SPECTRAL RESPONSIVITY vs. ACTION SPECTRUM IN DIGITAL PHOTOGRAPHY

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ABSTRACT

We propose an experimental and theoretical methodology based on spectroradiometric procedures to determine the spectral sensitivity of digital still cameras (DSC). The opto-electronic conversion spectral functions (OECSF's) are obtained from normalized digital level (NDL) vs. spectral exposure data, fitted by a typical sigmoidal transition curve. At this stage, we define spectral responsivity r(λ, H) and action spectrum a(λ, NDL), which are conceptual derivations of the general concept of spectral sensitivity of any image sensor. Then, the real spectral responsivity and action spectrum are represented as 3-dimensional functions, where r(λ, H = constant) and a(λ, NDL = constant) profiles are scaled relatively to determine the valid linear output range of the digital image capture device. This range would serve to design the colorimetric profile of the camera with CIE-1931 XYZ standard observer, which is considered as a linear color image sensor.

Keywords: *Capture of color image & calibration, Physics of color image formation.*

1. INTRODUCTION

In Systems Theory, the response to an input can be written as *response = sensitivity*energy*. In Digital Photography, this principle can be stated as follows:

$$NDL_\lambda = H_\lambda \left[\frac{1}{(2^{bit}-1)} \frac{\lambda}{hc} \frac{QE_\lambda}{K_\lambda} \right]$$

$$NDL_\lambda \propto \frac{L_e(\lambda)}{N^2} t \left[\frac{1}{(2^{bit}-1)} \frac{\lambda}{hc} \frac{QE_\lambda}{K_\lambda} \right] \quad \text{(EQ. 1)}$$

$$\text{where} \quad H_\lambda \propto \frac{L_e(\lambda)}{N^2} t \quad \text{Exposure} \, [\mathrm{J}]$$

NDL_λ is the spectral normalized digital level, H_λ the spectral exposure in joules (J), $L_e(\lambda)$ the spectral radiance of the monochromatic target, N the *f-number* of the zoom-lens, t the *photosite integration time* of the electronic shutter, QE_λ the spectral quantum efficiency in photoelectrons (e^-) per incident photons and K_λ (e^-/DL) the inverse of the optoelectronic conversion constant obtained by photon-transfer technique [1].

In general, we may consider the spectral exposure H_λ as the energy input and the rest of variables enclosed by brackets as the spectral sensitivity *s*(λ) of the digital image capture system.

The above expressions are totally analogous to those the colorimetric standard observer CIE-1931 XYZ. This is so because Colorimetry is based on a linear color image sensor: the response to spectral stimuli with constant energy, denoted by *spectral responsivity r*(λ), is equivalent to the inverse of the energy of the spectral stimuli which give constant response, denoted complementarily by *action spectrum a*(λ). However, although the linear range in Colorimetry is very large, this does not happen with digital image capture devices (scanners, cameras, etc), whose responses are limited by the equivalent spectral exposure of noise (ESEN) and the equivalent spectral exposure of saturation (ESES). Therefore, it seems better to describe physically the spectral responsivity and the action spectrum of real scanners and cameras as *r*(λ, *H*) and *a*(λ, *NDL*), respectively.

2. EXPERIMENTAL METHODS

Our digital image capture device consisted of a Sony DXC-930P CCD-RGB camera connected with a Matrox MVP-AT 850 frame grabber, inserted into a PC unit. Target radiance was varied using the entrance/exit slits of the CVIS Laser Digikröm DK240 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 ensure minimal influence on color output, according to the manufacturer specifications. With these initial parameters, we were sure that the RGB data were raw, without unknown internal color matrixing. The target radiance $L_e(\lambda)$ was measured by a Photo Research PR-650 tele-spectracolorimeter for the 380-780 nm wavelength range at 10 nm steps, maintaining the photosite integration time at $t = 20$ ms (offset value) with some selected f-numbers *N*. The spectral exposure H_λ averaged in the exposure series ($L_e(\lambda)$, *N*, $t = 20$ ms) for each monochromatic image was given by:

$$H_\lambda = 514.982310^{-9}\,\frac{L_e(\lambda)}{N^2}\,t \quad [\mathrm{J}] \quad \text{(EQ. 2)}$$

Dark current/frame subtraction was applied to each monochromatic image and the normalized digital level *NDL* was obtained averaging on eight statistical windows larger than 64x64 pixels.

3. RESULTS AND DISCUSSION

The alternative opto-electronic conversion spectral functions (OECSF's) [2], that is, the NDL_λ vs. H_λ curves for each RGB channel, were fitted mathematically by sigmoid functions, defined by four parameters as follows:

$$NDL_{\lambda i} = a_{\lambda i} + \frac{b_{\lambda i}}{1+\exp\left(-\dfrac{H_{\lambda i}-c_{\lambda i}}{d_{\lambda i}}\right)}\,, \quad \text{(EQ. 3)}$$

$$i = R, G, B$$

For CIE-1931 XYZ observer, the equivalent OECSF's are essentially the same in the XYZ channels:

$$\begin{aligned} X_\lambda &= \left(683\,\bar{x}_\lambda\,\Delta\lambda\right)L_{e\lambda} \\ Y_\lambda &= \left(683\,\bar{y}_\lambda\,\Delta\lambda\right)L_{e\lambda} \quad \text{(EQ. 4)} \\ Z_\lambda &= \left(683\,\bar{z}_\lambda\,\Delta\lambda\right)L_{e\lambda} \end{aligned}$$

According to these equations, the CIE-1931 XYZ standard observer is considered as a linear color image sensor. However, any digital still camera is strictly a non-linear color image sensor because their OECSF's are non-linear functions. As an example, the next figure (FIG. 1) shows the experimental results for λ = 570 nm in the R and G channels. The B channel was not sensitive for this wavelength, unlike other digital still cameras [3,4]. In the CIE-1931 XYZ case (FIG. 2), the three XYZ channels respond to this wavelength and the three OECSF's are linear although they are represented in logarithmic axes.

From these experimental and modelling data, the spectral responsivities $r_R(\lambda, H)$, $r_G(\lambda, H)$, $r_B(\lambda, H)$ and the action spectra $a_R(\lambda, NDL)$, $a_G(\lambda, NDL)$, $a_B(\lambda, NDL)$ are described by:

$$responsitivy = \frac{response}{constant\ energy}$$

$$r_i(\lambda, H) = \frac{a_{\lambda i} + \dfrac{b_{\lambda i}}{1 + \exp\left(-\dfrac{H - c_{\lambda i}}{d_{\lambda i}}\right)}}{H} \quad \text{(EQ. 5)}$$

$$action\ spectrum = \frac{constant\ response}{energy}$$

$$a_i(\lambda, NDL) = \frac{NDL}{c_{\lambda i} - d_{\lambda i} \ln\left(\dfrac{b_{\lambda i}}{NDL - a_{\lambda i}} - 1\right)} \quad \text{(EQ. 6)}$$

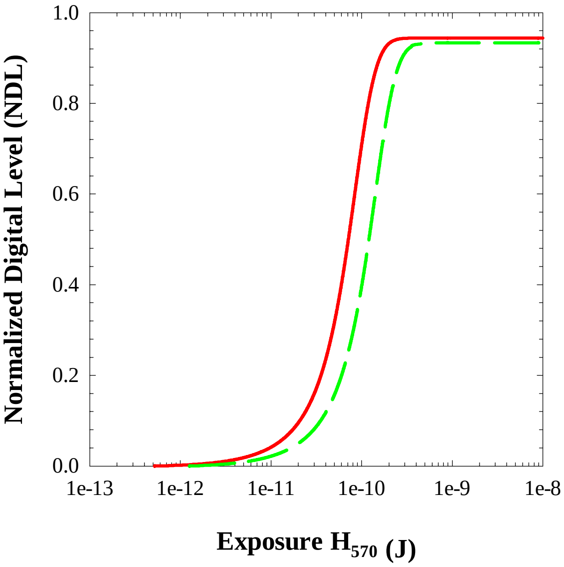


FIG.1: OECSF's measured with λ = 570 nm, corresponding to the R and G channels of a Sony DXC-930P camera plus a Matrox MVP-AT 850 frame grabber. (Solid line: R channel; dashed line: G channel.)

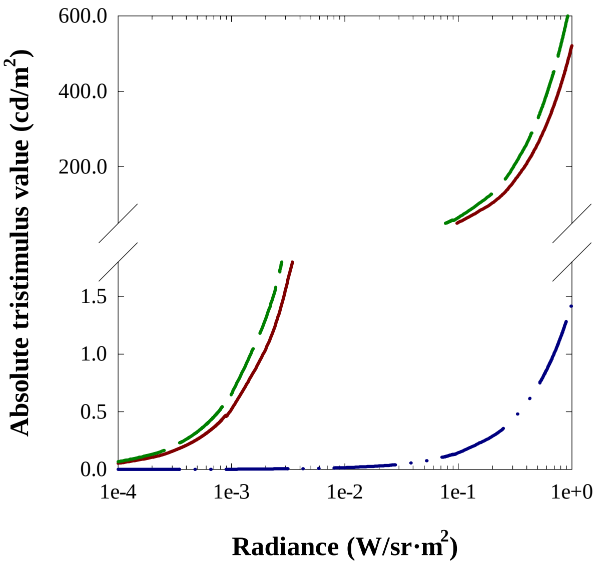


FIG. 2: OECSF's calculated with λ = 570 nm, corresponding to the XYZ channels of CIE-1931 standard observer. (Solid line: X channel; dashed line: Y channel; dashed-dot-dot line: Z channel.)

Following with the same example, the next figures (FIG. 3 & 4) show the spectral responsivities and the action spectra of our digital image capture system. The non-linear behavior is clearly seen because, in the CIE-1931 XYZ case, these functions would be constant versus radiance (energy) and tristimulus value (response). It is obvious that the dimensional scale of the spectral responsivities and action spectra is the same due to the opto-electronic conversion spectral function (OECSF) in each wavelength-channel combination. The sudden rise in the responsivity or in the action spectrum marks that the spectral exposure (incident photon rate) surpasses the opto-electronic threshold level (dark current/frame photocurrent). The sudden drop in the responsivity (action spectrum) when the digital value approaches its maximum level indicates the saturation of the full opto-electronic wells in both channels. In the middle range, the responsivity (action spectrum) varies smoothly versus spectral exposure (normalized digital level), but never in linear form like a true linear image sensor.

From a global perspective, the above graphs are the 2-dimensional profiles of $r_i(\lambda, H)$ and $a_i(\lambda, NDL)$ 3-D functions (FIG. 5 & 6). The important question is whether when we select spectral profiles with some constant exposures (or equivalently, normalized digital levels), the relative scaling of the spectral responsivity (action spectrum) would be constant although the absolute scaling were variable. If this supposition were verified, it would mean that our digital image capture system is approximately linear and on a level with CIE-1931 XYZ standard observer, which would allow us to find a colorimetric profile between these color space systems. In the CIE-1931 XYZ case, these spectral profiles are the color-matching functions, white-balanced to equal-energy stimulus: $\left(\bar{\mathbf{x}}^t \cdot \mathbf{E}\right) = \left(\bar{\mathbf{y}}^t \cdot \mathbf{E}\right) = \left(\bar{\mathbf{z}}^t \cdot \mathbf{E}\right) = 21.3714$ with $\Delta\lambda = 5$ nm and $\mathbf{E} = [1,1, ..., 1]^t$.

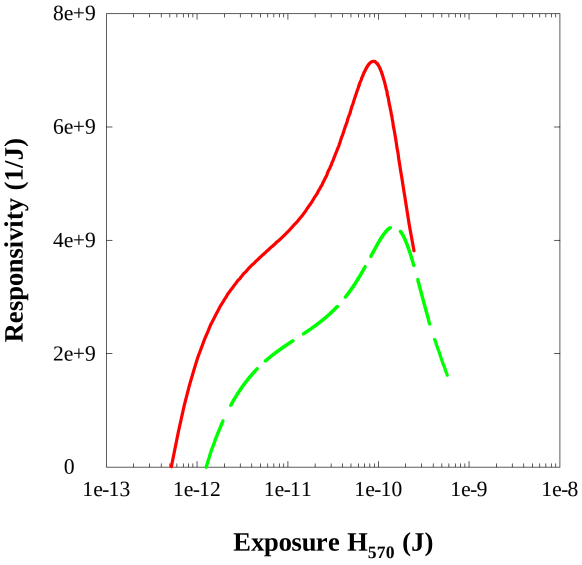


FIG. 3: Spectral responsivities of the R and G channels of a Sony DXC-930P plus a Matrox MVP-AT-850 measured with λ = 570 nm. (Solid line: R channel; dashed line: G channel.)

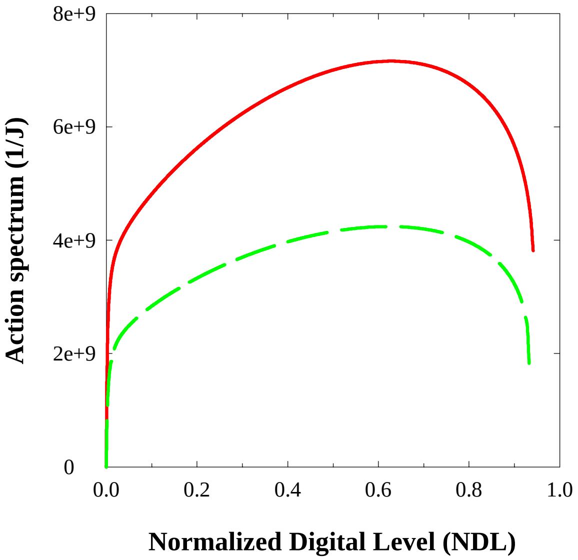


FIG. 4: Action spectra of the R and G channels of a Sony DXC-930P plus a Matrox MVP-AT-850 measured with λ = 570 nm. (Solid line: R channel; dashed line: G channel.)

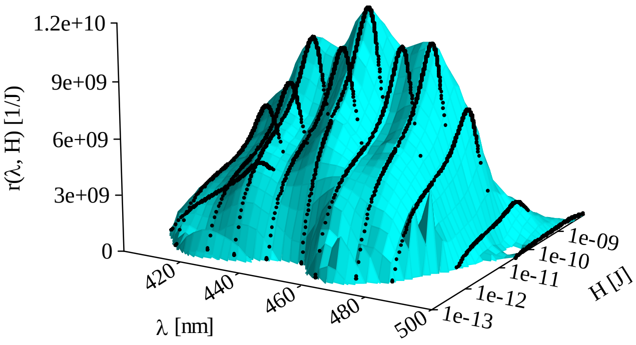


FIG. 5: 3-D spectral responsivity of the B channel of a Sony DXC-930P plus a Matrox MVP-AT-850. The solid lines are the spectral profiles of the responsivity at variable exposure and fixed wavelength.

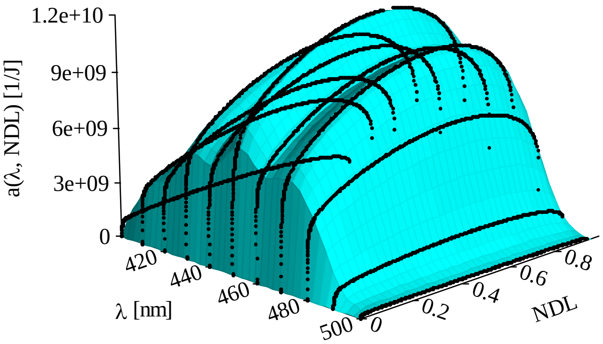
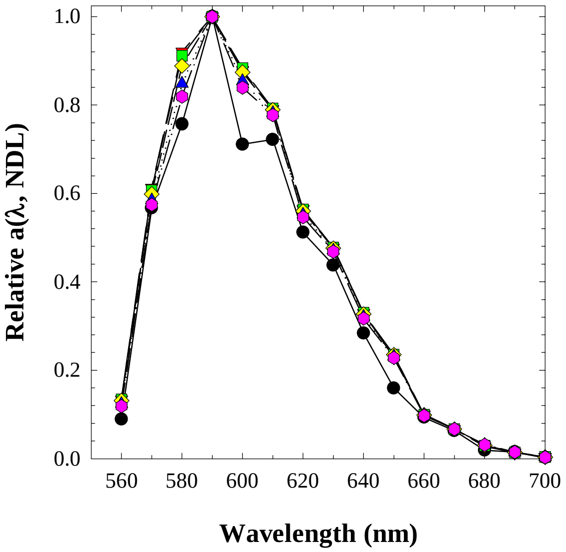


FIG. 6: 3-D action spectrum of the B channel of a Sony DXC-930P plus a Matrox MVP-AT-850. The solid lines are the spectral profiles of the action spectrum at variable normalized digital level and fixed wavelength.

If we select some normalized digital levels in the action spectrum of each color channel, the absolute scaling is different in each spectral profile, but the relative scaling is approximately the same as it is shown for the RG channels (FIG. 7 & 8). This means that we can obtain a relative action spectrum (spectral responsivity) averaging on some spectral profiles (FIG. 9). But the next problem is to re-scale the maximum levels in the RGB action spectra because their absolute scalings are not identical. Moreover, this question cannot be solved independently from the calculation of the colorimetric or real white balance of our digital image capture device: although the white balance provided by the manufacturer was 5600 K, this does not mean that the true white balance were 1:1:1. The algorithm to solve both questions needs to take into account the pseudo-tristimulus digital values formula proposed below:

$$ND_{R,G,B} = \left(2^{bits}-1\right)\sum_{380\,nm}^{780\,nm} NDL_{\lambda R,G,B}\,\Delta\lambda = \qquad \text{(EQ. 7)}$$
$$= \left(2^{bits}-1\right)\sum_{380\,nm}^{780\,nm} H_{\lambda}\cdot r_{R,G,B}(\lambda,H)\Delta\lambda$$



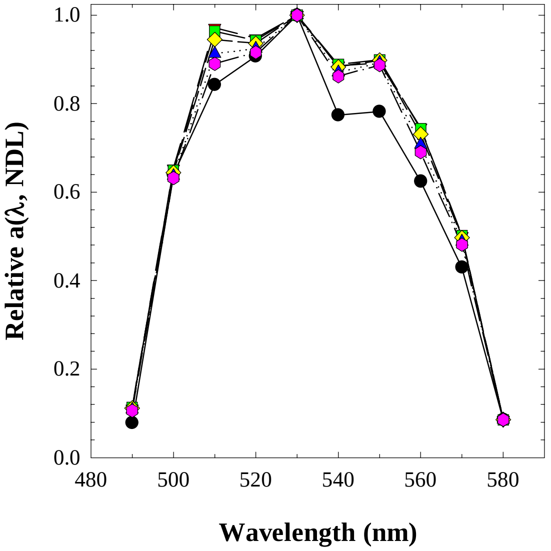


FIG. 7 & 8: Relative scaling of the action spectra (spectral responsivities) of the R and G channels of our digital image capture system. The solid symbols correspond to the following normalized digital levels: 1/255 (threshold, lower solid-line), 10/255, 0.1, 0.2, 0.5 and 0.8.

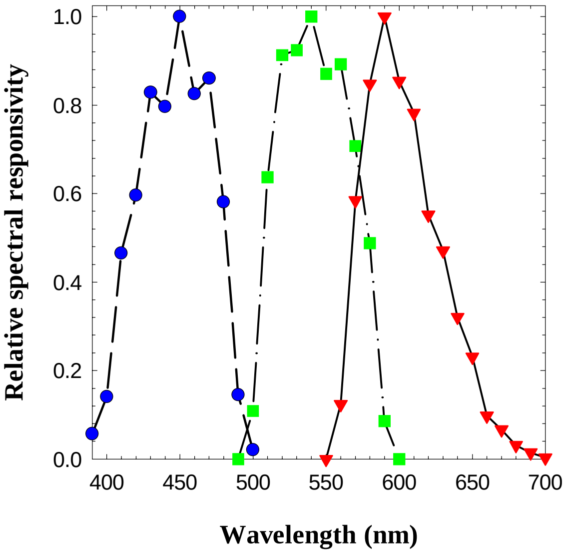


FIG.9: Relative spectral responsivities of our digital image capture system, composed by a Sony DXC-930P plus a Matrox MVP-AT 850. (Circles: B channel; squares: G channel; triangles: R channel)

With Equation 7 and the experimental data about the absolute spectral responsivities, we are ready to obtain the absolute scaling of the three color channels, the colorimetric or real white balance, and the pseudo-color matching functions, which are necessary to transform this digital still camera into an absolute tele-colorimeter using a color space regression algorithm between RGB camera space and CIE-1931 XYZ [5,6]. Nevertheless, this task pertains to another work.

4. SUMMARY AND CONCLUSIONS

We have presented an experimental and universal spectral characterization for any digital still camera using the equivalent terms of spectral responsivity and action spectrum, and a new camera formula. We have also proved that any digital still camera is a non-linear color image sensor, because, their spectral sensitivities being really 3-dimensional functions, they are not constant versus the spectral exposure and normalized digital level. However, the relative scaling of these spectral profiles is approximately the same so we may consider any digital still camera as a linear color image sensor. Even so, these relative spectral responsivities are not sufficient to transform the RGB raw data into XYZ colorimetric data.

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