

Radiance source for CCD low-uncertainty absolute radiometric calibration

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Abstract. A radiant source for CCD absolute radiometric calibration based on an integrating sphere externally illuminated by a dye laser has been developed. A rotating diffuser has been used for speckle reduction. The field uniformity has been measured at several distances from the exit port, and compared to the predicted radiance of a lambertian disc.

Introduction

In addition to their wide use as imaging systems, CCD cameras would be a very interesting measurement instrument for optical radiation if the measurement uncertainty was kept low. A great part of the difficulty to do that lays in obtaining a radiant source able to produce an uniform irradiance over all the pixels (when the camera is used without its objective) and whose radiance be accurately predicted¹ (when the objective is in place) at the radiometric calibration stage. Some previous works done in our laboratory² have shown that an integrating sphere externally illuminated by an incandescent lamp gives very good results regarding pixel irradiance uniformity and accurate predictability of its radiance. However this source provides low power for spectral calibration which is a major disadvantage. To avoid this problem the incandescence lamp can be replaced by a dye laser, increasing the available spectral power density.

This work describes the key elements of a radiant source formed by an integrating sphere externally illuminated by a dye laser to obtain an uniform and predictable radiant source as well as the uniformity of the radiation field as a function of the distance to the sphere's exit port. Moreover, the emission of the exit port has been modelled by assuming an uniform lambertian disc. The goodness of this model has been tested by comparing the irradiance field uniformity predicted by the model to the one measured at several distances of the exit port.

The irradiance produced by a lambertian disc at a distance is given by an integral equation that has to be solved numerically. A series development of this equation has been done, and the irradiance calculated from it has been compared to that obtained from the numerical integration. The agreement between both values is very good in the distance range where the CCD calibration can be done. This result allows easily to predict the irradiance produced at any point away from the source, that is interesting in radiometric calibration.

Radiance source description

This source consists of a 50 cm diameter integrating sphere externally illuminated by a power-stabilized dye laser. A rotating diffuser is located for reducing the speckle of the laser radiation^{3,4}. We have checked that the speckle

noise is reduced to a negligible level by rotating the diffuser at very low frequencies. However, we had to increase the rotation frequency in order to avoid the instability due to the own rotation movement. Behind the diffuser, and before the entrance port, a 3 cm focal length lens is placed in order to focus inside the sphere the radiation diffused by the diffuser. Varying the distance from the diffuser to the lens the spot size of the radiation impinging the sphere is varied. The sphere is used without internal baffles, because the CCD will be calibrated at enough distance for avoiding radiation from direct incidence and first reflection.

Field uniformity

The field uniformity at the exit port was measured to check whether the emission could be assumed as the emission of a lambertian source. With this purpose, it was scanned by a photodiode mounted over a XY displacement system, controlled by a stepper motor. This scan was done at three different distances from the exit port (7.3 cm, 11.8 cm and 20 cm). For the three distances an irradiance distribution of concentric circles was obtained, according to the exit port geometry. The smaller the distance, the larger the non uniformity produced by this irradiance distribution. The uniformity, defined as the ratio between the standard deviation of the measurements and its mean value, inside a circle 4 mm in radius is shown in the first column of table I.

Table 1: Experimental and theoretical results on field uniformity at distance z from the sphere's exit port.

z (cm)	Experimental uniformity (%)	Theoretical uniformity (%)
7.3	0.00657	0.00580
11.8	0.00555	0.00549
20	0.00237	0.00225

These results were obtained with the laser beam focused over the internal wall of the sphere. There are signs in the literature that point out a field uniformity dependence on the size of the spot on the sphere wall at the first incidence on the sphere⁵. The distance from the diffuser to the lens was varied for having several spot sizes. In figure 1, it is represented the relation between the irradiance over an infinitesimal surface located at a distance 'a' from the optical axis (E_a) and the irradiance over an infinitesimal surface located onto the optical axis (E_0). The error bars represent the standard deviation of all the measurements that are placed at a distance 'a' of the geometrical center of the irradiance circular distribution. For clarity, only those corresponding to the widest spot are represented in the plot. They are representative of the other cases. It can be observed that the difference due to spot size at first reflection is smaller than these error bars. So,

we have proven that field uniformity is independent on the spot size at first reflection.

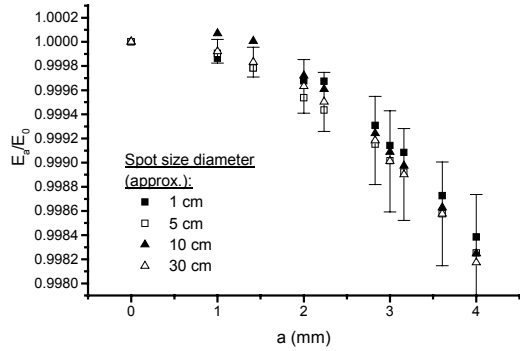


Figure 1: Uniformity experimental data for several spot sizes at first reflection in the sphere.

Lambertian disc model

As the radiance of a source depends on its geometry and it is independent on its topography⁶, it can be assumed that, if the internal coating of the integrating sphere (BaSO₄, in this case) is perfectly lambertian, the emission of the exit port can be modeled with a lambertian disc. According to figure 2, and the relation

$$E = \int_{A_0} dE = \int_{A_0} L dA_0 \frac{\cos^4 \theta}{z^2} \quad (1)$$

where A_0 is the exit port area and E is the irradiance in a point located at a distance 'z' to the disc, it can be written:

$$E = Lz^2 \int_0^{2\pi} d\varphi \int_0^R \frac{r dr}{(z^2 + a^2 + r^2 - 2ar \cos \varphi)^2} \quad (2)$$

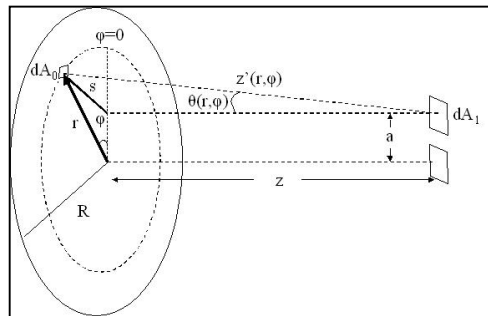


Figure 2: Irradiance produced by a lambertian disc over an infinitesimal surface.

With this equation it is possible to know the irradiance over all points. Although the integration could be numerically solved, we did an approximation based on a Taylor expansion, valid only for negligible 'a' values compared to 'z'. This approximation is written as:

$$E = \pi L \left(\frac{z^2}{z^2 + a^2} \right) \left(\frac{z^2}{R^2 + z^2 + a^2} \right) \times \left[1 + \left(\frac{aR}{R^2 + z^2 + a^2} \right) \left(3 + \frac{R^2}{z^2 + a^2} \right) \right] \quad (3)$$

In figure 3 the comparison of this approximation to the exact result is shown.

After this equation the uniformity can be calculated inside an 'a' radius circle, at a distance 'z'. It was

calculated for the same distances of the previous section, and the results were compared to the experimental ones. The concordance is good, as can be seen in table 1. The experimental uniformity is always higher than the theoretical one, probably due to the temporal noise. Anyway, the maximum difference between both uniformities is something less than 13%, that is produced in the 7.3 cm case.

The goodness of the comparison allows to conclude that the developed radiant source radiates as a lambertian disc, therefore, in a predictable way.

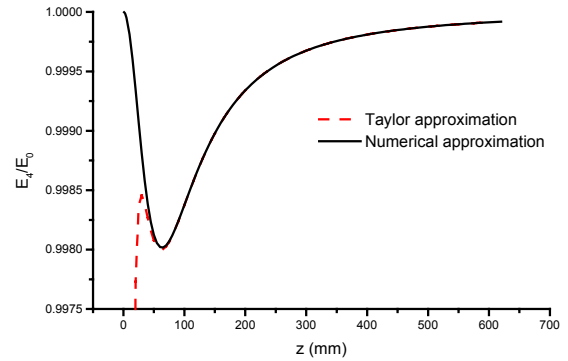


Figure 3: Comparison of Taylor approximation to the exact result.

Conclusions

A radiant source for CCD absolute radiometric calibration has been developed. This source is based on an integrating sphere externally illuminated by a dye laser. The field uniformity at the sphere exit port has been measured, at several distances from this port and several solid angles of the incident beam. It has been proven that the uniformity results can be explained assuming a lambertian disc model for the exit port. So, the emission of the exit port is predictable, resulting of great importance to do radiometric calibrations.

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