



International Commission on Illumination
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Internationale Beleuchtungskommission

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PROCEEDINGS of the CIE Symposium on Advances in Measurement of Temporal Light Modulation

October 11, 2022

**hosted by the National Technical University of Athens,
Greece**



**Institute of Communication
& Computer Systems**
National Technical
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CIE x049:2022

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The following table provides an overview of the oral presentations presented at the symposium, for which full papers have been submitted for these proceedings. The papers are listed in consecutive order of presentation.

The papers have not been peer-reviewed. The authors are responsible for the contents of their papers.

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EVALUATION OF DATA ACQUISITION SYSTEMS FOR MEASUREMENT OF TEMPORAL LIGHT MODULATIONS

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Abstract

We evaluated several data acquisition systems for measurement of temporal light modulations. A waveform generator was used to simulate temporal light modulation waveforms for this evaluation. The generated waveform was used as the waveform reference and was measured using three representative data acquisition systems with resolutions of 24 bits, 16 bits, and 8 bits. The temporal light artefacts quantities, the short-term flicker index, P_{st}^{LM} , perception modulation, M_p , and stroboscopic effect visibility measure, SVM, of the reference waveform and three measured waveforms were calculated and compared.

Keywords: DAQ, evaluation, perception modulation, short-term flicker index, stroboscopic effect visibility measure.

1 Introduction

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 evaluate their severities of associated temporal light artefacts (TLAs).

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 investigate influence of DAQ performance on the measurement results of TLM and TLA, we evaluated several DAQ devices for measurement of temporal light modulations. To exclude variation due to different measurement setups, lamp drivers, and power supplies, a waveform generator (WFG) was used to simulate temporal light modulation waveforms for this evaluation. The generated waveform was used as the waveform reference and was measured using three representative DAQs with resolutions of 24 bits, 16 bits, and 8 bits. The temporal light artefacts quantities, the short-term flicker index, P_{st}^{LM} (IEC 2010) (IEC 2020), perception modulation, M_p (ASSIST 2015), and stroboscopic effect visibility measure, SVM (CIE 2016) (IEC 2018), of the reference waveform and three measured waveforms were calculated and compared.

2 Evaluation method

A waveform generator was used to provide known (reference) TLM waveforms for this evaluation.

2.1 Measurement setup

The setup for the evaluation is shown in Figure 1. The reference TLM waveform from the WFG was measured using three representative DAQs (DAQ 1, DAQ 2, and DAQ 3) with resolutions

of 24 bits, 16 bits, and 8 bits. Note for the reference waveforms used in this evaluation, a low pass filter between the WFG and DAQs is not needed, which eliminates the waveform distortion error resulting from a lowpass filter.

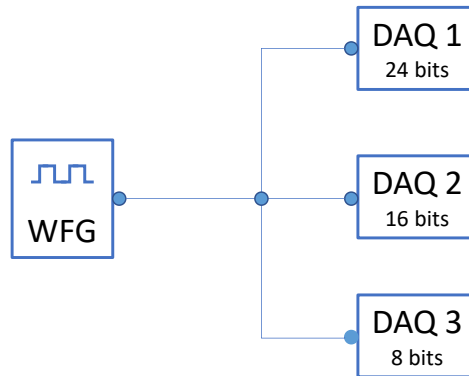


Figure 1 – Setup for the DAQ evaluation

The information of the WFG and DAQs used for this evaluation are shown in Table 1 and Table 2, respectively.

Table 1 – Specifications of the WFG

Voltage resolution	16 bits	
Bandwidth	20 MHz	
Frequency range	20 MHz	For sine and square waveforms

Table 2 – Specifications of the three DAQs

	DAQ 1	DAQ 2	DAQ 3
Type	High-accuracy DAQ	High-speed digitizer	Oscilloscope
A/D resolution	24	16	8
Bandwidth	125 kHz	20 MHz	200 MHz
Speed	800 k Samples/s	20 M Samples/s	2.5 G Samples/s
Input configuration	Differential	Differential	Single end

2.2 Measurement of TLM waveforms

The waveforms used for obtaining P_{st}^{LM} and M_p values are 1 V DC modulated by a fixed 100 Hz, 0.25 V peak to peak sine wave to simulate the light waveform of a lamp powered by 50 Hz AC power. In addition, the amplitude of this waveform is modulated by another lower frequency sine wave, f_m , with frequency varying from 1 Hz to 60 Hz to simulate an unstable amplitude of the AC power. A TLM waveform with a modulation frequency of $f_m = 5$ Hz is shown in Figure 2.

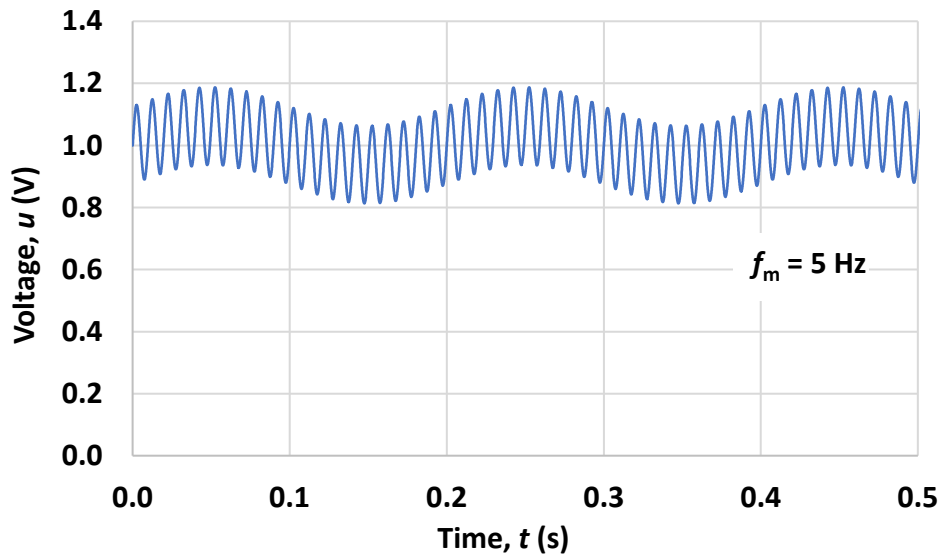


Figure 2 – A TLM waveform for P_{st}^{LM} and M_p measurements

The waveforms used for obtaining SVM values are square waveforms (i.e., 50 % duty cycle) with an amplitude of 1 V and frequency varying from 80 Hz to 3000 Hz to simulate a pulse-width-modulation (PWM). A 100 Hz square waveform is shown in Figure 3.

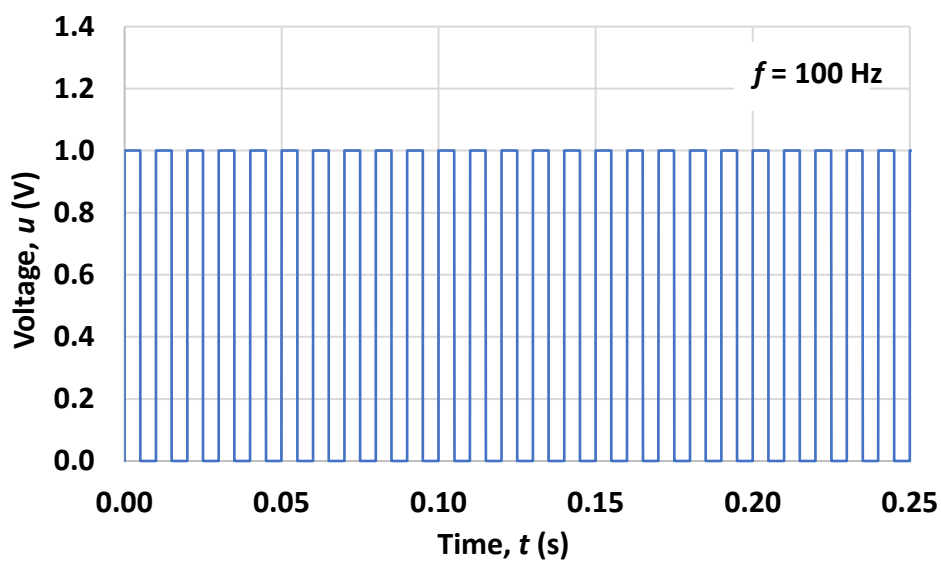


Figure 3 – A TLM waveform for SVM measurements

The TLM measurements were performed following the CIE general guidance for measurement of TLMs (CIE 2021). The DAQ settings are shown in Table 3 for measurements of P_{st}^{LM} and M_p and Table 4 for measurement of SVM.

Table 3 – DAQ settings for measurements of P_{st}^{LM} and M_p

	DAQ 1	DAQ 2	DAQ 3
Bandwidth	125 kHz, not selectable	200 kHz, min. value	20 MHz, min. value
Sampling rate	12.5 k samples/s	10 k samples/s	10 k samples/s
Duration	60 s	60 s	100 s (60 s used)
Note			Set to “Hi Res” mode

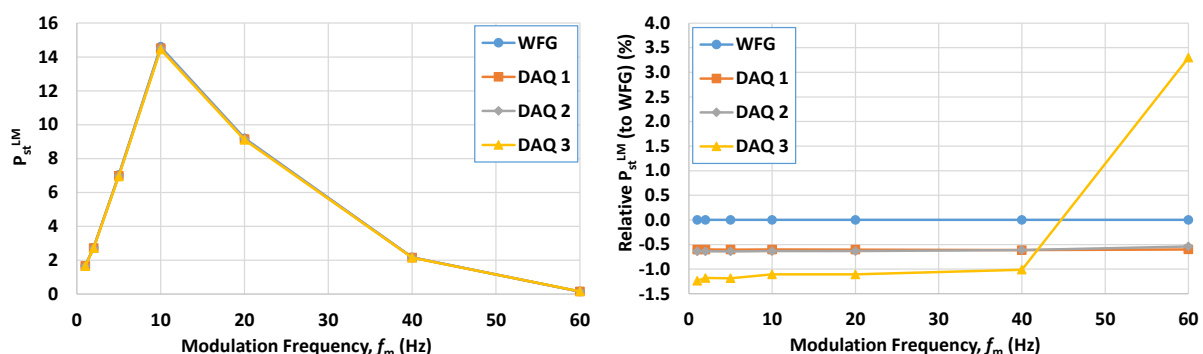
Table 4 – DAQ settings for measurement of SVM

	DAQ 1	DAQ 2	DAQ 3
Bandwidth	125 kHz, not selectable	200 kHz, min. value	20 MHz, min. value
Sampling rate	50 k samples/s	50 k samples/s	50 k samples/s
Duration	2 s (1 s used)	2 s (1 s used)	2 s (1 s used)
Note			Set to “Hi Res” mode

After the measurements of the waveforms, the TLA quantities were calculated following the published methods for P_{st}^{LM} (IEC 2010) (IEC 2020), SVM (CIE 2016) (IEC 2018), and M_p (ASSIST 2015). The corresponding Matlab codes were used for calculating the P_{st}^{LM} values (Banerjee 2022), M_p values (ASSIST 2015), and SVM values (Banerjee 2022). A LabVIEW program was developed for calculating all the three TLA values simultaneously.

3 Results

The measurement results of absolute and relative values (to the corresponding WFG values) for P_{st}^{LM} , M_p , and SVM are plotted in Figures 4, 5, 6. The TLA values for the WFG are determined mathematically based on the input TLM waveform parameters, assuming the WFG output was exactly what it was programmed to be. Note that the M_p values under frequency of 5 Hz is not defined, thus, under the 5 Hz modulation frequency the M_p values for WFG is 0 and for DAQs are nearly zero due to the measurement noise.

**Figure 4 – Comparison of P_{st}^{LM} values**

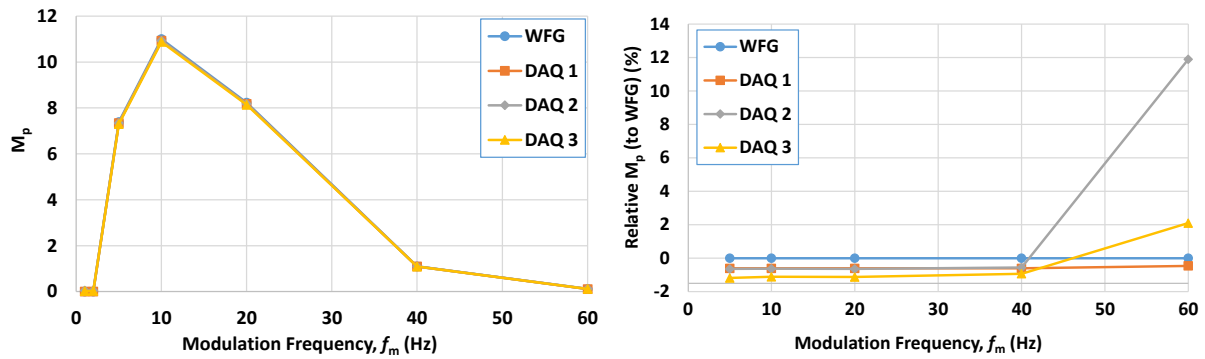
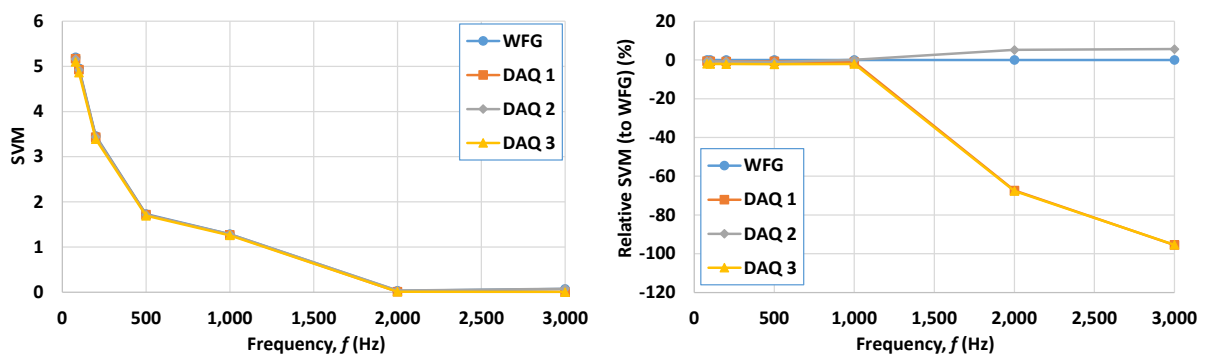
Figure 5 – Comparison of M_p values

Figure 6 – Comparison of SVM values

4 Summary

The measured TLA values of P_{st}^{LM} , M_p , and SVM do not show a significant difference even though the resolutions of the three representative DAQs vary significantly from 24-bits to 8-bits.

Compared to the TLA values determined mathematically (i.e., the WFG values), the measured P_{st}^{LM} and M_p values have a difference of approximately 0.6 % for the 24-bit DAQ 1 and 16-bit DAQ 2, and have a difference of approximately 1.2 % for the 8 bit DAQ 3, except those at the modulation frequency of $f_m = 60$ Hz where the TLA values approach zero.

The measured SVM values have a difference of approximately 1 % for the 24-bit DAQ 1 and 16-bit DAQ 2, and have a difference of approximately 2 % for the 8 bit DAQ 3, except those at the frequencies of $f = 2000$ Hz and $f = 3000$ Hz where the TLA values approach zero.

Acknowledgement

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CHARACTERIZATION OF KEY PERFORMANCE OF TLM MEASUREMENT INSTRUMENTS

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Abstract

The performance of the TLM measurement instrument plays important roles in the measurement results and uncertainties. To characterize a TLM measurement instrument, some indices and relevant measurement procedures can be learned from current CIE publications for photometers measuring time-averaged luminous quantities. However, as the fast and time resolved photometric data is captured, other more characteristics of TLM measurement instrument need to be addressed. In this paper, the characterization linearity, frequency response and noise properties and their of the TLM measurement instrument was studied. Considering the actual application, quality indices were proposed based on traditional appraising metrics, and the measurement procedures were developed correspondingly. Furthermore, several TLM measurement instruments were measured, and the results showed fine applicability of these quality indices.

Key words: Instrument characterization, TLM measurement, Frequency response, Noise

1 Introduction

The temporal light modulation (TLM) quantities, such as I_F , PF, M_{SV} , 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 (CIE, 2021a), the overall performance of the measurement instrument is more important to be ensured so as to obtain accurate and reproducible TLM quantities.

CIE have defined the indices and measurement procedures for the characterization of the performance of single-channel photometers and multi-channel luminance meters (ISO/CIE, 2014) (CIE, 2021b). However, 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.

The linearity, frequency response and noise properties of the TLM measurement instrument are main factors affecting the waveform acquisition. There are inner connections among the three properties, but as long as the conditions are well controlled, independent quality indices can be identified. Traditionally, there are indices to characterize these performances of an instrument, but for the specific application for TLM measurement, the characterization needs to be reconsidered.

2 Linearity and Dynamic Range

2.1 The linearity index

Unlike photometers for arithmetic mean value measurement, the instrument for fast and time resolved photometric data acquisition usually dose not change range during one

measurement sampling. In order to take the maximum and minimum readings of the luminous waveform accurately, the linearity in the range should be quite well. The method to characterize the linearity in a fixed measurement range was already defined (ISO/CIE, 2014), and can be applied to TLM measurement instruments. The index f_3 of a TLM measurement instrument is given for each measurement range, and largest f_3 of all ranges can be reported as the declared linearity index of the instrument.

2.2 The linear dynamic range

To be noticed, linearity is closely connected to its evaluation range. In current ISO standard (ISO/CIE, 2014), the linearity deviation is measured from 10 % of the range value to the full range value for all but the highest sensitive range. But for the TLM measurement, it is quite possible that the luminous wave trough is beneath 10 % range while the time averaged value far above this. Therefore, the linear dynamic range of a TLM measurement instrument, i.e. the maximum and minimum measurable value in a range determined by a linearity deviation threshold, is more meaningful than the linearity quality itself, and it can also provide more information for uncertainty estimation.

2.3 Measurement of linearity

The linearity deviations of an instrument can be measured by the differential responsivity method (CIE 2020), and the linearity of a measured photometer is obtained by comparison with a reference photometer of known fine linearity, as given by the following equation:

$$f_3(Y) = \left| \frac{Y}{Y_0} \cdot \frac{Y_{0,ref}}{Y_{ref}} - 1 \right| \times 100\% \quad (1)$$

where

Y is the value from the measured TLM measurement meter at corresponding inputs;

Y_{ref} is the value measured by the reference photometer;

Y_0 and $Y_{0,ref}$ is the output signal corresponding to an input signal in the linear dynamic range.

The maximum and minimum measurable value in a measurement range, Y_{max} and Y_{min} , are determined at the point where $f_3(Y)$ exceeds a preset threshold limit. In this work, the threshold limit is 1 % for benchtop TLM measurement instruments and 2 % for handheld instruments, corresponding to CIE Class 3 and CIE Class 4 respectively.

2.4 Practical measurement result analysis

2.4.1 TLM measurement instruments under investigation

In this work, three TLM measurement instruments are measured and compared using the proposed procedures. To be specific, instrument A is a benchtop instrument, for the research of this work, its anti-aliasing filter, sampling rate and measurement range can be modified and preset; instrument B and instrument C are handheld, while the sampling rate and measurement range of instrument B is adjustable and instrument C has automatic range and can only display the PF value.

2.4.2 Measurement of linearity index and dynamic range

The linearity index, f_3 , of the TLM measurements is measured and the measurement of dynamic range, i.e. the maximum and minimum measurable value in a range, is researched based on.

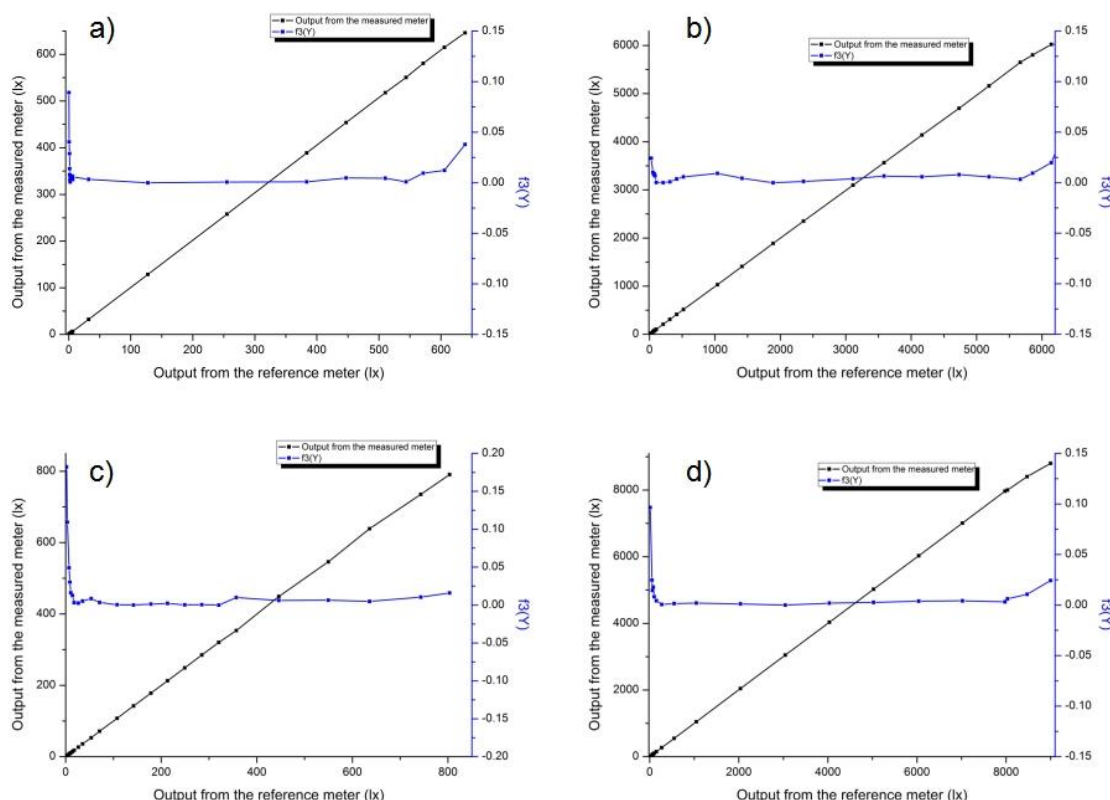


Figure 1 – Linearity curves of TLM measurement instruments

**a) Instrument A at measurement range 1; b) Instrument A at measurement range 2;
c) Instrument B at measurement range 1; d) Instrument B at measurement range 2.**

Figure 1 shows linearity curves of two TLM measurement instruments, both measured in two measurement ranges using the method above, from which similar trends can be seen. As the measured value increases or decreases, i.e. approaching the limits of the measurement range, the linearity deviation gradually becomes unacceptable. Table 1 lists the linearity index f_3 and the linear dynamic range of the two TLM measurement instruments.

Table 1 – The linearity index f_3 and linear dynamic range

	Benchtop instrument A		Handheld instrument B	
Declared maximum value of the range	500 lx	5000 lx	800 lx	8000 lx
Linearity index	0,8 %	0,5 %	1,2 %	0,6 %
Dynamic range	1.6 lx~573 lx	55 lx ~5890 lx	2.2 lx~850 lx	54lx~8390 lx

However, when it comes to an instrument with automatic range and unknown actual each range value, like instrument C, only the maximum and minimum value of the overall instrument range can be acquired, rather than each range respectively. Further research is needed to evaluate the linear dynamic range of this type of TLM measurement instrument. The full-scale dynamic range of Instrument C is about 70 lx to 200 klx by setting the threshold limit of linearity deviation at 2 %.

2.4.3 Measurement of modulated light

Furthermore, actual modulated light has been measured using the instruments above to further verify the practicability of the linearity index. The input light signal has sinusoidal waveform whose frequency is 100 Hz, and modulation depth is about 100 %. The TLM quantities measured are shown in the following table:

Table 2 – TLM quantities of 100 % modulated sinusoidal light waveform measured by different instruments

Peak illuminance	50 lx			500 lx			5000 lx		
TLM quantity	PF	I_F	M_{SV}	PF	I_F	M_{SV}	PF	I_F	M_{SV}
Instrument A	99,9 %	0,32	3,9	99,9 %	0,32	3,9	99,9 %	0,32	3,9
Instrument B	113,8 %	0,31	3,8	100,9 %	0,32	3,9	100,1 %	0,32	3,9
Instrument C	0,0 %	-	-	107,3 %	-	-	107 %	-	-

From the light waveform measurement, we can find that the benchtop instrument A with better linearity has more stable and reasonable TLM quantities, while quantities measured by instrument C which has the worst linearity have large errors. In actual applications, the error due to non-linearity depends on the actual waveform and modulation depth. Especially in the low illuminance level, the non-linearity error would be much higher. And we can also find PF values over 100 %, which is caused by the negative values due to noises when detecting the lower end of the light waveform; and the 0,0 % PF occurs because the signal is all submerged in the noise, and its algorithm processing smooths all the instrument response. Noise is an important factor contributing to linearity, meanwhile it is worthy of being evaluated individually.

3 Noise

3.1 Characterization of noise property

The noises would not only add an offset but also enlarge the fluctuations of the luminous waveform, and they cannot be easily reduced by time-averaging in the TLM measurement. For a TLM measurement instrument, noises may differ with different applied measurement range, sampling rate and low-pass filter if applicable. And the influence of noises to the final measurement results also depends on the measured signal level.

3.2 Measurement of noise property

To characterize the noise of an instrument for TLM measurement, an index named noise-equivalent modulation (NEM) is proposed, whose symbol is M_{en} . NEM means the light modulation input to the detector of a TLM measurement instrument that produces an output of modulation depth equals to the maximum fluctuations the noise superimposed on a measured signal.

In order to measure the NEM, it is recommended to cover the detector, and measure the baseline noise for a certain duration after dark correction, and the readings should be taken in each measurement range and sampling rate. The NEM for a measured signal is given by:

$$M_{en}(Y) = \frac{Y_{base}}{Y} \quad (2)$$

Wherein,

Y_{base} is the maximum fluctuations of the baseline noise, i.e. the maximum value minus the minimum value;

Y is the averaged value of a measured signal.

Usually Y is unknown, to make it more universal and stringent, take 10 % of the range value, i.e. 10 % Y_{max} , to represent the noise-equivalent modulation for a given measurement range.

$$M_{en} = M_{en}(10\%Y_{max}) \quad (3)$$

The index M_{en} is suggested to be given for each measurement range and sampling rate, and report the largest M_{en} of all ranges as the declared noise index of the TLM measurement instrument.

3.3 Practical measurement result analysis

3.3.1 The noise of the TLM measurement instruments

First, we investigate the noise property under different conditions by changing the settings of the benchtop instrument A, such as filters and sampling rates. The M_{en} values for each measurement range and sampling rate are given as table 3:

Table 3 – M_{en} values of an instrument in different presetting

Filter	2 kHz cut-off			20 kHz cut-off		
Sampling rate	1 kHz	10 kHz	100 kHz	1 kHz	10 kHz	100 kHz
Range 1	0,20 %	0,22 %	0,30 %	0,22 %	0,26 %	0,36 %
Range 2	0,11 %	0,16 %	0,25 %	0,12 %	0,18 %	0,30 %
Range 3	0,11 %	0,14 %	0,27 %	0,12 %	0,14 %	0,29 %
Range 4	0,12 %	0,13 %	0,22 %	0,12 %	0,14 %	0,24 %

The noise property of the lowest measurement range is higher than the others at the same sampling frequency, which explains why the measurement accuracy of small signals is difficult to guarantee. Also, the index, M_{en} , increases with the increasing sampling rate and cut-off frequency. In the measurement, we also found that the average value of the noise, i.e. the offset, is quite stable under the same range.

The M_{en} of handheld instrument B varies from 1,5 % to 5,3 % depending on the sampling rate. The handheld instrument C may apply special algorithm when processing the data for stable light, that the noise reading is always 0 when covering the detector, therefore the M_{en} is unavailable.

3.3.2 Measurement of stable light sources

TLM quantities are measured and compared by three TLM measurement instruments for the same stable sources, the results are listed as follows:

Table 4 – TLM quantities of DC light waveform measured by different instruments

Instrument	Illuminance	PF	I_F	P_{st}^{LM}	M_{sv}
Instrument A (20 kHz sampling)	50 lx	0,03 %	0,00	0,00	0,00
	500 lx	0,01 %	0,00	0,00	0,00
Instrument B (5 kHz sampling)	50 lx	9,06 %	0,01	0,049	0,01
	500 lx	1,29 %	0,00	0,059	0,01

From the measurement results we can see that, the instrument B has bigger errors caused by noise, especially when the illuminance value is approaching the lower limit of the measurement range. Therefore, in practical measurement, it should be noted that the instrument itself may contribute a lot when the measured TLM quantities are small.

4 Frequency Response

4.1 Characterization of frequency response

The frequency dependent 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.

Assuming an input light signal's frequency components are all within the equipment's frequency bandwidth, the equipment should respond to changes in the input signal as quickly as they occur, resulting in output signals with low distortion. If some fractions of the input light signal's frequency components exceed the system's bandwidth, the system's response to this portion of the signal will lag. As a result, the output signal will not accurately reproduce the fastest, most abrupt amplitude transitions of the input signal. This will result in output signal which may have features of lower amplitudes, wider waveform and rounder edges than the corresponding features of the input signal.

To fully understand the frequency response of a TLM measurement instrument, it is necessary to make measurements at different modulation frequencies of the incident light with sinusoidal waveform. The frequencies should span the frequency range of interest, and it is important that suitable means shall be employed to ensure that peak-to-peak amplitude of light source used for the measurement remains constant as the modulation frequency varies.

Acquire the peak-to-peak amplitude of the instrument's output waveform to sinusoidal input light at different frequencies with constant modulation depth, noted as $A(f)$. Normalize $A(f)$ with respect to a reference value to get relative amplitude $A_{rel}(f)$ in percentage, in which the reference value is taken as the amplitude obtained at a frequency close 0 Hz, for example, 10 Hz here. The $A_{rel}(f)$ is the frequency response of the measurement instrument, which can be illustrated in a figure, as shown in figure 3.

To characterize the frequency response of a TLM measurement instrument with an index, the frequency bandwidth can be referred, which is upper limit of a frequency range in which the measured waveform is proportional to that of the input light signal. However, the frequency of 3 dB point, i.e. the point where the $A_{rel}(f)$ decreased to 0.707, is usually taken as the threshold, which is unacceptable 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 $A_{rel}(f)$ falls to 95 %.

4.2 Measurement of frequency response

In this work, a reference light source for frequency response measurement is applied to produce pure sinusoidal irradiation whose frequency is adjustable and can cover all the interested frequencies. The reference light source is realized by means of a single colour LED, whose luminous intensities are modulated sinusoidally using a suitable power supply, as shown in Figure 2. The output light of the LED can be easily and accurately modulated by a suitable input voltage V_{in} of the amplifier.

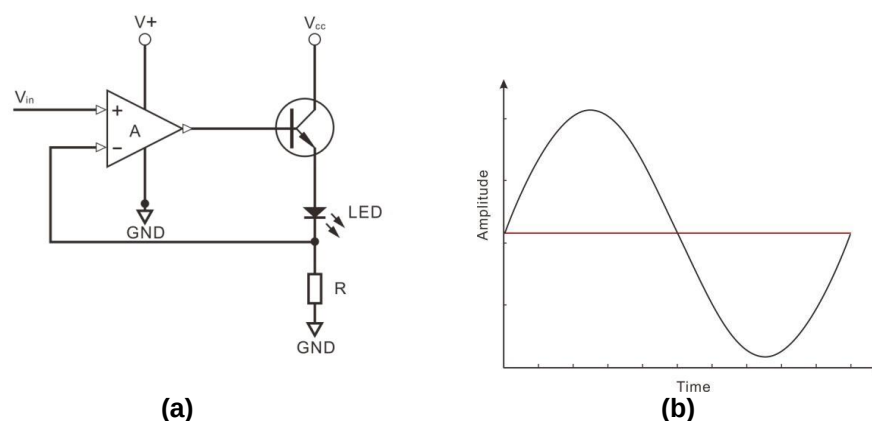


Figure 2 – Scheme of a reference light source for frequency response measurement (a) and its light waveform output: sinusoidally modulated light with DC component (b)

It should be noted that the length of the wire between the power supply and the light source should be small enough to reduce the power loss and the reduction of the light output caused by the inductance of the wire at high frequencies.

4.3 Practical measurement result results analysis

4.3.1 Measurement of frequency response of the instruments

Using the reference sources above, the frequency response characteristics of the TLM measurement instruments were measured. It should be noted that the sampling frequency during the measurement should be at least one order of magnitude higher than the measured frequency, otherwise the waveform distortion will be caused due to undersampling, leading to the inaccuracy of the measurement results.

Firstly, the cut-off setting of the benchtop instrument A is adjusted to make the -3dB point to be 2 kHz and 20 kHz respectively, while the cut-off filter keeps the same. The measured frequency response curves and corresponding frequencies are as follows:

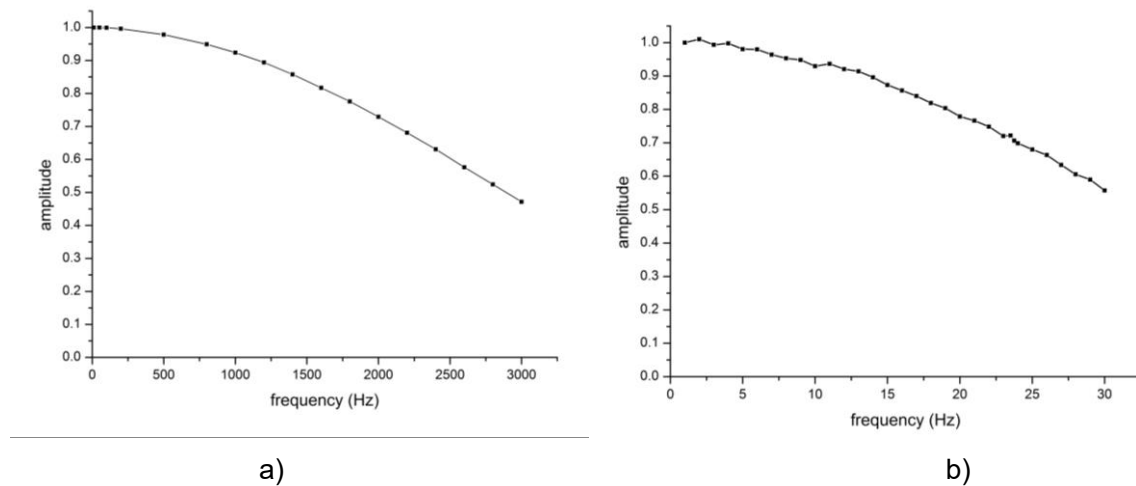


Figure 3 – Measured curves of frequency response function of the low pass filter a) Cut-off frequency at 2kHz b) Cut-off frequency at 20kHz

Table 5 – Frequency response of the TLM measurement instruments

	Instrument A_2kHz	Instrument A_20 kHz	Instrument B	Instrument C
-3 dB point	2,13 kHz	23,8 kHz	3,75 kHz	1 kHz
95 % f_{BW}	760 Hz	8,6 kHz	1,6 kHz	320 Hz

4.3.2 Measurement of light waveform

A square waveform at different frequencies with modulation depth at 100 % is measured using three TLM measurement instruments, and the peak illuminance is around 500 lx. The results are listed as follows:

Table 6 – TLM quantities of square light waveform measured by different instruments

Frequency	65 Hz				100 Hz			400 Hz		
TLM quantity	PF	I_F	P_{st}^{LM}	M_{sv}	PF	I_F	M_{sv}	PF	I_F	M_{sv}
Instrument A_20 kHz	100 %	0,50	1,82	5,05	100 %	0,50	4,98	100 %	0,50	2,06
Instrument A_2kHz	100 %	0,50	1,76	5,05	100 %	0,49	4,96	100 %	0,46	2,03
Instrument B	102 %	0,51	1,76	5,03	101 %	0,49	4,95	102 %	0,47	2,05
Instrument C	100 %	-	-	-	100 %	-	-	100 %	-	-

From the results we can see that, when we measure the high frequency square light waveforms, the PF values would not change much, while errors of I_F and M_{sv} values arise by comparing the values of the instrument whose 95 % f_{BW} is 8,6 kHz.

Because the measured light waveforms are unknown beforehand, It is important to make sure the TLM measurement instrument has flat frequency response in the frequency range of interest, say 2 kHz for M_{SV} , and even high for phantom array phenomenon. The difference between the -3dB point can not ensure such flatness, therefore, the defined 95 % f_{BW} is a good index.

5 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. This work mainly discusses the instrument performance related to TLM measurement, including linearity, noise and frequency response, and proposes clear quality indices for the characterization.

Through theoretical analysis and practical measurement, the availability of these quality indices is verified, and the following conclusions are obtained:

- (1) The linearity index f_3 for photometers measuring time-averaged luminous quantities is also applicable for TLM measurement instruments. However, linear dynamic range in a measurement range should be emphasized, which is determined by measuring the linear deviation of the instrument and setting the threshold. The narrower the dynamic range, the greater the possible deviation of the measured TLM values.
- (2) Noise-equivalent modulation M_{en} is used to characterize noise. According to the actual measurement of DC light sources, devices with larger noise will produce larger measurement errors, especially when the measured light is in the lower part of the instrument range.
- (3) The frequency response will affect the accuracy of measuring high-frequency light waveform, which can be measured by light source with a sinusoidal waveform and adjustable frequencies. For TLM measurement, it is not enough to just specify the cut-off frequency of the anti-aliasing filter at -3dB point, and uses the 95 % attenuation frequency to determine f_{BW} . It is worth noting that high frequency response brings more noises, and these parameters should be balanced in actual measurement.

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

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Abstract

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 applications to extract small, modulated signals buried in noise that could not directly be measured otherwise.

In most lighting products, temporal light modulation is usually a periodic fluctuation of 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.

Different methods of lock-in detection are applicable to photometric and spectroradiometric measurements in the presence of temporal light modulation: electrical lock-in detection with a lock-in amplifier, digital lock-in detection based on synchronous sampling, and purely optical lock-in detection.

The practical implementations of these methods are detailed, illustrated, and compared. Their respective advantages and drawbacks are presented in the case of photometric and in the case of more complex measurements based on array spectrometers and imaging photometric instruments. New applications enabled by temporal light modulation are given.

Keywords: Photometry, Spectroradiometry, Lock-in detection, Temporal light modulation

1 Principles of lock-in detection

The principle of lock-in detection is to multiply the signal by a reference signal defined as a pure sine wave locked to the frequency and phase of the modulated component to measure. The resulting product includes alternating components at various frequencies (sum and difference of each frequency in the signal with the reference frequency). The only dc component remaining after the multiplication is the component of the signal at the exact reference frequency. A low-pass filter is used to remove all the alternating components and keep the dc component.

In practice, a “dual phase” approach is often used in lock-in detection. The lock-in operations (multiplication followed by low-pass filtering) are applied using the reference sine wave in a first channel (in-phase channel). In a second channel (quadrature channel), the reference sine wave is shifted by 90°. The output of the two channels are respectively the real part X and imaginary part Y of the Fourier component of the signal at the frequency of the reference signal. They can be combined to generate the amplitude A and phase φ of the modulated signal using the following relationships:

$$A = \sqrt{X^2 + Y^2} \quad ; \quad \varphi = \text{atan}\left(\frac{Y}{X}\right) \quad (1)$$

Figure 1 illustrates the principle of lock-in detection. Lock-in detection can be seen as a very narrow phase-sensitive electrical bandpass filter centred on the reference frequency, rejecting the dc component and ac components at other frequencies.

The design of the low-pass filters is important in lock-in detection. Their time constant determines the effective frequency bandwidth of the lock-in detection and the passband uniformity. The slope of the cut-off determines the rejection of unwanted out-of-band frequency components. Steep slopes are generally produced by using high-order filters, which take more time to reach a stable output.

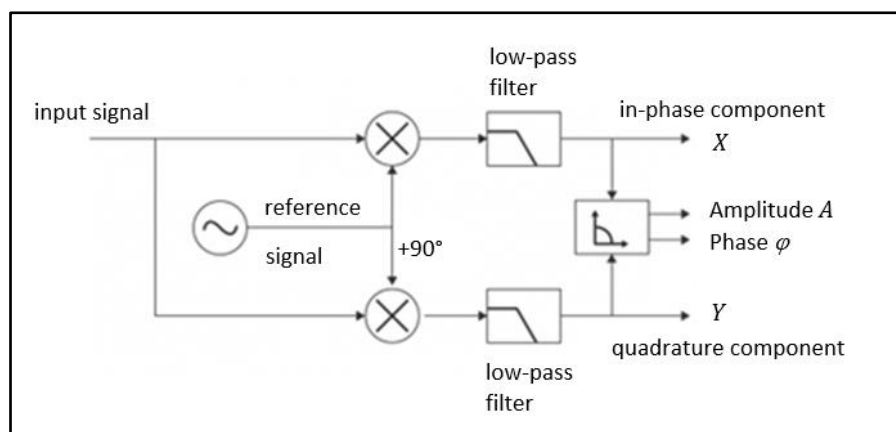


Figure 1. General principle of lock-in detection

The electrical lock-in detection technique has been integrated in the hardware of special types of sensor arrays. These devices incorporate an electronic lock-in circuitry implemented at the pixel level. There are a few commercially available lock-in cameras working on this principle (Bonati *et al.*, 2022).

2 The reference signal in lock-in detection

The implementation of a lock-in technique requires using a reference signal whose frequency and phase are locked to the modulated signal to measure. The reference signal can be generated using the device responsible for modulating the signal. It can be an ac power supply, a signal generator, an optical chopper, an electrical oscillator, etc. In the case of measuring an optical signal, the reference signal can be extracted from an optical detector placed close to the light source. If the light source is externally modulated using an optical modulator such as a chopper, the reference signal can be the driving signal of the modulator itself. If the light source is modulated using an ac power supply, then the reference signal is provided by a current or a voltage sensor. Current sensors have the advantage of being contactless (inductive loop or hall effect probe).

Figure 2 shows an example of electronic circuit used to generate a TTL reference signal from an analogue signal delivered by a sensor monitoring the signal modulation. The circuit is based on an ac coupling capacitor, a voltage divider producing a constant bias voltage and a comparator with hysteresis, also called a Schmidt trigger. The hysteresis is defined by an adjustable upper and lower threshold to eliminate the multiple transitions caused by noise. The TTL reference signal can trig a function generator to obtain a pure sine wave used as the reference signal in lock-in detection. A phase-lock loop (PLL) is required to maintain a constant phase between the TTL and the sine wave signal.

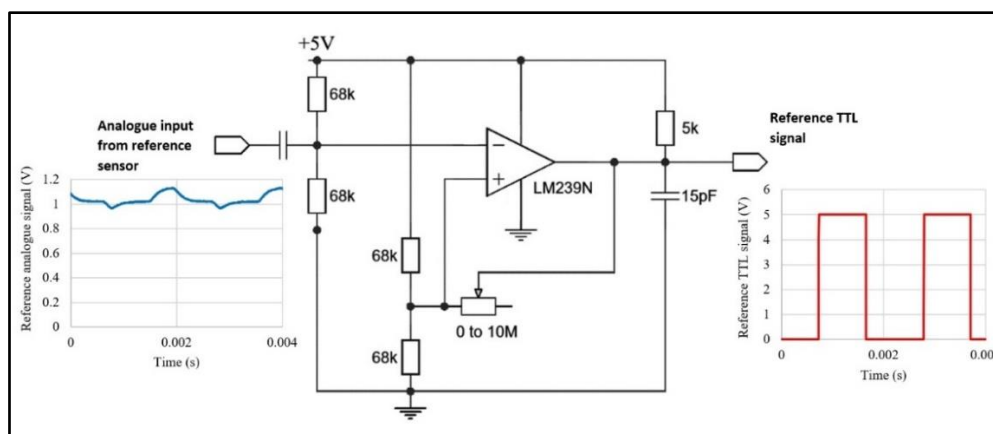


Figure 2. Example of electronic circuit designed to convert an analogue signal to a digital TTL reference signal

2.1 Measuring harmonics and sub-harmonics

In the previously described embodiment, lock-in detection provides the modulated component of a signal at the exact frequency of the reference signal. In many applications, it is useful to perform lock-in detection at a harmonic frequency or a sub-harmonic frequency of the reference signal. It is the case when studying non-linear phenomena, which exhibit modulated components at multiples of the modulation frequency of a periodic physical excitation. For instance, light sources powered by an ac current often have a strong temporal light modulation at twice the electrical frequency.

Lock-in detection at harmonic and sub-harmonic frequencies can be performed by processing the reference signal using frequency multipliers or dividers, with the constraint of keeping the synchronization in frequency and phase with the original reference signal.

3 Electrical lock-in detection (lock-in amplifier)

When the signal to measure is generated by a sensor having a voltage output, the use of commercially available lock-in amplifiers is the most robust approach to perform lock-in detection. Modern lock-in amplifiers are digital: they rely on internal A/D converters to digitise the electrical signals to measure. The multiplication and filtering stages are performed using digital operations.

Commercial lock-in amplifiers incorporate a signal generator and a PLL circuit in order to generate their own reference signal that can be used to drive a power supply or an optical modulator. The most common lock-in amplifiers can measure signals at frequencies up to 500 kHz but some instruments can operate up to 600 MHz.

Lock-in amplifiers have been universally used to measure very low levels of signals in many types of physical measurements, whenever a periodic modulation can be applied to an optical, mechanical, or electrical excitation. For example, laser beams used to probe solids, liquids, gases and biological materials in microscopy and spectroscopy are very often modulated to produce a signature detected by a sensor associated with a lock-in amplifier.

In photometry, lock-in amplifiers can be used to measure light sources emitting modulated light or repeated pulses. In the field of spectroradiometry, scanning grating monochromators give very little light at the exit slit. To improve the signal to noise ratio, the light source can be modulated before the input slit while the photodetector at the exit slit is associated with a lock-in amplifier.

Angularly resolved measurements of the optical properties of surfaces and materials (reflectance, transmittance and BRDF measurements for instance) can work with a modulated incident beam and a lock-in amplifier after the detector to improve the signal to noise ratio in the directions where the light exiting the sample is very low.

4 Digital lock-in detection for array sensors (synchronous sampling methods)

Commercial lock-in amplifiers are currently limited to 32 simultaneous measurements. This is the reason why lock-in measurements are difficult to perform with array sensors such as CCD and CMOS sensors because a much higher number of individual signals need to be processed in parallel. This is typically the case with array spectrometers and imaging luminance meters with sensors typically having 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 precise time intervals controlled by the reference modulation period. The sampling should be done in synchrony with the reference signal. A fixed integer number N of samples should be acquired during one modulation cycle T of the reference signal. In doing that, the sample interval is T/N and there is no phase lag in the distribution of the samples with respect to the reference signal. All the pixels should be synchronously sampled. These techniques are also referred to as synchronous sampling methods.