# Testing the Reciprocity Law in Digital Photography

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## Abstract

An experimental and theoretical methodology based on spectroradiometric measures is proposed to test if the reciprocity law is verified in digital photography. Taking into account that the spectral exposure $H(\lambda)$ is proportional to the spectral radiance $L_e(\lambda)$ of the object and the photosite integration time $t$ of the electronic shutter time and inversely proportional to the f-number $N$ of the zoom-lens, this radiometric law declares that identical values of spectral exposure yield identical responses even if the f-number $N$ and/or the exposure time $t$ change. Historically, the photochemical materials present some deviations to this law, but it is not clear if this law holds for the image sensors of digital cameras. The test is based on the new concept of the opto-electronic spectral function (OECSF), that is, the empirical relationship between the normalized digital output level of the camera and the spectral exposure obtained by a monochromator set-up. The transition curve that fits the OECSFs in the color channels for our digital image capture device is the sigmoid function with four parameters. Varying exclusively the f-number $N$, the OECSFs in some irradiance scale exposure series ($L_e(\lambda)$ and $N$ free, $t$ fixed) overlap in any color channel. The same occurs with time scale exposure series ($L_e(\lambda)$ and $t$ free, $N$ fixed) or mixed scale exposure series ($L_e(\lambda)$, $N$ and $t$ free). These results indicate that this radiometric law, unlike in photochemical photography, is verified in digital photography with monochromatic light.

## Introduction

For a given color stimulus, there are some parameters that can alter the digital output data of a digital camera. The input to the digital image capture device is always the spectral radiance $L_e(\lambda)$ measured in W/sr·m$^2$. The first parameter that can influence the light reaching the image sensor is the *f*-number (*f/#*) or lens aperture $N$ of the zoom-lens. This is an optical parameter that denotes the value of the entrance pupil diameter of the optical system that focuses the object on the image sensor. In this step, other parameters condition the opto-electronic response of the system. The structural design of the RGB sensors or color imager architecture is the second. The exposure or photosite integration time $t$, the total time period during which the photosites of an image sensor are able to integrate the light from the scene to form an analogue image, is the third. The current technology for digital camera design handles a wide variety of color architectures: 3 CCD sensors with block of 3 RGB dichroic prisms, RGB or CMY stripe color filters, etc. Since these parameters act before or simultaneously with the raw opto-electronic conversion, it is adequate to denote them as the *extrinsic parameters* of a digital camera (Fig. 1).

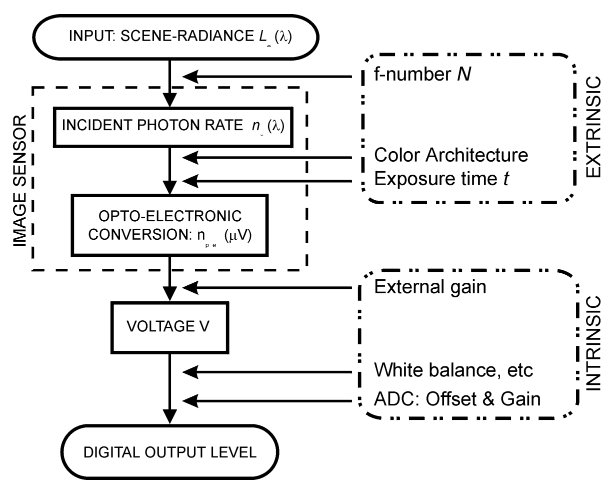


*Figure 1. Scheme of the extrinsic and intrinsic parameters that can alter in a non-controlled and/or controlled way the raw opto-electronic conversion of a digital camera.*

At this stage, the radiometric input has been converted into a raw analogue signal about several microvolts (µV). To become a digital output level (*DOL*) the analogue signal goes through multitude of electronic stages, the more relevant being the video gain, the white balance and the parameters (gain and offset) of the analog-to-digital converter (ADC). These parameters can influence *a posteriori* the raw opto-electronic conversion and, because they are built-in parameters, we may denote them as the *intrinsic parameters* of a digital camera (Fig. 1). Nevertheless, these intrinsic parameters, all of them of electronic type, can be numerous and then they require careful control. For example, if video gain is selected by control menu in automatic mode, we lose control of the global generation process of the digital output from the radiometric input, because the digital image capture device will change freely this process. This means that, if we wish to calibrate the device, we must use a characterization model for each video gain value because, with a fixed radiometric input, the device gives different output data. This prevents for instance the determination of the raw RGB color space associated to the spectral sensitivities of the digital camera.

### The Reciprocity Law in Digital Photography

From the former discussion, the key to control the input-output process in a digital camera is to know and to control all the sub-processes that play a role before, during and after the raw opto-electronic conversion. For example, independently of the choice of extrinsic and intrinsic parameters, the incident photon rate[1,2] $n_\nu(\lambda)$ on the image sensor in direct angle incidence in an electronic or digital still picture camera is:

$$n_\nu(\lambda) = \frac{\pi}{4}\frac{\lambda}{hc}\frac{L_e(\lambda)A_{\mathrm{SENSOR}}\,t}{N^2\left(1+m'_{\mathrm{LENS}}\right)^2}\tau_{\mathrm{LENS}}(\lambda)T_{\mathrm{ATM}}(\lambda) \qquad (1)$$

where $\lambda$ is wavelength, $h$ is Planck's constant, $c$ is the speed of light in the medium, $L_e(\lambda)$ is the spectral radiance of the object or target, $A_{\mathrm{SENSOR}}$ is the effective or irradiated sensor area, $t$ is the photosite integration time of the shutter, $N$ is the f-number of the zoom-lens, $m'_{\mathrm{LENS}}$ is the lateral magnification of the zoom-lens, $\tau_{\mathrm{LENS}}(\lambda)$ is the spectral transmittance of the zoom-lens and $T_{\mathrm{ATM}}(\lambda)$ is the spectral transmittance of the atmosphere.

Thus, the spectral exposure $H(\lambda)$ is expressed as:

$$H(\lambda) = \frac{hc}{\lambda}n_\nu(\lambda) \qquad (2)$$

The simplest way to understand the opto-electronic conversion that takes place in a digital still camera is to express the spectral exposure $H(\lambda)$ as proportional to the spectral radiance $L_e(\lambda)$ of the target and to the photosite integration time $t$, and inversely proportional to the square of the f-number $N$. If we take into account that spectral transmittance of the atmosphere $T_{\mathrm{ATM}}(\lambda)$ in the visible range is one and that, for most zoom-lenses, spectral transmittance $\tau_{\mathrm{LENS}}(\lambda)$ is approximately constant in the visible range with a value also close to one, the previous expression becomes:

$$H(\lambda) = k\frac{L_e(\lambda)}{N^2}t\,, \quad k = \frac{\pi}{4}\frac{A_{\mathrm{SENSOR}}}{\left(1+m'_{\mathrm{LENS}}\right)^2}\tau_{\mathrm{LENS}}T_{\mathrm{ATM}} \qquad (3)$$

From Eq. (3) and independently of considering exposure processes with spectral or gray scale patterns, it seems that different combinations of spectral radiance $L_e(\lambda)$, f-number $N$ and photosite integration or exposure time $t$ will provide equivalent exposures with identical camera responses. If the spectral exposures are equal, $H_1(\lambda) = H_2(\lambda)$, then, according to Eq. 3:

$$L_{e2} = m \cdot L_{e1}\,, \quad m = \left(\frac{N_2}{N_1}\right)^2\frac{t_1}{t_2} \qquad (4)$$

Note than, whereas for $m$ equal to one the values of radiance that yield equal exposures will be equal (equivalent exposure series), for $m \neq 1$ the values will be different (non equivalent exposure series).

This argumentation is known as *reciprocity law*, either in Photochemical (classical) or Digital Photography. Even though it seems well established historically that AgX[3-7] and other photosensible[8] materials present some deviations from this law, it is still to be determined whether or not the same law holds in the image sensors of digital cameras. Although concerned with the shutter in the image capture, the ISO 516 normative[9] has been devised by the WG4 (Mechanical Elements for Photography), and not the WG18 (Electronic Still Picture Imaging). Therefore, it is basically a revision of the ISO 516:1986 standard applied to the electro-mechanical shutters, and not for the electronically shuttered sensors, which are coupled to the image sensor and are the most widely used at present. There is no reference in the current ISO norms to the reciprocity law problem in Digital Photography, which implicitly assume that this law is not verified under any circumstance. This is valid too for the ISO 14524 normative[10] because the opto-electronic conversion functions (OECFs) associated to different $N$ or $t$ values are not equivalent. Although it is well established that the reciprocity law does not hold with white light, maybe it is verified using monochromatic light. So, it is valid to extrapolate the OECF concept to OECSF (*opto-electronic conversion spectral function*) as the starting point of the study of the applicability of the reciprocity law in Digital Photography.

## Experimental Set-Up

Figure 2 shows the experimental set-up, which can also be used to obtain the spectral sensitivities[11] of any camera. Light coming from a broadband light source (LS, Osram HQI T 250 W Daylight Hg vapor fluorescent lamp) passes through a monochromator (MC, CVIS Laser Digikröm DK240) to produce a monochromatic target over the opal glass (OG). The target radiance $L_e(\lambda)$ was measured by a tele-spectroradiometer (TSRM, Photo Research PR-650 SpectraColorimeter) that could be removed to allow the electronic still camera (ESC, Sony DXC-930P) to capture the monochromatic target, which lied on the camera optical axis. The analogue camera output was spatially and digitally processed by a frame grabber (Matrox MVP-AT 850) which was inserted into the PC unit. With these components it was not necessary to apply demosaicking and compression operations because the camera architecture is 3-CCD type (with dichroic prism block) and the images captured by the frame grabber were in 512x512 format. The computer and a TV display were used to display and control the captured images. Among the fixed initial conditions, which might alter the color output, we set the electronic 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. According to the guidelines of ISO 14524[10], raw RGB digital data are always used.

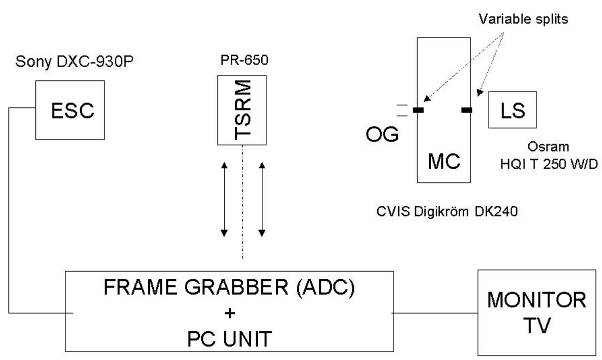


*Figure 2. Scheme of the experimental set-up.*

To obtain the opto-electronic conversion spectral functions (OECSF's), each digital output level (*DOL*) was obtained averaging eight monochromatic images with the same spectral radiance value $L_e(\lambda)$. To draw all the empirical curve data, the spectral radiance values were varied through the width of the input and output splits of the monochromator. This could be done because we demonstrated that our monochromator had constant spectral resolution when the I/O splits changed such as indicated by the manufacturer. The dark current noise and fixed pattern noise were removed by subtracting the background image.

According to Eq. 1-3, the effective irradiated sensor area $A_{SENSOR}$ and the lateral magnification $m'_{LENS}$ should be calculated to obtain the real value of the spectral exposure $H(\lambda)$ of the camera. (We assumed that $\tau_{LENS}$ = 0.9 and $\tau_{ATM}$ = 1, as it was remarked above.) The effective focal length $f'_{LENS}$ of the zoom-lens was 90 mm and the diameter $\phi_T$ of the monochromatic target was 8 mm. According to paraxial optics, the lateral magnification $m'_{LENS}$ was -0.1025 with the target centred on the optical axis of the CCD-RGB camera and $A_{SENSOR}$ was equal to 528.1604 $10^{-9}$ $m^2$.

With a pixel area $A_{pixel}$ of (8.5x8.2) $\mu m^2$ the scaling image compression ratio of image aspect ratio (752*582) to the raw image format (512*512) was equal of 0.5990. So, the effective total number of pixels in the image data format was above 4500 pixels. Therefore, following the ISO 14524 recommendations it was possible to select a statistic window of 64x 64 = 4096 pixels to calculate the mean and the variance of the captured monochromatic RGB images.

With these values of $m'_{LENS}$ and $A_{SENSOR}$, the spectral exposure for each image averaged in the exposure series ($L_e(\lambda)$, $N$, $t$) results:

$$H(\lambda) = 514.98e - 12\frac{L_e(\lambda)}{N^2}t \qquad (5)$$

where $L_e(\lambda)$ is the spectral radiance of the monochromatic target in mW/sr·m², $N$ is the f-number and $t$ is the shutter time, in seconds, of the electronic shutter controlled by menu according to the manufacturer specifications (Table 1).

**Table 1. Manufacturer's specifications on the control of the electronic shutter time of the CCD-RGB camera of our experimental set-up.**

| | | | |
|---|---|---|---|
| **Trademark:** Sony **Model:** DXC-930P | | | |
| Offset electronic shutter time: $t_0$ = 20 ms | | | |
| | **Variable** | **Range** | **Equation** |
| $t > t_0$ | Unit of frame ($F$) | [2,3,...,255,256] | $t = \frac{1}{25}F$ |
| $t < t_0$ | Horizontal scan cycle time ($P_H$) | [1,2,...,309,310] | $t = 64\,P_H + 35.6$ (in µs) |

## Experimental Procedure and Results

Selecting the parameters ($N$, $t$) of the camera and varying conveniently the radiance level $L_e(\lambda)$ of the monochromatic target by the input and output splits of the monochromator, the camera was exposed to exposure series of 450, 550 and 650 nm that were captured by the color channels R(650 nm), G(550 nm) and B(450 nm), respectively. These wavelengths were chosen because, in our particular digital image capture device and for all the spectral exposure range used in all variations of this experiment, they produced non-zero responses only in one of the three channels, that is, G(650) = B(650) = 0, R(550) = B(550) = 0, and R(450) = G(450) = 0.

Using normalized digital output levels (*NDOL*) instead of digital output levels, the opto-electronic conversion spectral functions (OECSFs), that is, the $NDOL_\lambda$ vs. $H_\lambda$ curves for each RGB channel, were fitted by transition curves (sigmoidal functions), defined by four parameters {$a$, $b$, $c$, $d$} as follows:

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

From experimental spectral exposure series, we analyzed the statistics of the OECSFs by means of the statistical dispersion of the sigmoid fitting parameters. That is, we proved whether, independently of the selected ($L_e(\lambda)$, $N$, $t$) values, the digital camera output was the same and constant along the linear and non-linear spectral exposure sensitivity range.

**Results with Irradiance Scale Exposure Series**

Fixating the shutter time at $t = t_0 = 20$ ms and changing only the f-number $N$ to values 5.6, 4 and 2.8, the associated OECSFs are overlapped in any color channel. This is shown for irradiance scale exposure series ($L_e$(650 nm), $N$, 20 ms) in the red channel in Fig. 3.

The above graph shows that the reciprocity law holds when only the lens aperture $N$ is changed in the exposure series ($L_e(\lambda)$, $N$, $t_0$). This can be affirmed quite conclusively for each λ-color channel combination because, as it can be seen for 650 nm - R channel data, the variation coefficients of the ($a$, $b$, $c$, $d$) parameters are very low (Table 2).

**Results with Time Scale Exposure Series**

We measured the digital camera response to spectral exposure series with constant lens aperture $N = 2.8$ but the shutter time $t$ took values 20, 10 and 5 ms, all of them below the offset shutter time $t_0$. This means that the values of the local variable $P_H$, the horizontal scan cycle time (Table 1), were 159 (10 ms) and 78 (5 ms). From Fig. 4 it seems that that the reciprocity law does not hold when only the shutter time $t$ is varied in the exposure processes because the three OECSFs represented in the graph do not overlap. This fact is corroborated by the statistical data of Table 3. The statistical variation of sigmoid parameters $c$ and $d$ is very high, unlike parameters $a$ and $b$. This means that a change of shutter time from 20 ms to 10 or 5 ms shifts the OECSFs from the "offset" position. It is as if the reciprocity law held in two groups of different shutter times, those with $t = t_0$ and those with changing $t$, because if we do not take into account the OECSF for $t_0$ the remaining OECSFs would follow the reciprocity law. Analogous measurements performed with the remaining λ/channel pairs lead us to the same conclusions.

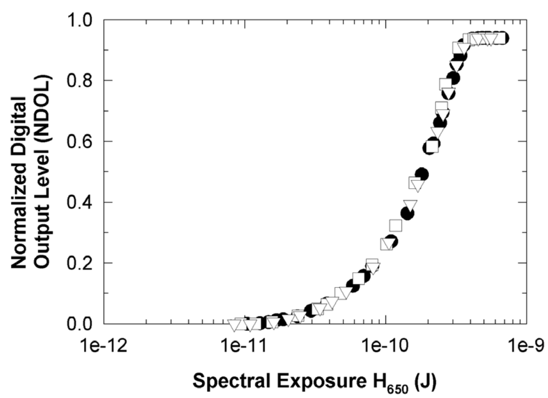


*Figure 3. OECSFs of the R channel under spectral exposure series of λ = 650 nm, varying N as 5.6 (solid circle), 4 (hollow square) and 2.8 (hollow triangle down) with the same shutter time $t_0$ = 20 ms.*

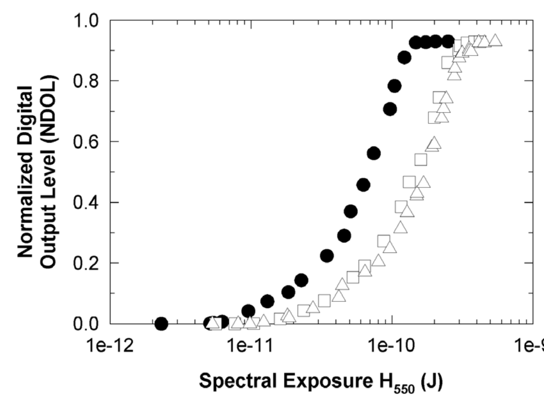


*Figure 4. OECSFs of the G channel under spectral exposure series of λ = 550 nm, varying internally t as 20 ms (solid circle), 10 ms (hollow square) and 5 ms (hollow triangle up) with the same f-number N = 2.8.*

**Table 2. Statistics of the (*a*, *b*, *c*, *d*) parameters that fitted the experimental OECSFs for the combination 650 nm / R channel under irradiance scale exposure series (only lens aperture *N* was varied).**

| 650 R | Exposure series | | | Mean | Std. Dev. | CV (%) |
|---|---|---|---|---|---|---|
| | $N = 5.6$ | $N = 4$ | $N = 2.8$ | | | |
| *a* | -0.170 | -0.192 | -0.203 | -0.188 | 0.017 | 8.92 |
| *b* | 1.132 | 1.154 | 1.171 | 1.152 | 0.020 | 1.70 |
| *c* | 1.5e-10 | 1.4e-10 | 1.5e-10 | 1.4e-10 | 0.1e-10 | 3.93 |
| *d* | 8.2e-11 | 8.0e-11 | 8.7e-11 | 8.3e-11 | 0.3e-11 | 4.16 |

**Table 3. Statistics of the (*a*, *b*, *c*, *d*) parameters that fitted the experimental OECSFs for the combination 550 nm / G channel under time scale exposure series (only shutter time *t* in ms was internally varied).**

| 550 G | Exposure series | | | Mean | Std. Dev. | CV (%) |
|---|---|---|---|---|---|---|
| | $t = 20$ | $t = 10$ | $t = 5$ | | | |
| *a* | -0.161 | -0.194 | -0.133 | -0.163 | 0.031 | 18.8 |
| *b* | 1.110 | 1.159 | 1.090 | 1.120 | 0.036 | 3.17 |
| *c* | 5.5e-11 | 1.2e-10 | 1.4e-10 | 1.0e-10 | 0.5e-10 | 43.4 |
| *d* | 3.0e-11 | 6.8e-11 | 7.2e-11 | 5.7e-11 | 2.3e-11 | 41.4 |

From the previous results, it seems that the reciprocity law in Digital Photography is verified when only the optical parameter *N* is changed and not when the electronic parameter *t* is changed. A simple test to avoid the difficulties of the electronic control of the exposure time, and prove again the verification of the reciprocity law, would be to control the exposure time outside the camera and keep it with a longer exposure time. In order to test this, an external shutter was positioned between the opal glass (OG) and the exit slit of the monochromator (MC). The shutter time of the Sony DXC-930P camera was kept to 2 seconds by the local variable frame ($F$ = 100, Table 1). The lens aperture *N* was always fixed to 5.6. With these contour conditions and selecting from the external shutter the values $t$ = 19, 38 and 76 ms, the data of Fig. 5 for green channel with 550 nm show that the reciprocity law holds. This fact is proved too looking at the statistical results of Table 4 about the sigmoid curves of the exposure series ($N$ = 5.6, $t$ = 19 ms), ($N$ = 5.6, $t$ = 38 ms) and ($N$ = 5.6, $t$ = 76 ms). Analogous measurements performed with the remaining λ/channel pairs lead us to the same conclusions.

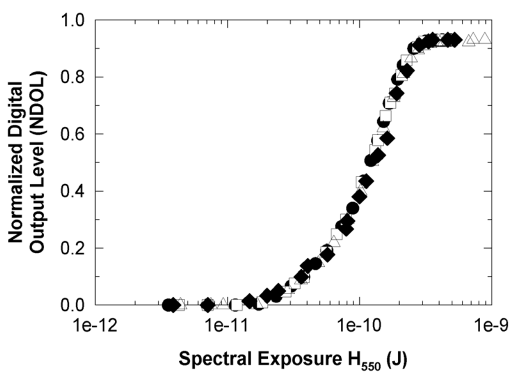


*Figure 5. OECSFs of the G channel under spectral exposure series of λ = 550 nm, varying externally t as 19 ms (solid circle), 38 ms (hollow square) and 76 ms (hollow triangle up) with the same f-number N = 5.6. The OECSF curve (solid diamond) with N = 4 and the internal shutter time t = 10 ms has been included.*

**Table 4. Statistics of the (*a*, *b*, *c*, *d*) parameters that fitted the experimental OECSFs for the combination 550 nm / G channel under time scale exposure series (only shutter time *t* in ms was externally varied).**

| 550 G | Exposure series | | | Mean | Std. Dev. | CV (%) |
|---|---|---|---|---|---|---|
| | $t$ = 19 | $t$ = 38 | $t$ = 76 | | | |
| *a* | -0.160 | -0.181 | -0.169 | -0.170 | 0.011 | 6.20 |
| *b* | 1.098 | 1.118 | 1.096 | 1.104 | 0.012 | 1.10 |
| *c* | 9.8e-11 | 9.6e-11 | 9.8e-11 | 9.7e-11 | 0.1e-11 | 1.42 |
| *d* | 5.2e-11 | 5.4e-11 | 5.4e-11 | 5.3e-11 | 0.1e-11 | 2.77 |

Therefore, this simple experimental test proves some electronic parameter hinder the verification of the reciprocity law with changes in shutter time by camera menu. But, what is this parameter? Besides, any set of different shutter times of the offset value ($t_0$ = 20 ms), controlled or not by camera, is valid to verify the reciprocity law maintaining the lens aperture *N*, but what is the reason? To test this last conjecture and to cover all the possible parameter changes, we selected two groups of equivalent exposure series. The first group was formed by the series ($N$ = 5.6, $t$ = 20 ms), ($N$ = 4, $t$ = 10 ms) and ($N$ = 2.8, $t$ = 5 ms). The second group was formed by the series ($N$ = 4, $t$ = 20 ms), ($N$ = 2.8, $t$ = 10 ms) and ($N$ = 2, $t$ = 5 ms). Both series were for the 450 nm / B channel pair. The OECSFs plotted in Fig. 6 show that the reciprocity law holds for exposure series ($L_e(\lambda)$, $N$, $t = t_0$), and for exposure series ($L_e(\lambda)$, $N$, $t \neq t_0$) separately.

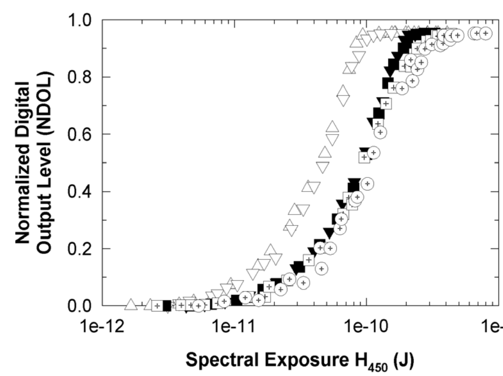


*Figure 6. OECSFs of the B channel under spectral exposure series of λ = 450 nm varying N and t to select two groups of three equivalent exposure series. First group: (hollow triangle up) for (N = 5.6, t = $t_0$=20 ms), (solid triangle down) for (N = 4, t =10 ms) and (x-hair squares) for (N = 2.8, t = 5 ms). Second group: (hollow triangle down) for (N = 4, t = $t_0$=20 ms), (solid square) for (N = 2.8, t = 10 ms) and (x-hair circle) for (N = 2, t =5 ms).*

From our point of view, there are two hypotheses to explain the behavior of the shutter time *t*:

1. The image sensor response for times below 20 ms is different. That is, there is some threshold time above which the response will be constant, but below which the response will be different.
2. The shutter time by control menu, $t_{menu}$, and the true photosite integration *t* (Eq. 3) do not coincide.

To determine which is the correct hypothesis, we performed several exposure series with the 650 nm / R channel combination fixating the lens aperture $N$ = 2.8, but selecting shutter times quite close to offset time 20 ms by means of the control menu. According to the relationship between the local variable $P_H$ and the shutter time *t* (see Table 1) provided by the manufacturer the following values were selected: 15 ms ($P_H$ = 234), 17.5 ms ($P_H$ = 273), 19.5 ms ($P_H$ = 304) and 19.9 ms ($P_H$ = 310). Fig. 7 shows the OECSFs corresponding to these four exposure series ($L_e$(650), $N$ = 2.8, $t_{menu}$) together those derived previously with $N$ = 2.8 and shutter times $t_{menu}$ equal to 20 ms (offset value), 10 and 5 ms. Careful analysis of this figure indicates that all the OECSFs associated with spectral exposure series with shutter times 5, 10, 15, 17.5, 19.5 and 19.9 ms are shifted to the right when compared with offset shutter time $t_0$ = 20 ms. Unless we still consider hypothesis "1" and admit that there is such thing as a threshold time and that it would be inferior to 0.1 ms, but we can not prove its existence because that $P_H$ = 310 is the last integer value of the $P_H$ scale that controls the manufacturer. Therefore, it seems quite evident that hypothesis "2" is demonstrated. It is as if the shutter time $t$ controlled through the specifications (Table 1) of the manufacturer were not the real photosite integration or exposure time that must be taken into account in the initial equations of this work. Then if this were true, using the correct relationship between the time $t_{menu}$ for electronic control and the real exposure time $t$, all the OECSFs of Fig. 4, 6 and 7 would be overlapped. This will be proved in other work.

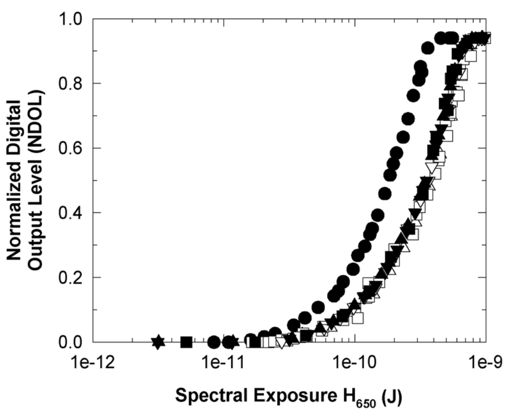


*Figure 7. OECSFs of the R channel under spectral exposure series of λ = 650 nm, varying t as 20 ms (solid circle), 19.9 ms (solid triangle up), 19.5 ms (solid triangle down), 17.5 ms (solid square), 15 ms (hollow triangle down), 10 ms (hollow triangle up) and 5 ms (hollow square) with the same f-number N = 2.8.*

## Conclusions

An experimental and theoretical methodology based on spectroradiometric measures, valid for any digital image capture device, has been proposed to test if the reciprocity law is fulfilled in digital photography. Unlike in photochemical photography, this radiometric law was fulfilled for irradiance and time scale exposure series. Therefore, independently from the wavelength-channel selection, for different combinations of spectral radiance, f-number and exposure time, the digital response will be the same because the device is sensitive exclusively to the incident spectral exposure, regardless of how that spectral exposure is obtained. The only topic not clarified was that the relationship provided by the manufacturer between the electronic shutter and the real exposure times is not correct to verify the reciprocity law. It would be interesting to know the real relationship between both time variables.

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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 Technical University of Catalonia at Terrassa (Barcelona) in 2001. Since 1998 he teaches Vision Sciences at the School of Optics & Optometry in the University of Alicante (Spain). His work is primarily focused on Color Imaging (device calibration and characterization, color management) and Industrial Colorimetry. He is a member of the IS&T and the Spanish Optics Society. E-mail: verdu@ua.es.