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# MEASURING AND COMPARING WAVEFORMS OF TEMPORAL LIGHT MODULATION

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## Abstract

This paper presents a comparison of measurements of the waveforms of temporal light modulation (TLM) from eight light sources performed by two different laboratories. The study focuses on the methodology of extracting relevant numerical differences between the measured waveforms. The methodology involves frequency matching, duration matching, selection of sampling interval, phase matching, and normalization. Results of the use of the methodology are presented. The results show that for some waveforms the comparison method can be used to practically explore equivalency of measurements.

*Keywords*: flicker, temporal light artefacts, signal analysis, intercomparison, temporal light modulation

## 1 Introduction

Temporal light modulation (TLM) of lighting products is of interest due to its possible adverse effects on human health and wellbeing (Wilkins et al., 2010). The topic has increasing relevance due to the surge of modulated lighting from widely used light sources such as LED lighting powered by current drivers based on pulse-width-modulation or simple AC rectification (Li et al., 2016).

Visual perception effects of TLM on humans are called temporal light artefacts (TLA) and the basis of the calculation of these effects is the modulation waveform i.e. the variation of light intensity as function of time over one or more modulation periods. In 2016, the International Commission on Illumination (CIE) published a Technical Note TN 006 (CIE, 2016), which outlined the main types of TLA and principles for their quantification. This work was an intermediate product of the work of CIE TC 1-83 "Visual Aspects of Time-Modulated Lighting Systems". The CIE has subsequently established an additional technical committee to recommend guidelines for the measurement of TLM (TC 2-89).

Given the large international market for lighting, measurements of quantities such as the TLM related metrics should be comparable between regions, manufactures, etc., so there is a clear need for measurement methods that provide accurate and reproducible results. In order to verify the reproducibility of a given method, a rigid method of comparison is needed. Since the various TLM related metrics are aggregate numbers reducing the measured waveforms to one or a few numbers, there is a need for objective methods for comparison of the waveforms themselves measured under various circumstances. In this paper, we will propose mathematically rigorous methods needed for objective comparisons.

This paper presents a comparison of measurement of TLMs from two different laboratories both under conditions similar to those in the standard CIE S 025 (CIE, 2015). From the measured waveforms, the various metrics are calculated such as; Modulation Depth/Percentage Flicker (CIE, 2014), Stroboscopic Visibility Measure (SVM) (IEC TC 34, 2018), Flicker Perception Metric (Bodington et al., 2015) and Flicker Index (IES, 2005). The compared waveforms are short and therefore not suited for calculations of short-term flicker indicator (PstLM) (IEC TC 34, 2017).

## 2 Methods

The laboratory comparison presented here is between measurements from two laboratories; at Department of Photonics Engineering at Technical University of Denmark (DTU Fotonik), Denmark and at Photometric Solutions International, Australia. The eight artefacts used in the comparison are of the general type filament LEDs bulbs. This type is prone to produce TLM due to the typical design, which leaves very limited space for the AC power converter and current driver. This paper will only briefly describe the measurement setups used in the comparison.
Instead, the paper will focus on methods of comparison and secondly present and discuss the differences in the measured results and their relation to the experimental setups. The comparison was arranged such that the devices under test (DUT) were measured in laboratory 1 (DTU Fotonik) and then transported to laboratory 2 (Photometric Solutions International), for the second round of measurements.

### 2.1 Devices under tests

The DUTs for this comparison were chosen as to highlight the effects of TLM that are often intensified when AC power supplies have to be fitted into small compartments such as a E27 or E14 bulb screw base. The DUTs were bought from the open market in and around Denmark in 2017. The TLM waveforms are shown in Figure 2.

### 2.2 Measurement methods

In this section, we briefly describe the method of measurement setups at laboratory 1 and laboratory 2.

#### 2.2.1 Laboratory 1

The light sources were powered by an Elgar CW1251P power supply. A photodiode (United Detector Technology) with a photometric filter was used as a detector, all placed in a 2 m integrating sphere. The signal from the photodiode was fed to a variable gain low noise amplifier (FEMTO DLPCA-200). The amplifier has a datasheet bandpass of 500kHz (rise/fall time ~ 0.7 ns). The amplified signal was thereafter recorded at a sample rate of 100 kHz (National Instrument USB-6215 Multifunction I/O device). The recorded data was treated using various in-house and publicly available MATLAB routines.

#### 2.2.2 Laboratory 2

The light sources were powered by the AC power supply California Instruments 2001RP. The photometric measurements where done using photometer head (Czibula & Grundmann M/no. Ph-St-B25-Th) in a single direction and at a distance of approx. one meter. The waveform was recorded using a photocurrent amplifier (Czibula & Grundmann M/no. Ph-Amp MB14) and a (Keysight 34465A). The measurement system had an established response time (rise/fall time, 5 % to 95 %) of 0.1 ms. The software used to process the results is a custom program from Photometric Solutions International. The light sources where stabilized between 10 and 45 minutes, according to when the values of the measured TLA metrics would stabilize.

### 2.3 Waveform comparison

In order for a comparison to be possible, the measured waveforms have to be transformed to a comparable state. This process involves a number of steps described in the sections below, and outlined in the flow chart in Figure 1.

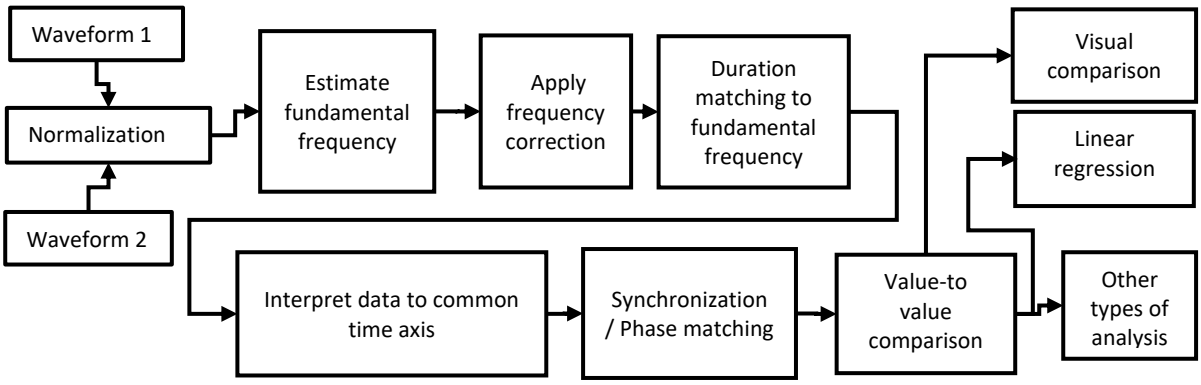



**Figure 1 – Flowchart of the comparison method**

### 2.3.1 Frequency matching

Even small a differences in the fundamental frequencies $f_1$ and $f_2$ leads to a beat effect between waveforms where the phase seems to change with a characteristic beat frequency $f_{beat} = f_1 - f_2$. For example, a 1 Hz difference in fundamental frequency will lead to one complete phase shift over a 1 s duration sample. This beat effect will disturb a value-to-value comparison, therefore, any difference in the fundamental frequency needs to be calculated and corrected for. Here, we have used the fast Fourier transform (FFT) to estimate the fundamental frequency. Correction can be done by scaling the time axis of the waveforms with a factor $h = f_1/f_2$. For samples of low duration/small number of fundamental cycles, the resulting frequency spectrum becomes too low in resolution to directly use the discrete FFT frequency at which maximum power occurs, so here we have used the centroid frequency calculated between 3/4 $f_0$ and 5/4 $f_0$ of the approximate fundamental frequency to get a more precise value of $f_0$. For large duration waveforms, the maximum of the discrete FFT may provide sufficient resolution.

### 2.3.2 Duration matching

In order for the phase matching (Section 2.3.4) to work correctly, the waveform has to be able to be circularly shifted, without causing a discontinuity in the signal. This is avoided by making sure that the duration of the compared signal $T_{total}$ consists of an integer number of fundamental periods, i.e. $T_{total} = Tn$ where $T = 1/f_0$ and $n$ is the number of periods in the sample. In practise, this can be done by truncating a series of common time stamps that are used for interpolation, such that the duration is equal to $T_{total}$. It is important to note that the number of data points in a waveform affects the resolution of the frequency spectrum of the Fourier transform (reversely proportional).

### 2.3.3 Sampling interval

The sampling intervals $\Delta t_1$ and $\Delta t_2$ of two measured waveforms are likely to be different, and for one-to-one comparison of measured values a common interpolation is needed. If the two sampling intervals are only slightly different, the time difference between adjacent time stamps will be close in many instances and the smallest interval can for instance be chosen as the common one. If variations of both waveforms are slow compared to the sampling interval (oversampling), any common sampling interval $\Delta t_c$ may be selected to meet the Nyquist sampling criterion(IEC, 1997). On the other hand, $\Delta t_1 \gg \Delta t_2$ for two signals (1) and (2), the selection of $\Delta t_c$ involves some compromises. The timestamps of the signals will rarely overlap and consequently one is faced with the dilemma outlined in Table 1. It is an option to select all measured timestamps for a merged time axis, however this would cause $\Delta t$ to vary across the time axis making many standard calculations more difficult.

**Table 1 – Consideration when selecting the common interpolation decided, both waveforms need to be interpolated to this new interval**

| | Selecting a big $\Delta t$ | Selecting a small $\Delta t$ |
|---|---|---|
| Arguments for | Only measured values are compared | All available data is being utilized |
| Arguments against | Resolution/information on high frequency components is lost, | Interpolation in time domain becomes extrapolation in frequency domain |

With a common duration and a selected sampling interval for the two samples, a common axis for interpolation of both waveforms can be constructed. Selection of an interpretation method (linear, cubic, spline etc.) then becomes important as it has implications - especially for frequencies that are on the order of $1/\Delta t$. It is important to remember that an interpolation in the time domain becomes an extrapolation in frequency domain, essentially producing different guesses of the higher frequency components of a waveform. Here we have only used a linear interpolation for simplicity.

### 2.3.4 Phase matching

When a TLM is measured, the start time and thereby phase of the signal is arbitrary. Value-to-value comparison of waveforms requires synchronization, such that the peaks and valleys of the compared waveforms overlap. The process is also called signal alignment, see for instance (Coakley and Hale, 2001)(Bayram, 2014). Synchronization can be done by adding $jT + \tau$ to all timestamps of one waveform where $\tau$ is the phase difference, $T$ is the period and $j$ is an arbitrary integer. So in order to achieve repeatable synchronization, we suggest to use the cross-correlation or sliding inner-product (equation (1)), and select the $j$ at which maximum phase matching of the signals occur. The cross correlation $K$ is calculated as an integral or sum:

$$K(\tau) = \int_0^{T_{Total}} S_1(t) S_2(\tau - t) dt\,, \qquad K(m) = \sum_{n=1}^{N} S_1\,(n) S_2(n - m) \Delta t \tag{1}$$

where $t$ is time

$S_1(t)$ and $S_2(t)$ are the continuous waveforms as a function of time

$S_1(n)$ *and* $S_2(n)$ are the waveform signals at discrete timestamps numbered $n$. Note: $S_2$ is the circularly shifted waveform.

$\tau$ and $m$ is the displacement of the continuous and discrete signal

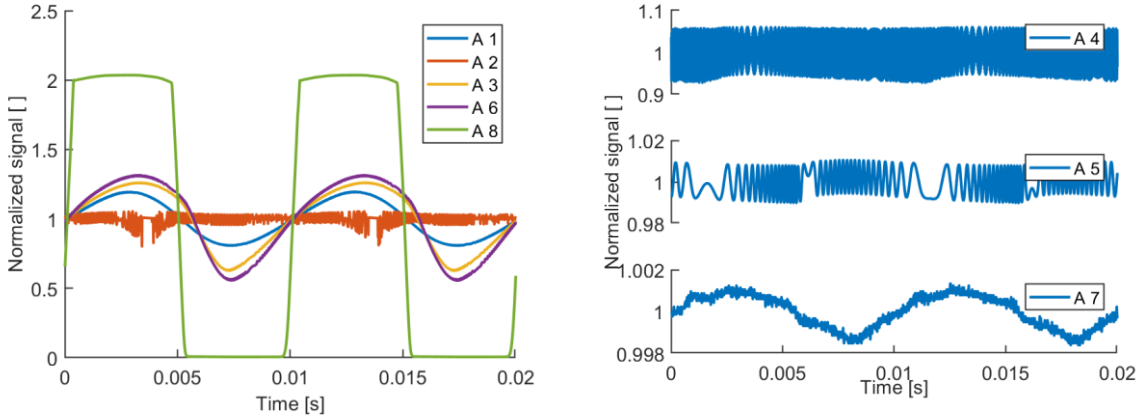
For two periodic waveforms, $K(\tau)$ will take the form of a saw-toothed function with maxima at the displacements $\tau$ with the biggest overlap (see Figure 4). To match the phase as repeatably as possible, we propose to use the displacement with the global maximum of cross-correlation, i.e. the largest value of $K$. It should be noted, that most algorithms for signal matching are not directly suited for signals with strong DC components as the DC components can overshadow the alternating component. This problem is sidestepped by using a circularly shiftable waveform representation.

### 2.3.5 Normalization

Since the photometric quantity used for TLM measurement can be illuminance, luminance, luminous intensity, or any related quantity, measured TLM waveforms can easily be handled as having arbitrary units on the y-scale. However, the choice of normalization factor can influence the result of a comparison. Here we propose to use the average value of the signal, since quantities of light perception are almost always derived as averages over given time intervals. Other factors that could be used to normalize waveforms would be RMS, median, peak, etc. The choice of normalization will affect the impact of, for instance, outliers and noisy signals on the normalization factor.

## 3 Results

In this section, the results of the comparison are presented. For this comparison, eight artefacts have been studied. Example of the captured waveforms are seen in Figure 2. The waveforms represent many of the varieties of waveforms that can be observed; from severe pulse-width modulation of 100%, over sinusoidal signals, to approximately constant signals.




a) b)

**Figure 2 – The measured and compared waveforms from artefacts numbered "A #", with high modulation depth (a) and with more moderate modulation depth (b), all acquired in Laboratory 1.**

### 3.1 Comparison of frequency spectrum

When comparing frequency spectra calculated directly from the waveform, the amount and complexity of the data is not reduced but rather transformed. As seen in Figure 3a and c; the complexity and information density is quite high. To make the data more accessible, we have collected the spectral content in bins centred around each harmonic component $f_0 n$, this is shown in Figure 3b. The difference between the magnitude of the binned spectral components are quite different for the higher frequencies in this comparison. Furthermore, it is not necessarily interesting to study high frequency components (above 3 kHz for instance).

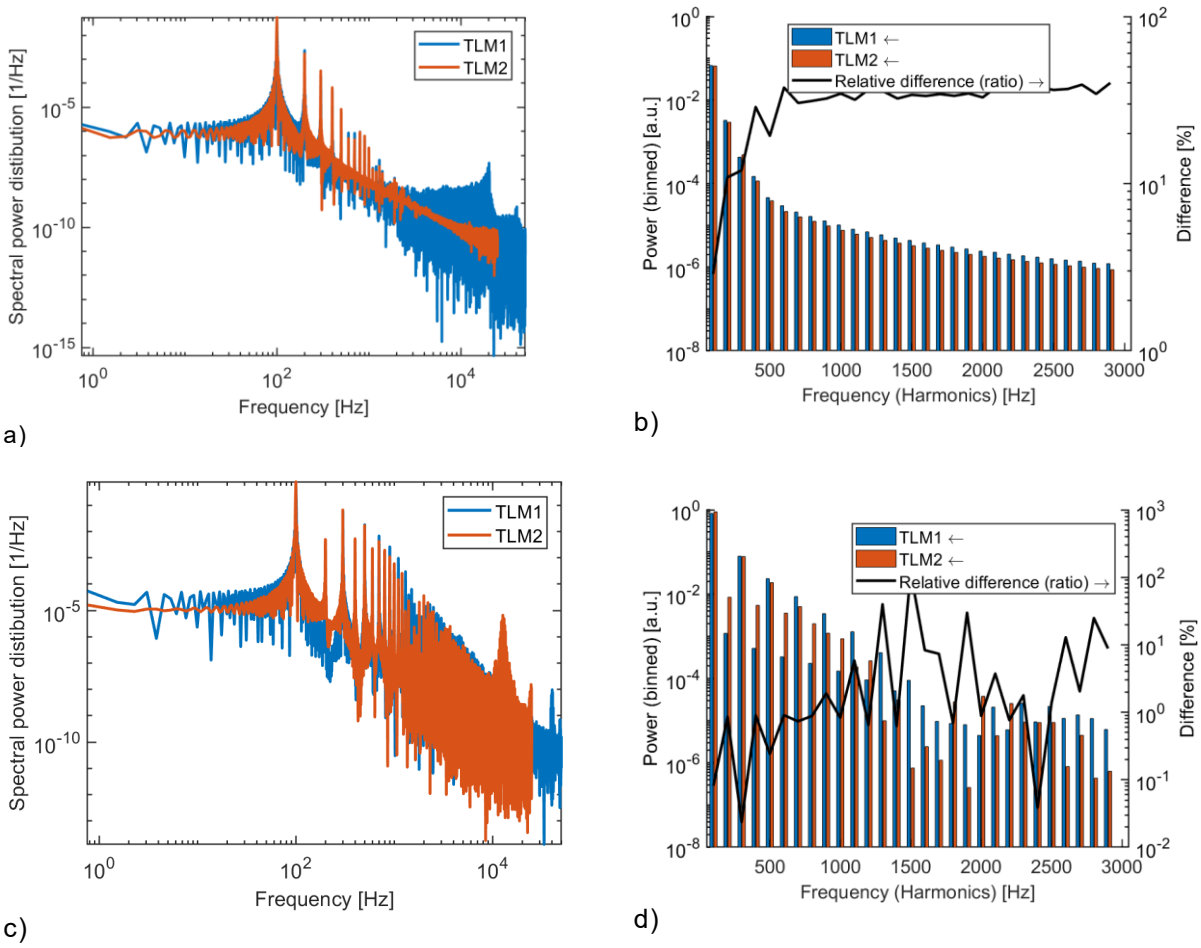



**Figure 3 – Example frequency component comparison for sinusoidal (a,b) and square waveforms (c,d). Plots (a,c) show the unaltered frequency spectrum while (b,d) show bandwidth limited and binned spectrum.**

## 3.2 Phase matching

The result of the phase matching/convolution calculated in equation (1) should be a saw tooth pattern with each local maximum representing a good alignment of the two waveforms. This is seen in Figure 4.

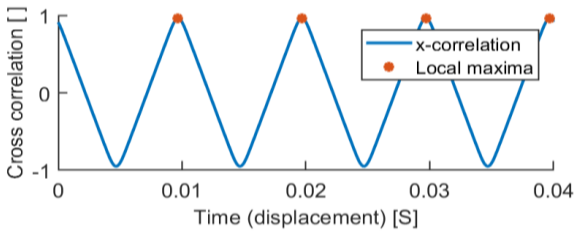



**Figure 4 – Cross correlation used for phase matching the waveforms from artefact 8.**

## 3.3 Visual comparison

Visual inspection of the results can give some insight, so in Figure 5, we present two periods of the normalized and synchronized waveforms that have remarkable features. In Figure 5a a non-linearity is visible between two waveforms for the high and low values of the sinusoidal. Figure 5b shows a situation where the synchronization routine seem to have failed, probably due to the high frequency oscillation in TLM1. Figure 5c again shows a fast oscillation pattern that is only present in the waveform from laboratory 1 with the difference being clear although

numerically small. Figure 5d seems to indicate a difference in the measured duty cycle – the exact origin of these differences is not clear at this time.

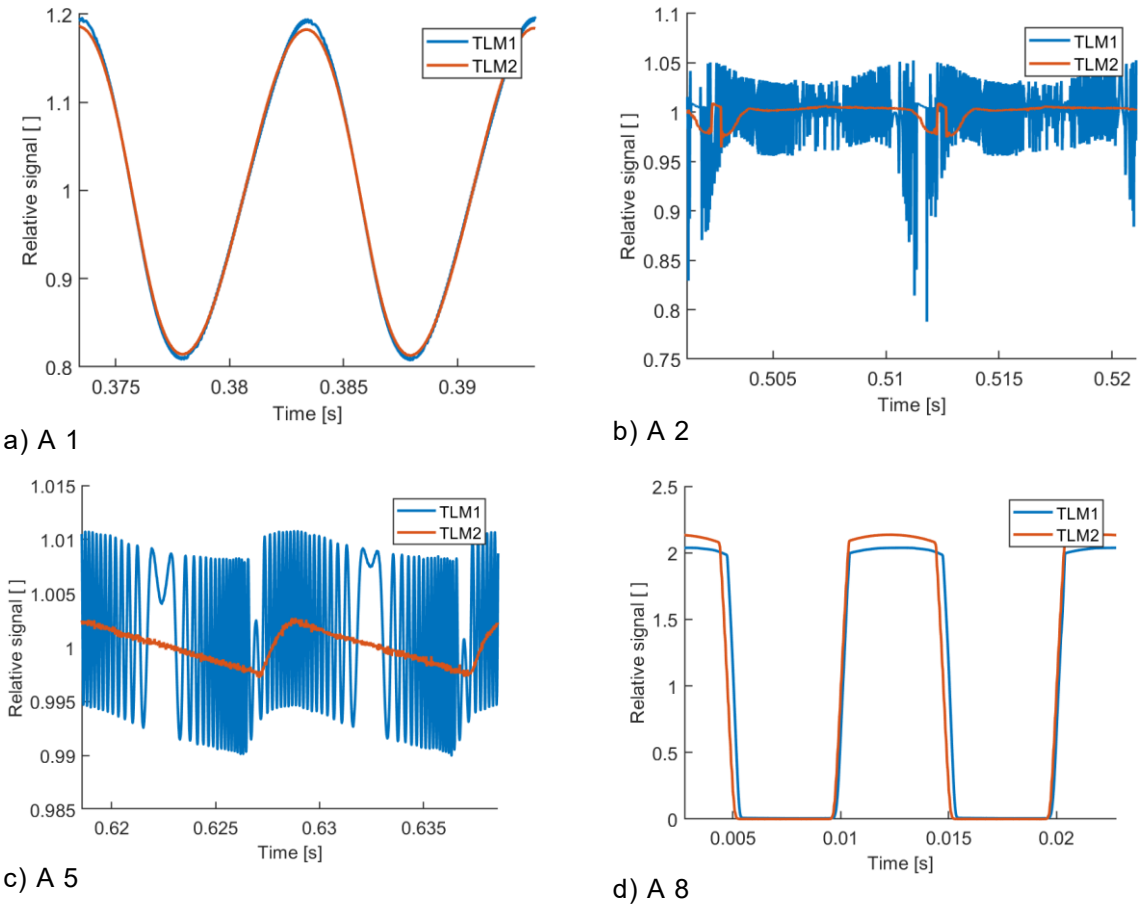



**Figure 5 – Normalized and synchronized waveforms for visible comparison, where various effects can be observed.**

## 3.4 Regression analysis of the waveforms

After frequency matching, common interpolation and phase matching of the waveforms, the values of the individual data points of the waveform can be compared value-to-value. Here we use linear regression to compare the values. In Figure 6 the regression is exemplified for four different compared waveforms. The point clouds are collected as 2D histograms for clarity. The point clouds show large variations in the shape and point density. One aspect that can be seen is that the regression can indicate non-linearities. For instance, in Figure 6 (a,c) the offset deviates from the theoretical offset of 0 by approximately 2%.

For some waveforms, for instance with a high constant offset (DC component), the correlation between two compared measurements can be very low, while for waveforms with large and slow variations the correlation becomes much larger. As seen in Figure 6 and Table 1, the coefficients of determination $R^2$ are vastly different for - on one hand the sinusoidal waveform A 1 and the square wave A 8 (a,c) $R^2 \sim 0.99$, and on the other hand the low modulation depth sources (b,d) $R^2 \sim 0.1$. Comparing square wave signals (Figure 6d) yield two distinct point clouds connected by a band of points. The thickening of this band originates from discrepancies between the measured timing of the rise and fall of the signal.

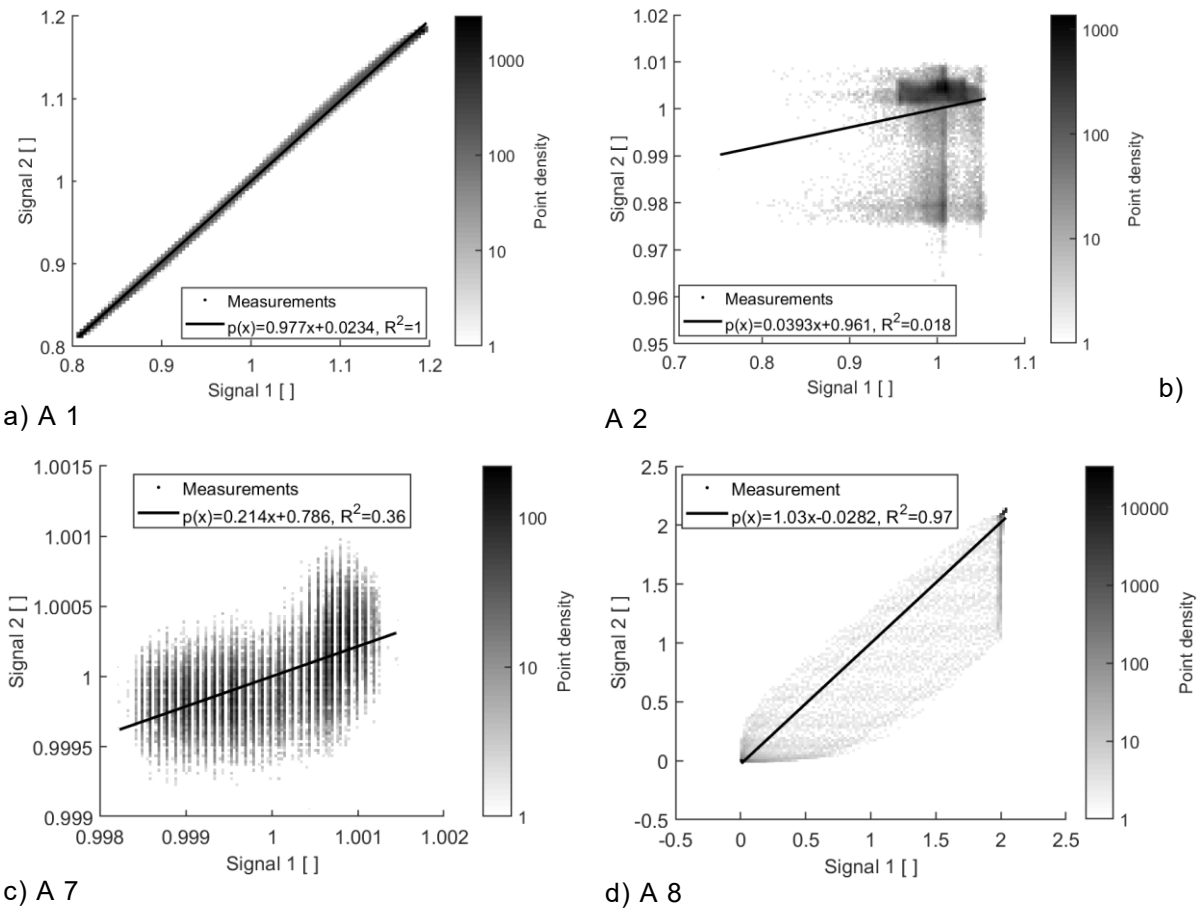



**Figure 6 – Linear regression between compared signals: sinusoidal signals from DUT A 1 (a), DC signals A 2 (b) and A 7 (c), square wave PWM A 8 (d).**

## 3.5 Normalization

The impact of the normalization is shown by the variation in the difference in ratio between the various normalization factors for all the measurements. The results for average compared to root mean square (RMS) and median values are shown in Figure 7. It is not clear from this study which normalization factor should be used but it is illustrated that the result of the comparison can be influenced by the choice of the factor.

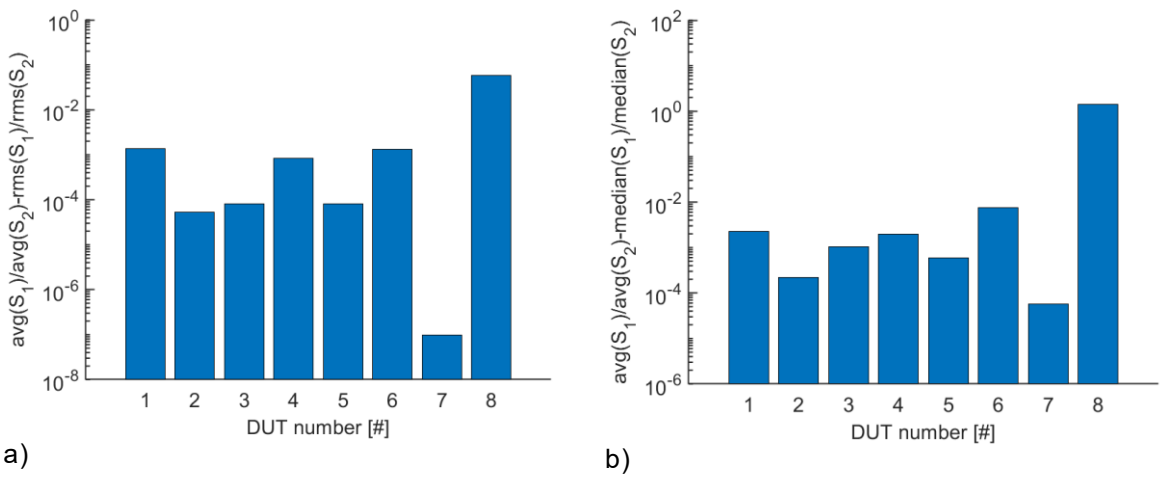



**Figure 7 – Variation in the calculated normalization factors for average value compared to RMS value and average value compare to median value.**

### 3.5.1 Derived values

The values of the derived TLA characteristics are of importance and these are summarized in Table 2. This table shows an overview of the derived values from the comparison: fundamental frequency, Stroboscopic visibility measure (SVM), Modulation depth (MD) and Flicker Index (FI), along with the difference in percentage between each measurement and the coefficient of determination $R^2$ showing the correlation between the compared measurements. It is clear from the table that when the correlation $R^2$ is low, the difference in measured values grows significantly.

Here it is also seen that for one waveform (A 7 measured in Laboratory 2), the fundamental frequency could not be established by the algorithm. This will also disrupt further calculations.

**Table 2 – Derived values of from the comparison of the waveforms**

| A # | Fun. Freq 1 [Hz] | Fun. Freq 2 [Hz] | Diff. [%] | SVM 1 | SVM 2 | Diff. [%] | MD 1 [%] | MD 2 [%] | Diff. [%] | FI 1 | FI 2 | Diff. [%] | $r^2$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 99.84 | 99.76 | 0.74 | 0.71 | 0.999 | 19 | 18.73 | 0 | 0.3 | 0.061 | 0.06 | 1.83 | 0.999 |
| 2 | 100.3 | 99.77 | 0.025 | 0.028 | 0.018 | 17 | 3.037 | 0 | 0 | 0.01 | 0.003 | 234 | 0.018 |
| 3 | 99.9 | 99.75 | 1.157 | 1.135 | 0.999 | 34 | 33.15 | 0 | 0.6 | 0.096 | 0.097 | -0.4 | 0.999 |
| 4 | 99.84 | 99.76 | 0.02 | 0.019 | 0.008 | 6.8 | 0.709 | 0 | 0 | 0.019 | 0.002 | 1049 | 0.008 |
| 5 | 99.6 | 99.74 | 0.007 | 0.007 | 0.028 | 1.1 | 0.312 | 0 | 0 | 0.003 | 6E-04 | 350 | 0.028 |
| 6 | 99.85 | 99.75 | 1.402 | 1.357 | 0.999 | 41 | 39.93 | 0 | 2 | 0.117 | 0.115 | 1.98 | 0.999 |
| 7 | 99.92 | 11.01 | 0.005 | 0.003 | 0.361 | 0.2 | 0.101 | 0 | 0 | 3E-04 | 1E-04 | 194 | 0.361 |
| 8 | 99.91 | 99.76 | 5 | 5.109 | 0.974 | 100 | 100 | 0 | 6.6 | 0.475 | 0.492 | -3.3 | 0.974 |

## 4 Discussion

An important aspect, of these results, that was discovered in the analysis of the data, is the possible influence of the supply voltage or more broadly the supply circuit. For simple power converters such as the ones typically present in small form factor lamps, the supply voltage may influence the light output significantly. Any feedback or resonance between supply and load could make it difficult to distinguish noise or errors arising from the light measurement setup from noise created by the DUT. It is possible that the relation between electrical input and light output may have to be established to make sure that the supply circuit does not have a significant and irreproducible effect on the measured result.

Given only two waveforms from two unknown TLM instrumentations and a single device under test, which are the basis of the value-to-value comparison, it can be difficult to distinguish between noise in the measurement instrumentation and a DUT with a high randomness in the light output or noisy output. Some signals show a low degree of repeatability even from period to period. One option could be to statistically study the distribution of values in the high frequency residual from the signals. If the distributions of values are measured to be similar between different laboratories, it is likely that the noise originates in the DUT. We recommend a larger intercomparison be established to further study these issues.

It is clear that in this study, the largest difference were to be fund at high frequencies. As different instrumentation has different frequency response, the deviations in high frequency components are likely to cause deviations in value-to-value comparisons. To level the playing field when comparing two waveforms, one could, equivalent with the frequency correction, search for a common filtering to apply on both measurements. This study at least indicates that frequency response and electrical response in the experimental setup could be a significant contribution to differences in TLM waveforms.

## 5 Conclusions

In this paper, we have conducted a comparison between measurement of temporal light modulation (TLM), and we propose a methodology to align the TLM waveforms such that they can be compared across various experimental setups and conditions. We show that the proposed comparison method can align the waveforms so that a value-to-value comparison can be made. In turn, we show that this comparison can be used to identify various differences and

deviations between the compared measurements. Through the comparison, we find that only some of the laboratory results can be said to be equivalent. One set of measured waveforms contain high frequency components that the other does not and this affects some of the derived quantities. These are used for characterizing light sources regarding temporal light artifacts (TLA) that can affect humans and other living organisms. We further find that comparison of the rich data from the waveforms may provide insights into the quality of measurement, uncertainties, and other important details.

## Acknowledgments

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