Luminance Calibration and Linearity Correction Method of Imaging Luminance Measurement Devices

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Abstract—This paper shows that the opto-electrical characteristic of a typical CCD based digital camera is nonlinear. It means that a digital electric signal of the camera CCD detector - is not a linear function of the luminance value on the camera lens. The opto-electrical characteristic feature of a digital camera needs to be transformed into a linear function if this camera is to be used as a luminance distribution measurement device known as Imaging Luminance Measurement Device (ILMD). The article presents the methodology for obtaining the opto-electrical characteristic feature of a typical CCD digital camera and focuses on the non- linearity correction method.

The imaging luminance measurement device (ILMD) is also known as a luminance meter [1–7], an array (or matrix or digital) luminance meter [8–10], a multi-channel digital luminance meter [11], a luminance mapper [12], a video photometer [13], a luminance camera [14–17] or a spatial luminance profile device [18]. It is important to highlight the fact that the traditional spot luminance measurement device (LMD) gives the user information only about one spatially averaged luminance value of light sources or illuminated surfaces. However, the user of ILMD gets the luminance image [19] which gives information about spatial distribution of luminance (see Figure 1). It is because ILMD measures object luminance at many points at the same time.

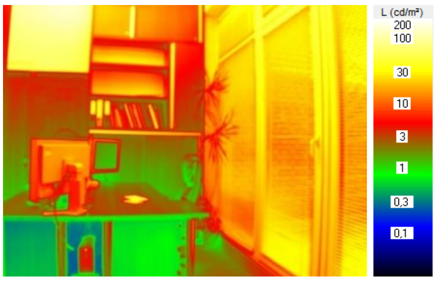

Fig. 1. Example of ILMD luminance distribution measurement.

The schematic diagram of a typical ILMD construction based on an ordinary digital camera is presented in Fig. 2. It consists of a lens system, V(λ) correction filter, CCD sensor with an amplifier, low noise analog electronics, A/D conversion and digital data transfer.

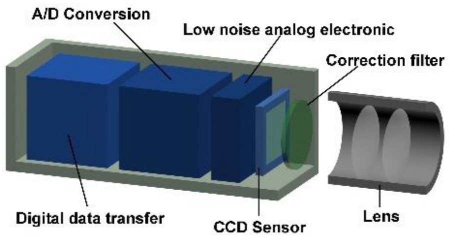

Fig. 2. The schematic diagram of ILMD.

This kind of device needs to be calibrated. It means that the relationship between the values of quantities indicated by a CCD sensor and the corresponding values realized by luminance standard needs to be set. The characteristics of optical input signal (luminance) conversion into an output digital electrical signal were tested to check whether it is possible to use the classical Canon QV-5700 digital camera (see parameters at Table 1) to measure luminance distributions. The tested digital camera has 3 channels for converting an optical signal into an electrical one, i.e., RGB.

Table.1. Technical parameters of Canon QV-5700 digital camera.

Parameter	Value
Sensor type	CCD 1/1.8’’
Effective pixels	5.0 megapiksel (2560 ×1920)
Lens Aperture	f/2.0 – f/2.5 to f/8.0
Shutter Speeds	60 s – 1/1000 s
Sensitivity	auto, ISO: 50, 100, 200, 400, 800
Metering	Multi-pattern, Center-weighted average, Spot
Exposure Compensation	± 2 EV in 1/3 EV steps
Autobracketing	AEB
Manual focus	Yes
Focus lock	Yes

Figure 3 shows the luminance standard set-up typically used for the calibration of ILMDs. It is based on the luminance standard OL 455. The parameters characterizing that standard are presented in Table 2. The results of calibration allow to assign the values of standard luminance to the values measured by ILMD. In the case of ILMDs, the luminance unit is candela per square meter.

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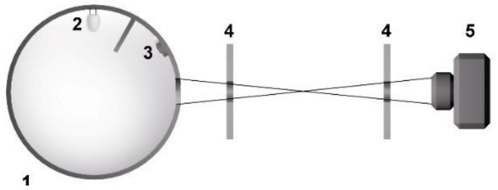

Fig.3. The set-up used for the calibration of Canon QV-5700 digital camera, where: 1 – photometric sphere, 2 – reference light source, 3 – photometric head, 4 – shutters, 5 – digital camera.

Table. 2. Technical parameters of OL 455 standard.

Parameter	Value
Luminance Uncertainty	(@2856 K, 90% max. luminance) ± 0.5% relative to NIST
Luminance Stability	@ 2856 K, Short Term ± 0.5%
Luminance Range	0 ÷ 30000 cd/m^2

The measured input-output characteristics of Canon QV-5700 digital camera showed significant nonlinearities in the processing of an optical signal into an electrical one. The output signal from this digital camera can be read for three channels: Red (R), Green (G) and Blue (B). The examples of measurement results for the R channel are shown in Fig. 4.

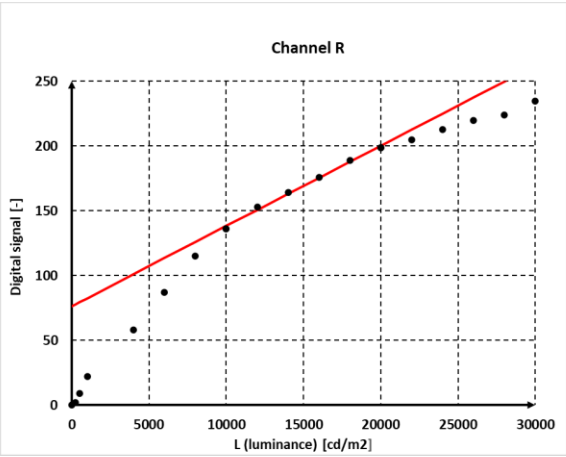

Fig. 4. The measured input-output characteristics of Canon QV-5700 digital camera.

In measuring practice, the calibration of a measuring instrument does not ensure the perfect linearity of its input-output characteristics. Therefore, the international measurements standards introduce an error f_3 as a measure of quality of the ILMD meter. The error f_3 is calculated according to the formula (1) [20]. Based on the f_3 value, the ILMD class is determined. According to the information provided by DIN 5032-7:2017 [18], these classes can be categorized as shown in Table 3. The other categorization methods are given by the EU standard EN 13032-1:2004 [19] (Table 4) and by CIE 231:2019 technical report [20] (Table 5).

$$f_3 = \left|\frac{Y}{Y_{max}}\frac{X_{max}}{X} - 1\right| \quad (1)$$

where: Y is describing the output signal of a luminance meter; X_{max} is used for the input value corresponding to the maximum output signal Y_{max}.

Table. 3. Luminance meters classification according to DIN 5032-7:2017 standard.

Index	Symbol	Class L	Class A	Class B	Class C
Linearity	f_3	0.2 %	1.0 %	2.0 %	5.0 %

Table. 4. The luminance meters classification defined by EN 13032-1:2004 standard.

Index	Symbol	Maximal Value
Linearity	f_3	0.2 %

Table. 5. Luminance meters classification defined by the CIE 231:2019 technical report.

Index	Symbol	Class 4*	Class 3*	Class 2*	Class 1*
Linearity	f_3	0.2 %	1.0 %	2.0 %	5.0 %

By analyzing data showed in Figure 4, it was found that there are three areas for relatively linear operation of this digital camera. They can be distinguished as follows: the first one – from 0 cd/m^2 to 10000 cd/m^2, the second one – from 10000 cd/m^2 to 20000 cd/m^2, and the third one – from 20000 cd/m^2 to 30000 cd/m^2 (see Figure 5).

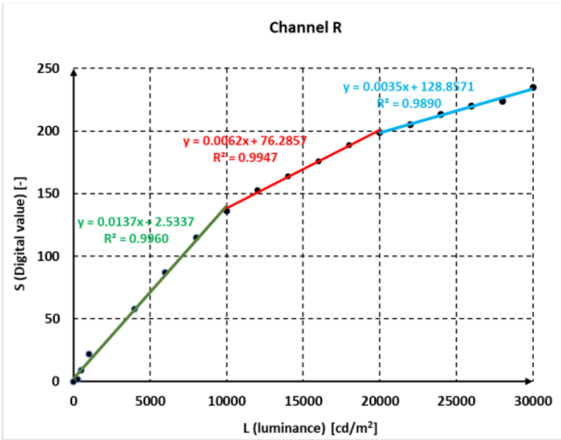

Fig. 5. The approximation of Canon QV-5700 digital camera input-output characteristics by three different linear functions

Another way to approximate the camera input-output characteristics is to use the polynomial function. The polynomial functions (order 2, 3 and 4) describing an output signal from the red (R) channel of this digital camera are presented in Figs. 6, 7 and 8, respectively. The polynomial equation (trend line) and factor R^2 are provided in each Figure (Fig. 6, 7, and 8). However, the R^2 for each of these polynomials is greater than 0.99. It is worth noting that using a 2nd order polynomial for this application is not recommended because it causes significant deviations for the luminance of 30000 cd/m^2.

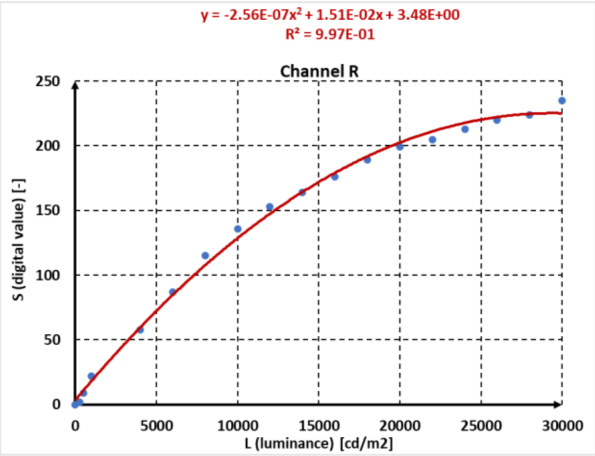

Fig. 6. The approximation of Canon QV-5700 digital camera input-output characteristics by a 2nd order polynomial.

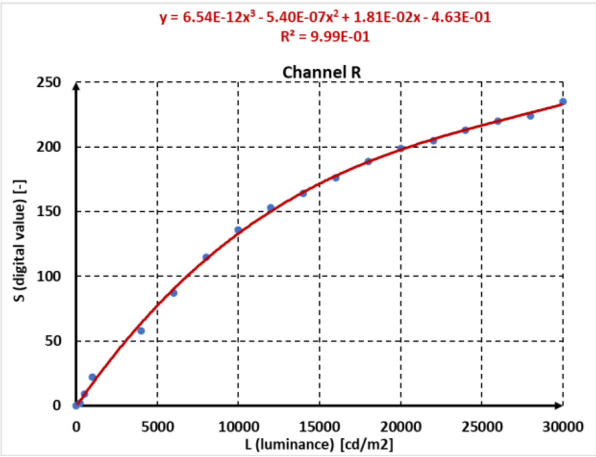

Fig. 7. The approximation of Canon QV-5700 digital camera input-output characteristics by a 3rd order polynomial.

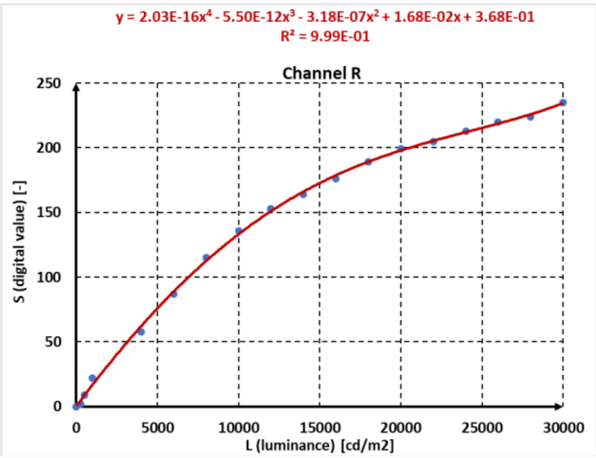

Fig. 8. The approximation of Canon QV-5700 digital camera input-output characteristics by a 4th order polynomial.

To linearize the function of converting a light signal into an electric one, the measurement data should be multiplied by the inverse function. Therefore, it is recommended to approximate the calibration points by at least a 3rd order polynomial function (see Fig. 7 and Fig. 8), and then to determine the inverse function (Table 5). If the relation describing a given polynomial function S(L) (where: S is Signal in digits, L is Luminance cd/m^2) is written (Eq. (2)), then the function inverse to a given function S(L) with respect to L will be the function $f^{-1}(S)$ described by the Eq. (3).

$$S = f\,(L) \tag{2}$$

$$L = f^{-1}\,(S) \tag{3}$$

Table. 5. The ILMD input-output S = f (L) characteristics approximation function and its inverse $L = f^{-1}$ (S) polynomial.

S = f (L)	$L = f^{-1}$ (S)
$y = 6.54E\text{-}12x^3 – 5.40E\text{-}07x^2 + 1.81E\text{-}02x – 4.63E\text{-}01$	$y = 2.66E\text{-}03x^3 – 4.65E\text{-}01x^2 + 8.06E{+}01x – 9.84E{+}01$
$y = 2.03E\text{-}16x^4 – 5.50E\text{-}12x^3 – 3.18E\text{-}07x^2 + 1.68E\text{-}02x + 3.68E\text{-}01$	$y = \text{-}1.65E\text{-}06x^4 + 3.35E\text{-}03x^3 – 5.87E\text{-}01x^2 + 8.91E{+}01x + 1.16E{+}02$

The 5th order polynomial function linearizing luminance measurements (for RGB channels of this camera) and its inverse function are presented in the paper [24].

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