Apparent violation of the radiant exposure reciprocity law in interline CCDs

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We analyze in detail the apparent violation of the reciprocity law that occurs for an interline CCD array due to its responsivity varying with exposure time, and we investigate other parameters having an influence on this variation, such as the numerical aperture of the system or the illumination wavelength. The variation can be explained from a qualitative point of view by the charge leakage that occurs from the sense region to the register region during readout time. This change of the responsivity can be avoided either by using a synchronized external shutter or by limiting the numerical aperture while keeping relatively high exposure times. A detailed characterization for each particular CCD model must be carried out, if it is to be employed in low-uncertainty radiometric measurements. © 2005 Optical Society of America

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1. Introduction

The response of a CCD pixel (N_i), can be expressed as a function of the incident optical radiation in the following way:¹

$$N_i = N_{o,i} + \mathfrak{R}_i E_i t_{exp} \quad (1)$$

where $N_{o,i}$ is the dark response of the pixel; $\mathfrak{R}_i$ is the responsivity, which is a proportionality constant and whose value depends on both the external quantum efficiency and all the electronics transformations from the photo-generated charge to the digital response; E_i is the irradiance over the pixel, which is supposed to be constant; and t_{exp} is the exposure time, i.e, the time range during which the incident irradiance is integrated. This equation reveals the reciprocity between the irradiance and the exposure time, in terms of generating the same response in a given pixel. However, there are results that suggest that this reciprocity law does not apply to certain situations, for instance, when only a few pixels in the CCD array are irradiated. In these cases, under specific conditions,² the response obtained for the non-illuminated pixels is dependent on the exposure time used. This response has been related to the charge leakage that occurs from the sense region to the register region of the pixel. Anyhow, the reciprocity law between the irradiance and the exposure time is usually assumed for the present CCDs [when the entire array and not only certain pixels are illuminated], even though certain signs suggest limits to the fulfillment of this law.³⁻⁶ Note, for instance, that the aforementioned charge leakage can have a small but noteworthy impact on low-uncertainty radiant energy measurements. Taking into account equation 1 and the definition of responsivity according to the international

vocabulary of illumination,⁷ the responsivity of each pixel can be written as:

$$\mathfrak{R}_i = \frac{N_i - N_{o,i}}{E_i t_{exp}} \quad (2)$$

which should be constant if this reciprocity law was fulfilled and the response to the irradiance was linear. The aim of this work is to study the responsivity $\mathfrak{R}_i$ of each pixel under constant irradiance and geometrical conditions, while varying the exposure time. We also investigate potential influence of other variables as the numerical aperture (NA) of the incident beam or the beam's wavelength in the change of the responsivity vs. the exposure time. Taking into account that the pixel region where the photon absorption is produced depends largely on the aforementioned parameters, these variables could influence a priori the responsivity variation with the exposure time, since they would play an important role in the leakage mechanism. This work completes our previous study aiming to determine the experimental conditions that would allow to perform reliable low-uncertainty radiometric measurements with CCDs.⁸

2. Experimental setup

To study the variation in the responsivity of each pixel with the exposure time, under constant-irradiance, a radiance source was designed (Figure 1) that consisted, essentially, of a power-stabilized argon laser irradiating a 0.5m-diameter integrating sphere. A rotating diffuser was placed in front of the entrance port to minimize the speckle pattern over the CCD.^{9,10} This radiant source behaves as a lambertian spectral source¹¹ and ensures a uniform and predictable irradiance distribution over the CCD array. The CCD used for this study was an interline Sony ICX414AL of 0.5 inches,

having a dimension of 640×480 pixels, and a pixel size of $9.9 \mu m \times 9.9 \mu m$. Each pixel is coupled with a microlens located in front of it in order to maximize the light capture.

The CCD array is integrated in a camera, model Imager Compact, which is equipped with a 12-bit A/D converter. Although the device permits two different readout modes (video and asynchronous), this work was confined to the asynchronous reading mode, that allows flexible exposure times ranging from $10 \mu s$ to $10000 \mu s$.

To carry out the measurements, the CCD was located in front of the integrating sphere exit port at a distance of 8 cm, in normal incidence, centered on the optical axis and without objective. For each measurement, we determined the power level of the laser so as to obtain the required irradiance over the CCD to produce a response of around 3700 counts for an exposure time of $10000 \mu s$. This value is close to the maximum one, and ensures that no pixel reaches its saturation level. While maintaining a constant irradiance and a constant gain, the response of each CCD pixel was registered for a series of exposure times down to $10 \mu s$. Each value is the result of averaging 100 frames. We have previously carried out a statistical study of the temporal noise (at high and low frequencies), and the result was that a 100 frames average guarantees that the responsivity variation under study is not meaningfully affected by the temporal noise.¹² Finally, this measurement process was repeated for a series of wavelengths within the visible spectrum and for different numerical apertures (which were obtained by varying the exit port diameter while maintaining the distance between the CCD and the port) in order to study the influence of these parameters on the responsivity variation vs. exposure time. It is interesting to note that, although for

radiometric measurements it is very important a perpendicular incidence of the light beam with very low divergence, this is not the case, because for a lot of applications a CCD camera is used with an objective.

3. Results

The values of the responsivity shown in the present work are normalized, for each measurement condition, to the corresponding value obtained for an exposure time of $10000 \mu s$, since the aim of this work was to analyze the variation in the responsivity and not to study its absolute value. Moreover, except when explicitly stated otherwise, the responsivity values shown in the graphs correspond to the mean value across all the pixels of the CCD array, since it has been demonstrated that the behavior of the average matches, in all cases, that of the individual pixels.

Figure 2 shows a first example of how the relative responsivity ($\langle \mathfrak{R}^p \rangle$) averaged across all the pixels of the array and plotted as a function of the exposure time varies within the $[10 \mu s - 10000 \mu s]$ range. In this particular example, the sphere (Figure 1) was illuminated with the beam obtained from an argon laser adjusted to emit wavelengths of 454.6 nm, 496.5 nm and 514.5 nm. The CCD was located directly (using no camera objective) at a distance of 8 cm from the exit port, which had, in its turn, a diameter of 12.5 cm. As can be inferred from the plot, the average relative responsivity does not remain constant; in fact, it increases notably when the exposure time is decreased, reaching a relative value of 4 for $10 \mu s$ (i.e., the responsivity being 4 times bigger than the reference value obtained for $10000 \mu s$). This result contradicts the reciprocity law, which states that the responsivity remains constant for a given

set of measurement conditions while varying the exposure time.

Bearing in mind that the responsivity value depends on the numerical aperture of the beam illuminating the CCD, it is reasonable to investigate whether or not the value of the numerical aperture affects the amplitude of this variation in the responsivity and even whether or not this variation occurs always and for every value of the numerical aperture. For this purpose we obtained a set of plots of the relative responsivity vs. exposure time for a series of numerical apertures, as shown in figure 3. This graph clearly indicates that the smaller the diameter of the exit port (i.e. the smaller the numerical aperture), the smaller the variation in the average relative responsivity across the exposure time range under study. Moreover, it can be observed that the variation in the responsivity seems to undergo a certain saturation effect for large numerical apertures.

When the numerical aperture is modified by changing the diameter of the exit port the change encompasses a variation of the angular distribution within the solid angle. To verify that the variation in the responsivity is indeed linked to the variation in the solid angle, and in order to be able to attain smaller solid angles, we carried out complementary sets of measurements but, in this case, making use of the camera objective and varying its f-number value. The resulting plots of the average relative responsivity across the range of exposure times under study are represented in figure 4, where it can be seen that the larger the f-number, the smaller the amplitude of the variation in the responsivity with exposure time. It is noteworthy to add that the shorter the exposure time, the noisier the data are, due to the fact that as the number of counts decreases, the relative importance of the readout noise and the dark noise

increases notably. In fact, for an exposure time of $10\ \mu s$, the resulting signal after subtracting the dark signal consists only of 7 counts, which implies an uncertainty of over 4%.

Figure 5 shows a subset of the data plotted in figure 4, where we have removed the data points for the shortest exposure times. This way, it can be clearly seen from this plot that for large f-numbers (values above 2.8), we obtain, in a first approach, a constant behavior of the average relative responsivity with exposure time.

Thus, a first conclusion could be that for f-numbers above a given threshold (2.8 in this case), the variation in the average relative responsivity as a function of the exposure time does not depend on the f-number of the objective lens.

Finally, in order to round off the analysis of the different parameters that affect the evolution of the responsivity with exposure time, we studied the behavior of the system for different wavelengths of the illumination beam. For this purpose the CCD was equipped with an objective lens (f-number=2.8) focusing the exit port of the integrating sphere. Three sets of data of the average relative responsivity as a function of the exposure time were registered for the argon-laser wavelengths of 454.6 nm, 496.5 nm and 514.5 nm respectively. In this case we limited the exposure time to the $10\ \mu s$ - $100\ \mu s$ range, which is the region where the effect can be more clearly observed. The joint result is shown in figure 6. From the plot it can be observed that the amplitude of the variation in the responsivity is largest for the shortest wavelengths. In fact, the variation in the responsivity is approximately 10% higher for $\lambda=454.6\text{ nm}$ with respect to $\lambda=514.5\text{ nm}$.

To demonstrate whether or not the CCD under study is affected by leakage

effects similar to those in reference,² we irradiated the CCD with a non-expanded laser beam in order to illuminate only a few pixels of the array. Figure 7 shows two snapshots recorded (a) for an exposure time of $10\ \mu s$, which amounted to a count of approximately 3500 at the center of the spot and (b) for an exposure time of $320\ \mu s$ and with a similar number of counts.

In frame (a) a faint vertical fringe above and below the laser spot reveals a considerable number of counts for the non-illuminated pixels that belong to the columns where the laser beam falls onto. Moreover, it can be seen that the higher the number of counts for the irradiated pixels, the higher the count level for the non-illuminated pixels within the same column.

On the contrary, in frame (b) there is no trace of the aforementioned vertical fringe. Thus, this experiment reveals two important facts: on the one hand, it has been shown that illuminating a given pixel can affect the response of the rest of the pixels within the same column of the array under certain conditions; on the other hand, this effect upon the pixel's responsivity is more severe for shorter exposure times.

Remember that the gain is the same and constant in both cases. Moreover, the CCD has got a blind pixel, and its response is subtracted to the rest of the pixel responses, so this effect has nothing to do with the dark response.

In order to visualize this effect more clearly, we have plotted in figure 8, for the whole range of exposure times, the different count levels measured for the non-illuminated pixels of a partially-irradiated column of the array. The plot demonstrates that for exposure times above a given threshold the non-illuminated pixels remain

unaffected by the irradiation, since their count level is equal to the array's dark response (23 counts). In fact, it is interesting to note that this graph follows a similar trend to that in figure 2, even though in that case the CCD array was homogenously illuminated by a beam confined to a solid angle, whereas in this case the array is irradiated with a bundle of parallel rays. Therefore, the variations of the response are of different order.

4. Discussion

The results detailed in the previous section show that the dependency between the responsivity of the irradiated pixels of the CCD array and the exposure time is of a complex nature; in fact several experimental parameters, such as the numerical aperture, the angle of incidence or the beam's wavelength influence the specific features of this dependency. Moreover, it has been shown that the non-illuminated pixels contained in a partially-irradiated column present as well a certain response well above dark signal values for some experimental conditions.

One possible explanation for these phenomena could be the existence of a charge leakage from the sense region to the register region within the pixel. Following the exposure period, the charge is transferred from the sense region to the register region. During the readout period, the accumulated charge is transferred to the readout sense node. If during this period there is a leakage between the sense region and the register region, then the sense node will receive two charge contributions: the charge that has been integrated during the exposure period as well as the charge that leaks during the readout period, even though in principle, during this period no charge accumulation

should be allowed. Thus, the response of a given pixel i located in a column containing M_c pixels can be expressed as the sum of those two contributions in the following way:

$$N_i = N_{o,i} + k'Q_i t_{exp} + k'rQ_{col}t_l \quad (3)$$

where t_l is the readout time, Q_i is the number of charges per unit of time that the irradiance upon pixel i generates, Q_{col} represents the number of charges that the irradiation upon pixel i generates at the other pixels located in the same column as pixel i ($\sum_{i=1}^{M_c} Q_i$) during readout time, k' is the inverse of the conversion factor e^-/count , and r is the magnitude of the charge leakage that occurs from the sense region to the register region.

Equation 3 can be rewritten as:

$$\frac{N_i - N_{o,i}}{k'Q_i t_{exp}} = 1 + r \frac{Q_{col}}{Q_i} \frac{t_l}{t_{exp}} \quad (4)$$

Moreover, if the irradiance pattern is homogeneous across the whole column of the array, as was the case with most of the measurements carried out for the present work:

$$\frac{N_i - N_{o,i}}{k'Q_i t_{exp}} = 1 + rM_c \frac{t_l}{t_{exp}} \quad (5)$$

This equation shows that there is a hyperbolic dependence with exposure time, which increases linearly with the number of pixels in the column, with r and with t_l .

If we fit the experimental values of the CCD's average responsivity shown in figure 2 to equation 5, and take $t_l=25$ ms and $M_c=480$ pixels, which are the real values for the CCD array under study, we obtain the curve shown in figure 9. The only free parameter to adjust in equation 5 is the leakage rate r , for which we obtained

a best-fit value of 2.19 ± 0.02 millionths. In principle the fit should be made on a pixel-by-pixel basis; i.e. taking the responsivity of each individual pixel, since it is not clear whether or not the leakage rate r is constant across the array. However, as was previously mentioned, the average responsivity follows a similar behavior to that for the individual pixels. The standard deviation of the global fit was 0.027. In this sense, it can be concluded that even leakage rates as low as 0.002% (which amounts to 0.07 electrons for a full well) can induce a variation in the responsivity of up to 300%.

If the leakage that occurs from the sense region to the register region during the readout period can explain the variation in the responsivity with exposure time for a given set of measurement conditions, it is interesting to investigate whether or not the leakage can be influenced by the value of the numerical aperture and by the wavelength of the illumination beam, since it has already been demonstrated that these two parameters have an essential effect upon the variation in the responsivity. In this sense, it is worth at this point to remember that each pixel of the CCD is coupled to a microlens located in front of it whose aim is to maximize the system's external quantum efficiency, since it focuses the incident beam onto the sense region of the pixel. In consequence, the area within the sense region that effectively absorbs the radiation is determined, among other factors, by the angle of incidence.¹³ On the other hand, the greatest leakage rates should occur when the radiation is absorbed the closest to the register region, which, in turn, happens for large solid angles.

Going back to the experimental parameters under analysis, the beam wavelength has an influence over the spot size and the region where the photons are absorbed,

since the microlens' effective refractive index and the absorption at the semiconductor are both a function of the wavelength. Thus, it is to be expected that the leakage rate should also depend on the wavelength of the illumination beam.

The hypothesis of the charge-leakage from the sense region to the register region occurring during the readout interval could account, at least in a qualitative manner, for the change of responsivity with exposure time documented in the present work. However, a deeper understanding of the leakage mechanisms would be required if we were to formally develop a correction function for the responsivity as a function of the exposure time and the rest of the parameters involved.

The experimental facts shown in this paper, supported by equation 5, result in an apparent violation of the reciprocity law, violation produced by the leakage current during the readout time. It could be thought that actually this is not a violation because the signal increase is produced by a charge storage not coming from the light incident during the exposure time, something similar to the dark response. But, unlike dark response, the user has not got any way to know or estimate the signal resulting from the leakage, so it cannot be subtracted to the pixel response, and everything will happen as if a real violation occurs. Indeed, if somebody wanted to know a radiometric quantity associated to the pixel's response without being aware of this apparent responsivity inconstancy, would get a wrong value.

Consequently, if the measurement conditions are such that the CCD responsivity does not remain constant, but this variation needs to be minimized or even avoided, there are two available alternatives: the first one is to use an external shutter synchronized to the camera, so that no light falls onto the CCD during the readout period.

The second alternative is to limit the numerical aperture of the system in such a way as to achieve a small responsivity variation compared to the acceptable value for the uncertainty of the measurement.

Even though the present work has focused on a single CCD array, similar results have been found for other cameras (*PixelFly* HiRes, *Q-imaging* 10 bits and *Sensys* KAF-1400-G2). In fact, equation 5 can be applied to all of them, since they all follow the same hyperbolic dependence of the responsivity with exposure time. Furthermore, it has been observed that the amplitude of the variation in the responsivity increases with the number of pixels in the array, following the same pattern predicted by equation 5.

5. Conclusions

It has been demonstrated that the reciprocity law between the irradiance and the exposure time cannot be applied, in general, to CCD interline devices. An apparent violation of the radiant exposure reciprocity law has been observed. We call it "apparent" because it is not a real violation, as discussed before, but it has to be considered as if it were real when doing high accuracy radiometric measurements.

Moreover, the responsivity change vs. exposure time shows a hyperbolic relation with the exposure time, and it depends as well on the numerical aperture of the irradiation system and on the wavelength of the illumination beam, as the responsivity itself does. It also has been shown that, because of the charge leakage during the readout period, the response of a given pixel may be affected by the response of the rest of the pixels within the same column, in agreement with the findings by other

authors in the literature.

Based on that, it has been shown that this variation in the responsivity with exposure time can be qualitatively explained by the charge leakage from the sense region to the register region that occurs during readout time.

Therefore, this variation in the responsivity could be avoided simply either by using a synchronized external shutter or by limiting the numerical aperture of the system while keeping relatively high exposure times (between $1000\ \mu s$ and $10000\ \mu s$ for the CCD under study), the exact threshold being dependent on the particular CCD.

Finally, this work highlights the need to carry out a detailed characterization of the responsivity versus exposure time feature for each particular CCD model, if it is to be employed to perform low uncertainty radiometric measurements.

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References

1. A. J. P. Theuwissen, "Fundamentals of Solid-State Imaging", in *Solid-State Imaging with Charge-Coupled Devices*, (Kluwer Academic Publishers, Dordrecht, The Netherlands, 1995), pp. 131-156.
2. Thomas Seelemann, Manager Camera Group, LaVision GmbH, Anna-Vandenhoeck-Ring 19, D-37081, Goettingen, Germany (private communication,

- 2004).
3. J. R. Janesick, "Linearity", in *Scientific Charge-Coupled Devices*, (SPIE Press, Bellingham, Washington, USA, 2001), pp. 117-120.
 4. F. Martinez Verdu, *Diseño de un Colorimetro Triestimulo a partir de una camara CCD-RGB* (Doctoral Thesis, Universitat Politècnica de Catalunya, 2001).
 5. A. Ferrero, J. Campos and A. Pons, "Experimental results on integration time-irradiance non equivalence on a CCD Camera", in *Proceeding of The 10th Congress of the International Colour Association*, J. L. Nieves and J. Hernandez-Andres, eds. (Granada, Spain, 2005), pp. 1283-1286.
 6. H. J. Deeg and Z. Ninkov, "Characterization of a large-format charge-coupled device", *Optical Engineering*, **34**, No. 1, 43-49 (1995).
 7. International Commission on Illumination, *International Lighting Vocabulary*, (Publication CIE 17.4, Wien, Austria ,1987).
 8. J. Campos, "Radiometric calibration of charge-coupled-device video cameras", *Metrologia*, **37**, 459-464 (2000).
 9. S. Lowenthal and D. Joyeux, "Speckle Removal by a Slowly Moving Diffuser Associated with a Motionless Difusser", *J. Opt. Soc. Am.*, **61**, No. 7, 847-851 (1971).
 10. E. Schröder, "Elimination of granulation in laser beam projections by means of moving diffusers", *Optics Communications*, **3**, No. 1, 68-72 (1970).
 11. A. Ferrero, J. Campos and A. Pons, "Flat field correction algorithm for CCD radiometric calibration using integrating spheres", in *Proceeding of The 10th*

Congress of the International Colour Association, J. L. Nieves and J. Hernandez-Andres, eds. (Granada, Spain, 2005), pp. 1283-1286.

12. A. Ferrero, J. Campos and A. Pons, "Reduccion del ruido en CCD", Resumenes de la VII Reunion Nacional de Optica, Universidad de Cantabria, p. 151, Santander, 2003.
13. J. Furukawa, I. Hiroto, Y. Takamura, T. Wada, Y. Keigo, A. Izumi, K. Nishibori, R. Tatebe, S. Kitayama, M. Shimura and H. Matsui, "A 1/3 inch 380k pixel (effective) IT-CCD image sensor", IEEE Transaction on Consumer Electronics, **CE-38**, No. 3, 595-600 (1992).

Figure captions

1. Experimental set-up.
2. Variation in the relative responsivity averaged across all the pixels of the CCD array $\langle \mathfrak{R}^p \rangle$ as a function of exposure time.
3. Variation in the relative responsivity averaged across all the pixels of the CCD array $\langle \mathfrak{R}^p \rangle$ as a function of exposure time for different values of the numerical aperture of the system (obtained by varying the diameter of the integrating sphere's exit port). The CCD array was located at a distance of 8 cm from the port.
4. Variation in the relative responsivity averaged across all the pixels of the CCD array $\langle \mathfrak{R}^p \rangle$ as a function of exposure time for different values of the f-number of the camera objective.
5. Variation in the relative responsivity averaged across all the pixels of the CCD array $\langle \mathfrak{R}^p \rangle$ as a function of exposure time for different values of the f-number of the camera objective (detail).
6. Variation in the relative responsivity for pixel (300,230) as a function of exposure time for different wavelengths.
7. Snapshots of the CCD array after irradiation with a non-expanded laser beam:
(a) for an exposure time of $10 \mu s$, (b) for an exposure time of $320 \mu s$.

8. Response of the non-illuminated pixels contained in a partially-irradiated column as a function of exposure time.
9. Variation in the relative responsivity averaged across all the pixels of the CCD array $\langle \mathfrak{R}^p \rangle$ as a function of exposure time together with a fit to the data by means of equation 5 .

Fig. 1.

Fig. 2.

Fig. 3.

Fig. 4.

Fig. 5.

Fig. 6.

(a)

(b)

Fig. 7.

Fig. 8.

Fig. 9.