective

Inconsistencies have been observed in the calculation of the quantity, stroboscopic effect visibility measure (SVM) for the recommended verification waveforms specified in the technical report, IEC TR 63158, dependant on the calculation method applied.

The technical report provides reference to a recommended Stroboscopic effect visibility measure toolbox available at Matlab Central for the calculation of SVM. When using this method for determination of the SVM values for several recommended verification waveforms, large uncertainties up to 2.2% are incurred. These uncertainties fluctuate in magnitude for a given verification waveform with sampling rates varying from 10 kHz to 50 kHz. It is conceivable that the application of this calculation method to actual (complex) temporal light waveforms could give rise to even larger uncertainties.

The objective of this study is to reduce the error in calculated results for SVM of these verification waveforms, while also improving the reproducibility across different sampling rates.

With the increasing demands for testing laboratory accreditation for TLM quantities, the International Energy Agency (IEA) 4E Solid State Lighting Annex is planning on conducting an Interlaboratory Comparison (IC 2022) for the measurement of TLM of solid-state lighting (SSL) products. Designed to meet proficiency testing requirements, IC 2022 is organised to compare measured TLM waveform data and calculated *stroboscopic effect visibility measure* (SVM, M_{VS}) as well as *short term flicker index* (P_{st}^{LM}) of comparison artefacts. It is therefore critical to the endeavours of IC 2022, to resolve the identified issues in the referenced method for calculation of SVM values and achieve accurate SVM results with minimal uncertainties prior to commencement of IC 2022.

2. Methods

The problem arises from the method of peak finding used in the recommended Matlab program, which employs a simple maximum value “findpeak” function that introduces significant error in its identification of peak amplitudes and peak frequencies. Nulling to the nearest power of 2 above the sample size is used in order to enhance frequency resolution of the Fast Fourier Transform (FFT), but this results in peak frequencies away from integer numbers.

We propose essential improvements to this calculation method to resolve this issue. The uncertainty on SVM calculations by this method can be minimised by improving the accuracy of the estimation of peak frequency and amplitude, specifically through:

- increasing the frequency resolution for peak identification by increasing the nulling in the FFT
- introducing minimum thresholds for peak identification, to discard peaks arising from signal noise and,
- using optimal interpolation methods, using the three FFT frequency bins around each true peak to determine its parameters (frequency and amplitude).

Measurement of other reference waveforms implemented on a programmable light generator will then also be evaluated and compared.

3. Results

Initial calculations for the verification waveforms, which are square and sinusoidal waveforms, have been performed. Simulation of these waveforms at 10 and 50 kS/s and 1 s duration, have shown large deviations from the given reference values of SVM dependent on the calculation method applied.

Using the recommended Matlab script yields deviations in the order of 0.2% - 2.2%. Using an FFT without nulling, (i.e., creating frequency bins at integer values), shows deviations lower than 0.1 %. This however will not yield adequate results for real measured temporal light waveforms with non-integer component frequencies.

Initial investigations suggest that:

i. A computationally intensive improvement to the methodology is demonstrated by incrementally increasing the nulling in the FFT (i.e., higher orders of the power of 2) which increases the frequency resolution to a point where it converges to the result with minimum deviation from the reference values.
ii. Where computational speed is a priority, suitable accuracy can be achieved using a combination of limited nulling in the FFT and peak finding algorithms using three FFT frequency bins around the maximum value for real-time, accurate determination of the true peak frequency and amplitude, and calculation of SVM.

Calculations will be given for simulated and measured reference waveforms.

4. Conclusions

It is important that recommended methods for the calculation of SVM offer minimal uncertainties that remain consistent across a range of temporal light waveform measurement parameters (e.g., sampling rate and duration). Without such consistency, it is challenging to produce reliable results that see agreement across laboratories that employ different commercial and in-house temporal light measurement systems.

These issues, and others concerning uncertainty and laboratory proficiency in SVM measures will require resolution in preparation for the International Energy Agency (IEA) 4E Solid State Lighting Annex IC 2022.

IMPROVEMENT IN THE TEMPORAL LIGHT ARTEFACT METRICS OF COMMERCIAL LED LAMPS

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Abstract

1. Motivation, specific objective

The new EU Ecodesign regulation set requirements for lighting equipment on the European market starting September 2021. This regulation defined restrictions for two temporal light artefact (TLA) metrics, short-term flicker severity index (P_{st}^{LM}) and stroboscopic visibility measure (SVM): $P_{st}^{LM} < 1$ and SVM < 0.4, to limit TLA effects. For both metrics, the value 1 means that an average observer has 50 % chance to perceive these TLAs. When these values are less than one, as their limits are set, they are not visible on the average.

We wanted to study the development of luminaires to observe how severe the TLA metrics of the consumer-grade LED lamps were before and after the regulation became in force. Furthermore, we also wanted to collect information on how the manufacturers have changed LED lamps to meet the requirements of EU Ecodesign regulation.

2. Methods

In total 80 different commercial E27-based LED lamps from multiple manufacturers were measured for TLA visibility with a validated integrating sphere setup. The data were gathered with an oscilloscope and then P_{st}^{LM} and SVM values were calculated with a MATLAB implementation of a flickermeter and SVM-meter. The lamps were driven with an AC power source and the input voltage and current were monitored with a power analyzer. We also provide uncertainty estimation for the results, based for example on different digital implementations of the flickermeter and SVM-meter.

The lamps could be divided into four different LED driver topologies A-D. Type A lamps have a full-wave rectifier with a smoothing capacitor and a DC-DC converter circuit at the output, type B lamps have a capacitive dropper circuit, type C lamps have a linear constant current regulator circuit, and type D lamps have switch-mode driver circuits. The type of the lamp driver can be distinguished by investigating the waveform of the input current in the system with the power analyzer.

Most of the lamps (60 out of 80) were acquired prior to the EU Ecodesign regulation during the year 2016 or before. The remaining 20 lamps were purchased in December of 2021. The nominal luminous flux of the older lamps ranged from 150 lm to 2452 lm, and their nominal electrical power values were between 1 W and 20 W. Similarly for the new lamps, nominal luminous flux was between 30 lm and 1521 lm, and the nominal power values ranged from 0.6 W to 14 W.

3. Results

In our study, all four different lamp driver types were found in the 80 lamps that were measured. Within the group of older lamps, 42 were type A lamps, 4 type B lamps, and 14 type D lamps. In the group of new lamps, only type A and C lamps were present, 18 and 2 pieces, respectively. It was found out that the driver topology had a significant effect on the TLA metrics of the lamps. All lamps were found to have P_{st}^{LM} value below 0.30, being less than the threshold of 1 of the EU Ecodesign regulation. The type A lamps had the best P_{st}^{LM} behaviour when comparing to lamps with other driver types. This is quantified in the average of P_{st}^{LM} values of 0.03 for type A lamps, while it was approximately 0.1 for lamp types B, C and D.

Considering the SVM, the driver topology had even more significant effect. Most type A lamps had practically zero SVM for both the older and the new lamps. Only one type A lamp (in the older lamp group) had SVM larger than the threshold value of 0.4 set in the regulation. However, lamp types B and D had on the average SMV higher than 0.4, type D having average SVM > 1 and type B having average SVM > 0.4. One of the two type C lamps had SVM < 0.4, and the other had SVM > 0.4, being the only new lamp that failed to comply with the Ecodesign regulations. The uncertainties of the numerical values of both TLA metrics are so small that they do not affect the above results.

4. Conclusions

By comparing the TLA results obtained from the older and new lamp groups, it can be concluded that the luminaire manufacturers have taken the EU Ecodesign regulation into account. This has been done by favouring the type A LED driver topology, which in general results in lower P_{st}^{LM} and SVM values as compared with the other driver types. They also have stopped using the B and D type lamp driver topologies which exhibit bad TLA behaviour.

NOVEL IMPLEMENTATIONS OF DIGITAL METERS FOR FLICKER AND STROBOSCOPIC EFFECT

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Abstract

1. Motivation, specific objective

Due to the different operating principles, LED sources have different Temporal Light Modulation (TLM) behavior to incandescent lamps. These TLM effects can result in visible effects, called Temporal Light Artefacts (TLA) that can be harmful to humans. Initially, characterization methods for TLAs were developed for incandescent lamps. The EU Ecodesign regulations set limits that LED manufacturers need to abide in the case of two of these metrics: Short-term flicker severity index (PstLM) and Stroboscopic effect visibility measure (SVM).

PstLM and SVM can be calculated from the light waveform measured with digital TLA meters. There is a freely available MATLAB-implementation by Philips Lighting which is referred in the IEC TR 61547 as a suitable TLA meter for both PstLM and SVM. We observed some anomalies in the implementation with the built-in MATLAB functions *butter()* and *filter()* used to discretize the filters. It seems that these functions do not follow the analog response of the band of interest, when using a sampling frequency f_s = 50 kHz. Thus, novel flicker and SVM-meters were created to address the question on the reliability of the TLA characterization results.

2. Methods

Flickermeter (PstLM) and SVM-meter implementations can be divided into four different blocks A-D.

In flickermeter, Block A works as an input adapter for the measured light waveform. The light waveform is normalized with its average value. In Block B, the time-resolution effect of the human eyes is simulated. This is achieved by three different filters, a 1st order high-pass filter, 6th order Butterworth low-pass filter and a specialized bandpass filter, which has a peak at 10 Hz, mimicking the eye-brain frequency response of an average observer. In Block C, the brain response for the flicker sensation is simulated. The input signal is first squared, which represents the non-linear perception of the flicker in the human brain. This is followed by a 1st order low-pass filter, which simulates the brain memory storage effect. Then, the signal is scaled with a scaling factor S defined in such a way that the maximum instantaneous flicker gets a value of P_{inst} = 1, when a reference relative illuminance waveform is fed to the light flickermeter. In Block D, this scaled instantaneous flicker sensation P_{inst} is analyzed statistically with Cumulative Distribution Function (CDF) and the value of PstLM is calculated from CDF.

For SVM-meter, Block A is identical to the flickermeter's Block A. Block B calculates the Power Spectral Density (PSD) from the normalized signal via a Fourier transform. Before the Fourier transform, standards recommend using Hanning-windowing to account for spectral leakage effects caused by possible non-integer number of periods in the sampled data. This windowing causes attenuation that needs to be corrected before the Fourier transform. Block B results in a frequency spectrum $C(f)$. In Block C, the output of Block B is weighed by visibility threshold modulation depth for stroboscopic effect. In Block D, components of the weighed spectrum are summed in Minkowski space resulting in the SVM-value.

We implemented both PstLM and SVM meters in MATLAB by following the IEC TR 61547. For the flickermeter, the digital implementation of the analog filters was done using Tustin's method. The filter transfer functions were organized to zero-pole-gain-representation (ZPK) and the filtration was conducted with *lsim()*-function instead of *filter()*. This method was found to be more accurate in MATLAB with higher sampling frequencies, when compared to regular polynomial form transfer function models combined with *filter()*-function. The scaling factor *S*=1101910.830 in Block C was calculated from the discretized transfer functions. This is only 0.116 absolute units smaller than the ideal analog *S*, demonstrating the high quality of the novel digital implementation.

For SVM-meter, the Hanning window was modelled as described in the standard, and the coherent power gain was compensated. For Fourier transform, we used MATLAB *fft()*-function. This SVM-meter utilizes the built-in peak-finding algorithm of MATLAB. The minimum peak distance used was 1 Hz as recommended in standards. The peak caused by the 0 Hz DC component was discarded, as it is a peak in any light source.

The differences between the two flickermeter implementations were studied using IEC TR 61547 reference light waveforms. Philips has provided a MATLAB-script that creates these 35 reference waveforms. The requirement is that the reference light waveforms should have a percentage error of less than 5%.

For SVM-meter, there are nine reference waveforms given by IEC TR 63158, five of which are rectangular and four sinusoidal with different modulation frequencies and depths. For each waveform, there is a given reference value as the target.

Furthermore, the performance of the flickermeters and SVM-meters was also compared in measurements of real LED lamps.

3. Results

Results for flicker were acquired by running the 35 reference waveforms through the novel implementation and Philips implementation, using the sampling frequency of 50 kHz and duration of 200 s. Both methods gave percentage errors of less than 5% and are thus acceptable. However, at frequencies between 0.325 Hz and 8.8 Hz, the novel implementation reduced the percentage errors from 2% to less than 0.1%. At 13.5 Hz, the results were practically the same, and at 33.3 Hz, the percentage error of 1% reduced to 0.3% with the novel implementation.

With SVM-meters, the errors are less than 1% in all but one case, and both implementations also pass the 5% percentage error limit. With the novel implementation, the errors are smaller than with the Philips implementation, except for one case.

4. Conclusions

The results confirm that the freely available flickermeter and SVM meter pass the 5% error limit, and the results obtained with them are reliable with the reference waveforms and in measurements of real LED lamps. However, the novel implementations of the flickermeter and SVM meter generally produced significantly smaller errors with test waveforms than the freely available implementations. This is most likely due to careful treatment of the scaling factor *S* as compared to the experimentally found *S* that is used in Philips flickermeter and some fundamental problems with MATLAB functions *filter()* and *butter()*.

EVALUATION OF DATA ACQUISITION SYSTEMS FOR MEASUREMENT OF TEMPORAL LIGHT MODULATIONS

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Abstract

Compared to traditional incandescent lamps, solid-state light sources are prone to unwanted and perhaps hazardous temporal light modulations (TLMs), which are measurable change of the light level or the spectral distribution of light over time. TLMs may cause undesired effects on human perception, health, performance, and safety, thus, it should be measured to obtain associated temporal light artefacts (TLAs).

The TLM of a light source may vary with the measurement setup, electrical driver, and power supply. The goal of a TLM measurement is to accurately acquire the TLM waveform (often with high-frequency components) without distortion under a specified condition. TLM is measured using a high-speed data acquisition (DAQ) system, which typically consists of a photometer, a transimpedance amplifier, a lowpass electrical filter, and an analog-to-digital converter (ADC). The uncertainty of a TLM measurement tends to be large compared to that of a DC signal measurement using a DMM. Due to the required high-speed sampling (>10,000 samples per second) the achievable uncertainty of each measured signal is limited. Further, the measured TLM waveform is often distorted due to imperfections in the DAQ system (e.g., nonlinearity, timing jitter, and imperfect lowpass filter, etc.). To assist measurement of TLMs, CIE published a Technical Note TN 012:2021 that provides general guidance.

We are evaluating many DAQ devices for measurement of TLMs to develop the TLM measurement capability. The DAQ devices includes 12-bit, 16-bit, 18-bit, and 24-bit digitizers, and digital multimeters with a built-in high-speed digitizing function. To exclude variation due to different measurement setups, lamp drivers, and power supplies, we use a pulsed current source to drive an LED to generate various TLM waveforms and trig the DAQ systems to measure the same signal from the photometer simultaneously. The measured TLM waveforms are compared directly. The results of this evaluation will be presented.

IEA 4E SSL ANNEX INTERLABORATORY COMPARISON OF MEASUREMENTS OF TEMPORAL LIGHT MODULATION – PLAN

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Abstract

1. Motivation, specific objective

Many national and regional regulations and voluntary programmes on energy efficient lighting products now require limits for temporal light modulation (TLM) quantities for LED lighting products. This highlights the importance and urgency of verifying the level of agreement in measurements of TLM quantities and investigating the validity of measurement uncertainties reported by the laboratories measuring TLM quantities. In addition, there are demands for testing laboratory accreditation for TLM quantities and proficiency testing is the preferred pathway. To meet these needs in TLM measurements, the International Energy Agency (IEA) 4E Solid State Lighting Annex is planning on conducting an Interlaboratory Comparison (IC 2022) for the measurement of TLM of solid state lighting (SSL) products. This builds on the experience from its previous two interlaboratory comparisons (IC 2013, IC 2017) for measurement of SSL products. IC 2022 is organised to compare measured TLM waveform data and calculated *short term flicker index* (P_{st}^{LM}) and *stroboscopic effect visibility measure* (SVM, M_{VS}) of the comparison artefacts.

2. Design of the comparison

IC 2022 is planned as a technical study but will also be designed to serve as a proficiency test (PT) for SSL testing accreditation programmes, by maintaining compliance with ISO/IEC 17043 (Conformity assessment - General requirements for proficiency testing). The IC 2022 comparison protocol will be based on - and conform to - IEC TR 63158 (Equipment for general lighting purposes - Objective test method for stroboscopic effects of lighting equipment) and IEC TR 61547-1 (Equipment for general lighting purposes – EMC immunity requirements - Part 1: Objective light flickermeter and voltage fluctuation immunity test method). Thus, if recognised by accreditation bodies, the IC's test reports may also be used as PTs for regional and national test methods based on IEC TR 63158 and IEC TR 61547-1. The comparison protocol will also consider the recommendations in CIE TN 012:2021.

The measurement quantities to be compared are:

1) TLM quantities
   a) Short-term flicker index (P_{st}^{LM}), and
   b) Stroboscopic effect visibility measure (SVM, M_{VS}).
2) Optical waveform data
   a) for P_{st}^{LM}
   b) for SVM (M_{VS})

For the waveform data, the normalisation procedure and file format in CIE TN 012:2021 are to be used. The participants are also to report the dominant frequency and modulation depth (MD) and measured electrical quantities: RMS voltage, RMS current, Active power, frequency, and current THD, some of which may also be compared.

For comparison artefacts, four LED lamps (ART-1 to ART-4) and one TLM generator source (ART-5) will be used. The four LED lamps have designation A60 with E27 base and are rated as 230 V AC, 50 Hz, with the following TLM waveforms:

- ART-1 has complex TLM waveform,
- ART-2 has high P_{st}^{LM} value and low SVM (M_{VS}) value,
- ART-3 has low P_{st}^{LM} value and high SVM (M_{VS}) value,

- ART-4 has low P_{st}^{LM} value and low SVM (M_{VS}) value.

ART-5 is a TLM generator light source and may be used for several pre-set waveforms for specific features.

3. Method

Two to four Nucleus Laboratories with suitable facilities and recognition in optical measurements will be sought to run IC 2022 confidently and effectively. These Nucleus Laboratories will offer their commitments to serve this IC, and they may serve as reference laboratories to run measurement rounds with participants in different regions of the world.

Another option may be that one or two similarly qualified laboratories (called Operational Nucleus Laboratory) will serve as the reference laboratories to carry out the measurement rounds of IC 2022, while other Nucleus Labs (called Supporting Nucleus Laboratory) will only participate in a comparison among all Nucleus Laboratories to verify agreement in measurement results and to establish the reference values of the comparison. These options will be decided based on the availability and capacity of the Nucleus Labs and the total number of participants.

Thus, IC 2022 will be conducted in two parts:

1) A comparison among the Nucleus Laboratories (called IC 2022 Nucleus Laboratory comparison) to compare the measurements between all Nucleus Laboratories using the IC 2022 comparison protocol to confirm the competence and equivalence of the Nucleus Laboratories and to establish the reference values and their uncertainties for comparison quantities for each artefact; and

2) Measurement rounds of IC 2022 with participating laboratories to assess the variations of measurement results among all participants and also to serve as PT for each participant.

The measurement rounds will be carried out as bilateral comparisons between each participant and the assigned Nucleus Laboratory. The Nucleus laboratory will: (1) prepare and measure the set of comparison artefacts, (2) ship them to the participant, (3) measure them again upon their return after participant's measurement, and (4) carry out data analysis. In case the two measurements (before, after) by the reference laboratory for a particular artefact do not reproduce sufficiently, that four-step process will be repeated for that artefact.

4. Status

A survey for potential participants for IC 2022 is being circulated among members of the lighting metrology community. The comparison protocol and official announcement of IC 2022 are being developed. The IEA 4E SSL Annex has established a liaison with the EMPIR project – Metrology for Temporal Light Modulation (MetTLM) and will coordinate the efforts of IC 2022 with this project.

This paper will provide further details on the TLM waveforms selected for IC 2022, analyses on stability of similar LED lamps as comparison artefacts for waveform, P_{st}^{LM} and SVM values, as well as an update on the IC 2022 comparison protocol and the status of the Nucleus Laboratory comparison.

DEVELOPMENT OF A CONTROL SYSTEM TO EVALUATE THE IMPACT OF ARTIFICIAL LIGHT MODULATION ON INSECTS

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Abstract

1. Motivation, specific objective

The rise of Light Emitting Diodes (LEDs) in public lighting has a positive impact on society regarding safer traffic conditions. However, common side effects are the amplification of light pollution and a hitherto almost completely unknown impact on fauna and specifically nocturnal insects. Artificial light at night (ALAN) has shown to affect insects by e.g. attraction, interfering with pollination, feeding, chemical communication, mating behavior, and initiation of diapause. A thorough understanding of the complex relationship between fauna and ALAN is thus required.

The effects of public lighting on bats and glowworms have been studied in the past, although the results are still under debate. This subsequent expertise is already being used by innovative cities like Ypres, Belgium and Worcester, United Kingdom to create more fauna friendly habitats. In these cases, the spectral distribution of LED-based public lighting is adjusted with an emphasis on 600-750 nm as to minimize bat disturbance in certain key areas and flight routes. Similarly, our goal is to achieve a street-lighting source with customized lighting properties that allows the creation of urban insect highways through flickering-provoked positive and negative insect phototaxis (a movement-based response to the stimulus of light). By strategically guiding insects through urbanization into clusters of nature-dense areas, biologists can contribute to the preservation of local ecosystems and by extent the well-being of humans as well. Thus, to adjust and create a harmonious environment for both humans and other animals there is a dire need of trustworthy studies and the knowledge that follows.

To solve the issue of declining urban insect populations due to ALAN, the information gathered from this research can be used first and foremost to incorporate suitable flickering in public lighting. It might become possible to control insect phototaxis by means of identifying flicker frequencies that evoke (positive or negative) phototaxis by nocturnal insects. E.g., in the case of malaria-carrying mosquitoes, negative (repelling) effects might be favorable for application. The flicker fusion threshold has proven to be different for humans and different kind of insects, sequential it might be possible to adjust public lighting modulation with drastic consequences and insects but none for humans. Secondly, insects have a different visual spectrum than humans and by using future awareness on this dissimilarity, it might be possible to create a spectral distribution that is less disruptive for insects while also constitutes a white light with an adequate Color Rendering Index (CRI) that is conform to EN 13201 Road lighting.

2. Methods

The influence of a specific lighting setting on insects is measured by taking a picture of a light source. Four different case setups is secured to trees on four different locations across the Vrije Universiteit Brussel (VUB) main university campus ensuring optimal statistical distribution. These locations are absent of other artificial lighting sources. Pictures are taken

based on a combination of delay and the triggering of an infrared (IR) motion sensor. Measurements are performed in May and June 2022, spanning 21 testing nights in total. The collected data is processed immediately after.

The case study setup including a grit powered control system and light source is built. The control system includes multiple sensors, an infrared camera and a microprocessor which runs an automated script to collect and process relevant data, such as lighting conditions (flicker frequency, spectral distribution, illuminance levels of the artificial light source) and environmental conditions (temperature, humidity, wind speed, illuminance of the sky). The light source consists of individually addressable RGBW LEDs mounted below a diffusing screen to achieve a uniform luminance distribution. Measured data and images taken by the infrared camera are automatically forwarded to researchers. The control system can collect data for over several weeks without human interference in the nearby environment. Counting of the insects is done manually using the pictures. Density is used as a unit, rather than total amount of a species group. Based on a literature study regarding insect behavior, a list of circumstances was assembled that could affect the insect presence studied in this research. To rule out parameters that could affect the integrity of its conclusions like temperature, humidity, wind speed, illuminance of the sky and general weather patterns like rain and moon phase are considered.

The first stage of the research aims to identify which frequencies of flickering are attracting, repelling or neutral to the following species groups, abundant in the test area: Lepidoptera, Coleoptera and Hemiptera. In a second stage, the gathered data is used as a control group while new parameters like spectral distribution or luminous flux become the experimental intervention group.

3. Results

At the time of writing, the setup was built and measurements are starting as of now, spanning 21 nights in total. We expect the first results to emerge by mid-July, in due time to present them at the conference.

4. Conclusions

After a measurement campaign of 21 nights, data processing will occur and it will be possible to get an insight in how to control insect phototaxis by means of identifying the causal relation between flicker frequencies and (positive or negative) phototaxis by species-specific nocturnal insects.

VERIFICATION OF A TEMPORAL LIGHT MODULATION MEASUREMENT FACILITY AT THE NATIONAL METROLOGY INSTITUTE OF SOUTH AFRICA

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Abstract

1. Motivation, specific objective

Temporal light modulation (TLM) can have adverse effects on users of lighting products, including an increase in fatigue, and acute health problems such as epileptic seizures. Therefore, accurate measurements of TLM quantities are critical. The National Metrology Institute of South Africa (NMISA) is setting up a facility that will enable both the measurement of TLM of lighting products as well as the calibration of equipment used for measuring TLM. This will ensure that traceable TLM measurements can be provided to customers and will support proposed local and regional regulatory requirements. The objective of this study is to verify the use of two commercially available TLM measurement devices for the measurement of TLM quantities.

2. Methods

A programmable AC power source and two TLM measurement devices have been procured and installed in the NMISA LED laboratory. Following the “CIE Guidance on the Measurement of Temporal Light Modulation of Light Sources and Lighting Systems” (CIE TN 012:2021) and IEC TR 61547-1:2020 on “Equipment for general lighting purposes - EMC immunity requirements - Part 1: Objective light flicker meter and voltage fluctuation immunity test method”, both measurement devices were used to determine the TLM quantities and flicker immunity of typical lighting products available on the market. The uncertainty of measurement was evaluated using manufacturer specifications and empirical tests, as far as possible. A comparison between the results of the two TLM measurement devices was used to verify the use of the two devices for performing TLM measurements. The software supplied with the two devices was also verified using in-house developed software and data analysis of the measured signals.

3. Results

We present the results from the two TLM measurement devices including the estimated uncertainty of measurement for comparison. The device software results were also compared with the in-house developed software results.

4. Conclusions

Conclusions were drawn on whether the two measurement devices can be used for the accurate measurement of TLM quantities. Issues experienced during the set-up of the TLM measurement facility are highlighted, as well as possible future improvements.

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