Characterization and Calibration of a CCD Detector for Light Engineering

Pietro Fiorentin, Paola Iacomussi, and Giuseppe Rossi

***Abstract*—This paper describes the methodology developed for characterizing a commercial charge-coupled device (CCD) camera as a luminance meter for analyzing lighting systems and especially for measurements in road light plants. Today, several luminance meters based on commercial CCD cameras are on the market. They are very attractive for the lighting engineer: The availability of a high number of closely spaced small detectors (pixels) on a single chip permits analyses almost impossible with a traditional luminance meter. These commercial-industrial CCD cameras are sold at prices lower than scientific grade ones. They are factory equipped with a dedicated filter to reach the correct photopic sensitivity $V(\lambda)$, and they are factory calibrated in luminance SI units. The main counterparts in using these cameras are in the difficulties to define the measurement accuracy and the influence of the environment luminance on the measured values of the framed scene, in the low resolution of their A/D converter (usually 8 or 12 bit), and the higher noise level (usually the CCD chip is not cooled). To reach the measurement accuracy required by lighting norms, it is necessary to characterize metrologically a camera and quantify all the possible external influences which could degrade its performances, in real measurement situations, and which could affect the measurement results. A carefully controlled measurement set up and operating procedure could limit the causes of errors and improve the accuracy of measurements obtained in operating conditions. In this way, the measurement uncertainties might be evaluated completely, and considerations on the results could suggest particular operating practices to limit the causes of error due to measurement setup and environmental conditions.**

***Index Terms*—Blooming, calibration, charge-coupled device (CCD), dark current, defocusing, linearity, luminance meter.**

I. Introduction

THE STIMULUS received by retinal photoreceptors of the human eye is related to a photometric quantity called luminance, i.e., the luminous intensity per unity area. Relative luminance differences on contiguous surfaces allow the perception of object details. Therefore, luminance plays a leading role in lighting engineering, determining the quality of lighting systems and conditions both in indoor and in external environments.

Traditional luminance meters are only able to evaluate the mean luminance of a surface viewed from a given direction [1].

The devices considered here are charge-coupled device (CCD) luminance meters, where an optical system focuses the framed surface on the CCD matrix. Any single pixel can be associated with an element of the surface under measurement whose uniformity can be evaluated.

A CCD-based luminance meter could evaluate the luminance of several small portions of a surface ("point" luminance) and for several directions of observation: Large scenes can be captured and converted to digital photometric information [2].

CCD detectors are integrating devices: the number of charges stored in each pixel is directly proportional to exposure time and to array irradiance. To evaluate the luminance in SI units [candela per square meter], the camera must be equipped with an *ad hoc* filter to obtain a spectral sensitivity of the device equal to the spectral luminous efficiency [3] $V(\lambda)$ (i.e., the normalized spectral sensitivity of the standard observer used as a weight factor for photometric quantities) and calibrated against a luminance standard source.

A complete calibration procedure to verify and, if possible, improve the performance of the CCD luminance meter, when applied in lighting engineering, was developed and described here. The main causes of error are described, together with their analysis, and possible solutions in the measurement procedure, are presented.

The methodology is a general one and was arranged at the Istituto Elettrotecnico Nazionale (IEN) for the characterization of scientific CCD cameras for metrological applications [4].

This paper shows some simplifications in the calibration procedure in order to reduce its cost and time when we have the following:

- commercial or industrial grade CCDs are considered;
- the CCD luminance meter is mainly used for environment characterization, i.e., road lighting plant evaluation.

The measurement examples described in this paper are obtained using a commercial camera "LMK96." The original lens had a fixed diaphragm, the right choice to simplify the work in the field, but a great restraint in research work. It was replaced with a Zeiss 50 mm $f/1.4$ photographic lens. The scientific grade camera used in the development of the characterization procedures was a "Photometrics 350" camera with a 1024×1024 CCD and a Nikon 50 mm $f/1.8$ lens.

II. Calibration and Characterization Procedure

A camera calibration procedure gives for each pixel of the CCD array the value that links the A/D converter output with the luminance of the pixel-framed surface (luminance calibration coefficient).

These values depend essentially on the pixel sensitivity, on the optical system characteristic (i.e., the diaphragm) and on the

Manuscript received June 15, 2003; revised June 15, 2004.

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Digital Object Identifier 10.1109/TIM.2004.834055

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gain of the CCD output amplifier. These operating conditions should be recorded in the calibration certificate.

The knowledge of the calibration values is not enough to obtain accurate measures because several parameters could influence the pixel reading in real measurement conditions (linearity, spectral sensitivity, dark frame, presence of saturated pixels, ghost images, etc.). Furthermore, the same calibration procedure could introduce some discrepancies; it usually happens as it is carried out with a source lighting the entire chip [5]–[7].

For these reasons, the above quoted parameters should be evaluated to understand their influence.

In a CCD matrix, the luminance calibration coefficients can be different for each pixel and must be evaluated [8]. Discrepancies between pixels depend mainly on three factors:

- manufacturing tolerances on the pixel sensitivity over the chip (sensitivity matrix);
- optical system setup;
- lens shutter position.

Due to optical reasons, for a given luminance, the optical system produces on the CCD surface an illuminance distribution according to the fourth power of the cosine of the angle subtended by the pixel, approximately. The real distribution depends on the correction applied in the system design. Furthermore, some ghost images appear due to internal reflection in the optical system and in the CCD case [9].

A well-mounted central radial mechanical shutter does not introduce any nonuniformity (due to its opening and closing times) on the CCD surface illuminance distribution. Otherwise, its contribution shall be considered [8].

The table of the luminance calibration coefficient is called the "calibration matrix"; it tries to correct the influence of all the factors considered above. It is recorded in the CCD computer control memory and applied to every measured frame.

Following the procedure developed at IEN for calibration of the CCD detector used for luminance measurements in metrological applications, both the calibration matrix and the presence and influence of ghost images can be evaluated. A uniform diffuser was lighted by a calibrated intensity lamp, the fundamental property of which is its stability [4].

Referring to Fig. 1, a standard illuminant A lights the calibrated white diffuser: Its luminance and uniformity are therefore known. A field diaphragm limits the field of view of the camera: only groups of at least 16 pixels are lighted, but only the four inner pixels are considered for calibration. The groups of pixels are selected by rotating the CCD camera around the first nodal point of the lens system in front of the CCD matrix. In this way, each group of four pixels can be calibrated for luminance measurements. Contemporarily, ghost images can be discovered and their influence correctly evaluated (if other pixels appear lighted, this is due to ghost images).

The calibration could be applied for different camera conditions, and the influence of each parameter on the device performance could be easily obtained. Usually, the procedure is repeated for different exposure times and lens diaphragms. For road applications, the distance between the detector and white standard target is 60 m, to simulate the real working conditions.

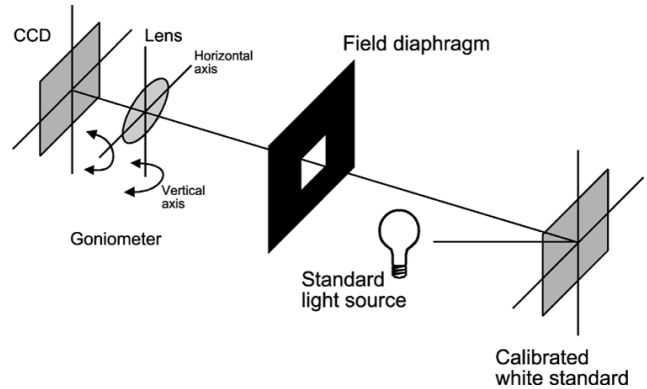

Fig. 1. Calibration set up.

This is a very time-consuming procedure: It is possible to reduce the characterization time by considering bigger groups of pixels, but, obviously, this brings lower accuracy.

A. Commercial CCD Camera Calibration Procedure

Commercial CCD cameras do not have such technical characteristics to justify the use of such a heavy procedure.

The usual approach [6], [10] requires a flat luminance source, but three points should be considered:

- the uniformity of a state-of-the-art luminance source is not better than 1%;
- the calibration is done at low distances because the source light shall shoot all the chip pixels;
- ghost images are not highlighted and their influence is erroneously recorded in the calibration matrix.

The last point could be very important if the energy in ghost images, produced by scattering in the lens system, is greater than the device noise or resolution (the A/D converter has 8 or 10 bits); in fact, an overestimation of the sensitivity matrix is introduced.

For the above reasons, a simplified procedure was developed. A commercial calibrated luminance source (illuminant standard A equipped with a diffusing device like a sphere) is used. At a short distance, the source lights the whole CCD chip of the camera without lens. In this way, the illuminance on the detector surface is extremely uniform, and the sensitivity matrix is obtained. Of course, the reflection of the lens holder shall be carefully avoided.

Alternatively, the camera with the lens frames the source. The output image considers also the influence of the lens, but the illuminance among adjacent pixels could be considered uniform and the sensitivity matrix is obtained.

To improve accuracy several measurements can be done by rotating the source or the camera.

Then, the luminance source is placed 60 m from the camera (the typical working distance in road plant measurements). In this condition, the luminance source lights uniformly a group of nine pixels. The camera is rotated to define a grid of 35 equally spaced groups of nine pixels, as in the original IEN method. From these measurements, the influence of the lens is obtained. This function represents a very regular surface, without spikes,

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which can be interpolated for intermediate pixels with adequate accuracy.

The calibration matrix is then obtained by extrapolating the results of the two sets of data and minimizing discrepancies.

In Fig. 2, a tridimensional interpolation shows these results. The standard source used in the calibration procedure had a luminance of 1035 $\mathrm{cd/m^2}$, and the camera lens aperture was $\mathrm{f/4}$. Usually, commercial cameras, like the model here considered, have an electronic shutter and automatic exposure time. For each acquisition, the automatic exposure feature was used to reduce noise influence. With the same aim, the calibration results were the mean values of three records.

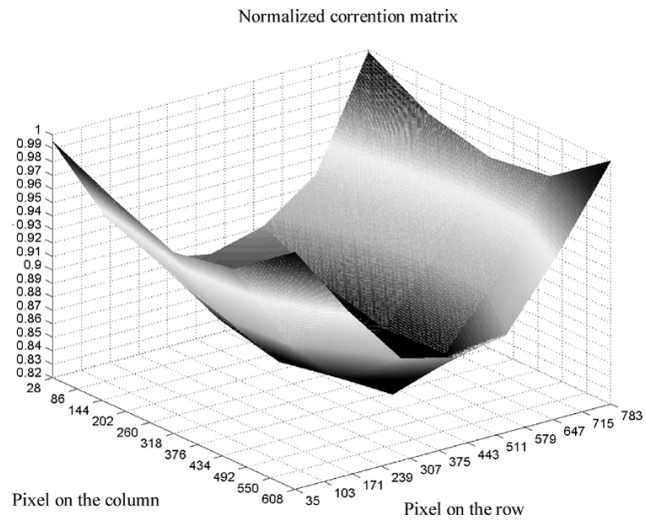

Fig. 2. Normalized calibration matrix.

III. CCD Camera Characterization: Road Lighting Measurement Constraints

To improve the accuracies in road lighting measurements, the camera performances should be characterized following an *ad hoc* procedure. Two constraints are very important in photometric road measurements:

- the luminaries use discharge lamps;
- international or national norms [11] and technical documents [12] require the luminance of road surface at an observation angle of $(1.0 \pm 0.5)^\circ$, i.e., the camera must be at about 1.5 m over the road surface and 60 m from the observed point.

Discharge lamps have an emitted spectrum strongly different from the illuminant A spectrum of the source used for luminance calibration (Black Body at 2856 K). The more the total spectral sensitivity of the system (lens, filter, and CCD) matches the $\mathrm{V}(\lambda)$, the less are the spectrum influences on the luminance results.

Commercial CCD cameras are factory equipped with a calculated filter approximating the $\mathrm{V}(\lambda)$. How close the spectral sensitivity fits the $\mathrm{V}(\lambda)$ is stated in the data sheet: The CIE f_1' parameter [1] must be considered in the measurement uncertainty budget.

Theoretically, the output emission of road lighting lamps has a period half of the power supply one. In Europe, the line frequency is 50 Hz: Therefore, the camera integration time (exposure) should be an integer multiple of 10 ms. Practically, for some types of lamps, the light output during the negative part of the electric energy wave could differ by several percent from the output during the positive semiperiod. Therefore, if high-level accuracy measurements are required, the integration time shall be an integer multiple of 20 ms.

Luminance meter calibrations are usually carried out at short distances, with only the calibration source in the environment. In road lighting measurements, the lighted surfaces are at great distances (60 m), and several lighting sources are present in the environment. Therefore, it is necessary to consider both the effect of the difference in lens position (focus) between the calibration and measurement setup and to evaluate the influence of ghost images (i.e., light sources in the environment, even if not framed, can generate stray-light in the lens and on the detector surface). To overcome the first problem, the camera should be calibrated in luminance units pacing the reference source at a distance equal to 60 m. The influence of off-axis light sources as ghost images is described in detail in the following, where some parameters of the optical system performances are analyzed too. The camera should also be tested for the most important quality aspects of a CCD: linearity, blooming effect, and dark current (dark frame). The performances are good indicators of the differences between commercial and scientific CCDs.

IV. Influences of the Optical System

A. Lens Aperture

In our example, the calibration matrix was determined for an aperture value of $\mathrm{f/4}$; different calibration matrices should be used for different aperture values. This means a calibration process for every aperture value. To avoid so many calibrations, it is possible to introduce a multiplicative factor to scale the calibration matrix at different apertures. The values of this correction factor are not constant for every pixel, but in our camera, the differences are less than 4%. Obviously, this simplified method lowers the global measurement accuracies of the system; in any case, it is acceptable for the particular application we are interested in, especially if the measured surface is framed in the center of the CCD matrix.

Experimentally, a uniform luminance source is framed at different lens apertures. For every aperture, the average of the reading (corrected using the sensitivity matrix of Section II) of seven pixels along the diagonal of the CCD matrix is considered. Then, each mean value is normalized referring to the value obtained with the luminance source in the same conditions at $\mathrm{f/4}$ aperture (condition used to define the calibration matrix). An example of these correction values is plotted in Fig. 3.

B. Defocusing Effect

If an object is not perfectly focused on the CCD matrix, an error arrives in measuring its luminance. As the lens aperture defines the depth of field, the focusing effect should be considered for all the lens apertures available.

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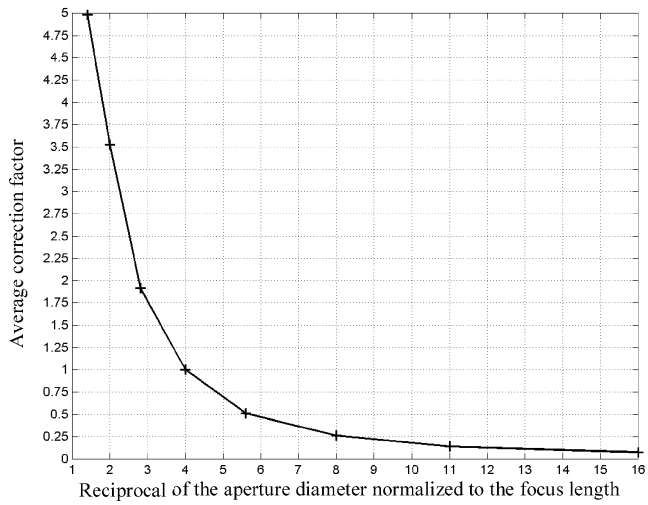

Fig. 3. Aperture correction coefficient normalized to f : 4 value versus f values.

Experimentally, the measurement is carried out with a luminance standard source at a fixed distance, changing the lens focusing. In our example, to highlight the problem, a uniform luminance source (9640 ± 10 cd/m^2) was placed at a distance of 2.5 m from the CCD camera (Table I) and at 15 m to simulate experimental condition more convenient for lighting engineering applications (Table II).

To evaluate the errors due to defocusing, the mean value of the nine central pixels is considered and compared to the value obtained in the same condition but with the lens perfectly focused.

The error increases rapidly if a shorter focus distance is used and reaches unacceptable values. If the focus distance is very large, the luminance error remains small. Comparing different apertures, obviously, the closer presents the smallest error.

C. Influences of Off-Axis Sources

To quantify the effect of sources not directly framed by the camera, a light source of uniform luminance (1035 cd/m^2) is positioned behind a dark target on a lateral movable support. The experimental setup is shown in Fig. 4. The luminance of the target versus the angle between the normal to the target and the line connecting the CCD sensor and the luminance source (Φ_1 in Fig. 4) was considered. This situation is very common during street light measurements.

The result of the test is shown in Fig. 5, where luminance values of the target (normalized to the luminance of the source) versus the angular displacement of the source are shown. It is also apparent that a light source, not directly framed by the camera, produces an illuminance on the CCD sensor. The farther the source is from the field of view of the detector, the less is the effect on the CCD. This is a typical behavior in road lighting measurements: The luminance of a target on the road surface is measured at night in the presence of several not framed luminaries.

V. Linearity Check

Linearity has been checked for about 37 000 pixels of a central zone of the CCD matrix. They were excited by a source of a uniform luminance, variable from 1.2 to 40 000 cd/m^2 with a relative uncertainty of 0.1%. Even if the optical system has several diaphragm apertures, the linearity was verified under the condition of f/16. The results obtained can also be considered partially valid for the other diaphragm values, provided that the gain value is opportunely scaled.

To estimate the repeatability of the instrument, three frames of the luminance source were correlated with the luminance values of the standard source. A good response was found, as shown in Fig. 6. To emphasize the discrepancy from linearity, the mean square linear interpolation of the data was considered: The maximum error (considered as the dispersion of the three measurements) relative to the maximum measured luminance is about 0.5%.

The errors relative to the read luminance are less than 5% if the average linearity factor is used to interpolate the data, instead of the mean square method. For the two approximations, Fig. 7 presents the absolute errors normalized to the maximum read luminance versus the standard luminance.

TABLE I
Luminance Error Caused by an Incorrect Focusing: Focusing Distance 2.5 m, Diaphragm Aperture f/4

focus distance	Luminance error
∞	3 %
2,5 m	0 %
2 m	13 %
1,5 m	55 %
1 m	60 %
0,60 m	75 %
0,45 m	80 %

TABLE II
Luminance Error Caused by an Incorrect Focusing: Focusing Distance 15 m, Diaphragm Aperture f/4

focus distance	Luminance error
∞	0,7 %
60 m	0,2 %
15 m	0 %
7 m	2,8 %
3 m	80,6 %
2 m	93,1%
1 m	98,5 %

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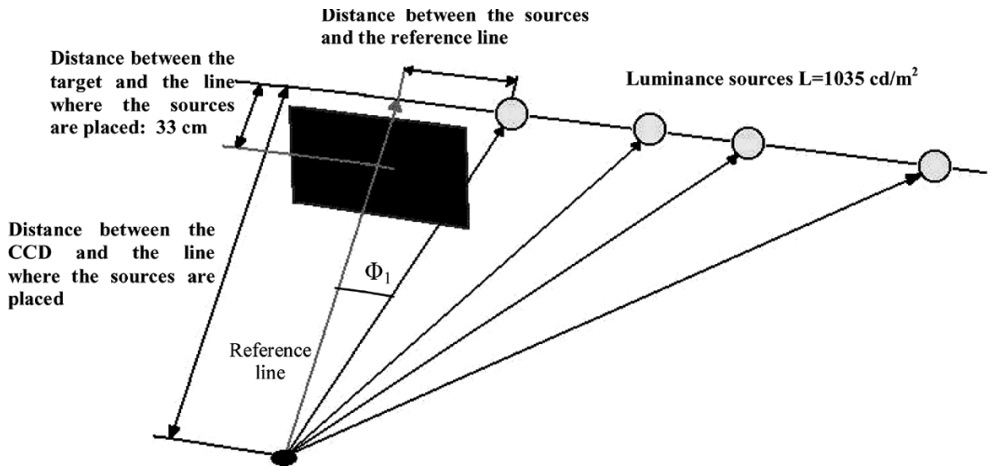

Fig. 4. Road lighting measurements set up.

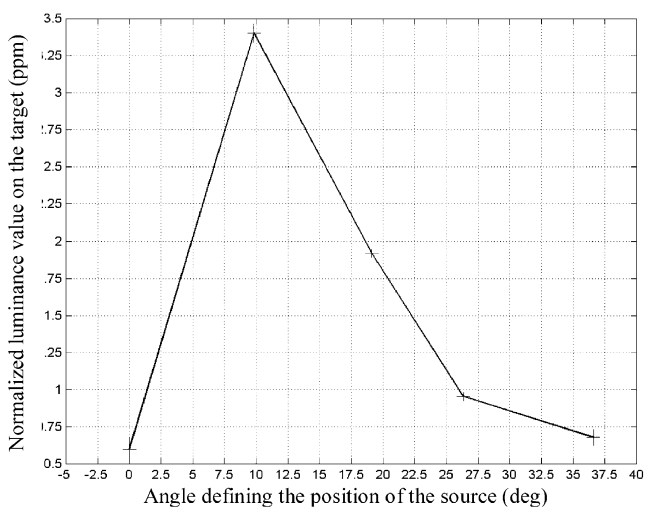

Fig. 5. Effect of light sources not included in the framing field on the luminance of the target.

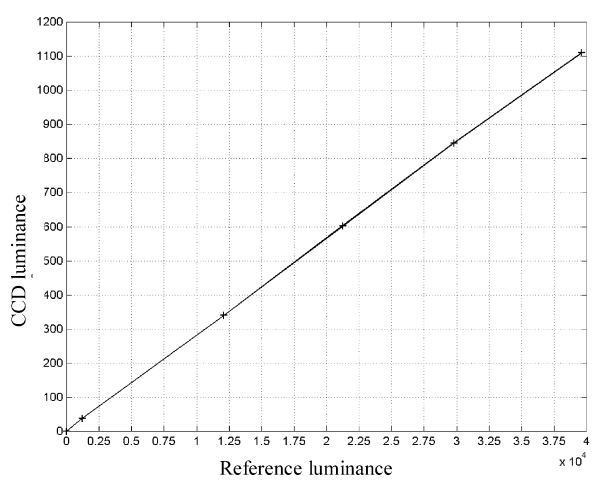

Fig. 6. Linearity test.

VI. Pixel Saturation and Blooming

When light shoots the CCD for a too long time, the charge accumulated into a pixel can exceed its ability of storing it (called full-well capacity). The exceeding charges move to the adjacent pixels: This effect is called blooming. If blooming is present, an error arrives in the evaluation of luminance: Fig. 8 shows the same source shot at different exposition times.

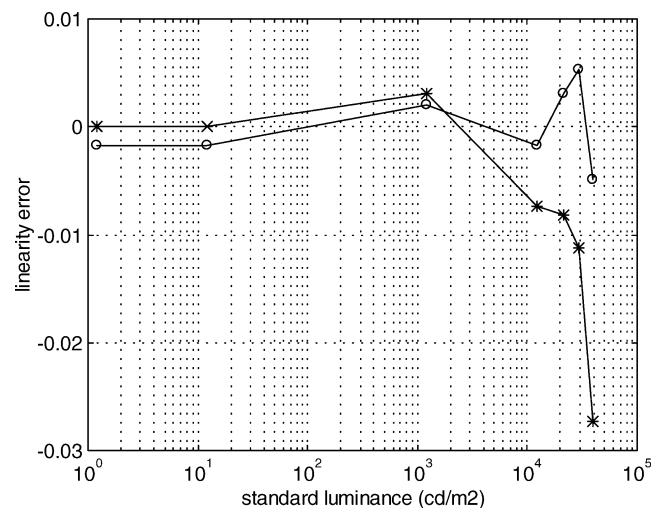

Fig. 7. Errors with respect to the minimum square error interpolation (∘) and to the interpolation with the mean gain (∗).

This effect is particularly important when the luminance of a dark target must be evaluated and there is a very bright surface or source in the frame. The object is dark and a long integration time is necessary, but because of the source, some pixels can be saturated. This situation is quite common in street lighting measurements. To evaluate the luminance of the scene correctly, the quantification of the blooming effect is necessary.

A uniform luminance source of 1035 cd/m^2 was placed on a black background and framed with the CCD camera under test. The aperture $f/4$ was used to simulate a situation analogous to street measurements (Fig. 8). Three acquisitions were recorded for twelve different integration times. The results, as the number of counts along a central column of the CCD matrix, are shown in Fig. 9. The limits equal to 10%, 15%, and 25% of the saturation value are also shown in the same figure. For integration times longer than 1 ms, the effect of charge dispersion from the central pixels toward the adjacent pixels is clearly shown and

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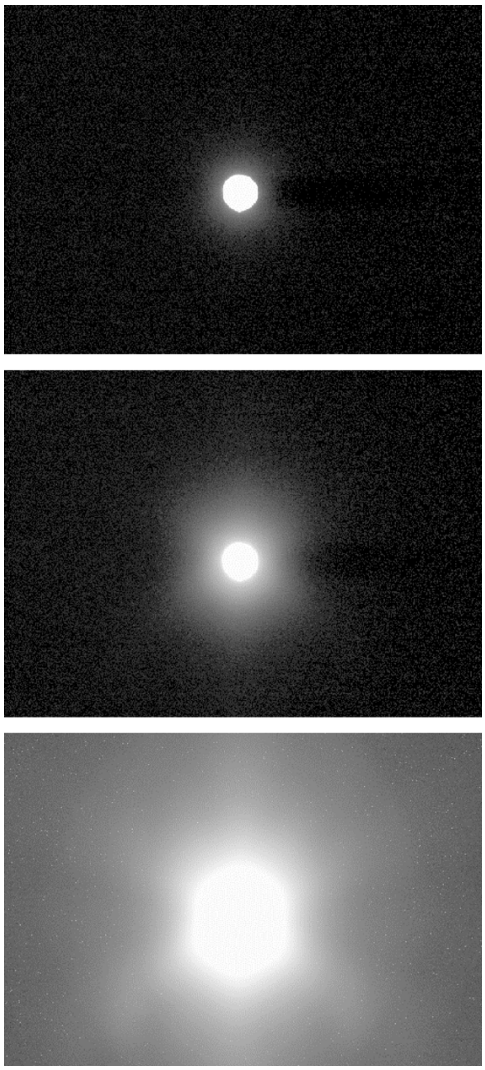

Fig. 8. Blooming effect depending on the integration time for the analyzed device. Integration time 40 ms (top). Integration time 400 ms (middle). Integration time 15 s. (bottom).

is stronger as the integration time increases. Four areas can be identified: 1) the source circle (in the center); 2) the area where the effect goes down to 25% of the saturation value; 3) the area where it decreases to 15%; and 4) the area where it decreases to 10%. The dimensions of these areas can be used to evaluate the errors in measuring the luminance of objects close to an intense source. When the integration time of the electronic shutter is quite equal to the reading time of the CCD, other effects could appear (see 0.1 ms in Fig. 9). This situation is not analyzed here, the application of interest always requires an integration time greater than 20 ms (see Section III).

VII. Dark Frame

Even if a CCD is not exposed to a light source, the output signal of each pixel is not zero, due to noise of both the CCD sensor and of the acquisition electronics. The CCD image obtained when the sensor is not exposed to light is called the dark frame. The counts of each pixel can be considered only due to the noise. Fig. 10 shows the average values of the dark frame

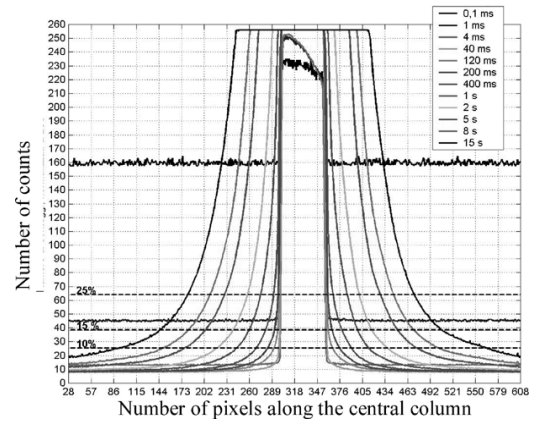

Fig. 9. Blooming effect.

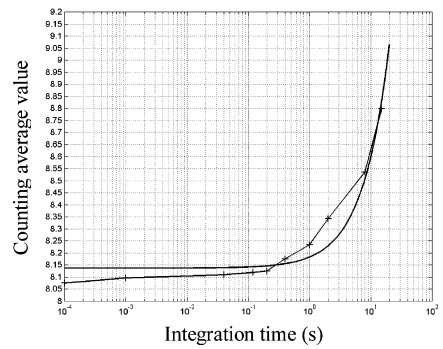

Fig. 10. Dark current versus the integration times.

counts versus the integration time. The uniform values at integration times shorter than 1 s are due to an internal algorithm of the control software of the CCD camera; it is able to compensate partially the effects of the thermal noise. The values at the shortest integration times are mainly due to the noise of reading electronics: It is about 3% of the maximum measurable luminance (the camera has an 8-bit A/D converter).

VIII. Conclusion

The paper shows the experimental procedure used to characterize a commercial CCD camera for luminance measurement in a road lighting plant. In order to calibrate it and to evaluate its measurement uncertainties, several tests have been carried out. The camera has been checked for several aspects closely connected with its measurement application: road lighting measurement. As commercial CCD cameras could show low metrological performances, the best solution to improve the measurement accuracy is to study how the camera behaves in its typical measurement conditions. *Ad hoc* corrections and attentions can be used so as to reduce the influences of the dark noise, the blooming and the optical system nonidealities (especially ghost images). In the presented case, the above practices allow obtaining an overall uncertainty of 5%. A nonoptimized measuring procedure could cause the uncertainty to grow up to about 10%. The improvements in the global measurement uncertainty, obtained when the corrections are applied, can be considered proportionate to the technical characteristic of the device and suitable for lighting engineering applications.

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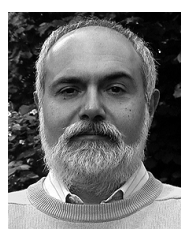

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