DOI: 10.7795/810.20240408

SYSTEMATIC ERRORS OF TEMPORAL LIGHT MODULATION METRICS RELATED TO SAMPLING DURATION

Annika Stein, Philipp Wiswesser, Johannes Ledig

Physikalisch-Technische Bundesanstalt, Braunschweig and Berlin, Germany

Acknowledgement: This work was carried out within the joint normative research project 20NRM01 MetTLM which has received funding from the EMPIR programme, co-financed by the Participating States and the European Union's Horizon 2020 Research and Innovation Programme.

SYSTEMATIC ERRORS OF TEMPORAL LIGHT MODULATION METRICS RELATED TO SAMPLING DURATION

Stein, A.[1], Wiswesser, P., Ledig, J.[1]
[1] Physikalisch-Technische Bundesanstalt, Braunschweig, GERMANY
annika.stein@ptb.de

Abstract

Due to the wide range of applications of LEDs, people are exposed to various forms of temporal light artefacts (TLAs) in many everyday situations. It is important to define and evaluate TLAs in order to raise public awareness of this issue one approach is by using imaging. In this work, established metrics for TLM and TLA are discussed regarding systematic errors and uncertainty contributions related to the sampling duration with respect to the periodicity of the waveform are to be shown and estimated.

Keywords: TLM, TLA, Flicker, Stroboscopic Effect, Phantom Array Effect, Flicker Index, sampling duration

1 Introduction

Smart lamps that are dimmable or variable in colour (i.e. tunable white) often exhibit significant temporal light modulation (TLM), namely if not operated at full load and in case dimming is implemented by means of pulse-width modulation (PWM). TLM can lead to temporal light artifacts (TLAs) and can have a negative impact on the health, well-being and safety of humans or animals. Therefore, the new EU Ecodesign Regulation 2019/2020 "Uniform Lighting Regulation" sets limits for TLM. The CIE Technical Note TN 006:2016 defines three types of TLA: flicker, stroboscopic effect, and the phantom array effect. [Dekker, P. 2022], [European Commission 2019]

In a frequency range of 0 to 80 Hz, this effect is called flicker. The fluctuating luminous flux is perceivable by a stationary observer in a static environment, although this perception is often more pronounced in the peripheral field of view. Voltage fluctuations or low-frequency PWM can be causes of flicker. [CIE 2021]
In the frequency range of 80 Hz to 2 kHz, the stroboscopic effect is defined. This effect causes moving objects to be perceived by the human eye not as continuous motion but as individual image sequences. This is due to the periodic flashing of light, illuminating the object only at specific intervals and providing intermittent visual information to the observer. The stroboscopic effect can make rotating objects appear stationary. This occurs when the frequency of the light matches the rotation frequency. [CIE 2016], [CIE 2021]
The third temporal light artifact is the phantom array effect. It is defined as a "change in perceived shape or spatial positions of objects, induced by a light stimulus the luminance or spectral distribution of which fluctuates with time" and it is induced by a saccadic eye movement over a modulated source. Like the stroboscopic effect, the phantom array effect is defined within the frequency range of 80 Hz to 2 kHz. [CIE 2016], [Roberts, J. 2013]
Scalar metrics are already recommended by the CIE for the evaluation of flicker and the stroboscopic effect.

Due to the wide range of applications of LEDs, people are exposed to various forms of TLAs in many everyday situations. It is important to define and evaluate TLAs in order to raise public awareness of this issue. The luminance distribution is very relevant for the evaluation of the TLAs, for which an imaging measurement method with a high-speed camera is very promising [Stein, A. 2023]. TLAs can trigger headaches or even cause epileptic seizures, especially in sensitive individuals. Additionally, they can unconsciously induce stress reactions in the body, which can pose long-term health risks. The stroboscopic effect can make rotating machinery appear stationary, tempting people to reach into the machine and potentially causing serious injuries. It is crucial to recognize these potential risks and implement appropriate measures to minimize the hazards associated with TLAs. This includes, for instance, adhering to safety

standards when designing lighting systems and providing training to educate people about the potential dangers of TLAs. Such measures can significantly reduce the risk of injuries and health problems caused by TLAs. [Wilkins, A. 2010], [IEEE 2015]
In this work, systematic errors and uncertainty contributions related to the sampling duration with respect to the periodicity of the waveform are to be shown and estimated.

2 TLM measurements using imaging measurement devices

The measurement of temporal light modulations refers to the detection and evaluation of variations in light intensity or colour over time. These measurements can be performed using specialized devices such as illuminance photometers (as TLM measurement devices). These instruments capture light data over a specific period and enable the analysis of temporal variations. Light scenes with different sources require multiple individual measurements using such spot TLM measurement devices. Using high-speed cameras or imaging luminance measurement devices (ILMD) these scenes can be simultaneously captured and spatially or angularly analysed: A sequence of images of the scene with all active light sources is recorded at the highest possible frame rate (frames per second = fps). Each frame of the sequence can then be evaluated pixel by pixel or by averaged regions using a Python program. The pixels accumulate different amounts of charge depending on the average incident light within the chosen integration time. From the image sequence, the luminance signal waveform can be represented for each pixel of the sensor.

For the given examples, an IDT OS 7 - S3 high-speed camera from Imaging Solutions (Figure 1) is used. It is based on a CMOS sensor with a dynamic signal range of 12/36 bits and a 32 GB DDR ring memory. The sensor employs a global shutter and, according to specifications, has a minimum integration time of 1 microsecond. Image sequences can be captured with rates of up to 4200 fps with full resolution of 1920 x 1280 pixels and with up to 130000 fps with reduced resolution. Additionally, the camera features a Bayer matrix RGB colour filter. [Image Solutions 2020]

Figure 1 – Photo of the high-speed camera IDT OS 7 - S3 from Imaging Solutions GmbH with a ZF.2 Makro-Planar 2/50 lens from Carl Zeiss.

3 Results

This measurement method has many advantages such as visualizing TLM, spatial and angular measurement, and colour representation. But there is a significant drawback when using a high-speed camera or ILMD for measurement, which is the data volume. While spot TLM measurement devices capture data for 1 second and more, requiring only about a few hundred kilobytes of storage, recordings with a high-speed camera at the same sampling duration in HD resolution require a data volume of many ten GB. Storing and processing such data demands a high amount of memory and computational power. To reduce the data volume, the sampling duration can be significantly shortened. The short sampling duration leads to a considerable uncertainty contribution in the progressing flicker index and the SVM. For both metrics, the average value of the signal is a crucial quantity inside the denominator. The progressing average value oscillates around the correct average value and is only correct at the time of each complete waveform period, while the error interval depends on the waveform, i.e. it gets most significant for rectangular waveforms of short duty cycle, and converges to zero for long sampling durations. With a sufficiently large sampling duration in terms of number of complete waveform periods, the resulting error becomes sufficiently small compared to other uncertainty contributions. This is not achieved for a short sampling duration. For short sampling durations, the average value of the waveform and other parameters depending on it must be determined exclusively from a sampling sequence (duration) that corresponds to an integer number of waveform periods.

3.1 Simulation of the TLM with the progressing average value

To illustrate this, a simulation was performed showing a sinusoidal signal A with a modulation depth of 100%, the correct average of the waveform, and the progressing average versus the number of considered samples (Figure 2). The progressing average matches the correct average whenever the considered samples correspond to an integer number of periods. The largest deviation from the correct average occurs when the considered samples correspond to half of the waveform periods. In this case the error is about 10% for 3.5 periods. This error decreases as the number of periods increases.

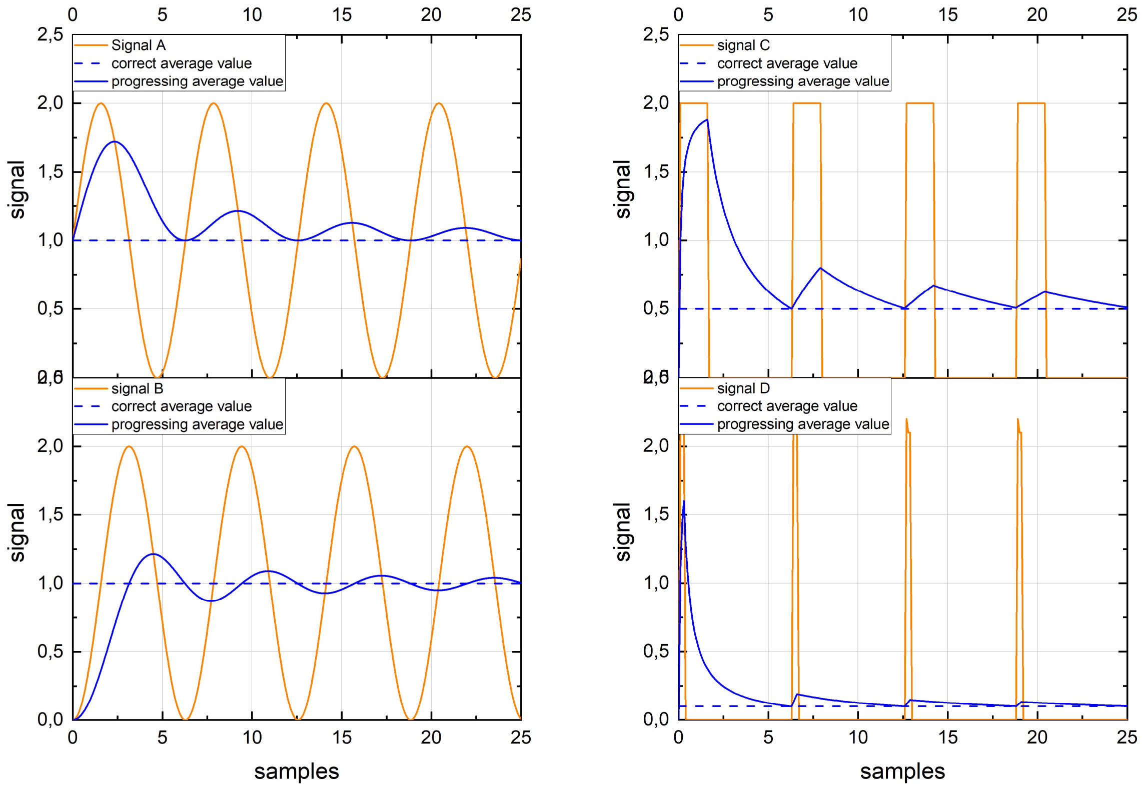

Figure 2 – Simulation of the error at short sampling duration for the progressing average value for a sinusoidal signal (signal A) and a phase shift of 90° (signal B), and a pulse-width modulated signal with a duty cycle of 25 % (signal C) and 5 % (signal D)

Figure 2 also displays signal B, which is phase-shifted by 90° compared to signal A, along with its correct average value and the progressing average value across the samples. Due to the shifted waveform start, the progressing average value oscillates around the correct average value. This results in a smaller absolute deviation, with the highest value occurring when the considered samples correspond to deviates by ¼ or ¾ of a period from the integer number of periods. The maximum error occurring after 3 periods is 5%. When estimating this uncertainty contribution, the alignment with the waveform phase needs to be considered. Aligning the sampling duration to the signal phase, i.e. by using a trigger, would conceal this effect but not eliminate it.

Another simulation shows in Figure 2 the results for a rectangular signal with a duty cycle of 25 % (signal C) and 5 % (signal D). The problem with such a low duty cycle PWM signal is that if the integer period is slightly exceeded, all or part of the peak of the next period is already included in the averaging. The largest deviation from the correct average value is due to the complete inclusion of the following peak.

The maximum deviation (error) from the correct average value of the different phase shift at increasing integer periods are presented in Table 1.

Table 1 – Maximum error for a sinusoidal signal (signal A) and a phase shift of 90° (signal B), and a pulse-width modulated signal with a duty cycle of 25 % (signal C) and 5 % (signal D) by different numbers of periods

periods	max. error signal A	max. errror signal B	max. error signal C	max. error signal D
> 3	≈ 10 %	≈ 5 %	≈ 25 %	≈ 25 %
> 5	≈ 6 %	≈ 3 %	≈ 17 %	≈ 17 %
> 20	≈ 1.5 %	≈ 0.8 %	≈ 6 %	≈ 7 %

3.2 TLM measurements with the progressing flicker index

The average value is needed to determine the flicker index [CIE 2021]:

$$I_{\mathrm{F}} = \frac{A_1}{A_1 + A_2} \qquad (1)$$

where

I_{F} is the Flicker Index;

A_1 is the area of the signal above the average value;

A_2 is the area of the signal below the average value

In this section, the influence of short sampling duration on the progressing flicker index is explained using real measurements. For this purpose, images of LED luminance standards were taken with the high-speed camera. The waveform, intensity, frequency, and duty cycle of the luminance standard can be adjusted via the control software. Figure 3 shows three luminance standards used. [Image Engineering 2022]

Figure 3 – Photo of the LED luminance standards Vega by Image Engineering GmbH & Co. KG

For all measurements, the Vega intensity setting of 10 % and the camera sampling duration of 120 ms were not changed. Such an image sequence at HD-resolution corresponds to a data volume of approximately 7 GB. The influence of the frequency on the uncertainty of the progressing flicker index was investigated on sinusoidal signal of type E with 100 Hz and

signal F with 50 Hz (Figure 4). For the 100 Hz signal, eleven full periods are recorded. When more than eleven periods are considered for the progressive average of the signal, the maximum uncertainty is 3.4%. There is a maximum uncertainty of 2.5 % in the progressing flicker index. For a signal of type F with a frequency of 50 Hz, the number of whole periods is also reduced for the same sampling duration, five whole periods are recorded. This increases the error in the progressing average value to 4 % and the flicker index to 5 %.
To demonstrate the effect of the short sampling duration with varying duty cycle on the progressing flicker index, signal G with 25% duty cycle and signal H with 5% duty cycle are given in Figure 4. For both signals the error after five periods is approximately 4%.

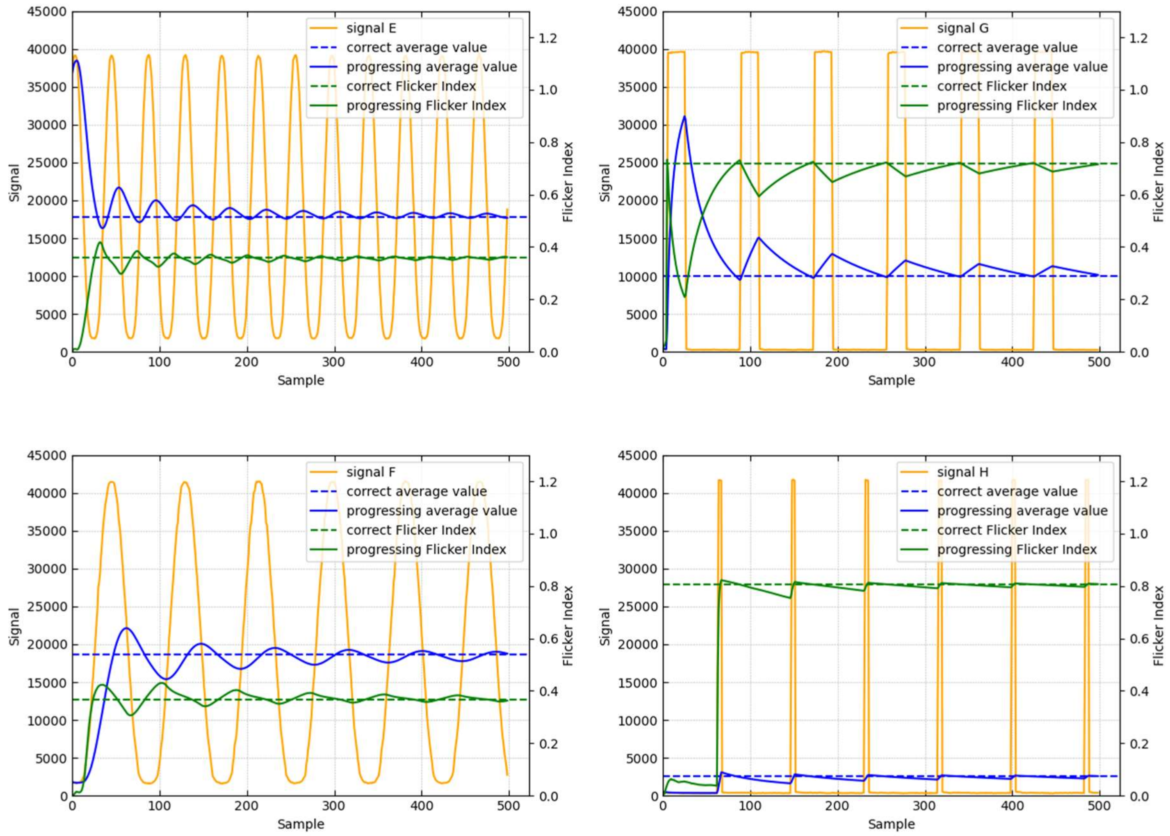

Figure 4 – Error at short sampling duration for the progressing Flicker Index for a sinusoidal signal 100 Hz (signal E) and 50 Hz (signal F), and a pulse-width modulated signal with a duty cycle of 25 % (signal G) and 5 % (signal H)

4 Conclusion

The systematic error and therefore the related uncertainty contribution from the progressing average value of a waveform increases significantly when the measurement duration is shortened. For short sampling durations, attention must be paid to evaluate a sampling sequence that corresponds to an integer number of waveform periods for the progressing flicker index and the SVM. If this is not observed, a PWM-waveform with a very small duty cycle and a small fractional deviation from an integer number of periods can lead to a significant error in the average value, i.e., of up to 25 % then considering slightly above three periods. This also affects the inaccuracy of the progressing flicker index. Considering a small deviation from 100 periods, the error is reduced to 1%, but this is still not just negligible but to be considered as an uncertainty contribution to the TLM and TLA metrics. For a sine or triangular shape, the error is highest at half periods and is 10% when considering 3.5 periods.

Acknowledgment

This work was carried out within the joint normative research project 20NRM01 MetTLM which has received funding from the EMPIR programme, co-financed by the Participating States and the European Union's Horizon 2020 Research and Innovation Programme.

References

Dekker, P. 2022. *Publishable Summary for 20NRM01 MetTLM Metrology for temporal light modulation*. Delft. Euramet.

CIE 2021. CIE TN 012:2021. *Guidance on the Measurement of Temporal Light Modulation of Light Sources and Lighting Systems.* Vienna: CIE.

European Commission 2019. COMMISSION REGULATION (EU) 2019/2020. *Laying down ecodesign requirements for light sources and separate control gears pursuant to Directive 2009/125/EC of the European Parliament and of the Council and repealing Commission Regulations (EC) No 244/2009, (EC) No 245/2009 and (EU) No 1194/2012.* European Union.

CIE 2016. CIE TN 006:2016. *Visual Aspects of Time-Modulated Lighting Systems – Definitions and Measurement Models.* Vienna: CIE.

Roberts, J. 2013. *Flicker can be perceived during saccades at frequencies in excess of 1 kHz*. Lighting Research & Technology, 45, 124-132.

Wilkins, A. 2010. *A Review of the Literature on Light Flicker: Ergonomics, Biological Attributes, Potential Health Effects, and Methods in Which Some LED Lighting May Introduce Flicker*. IEEE standard P1789.

IEEE 2015. IEEE Std 1789™. *IEEE Recommended Practices for Modulating Current in High-Brightness LEDs for Mitigating Health Risks to Viewers.* New York: IEEE.

Stein, A. 2023. *Auswertung der zeitliche Lichtmodulation unter Verwendung von bildauflösenden Messgeräten.* Proceedings of Lux junior 2023.

Image Solutions 2020. Data sheet *IDT OS – Serie, Image Solutions*.

Image Engineering 2022. Data sheet. *Vega.*