Application of a commercial digital photo camera as a metering device for spatial light distributions measuring

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Abstract

Wide expansion of commercial digital photo cameras with high-quality solid-state photo sensors allows to use such cameras in various practical applications. It is experimentally shown that the application of special raw converter dcraw allows to use full linear dynamic range of images obtained from cameras for spatial light distributions measuring. Results on measurements of the radiometric function, camera’s linearity, linear and full dynamic ranges, and noise properties for used commercial digital camera are presented. The comparison of results provided by conventional converter and special converter are provided. It is shown that the application of special converter dcraw allow to increase linear dynamic range of the registered images in approximately 10 times.

1 Introduction

Solid-state photo detectors have achieved a high degree of excellence in modern commercial digital cameras. Such circumstance allows to use inexpensive commercial cameras as metering devices for various practical applications instead of technical cameras. With appropriate software raw-files converters it is possible to obtain unprocessed linear image data from the raw files without gamma-correction, colour interpolation, and other unwanted image postprocessing operations.

Consumer-grade digital cameras are being applied in such systems as inexpensive microscopic system [1] and in industrial imaging system [2]. As an another example of practical application of consumer-grade digital cameras as metering devices, hybrid optical-digital systems [3, 4] can be mentioned. Such systems allow to create devices that combine highly paralleled optical processing and flexibility of digital image processing techniques. Imaging schema of such systems is changed by inserting a synthesized diffraction optical element that enables carrying out optical convolution and registering optically convolved

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image using digital photo sensors. All information about the input scene is included in the grey levels of the convolved image. Hence any non-linear image processing can distort a convolved image; that is why the storage of images in a linear format is so important.

In order to use commercial digital photo cameras as metering devices, one have to compensate or turn off postprocessing procedures introduced by digital camera. The introduced non-linearity of camera’s signals can be compensated by application of inverse gamma-curve that determined by compararametric method [5, 6] or reflection from the calibrated samples [7]. Then approximation with polynomials [8] or least-squares [9] of camera’s response is performed and then inverse gamma-curve is found. Then using the inverse gamma-curve it is possible to compensate introduced non-linearity and hence obtain linear image. Modern single lens reflex (SLR) cameras can output raw image data to raster image files. Hence using special software raw-files converters it is possible to turn off any postprocessing operations such as gamma-correction and colour interpolation. As an example of such converters, open source Dave Coffins’s raw-files converter dcraw [10] can be mentioned. This converter was used for analysing raw image data and estimation of camera’s characteristics [11]. In our previous works [12, 13] it was shown that metering characteristics of commercial digital cameras are acceptable for using them in optical-digital correlators.

The aim of this paper is to demonstrate the application of a consumer-grade photo camera for measuring spatial laser light distributions and give estimations of metering capabilities of the camera. As an example of the photo camera, Canon EOS 400D digital SLR was used. The procedure of linearization of camera’s data is provided. The experimental demonstration of camera’s linearity is performed: far-field diffraction pattern on a rectangular aperture registered by camera is compared with numerical calculations. Camera’s linearity estimation is performed. Measuring properties of the camera such as dark noise and light-depended noise are provided. Linear and full registration’s dynamic ranges of the camera are evaluated.

2 The procedure of data linearization from the commercial photo camera

The main problem of using commercial cameras as metering devices is the unwanted postprocessing that is applied to registered data. Human’s visual system is known to have a non-linear response to light [14] that gives the ability of high dynamic range vision. But camera’s photo sensor has linear response to light and hence lesser dynamic range than human vision system. In order to overcome such limitation, postprocessing methods such as on-chip noise-cancelling [15, 16], colour data scaling, gamma-correction, colour interpolation, and gamma-correction are applied by camera’s manufacturers. As a result, registered data is being transformed into a photograph that has a significantly non-linear response to light. Hence to obtain unprocessed data from a commercial camera, special linearization procedure must be performed.

In this section are described the linearization procedure of the Canon EOS 400D camera used in this work. Dave Coffin’s dcraw converter was used to obtain unprocessed data in “document mode” from the captured images. It is
noteworthy that dcraw is applicable for processing raw-files of more than 400 commercial digital cameras. For such purpose it is necessary to write 12-bit raw data in 16-bit TIFF files with command dcraw -4 -T -D -v filename.cr2. It is remarkable that in the verbose mode dcraw can provide the information about multipliers of the colour channel’s amplification and black level offset (BLO). In a command line one can see:

```
Loading Canon EOS 400D DIGITAL image from filename.cr2 ...
Scaling with black 256, multipliers 2.630775 1.000000 1.249379 1.000000
Building histograms...
Writing data to filename.tiff ...
```

Amplification multipliers are written down in the raw file by camera’s electronics. It is significant to note that the raw data itself is not multiplied by amplification multipliers: amplification occurs on the next stage of raw files conversion by raw-files converter. These colour multipliers are used for human comfortable images viewing. Conventional raw-file converter shipped with camera multiplies data from the R G B G pixels by 2.630775 1.000000 1.249379 1.000000 respectively. If dcraw converter is used with -D option, an unprocessed linear 12-bit image is converted to 16-bit image without colour channel’s multiplication, colour interpolation, and gamma-correction. To obtain totally unprocessed raw data from a commercial digital photo camera, the use of dcraw with -D option is necessary.

The demonstration of the commercial camera’s linear response to light if dcraw converter applied is provided in the further section.

3 Experimental demonstration of camera’s linearity

To demonstrate that the commercial camera can output linear signal as a response to the light, far-field diffraction pattern on a rectangular aperture was registered by a camera’s photo sensor. We use Canon EOS 400D consumer grade digital camera with Bayer colour filters array. The camera is equipped with CMOS sensor with $3888 \times 2592$ pixels, 12-bit ADC, and $5.7 \times 5.7 \mu m^2$ pixel size.

The key diagram of the experimental setup is shown in Fig. 1. Radiation of the YAG:Nd laser $\lambda = 0.53\mu m$ (with KDP frequency doubling) is attenuated by filter 2 and then focused by the microscopic lens 3 on the filtering pinhole 4. Light is passing through the lens 5 so collimated beam illuminates the rectangular aperture 6 (aperture’s sizes are $l_X = 130\mu m$ and $l_Y = 200\mu m$). Far-field diffraction pattern is formed in the back focal plane of the lens 7 ($f = 500$ mm), registered by the commercial digital camera 8 (there was no lens attached to the camera), and saved in raw format for further processing and analysing. The computer 9 allows to remotely control the digital camera 8 as well as to process registered images.

The intensity $I$ in the back-focal plane for the light diffracted on the rectangular aperture [17] with width $l_X$ and height $l_Y$ is following:

$$I(x_0, y_0) = I_0 \left( \frac{\sin(k_1)}{k_1} \right)^2 \left( \frac{\sin(k_2)}{k_2} \right)^2,$$  \hspace{1cm} (1)
Figure 1: The key diagram for registration of diffraction pattern: 1 - Nd laser, 2 - attenuated filter, 3 - microscope lens, 4 - filtering pinhole, 5,7 - lens, 6 - rectangular aperture, 8 - digital photo camera, 9 - computer.

where $k_1 = \frac{lx_0}{\lambda f}$, $k_2 = \frac{ly_0}{\lambda f}$, and $x_0$ and $y_0$ are coordinates in the plane of registration. The width of the zero diffraction order $\Delta x_0 = \frac{2k_1}{lx}$ must be equal to 4.0 mm according to Eq. (1) in this case.

The raw-file image of the diffraction pattern registered by camera was processed by special converter dcraw in “document mode” (no colour, no interpolation, totally raw). Two green colour channels were extracted from the raw file and averaged (green pixels are corresponding to laser’s wavelength). Such procedure gives the linear image for measuring purposes (see mesh plot in Fig. 2a).

Then the width of zero diffraction order was measured. There was calculated the number of pixels occupied by zero diffraction order. The width of the zero diffraction maximum was 352 pixels on the diffraction picture registered by the photo sensor. Taking into account that pixel’s period is $11.4 \mu m$ per colour channel, we can calculate diffraction order’s width that is $4.1 \pm 0.1$ mm; it is consistent with calculations performed using Eq. (1).

The comparison of the registered intensity distribution and theoretical one (see Eq. (1) is provided by central horizontal cross-section that is presented in Fig. 2b. It seems that the registered intensity distribution is very close to the theoretical function (fitting root mean squared error is only 1.7%).

Thus we conclude that camera’s response to the light is linear and hence one can use a commercial digital photo camera as a metering device.

4 Estimation of camera’s measuring properties

The data registered by the commercial photo camera has linear response to light as it follows from the previous section. Hence it is worth to estimate its measuring capabilities such as radiometric function (i.e. a signal versus exposure value dependency), black level offset (BLO), temporal dark noise, fixed pattern noise (FPN), light-depended temporal noise, and photo-response non-uniformity (PRNU). After that, linear and full dynamic ranges of signal’s registration can be evaluated. The results of evaluation of camera’s measuring capabilities are provided. Measurements were conducted using PixeLink’s guidelines [18] as well as EMVA1288 standard [19]. Registered images were processed by Canon conventional converter and special dcraw converter for comparison.
Figure 2: Experimental results on registration of diffraction pattern on a rectangular aperture: (a) mesh plot of intensity distribution and (b) comparison of experimental results with theoretical approximation over horizontal central cross-section.
4.1 Camera’s linearity

To obtain the radiometric function of the camera, it is necessary to take images of the flat-field scene with different exposure values. The light of white LEDs was passed through the ground glass to eliminate flat-field’s non-uniformity. Exposure value of the captured images was varied from 1/4000 to 10 seconds. For each exposure, four images were taken and averaged, and the standard deviation was considered as the uncertainty of measures. A 64 × 64 pixel area from the centre of the averaged images was used for the analysis. The value of the ISO was the smallest available (ISO 100). Black level offset (BLO) of 256 digital numbers (DN) was subtracted from the averaged image. The registered data were processed by dcraw converter (16-bit TIFF mono output with 12-bit unprocessed raw data, BLO 256 DN was subtracted) and conventional Canon converter (16-bit TIFF colour output, BLO was subtracted internally).

First, the registered images of flat-field scene were processed by the conventional raw-file converter that is shipped with camera. As seen in Fig. 3, the obtained radiometric function is non-linear because there were applied such postprocessing methods as gamma-correction, colour interpolation, and visual enhancing. The radiometric function can be considered as linear only in small region (see approximation line in Fig. 3).

Then the registered data were processed by special raw-file converter dcraw in “document mode” without interpolation and gamma-correction. The obtained signal is highly linear and maximum detectable signal is 3070 DN according to Fig. 4. Error bars on the plots are corresponding to the standard deviation of signal’s mean values.

The comparison of radiometric function in Fig. 4 and in Fig. 3 shows that the registered signal is linear in wider range of exposure values in case of using dcraw special converter (see also Fig. 5). Hence it can be concluded that special converters such as dcraw allow to turn off any postprocessing procedures for registered images.

Obtained results of dcraw processing allow to estimate the peak linearity error for the registered radiometric function. There were conducted measurements of peak linearity error according to the EMV A1288 standard [19] as:

\[
LE_{5-95} = \frac{\max(D_k) - \min(D_k)}{2}.
\]  

(2)

According to the EMV A1288 standard, the peak linearity error is given in % in the range of 5 - 95% saturation. To calculate peak linearity error, the discrepancy \( D_k \) must be evaluated for each measured point \( k \) of the radiometric function by comparison to the regression line:

\[
D_k = \frac{\mu_k - (A \cdot E_k + B)}{\mu_{\text{sat}} \cdot 0.9} \cdot 100\%.
\]  

(3)

where \( E_k \) is exposure at \( k \)-th measurement point in relative units, \( \mu_{\text{sat}} \) is the saturation signal, \( A \) and \( B \) are slope and offset of the regression line \( A \cdot E + B \). Black level offset (BLO) \( \mu_{k,\text{dark}} \) was subtracted from the mean signal value \( \mu_{k,\text{raw}} \) as \( \mu_k = \mu_{k,\text{raw}} - \mu_{k,\text{dark}} \) for each \( k \)-th exposure point.

The peak linearity error for our case was found using Eq. (2) as \( LE_{5-95} = 2.7 \pm 0.1\% \), the slope of the regression line was \( A = 3070 \pm 20 \) DN (the offset B was negligible small \( \leq 10^{-4} \) DN) within the area of estimation 64 × 64 pixels.
Figure 3: The radiometric function of the camera’s sensor, data is processed by the conventional converter. Mean value of signal in DN versus relative exposure value: in logarithmic axis (a) and in linear axis (b).

The obtained results show that the radiometric function of the commercial camera is linear when dcraw raw-file converter is used.
Figure 4: The radiometric function of the camera’s sensor, data is processed by dcraw converter. Mean value of signal in DN versus relative exposure value: in logarithmic axis (a) and in linear axis (b).

4.2 Camera’s dark noises

The results of measurements of dark noises are provided in this section for the commercial camera used in this work. Dark frames images were processed by
special converter dcraw for obtaining linear data and conventional converter in order to demonstrate the influence of converter’s postprocessing. Total dark noise, fixed pattern noise (FPN), and dark temporal noise were measured.

First of all, total dark noise was estimated. One dark frame for each ISO setting was registered, and standard deviation of dark signal was found. In the Fig. 6a and b it is shown the postprocessing’s influence on the data processed by the conventional converter that is shipped with camera and special dcraw converter. From Fig. 6a it can be seen an unexpected behaviour of total dark noise because it differs in different colour channels. Such circumstance can be explained by non-linear postprocessing performed by the conventional converter.

Then the data of total dark noise was processed by dcraw converter. The mean value of the dark frame (namely BLO) was stable $256 \pm 0.4$ DN and total dark noise values growing with ISO in all channels were almost identically (see Fig. 6b). It should be emphasized that total dark noise is almost the same in different colour channels.

In the next subsections are presented measuring of temporal and fixed pattern noises that are accomplished using dcraw raw-files converter only.

### 4.2.1 Dark temporal noise

A temporal component of the dark noise was estimated. For such purpose there were taken 64 dark frames (ISO speed was 100, exposure value 1/32 second). Only the central areas ($64 \times 64$ pixels) were used. Arrays of pixels were averaged over the frames and the standard deviation of each pixel $\sigma_{\text{dark temp.ij}}$ was calculated. In such way, two arrays were created: the array of pixel’s mean
Figure 6: Total dark noise versus ISO speed: a) processed by the conventional converter, b) processed by dcrw converter.

values $A_{\text{mean}}$ and the array of pixel’s standard deviations $A_{\text{std}}$. This procedure is analogous to the PixeLink’s method of the dark noises estimation [18].

To estimate the dark temporal noise quantitatively, the average standard
deviation from the array $A_{std}$ was calculated. Consequently, the dark temporal noise can be evaluated as follows:

$$\text{DarkTempNoise} = \sqrt{\frac{1}{MN} \sum_{i,j} \sigma^2_{\text{dark.temp.ij}},}$$  

(4)

where $M$ and $N$ is the height and width of the used area of the dark frame, respectively. According to our measurements, the dark temporal noise is $\text{DarkTempNoise} \approx 1.6 \pm 0.2$ DN.

### 4.2.2 Fixed pattern noise

Fixed pattern noise (FPN) can be referred as a pixel-to-pixel variation of the dark signal. In order to estimate the FPN, there were taken and averaged 64 dark frames. The ISO speed was 100 and exposure value was $1/32$ sec. Then value of BLO and variance $\sigma^2_{\text{dark.spat}}$ along the averaged dark frame were calculated. FPN can be estimated quantitatively [18] as following:

$$\text{FPN} = \frac{\sigma_{\text{dark.spat}}}{\text{MaxOutput}} \%.$$  

(5)

Maximal output signal ($\text{MaxOutput}$) of the used camera is 3470 DN (the black level offset of 256 DN must be subtracted from the saturation point 3726 DN). According to our measurements, mean value of the averaged dark frame is $256.0 \pm 0.4$ DN and its standard deviation is $\sigma_{\text{dark.spat}} \approx 0.4$ DN. Fixed pattern noise can be estimated by using Eq. (5) as $\text{FPN} \approx 0.1 \%$. We are emphasizing that such low spatial dark noise is due to the on-chip circuitry noise reduction of the Canon’s digital camera (see Section 5 for details).

### 4.3 Camera’s light-depended noise

The light-depended noises such as photon shot noise (light-depended temporal noise) and photo-response non-uniformity (PRNU) were measured for the camera.

### 4.3.1 Light-depended temporal noise

For the photon shot noise to be measured, the greyscale scene with a dynamic range of the irradiance that exceeds dynamic range of the tested camera was created. There were taken 64 frames of this scene. The registered frames were processed by dcraw converter in “document mode” and by Canon conventional converter for comparison. Obtained images were averaged and arrays of mean values of pixels $S_{\text{mean}}$ and pixels standard deviations $S_{\text{std}}$ were stored. Further, signal’s values were picked up from the array $S_{\text{mean}}$ with step of 1 DN. For each signal’s value of $S_{\text{mean}}$, the corresponding standard deviation’s value from the array $S_{\text{std}}$ was found as an estimation of a photon shot noise. Results are presented in Fig. 7a for dcraw and in Fig. 7b for Canon converted data respectively.

The results for data been processed by dcraw (see Fig. 7a) are indeed a photon shot noise because the results obey to Poisson statistics. That is because there were no postprocessing operations were applied during data conversion.
Figure 7: Light-dependent temporal noise versus registered signal: a) for dcraw converted data, b) for the data processed by conventional Canon converter.

Although in the Fig. 7b is presented the same photon shot noise, the reason of dramatically difference with Fig. 7a are postprocessing procedures being applied by conventional converter.
4.3.2 Photo response non-uniformity

As a measure of the spatial light-dependent noise, photo-response non-uniformity (PRNU) is commonly used. There were taken and averaged 64 images of the white LEDs illuminated flat-field scene. The images were taken with the same exposure value. ISO setting was 100, the smallest available in the camera.

Obtained average image with subtracted averaged dark frame $A_{\text{mean}}$ (see subsection 4.2.1) was decomposed on three images: pixels corresponded to red colour filters were stored in $B_r$ array, pixels corresponded to first green colour filter were stored in $B_g$ array, and pixels corresponded to blue colour filters were stored in $B_b$ array. Then for each array $B_r$, $B_g$, and $B_b$ was calculated a standard deviation $\sigma_{\text{light.spat}}$ and mean value $\text{FrameMean}$. PRNU for each colour component was evaluated as follows [18]:

$$PRNU = \frac{\sigma_{\text{light.spat}}}{\text{FrameMean}} \%.$$  
(6)

According to our measuring, averaged over all colour channels PRNU can be estimated as $PRNU \approx 0.5\%$ at the light signal around 2300 DN.

4.4 Estimation of camera’s dynamic range

Using obtained data now we can evaluate the dynamic range of the digital camera used. All estimations were accomplished in the consideration that minimal signal-to-noise (SNR) ratio is SNR=2 instead of conventionally used SNR=1. Such decision is explained by the consumer grade nature of the used camera. Minimal detectable signal is equal to 4 DN that corresponds to SNR=2 (see Fig. 7a). This is because the dark temporal noise is around 1.6 DN and dark spatial noise (corresponded to FPN) is around 0.4 DN. Relative exposure value that corresponds to the minimum detectable signal is equal to $E_{\min.signal} = 1.3 \cdot 10^{-3}$ rel. units, as seen from Fig. 4a.

A linear model was fitted to the experimental data of the radiometric function. Then the value of signal, which corresponding to the end of a linear dynamic range, was estimated as 3070 DN (see Fig. 4b, BLO 256 DN is subtracted), and exposure value for this signal is $E_{\text{end.linear.signal}} = 1.0$ rel. units. Linear dynamic range (LDR) was estimated as follows:

$$LDR = 20 \log_{10} \frac{E_{\text{end.linear.signal}}}{E_{\min.signal}}.$$  
(7)

Hence according to our measurements, the linear dynamic range is 58 dB.

To estimate full dynamic range of the camera, it is necessary to find the maximum saturation signal and the lowest detectable signal. As above, minimal distinguishable signal remains 4 DN with relative exposure value $E_{\min.signal} = 1.3 \cdot 10^{-3}$ rel.units. Saturation signal is 3470 DN (BLO 256 DN is subtracted), hence relative exposure value for this point is $E_{\text{sat.signal}} = 1.12$ rel. units (see Fig. 4b). The value $E_{\text{sat.signal}}$ was determined as follows. The line that corresponds to saturation signal’s level was expanded through the intersection with data’s approximation line. The exposure value corresponding to such intersection was accepted as $E_{\text{sat.signal}}$. The full dynamic range (FDR) can be estimated as follows:

$$FDR = 20 \log_{10} \frac{E_{\text{sat.signal}}}{E_{\min.signal}}.$$  
(8)
Therefore the full dynamic range can be estimated as 59 dB.

The same calculations were provided for data converted by Canon conventional software. Using obtained radiometric function (see Fig. 3) and taking in account Fig. 7b it is possible to estimate linear and full dynamic ranges for non-linearized data. As above, minimal SNR is 2; hence minimum detectable signal value can be estimated as 400 DN (see Fig. 7b), and corresponding relative exposure value is $E_{\text{min.signal}} = 8.2 \cdot 10^{-4}$ rel. units (see Fig. 3a). Maximum value of linear signal is estimated by fitting linear function to experimental data (see Fig. 4b), and equals to 24500 DN. Corresponding relative exposure value for this signal is $E_{\text{end.linear.signal}} = 5.0 \cdot 10^{-2}$ rel. units (see Fig. 3b). Thus linear dynamic range is considered to be 36 dB (see Eq.(7)).

Thus using special raw converters such as dcraw it is possible to increase the linear dynamic range of signal’s registration approximately in 10 times by turning off any postprocessing procedures.

5 Results discussion

It is noteworthy that the obtained results are only an approximation of the commercial camera’s metering characteristics. This is because of presence of on-chip noise reduction circuitry and sufficient dispersion of noise characteristics between cameras of the same model.

As it mentioned in [16], for reducing noise in commercial cameras are implemented on-chip technology to reduce fixed pattern noise based on correlated double sampling, CDS [15]. First, only the noise is red. Next, it is red in a combination with the signal. When the noise component is subtracted from the combined signal, the fixed pattern noise is eliminated. That is why the spatial dark noise (FPN) in our camera is estimated at only about 0.4 DN.

Moreover, light-depended noise is also suppressed by on-chip circuitry [16]. Such method is called complete electronic charge transfer. By first transferring the residual discharge (light and noise signals) left in a photodiode to the corresponding signal reader, the sensor resets the photodiode while reading and holding the initial noise data. After the optical signal and noise data is red together, the initial noise data is used to remove the remaining noise from the photodiode and suppress random noise. This is the reason of low light noise in consumer cameras. For example, the camera used in this work is characterized by the spatial light-depended noise that are only $PRNU \leq 0.5\%$. Thus only an estimation of the commercial camera’s noise characteristics is possible.

6 Conclusion

The use a commercial digital photo camera as a metering device for spatial light distributions measuring is presented in this paper. Using special software raw-file converter dcraw it was demonstrated the ability of commercial digital camera to output unprocessed linear image data. Hence one can use a commercial digital camera as a metering device.

According to conducted measurements, the commercial digital camera Canon EOS 400D used in this work can be considered as a relatively good metering device. Peak linearity error for such camera was estimated as $LE\%_{5-95} =$
2.7 ± 0.1%, linear dynamic range 58 dB and full dynamic range 59 dB. Comparing with linear dynamic range of 36 dB given by shipped Canon’s conventional converter, it can be concluded that using special raw converters such as dcraw it is possible to increase the linear dynamic range of signal’s registration approximately in 10 times for our case.

Dark noise and light-depended noise were estimated for the used camera when dcraw converter had been applied. The dark temporal noise was estimated as 1.6 ± 0.2 DN and black level offset (BLO) was 256.0 ± 0.4 DN. Fixed pattern noise (FPN) was evaluated as 0.1%. Spatial light-depended noise was characterized by PRNU ≈ 0.5%. Temporal noise versus signal dependence was obtained as well. Obtained results are an approximation of the camera’s characteristics because of noise characteristics dispersion between cameras of the same model and presence of the noise-reduction on-chip circuitry.

Application of described linearization method allows to increase the linear dynamic range of images received from commercial digital photo cameras. From the obtained experimental results it follows that inexpensive commercial digital cameras can be used as metering devices for spatial light distributions measuring.

References


