

Reproduction Model with Luminance Adaptation for Digital Cameras

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Abstract

From real spectroradiometric data, we propose an algorithm to obtain camera opto-electronic conversion functions (camera OECFs) for different values of the lens aperture N from the opto-electronic conversion spectral functions (OECSFs). Working in the linear range of the inverse *OECFs*, we have found that the slope vs. lens aperture function is fitted by a second order polynomial. This happens also to the offset vs. lens aperture function. Therefore, we have included the inverse *OECFs* with luminance adaptation into a basic reproduction model, consisting in a 3x3 transform between the raw RGB space and CIE-XYZ space, opening the possibility of transforming any digital camera into an absolute tele-colorimeter.

Introduction

A digital image capture device (scanner or camera) is not a color measuring tool as a spectrophotometer or a tele-spectroradiometer. Although it encodes the spectral information enclosed in a scene into three RGB color channels, the RGB digital data associated to a visual stimulus are not the same than would encode a human observer, who is characterized by the CIE-1931 XYZ standard observer.^{1,2}

The color characterization of digital image capture devices consists of calculating the colorimetric profile between RGB device space and the CIE-1931 XYZ space associated to the same color stimulus under uncontrolled illumination conditions, for variations of chromaticity and intensity of the illumination. In this way, the digital image capture device should perform as an absolute tele-colorimeter because the color output data would be in cd/m^2 , i.e., the color device would be simultaneously a colorimeter and a luminance meter. From the digital output levels DOL_k ($k = R, G, B$ color channels) we could obtain the absolute tristimulus values CIE-XYZ (in cd/m^2), as are obtained by a tele-spectroradiometer (Eq.1).

$$\mathbf{t}_{XYZ} = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} = K_m \mathbf{T}_{XYZ} \mathbf{t}_{\mathbf{c}} \quad (1)$$

where K_m is 683 lm/W , $\mathbf{T}_{XYZ} = [\bar{x} \ \bar{y} \ \bar{z}]_{4 \times 3}$ is the color-matching functions in matrix format and $\mathbf{c} = \text{diag}(\mathbf{L}) \cdot \rho$ is the color stimulus, resulting of the spectral reflectance ρ of the object and the light source or illuminant \mathbf{L} in $\text{W/sr} \cdot \text{m}^2$.

The basic colorimetric profile³ is a 3x3 matrix \mathbf{M} which should associate the RGB relative colorimetric values or \mathbf{t}'_{RGB} with the relative tristimulus values \mathbf{t}'_{XYZ} normalized to the equi-energy stimulus $\mathbf{E} = [1, 1, \dots, 1]^t$ (Eq. 2). This matrix can be obtained by regression⁴ between the color-matching functions of the color device and the standard observer CIE-1931 XYZ. In this way, the estimated relative tristimulus values XYZ should be as follows:

$$\hat{\mathbf{t}}'_{\text{XYZ}} = \mathbf{M} \mathbf{t}'_{\text{RGB}} \quad \text{with} \quad \mathbf{T}_{\text{XYZ}}^t = \mathbf{M} \mathbf{T}_{\text{RGB}}^t \quad (2)$$

If our purpose is to get an absolute estimation, in cd/m^2 , of the tristimulus values XYZ, we must link a group of luminances associated to the equal-energy stimulus or illuminant \mathbf{E} with the corresponding RGB data of the color device. This relationship is the camera opto-electronic conversion function (OECF). For any scale exposure series –varying the lens aperture or f-number N of the zoom lens or the photosite integration time t –, the OECFs are described as follows:

$$\mathbf{t}'_{\text{RGB}} = \begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} \text{OECF}_R(L) \\ \text{OECF}_G(L) \\ \text{OECF}_B(L) \end{bmatrix} \quad (3)$$

where L is the luminance of the object in the scene.

Therefore, the relative colorimetric profile is obtained inverting the camera OECFs as follows:

$$\hat{t}_{XYZ} = \frac{1}{L_E} \mathbf{M} \begin{bmatrix} OECF_R^{-1}(R) \\ OECF_G^{-1}(G) \\ OECF_B^{-1}(B) \end{bmatrix} \quad (4)$$

where L_E is luminance of the adapted white⁷ or perfect white diffuser inside the scene.

The standard ISO 14524 proposes an algorithm to obtain this photometric function with fixed lens aperture N or photosite integration time t and any illumination different from illuminant \mathbf{E} . This standard is used in the standard ISO 17321⁶ to obtain the relative colorimetric profile associated to a digital still camera (DSC) measuring previously their spectral sensitivities.

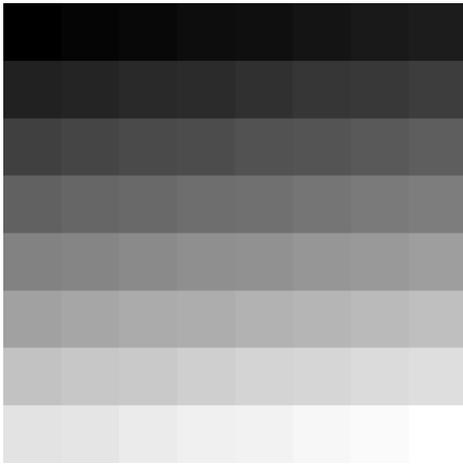


Figure 1. A gray scale test pattern appropriately captured with lens aperture N_0 in order to prevent the saturation of the white sample.

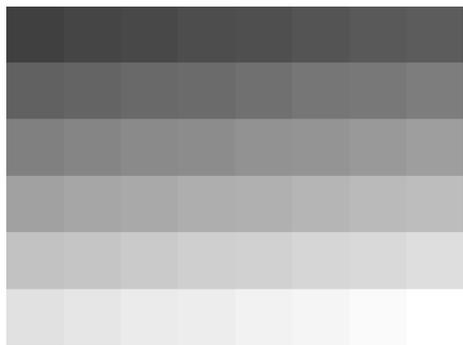


Figure 2. The gray scale test pattern captured with a lens aperture $N_1 < N_0$.

On other hand, we propose in this work a general algorithm of luminance adaptation to obtain the camera OECFs with illuminant \mathbf{E} for any lens aperture N of the zoom lens. This algorithm can to adapt the relative and shorter dynamic range of the device response into the real dynamic luminance range of any scene. For instance, we have a gray scale test pattern (Fig. 1) which

is captured optimally –that is, avoiding saturation of the white sample in spite of the clipping of the darker samples–, with certain (N, t) values. If we decrease the lens aperture N , i.e. if the exposure level is raised, the RGB data would be now different (Fig. 2) but the absolute tristimulus values XYZ remain fixed. If we increase the lens aperture N , i.e. if the exposure level is decreased, the RGB data would be now different (Fig. 3) but the absolute tristimulus values XYZ remain now fixed. How can we compensate the variation of the lens aperture N to obtain always the same absolute tristimulus values XYZ?

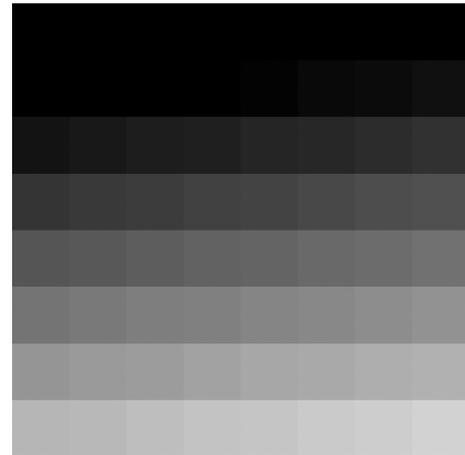


Figure 3. The gray scale test pattern captured with a lens aperture $N_2 > N_0 > N_1$.

From real spectroradiometric data and an alternative spectral characterization of digital image capture devices, we shall simulate the responses of a gray scale test pattern with illuminant \mathbf{E} , keeping the lens aperture N of the zoom lens as the free parameter. Because some OECFs vs. N relationships will be obtained, the scene-referred colorimetry obtained applying the basic colorimetric profile (Eq. 4) will be absolute (in cd/m^2) and not relative, unlike ISO 17321.

Spectral Characterization

The experimental set-up for the spectral characterization is a modification⁸ of the method A of the ISO 17321. Our digital image capture device consisted of a Sony DXC-930P 3CCD-RGB camera connected to a Matrox MVP-AT 850 frame grabber, inserted into a PC unit. Target radiance was varied using the entrance/exit slits of a CVIS Laser Digikrôm monochromator with constant spectral resolution, assembled to an Osram HQI T 250W/Daylight vapor fluorescent lamp. Among the fixed initial conditions, which might alter the color output, we set the white balance to 5600 K in manual menu-mode (offset value) and configured the gain and the offset of the analog-digital converter (ADC) to work with the raw response space. The target radiance $L_{e\lambda}$ was measured by a Photo Research PR-650 tele-spectroradiometer in the

380-780 nm wavelength range at 10 nm steps, maintaining the photosite integration time at $t_0 = 20$ ms (offset value) with some selected f-numbers N . Previously, we proved that the variation of N in the spectral characterization warranted the radiometric reciprocity law^{9,10}, i.e., identical values of spectral exposure yielded identical responses even if the lens aperture N changes. The spectral exposure H_λ , averaged in the exposure series ($L_{e\lambda}$, N , $t = 20$ ms) for each monochromatic image was given by⁹⁻¹¹:

$$H_\lambda \propto \frac{L_{e\lambda}}{N^2} t \quad [\text{J}] \quad (5)$$

The opto-electronic conversion spectral functions (*OECSFs*), that is, the normalized digital output level $NDOL_\lambda$ vs. H_λ curves for RGB channel, were fitted mathematically by sigmoid functions, defined by four parameters $\{a, b, c, d\}$ as follows:

$$NDOL_{\lambda k} = \frac{DOL_{\lambda k}}{2^{bits} - 1}, \quad k = R, G, B$$

$$NDOL_{\lambda k} = a_{\lambda k} + \frac{b_{\lambda k}}{1 + \exp\left(-\frac{H_\lambda - c_{\lambda k}}{d_{\lambda k}}\right)} \quad (6)$$

With this radiometric formalism, a new response model is proposed from the univariance principle:

$$DOL_{\lambda k} = (2^{bits} - 1) \sum_{380\text{nm}}^{780\text{nm}} NDOL_{\lambda k} \Delta\lambda$$

$$DOL_{\lambda k} = (2^{bits} - 1) \sum_{380\text{nm}}^{780\text{nm}} H_\lambda r_k(\lambda, H) \Delta\lambda \quad (7)$$

where $r_k(\lambda, H)$ is the complete spectral responsivity⁸ of the color-channel k .

Colorimetric Profile with Luminance Adaptation

With this model, we have proved⁸ that our digital camera has not an adapted, ideal or equal-energy white balance,⁷ so this result is used to transform the digital output levels into relative RGB values:

$$R = \frac{NDOL_R}{bal_R}; G = \frac{NDOL_G}{bal_G}; B = \frac{NDOL_B}{bal_B} \quad (8)$$

As in ISO 17321, with the support of ISO 14524, we propose then a reproduction model with luminance adaptation calculating the inverse of the camera opto-electronic conversion functions (*OECSFs*) from the obtained *OECSFs* (Eq. 6). If, for any (N , t) scale exposure series, it is verified that $R = OECF(L)$, $G = OECF(L)$ and $B = OECF(L)$, where L is the luminance of an object, we can simulate the responses of a gray scale test pattern by:

$$\frac{NDOL_k}{bal_k} = \frac{1}{bal_k} \sum_{380\text{nm}}^{780\text{nm}} \frac{L_e}{N^2} t_0 r_k\left(\lambda, \frac{L_e}{N^2} t_0\right) \Delta\lambda \quad (9)$$

where L_e is the uniform radiance of the adapted white in the position of the object and it is obtained from the luminance L_E of the adapted white as follows¹²:

$$L_e = \frac{L_E}{K_m (\bar{y}^t \cdot \mathbf{E}) \Delta\lambda} = \frac{L_E}{683 \cdot 21.37145} \quad (10)$$

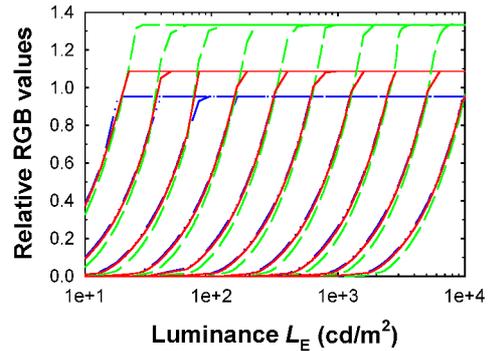


Figure 4. Balance of luminance adaptation of our digital image capture device. Each triad of *OECSFs* curves belongs to a (N , fixed t) scale exposure series: from left to right, $N = \{1, 1.4, 2, 2.8, 4, 5.6, 8, 11.2, 16, 22.4\}$. Solid line: Red channel; dashed line: Green channel; dash-dot-dot: Blue channel.

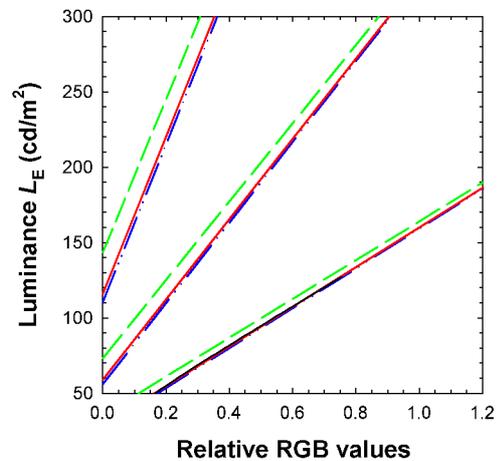


Figure 5. Linear representation of the inverse *OECSFs* of the previous figure for the values $N = 5.6, 4$ and 2.8 . Solid line: Red channel; dashed line: Green channel; dash-dot-dot: Blue channel.

The obtained *OECSFs* (Fig. 4), each of them associated to different dynamic ranges or N -scale exposure series, show linear mid-range, so we can invert the graphs to obtain the slope m and the offset h for each straight line or "linear" inverse *OECSFs* (Fig. 5):

$$\begin{aligned}
 OECF_R^{-1}(R) &= m_R(N) \cdot R + h_R(N) \\
 OECF_G^{-1}(G) &= m_G(N) \cdot G + h_G(N) \\
 OECF_B^{-1}(B) &= m_B(N) \cdot B + h_B(N)
 \end{aligned} \quad (11)$$

We have found that the relationships m_k vs. N and h_k vs. N are second-polynomial (Fig. 6 and 7):

$$\begin{aligned}
 m_k(N) &= m_{0k} + m_{1k}N + m_{2k}N^2 \\
 h_k(N) &= h_{0k} + h_{1k}N + h_{2k}N^2
 \end{aligned} \quad (12)$$

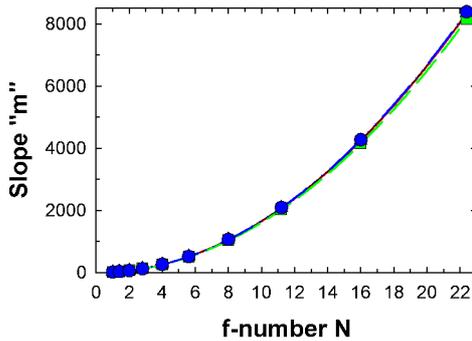


Figure 6. Second polynomial fitting of the slope "m" of the linear inverse OECFs vs. f-number N of the zoom lens. (Circles: B channel; squares: G channel; triangles: R channel)

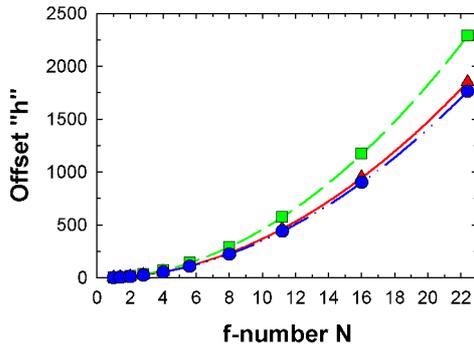


Figure 7. Second polynomial fitting of the offset "h" of the linear inverse OECFs vs. f-number N of the zoom lens. (Circles: B channel; squares: G channel; triangles: R channel)

So, we now may describe a colorimetric profile with luminance adaptation as follows:

- Original-referred image data⁷ (Eq. 1):

$$\mathbf{t}_{\text{XYZ}} = \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \frac{\text{cd}}{\text{m}^2} \quad (13)$$

- Scene-referred image data⁷:

$$\begin{aligned}
 \hat{\mathbf{t}}_{\text{XYZ}} &= \begin{bmatrix} \hat{X} \\ \hat{Y} \\ \hat{Z} \end{bmatrix} \\
 &= \mathbf{M} \left\{ \begin{bmatrix} m_R(N) & 0 & 0 \\ 0 & m_G(N) & 0 \\ 0 & 0 & m_B(N) \end{bmatrix} \begin{bmatrix} R \\ G \\ B \end{bmatrix} + \begin{bmatrix} h_R(N) \\ h_G(N) \\ h_B(N) \end{bmatrix} \right\}
 \end{aligned} \quad (14)$$

where \mathbf{M} is the 3x3 transform obtained by regression methods⁴ between the color-matching functions of our digital camera⁸ and the standard observer CIE-1931 XYZ (Eq. 2).

With this new reproduction model for digital cameras and following the standard ISO 17321, we can face the calculation of the DSC color analysis accuracy index¹³ and the DSC color rendering of the natural scenes, converting any digital camera into an absolute tele-colorimeter.

Conclusion

The colorimetric characterization of digital image capture devices that we propose consists of transforming the RGB digital data into absolute tristimulus values CIE-XYZ (in cd/m^2) under variable and unknown spectroradiometric conditions. So, at the first stage, a gray balance (Eq. 8) has been applied to the RGB digital data to convert them into RGB relative colorimetric values. At a second stage, an algorithm of luminance adaptation has been included for the first time (Eqs. 9-14). With this algorithm, we can change suitably the lens aperture or f-number N of the zoom lens without changing the absolute tristimulus specification CIE-XYZ estimated from the colorimetric profile between RGB and XYZ color spaces. With these previous steps, the color reproduction level of our digital image capture device can be compared with that obtained with a tele-spectroradiometer, both in a raw state and with a model of color correction because the color-matching functions \mathbf{T}_{RGB} of our camera do not verified the Luther condition^{14,15}.

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Biography

Francisco Martínez-Verdú received his BS in Physics from the University of Valencia in 1993 and a Ph.D. in Physics from Polytechnic University of Catalonia at Terrassa (Barcelona) in 2001. Since 1998 he teaches Color Science at School of Optics & Optometry in the University of Alicante (Spain). His work is primarily focused on device calibration and characterization, particularly digital cameras and scanners, Industrial Colorimetry, Color Management and Imaging. He is a member of the IS&T and the Spanish Optics Society. E-mail: Verdu@ua.es.