Low-uncertainty absolute radiometric calibration of a CCD

A. Ferrero, J. Campos and A. Pons

Instituto de Física Aplicada, CSIC, Madrid, Spain

Abstract. A low-uncertainty absolute radiometric calibration system for CCDs has been developed. The calibration experimental setup and procedure are shown. The calibration procedure has been carried out by direct substitution. The CCD responsivity is also shown. The uncertainty budget has been analyzed in detail. The obtained uncertainty contribution apart from the reference radiometer uncertainty (0.29%, k=1) is about 0.18%.

Introduction

In addition to their wide use as imaging systems, CCD cameras would be very interesting measurement instruments for optical radiation if the measurement uncertainty was kept low[1]. For CCD calibration, it is necessary bearing in mind, unlike a photodiode calibration, that it is a two dimensional calibration and the added charge transfer and electronic problems. The low-uncertainty calibration of a CCD requires the previous design of a stable and uniform radiance source, whose radiance could be measured with low uncertainty. The designed source was an externally dye laser illuminated integrating sphere[2]. The radiance measurement was carried out by a silicon radiometer.

In this work, the calibration procedure is explained, and the results for an absolute radiometric calibration for an interline Sony ICX414AL having 640 x 480 pixels (9.9μm x 9.9μm) are shown. It is integrated in a camera, model Imager Compact, that has got a 12 bits A/D converter.

Experimental setup and procedure

The source consists of an integrating sphere externally illuminated by a power-stabilized dye laser. It was proved that this source is uniform and lambertian[2]. A rotating diffuser is located before the sphere's entrance port in order to reducing the speckle noise of the laser radiation[3,4]. For the calibration, it is not possible to locate the CCD at the plane of the exit port plane, because it is necessary to avoid radiation from direct incidence and first reflection. The exit port-CCD distance where there is enough uniformity for the calibration was studied. For this study was considered the shadow of the CCD mount over the own CCD, the radiation from direct incidence and first reflection, the field uniformity and the variation of the responsivity at different solid angles. As the pixels have different responsivity at different solid angles, it is necessary to know the maximum solid angle that assures a responsivity variation with respect to normal incidence smaller than the wanted measurement uncertainty. For determining this solid angle, the response of every pixel was evaluated increasing the exit port-CCD distance, finding that pixels' relative response becomes constant at a given distance. This distance defines the calibration solid angle.

The calibration is carried out by direct substitution, using a 10 ms exposure time. It was proved that at this exposure time there were not linearity problems produced by the relation between the exposure time and the readout time[5]. We consider the best CCD alignment the position where the most uniform response across the whole CCD is obtained. As reference radiometer was employed a silicon photodiode of proven linearity with an aperture. This photodiode was calibrated respect to the Spectral Responsivity Scale of Instituto de Física Aplicada (IFA)[6], that has got a standard uncertainty of 0.29%.

The responsivity measurement equation is

$$R_i = \frac{(N_i - N_{o,i})R_{rad}}{C_{NL,i} t_{\exp} r_{rad}} \quad (1)$$

where N_i is the pixel i response, $N_{o,i}$ is the pixel i dark signal, t_{exp} is the exposure time, r_{rad} is the response of the radiometer, R_{rad} is the responsivity of the radiometer, and $C_{NL,i}$ is a response non linearity correction factor. We have calculated $C_{NL,i}$ by studying, at constant irradiance, the variation of $(N_i - N_{o,i})/t_{exp}$ for several exposure times. Then the relation between a relative responsivity and N_i is obtained. So, R_i is a corrected responsivity, and has to be a constant for a given wavelength.

The calibration procedure was carried out measuring R_i for several wavelengths. We did this procedure three times in order to calculate the procedure uncertainty. N_i and E_i were averaged to minimize temporal noise. The higher N_i value, the lower CCD relative uncertainty. The calibration wavelengths were chosen according to the slope and curvature of a typical R_i, bearing in mind a potential interpolation.

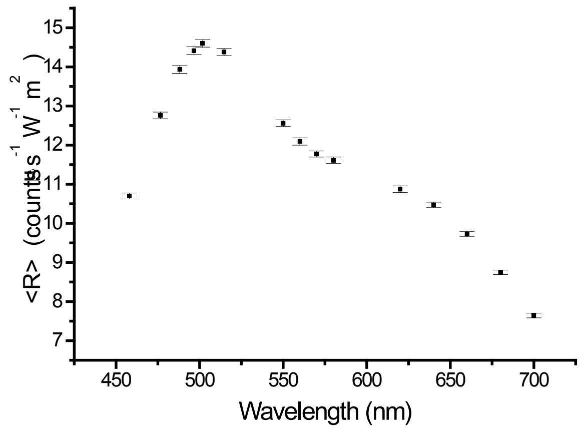

Figure 1: Average spectral responsivity of CCD Sony ICX414AL.

Results

In figure 1 the averaged spectral responsivity across the whole CCD in the range (460 nm - 700 nm) is shown. The averaged responsivity value is very similar to the responsivity values of all the pixels. In fact, the relative standard deviation of the pixels' responsivity is between about 0.4% (at 550 nm) and about 1% (at 460 nm).

A maximum in responsivity is observed at about 500 nm, and an inflexion point at about 600 nm. All the wavelengths were obtained using only two dies (550 nm - 580 nm, 620 nm - 700 nm) and argon lines (458 nm-514.6 nm).

The total uncertainty never reaches 0.4% (k=1). It was evaluated from the field non uniformity (0.012%, calculated from a lambertian disc model for the exit port[2]), the repeatability of the calibration procedure (around 0.1%, accounting repeatability of alignment, radiometer response and CCD response), the reference radiometer uncertainty (0.29%), and the CCD uncertainty, that is estimated bearing in mind the charge transfer noise, the quantization noise and the residual non linearity noise after the correction by $C_{NL,I}$ (each of these contributions to the CCD uncertainty is shown in figure 2). The larger contribution to the CCD uncertainty is the charge transfer noise. The higher N_i, the lower the CCD relative uncertainty.

It is useful to determine a function that relates the CCD relative uncertainty to N_i in order to know it for each N_i. This uncertainty goes from 0.6% (few counts) to 0.1% (close to the count saturation level). Therefore, it is important to carry out the calibration at a high count level.

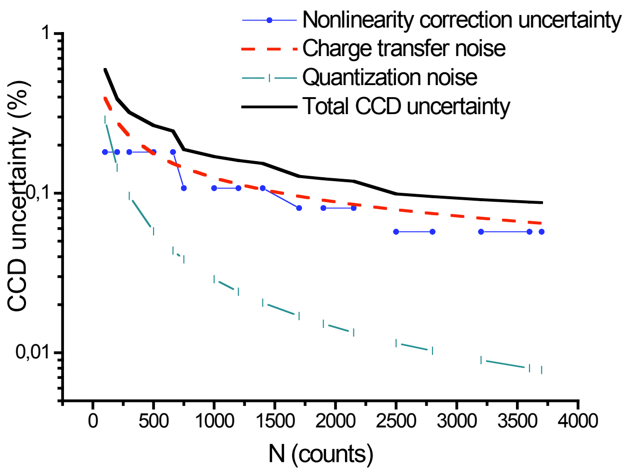

Figure 2: CCD uncertainty budget.

The total uncertainty of the absolute calibration and the quoted contributions are shown in figure 3. The obtained uncertainty contribution apart from the reference radiometer uncertainty is about 0.18%, so the calibration procedure can be considered good.

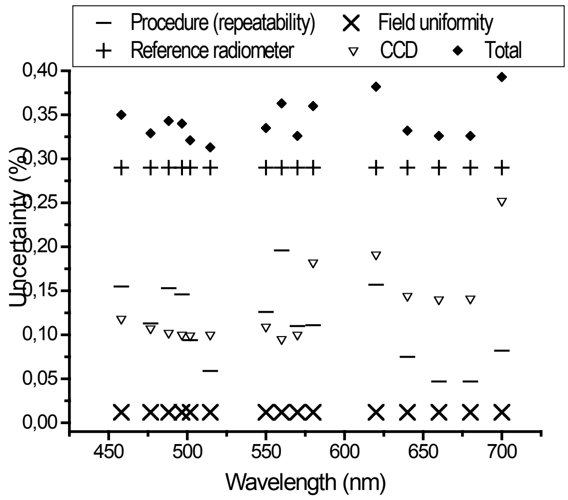

Figure 3: Calibration uncertainty budget.

Conclusions

A CCD absolute radiometric calibration system has been developed. We have analyzed in detail and quoted the uncertainty sources that contribute to the total uncertainty. The obtained uncertainty contribution apart from the reference radiometer uncertainty (0.29%, k=1) is about 0.18%.

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