Einsatz digitaler Kameras als Leuchtdichtemessgeräte

Diplomarbeit

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The Usage of Digital Cameras as Luminance Meters

Diploma Thesis

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Kurzbeschreibung

Titel: Einstaz digitaler Kameras als Leuchtdichtemessgeräte

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Zusammenfassung:

Diese Arbeit stellt ein Verfahren vor, mit dem digitale Kameras unabhängig von der Belichtung als Leuchtdichtemessgeräte eingesetzt werden können. Eine Kalibrierung der Kamera mit Hilfe einer OECF-Messung wird durchgeführt und die Leuchtdichte aus den digitalen RGB-Ausgabewerten der Kamera berechnet. Fehlerquellen, welche die Genauigkeit der Messung beeinflussen können, werden aufgezeigt. Abschließend wird die Anwendung am Beispiel der Untersuchung von Verkehrsunfällen erklärt.

Sperrvermerk: Die Arbeit unterliegt keinem Sperrvermerk.

Stichwörter: digitale Kamera, Leuchtdichte, OECF-Messung, Belichtungswert

Datum: Februar, 2006

Abstract

Title: The Usage of Digital Cameras as Luminance Meters

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Summary:

The thesis presents a method for the usage of digital cameras as luminance meters, independent from the exposure. A calibration of the camera is performed with the help of an OECF measurement and the luminance is calculated with the camera's digital RGB output values. Error sources, which can limit the accuracy of measurement, are demonstrated. Finally, the application is explained on the example of accident examination.

Remark of closure: This thesis is not closed.

Key words: digital camera, luminance, OECF-measurement, exposure value

Date: February, 2006

Contents

1 Introduction

Luminance-measuring tasks can be very complex. In many cases the measurement requires a luminance distribution of the total viewing field. Therefore, many measuring points are necessary for the determination of luminance ratios in a whole scene. If a conventional luminance meter, which can only perform point-by-point measurements, is used for such large-scale assessments, the process of measuring will be very time-consuming. Likewise, measuring small details can not be realised with a luminance meter because of its fixed measuring angle, which is usually not small enough.

The approach of image-resolving luminance measurement, which could benefit from the continual development of position-resolving radiation detectors, represents a simplification of such measuring tasks.

Using the image-resolving measuring method proves the following advantages over the luminance measure with a one-dimensional detector:

- Position-resolving representation: all information about luminance in a scene can be recorded in one image. Therefore, the connection between different measuring points can easily and quickly be assessed, both visually and metrologically.

- Less time intensive: a measurement on location can occur much more quickly than with a conventional luminance meter, because all measuring points can be recorded at once within only one image.

- Luminance constancy: because all measuring points can be recorded at the same time, the existing luminance can not be varied during the measurement.

- Reproducibility: the measured image can be saved and permits repetition of the evaluation at a later time.

Luminance measure cameras, which are very reliable in their measurements, are produced by the German firm TechnoTeam [1]. They are manufactured for measuring tasks with very high requirements, for example for measuring the luminance of a spiral-wound filament. These cameras are very precise, because image-processing algorithms and exact mechanical components, which minimize error sources, are used for their production. Due to these high-precision solutions these cameras are very expensive.

The image-resolving measurement method is very advantageous for many luminance measuring tasks, but in many cases not worth the cost.

The purpose of this thesis is to determine if it is possible to measure luminance with digital still cameras (DSC), which are available to everyone at reasonable prices. For this, a calibration of the digital camera is necessary, which should be undertaken according to the standard for the determination of the OECF curve. The calibration assigns the digital output values to different input luminance, in regards to the individual characteristic response of a camera. In addition to calibration, the characteristic response of a digital camera must be examined to see if it remains unchanged for different exposure conditions. The following conditions were taken into consideration:

- The inspection should be performed with cameras of all price classes.
- A calculation of the luminance based on the digital output values of a camera should be found, which can be applied to all digital cameras, independent of the exposure.
- A quick and simple method should be prepared for calibration as well as a subsequent test of certain camera-parameters, which can influence the suitability of the camera for the use of luminance measurements.

Difficulties came about through the use of image-processing algorithms, which influence the camera's characteristic response. As a user one can merely partially influence the image-processing, which is already performed inside the camera. Aside from this, the manufacturers provide no information about their large-scaled development of these algorithms.

In addition, a digital camera does not possess the precision which is expected from a measuring device. Therefore, one can assume that a typical digital camera will not yield such exact measurement results, as would be the case with a digital camera that has been especially manufactured for luminance measurement.

However, there are some measuring tasks, which do not require a very accurate measurement. These mainly deal with assessing the illumination of different scenes. The following are some examples:

- Illumination of work places according to DIN 5035
- Measurements of exterior lighting on buildings
- Luminance measurements for streets and tunnels according to DIN 5044 and DIN 50724
- Assessment of the illumination of escape routes and emergency exits
- Evaluation of the visual range during the investigation of accidents
- Judgement of the uniformity of the luminance distribution on monitor displays

In the following sections, the tests which are to be performed with different cameras will be explained and a calculation is presented. This calculation results in, depending on the digital output values and exposure settings, the luminance value of a selected image area. Furthermore, all possible error sources in regards to the measurement result are discussed and proposals are made to minimize the deviation of the measuring data from a reference luminance meter. Finally, the practical uses and evaluation are explained exemplary to the luminance measurement in the investigation of traffic accidents at night.

2 Basics

2.1 Light Measurement

Light measurements and, especially in this case, luminance measurement is only practicable when the relative spectral response of the measuring detector matches the spectral luminous efficiency of the human eye for photopic vision. This relative luminous efficiency of the eye is represented in the following V(λ) curve.

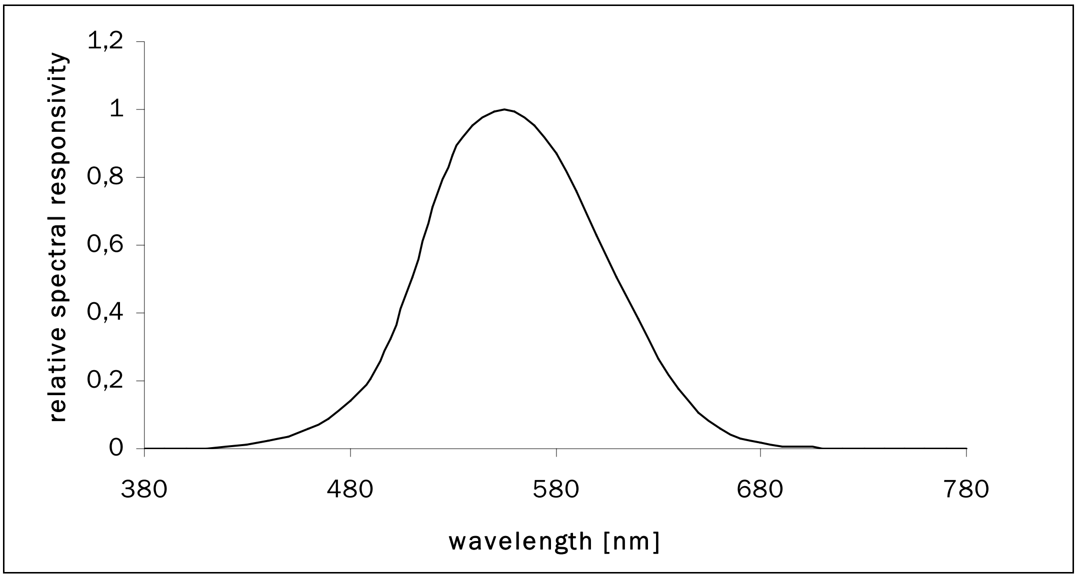

Figure 2.1: V(λ)-curve of photopic vision

Matching the luminance meter of V(λ) is achieved through a filter facing the light sensitive silicon photocell. The spectral transmission of this filter together with the spectral response of the photocell provides the response of the human eye V(λ).

Unfortunately, a digital camera has a poor approximation to V(λ). One major reason for this is the difficulty of selection and fabrication of transmittance filter sets that are suitable for imaging sensors and which, together with the spectral response of the chip, result in the adaptation of the relative spectral sensitivity to the V(λ) function.[2]

2.2 Image Formation

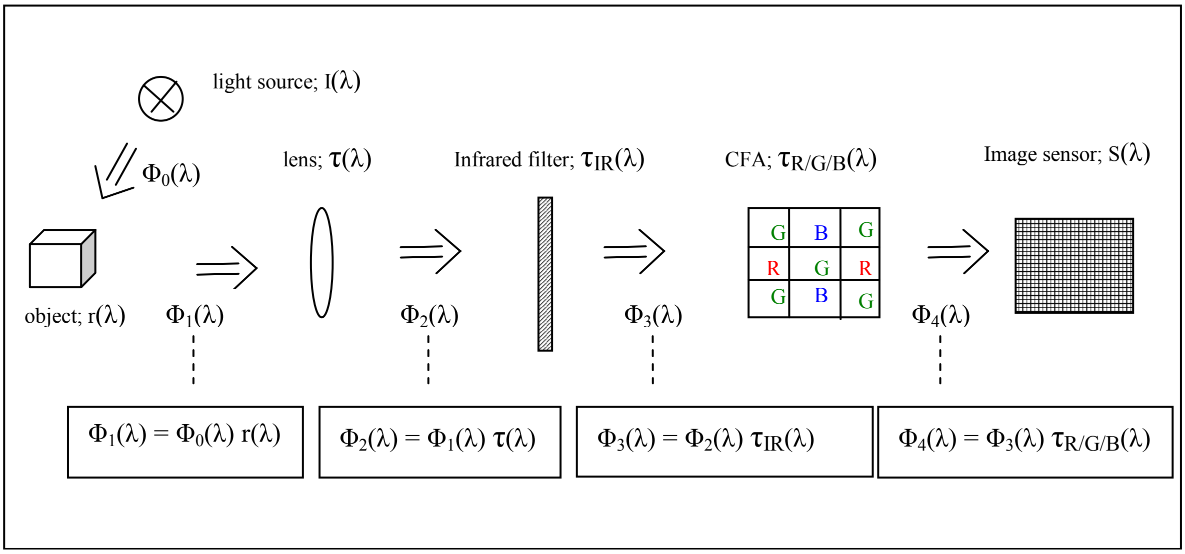

Figure 2.2: Image formation

Figure 2.2 illustrates a simplified process in image formation from an illuminated object onto an image sensor.

A light source with an illuminant spectrum $I(\lambda)$ lights up an object with a reflectance spectrum $r(\lambda)$. If this object is imaged on a chip, the reflected light has to go through a lens with a transmission of $\tau(\lambda)$. The resulting light flux has to go through the Colour Filter Array (CFA). There are different CFA patterns available, but the Bayer array (shown in the figure) is the most popular one. The light flux is decreased by the different spectral transmissions of each filter colour ($\tau_R(\lambda)$, $\tau_G(\lambda)$, $\tau_B(\lambda)$) and by the transmission of the infrared blocking filter $\tau_{IR}(\lambda)$ before it meets on the photosites of the image sensor. The native relative spectral sensitivity $S(\lambda)$ of the detector finally determines the incoming energy in each pixel.

The total light flux which is evaluated by the sensor is [8]:

$$\Phi_{tot} = \int_{380nm}^{780nm} I(\lambda) \cdot r(\lambda) \cdot \tau(\lambda) \cdot \tau_{R/G/B}(\lambda) \cdot \tau_{IR}(\lambda) \cdot S(\lambda) \cdot d\lambda \qquad (2.1)$$

2.3 Camera Image Processing

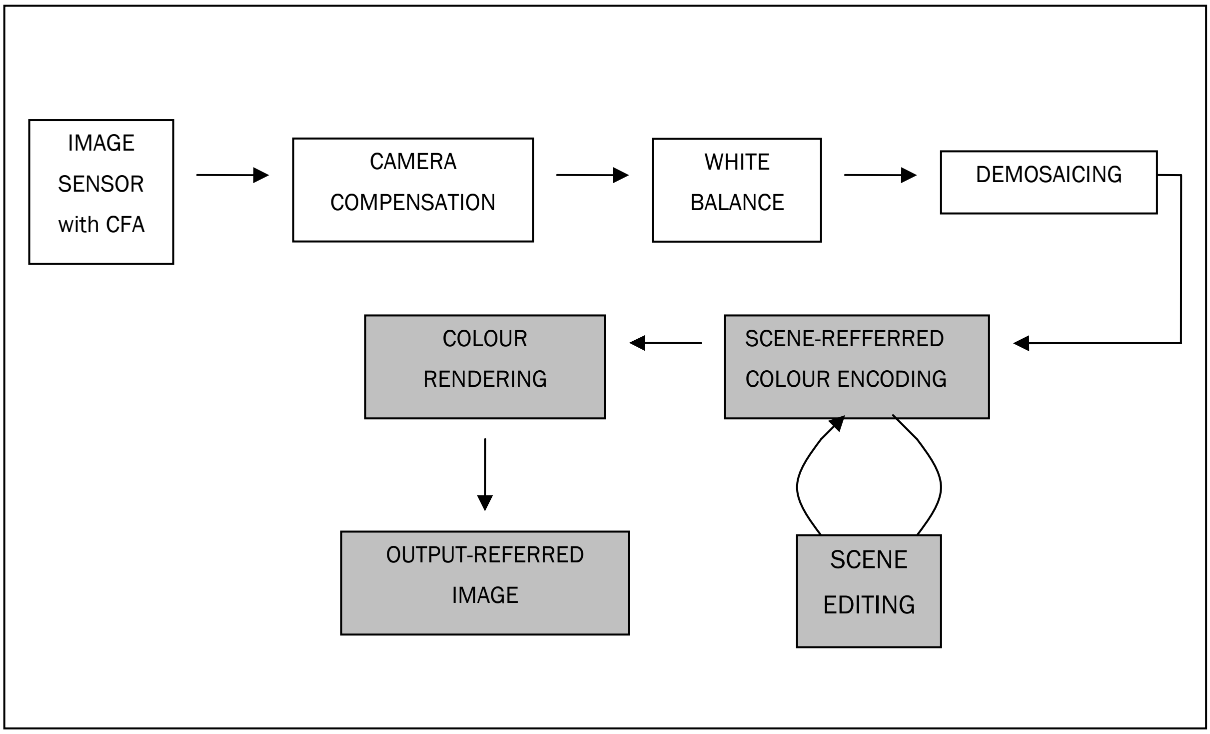

Figure 2.3: intern image processing chain [27]

Figure 2.3 briefly summarizes the steps of internal image processing of a digital camera. The sequence of operations and the location of A/D conversion differ from manufacturer to manufacturer. More details regarding A/D conversion and colour transformations (marked as grey steps in figure 2.3) are explained in chapter 5, which deals with the negative effects when measuring luminance. Errors that occur during the first four steps of the camera processing chain do not affect the luminance measurement or are considered during calibration of the digital camera. Nevertheless, these steps are shortly explained in the next sections.

2.3.1 Spectral Sensitivity of an Image Sensor

A silicon photo detector has a response as seen in figure 2.4. It is not obvious from this depiction that the silicon substrate used in the sensor is also sensitive to infrared light. The human eye is not sensitive to this kind of long-wave light. For this reason an infrared blocking filter has to be located in front of the imager.

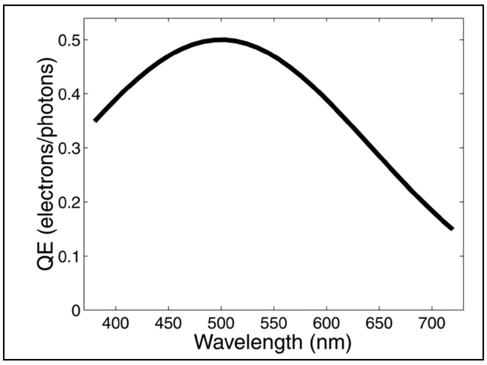

Figure 2.4: spectral response of a photo detector [3]

The final spectral response of a sensor equipped with a CFA is obtained when the spectral response of the silicon chip is combined with the transmittance of the filters.

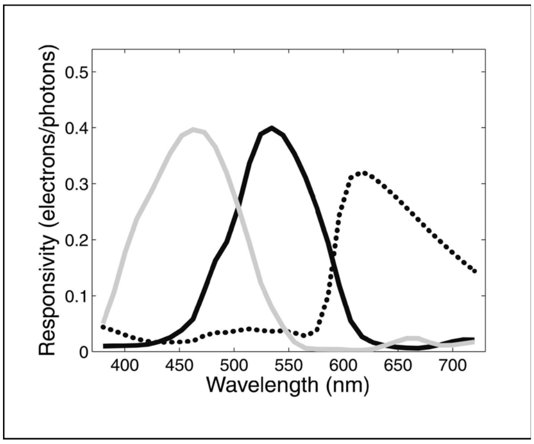

Figure 2.5: spectral response of a photo detector with an RGB-Filter Array [3]

2.3.2 Camera Compensation

Before processing the image data to get a satisfying representation of the captured scene, the raw data obtained directly from the image sensor have to be pre-processed. Such compensations mainly affect noise removal.

One step of the pre-processing is a defect-pixel correction which estimates defect or missing pixels by interpolating the data from their neighbouring pixels.

An image sensor has in general an inherently linear response. Electronics on the sensor can introduce nonlinearities. To correct this effect the raw data has to be linearised.

Another correction step is the compensation of dark current which is achieved by dark frame subtraction.

Flare is caused by the reflection and scattering of light entering the optics of the camera (also see section 5.1.9). This additional unwanted light is relatively uniform.

Flare compensation generally subtracts a fixed percentage (about 4%) of the mean signal energy. [4] [5]

2.3.3 White Balance

The human visual system has the ability to adjust to widely varying colour temperatures. Therefore, colour appearance of the object is approximately preserved when viewed by the human eye. A digital still camera is not in the position to map the white under the capture illuminant to the human sensation of white. The camera needs to be taught to do this with the help of the automatic white balance (WAB) function. The purpose of this camera function is to estimate the illuminant with the help of a special algorithm. Several illumination-estimation algorithms exist, for example the grey-world or white-patch algorithm (for more information see [6]).
After the whitepoint estimation the RGB channels are scaled so that the whitepoint in the image results in equal RGB responses. [4] [5]

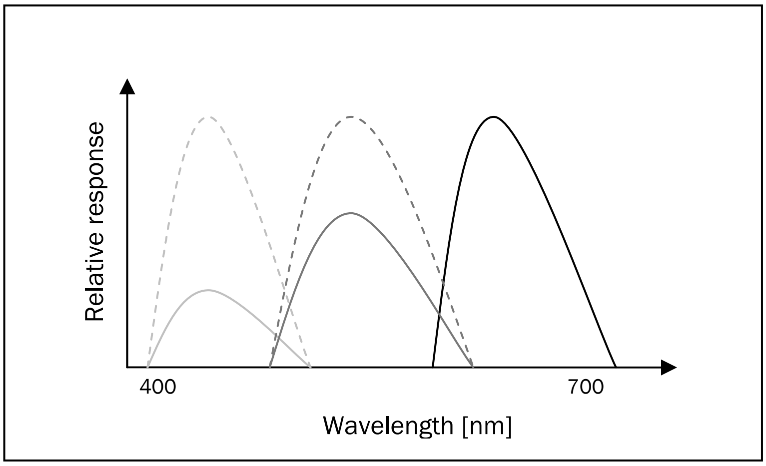

Figure 2.6: Scaling of RGB channels

In section 5.1.6 the relationship between white balance and luminance measurement is explained.

2.3.4 Demosaicing

A camera sensor is equipped with a colour filter array. Most of these arrays are red-green-blue checkered Bayer pattern with respective filters. Each individual pixel is overlaid with a single colour filter, so that three distinct sensor classes exist. The response of the two other sensor classes which are not available for a pixel is estimated for each individual pixel with the help of the demosaicing process. Different

demosaicing techniques exist which make use of the information from neighbouring pixels to determine the residual colour values of a respective pixel.
This process can lead to aliasing artefacts in the final full-colour image. [5]

2.4 Registration of Luminance on an Image Sensor

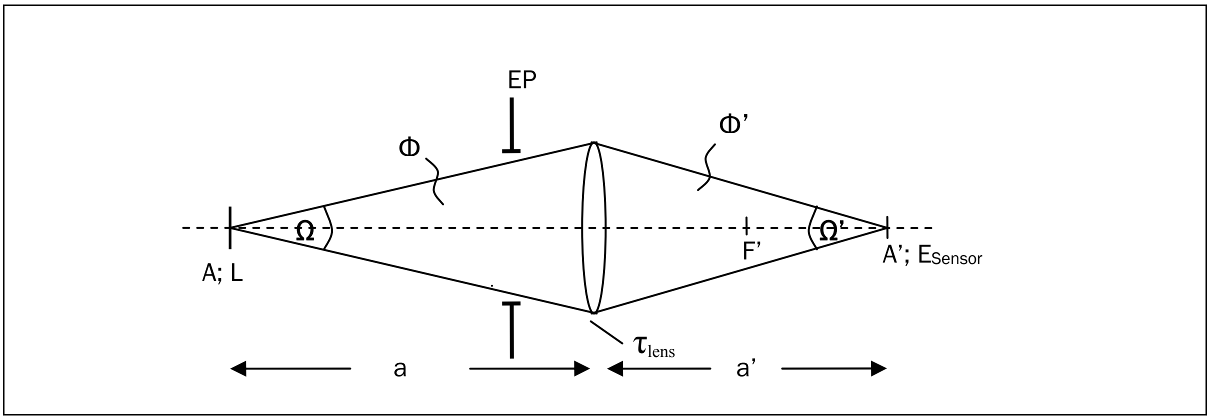

Figure 2.7: Illumination of an area A' by the relevant object-area A with a luminance of L

Figure 2.7 shows how a light flux of a small area (A) falls through a lens (here the presentation is simplified by a single lens) on a small area (A') of the image sensor (example A' can be the area of a single pixel).
The aperture located in front of the lens defines the amount of the incoming light flux and the dimension of the solid angles Ω and Ω'. Normally the mechanical aperture is located between several lenses of the lens. The amount of the incoming light is determined by the image of the aperture which results from an image formation by the front lenses. This image of the aperture is called entrance pupil. The above figure shows only the entrance pupil (EP) in front of the lens.
As mentioned above, the light flux Φ is decreased by the transmission of the lens τ_{lens} and the transmission of the colour filters τ_{fil} in front of the chip. To obtain the light flux Φ' which falls on the pixel-area A', the following equation results [7] [8]:

$$\Phi' = \tau_{lens} \cdot \tau_{fil} \cdot L \cdot A \cdot \Omega \qquad (2.2)$$

The illuminance of an area on the image sensor is defined as

$$E_{sensor} = \frac{\Phi'}{A'} \qquad (2.3)$$

From equation 2.2 and equation 2.3 it can be concluded that

$$E_{sensor} = \frac{\tau_{lens} \cdot \tau_{fil} \cdot L \cdot A \cdot \Omega}{A'} \tag{2.4}$$

Because

$$\frac{A'}{A} = \beta'^2 \tag{2.5}$$

and

$$\frac{\Omega}{\Omega'} = \beta'^2 \tag{2.6}$$

it follows that

$$E_{sensor} = q \cdot L \cdot \Omega' \tag{2.7}$$

with

$$q = \tau_{lens} \cdot \tau_{fil} \tag{2.8}$$

Equation 2.7 shows that the signal detected on the image sensor E_{sensor} is proportional to the luminance of the captured object-area. The solid angle Ω' increases with the widening of the entrance pupil and thus, the signal detected by the pixels increases as well.

2.5 Photographic Exposure

The photographic exposure H is defined as the product of image illuminance E_{sensor} and exposure time t. As mentioned above, the image illuminance depends on the size of the entrance pupil. Therefore, controlling the amount of incoming light on the sensor is achieved within a camera by controlling the exposure time and the aperture size.

2.5.1 Exposure Control

The control of exposure in cameras is a process which has to occur before the shutter is released. In most digital cameras light metering takes place on the image sensor. However, the exposure detector may just as well be separate, for example if a silicon photo diode (SPD) is used as the detector. In most cases today the image sensor is used as the ambient light detector and a SPD detector is used for flash metering. [9] Because the image sensor is a two-dimensional detector an analysis of the scene by evaluating the distribution of luminance is possible. For this kind of light metering, called matrix metering, the image sensor is divided into several blocks. In each of these segments the average luminance signal is measured. The resulting data are weighted differently and then combined to form a measure of exposure. Thus, the determination of exposure value (details see next section) depends on an algorithm, which may differ from manufacturer to manufacturer. [5] [9]

2.5.2 Exposure Value

According to ISO 2721 [10], the nominal exposure in the focal plane of an automatic camera should be

$$H_{sensor} = \frac{H_0}{S_{ISO}} \quad ; \text{ with } H_0 = 10\ lxs \tag{2.9}$$

This means that with a sensitivity of ISO 100 (S_{ISO}) the exposure on the sensor amounts to 0.1 lxs. The constant exposure in the focal plane differs only from the ISO speed setting.
By using the energy measured by the light-metering system of a camera, a combination of aperture and shutter time has to be calculated, which results in the defined exposure H_{sensor}.
Several combinations of exposure settings exist to obtain this exposure, which are expressed by the exposure value (EV).

$$2^{EV} = \frac{k^2}{t} \tag{2.10}$$

Each single value represented by the exposure value combines shutter time (t) and f-number (k) combinations which result in the same exposure (at unchanged light conditions and the same ISO speed setting).
Therefore, the exposure value depends on the amount of incoming light and the defined exposure in the focal plane, which again depends on the ISO speed setting.

2.5.3 Exposure Time

The exposure control of a camera system changes aperture size and/or the shutter speed to capture the whole object contrast of a scene.

The shutter speed determines how long the sensor or film is exposed to light. There are two kinds of shutters, mechanical and electronic.

The mechanical shutters are placed in front of the light sensitive detector (called focal plane shutter) or within the lens body (called central shutter, which today is only used in medium and large format lenses). The shutter opens and closes for a period of time determined by the shutter speed adjusted by the camera.

An electronic shutter works completely different. Exposure control gates are implemented on the light-sensitive cells on an image sensor. The photodiodes on the chip are illuminated permanently, because there is no mechanical light-protection. These generated electrons are discharged if there is no need for an exposure. When starting exposure, the shutter control gate divides a certain amount of electrons into a light shielded area, depending on the shutter time setting. Therefore, electronic shutters can only be implemented on Interline and Frame-Transfer sensors which have such darkened fields on the chip. The readout process of the collected charge can start while the light sensitive photodiodes are again illuminated with light. All digital single lens reflex cameras (dSLRs) are equipped with full-frame sensors, which do not have such darkened areas. Full-frame or similar large-sized chips with a corresponding resolution need the whole chip surface for image formation. Therefore dSLRs can not be equipped with an electronic shutter. [11]

An electronic shutter is a much more precise and reliable device than mechanical shutters are, because they can adjust the shutter time with high accuracy and they have a high level of repeatability.

2.5.4 Aperture

The aperture controls the amount of incoming light through the lens. The size of the opening is controlled by an adjustable diaphragm of overlapping blades.

The f-number on photographic lenses is defined as follows:

$$k = \frac{f'}{D_{EP}} \tag{2.11}$$

Therefore, the diameter of the entrance pupil D_{EP} depends on the focal length of the lens. This means that the same standardized f-number always results in the same image illuminance, regardless of which focal length the lens has, given that the object-luminance is the same.

The standard f-number series is a geometric series with the first term 0.5 and the multiplicative factor for the next step is $\sqrt{2}$. This standard scale markings are divided into half or third steps. These are calculated with the factors $\sqrt[4]{2}$ or for third subdivisions $\sqrt[6]{2}$, respectively.

The more exactly aperture and shutter are working the more accurate the exposure is. A further parameter which influences a correct exposure is the gain control corresponding to the ISO speed adjustment on the camera (details see section 5.1.3).

3 Test Method

All measurements discussed in this work were performed at the firm Image Engineering. The main tests were completed with four different types of camera.

3.1 Selected Camera Types

3.1.1 Professional d-SLR: Nikon D2X

The D2X is the high-end professional digital SLR camera from Nikon, which was introduced in September 2004. The resolution is defined by 12.4 million pixels on the DX-Format (23.7mm x 15.7 mm) CMOS sensor.
Important new features of this camera include new algorithms especially designed for auto white balance and for the pre-processing of analogue signal data before A/D conversion for all further image-processing. This system achieves a smaller quantisation error than previously. [12]

3.1.2 Prosumer d-SLR: Canon EOS 350D

The Canon EOS 350 D digital SLR camera was introduced in February 2005. It has a newly-developed CMOS sensor with 8 million pixels on an area of 22.2 x 14.8 mm^2. It is the successor of the 300D and has a faster processing speed, better image quality and an increased shooting speed because of the DIGIC II image processor. [13]

3.1.3 Prosumer Compact Camera: Nikon Coolpix 8400

Nikon’s Coolpix 8400 entered the market in September 2004, complete with 8 million pixels on a CCD sensor with a size of 8.8 x 6.6 mm^2. The ISO range from 50 to 400 is very small. In contrast to the Fuji F10, (see next section) with the Coolpix it is possible to manually adjust the aperture and exposure time. [12]

3.1.4 Consumer Compact Camera: Fuji Finepix F10

The Fuji Finepix F10 is equipped with a Super CCD HR sensor with 6.3 million pixels on a sensor size of 7.6 x 5.7 mm^2. An advantage for a consumer camera is the wide ISO range of 80 to 1600. Unfortunately, this camera does not include any options to manually set the aperture or exposure time. This camera was introduced in February 2005. [14]

3.2 Luminance Meter

In use for this work were two luminance meters.

The MAVO-Monitor from Gossen was used for measuring the luminance of the different luminance fields of the calibration test chart. This device is only usable for back lighted or luminous surfaces. The metering capacity ranges from 0.01 cd/m^2 to 19.99 kcd/m^2. It's a colour-corrected meter because its spectral sensitivity is matched to V(λ).

The second meter was a spot luminance meter with an SLR optical system from the firm Minolta. The LS-100, in contrast to the MAVO-Monitor, measures the luminance of reflective surfaces as well. It has a 1° acceptance angle and a TTL viewing system to allow an accurate indication of the area to be measured. The detector is a silicon photocell, which is filtered to closely match the CIE photopic luminance response. The possible luminance measurement ranges from 0.001 to 299 kcd/m^2.

3.3 Camera Settings

All camera settings used during calibration should be reported. Consistent starting conditions will always be maintained; these settings should be adopted for measuring luminance.

The utilized data format is JPEG, due to its very simple operation and the fact that all cameras are able to store such data. The compression should be minimized, thereby reducing the compression error. However a higher compression can only slightly affect the luminance result (see 5.1.11).

In order to get best results, the auto white balancing function should be set (details see section 5.1.6)

Any image improvements (e.g. sharpening, special colour settings) should be disabled.

As no additional light is permitted for measuring luminance, the flash should be turned off.

3.4 Calibration

Before using a digital camera for measuring luminance, the camera has to be calibrated first. The calibration defines which digital output value relates to which luminance input signal. This relationship between scene luminance and digital output levels of an opto-electronic digital image capture system is called opto-electronic conversion function (OECF). The measurement method and data analysis is described by the International Standard ISO 14524 [15]. Here the measurement for camera calibration is equivalent to this ISO standard. The only deviation from this standard is the captured test chart (see figure 3.1). It has 20 patches (instead of 12 as mentioned in the standard) and an object contrast of 10000:1. The high contrast test chart mentioned in ISO 14524 only shows an object contrast of 1000:1. However, most digital cameras are today in position to reproduce an object contrast up to 10000:1. A uniform illumination of this transmission target is achieved through the use of an ulbricht integration sphere equipped with daylight illumination (D55). The temperature (23°C +/- 2°C) remains steady, as required by the standard. When the test image is captured it is important to ensure that the grey fields are located in the middle of the camera’s field of view; this is due to vignetting (details in section 5.1.9). After the proper exposure is determined, so as to ensure saturation in the lightest patch, ten exposures are taken successively. These images are evaluated with a Photoshop-Plugin to get a mean value of at least 64 x 64 pixels of the 20 patches, while the constancy of the exposure of these ten images is simultaneously calculated (section 3.5.1). The presentation of the results in the ISO standard is defined to plot the digital output level vs. the logarithm of input luminance. In this case of luminance measurement it is advantageous to plot the input luminance vs. the digital outputs (see figure 3.2), because a polynomial approximation is calculated due to this resulting curve (see section 4.1).

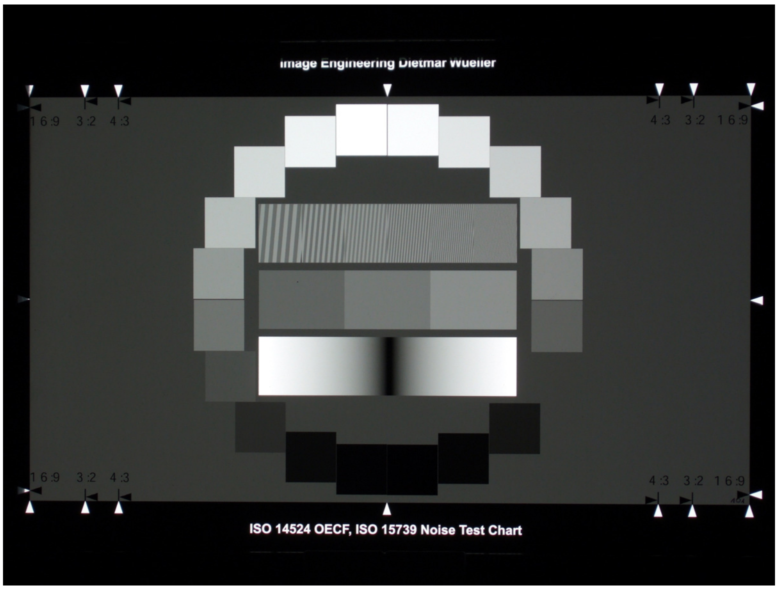

Figure 3.1: picture of the OECF chart with an object contrast of 10000:1

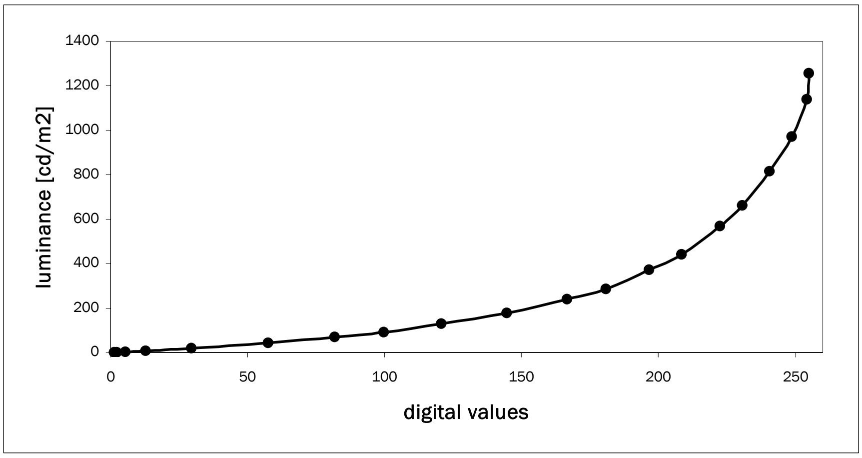

Figure 3.2: OECF curve plotted input luminance against digital values

3.5 Measurements

After calibrating the camera, some tests are carried out to see what happens with the shape of the characteristic line when different conditions, compared to those during calibration, dominate the exposure. Consequent tests were also done to see how cameras react to changes in exposure settings.

3.5.1 Constancy of Exposure

As mentioned earlier, ten pictures were taken during calibration. From these the constancy of exposure is determined by calculating the standard deviation of the digital output values from all 20 patches. On hand the amount of standard deviation, the repeatability of exposure with the same f-stop settings, exposure time and ISO speed can be assessed. Such variations in exposure can be caused as a result of the aperture mechanism or shutter adjustment not always being identical (see section 5.1.4).

3.5.2 Sensitivity

By changing the ISO speed it can be established if channel amplification works accurately. Specifically, it was noted if the camera indicated the correct aperture and exposure time to always obtain the same exposure value.
In fact, the Nikon D2X camera did not produce acceptable outcomes in this category. Therefore the calculation with exposure value can sometimes result in high errors. Details can be found in section 5.1.3 and in section 6.1 where the various cameras are evaluated.

3.5.3 Change in Luminance

The luminance of the target was reduced to allow a closer look at the change in the OECF curve when the exposure value is different from its calibration. Reducing brightness was achieved by suspending a grey foil in front of the chart. As it was to be expected, the shape of the new OECF curve (plotted log luminance against digital values as mentioned in ISO 14524, see figure 3.3) is exactly the same as the calibration OECF, just shifted to the left by a factor.

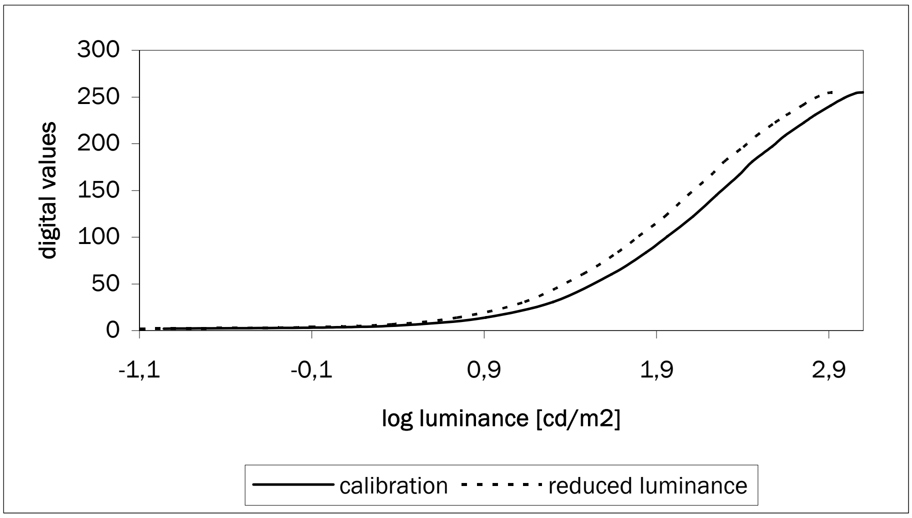

Figure 3.3: calibration curve and the curve obtained by reducing luminance

3.5.4 Over and Underexposure

Luminance measurement should work for under or overexposed images, too. In use it can occur that the luminance of an object is not located in the range of evaluation by capturing the object with automatic exposure. Therefore, the picture has to be purposely taken with an under or overexposure. In these cases, series of exposures of the OECF target were made.
This was usually done by using the EV compensating feature; however, a manual exposure series was made in addition (if possible) to test if the results are more reliable. (For more details see the evaluation of the four cameras in section 6.1.)

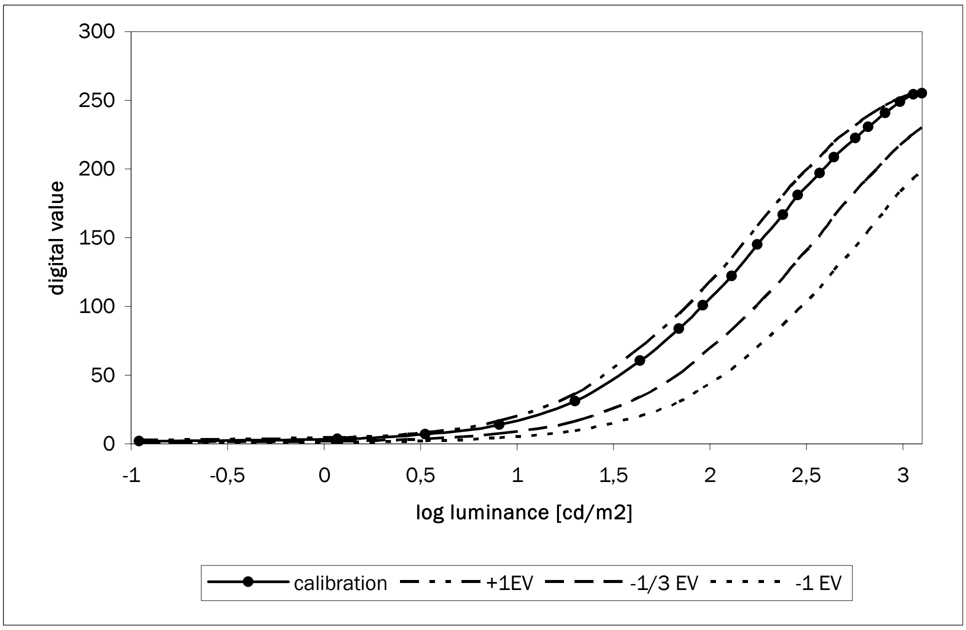

Figure 3.4: curves of over and under exposure of ± 1 EV with EV compensation of the camera

The OECF curves are also of the same shape as the calibration curve, but shifted to the left or right.

3.5.5 Different Objects in a Normal Light Scene

For the last test a scene with different objects was arranged and illuminated with a halogen light filtered to daylight. These objects were unicoloured and had less structure. The luminance of these was measured with the spot luminance meter and compared with the calculated luminance.
Previous tests were all performed with the neutral grey test chart. Therefore it was interesting to see if the luminance measurement works in a normal light scene with a few coloured objects.

As expected, the measurements of coloured objects showed a higher rate of error than those of neutral objects (for details see section 5.1.8).

3.5.6 Calibration of five Additional Cameras

Five additional cameras were also calibrated. Afterwards, a scene with coloured and uncoloured objects with known luminance was captured (see figure 3.5).

This test was done with different intentions. One reason was to enlarge the test field to see if more, or at best nearly all, cameras can be used as luminance measure cameras. Another was to test the process to calibrate cameras and to control the ability of a camera to measure luminance by capturing a measured scene. In most cases it should be sufficient to take only one control photo. It is however recommended that one have a look at the precision of the camera in changing the ISO speed and to test the EV compensation of the camera.

Figure 3.5: test scene with the measuring points

The following five digital cameras were chosen arbitrarily: Canon Digital IXUS 700, Olympus E-500, Fuji Finepix S3Pro, Casio Exilim EX-S500 and Sony DSC-W7.

4 Calculation of Luminance

From the test explained in the previous section it can be determined that the characteristic line of cameras always has the same shape, no matter how the image is exposed or which scene luminance is present. It can be assumed that these curves are shifted from the calibration curve by a factor. This factor depends on the exposure variations. Thus, the obvious solution is to calculate the luminance by using the exposure value. With the difference of the current exposure value to the exposure value of calibration, along with the digital output, the scene luminance can be determined. This calculation method is explained in this chapter.

4.1 Transformation of Output RGB Data into CIE Y Value

The CIE XYZ y(λ) curve is nearly equivalent to the spectral luminous efficiency of the human eye for photopic vision (see figure 4.1). Hence, this value is able to make a direct statement about the luminance of colours.

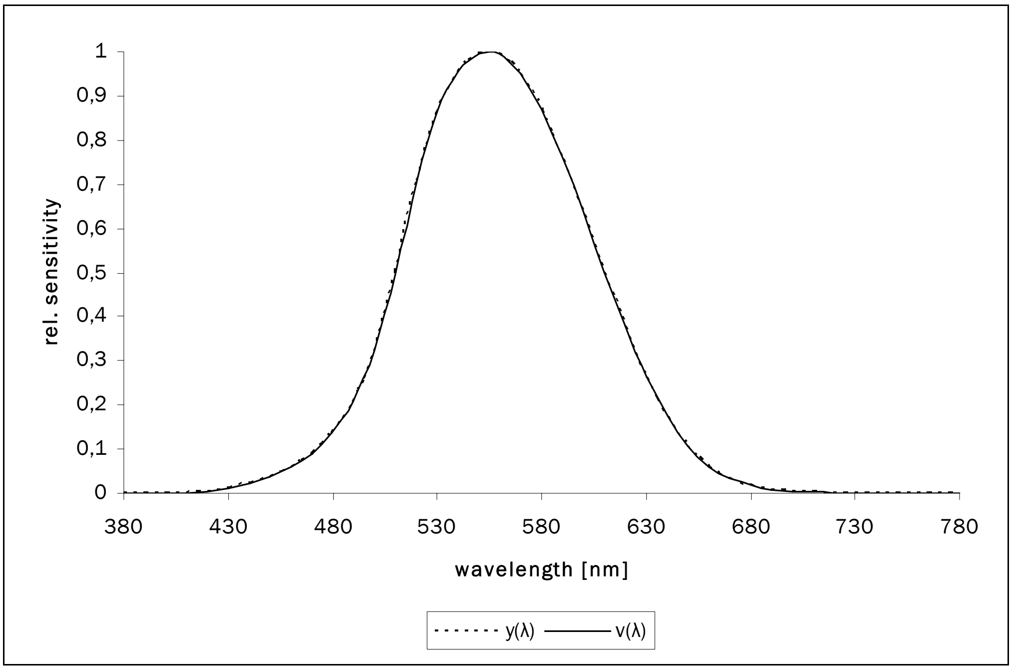

Figure 4.1: comparison with v(λ) curve and curve of CIE XYZ y(λ)

As it is explained in section 5.1.8 the linear RGB data of the camera (device dependent data) are approximated to XYZ colour space by a linear transformation. Further it is to assume that the output data of a digital camera is in the sRGB colour space [16].

Therefore, the CIE Y value can be found by employing the following defined equation on linear sRGB data [16]:

$$Y = 0.2162\ R_{linear} + 0.7152\ G_{linear} + 0.0722\ B_{linear} \quad (4.1)$$

Thus, for calculating only the brightness of a scene with digital output data, linear RGB output values are needed for obtaining the CIE Y value.

The native linear response of an image sensor is not received when measuring the OECF of a digital camera on hand of a JPEG or Tiff image. The nonlinearity of the OECF curve corresponds to a gamma correction introduced in the image processing system of the camera (see section 5.1.8). This gamma correction is performed to compensate the nonlinearity of intensity reproduction of a monitor's CRT. [17]

One consideration for procuring linear data was to calculate the CIE XYZ colour space from the nonlinear sRGB output data by using the transformation mentioned in IEC 61966-2-1 [16].

By applying this calculation to the nonlinear output data the resulting curve should have a linear shape. However, the resulting curves of three of four cameras tested appeared similar to that in figure 4.2.

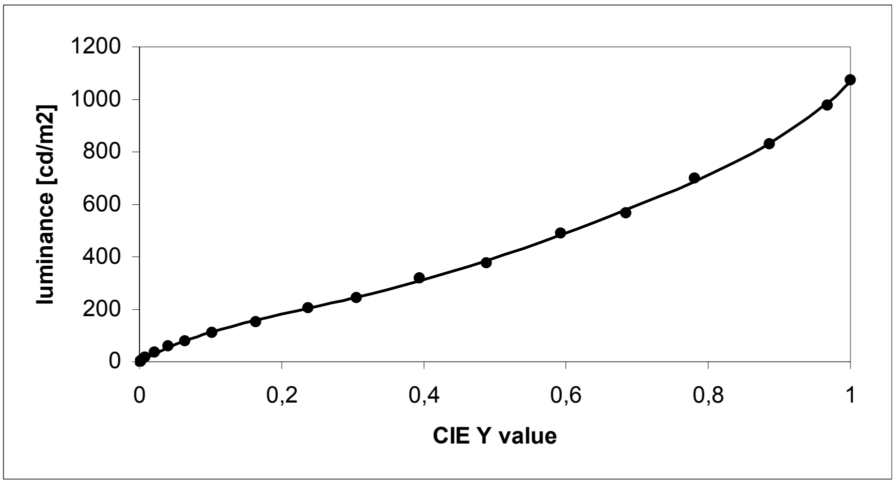

Figure 4.2: curve from Fuji F10 with CIE Y value calculated from sRGB data

Contrary to expectation, the curves are not continuously linear. Especially in the lower digital values, it is recognizable that the gamma value is lower than the sRGB gamma value of 2.4. Many manufacturers come towards customer's desire of getting pleasant pictures out of their camera. They go beyond a gamma correction and apply more of an S-shaped curve on the linear camera data to achieve a pleasing representation of the image on a monitor or print. That means, among other things, that there are still some details to distinguish in dark areas and in conditions of high luminance the manufacterers perform an effect called highlight compression.

Because of the nonlinearity of the resulting curve, this approach is not effective for producing linear data. Each manufacturer has its own method of changing the tonal response of camera data for obtaining pleasant pictures. For example, applying the calculation to the OECF curve of the Nikon D2X produces a nearly linear straight line. The professional dSLR camera does not manipulate the camera data to the extent that the consumer camera Fuji F10 does.

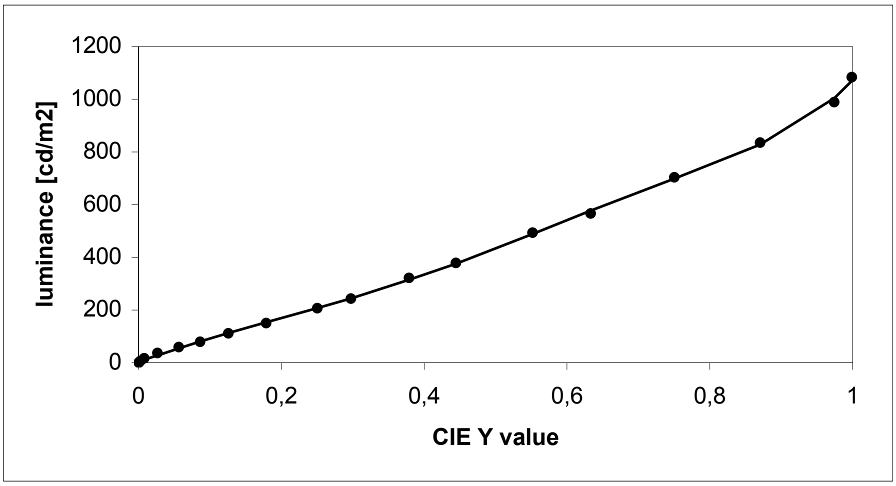

Figure 4.3: curve from Nikon D2X with CIE Y value calculated from sRGB data

In order to derive a method for measuring luminance with nearly all types of digital cameras, it is necessary to have a method for attaining linear output data which can apply to all digital cameras.

The first step is to approximate the curve obtained by the OECF measuring data by a sixth-degree polynomial. This is achieved by the method of the least square. Strictly, this method assumes that the best fitting curve, described by a polynom p of the degree n, is the curve that has the minimal sum of the vertical deviation squared from m data points:

$$\sum_{i=1}^{m} [\, y_i - p_n(x_i)\,]^2 \rightarrow min. \qquad (4.2)$$

It is indicated that this statement leads to a linear system of equations with the following matrix-representation (details in [18]):

$$\begin{pmatrix} x^0 & x^1 & x^2 & x^3 & \dots & x^n \\ x^1 & x^2 & x^3 & x^4 & \dots & x^{n+1} \\ x^2 & x^3 & x^4 & x & \dots & x^{n+2} \\ \dots & & & & & \\ x^n & x^{n+1} & x^{n+2} & x^{n+3} & \dots & x^{2n} \end{pmatrix} \begin{pmatrix} a_0 \\ a_1 \\ . \\ . \\ a_n \end{pmatrix} = \begin{pmatrix} x^0 y \\ x^1 y \\ . \\ . \\ x^n y \end{pmatrix} \qquad (4.3)$$

The coefficients a_n of the polynom can be determined by this matrix-equation.
All further calculations are based on this description of the OECF curve by a polynomial equation.
Afterwards, a linearization of this approximated curve is achieved by creating a look-up table (LUT) with the help of the sixth-degree polynomial. This LUT maintains the nonlinear output data according to the desired linear values. Now, it is possible to calculate the approximated CIE Y value by applying these linear values on the equation 4.1.
Actually, the results from measuring coloured objects should produce about the same rate of error as when measuring neutral objects because of determining and evaluating the approximated CIE Y value adapted by the camera. But in fact, measuring the luminance of coloured surfaces result in a higher rate of deviations than when measuring neutral grey surfaces. On one hand this might be caused because the adaption of camera's linear RGB output data to the standardized colour space XYZ is, dependent on the matrix used for the transformation, a more or less good approximation. And on the other hand there is a preferred colour rendering in the camera's internal image process (see chapter 5.1.8) where users cannot gain insight into its algorithms.

4.2 Calculation with Exposure Value

The calculation of luminance has to be irrespective of exposure variations. The calibration should be taken as a basis for all luminance computations. First, the current output data are assigned to luminance in the calibration curve. As concluded in section 3.5, the new exposure curves are apparently shifted from the calibration curve by a factor. To obtain the current luminance, the determined luminance of calibration is to be multiplied by a certain factor. This factor has to contain the difference of exposure between the calibration and the new exposure.

From equation 2.7 (with the neglect of the constant q) and the definition of photographic exposure (see section 2.5) it follows:

$$H = L \cdot \Omega' \cdot t \tag{4.4}$$

Due to the definition of the solid angle it follows (the variables refer to figure 2.7):

$$\Omega' = \frac{A_{EP}}{a'^2} \tag{4.5}$$

With the simplified assumption that $a \to \infty$ it is:

$$\Omega' = \frac{\pi \cdot D_{EP}{}^2}{4 \cdot f'^2} \tag{4.6}$$

From equation 2.11 it follows:

$$\Omega' = \frac{\pi}{4 \cdot k^2} \tag{4.7}$$

Therefore, equation 4.4 can be transformed in:

$$H = L \cdot \frac{\pi \cdot t}{4 \cdot k^2} \tag{4.8}$$

With equation 2.9 it follows:

$$L = \frac{4 \cdot k^2}{\pi \cdot t} \cdot \frac{H_0}{S_{ISO}} \tag{4.9}$$

Equation 4.9 can be transformed with equation 2.10 into:

$$L = 2^{EV} \cdot \frac{4}{\pi} \cdot \frac{H_0}{S_{ISO}} \tag{4.10}$$

For two different luminance and exposure settings it can be concluded:

$$\frac{L_{new}}{L_{cal}} = 2^{(EV_{new} - EV_{cal})} \cdot \frac{S_{ISO_{cal}}}{S_{ISO_{new}}} \tag{4.11}$$

$$L_{new} = L_{cal} \cdot 2^{(EV_{new} - EV_{cal})} \cdot \frac{S_{ISO_{cal}}}{S_{ISO_{new}}} \tag{4.12}$$

Equation 4.12 represents the calculation of a current luminance in dependence on the current exposure settings and the luminance and exposure settings of the calibration.
To estimate the luminance in a photo the user has to declare its exposure data, such as current aperture, exposure time and the ISO speed. In most cases information pertaining to exposure is stored in Exif data. In addition, the RGB values of the area which wants to be evaluated have to be declared, in order to calculate with the LUT and equation 4.1 the luminance of calibration L_{cal}.

4.3 Problems of Calculation

There are a few characteristics of a camera and its characteristic curve which lessen the simplicity of calculating luminance.

4.3.1 Exif Data

Exif (Exchangeable Image File Format) is a standard file format for storing information, created by JEIDA (Japan Electronic Industry Development Association) to encourage interoperability between imaging devices. The metadata of exposure (e.g., aperture, shutterspeed, ISO speed, date and time of exposure, number of pixels and most of the other camera settings) are stored in the image file in a seperate header.
This feature is very useful for users who want to measure luminance with their camera because it is then not necessary for them to copy the camera settings in an extra file or onto paper.
Cameras store exposure data with varying levels of accuracy in the Exif header. For example, the values included in Nikon's Coolpix 8400 Exif file are more precise than the exposure settings registered by the camera. For example, while the camera indicates an exposure time of 1/30 sec. the Exif data shows a shutter time of in fact 1/38.3 sec. In all cases, calculations with precise values of exposure yield a much better result than when calculating with the values indicated by the camera. Therefore,

the Exif data should always be used for the luminance evaluations, although not every camera's Exif file contains more precise values than the camera indicates. It cannot be excluded, that in rare cases the Exif data deviate from the real exposure data or that there are bugs in the cameras' software which results in completely wrong Exif data (this was the case for the Casio Exilim EX-S500; see section 6.1.5).

4.3.2 Restriction of the Digital Output Values

4.3.2.1 Definition of the Lower Limit

The values obtained during calibration of the camera are afflicted with measurement errors (see section 5.2.1 and 5.2.2). Therefore, it is sufficient to connect the measuring data with a polynomial approximation. In order to get an applicable approximation curve, the deviation from the measured value to the corresponding approximated value should be minimal (see equation 4.2).

Here a sixth-degree polynomial was used for the approximation. This polynomial yields a small deviation from the original data points, except in lower digital values. In this range the polynomial can oscillate. Dependent on the shape of the OECF curve, the polynomial oscillates sometimes strongly and sometimes only insignificantly.

In addition, a test of four different luminance meters shows, that there are especially in the lower luminances high deviations in the measuring results (see table 4.1).

	measure data of the OECF test chart				absolut deviation to MAVO Monitor [%]		
	MAVO Monitor	MAVO Lux	MINOLTA LS-100	MAVO Spot	MAVO Lux	MINOLTA LS-100	MAVO Spot
Step1	0,11	0,21	0,51	1,25	90,73	366,36	1034,83
Step2	1,10	1,15	1,54	2,30	4,90	40,27	108,85
Step3	3,10	3,15	3,89	4,57	1,52	25,52	47,54
Step4	7,50	7,55	8,32	8,51	0,70	10,95	13,43
Step5	18,50	18,57	19,70	19,83	0,36	6,48	7,17
Step6	39,90	39,86	41,10	41,02	0,10	3,00	2,80
Step7	64,10	64,09	62,50	63,78	0,01	2,50	0,50
Step8	84,40	84,23	84,91	84,97	0,20	0,60	0,67
Step9	120,80	120,74	114,63	119,38	0,05	5,11	1,18
Step10	162,10	166,79	158,11	161,23	2,89	2,46	0,54
Step11	224,00	224,49	207,87	221,34	0,22	7,20	1,19
Step12	263,00	262,25	257,28	263,30	0,29	2,17	0,11
Step13	348,00	348,27	326,06	343,02	0,08	6,30	1,43
Step14	409,00	407,01	400,96	410,16	0,49	1,97	0,28
Step15	533,00	532,89	501,32	527,65	0,02	5,94	1,00
Step16	613,00	612,62	601,35	611,57	0,06	1,90	0,23
Step17	764,00	762,62	748,93	761,57	0,18	1,97	0,32
Step18	905,00	903,19	903,13	896,90	0,20	0,21	0,90
Step19	1071,00	1069,98	1067,35	1069,98	0,10	0,34	0,10
Step20	1174,00	1174,88	1176,03	1164,39	0,07	0,17	0,82

Table 4.1: results of the measurements of OECF chart with four different luminance meters

The great difference in the low-luminance steps can be caused by stray light, although the test station was protected against light. The MAVO-Monitor and the MAVO-Lux are not as strongly affected by stray light as the spotmeters Minolta LS-100 and MAVO-Spot, because their measuring head is in close contact with the test chart during the measurement. According to this test it was difficult to establish which luminance meter yields the most reliable result in low luminances.

Because of these problems, the oscillating polynomial and the inaccuracy in measurement of low luminance (which refers to the low digital values), the low digital output values can not be used for a reliable evaluation of the luminance. A lower limit of the digital values has to be determined. Related to the luminance meter test, the minimum digital values are defined with an admissible minimum luminance value at the calibration. This luminance value depends on the desired accuracy. Here, the limit is set at 5 cd/m^2. That means, that the RGB output values of the OECF patch which represents a luminance under 5 cd/m^2 defines the minimal evaluable digital values. These resulting digital values (it mostly concerns the third patch of the test chart) are no more affected by the oscillating of the polynomial, because usually these values are high enough (they result in a digital value of around 10).

4.3.2.2 Definition of the Upper Limit

The restriction of the higher digital values depends on the shape of the characteristic curve. As one can see in figure 3.2 the measuring points are not regularily distributed over the luminance range. The lower half of the luminance range is determined by 15 measuring points and the upper half by only five measuring points. These are too few data points for a reliable approximation.

In the higher luminances the OECF curve is very steep in contrast to the flat part of the curve in the lower luminance range. In the steep part, the luminance area between two digital values is too huge for a reliable evaluation of luminance. This can result in high absolute deviations of the current luminance.

In order to evade this problem, the upper limit is determined by the gradation of the OECF curve. On the basis of the test experiences, digital values from the gradient smaller than 15 should only be used for luminance evaluation. Dependent on the shape of the OECF curve the maximum digital values are located between 225 and 245.

4.3.3 Steps of the Digital Output Values

Due to the different gradations of the OECF curve and the unregular distribution of the digital values, as mentioned above, the absolute luminance can only be determined in steps. These steps are wider in the higher digital values, because of the steepness of the characteristic curve.
Therefore, the absolute luminance can not be calculated continously, because of the finite number of digital values.
In addition, the second variable for calculating the current luminance, the exposure value, results in steps, too.

4.3.4 Exposure Steps

Today most digital cameras are equiped with adjusting aperture and shutter time in subdivisions of one-third. For this reason, the accuracy of the exposure value amounts to third steps as well. Thus, the calculation of the new luminance can only result in steps.
Some digital cameras' Exif data may issue aperture and shutter values which are more accurate than third steps (for example the Nikon D2X). When calculating with these fine-graded values mere minor failures in luminance are achieved.

5 Sources of Error

5.1 Camera Error

5.1.1 Exposure Control

The subdivision of the exposure value into one-third is a relatively rough division. Therefore, the automatic exposure control has to be rounded, for example if the exposure in the focal plane is located between two steps of exposure values. Moreover, it is possible that the algorithm for matrix metering (see section 2.5.1) contains rounding errors.

These are reasons for a possible incorrectly set exposure value, which would result in an incorrect exposure. In this case, the image would be under or overexposed. This effect is compensated by the calculation outlined in section 4.2, so it does not affect the luminance result.

However, a problem with the calculation of the luminance arises when the data determined by the camera's exposure control (f-number, shutter speed and the amplification due to the ISO speed) are not precisely realised. An explanation of this problem follows in the next two sections.

It becomes very problematic if the actual values of aperture, shutter and ISO speed of a digital camera are indicated neither in the camera indication nor in the Exif data. The exposure value is then not equivalent to the digital output data, making it highly probable that deviations from the correct luminance value will result.

5.1.2 Settings of Aperture and Exposure Time

The precision of the adjustment from aperture and shutter are associated with permissible tolerances, as mentioned in DIN 19016 and 4522-1. [20] [21]

The exposure time of the two dSLRs were measured and compared with the time set on the camera. By means of taking a picture of several LEDs which light up one after another with an adjustable frequency, the real shuttertime can easily be determined.

This test shows (the test data can be found in the appendix) that a camera's set shutter time of for example 1/250 sec. in reality amounts to an exposure time of 1/200 sec. This exposure time is equivalent to the subsequent time setting for an

exposure scale divided into increments of one-third. However, this value is still located within the permitted limits mentioned in DIN 19016 [20].
An electronic shutter (see section 2.5.3) can be adjusted much more accurately than mechanical shutters. It is remarkable that with cameras which have an electronic shutter, the exposure time is displayed in the Exif data with very precise numbers (e.g., 1/7.5 sec., 1/28 sec., 1/58 sec.). In this case it seems that the indicated exposure time corresponds with the actual shutter time.
The measurement of the actual area of the entrance pupil requires more effort than measuring the exposure time and will therefore not be performed.
This inaccuracy in shutter adjustment and aperture falsifies the calculated exposure value and consequently the resulting luminance.

5.1.3 Setting of ISO

Defining the ISO speed of digital cameras is similar to the method used to define film speed. The determination of a digital camera's speed is documented in ISO 12232 [19].
Each CCD or CMOS sensor has a native speed. This native sensitivity depends on the basic quantum efficiency of the photon-electron conversion process, the physical size of the pixel and depth of the potential well used to collect the electrons.
If a higher level of sensitivity is necessary for proper exposure than the original sensitivity of the chip, the electrons stored on the sensor are amplified. This amplification is obtained through an automatic gain controller on the chip [5].
Unfortunately, increasing the sensitivity also amplifies undesired noise. As it is to see in section 5.1.7, noise negatively effects the luminance measurement. However, the main problem of achieving reliable results for luminance measurements is attaining a reliable amplification of the signal. That means that the automatic gain control must be carefully calibrated. Should this not be the case, for example an ISO speed of 100 is in reality equivalent to ISO 80, this real value is not indicated in the Exif data. This leads to errors because the result is calculated using an incorrect value.
(Probably this was the reason for the resulting deviations in the ISO test of the Nikon D2X. (see explanation in the test analysis in section 6.1.1))

5.1.4 Constancy of Exposure

The constancy of exposure mainly depends on the ability to accurately reproduce the aperture and shutter settings. Apparently, aperture and shutter do not have the exact same exposure time and diameter with exposures taken successively, although the exposures were taken with the same f-number and exposure-time settings. The reason for this is the limit of accuracy of mechanical components.

5.1.5 Analog/Digital Conversion

Image sensors store images in the form of electrons generated by absorbed photons. This electrical charge is converted to a voltage which is amplified to a level at which it can be processed further by the Analog to Digital Converter (ADC). The ADC classifies the continuous values of voltage into a number of discrete numeric digital values. This step inevitably contains data loss and rounding errors, called quantization error. This error can be reduced by enlarging the depth of quantization which is defined by the number of bits. The resolution of an ADC in a digital camera can be determined by the dynamic range of the sensor. The higher the dynamic range is the higher the depth of quantization must be in order to avoid a loss of information.

Today most digital cameras are equipped with A/D converters which have resolutions of 10 to 14 bits. After the A/D conversion a tonal curve is applied to the digitized linear sensor data, so that images viewed on a monitor or printed images are more pleasing to the eye. To avoid posterization or banding when applying this tonal curve on the linear raw data the A/D conversion should have a sufficient depth of quantization, such as 12 bit. [23]

However, the output data of a JPEG image is only available as an 8-bit image data. Due to the nonlinearily coding of the signal the resolution of 8 bit is sufficient to prevent noticeable contouring for the eye, because the 256 digital values are distributed over the tonal range according to the characteristic of human vision. [17]

Human vision has a nonlinear perceptual response to luminance. The lightness perception can be expressed by an approximation of a logarithmic function or an approximation of a power function with the exponent of about 0.4. That means that the human eye can detect an intensity difference of two patches, when the ratio of their intensities differs by more than one percent. It is sufficient for an image coding

system to maintain this ratio of luminance values for a good perceptual performance. [17]
The A/D converter can be located following different steps in the image processing chain (see section 2.3). The first possibility to do so is after converting the raw sensor data. It can also be located some steps later, as with the Nikon D2X, just after the white balancing gain. In this way, the colour channel data are pre-conditioned prior to A/D conversion. This leads to finer gradations and smoother transitions across the colour range. [12]

Thus, limited accuracy in measuring luminance can lie in using an incorrectly converted digital output value (e.g., due to rounding errors) for computing the luminance.

5.1.6 White Balance

For the measurement of luminance with a digital camera, setting the automatic white balance is the best method for adapting to the perception of the human eye.
The chromatic adaption transformation maps the image appearance to colorimetry among different illumination sources. The attributes of scene adopted white, chromaticity and luminance, should be maintained by the transformation. [24]
In the case of luminance measurement it is very important to save the perceived luminance of the scene. A manually set white balance removes colour cast too extremely. For example, an object illuminated with tungsten light appears too bluish after the manual application of white balance. This image impression does not correspond with the perception of human eye.
The illumination-estimation algorithms for auto white balancing are developed for a good and natural reproduction of a scene, as the eye would see it. Therefore, these algorithms reproduce the scene luminance nearly correctly.
(A few tests referring to the automatic white balance can be found in the appendix.)

5.1.7 Noise

Each step involving sensor-based image formation is affected by noise. Various different noise sources exist. They can be classified as Fixed Pattern noise (FPN) (due to variations in the manufacturing of sensors, each pixel has small differences in sensitivity) and Random noise (e.g., Photon shot noise, Dark current shot noise, Reset noise and Thermal noise).

The Fixed Pattern noise does not change significantly from image to image. Thus, it can ideally be removed by taking pictures in absence of a signal and subtract this image from the real image. This step is carried out in the image processing system.

Random noise, like the name says, can not be removed as simple as the FPN.

The sources of noise depend on certain parameters such as temperature, exposure time and signal. [25]

Measuring luminance on a single pixel can result in an error as it potentially could be that it has the wrong shade. Therefore, to minimize the effect of noise on the luminance measurement, the mean value of several pixels has to be taken for the evaluation.

5.1.8 Colour Transformations

As is demonstrated in figure 2.1, there are two different colour transformations in the imaging pipeline. The purpose of scene-referred colour encodings is to represent the device dependent data in a device independent colorimetric colour space (also named as unrendered colour space) like CIE XYZ, CIE Lab or RIMM RGB (the definition of this wide gamut colour space is documented in ISO 22028-3 [30]).

This transformation from the RGB data in a camera's colour space to an unrendered colour space is simply linear.

$$RGB_{cam} \xrightarrow{M_{3x3}} RGB_{unrend} \tag{5.1}$$

Because the camera's response (RGB_{cam}) is non-colorimetric it is safe to assume that the camera values do not exactly match the values of a colorimetric colour space by a linear transformation. Its linearity is justified with a simpler and efficient implementation in the system. Camera manufacturers are attempting to find an optimal matrix (M_{3x3}) that maps the camera's colour space measurements to a colorimetric colour space in order to achieve a minimal difference between both colour spaces. This operation is usually an approximation and therefore the resulting data (RGB_{unrend}) are not accurately colorimetric. This fact affects the exactness of measuring luminance. [5] [26]

Any scene editing is done in this scene-referred image state. Scene modifications include for example the correction of overexposed regions of a backlit scene, or they can include making the grass greener and the sky bluer. Such modifications should be adjustable for the user. If this scene-dependent optimization is done automatically and if users are not able to switch it off, such a camera can not be used as a luminance measure camera, as original scene data are manipulated too much. [27]

The second colour process in the imaging chain is known as colour rendering. A colour rendering transformation is used to transform an image in an unrendered colour space to an output referred image. This nonlinear operation embodies a tone and gamut mapping and a colour preference adjustment. Human observers do not care as much for an accurate scene reproduction as they do for a pleasing reproduction of a scene. Large-scale colour rendering algorithms are responsible for this pleasant image, thereby accounting for the preferences of the human observer. (e.g., it is important for human observers to recognize as many details in dark areas as possible. That is why the gamut is different in dark areas than in lighter ones). In most cases the output of this image processing state resembles that of the sRGB colour space.

The development of applicable algorithms is very time-consuming, expensive and typically proprietary. So it is completely impossible to convert the rendered data back to the unrendered colour space without knowledge of the rendering transforms used. Sophisticated algorithms can in fact be image dependent and even locally varying within an image. [27] [28] [29]

On this basis the calculation of the CIE Y value, as explained in section 4.1, is only an approximation of the Y value. Because users gain no insight in the colour rendering process and the colorimetric adaption of the original device-dependent data is only an estimate, it is not possible to reconvert the output data in exact CIE XYZ values.

5.1.9 Vignetting

The light falling on the sensor is attenuated due to geometric effects. The capture of an off-axis object through a lens is connected with an illuminance fall-off in the peripheral areas of the image. This effect is known as vignetting. There are two sources for this darkening of the image corners: natural vignetting and artificial vignetting.

Natural vignetting is inherent to each lens. The wider the off-axis angle (α) of the object point, the higher the brightness fall-off is on the chip. Therefore, wideangle lenses are most affected by this effect. The decrease in illuminance from natural vignetting is proportional to the fourth power of the cosine of the off-axis angle. Natural vignetting is also known as the cosine fourth law [7]:

$$E(\alpha) = E \cdot cos^4 \alpha \tag{5.2}$$

Artificial vignetting relates to the fact, that oblique incident light is trimmed by the lens frames. This type of vignetting can be eliminated by stopping down the aperture.

Because all lenses are affected by vignetting (some more than others), it is not advisable to measure luminance on the outer edges of an image. It takes into account that those areas, which are to be measured, should not lie on the outer margin of the image. [7] [31]

A further kind of vignetting exists that only affects digital cameras, called pixel shading. It is caused because the light-sensitive photodiodes are pressed between walls, which arise from the production of a light-sensitive chip. Therefore, light incident at an oblique angle can potentially not reach the light-sensitive area and additionally the wall casts a shadow on the photodiode.

With each lens it is possible to measure the relative fall-off of brightness, depending on the locality on the sensor. This measurement is achieved by taking a photo with an opened diaphragm of a homogenously illuminated frosted glass pane. Here, the worst case of brightness fall-off is measured. The relative deviation from the highest digital value (averaging 64 pixels) is calculated for the remaining digital values (averaging likewise 64 pixels).

A tolerable limit for the evaluation of luminance is located at a relative deviation of 5%. The resulting luminance error for this difference of digital values depends on the shape of the characteristic line of each camera. In the region of larger digital values the relative difference in the resulting luminance is higher than in lower digital output values. A difference of 5% in the higher digital output values results in a luminance error of approximately 17%. This value was established by calculating the relative difference of luminance for digital values of 240 and 228 (difference of 5%) for the four cameras. The resulting luminance deviations were between 14% - 17%. This value depends on the gradation of the OECF curve.

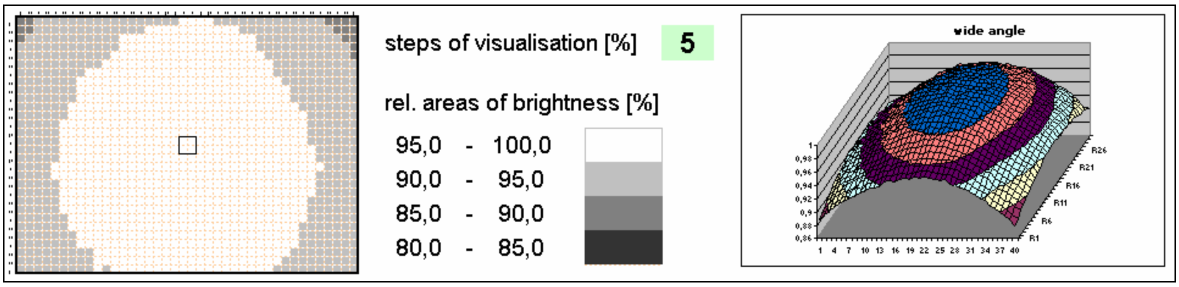

Figure 5.1: visual representation of vignetting areas on the sensor

A visual representation of the areas on the sensor which have a relative output fall-off of more than 5% can be realised as seen in figure 5.1. So every user can easily see in which image area he/she can safely evaluate the luminance. This representation shows the worst case with the smallest f-number.

5.1.10 Stray Light

Stray light occurs in most image capture systems. Different factors exist for the origin of stray light in a digital camera.

At barriers of two different optical materials a partial reflection of the incoming light arises. In a camera lens, this occurs on the barriers from glass to air. A lens with many lenses (e.g., zoom-lenses) shows a relatively high rate of stray light. The silicon image sensor also has a very high reflection rate as the protection glass installed before the image sensor reflects the incoming light, too. This diffused light strays around in the camera body and lens, as a result reducing the image contrast and therefore negatively affecting the output data for luminance measurement.

A method which reduces stray light is the surface-coating of lens elements in a lens and of the surface of an image sensor.

During the calibration process the stray light is taken into consideration; but any light of the surrounding field is shielded when measuring the OECF. The whole space of measurement is shaded so that no reflection is possible and the only illumination comes from the back illuminated test chart.

Such ideal conditions do not exist when applying luminance measurement to a real scene. Certainly there is a lot of light which is not actually in the field of view, but still falls obliquely into the lens (extreme oblique light can stray at the lens frame). This considerable effect of surrounding light can be minimized by using a lens hood.

5.1.11 JPEG-Compression

JPEG (Joint Picture Expert Group) is an 8-bit data format which is very easy to handle because every digital camera and all imaging applications support it, and the data volume is compressible. Although this is a lossy compression method, it is usable for this measurement without getting a high number of errors in the result.

The user can choose the compression rate in certain levels. After that, the same process is always applied to image data in several steps.

The first step of compression transforms the RGB data in a colour space which divides luminance and chrominance, such as YUV or YCbCr colour space. The reason for doing this is that one can afford to loose a lot more information in the chrominance components than in the luminance component, because the human eye is not as sensitive to high-frequency chroma info as it is to high-frequency luminance. The chrominance components can now be downsampled, for example with a 4:2:2–sampling. That means that the luminance channel is left at full resolution and both chrominance components are reduced by one-half.

After colour transformation, each component is divided into 8x8 pixel blocks transformed through a discrete cosinus transform (DCT). The fundamental lossy process step, the quantization, follows now. The coefficients obtained from the DCT are divided by a quantization table and then rounded to the nearest integer. The table values vary with the frequency. Higher frequencies are always quantified less accurately (given larger matrix values) than lower frequencies, since they are less visible to the human eye. The values of the quantization table differ by the setting of the compression rate. So the purpose of quantization is to discard information which is not visually significant and to compress data with no greater precision than is necessary to achieve a desired image quality. [32]

To restore a compressed JPEG data, a decoding and dequantisation is performed on the image data. Due to the quantistaion a restoration of the original image data is not possible. The lower the compression rate is the lower is the quantisation error.

Nevertheless, if the compression of the JPEG is changed, and with it the quantization, a luminance measurement is still possible, because only fine details (higher frequencies) in an area of 8x8 pixels are polished, but the meanvalue of a block remains nearly the same. As a minimal area of 5x5 pixels is necessary for the luminance evaluation a change in the JPEG compression should not affect strongly the luminance result.

5.2 Measurement Accuracy

5.2.1 Error of Luminance Meter

Minolta declares an accuracy error of 2% at an illumination with an illuminant A for the Minolta LS-100 luminance meter.
The Gossen MAVO-Monitor claims an error rate of 2.5% at the same illumination.
Both devices are assigned to grade B, as is defined in DIN 5032-7 [33]. Therefore the total error (including among other things the deviation of V(λ), error of indication, error of linearity etc.) of these devices range from 6% to 10%.

5.2.2 Error of the Luminance Measurement

Measurements of luminance of the patches from the OECF test chart are tainted with uncertainty. This uncertainty is a random error which describes the repeatability of measurements. It can be reported by calculating the standard deviation of the measurements which characterize the dispersion of the result.
As an example of the measurement error, one patch of the test chart was measured ten times with the MAVO-Monitor meter.
The mean of the obtained values is 23.287 cd/m^2 and the accessory standard deviation amounts to +/- 0.131 cd/m^2. The result of the measurement is:

$$L = (23.287 +/- 0.131)\ cd/m^2$$

This error calculation is to be viewed as exemplary to all measurements made for calibrations.

5.2.3 Error of the Approximation Curve

The polynomial approximation curve of the luminance measurement data is calculated using the method of the least square. Measurement data is often accompanied by noise so this estimation method for obtaining the trend of the outcomes is necessary.
The least square method is based on the desire to obtain a curve with a minimal deviation from all data points. This is expressed in equation 4.2.

The square of the correlation coefficient serves as a degree of correlation of the n measured (L_m) and n calculated luminance values (L_c).

$$r^2 = \left(\frac{n(\sum L_m L_c) - (\sum L_m)(\sum L_c)}{\sqrt{\left[n\sum L_m{}^2 - (\sum L_m)^2\right]\left[n\sum L_c{}^2 - (\sum L_c)^2\right]}}\right)^2 \tag{5.3}$$

This coefficient can assume values between 1 and 0. The higher the fit of the approximation according to the measuring points, the closer the coefficient is to value 1.

The higher the degree of a polynomial, the smaller is the sum of the squared deviations. However, the higher the degree the more turning points the polynomial can have. Therefore, the approximation curve oscillates between the data points, which results in high deviations by estimating the luminance in these areas. In this case, the sixth-degree polynomial oscillates only in lower digital values. These values are eliminated by defining a lower limit of digital values as it is described in 4.3.2.2.

5.2.4 Error of Measuring Objects with a Spot Luminance Meter

Unfortunately these measurements contain some sources of error.

The spot luminance meter averages the luminance in the whole measuring field determined by an angle of 1°. This measuring field should be marked as exactly as possible in the image. The marking is done with a selecting tool in Adobe Photoshop 7.0. The luminance is calculated with the mean value of the RGB digital values of this field. Deviations of measurement can arise if the measured object is structured or not illuminated uniformly. As is eximplified in figure 5.2, a deviation in the measuring field, which is marked in Photoshop, to the luminance meter measuring field can possibly yields to different results.

The uncertainty in marking and in the evaluation of the correct measure points can result in errors. To minimize this error of accuracy in measuring luminance, objects with unicoloured and untextured surfaces are utilized for this work.

Figure 5.2: these two measuring points on the structured object result in a different luminance value

Due to the use of the MAVO-Monitor for all camera calibrations, there is a deviation in measuring the object with the LS-100 luminance meter. The devices do not produce exactly the same resulting luminance values when measuring the OECF test chart patches at nearly the same time and illumination with both luminance meters (see table 4.1).

6 Analysis of the Results

6.1 Evaluation of the Individual Cameras

The results of the tests which are mentioned in section 3.5 and which were performed with the four cameras (introduced in section 3.1) as well as five additional cameras are documented and evaluated in this chapter. The detailed test data for each camera can be found on the enclosed CD. An extract of the resulted deviations to the measured luminance are presented in the appendix.

6.1.1 Nikon D2X

Calibration:

Looking at the output data of the D2X one will see that the digital values range from nearly 1 to 255. This camera and the Canon 350D are the only cameras in this test which dynamic ranges correspond with the object range of the test chart (10000:1).

In the area of high digital values the OECF curve is, contrary to some other cameras, relatively flat. This has consequences to the measuring range within one picture because the upper limit is higher than these of the other cameras. Therefore, the measuring range of the Nikon D2X is the widest with a luminance range of 130:1.

Constancy:

The mean value of the standard deviations, which are obtained from the ten exposures from calibration, is with a value of 0.149 the lowest of the measured cameras. This suggests that the D2X possesses a very precise and constantly working electronic and mechanical system.

ISO Speed Settings:

In this category the Nikon camera reveals its weak point. The error rate of this analysis is the highest of all tested cameras. It is highly probable that the incremental gain does not work very reliably. The ISO speeds set on the camera probably do not correspond precisely with the amplification factor of the gain control. It can be excluded that the Exif data are not accurately declared, because the exposure values which are calculated with the different exposure settings all result in nearly the exact same values. The error level in all three ISO speed settings (ISO 200, ISO 400, ISO 800) is comparable, amounting to approximately +15%. This means that all calculated luminance results appear brighter than the real input luminance. Therefore, it is highly probable that the gain control had adjusted the amplification to a level that is too high.

Over and Underexposure:

The Nikon D2X is exposed to the EV compensation function of the camera in this category. Images of the OECF chart are taken with an EV correction from +1 EV up to -1 EV in third steps. The camera achieves favourable outcomes in all exposures. In spite of the acceptable results, one must point out that the EV compensation does not yield the expected gradations of one-third, as set with the EV compensation. Instead, the steps were about half an EV or, as in one scenario, only about 0.15 EV. This inaccuracy on the part of the Exif data in connection with the use of the EV compensation occurs in the Canon EOS 350D camera, too.

Objects in a normal light scene:

Even though the D2X demonstrates a relatively high rate of deviation, especially regarding the saturated blue colour, it has together with the Fuji F10, the best result in this category of the cameras tested.

General annotations:

It has been established that the Exif data are more precisely graded than the exposure data indicated by the camera. Sometimes the Exif data specifies finer subdivisions of the f-number and exposure time than the customary third steps. Far better results are achieved if the calculation is performed by using the accurate Exif data.

6.1.2 Canon EOS 350D

Calibration:

The dynamic range of the Canon EOS 350D is nearly exactly the same as that of the Nikon D2X. It is striking that the OECF curve, in contrast to the other cameras' OECF curve, (which all have about the same shape) has a different shape. The 350D uses more digital values in the darker areas and less in the higher output values. Therefore the minimal permissible digital values for the evaluation are a little bit higher than the minimum values of the other three cameras. In the part of high digital values the gradation of the curve is relatively high. Due to this, the Canon EOS 350D has a smaller range of luminance for the evaluation in one picture, than the Nikon D2X and the Fuji F10. This luminance contrast amounts to 96:1.

Constancy:

The mean standard deviation is 0.388. In this category the Canon, together with the Fuji F10, can be ranked as middle-rate in comparison to the rest of the tested cameras.

ISO Speed Setting:

The outcome of exposures taken of the test chart with different ISO speed settings was sound. The exposure value always has the same value, as it is to be expected.

Over and Underexposure:

Over and underexposures created by the EV compensation function do not produce satisfactory results. The camera sometimes does not indicate the difference between the third steps, although it was set this way by the EV compensation. This means that the exposure value of the two images is exactly the same, while the exposure of the two pictures is different. The luminance calculation is thereby based on an incorrect exposure value in one of these pictures. The Exif data of the Canon 350D is equivalent to the cameras' indication. So, the 350D can not provide exposure data in its Exif data as exact as is seen in the Nikon D2X. Therefore, the safest way to obtain under and overexposed images with the Canon 350D is to create a manual exposure series. If the exposure time and aperture are adjusted manually, one can be sure that the Exif data show a difference in the exposures.

Objects in a normal light scene:

The luminance measurement results are not very satisfactory in this test category. The deviations of the luminance may occur from the inaccuracy of the Exif data or is due to the inaccuracy of the mechanical components, because they have nearly the same percentage of deviation. It is noticeable that the Canon 350D has different deviations in the blue object. Accordingly, the Canon 350D can not determine the luminance reliably of the blue colour, like the other cameras, too.

General annotations:

Unfortunately the Exif data on the Canon EOS 350D are exactly the same data as the camera indicates. Therefore, the camera can not keep up with the other three cameras which yield more accurate Exif data than the camera indicates. This accuracy is proven through better outcomes. In summary, the 350D does not produce results as exact as with the other tested cameras.

6.1.3 Nikon Coolpix 8400

Calibration:

The Nikon Coolpix exhibits a very high dynamic range, too. It uses 254 digital values for the reproduction of the test chart. The range of digital values which can be utilized for the luminance calculation is about 227 digital values. This corresponds to a luminance ratio of 91:1, which can be evaluated in one image.

Constancy:

The mean value of the standard deviation amounts to 0.926. In this test a difference of nearly five digital values occurs in the same grey field of ten images, which are succesively taken. Therefore, the repeatability of the Nikon Coolpix 8400 is not as reliable as the other three cameras.

ISO Speed Settings:

By using the very exact Exif data, the outcomes are very positive in this part of the test.

Over and Underexposure:

Taking an exposure series of the OECF test chart with the EV compensation, the result is very reliable when using the Exif data for the calculation. The Exif data of the Nikon Coolpix 8400 are very accurate. For example, the camera indicates an exposure time of 1/100 sec, but the exposure time is mentioned in the Exif data as 1/98 sec.

Objects in a normal light scene:

The highest deviation results in the blue object. This camera shows deviations in luminance of over 30% in this colour. All other luminance measurements in this scene were on target.

General annotations:

The Exif data of the Nikon Coolpix 8400 are very precise. Calculating with these precise values results in good luminance outcomes.

6.1.4 Fuji Finepix F10

Calibration:

This consumer camera has the smallest dynamic range of all four cameras. It uses only 251 digital values for an object contrast of 10000:1. The OECF curve has a low gradation in the higher digital values, like the curve of the Nikon D2X. For this reason the Fuji F10 has high maximum output values for the calculation of luminance. Thereby, the luminance range of 124:1 in one picture is nearly as wide as the luminance range of the Nikon D2X.

Constancy:

In this category the Fuji F10 performs as well as the Canon EOS 350D. The highest deviation of the bit values is about two digital values.

ISO Speed Setting:

By changing the ISO speed, the exposure time and f-number are adapted nearly perfectly and the amplification factor seems to be very exactly calibrated.

Over and Underexposure:

As there is no possibility to adjust the exposure time and f-number manually with the Fuji F10, an over or underexposure has to be manipulated by using the EV compensation. The outcomes are very reliable in this category, too.

Objects in a normal light scene:

The highest deviation of measured luminance to calculated luminance also results here with the blue object. However, the rate of deviation is not as high as that of the Canon 350D and Nikon Coolpix 8400 in this category.

General annotations:

The Fuji F10 consumer camera was the most reliable camera in this test field, when referring to modifications in exposure or the change of the ISO speed. The exposure times are documented very exactly in the Exif data. The low deviations in coloured objects also support the excellent results.

6.1.5 Five Additional Cameras

The five cameras mentioned in section 3.5.6 were calibrated and then used to take four different exposures of a scene with coloured objects. One exposure was taken with the automatic mode of the camera, one with a different ISO speed setting, and the remaining two images as under and overexposed.

The characteristic lines of all of these cameras are very normal, except with the Fuji S3Pro. This camera is calibrated with the setting of “extended dynamic range”. This is a special setting according to the Super CCD SR sensor from Fujifilm. The wide dynamic range is achieved through the use of a second, less sensitive photodiode. The camera’s image processor combines the values of the two different pixels to extend the dynamic range of the image (for more information see [34]). The OECF curve determined with this adjustment looks very different from all other OECF curves. In this mode the camera uses less digital values for the lower luminances and more for bright areas, as it is noted in all other cameras. The OECF curve is very steep in the higher digital values and very flat in the lower values. Because of this characteristic the evaluable digital value range is very small (about 200 digital values). Therefore the evaluable luminance ratio in one image only amounts to 43:1. However, if the normal mode “standard dynamic range” is used for calibration, the evaluable luminance range will be higher in one image.

Most of these cameras show no specific deviations. The rate of deviation with the Sony Cybershot and the Ixus from Canon is always under 30%. Even when testing with the saturated colours of the objects they are able to produce superior luminance results. This also applies to the Olympus E500 and the Casio camera. They only deliver high deviations (over 30%) in the outcome of the overexposed image, especially with the colours red and orange. The Fuji S3Pro shows high deviations in the blue colour.

The Casio Exilim has entirely wrong Exif data for the underexposed picture. The data are the same as the data of the exposure taken with the automatic mode. This incorrect Exif data can probably be traced back to a bug in the camera’s software. Calculating the luminance with the wrong exposure data, the outcomes show a very high level of deviation.

6.2 Determination and Evaluation of the Total Error

It is difficult to form a general statement concerning the total error which can be applied to all cameras. Through the tests which were performed for this thesis, it can be determined that a total error of about +/- 30% can be expected for the accuracy of the luminance result. This percentage of deviation from the actual luminance to the calculated luminance is only a guide. In some cases, when measuring coloured objects it can occur that the error is over 30%. These are probably colours which are poorly adapted to the CIE Y value or which can not be well reproduced because of a limited spectral sensitivity of the sensor. On the other side, all cameras generate much better results with uncoloured objects than this total error represents.

This evaluated total error contains all error sources mentioned in chapter 5. The errors which most often affect the result are an inaccuracy of exposure data, a wrongly calibrated ISO amplification and the inaccurate adjustment of aperture and shutter time. In measuring colour objects the main error will be an inadequate adaptation of the camera's data to the CIE Y value and further preferred colour renderings.

Therefore, each camera has a different total error, which again depends on the measured colour. For a more accurate definition of total error which applies to each individual camera, every camera has to be tested in even more detail than is done in this work.

6.3 Interpretation of the Results

The total deviation of +/- 30% from the calculated luminance to the measured luminance can also be expressed in stops. Then a deviation of +30% corresponds with a third stop and a deviation of about -30% is equivalent to somewhat more than a half stop.

When one considers that a digital camera is not an exact measuring instrument, this result of the total error is satisfactory.

The total error of luminance meter which is assigned to the class B (defined in DIN 5032-7 [33]) may amount to between 6% and 10%. This defined total error is the sum of several errors, for example V(λ)-adaptation, linearisation error, UV and IR sensitivity, dependence on the angle of incidence, dependence on temperature, and error of the indication device.

The test with cameras of all categories shows, that a professional camera, like the Nikon D2X, is just as qualified for use as a luminance measure camera as the consumer camera Fuji F10. This result was contrary to expectations. An argument to support this result is, that consumer cameras are equipped with electronic shutters which work very accurately, and it seems too, that the Fuji F10 has an acceptable colorimetric adaptation and less further colour renderings like the professional cameras.

The accuracy of the aperture and shutter adjustment, an exact calibration of the amplification (in regards to the ISO speed), and a good colour reproduction are the main characteristics for the evaluation of a luminance measure camera. In addition, a reliable declaration of exposure data in the Exif header is an important criterion.

In respect to these test results, the use of EV compensation is not advisable, because this mode in some cases states incorrect exposure data. A deliberate over or underexposure of a scene should be performed with the manual exposure setting, if possible. The cameras with which one can not manually adjust aperture and exposure time, do not pose any problems for the use of EV compensation in these tests.

Due to the restricted range of usable digital values, it is not possible to determine the luminance on high saturated colours.

7 Use in Practice

An Excel sheet has been prepared into which the calibration data can be entered and from which the user can obtain the luminance result by entering the RGB digital output values of the image area he/she wants to evaluate. This Excel sheet is based on the tests and calculations explained in this work. In this chapter the use of this Excel sheet will be explained and some important information is given with respect to the application of the luminance measurement. First, however, some important advantages of the luminance measure camera over a point-by-point measuring luminance meter are discussed.

7.1 Features of a Luminance Measure Camera

7.1.1 Measuring Range

The measuring range within an image of a calibrated digital camera amounts to a luminance contrast of about 90:1. This range varies from camera to camera. It depends on the minimum and maximum digital values, which define the lower and upper limit of the digital values for each channel. Due to the determination of these limits (explained in section 4.3.2), the luminance range which can be measured within an image depends on the shape of the OECF curve.

Very often, luminance scenes have a large object contrast. In order to measure higher luminance contrasts than the measurable contrast within an image, different exposures of the captured scene are needed (an example is shown in figure 7.1). With such an over or underexposure it must be ensured that the area of the scene which is to be measured provides digital output values which are located in the evaluation range of the camera.

Therefore, the selection of a measuring range is defined by the settings for integration time, aperture and ISO speed.

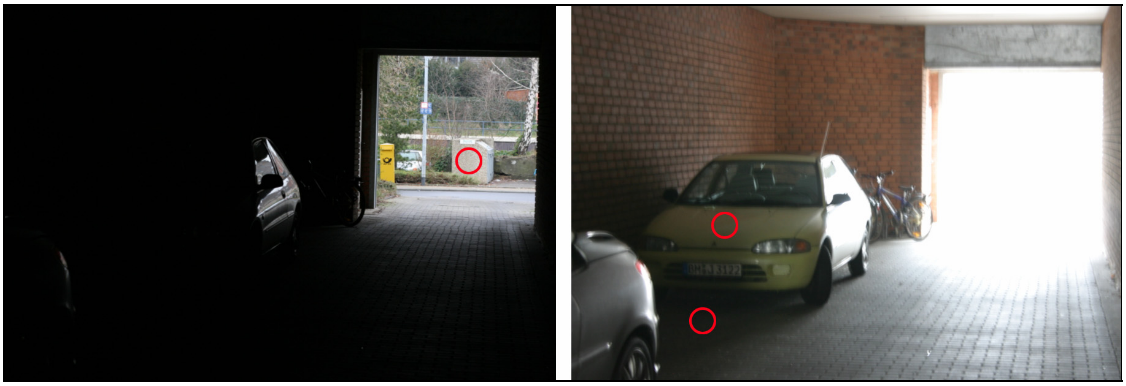

Figure 7.1: over and underexposure for the evaluation of the whole range of object luminance

The maximum luminance that can be measured can be calculated with the shortest adjustable exposure time, the smallest aperture and the minimal ISO speed, with the maximum digital output values. In contrast to the maximum luminance, the lowest measurable luminance can be calculated with the smallest f-number, the highest ISO sensitivity and a long exposure time, with the minimal digital values. The measuring range of a digital camera can sometimes exceed the measuring range of a luminance meter.

measuring range within an image			
luminance contrast	1: 90		
in stops	6,5		
total measuring range			
exposure time [sec] from	3	to	0,0005
f-number from	2,8	to	22
ISO speed from	1600	to	100
	0,001 cd/m^2	bis	492396 cd/m^2

Figure 7.2: detail of the Excel sheet: calculation of the measuring range

7.1.2 Number of Measuring Points

A luminance-measure image simultaneously delivers a multitude of measuring points. The number of these measuring points depends on the number of pixels located on the sensor and the minimal size of the evaluation area. The minimal evaluation area is set as 5x5 pixels to eliminate the negative effect on noise.

7.1.3 Measuring Angle

An advantage of luminance measurement with a digital camera is that this has a measuring angle which is smaller than that of a luminance meter. Most luminance meters have measuring angles of 1°. The minimal measuring angle of a digital camera is limited by the minimal evaluation area of 5x5 pixels and the image scale of the optical image formation.

7.1.4 Storage of Luminance Images

All images can, of course, be stored on severel storage media. The advantage to this is that each luminance measurement can be reconstructed long after the measured scene has been captured. The problem, for example, of realizing too late that an incorrect point has been measured or that additional points would have been necessary for measuring a certain location no longer exists with an image-resolving luminance measure camera. Furthermore, the notation of the luminance measure data and the corresponding location point is no longer necessary.

7.2 Information about the Use of the Excel File

The user of a luminance measure camera gets, in addition to his/her calibrated digital camera, an Excel file for the luminance calculation. This Excel file contains four visible sheets which hold the output of the luminance result and other camera information.

The first Excel sheet shows the output of the calculated luminance, referring to the camera's digital output data and the exposure data which correspond to the image. The user has to enter the RGB output data of the image area, which he/she would like to evaluate. The RGB data can be obtained by using an image-editing program, which can select and evaluate an area of at least 5x5 pixels (If the customer does not possess an image-editing program, there is a free software-tool on the internet page *www.foto-freeware.de/farbwert.php* which averages pixel-areas of 5x5 pixels in each picture-viewing program and indicates the corresponding RGB data). The resulting RGB digital values have to be entered in the predetermined fields on the Excel sheet. The user must also enter the exposure data of the image which he/she wants to evaluate. The exposure data of an image can be received through an Exif-reading program, which are also available for free on the internet.

When all of these data are entered into the corresponding fields, the luminance result is shown in the luminance-output field. If the user enters incorrect digital values (for example digital values smaller or higher than the permitted digital values) the words “Falsche Bitwerteingabe” appear in the luminace-output field.

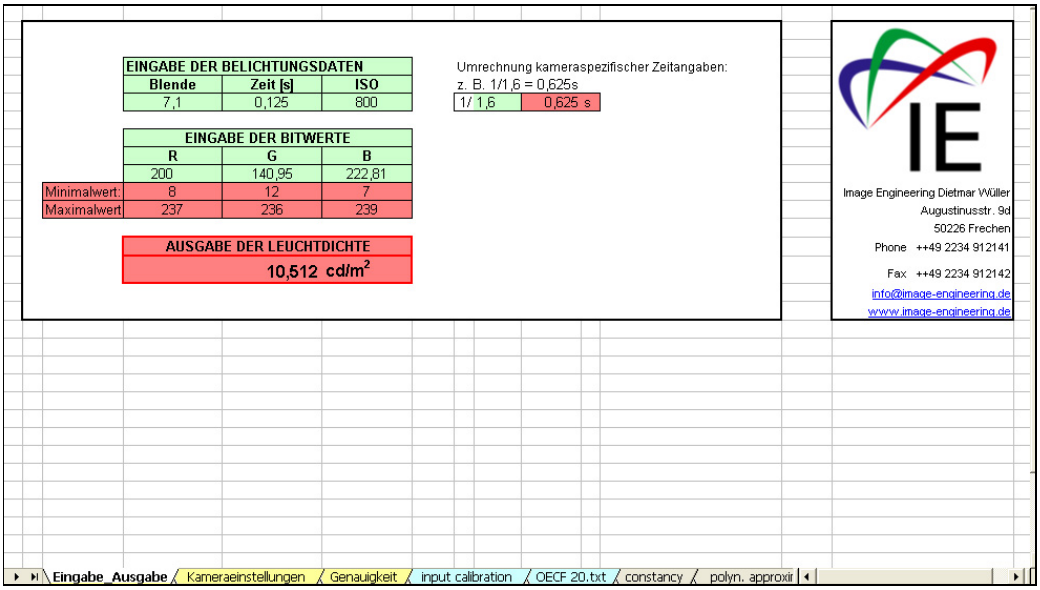

Figure 7.3: Excel sheet with the input of digital values and exposure data and the output of the luminance result

A description of the customer’s camera (e.g., manufacterer, camera model, serial number, and lens) is noted on the next sheet „Kameraeinstellungen“. Important information is found in the red-framed box. This is namely information about the camera menu settings which are adjusted on the camera before calibration. The settings which are documented in this box absolutely must be set when luminance measurements are to be performed with the camera. These documented settings mainly affect the colour, tone and contrast settings and maybe other special effects, which can change the characteristic of the OECF curve.

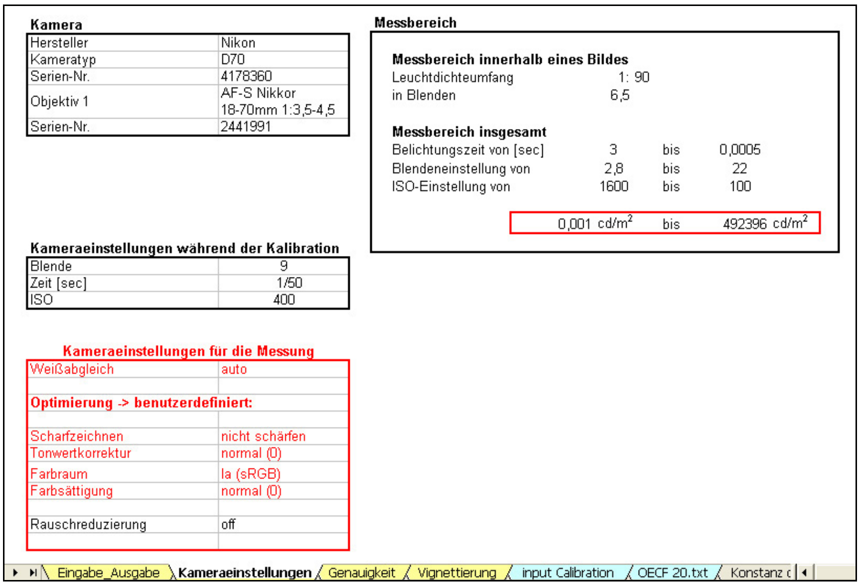

Figure7.4: documented camera settings

The third sheet shows the accuracy of the camera regarding calibration and ISO amplification. Given this data it is easy to see if the ISO amplification is calibrated reliably or not, or if the amplification is too high, making it impossible (because of a high noise rate in the image) to obtain acceptable luminance data.

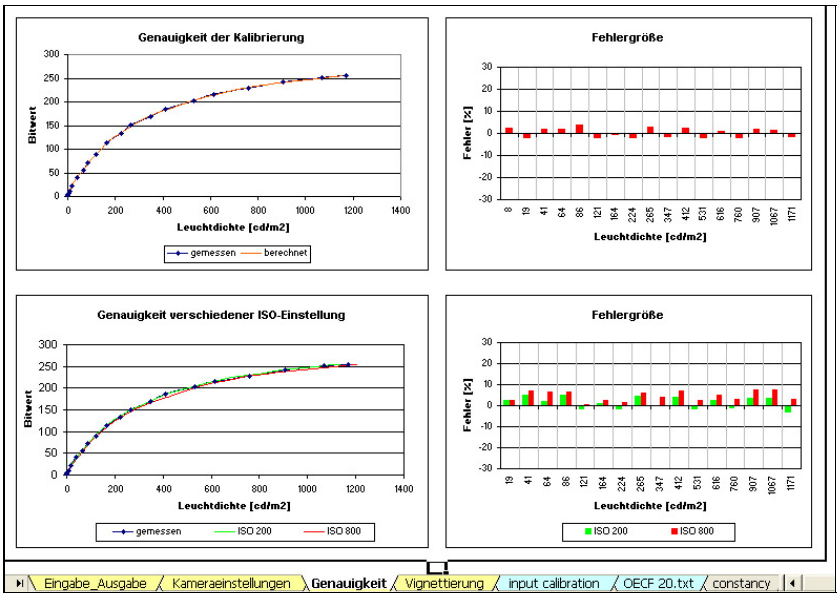

Figure 7.5: Excel sheet, which shows the accuracy of calibration and the ISO speed setting

The last worksheet which is available for the user contains a visual representation of the vignetting measurement of the camera's lens.

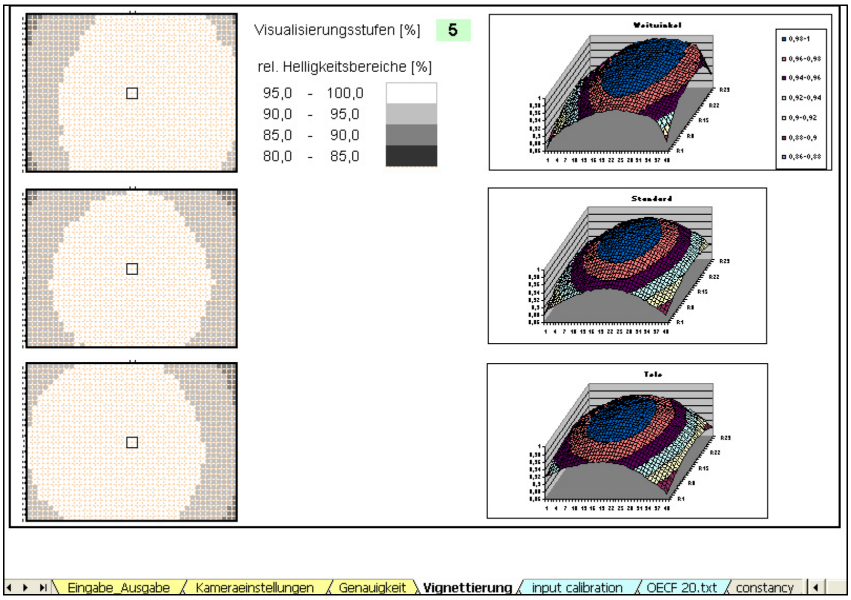

Figure 7.7: visual representation of vignetting

The sheets following the first four sheets contain all calculations described in chapter 4. These calculations refer to the OECF measurement data which have to be entered in the Excel file after the calibration.
This Excel sheet can be found on the enclosed CD.

7.3 Closer Inspection of the Application in the field of Accident Examination

During the completion of this thesis trainings have been carried out to users, who want to calibrate their cameras for the purpose of measuring luminance. Until now, these customers were all in the same professional field: accident assessor. Their operational area for taking luminance measurements is confined to night accidents. That means the luminance measure camera is used in very dark scenes where the most luminance values range between 5 cd/m^2 and about 0.01 cd/m^2. As a result it can be assumed that long exposure times and/or high ISO speeds are needed for capturing a scene with resulting digital values which are not too low for the calculation of luminance.
Increasing amplification by increasing the ISO speed as well as long exposure times both enhance the noise level of the camera signal. Long exposure times increase the dark current noise, which arises from thermically generated electrons in the sensor well and which is largely dependent on exposure time. Increasing the ISO speed means an amplification of the signal, which also amplifies the existing noise in the cameras' signal.

Extra tests have to be done, in reference to high ISO speeds and long exposure times, to see if the increase in noise was so high that it affected the luminance evaluation. A very high noise level can lead to high deviations from actual luminance, in spite of the fact that output values of 5 x 5 pixels are averaged.

The long-exposure-time test can be completed by capturing a test chart, for example the OECF chart with very low luminance (achieved with grey-filters). If the luminance result represents a brighter value than the measured luminance, it can be suggested that this is due to the dark current noise, which generates additional electrons than are generated by the incoming photons. While carrying out this test, the ISO speed can also be varried. Thus, the influence of the amplification on the luminance result can be evaluated. A high ISO speed in connection with a long exposure time can possibly have negative effects on luminance measurement. In this case, a confined range of the ISO speed setting must be defined for the measure of luminance.

The requirements referring to noise on digital cameras, which are used for such dark-measurements, are high. It is important that such cameras have image sensors with large light-sensitive areas. The larger the pixel-area, the higher the native sensitivity of the chip is and so the signal must not be amplified too much.

Accident scenes can also have high luminance contrasts, for instance if there is a very bright headlight and a pedestrian with dark clothes, which stands out in the headlight. Therefore, the user has to make several exposures to evaluate such a wide luminance range. To be on the safe side that the digital output values are usable for a luminance evaluation, the histogram function of the camera can be used (nearly all cameras today are equipped with this function). With this histogram the accident assessor can easily see that there are no low or no high used digital values in the image. Another possibility is to measure the exposure with the spot meter mode of the camera. Then the digital values of the area, where the spot meter has measured the exposure, correspond to the values of a medium grey.

An advantage for this occupational group is that they can present the documentation of their measuring points and results in court in order to prove that the measurement data is indeed correct. The assessor's measurements can also still be checked after the fact, for example should the case be reopened.

Equations exist for the calculation of the visual range of a car driver (for details see [35]). In these equations some values of the distribution of luminance in a scene has to be inserted. For such a calculation many measuring points are necessary and doing so with a point-by-point luminance meter is very time-consuming. The assessor can save time on the scene of accident, because with an image-resolving luminance measurement, all evaluations can be made later at his/her convenience on the computer.

Some more fields of application of a luminance measure camera are mentioned in the introduction of this thesis. The following pictures show measuring tasks where a high precision of the measurement result is not absolutely necessary and therefore can be performed with a calibrated digital camera.

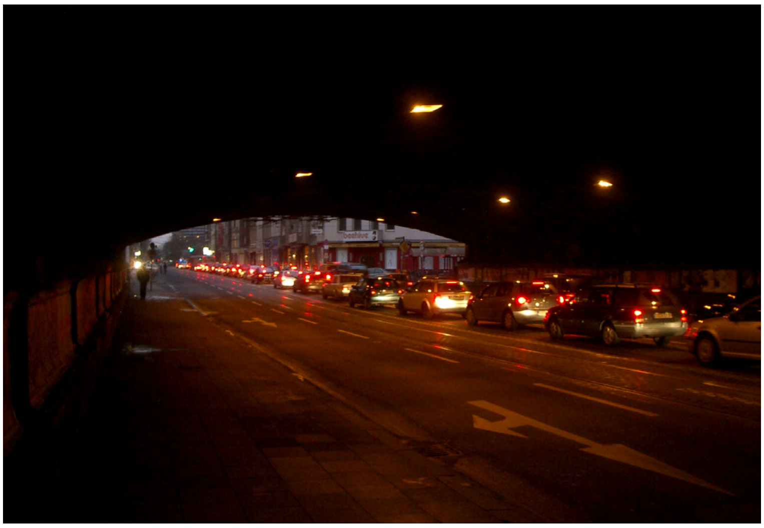

Figure 7.10: Luminance measurement according to standards for example for tunnels, streets or car parks (e.g., DIN 5044, DIN 67524, DIN 67528)

Figure 7.11: Assessment of workplace illumination

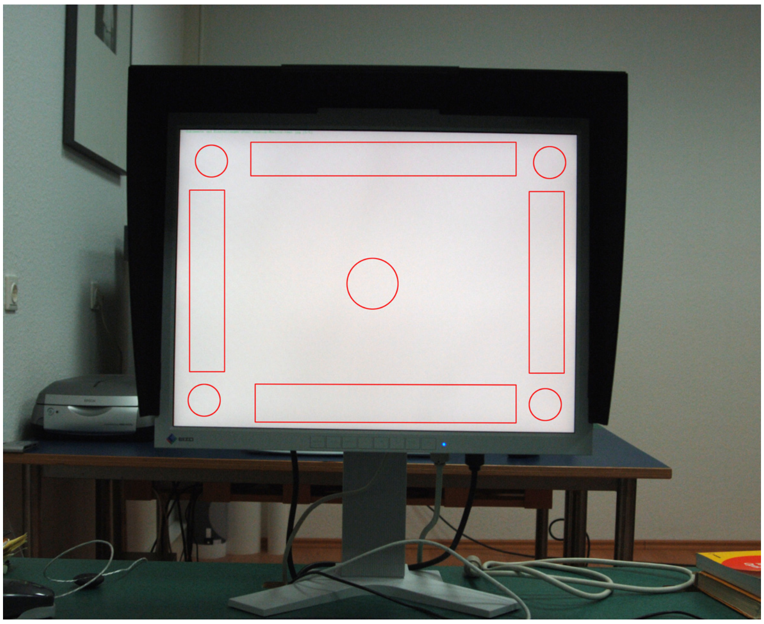

Figure 7.12: Inspection of the luminance distribution of a monitor display

Figure 7.13: Measuring small details is possible with a luminance measure camera

7.4 Utilization Tips

Important informations regarding the use of a digital camera as a luminance measure device are briefly summarized here:

- The user has to pay attention that the areas of evaluation provide digital output values which can be used for the calculation of luminance.

- If using a dSLR camera it is important that the chip is clean. For example, dust can reach the sensor when changing the lens. This results in incorrect digital values, which are usually not eliminated by averaging over numerous pixels.

- Due to vignetting, the luminance determination should not be completed on the edge of a picture and capturing a scene with an open aperture should be avoided.

- To minimize the influence of stray light, a lens hood should be used.

- Due to noise, the RGB output data used for the luminance calculation should be averaged at least 5x5 pixels.

- Images should not be edited in an image-editing program. If an edited image is stored the Exif data are lost and the original digital values are modified.

- When capturing a scene which is illuminated with a flickering light, for instance a fluorescent lamp, it is to see that the exposure time is long enough to avoid measuring errors.

8 Conclusion

The aim of this thesis was to find a reliable method for the measurement of luminance with digital cameras, which must accommodate both consumer cameras and dSLR cameras.

Several tests were performed with different camera types. These tests were utilized as an examination of the behaviour of the cameras' characteristic response under different conditions (different ISO speed settings, over and underexposures and different luminance scenes). In addition, a measurement of luminance was also tested on coloured objects.

A calculation of luminance was presented, which applies to the digital values of the RGB channels and the exposure settings.

Measuring luminance with a digital camera does not produce results as precise as achieved by conventional luminance meters.

Especially when measuring the luminance of coloured surfaces, high deviations result between the luminance calculated with the cameras' digital output values and the luminance measured with the V(λ)-adapted luminance meter. This occurs only with certain colours, for example with shades of blue or red.

A closer examination of this colour problem was not possible during the time which was available for this work. This should possibly be reviewed once more in detail.

Two further suggestions, which could possibly decrease the total error, are briefly mentioned here. A detailed analysis of these suggestions could not been completed due to the limitation of time.

- By restricting the use to only one definite ISO speed setting, possible inaccuracies which arise from an incorrectly calibrated amplification factor could be avoided. If the calibration is conducted with this ISO speed, the incorrect amplification factor is figured into the calibration. The measuring range is reduced by this restriction. For example, an f-number range of 2.8 to 22 and an exposure time range from 3 sec. to 1/1000 sec. amounts to a measuring range of 0.006 cd/m^2 to 186857 cd/m^2 with an ISO speed of 400 (this example bases on the data of the Nikon Coolpix 8400). This is however sufficient for nearly all measuring tasks.

- The use of RAW data may achieve better results in colour, as there would be no influence of a preferred colour rendering on the camera's colour reproduction. The ideal case would be if the RAW data yielded the linear RGB data of the device-dependent camera colour space. The spectral sensitivity of the sensor then has to be measured and the RGB channel weighted so that an approximation to $V(\lambda)$ is achieved by a matrix formation. This is a complicated and large-scale method, which has to be performed with each camera. This method would improve the accuracy of measuring colours, but an exact adaption to $V(\lambda)$ would not be achieved. In addition, handling the RAW data becomes problematic. The RAW image file is larger than a JPEG file and, until quite recently, a standard format for these files was not available. The RAW data could only be opened and edited in the cameras' RAW converter software. It is safe to assume that the manufacterer's software performs several renderings on the RAW image. At the end of 2004, Adobe introduced a publicly available archival format for all RAW files, which can be integrated as a plug-in in Photoshop CS. This is the only possibility to independently work with RAW data. According to this solution, measuring luminance with digital cameras is restricted to cameras which provide RAW data and it is restricted to Photoshop CS for the evaluation.

These two suggestions could possibly increase the accuracy of luminance measurement. However, the inaccuracy of the mechanical components, which unavoidably leads to deviations, can not be eliminated.

Instead of performing the evaluation with an Excel file, a program can be developed which reduces the utilization time and which would simplify the evaluation of luminance. The ideal case would be if the program could read the image and its Exif data, and the user only had to select an area of the picture (with a selecting tool) and the luminance value of this area would be directly indicated by the program. The input of exposure settings and the digital RGB values would thereby be inapplicable.
In connection with such a program, some image processings could be performed on the image. For example, the representation of a luminance-image with coloured areas refering to defined ranges of luminance would be possible. Thereby, the distribution of luminance can be very easily evaluated at a glance throughout the whole image. Or a

high dynamic range image can be produced with software, which can put the images of an exposure series together into one image. The result will be a high dynamic luminance image. A luminance evaluation of several images with different exposures is thereby not necessary, making the evaluation even less time-consuming.

However, the question is if such time and effort in image-processing is profitable. This has to be examined through a detailed market analysis. The realization of these ideas would increase the price of using a digital camera as a luminance measurement device. However, the low costs for the user, together with the merits of the practical use (mentioned in chapter 1 and section 7.1) present the advantages of this image-resolving luminance measurement method with digital cameras.

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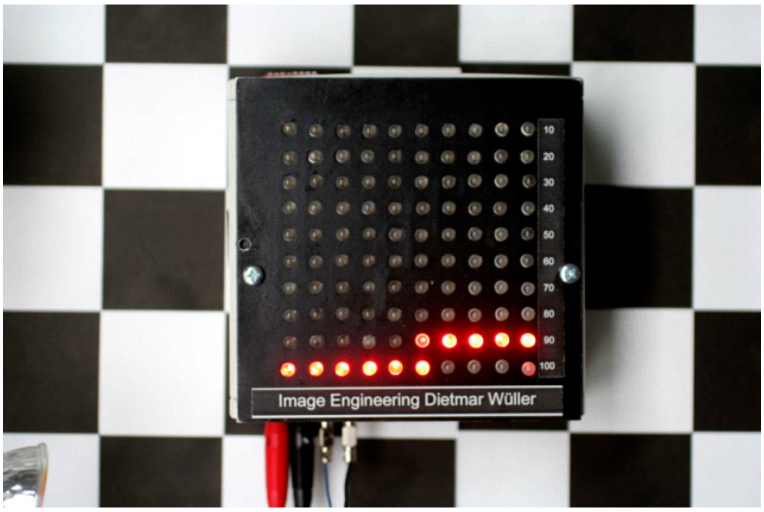
Appendix

A. Test of Shutter Time

The correlation of the camera setting and real exposure time was tested of the dSLR cameras Nikon D2X and Canon 350D.



LEDs which light up one after the other with an adjustable frequency

The frequency of the LEDs was set to 1000 Hz for the following tests. That means each LED lights up for a 1/1000 sec.

Nikon D2X

	Pic 1	Pic 2	Pic 3	Pic 4
camera indication [sec]	1/100	1/100	1/100	1/100
EXIF data [sec]	1/100	1/90	1/90	1/100
number of LED	11	10	10	11
expected number	10	10	10	10
measured exposure time [sec]	0,011	0,01	0,01	0,011

It is noticeable that the Exif data of the Nikon indicates very exactly the exposure time.

Canon EOS 350D

	Pic 1	Pic 2	Pic 3	Pic 4
camera indication [sec]	1/250	1/250	1/250	1/250
EXIF data [sec]	1/250	1/250	1/250	1/250
number of LED	5	5	5	5
expected number	4	4	4	4
measured exposure time [sec]	1/200	1/200	1/200	1/200

The measured exposure times are not equivalent to the cameras' setting and indication. However, this test has a limited accuracy of 1/1000 sec., which is not a high precision for short shutter times. In addition it is possible, that the first or last luminous LED was flashed for less than a 1/1000 sec. during the opening time of the shutter. It is difficult to notice this on a picture (at the image above, it seems that the first LED lights up less than a 1/1000 sec. during the exposure time, because it looks a bit darker than the others) and it is not possible to determine the exact time of the LED's illumination.

B. Test of Automatic White Balance

Fluorescent Lamp:

Image with automatic white balance adjustment

Image with manual white balance adjustment

		automatic white balance		manuell white balance	
	luminance (meas.) [cd/m2]	luminance (calc) [cd/m2]	deviation [%]	luminance (calc) [cd/m2]	deviation [%]
measuring point 1	1,97	2,102	6,28	1,812	-8,72
measuring point 2	2,31	2,451	5,75	2,117	-9,12
measuring point 3	2,11	2,211	4,57	1,961	-7,60

The apperance of the automatic white balance is a better approximation to the perception of the human eye and the measuring results are a bit better than those of the manual-white-balance image.

Sodium Discharge Lamp:

Image with manual white balance adjustment

Image with automatic white balance adjustment

		automatic white balance		manuell white balance	
	luminance (meas.) [cd/m2]	luminance (calc) [cd/m2]	deviation [%]	luminance (calc) [cd/m2]	deviation [%]
measuring point 1	1,35	1,985	31,99	1,177	-14,70
measuring point 2	0,72	1,36	47,06	0,558	-29,03

Again, the automatic-white-balance image looks better approximated to the perception of the human eye, but the colour cast is still too extreme. However, the image with a manual white balance setting yields better results.

Sodium discharge lamps emit a small spectral region of wavelengths. It is possible, that the illumination-estimation algorithm for auto white balancing has difficulties with this extreme colour cast of the illuminant. Therefore, an evaluation with an automatic white balance results in high deviations.

C. Deviations of the Four Tested Cameras

The following tables contain details of the deviations, which are results from the test data of the four cameras. These data are presented here from the fourth patch (dark) to the 18. grey patch (bright) of the OECF chart, because of the restriction of the digital values. Digital values which are still too low or too high are marked within the tables with “too low” or “too high”.
The whole test data can be found on the enclosed CD.

Accuracy of calibration

Nikon D2X	Canon EOS 350D	Nikon Coolpix 4800	Fuji Finepix F10
deviation [%]			
-4,32	2,91	10,36	-2,55
0,18	-3,38	-11,94	1,84
-2,33	1,34	2,88	0,32
-1,91	-0,20	1,07	-2,52
2,10	0,57	1,70	1,60
-2,27	-1,12	-3,59	-0,94
-0,76	0,91	1,39	2,24
-0,73	-0,72	-1,41	-1,03
0,42	1,61	3,09	2,04
-1,23	-0,97	-2,12	-2,95
-0,12	0,04	1,69	1,88
-2,09	0,04	-2,74	-1,94
0,71	1,01	1,90	1,95
-1,46	-1,25	-0,67	-1,31
-0,43	0,61	-0,60	0,73

Constancy

	Nikon D2X	Canon EOS 350D	Nikon Coolpix 4800	Fuji Finepix F10
standard deviation	0,149	0,388	0,926	0,388
difference of digital values	0,76	2,05	4,7	2,37

Change of the ISO Speed Setting

ISO 200

Nikon D2X	Canon EOS 350D	Nikon Coolpix 4800	Fuji Finepix F10
deviation [%]			
3,59	8,24	11,18	-5,63
8,46	-10,73	-9,79	5,95
7,73	-6,38	3,00	2,16
10,14	-4,19	-1,58	-2,82
16,87	-1,80	1,25	2,80
13,64	-4,75	-3,93	-0,71
16,85	-3,97	1,19	3,44
17,99	-4,31	-1,20	-1,26
19,00	-2,23	2,81	3,28
17,00	-4,63	-2,52	-1,78
17,93	-2,72	1,35	3,22
16,22	-4,29	-2,62	-1,75
17,60	-3,72	1,88	3,21
15,65	-4,62	-0,37	-0,63
16,89	-3,48	-1,44	1,43

ISO 400

Nikon D2X	Canon EOS 350D	Nikon Coolpix 4800	Fuji Finepix F10
deviation [%]			
-4,48	2,86	15,74	-4,55
-1,83	-11,32	-5,78	3,95
-0,47	-6,38	3,38	0,55
3,25	-4,49	0,88	-3,71
10,06	-2,41	1,36	0,20
7,16	-5,65	-2,72	-2,41
9,65	-3,83	4,09	0,33
9,66	-4,07	1,26	-2,89
10,65	-2,37	5,75	0,38
10,33	-4,45	0,74	-3,67
10,86	-2,46	4,84	1,18
9,29	-5,24	0,67	-2,55
10,89	-4,22	5,75	0,24
9,05	-4,93	2,82	-2,26
12,06	-4,04	3,23	-0,52

ISO 800

Nikon D2X	Canon EOS 350D	Nikon Coolpix 4800	Fuji Finepix F10
deviation [%]			
1,57	2,86		12,52
0,94	-11,32		6,14
4,07	-6,38	not	4,40
8,83	-4,49	available	1,25
15,32	-2,41		4,00
12,43	-5,65		1,34
15,05	-3,83		5,11
14,80	-4,07		1,96
17,00	-2,37		5,15
14,95	-4,45		2,05
16,94	-2,46		5,80
15,53	-5,24		2,20
17,09	-4,22		5,86
14,95	-4,93		3,60
16,74	-4,04		5,76

Under and Overexposure

+1 EV

Nikon D2X	Canon EOS 350D	Nikon Coolpix 4800	Fuji Finepix F10
deviation [%]			
0,48	7,44	3,67	12,63
-2,08	-3,20	-2,44	7,11
-1,00	2,69	7,14	3,36
-2,78	2,72	0,82	2,90
-2,09	3,64	2,98	6,03
-3,96	0,39	-1,17	1,61
-1,42	3,38	3,41	3,28
-2,91	1,09	0,72	1,58
-1,74	4,49	4,54	5,33
-2,60	2,64	-1,26	1,88
-1,74	3,45	2,99	5,39
-2,92	1,74	-0,69	0,68
-1,45	3,98	3,35	1,95
too high	2,14	-1,24	-5,63
too high	3,57	-3,03	too high

-1 EV

Nikon D2X	Canon EOS 350D	Nikon Coolpix 4800	Fuji Finepix F10
deviation [%]			
-5,98	too low	too low	-2,56
-4,05	-4,06	-16,15	1,83
-6,66	-3,83	-0,21	-2,24
-7,39	0,59	0,91	-4,10
-3,16	2,37	2,61	-1,33
-6,85	0,54	-2,24	-3,68
-6,49	1,00	1,31	-0,34
-6,43	0,61	-0,99	-3,21
-5,14	3,05	2,14	-1,01
-6,10	1,12	-1,05	-3,97
-5,16	3,00	3,19	-0,54
-6,74	1,78	-1,31	-3,35
-4,84	1,83	2,25	-0,56
-6,57	0,83	0,94	-2,79
-5,73	2,59	2,36	-1,78

Objects in a normal light scene

Captured scene:

Automatic exposure

	Nikon D2X	Canon EOS 350D	Nikon Coolpix 4800	Fuji Finepix F10
wall	-9,83	-30,90	-11,13	-13,33
file	19,26	13,22	39,79	21,34
carton	-2,88	-30,28	-10,04	-6,70
grey chart	-3,47	-24,41	-4,51	-9,66
white box	0,47	-23,81	-2,84	-6,20

ISO 200

	Nikon D2X	Canon EOS 350D	Nikon Coolpix 4800	Fuji Finepix F10
wall	1,77	4,60	-12,97	-13,54
file	35,37	-54,03	41,68	22,85
carton	10,53	4,33	-9,11	-5,75
grey chart	9,60	-3,13	-4,15	-9,61
white box	14,50	-5,78	-2,38	-5,19

Overexposure

	Nikon D2X	Canon EOS 350D	Nikon Coolpix 4800	Fuji Finepix F10
wall	-14,13	25,05	-5,53	-2,24
file	9,98	18,09	58,77	35,17
carton	-17,14	28,13	-3,41	-18,22
grey chart	saturated	25,11	0,55	saturated
white box	saturated	22,20	saturated	saturated

Eidesstattliche Erklärung

Ich versichere hiermit, die vorgelegte Arbeit in dem gemeldeten Zeitraum ohne fremde Hilfe verfasst und mich keiner anderen als der angegebenen Hilfsmittel und Quellen bedient zu haben.

Köln, 22.02.2006

(Helke Gabele)

Sperrvermerk

Die vorgelegte Arbeit unterliegt keinem Sperrvermerk.

Weitergabeerklärung

Ich erkläre hiermit mein Einverständnis, dass das vorliegende Exemplar meiner Diplomarbeit oder eine Kopie hiervon für wissenschaftliche Zwecke verwendet werden darf.

Köln, 22.02.2006

(Helke Gabele)