Experimental results on integration time-irradiance non equivalence on a CCD Camera

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ABSTRACT

The response of four CCD cameras under constant irradiance has been studied as a function of integration time. It has been found that the response is not constant, showing a larger change at the shortest integration time. The response change depends on beam parameters: The numerical aperture and its spectral distribution; and on the pixel size. In the case of the studied colour camera, the change is different for every colour channel.

1. INTRODUCTION

A project to study how accurate radiometric measurements can be done by using CCD cameras has been started at the Department of Metrology within the Institute of Applied Physics. The project consists of several parts and one of these is to study the linearity in the behaviour of CCD's radiant exposure response whose fault would make very difficult to perform high accuracy radiometric measurements with CCD. In principle, CCD response is proportional to radiant exposure once the dark response has been subtracted. However, there are some references in the literature that appoint a violation of the reciprocity law of integration time and irradiance to produce the same radiant exposure, especially with respect to the integration time.

Testing the validity range of the integration time – irradiance reciprocity law is the object of this work. To check it, the response variation of four different CCDs has been studied by keeping a constant irradiance over them. Experimental results will be shown that put in evidence the infringement of the reciprocity law to produce a given CCD response. At least in the case of two CCD cameras this non-equivalence depends on the f-number and the angle of incidence of radiation, and on wavelength. It seems that the non-equivalence could also be related to the pixel size. The work has been done in three different laboratories in order to study various camera model.

2. EXPERIMENTAL METHOD DESCRIPTION

Four CCD from different manufacturers or models, comprising three B/W cameras and a colour one, have been tested in this work: An Imager Compact VGA, an Imager Compact HiRes, a Q-imaging 10 bits and a Photometric Sensys KAF-1400-G2. All of them were uniformly irradiated, without objective, by putting them at the output port of an integrating sphere in two laboratories and an integrating cube in the other laboratory. Several images were taken an averaged for every integration time (t_{int}) and irradiance level, taking also the same number of images of the dark response for every integration time. The automatic gain feature was disabled in those cameras that have got it. The video mode was not used in these measurements. The number of images averaged was high enough to minimize temporal noise so that it cannot hide the response variation due to non equivalence. With these data a factor R was calculated according to:

$$R = \frac{\langle N_i - N_{0,i} \rangle}{t_{\mathrm{int}}} \tag{1}$$

Where N_i is the averaged pixel response and $N_{0,i}$ is the average pixel's dark response. In this case the brackets indicate the spatial average over the complete CCD. This factor R will be constant within the temporal noise if the individual pixel's response is proportional to radiant exposure.

This experiment was done with a broad band radiation source (an incandescence lamp) for all the CCDs and with some spectral lines coming from an argon laser for two of them (B/W cameras), so that the spectral dependence of the phenomena can be observed. In this case care was taken to minimize speckle over the CCD by using a rotating diffuser.

Furthermore, the experiment was also done by irradiating the CCDs with beams of different numerical apertures in order to check for this type of dependence too.

3. RESULTS

The results obtained are shown in the next sections, presented separately for every one of the studied cameras.

3.1 Camera Imager Compact VGA

The response of this CCD has been tested with broad band radiation and with spectral radiation. The results obtained with broad band radiation are not presented here because the behaviour is similar to those obtained with the spectral source. For all the measurements done with this camera, the figure that better represents the change of factor R versus integration time is a "hyperbolic form". As the integration time decreases more changes factor R. This means that the non-equivalence cannot be attributed to a systematic non-correct determination of the real integration time due to software inaccuracies.

Figure 1 shows the relative change of R versus integration time for several values of f-number. It can be seen that the infringement of reciprocity is higher for low f-numbers.

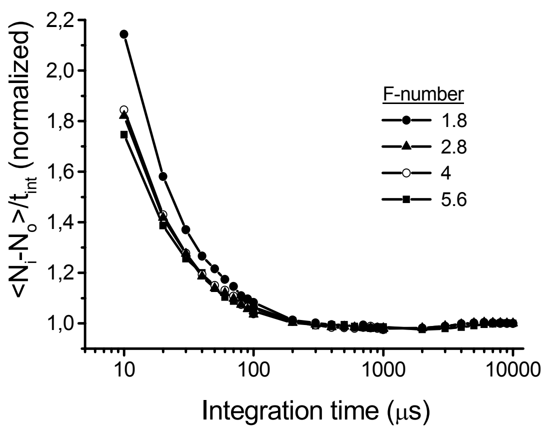


Figure 1. Response change under constant irradiance as a function of integration time for different f-numbers.

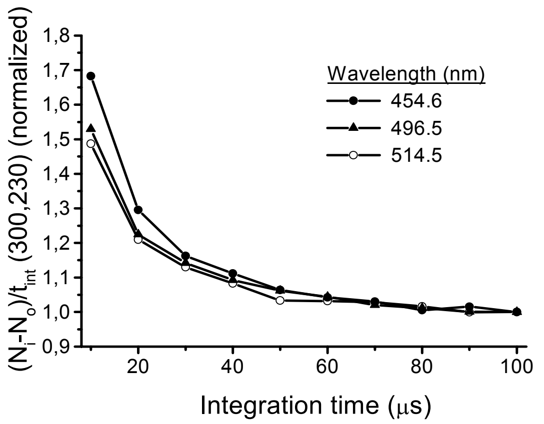


Figure 2: Response change under constant irradiance as a function of integration time for a given pixel at several wavelengths.

Figure 2 shows the results obtained by irradiating the CCD placed at the output port of the sphere with several laser wavelengths. It can be seen a soft response dependency on wavelength. This figure shows only the result obtained for one pixel (300, 230), the same results are obtained for all the pixels in the CCD. Moreover, it can be seen that the response change for one pixel has got the same form as the average over the CCD, then the average over the CCD can be used to show the behaviour of individual pixels without hiding any feature.

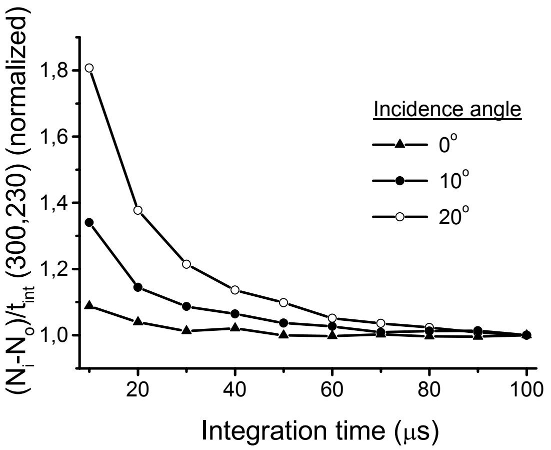


Figure 3. Response change under constant irradiance as a function of integration time for several incidence angles.

Figure 3 shows the response change as a function of integration time for different angles of incidence. This measurement was done by irradiating the CCD directly with the laser beam, rather than placing it at the output port of the integrating sphere, in order to be able to precisely determine the angle of incidence. It can be seen that the response changes more as the angle of incidence of the incoming radiation increases.

3.2 Camera Imager Compact HiRes

This camera is from the same manufacturer than the previous one. The main difference is that pixels are smaller in this one to get a higher spatial resolution. The results obtained are similar to the previous one: The CCD response under constant irradiance changes with integration time and this change depends also on the f-number of the incoming beam and on the wavelength. However the change is more dramatic in this case, as it can be seen in figures 4 and 5 below. It raises up to 2400 % in the worse case. Note that in this case the numerical aperture of the beam impinging the CCD was varied by pulling the CCD away from the integrating sphere output port (the highest the distance, the highest the f-number), rather than adding the objective. Nevertheless the uniformity over the pixels was still good enough.

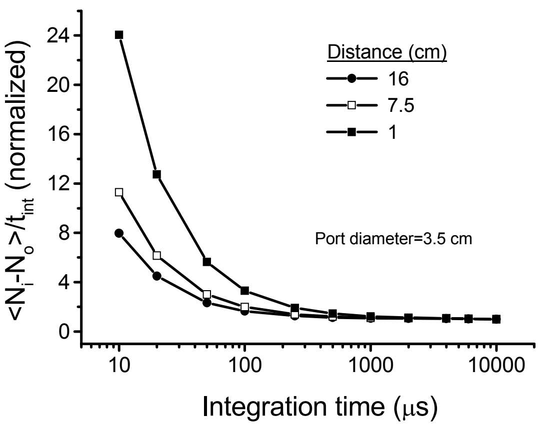


Figure 4. Response change under constant irradiance as a function of integration time for different numerical apertures of the incoming beam.

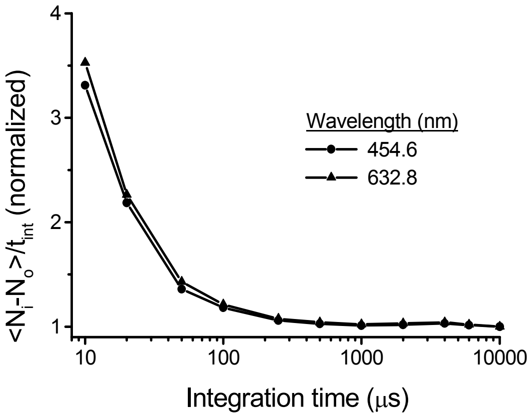
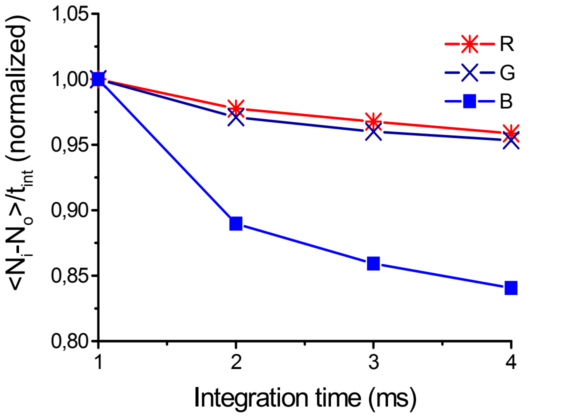


Figure 5. Response change under constant irradiance as a function of integration time for different wavelengths.

3.3 Camera Q-imaging 10 bits

This CCD has been studied only when irradiated by a broad band spectral distribution coming from an incandescence lamp, because this is a RGB colour camera. The reciprocity law fault has been observed in the three channels as can be seen in Figure 6, although the response change is smaller than the previous ones (about 4 % in the R and G channels). The relation between factor R and integration time is given by a “hyperbolic form” as for the previous studied cameras. In order to clarify the graph, the data normalization has been done at the shortest integration time value. It can be seen that the blue channel changes more than the green and red ones. This means that in addition to a degradation in the measurement of optical radiation, a colour degradation is also produced since the channels are not equally disturbed.



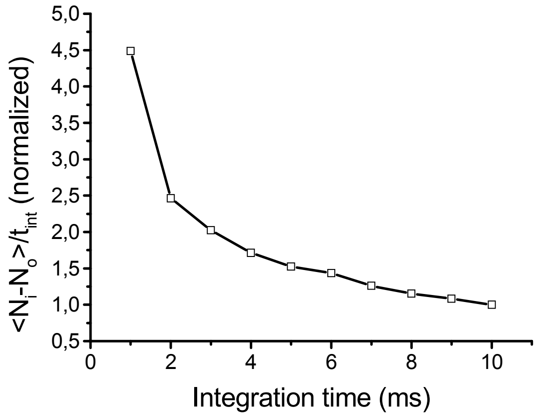


Figure 6. Response change under constant irradiance as a function of integration time for the three channels of a colour camera (Q-imaging 10 bits).

Figure 7. Response change under constant irradiance as a function of integration time (Photometric Sensys KAF-1400-G2).

3.4 Camera Photometric Sensys KAF-1400-G2

This CCD has got a mechanical shutter that can be synchronized with the CCD electronic clock to be able to trigger measurements at given time. The study of this system has been done only with the incandescence lamp. The results obtained are shown in Figure 7. The same behaviour as for the other cameras can be seen in factor R. It changes more at short integration times than at longer ones, and the functional relation looks like a hyperbolic form.

4. CONCLUSIONS

A noticeable response change under constant irradiance has been observed in four CCD cameras, including B/W and colour ones, that agrees with other results in literature. This linearity fault has to be evaluated and corrected if cameras are to be used in low uncertainty radiometric measurements. Low uncertainty colour measurements made with colour cameras also has to consider this effect since the RGB channels are affected differently.

The largest response variation has been observed for the camera Imager Compact HiRes which has got the smallest pixels. The minimum response change has been observed for the colour camera. For two cameras it has been shown that the response change depends on the f-number of the beam impinging the CCD and on the wavelength. This means calibration has to be done not only spectrally but for every f-number. Whenever possible, measuring with high f-numbers reduce the problem of response change with integration time.

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