Calibration Procedure for Low-End CCD Cameras

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Introduction

Scientific CCD cameras can be fast and robust instruments for optical measurements. On the other hand, most of reasonably priced scientific CCD cameras are constructed to give rather qualitative than quantitative results. Nevertheless, they can be used for scientific purposes, although with some precautions. In the paper we discuss common inaccuracies of these CCD cameras (section 1), propose calibration and measurement procedures (section 2) and address the often-occurring problem of too small dynamic range (section 3).

1. CCD camera unreliability factors

The quality of a single CCD camera measurement is strongly influenced by several factors, we mention below the most important. For the practical examples a DALSA CA-D4 camera with the following characteristics was chosen:

- 1024×1024 pixel resolution,
- Bit depth of 8 bpp (bit per pixel), what means 256 distinct gray levels [GL],
- Exposure time 50 ms – 1000 ms.

1.1 Dark profile

Dark profile is camera's output under zero illumination, thus it is the constant bias of all measurements taken with the camera. As the dark profile is strongly temperature-dependent and most of low-end cameras are not cooled, all measurements should be taken after stabilization of the temperature of the CCD sensor. The dark profile of our camera at 200 ms exposure time is shown on Fig. 1, while Fig. 2 is a magnification of its fragment. A clear wave-like pattern may be observed, it is probably related to the row arrangement of the CCD cells within the sensor.

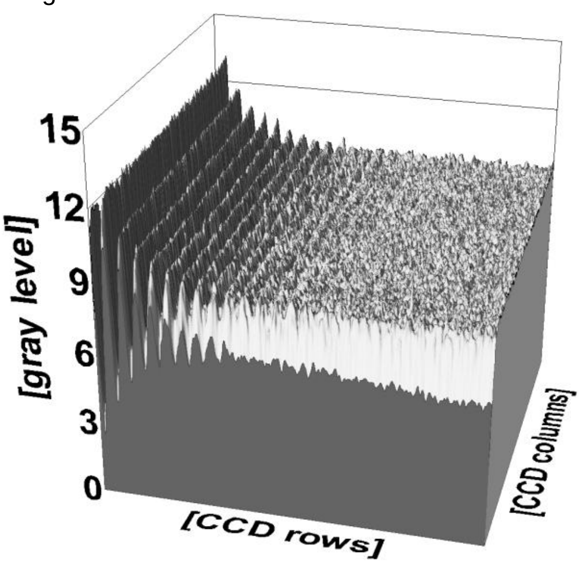

Fig. 1. The camera's dark profile at 200 ms exposure time.

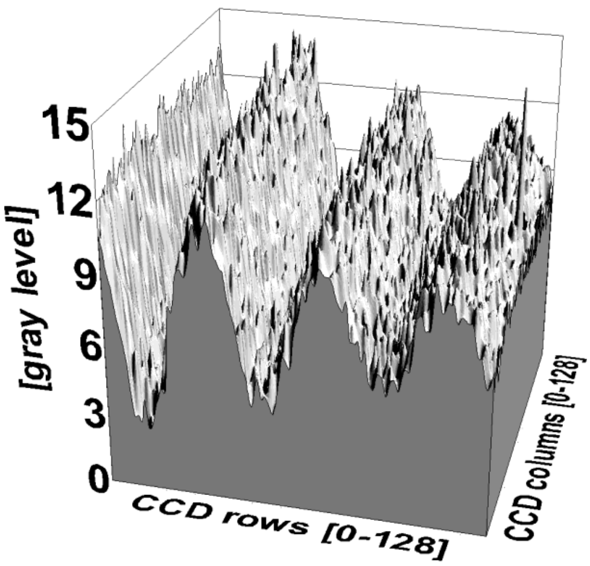

Fig. 2. Fragment of the camera's dark profile at 200 ms exposure time.

1.2 Random noise

Sensor random noise results in differences between successive measurements taken under exactly the same conditions. Random noise may be modelled with a centred Gaussian random distribution and may be characterized by means of its sample standard deviation s. As a measure of random noise the $3s$-level (99.7 % certainty level under normal distribution) will be used. The average $3s$-level of our CCD camera at 200 ms exposure time and under bright illumination is 2.4 GL, what means measurement uncertainty of $\pm$2.4 GL and the real bit per pixel rate reduced from 8 bpp to 6.7 bpp only due to random noise.

1.3 Non-linear response function

Response function of an ideal CCD cell should have a linear relationship between input and output. However, response function of a real CCD cell is rarely linear. Fig. 3 shows, as an example, the relative non-linearity of a typical CCD cell response function of our camera. The average (over all cells) relative non-linearity was found to be 7% at 200 ms exposure time.

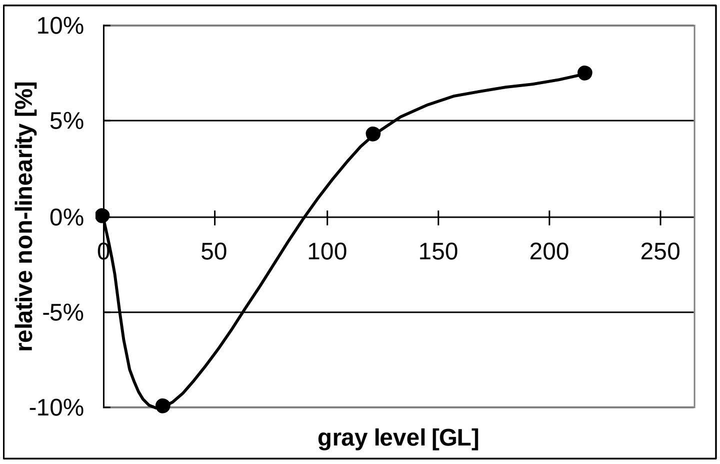

Fig. 3. Relative non-linearity of a typical CCD cell response function (in reference to the relative linear best-fit).

1.4 Non-uniform sensitivity

Non-uniform CCD sensor sensitivity is caused by differences between response functions of its CCD cells. As response functions are also non-linear, the sensor's sensitivity profile may be different at different illumination levels. Fig. 4 presents a relative sensitivity profile of our CCD camera at 200 ms exposure time and under bright illumination.

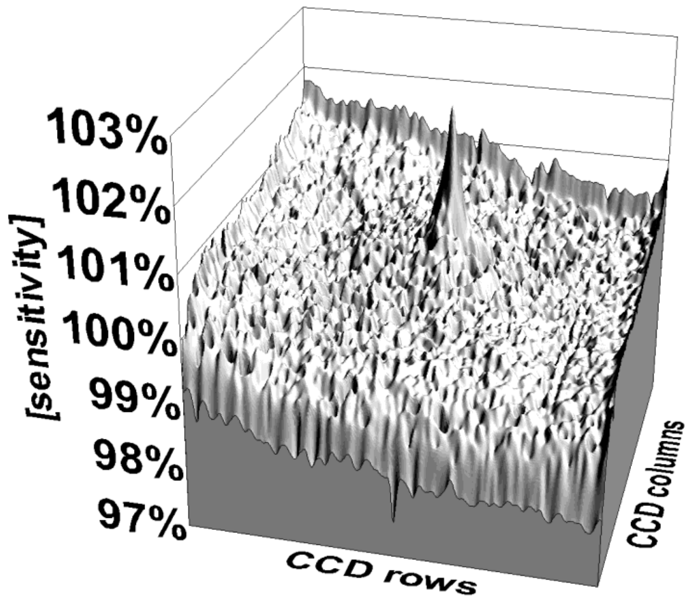

Fig. 4. Sensitivity profile of the camera under bright illumination at 200 ms exposure time. The profile was slightly smoothed to reduce the effect of unreliable cells and noise.

1.5 Damaged CCD cells

In a real CCD sensor some cells may be damaged or dead or there may be some dust and scratches on the CCD sensor's surface generating a remarkable local sensitivity change. Such cells will be called irregular. Measurements of those cells are unreliable and should be approximated based on measurements of neighbouring cells. Fig. 5 presents two defects of our CCD camera identified via sensitivity profile analysis. The total number of irregular cells of our example CCD camera (according to the criteria outlined in section 2.1) was found to be about 3% (approx. 30,000 of the total cell number ~1,000,000). In Fig. 6 irregular cells are represented by black dots. Note the vertical dotted lines on the left hand side of the figure; they correspond to the wave-like structure on the left part of the camera's dark profile (Fig. 1 and 2).

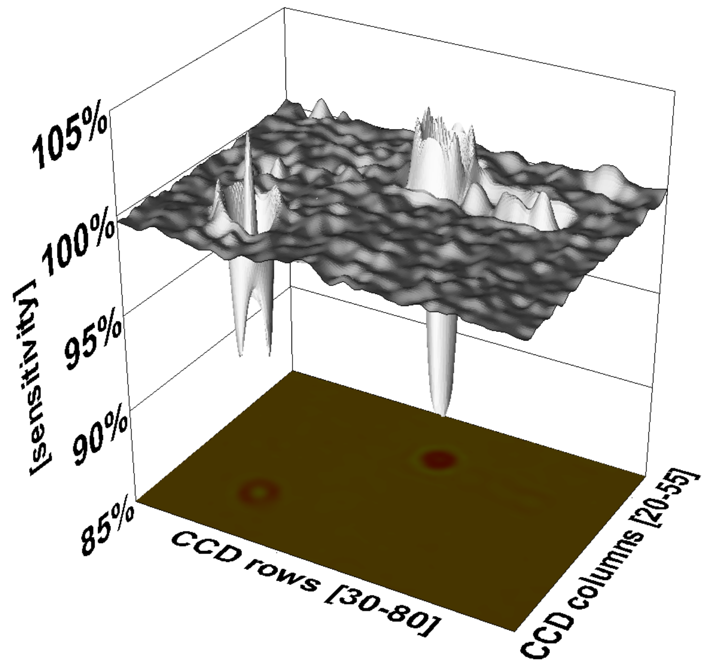

Fig. 5. Fragment of the sensitivity profile of the camera under bright illumination at 200 ms exposure time. The magnification clearly shows two defects of the CCD sensor.

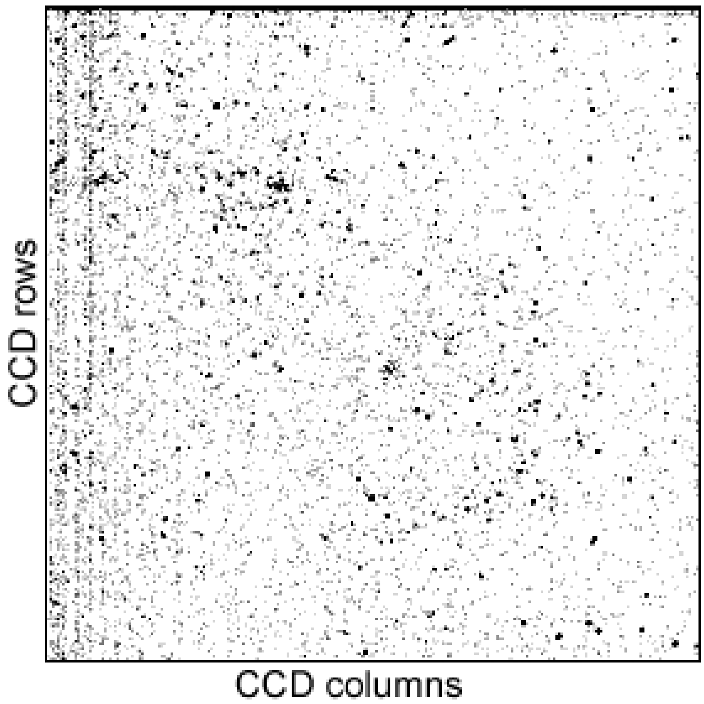

Fig. 6. Irregular cells (black dots). Due to representation limitations, the total number of irregular cells seems to be higher than in reality (3 % of the sensor area).

2. Calibration

The factors mentioned in the previous section strongly influence reliability of measurements taken with a CCD camera. Nevertheless, the measurement quality has been strongly improved with the below-described calibration procedure. As a first step the camera-specific calibration data were collected.

2.1 Calibration data

Following measurement series, each one of sufficient many N measurements (for the camera under test $N = 32$ was used), were made in order to obtain the calibration data:

1) A series of N measurements X_0 taken under completely dark conditions.
2) Several series of N measurements X_i taken under uniform lighting conditions, which may be generated with a huge integrating sphere or a distant light source. For the described camera three measurement series were made, corresponding to approx. 25%, 50% and 75% of maximal CCD sensor lighting level. The relative level of real lighting intensity m_i was measured for each series separately with a calibrated photo-element.

With those measurements the following calibration data were calculated:

1) *Random noise* 3s-level of each cell. For each of the calibration measurement series and each of the cells its 3s-level (tripled sample standard deviation) was computed. As cell's final 3s-level the maximum value was taken.
2) *Dark profile*. The camera's dark profile is an average of the N measurement series taken under completely dark conditions.
3) *Fitted response function* of each of the CCD cells. For each cell the average measurements of the calibration series X_i and the corresponding measured relative lighting intensities m_i form a series of points (m_i, X_i) on the cell's response function. For each cell those points should be fitted with a (linear, quadratic, exponential, etc.) function $x = f(m)$. The inverse function $m = f^{-1}(x)$ is further used to correct the non-linearity of the cell's response function. As for the described camera average non-linearity was of approx. 7%, the quadratic function was used with an average-square-error (and so after the correction the average non-linearity) of approx. 2%.
4) *Irregular cells*. As an irregularity criterion the following may be used: The cell is irregular if: *(a)* Its random noise 3s-level is too high (e.g. more than a given r-percentile of all cells' 3s-levels) or *(b)* the fit quality (average square error) of its fitted response function f is too bad (e.g. the error is more than a given r% or r-percentile of fit errors of all cells) or *(c)* its fitted response function f differs too much from the average fitted response function (or e.g. is not monotonical).

2.2 Measurement procedure

With the calibration data collected, a calibrated measurement may be obtained in the following steps:

1) Take a series of N subsequent measurements and compute their average. The random noise 3s-level is reduced by the factor of $\sqrt{N}$.
2) Subtract the camera's dark profile from the average.
3) For each CCD cell correct its measurement non-linearity with its function $m = f^{-1}(x)$.
4) For each irregular cell approximate its measurement value using the calibrated measurement values of neighbouring regular cells.

As unreliability factors may be wavelength-dependent, the calibration and final measurements should be done with the light source of the same spectrum.

3. Expanding the dynamic range

Another practical problem with the most of the low-end scientific cameras is their restriction to the bit depth of 8 bpp only and thus to the dynamic range of 1:256 at the very best. This dynamic range, relatively small for many applications, may be further reduced considerably by the above-mentioned unreliability factors. It was found that this limitation might be overcome by combining several calibrated measurements taken with different exposure times, according to the following procedure:

1) Make several calibrated measurements using different exposure times.

2) Downscale those made at longer exposure times to match the shortest exposure time measurement. As the exposure time rate may only roughly determine the downscaling factor, use the least-square-error method instead.

3) Merge scaled measurements into final measurement.

The absolute resolution of the downscaled measurements improves with the exposure time (as the 3*s*-levels are also downscaled), so the merging process improves mostly low excited areas. At the most excited sensor areas the absolute resolution obviously equals that of the original shortest exposure time measurement (as only this one is not downscaled).

Note that for each of the calibrated measurements in 1) a separate calibration procedure should be performed and a separate set of calibration data (section 2.1) should be used. Note also that at long exposure times in highly excited areas overexposure (blooming effect) should be avoided.

4. Improvement example

The above-mentioned CCD camera was calibrated according to the procedure from section 2.1. The procedure was repeated five times for five exposure times (50 ms, 100 ms, 200 ms, 400 ms and 800 ms) and five different sets of calibration data were obtained. Some of the results for 200 ms were presented in section 1.

For demonstration purposes light was sent through a 10 m piece of plastic optical fibre to illuminate the CCD sensor in a simple setup. The distance between fibre end-face and sensor was approx. 6 mm. The fibre input face was lighted with a parallel beam under the angle of approx. 28°.

The measurements were done at the same five exposure times as the calibration procedure, at each exposure time an average of four measurements was used to decrease the random noise effects by a factor of two (section 2.2). Fig. 7 shows in logarithmic scale the calibrated and combined measurement.

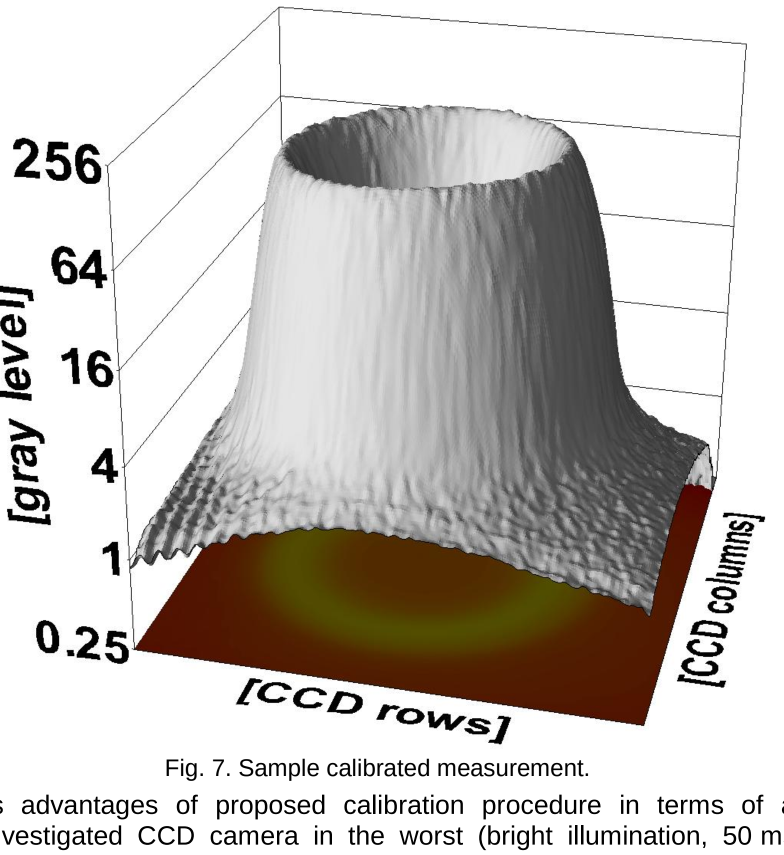

Fig. 7. Sample calibrated measurement.

Table 1 summarises advantages of proposed calibration procedure in terms of average accuracy improvements for investigated CCD camera in the worst (bright illumination, 50 ms exposure time), standard (middle illumination, 200 ms) and best cases (weak illumination, 800 ms). The data relate to quadratic interpolation of cell response function and four-snap average at all exposure times. The average total uncertainty was calculated as the sum of the 3s-level and the average error stemming from the non-linearity.

		Average dark profile	Damaged cells	Average relative non-linearity	Random noise 3s-level	Average total uncertainty
Raw measurement at 200 ms		8 GL	3 %	7 %	2.4 GL	11.36 GL
Calibrated measurement	Worst case	0 GL	interpolated	2 %	1.2 GL	5.04 GL
	Standard case				0.3 GL	1.26 GL
	Best case				0.075 GL	0.24 GL

Table 1. Summary of accuracy improvements due to calibration procedure for the investigated CCD camera, quadratic interpolation of cell response functions and four-snap average at five exposure times.

Conclusions

Common inaccuracy factors of a typical low-end CCD camera were discussed and reliable calibration and measurement procedures were proposed. As the presented measurement procedure is easy to implement and considerably increases measurement reliability, it can be used for the improvement of fast and reliable digital measurements.

Acknowledgements

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