The linearization of the relationship between scene luminance and digital camera output levels

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Abstract—This paper presents the results of linearity testing of the integrated image sensor of a CCD-equipped digital camera. The study demonstrated the lack of linearity of the characteristics of the sensor when scaling with the luminance standard signal. In the course of the research the function approximated by the fifth-degree polynomial was determined. After the appropriate transformation, this function would enable the linearization of the signal from the studied image sensor. The study demonstrated the possibility of linearizing the signal of integrated image sensors for correct luminance measurements. Thus, the possibility of reducing the nonlinearity error of integrated image sensors was discussed.

Luminance is one of the basic photometric quantities. Luminance distributions are most often determined for interiors [1÷3], in road lighting [4÷7], in luminaire design [8÷13], or in the evaluation of displays (e.g., phones or TVs) [14÷15].

Modern matrix luminance meters are used to measure luminance distributions [16]. ILMD (image luminance measuring device) matrix meters were developed while improving the technology of digital cameras construction. [17÷18]. The major components of an ILMD include an optical system (lens), correction filter (matching V(λ)) [19÷23], sensor (photosensitive matrix) and an image converter. The optical system consists of several or even over a dozen lenses which function is to project a sharp image onto a photosensitive matrix such as a Charge Coupled Device (CCD) [3], [19÷21], [24÷25] without distortion or noise. Modern CCD matrices consist of many photosensitive elements (so-called pixels - there are from several hundred thousand to tens of millions of them). These photosensitive elements transmit information about the brightness of an object projected onto the matrix through an optical unit [26]. The information from the pixels in a CCD matrix is read out sequentially row by row. CCD matrices make it possible to measure the luminance distribution on the measured surface. Photosensitive matrices are made in two technologies, i.e., B/W (black and white) and RGB (color).

The accurate laboratory meters use B/W matrices while portable luminance meters, often with lower measurement accuracy, use RGB matrices. The meters equipped with RGB matrices average the results from at least four adjacent cells (pixels) that are covered with RGB filters (usually two green, one red, and one blue) to determine luminance. Hence, the resolution of this type of meter is lower than that of monochromatic meters.

Due to high prices of specialized photosensitive matrices dedicated for measurement purposes, portable luminance meters are developed on the basis of cameras, e.g. with CCD matrices [24]. CCD matrices are characterized by many technical parameters depending on their design solution and manufacturing technology. Due to the possibility of using these CCD matrices in luminance meters, the most important parameters include: the linearity of a sensor [27] and spectral characteristics of its sensitivity [28]. Controlling exposure conditions such as time and aperture setting [22] manually is of key importance. The spectral characteristics of the photometer's sensitivity can be well corrected with appropriately selected filters [19÷21]. However, the linearity of the converter is the necessary condition that needs to be fulfilled in luminance meter design [24].

It was decided that the linearity of the camera's CCD would be checked in the initial stage of the research conducted. The camera chosen for the presentation of the results was named Camera 1 in order not to use manufacturers' names. The conducted research allowed to verify the possibility of using this type of digital cameras in luminance measurements.

The laboratory station consisted of a reference source to which Camera 1 was attached perpendicularly (in the axis of the measurement window). The chosen camera was equipped with a CCD matrix with a resolution of 5 million pixels and a 12-bit/color sensor. Additionally, Camera 1 enabled manual setting of exposure time and aperture.

After passing through the lens, the radiation from a luminance-controlled standard radiation source OL 455, fell on the surface of the tested CCD matrix. After being processed by an analog-to-digital converter, the electrical signal generated by this matrix, was saved in the form of a graphic file (bitmap). The used OL 455 standard optical

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radiation source allowed for smooth adjustment and measurement of the luminance source without changing the spectral distribution of its radiation. The reference source was characterized by the following parameters:
- Luminance Uncertainty (@ 2856 K, 90% max. luminance) ± 0.5% relative to NIST,
- Color Temperature Range 2000 to 3000 K,
- Luminance Stability @ 2856 K, Short Term ± 0.5%.

The reference source allowed the luminance to be varied over the range tested, i.e., from 0 to 30000 cd/m^2.

By performing measurements under constant exposure conditions (its time and aperture used) for various values of luminance of the source of optical radiation, the characteristics of CCD matrix sensitivity were examined, which in turn allowed to assess its linearity.

In the study, the output signal was found to be nonlinear.

Hence, it was decided to investigate the possibility of linearizing the output signal from the camera matrix. To linearize[29] the matrix signal from Camera 1, the output signal values for each RGB channel were read separately. Figure 1 shows the results for channel R, Fig. 2 shows the results for channel G and finally Fig. 3 shows the results for channel B. Then, each of the obtained line graphs was approximated by a trend line [30], describing it as the polynomial of the fifth degree. The polynomial equation can be found above each figure: above Fig. 1 for channel R, above Fig. 2 for channel G 2, and above Fig. 3 for channel B. In each figure, the blue line represents the line passing through the measurement points, while the red line represents the trend line described by the polynomial of the fifth degree. The next step was to select a function that would transform the trend lines into a linear function. Following the mathematical conversion rules, we had to determine the function inverse to the function (polynomial) describing the output signal from a given channel of Camera 1. If the relation describing the given trend function S(L) (where: S is Signal, L is Luminance) is written according to the general relation (equation (1)), then the function inverse to the given function S(L) with respect to L will be the function $f^{-1}(S)$ described by the Eq. (2).

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

$$L = f^{-1}\,(S) \tag{2}$$

The polynomial equation of the given trend function (as an inverse function) was determined according to the formula above Figs. 4, 5, and 6 for each channel R, G, B, respectively. In each figure, the blue line represents the function inverse to the scaling function and the green line represents the trend line of the inverse function. When the two functions (the scaling function and the function inverse to it) were put together, a linear scaling function for each channel was obtained. Thanks to the applied transformation, it was possible to reduce the error of nonlinearity of the given converter (photosensitive matrix). The applied method can be also used for other converters, and in other digital cameras which can be used for luminance measurement.

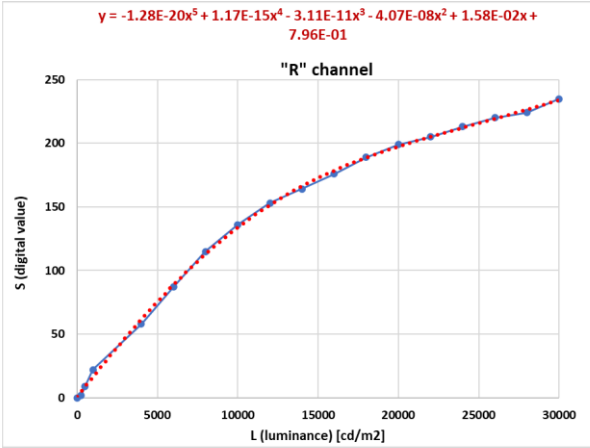

Fig. 1. Camera 1 (channel R) matrix sensitivity characteristics - the blue line indicates the scaling curve and the red line the trend line.

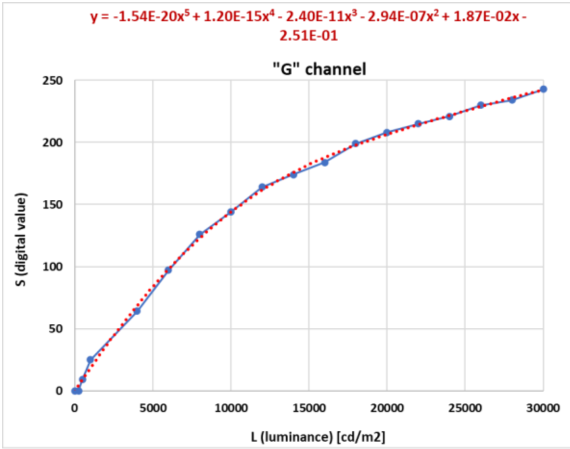

Fig. 2. Camera 1 matrix sensitivity characteristics (channel G) - the blue line indicates the scaling curve and the red line the trend line.

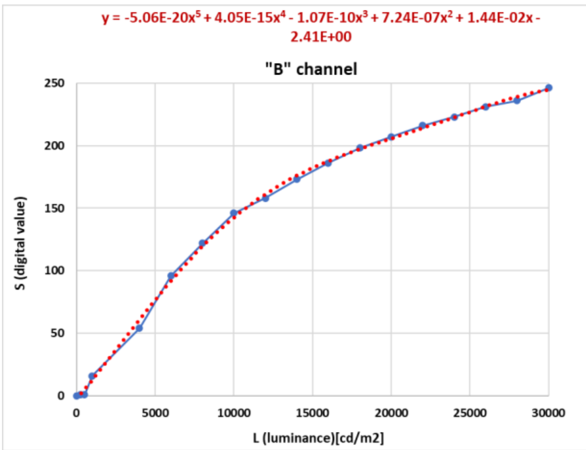

Fig. 3. Camera 1 matrix sensitivity characteristics (channel B) - the blue line indicates the scaling curve and the red line the trend line.

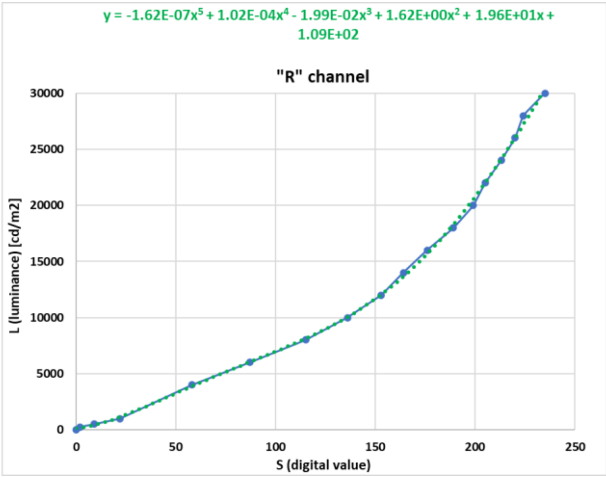

Fig. 4. Camera 1 (channel R) sensitivity linearization function plot - the blue line represents the function inverse to the scaling function, and the green line represents the trend line of the inverse function.

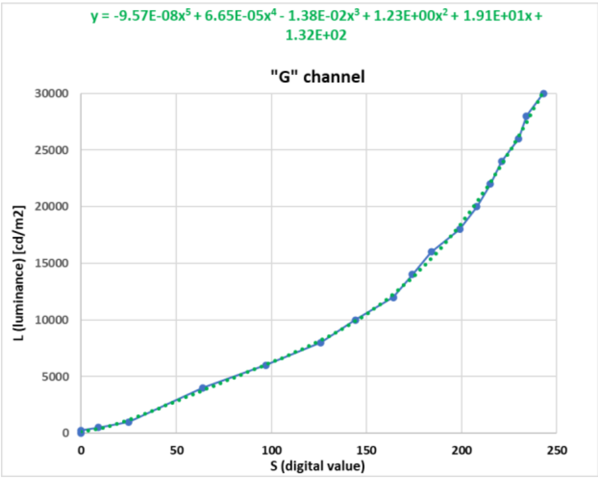

Fig.5. Camera 1 (channel G) sensitivity linearization function plot - the blue line represents the function inverse to the scaling function, and the green line represents the trend line of the inverse function.

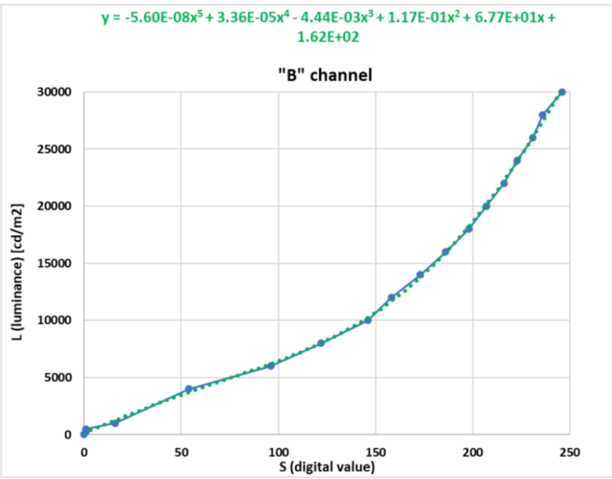

Fig. 6. Camera 1 (channel B) sensitivity linearization function plot - the blue line represents the function inverse to the scaling function, and the green line represents the trend line of the inverse function.

During the research work it was found possible to linearize the CCD camera's digital signal output. Thus, it meant subjecting the data to such digital processing that the obtained output could be a linear function of measured luminance. Summarizing, in the conducted research the example of transformation has been presented and in this way the method for reducing the nonlinearity error of integrated image sensors has been discussed.

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