Measurement of the spectral response of digital cameras with a set of interference filters

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Messung der spektralen Empfindlichkeit von digitalen Kameras mit Interferenzfiltern

Diplomarbeit im Fachbereich
Medien- und Phototechnik
an der Fachhochschule Köln

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Abstract

Title: Measurement of the spectral response of digital cameras with a set of interference filters

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Abstract: This diploma thesis describes the measurement of the spectral response of digital cameras with a set of interference filters. The setup, processing of the data and the assessment of the measurement are discussed.

Keywords: spectral response, interference filter, monochromator

Remark of closure: The thesis is not closed.

Date: 14. January 2009

Zusammenfassung

Titel: Messung der spektralen Empfindlichkeit von digitalen Kameras mit Interferenzfiltern

Autor: Christian Mauer

Referenten: Prof. Dr.-Ing. Gregor Fischer
Dipl.-Ing. Dietmar Wüller

Zusammenfassung: Diese Diplomarbeit beschreibt die Messung der spektralen Empfindlichkeit von digitalen Kameras mit Hilfe von Interferenz-Filtern. Der Messaufbau, die Verarbeitung der Daten und Qualität der Messung werden behandelt.

Stichwörter: Spektrale Empfindlichkeit, Interferenz-Filter, Monochromator

Sperrvermerk: Die vorgelegte Arbeit unterliegt keinem Sperrvermerk.

Datum: 14. Januar 2009

Contents

Chapter 1

Introduction

To know the spectral response of a digital camera is necessary to design its color processing. The generation of the color transformation matrix is much easier and provides better results, when sample colors are simulated with the spectral response. In contrast to the use of color test charts with a limited amount of sample colors, the use of the spectral response makes it possible to use much more sample colors. The influence of real light can be simulated and the range of sample colors is not limited to printable colors.

There are different approaches to acquire the spectral response. The most obvious one is to ask the sensor manufacturer for the data sheet. Unfortunately there are some shortcomings. First is that only some manufacturers publish the data sheets. Even if the data sheet is available there are problems. Often the manufacturer does not give much information how the measurement was performed. In detail that means: What filters were used? Was a lens used? Additionally to these issues there might be variations in spectral response from device to device. [7] Relying just on the data published by the manufacturer might not give the best possible quality.
So a measurement of the spectral response is necessary.

One possibility to get the spectral response is the use of reflectance charts in combination with estimation algorithms. These algorithms offer reasonable results and are inexpensive and fast. To improve the quality of the measurement the use of monochromatic light is imperative. To generate monochromatic light normally a monochromator is needed. Unfortunately theses devices are very expensive, difficult to setup and the measurement is very time consuming.

Another possibility to generate monochromatic light is the use of narrow-band interference filters. The handling of the filters might be complicated, too. This thesis describes the hard- and software which was developed to overcome these issues. The quality of the measurement is discussed, too.

Chapter 2

Basics

2.1 Camera response model

A camera response model is used to characterize how a digital camera responses to a spectral power distribution. The image sensors in digital cameras are inherently linear devices. So a linear camera response model is usually appropriate. The assumption of linearity has to be verified. If the device is not linear, the response model needs to be extended with a function that describes the non-linearity [2].

2.1.1 Linear camera response model

The response model for linear digital cameras is as follows:

$$r_i = e \int_{\lambda_l}^{\lambda_h} s_i(\lambda) i(\lambda) d\lambda + n_i \tag{2.1}$$

With i for the i^{th} color channel, e the exposure time, $s_i(\lambda)$ the spectral response of the i^{th} color channel, $i(\lambda)$ for the spectral incident power and n_i as a random variable. The limits λ_l and λ_h enclose the sensitive spectral area of the image sensor. Often the limits of the human visual area are used (380 nm to 720 nm).

2.1.2 Non-linearity camera model

Is the assumption wrong that the camera imager is a linear device, the non-linearity needs to be considered in the camera response model. Equation 2.1 is extended to:

$$r_i = F(e \int_{\lambda_l}^{\lambda_h} s_i(\lambda) i(\lambda) d\lambda + n_i) \tag{2.2}$$

Function F describes the non-linearity of the device.

2.1.3 Spectral incident power

The spectral incident power $i(\lambda)$ which reaches the image sensor is influenced by several factors. A lightsource $I(\lambda)$ illuminates an object with a spectral reflectance $\rho(\lambda)$. The multiplication $i(\lambda)$ of both spectra is the color stimulus seen by an observer or a camera:

$$i(\lambda) = \rho(\lambda) I(\lambda) \tag{2.3}$$

2.1.4 Spectral response

The spectral transmittance of the lens $\tau_{lens}(\lambda)$ changes the color stimulus. The spectral transmittance of the infrared blocking filter $\tau_{IR}(\lambda)$, each channel of the color filter array $\tau_{CFAi}(\lambda)$ and the spectral response of the imager $S_{Sensor}(\lambda)$ resulting into the spectral response of the image sensor $s(\lambda)$:

$$s(\lambda) = \tau_{IR}(\lambda)\tau_{CFAi}(\lambda)S_{Sensor}(\lambda) \tag{2.4}$$

With τ_{CFAi} for the spectral transmittance of the i^{th} color channel of the color filter array.

2.2 Interference filters basics

Interference filters are multilayer thin-film devices. They utilize the interferences of single or multiple reflected beams of light to block certain wavelengths.

2.2.1 Interference

The incident light passes two coated reflecting surfaces. The distance between the coatings determines the effect of interference. If the reflected beams are in phase, the light is passed. If they are not in phase, the transmittance is reduced by destructive interference of these wavelength [12]. Figure 2.1 shows the interference at a thin layer [13]:

The transmittance of a double-layer setup according to figure 2.1 is:

$$\tau\lambda = \frac{(1 - s_1^2) * (1 - s_2^2)}{1 + s_1^2 * s_2^2 + s_1 * s_2 * cos(\varphi)} \tag{2.5}$$

With:

$$s_1 = \frac{n_0 - n_1}{n_0 + n_1} \qquad s_2 = \frac{n_1 - n_2}{n_1 + n_2} \qquad \varphi = 2\pi * n_1 * \frac{d}{\lambda}$$

The interference at the boundary layer causes a strong influence on the wavelength dependency of the transmittance. Interference filters with several layers utilize this effect. Usually these layers are made of translucent material. So the influence of the absorption can be neglected.

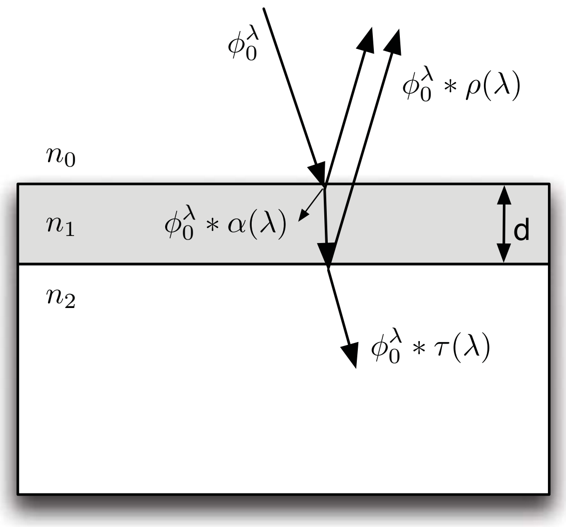

Figure 2.1: Interference at a thin layer.

2.2.2 Interference filter design

The distance between the reflecting surfaces is a thin film of dielectric material called a spacer. The spacer has a thickness of one-half wave of the desired peak transmittance wavelength. On both sides of the spacer are two reflecting layers. These layers consist of several film layers with of a thickness of one fourth of the desired peak transmittance wavelength. The stack of the one-fourth layers consists of alternating layers of high and low refraction index material. Together two stacks and one spacer result in a one-cavity-bandpass-filter (see figure 2.2).

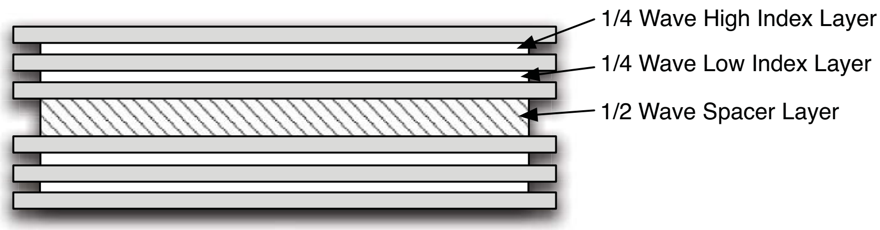

Figure 2.2: Layers of an interference filter with one cavity.

Single cavity bandpass filter does not have a sharp transition between the passband and the blocking range. To improve the transition several cavities are combined (multi-cavity bandpass filter). A complete interference filter does not have just several cavities. Additional thin-film coatings are applied to block transmittance outside to the blocking range of multi-cavity bandpass filter.

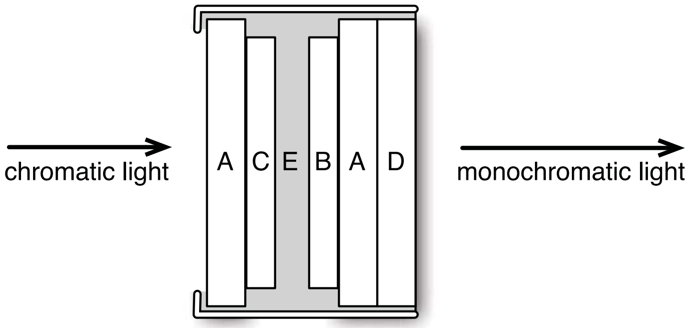

Figure 2.3: A complete interference filter.

With:

A: Glass Substrate

B: Multi-cavity Bandpass

C: Blocker

D: Color Glass

E: Epoxy

F: Metal Ring

2.2.3 Interference filter parameters

Following therms are used to describe the characteristics of interference filters (see figure 2.4 on page 15) [11][12]:

Passband: The range of wavelengths passed by the wavelength-selective filter (1st order).

Blocking: The degree of light attenuation at wavelengths outside the passband of the filter.

Center Wavelength (CWL): The wavelength at the middle of the half power bandwidth (FWHM).

Full-Width Half-Maximum (FWHM): The width of the passband at 50% of the maximum transmittance (τ_{max}).

Tenthbandwidth (TBW): The width of the passband at 10% of τ_{max}.

Hundredthbandwidth (HBW): The width of the passband at 1% of τ_{max}.

Filter Cavity: Most interference bandpass filters are designed with multiple cavities. The combination of several cavities determines the shape of the passband of the filter. Multiple cavities allow to get a nearly rectangular transmittance function.

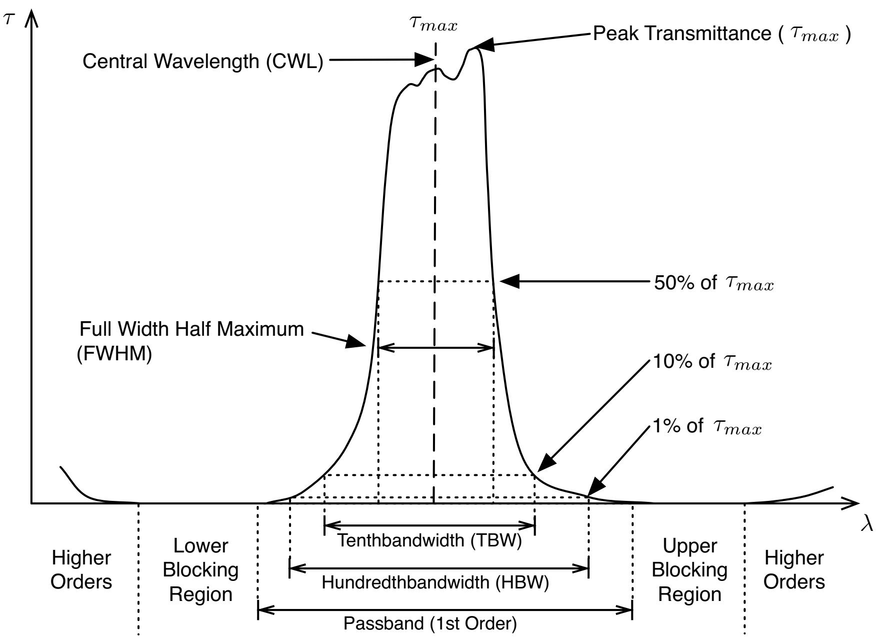

Figure 2.4: Interference filter parameters.

2.3 Exposure value

The nominal exposure in the focal plane of a camera is expressed by [10]:

$$H = \frac{H_0}{S_{ISO}} \tag{2.6}$$

With $H_0 = 10lxs$.

With a ISO speed of 100 (S_{ISO}) the exposure is $0.1lxs$. The exposure value (EV) represents several combinations of the shutter speed (t) and aperture (k) which leads to this exposure:

$$2^{EV} = \frac{k^2}{t} \tag{2.7}$$

The exposure value (EV) is calculated as follows:

$$EV = \frac{2log10(k) - log10(t)}{log10(2)}. \tag{2.8}$$

The ISO speed settings need to be considered for the EV calculation. So equation 2.8 is extended to:

$$EV = \frac{2 * log10(k) - log10(t)}{log10(2)} + \frac{21 - S^\circ}{3} \tag{2.9}$$

With S° = actual ISO speed (DIN, logarithmic).

In equation 2.9 a reference ISO speed (21°) is used. A difference of 3° is equal to 1 EV.

Since the ISO speed is generally given in the arithmetic ASA scale (S) the value is converted to the logarithmic DIN scale (S°) with following equation:

$$S^{\circ} = 10 * log10(S) \tag{2.10}$$

The final equation used for the calculation of the exposure value is:

$$EV = \frac{2 * log10(k) - log10(t)}{log10(2)} + \frac{21 - (1 + 10 * log10(iso))}{3} \tag{2.11}$$

2.4 Color filter array

The image sensors used in digital cameras are inherently just monochrome. By applying color filters in front of the imager the camera gets the ability to provide color information. The spectral response of the imager highly depends on the spectral transmittance of the color filters. The most common way of color filters is to apply an array of color filters directly in front of the sensor. The Bayer pattern layout of these color filters is the most popular one. Figure 2.5 on page 18 shows the Bayer color filter array.
In the example shown in figure 2.5 the red channel (R) is placed in rows and columns with an odd number. The blue channel (B) is placed in rows and columns with an even number. The design varies from camera to camera. Since most cameras use the Bayer-pattern with two green channels (G1 and G2) arranged diagonally it is appropriate to know the positions of the red and blue pixels.

	1	2	3	4	5	6
1	R	G1	R	G1	R	G1
2	G2	B	G2	B	G2	B
3	R	G1	R	G1	R	G1
4	G2	B	G2	B	G2	B
5	R	G1	R	G1	R	G1

Figure 2.5: Bayer color filter array.

2.5 OECF

The **O**pto-**E**lectronic **C**onversion **F**unction (OECF) describes the relationship between the input scene luminance and the digital output levels for an opto-electronic digital image capture system. To apply a camera response model (2.1.1) it is necessary to verify if the camera provides linear RAW-data or not.

Chapter 3

Hardware

This chapter describes the hardware and software, that was used to measure the spectral response. In the following, the term camSPECS is used when referring to the developed hard- and software. CamSPECS is an abbreviation for "**Cam**era **Spe**ctral **C**alibration **S**ystem".

3.1 Generation of monochromatic light

A set of 39 interference filters is used to generate narrow-band light. The filters cover the area of 380 nm to 905 nm to provide a complete spectral characterization even for cameras without infrared blocking filter.

3.1.1 Interference filters

The filters from 380 nm to 720 nm have a bandwidth of 10 nm (FWHM see 2.2) and are evenly distributed in 10 nm steps. The other filters with center wavelengths (CWL see 2.2) of 750 nm, 800 nm, 850 nm and 905 nm have a FWHM of 35 nm up to 50 nm. The diameter of the filters is 12.5 mm. The thickness varies between 2 mm and 3.8 mm. Table 3.1 shows the specifications of the used interference filters.

3.1.2 Interference filter mounting

The inference filters are mounted to aluminum plates with the size of a regular 35 mm slide (49 mm x 49 mm x 2 mm). To reduce glare the plates are painted matte black. The plates are stored in a slide magazine like regular slides. To move them one after another in front of the light source the transportation system of the projector is used.

Figure 3.1: One of 39 camSPECS filter plates.

A interference filter

B neutral density filter

The interference filter is installed in a hole with a diameter of 12.5 mm. It is fixed with adhesive. Black paint is used to block any light leaking around the filters. To reduce thermal effects, which may damage the filter, the mirror-like reflective side of the interference filter is orientated towards the light-source. So most of the blocked radiance is not absorbed, but reflected.

A neutral density filter with a diameter of 10 nm is located beside the interference filter. This filter is used as a brightness reference to correct for exposure variations.

Table 3.1: Specifications of the used interference filters

CWL normative [nm]	FWHM [nm]	transmittance [%]	rel. radiance power
380	10	30	0.16
390	10	33	0.26
400	10	33	0.38
410	10	43	0.45
420	10	45	0.44
430	10	45	0.58
440	10	45	0.55
450	10	45	0.56
460	10	45	0.62
470	10	45	0.57
480	10	45	0.61
490	10	45	0.64
500	10	50	0.76
510	10	50	0.82
520	10	50	0.79
530	10	50	0.97
540	10	50	0.68
550	10	50	1.00
560	10	50	0.84
570	10	50	0.91
580	10	50	0.64
590	10	50	0.66
600	10	50	0.58
610	10	50	0.51
620	10	50	0.53
630	10	50	0.43
640	10	50	0.41
650	10	50	0.37
660	10	50	0.36
670	10	50	0.38
680	10	50	0.48
690	10	50	0.41
700	10	50	0.36
710	10	50	0.34
720	10	50	0.30
750	40	75	1.29
800	35	75	0.89
850	40	75	0.85
906	50	75	0.87

In the following the term "sample channel" is used when referring to the narrow-band light. The term "reference channel" refers to the neutral density filters.

The distance between the channels is as wide as possible to avoid a contamination between them. The maximum distance between the channels is limited by the size of the uniform illuminated area. The small diameter of the reference channel helps to reduce the stray light.

To simplify the positioning of the camera and the selection of the position of the sample and the reference channel during the data processing a filter mounting plate without interference filter, but two neutral density filters is used. This plate is called adjustment plate.

3.1.3 Quality of the monochromatic light

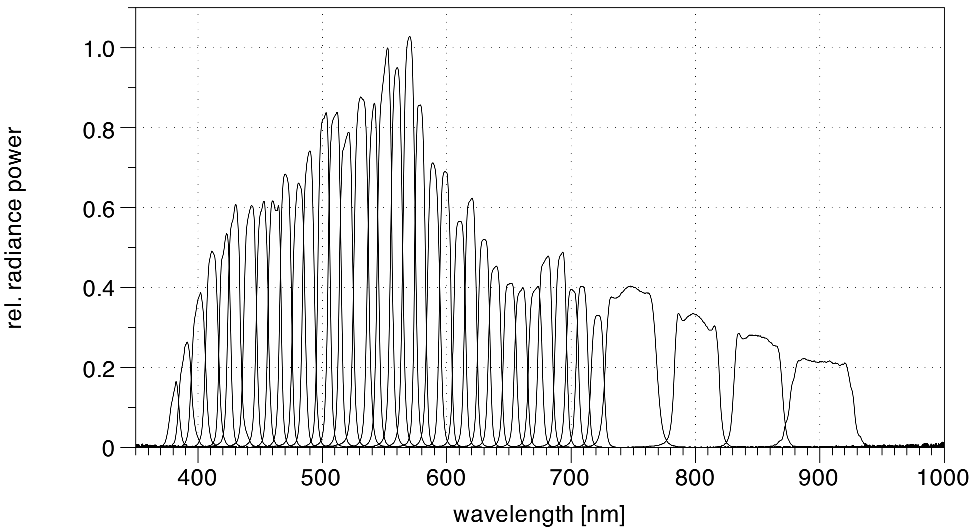

Figure 3.2: The spectral power distribution of the radiance emitted by the interference filters.

Figure 3.2 shows the spectral distribution of the light passed by the interference filters. For the generation of monochromatic light it is critical that

the filters block all radiation outside the filter bandpass. One way to describe the quality of an interference filter is the integrated blocking. The integrated blocking is the ratio of the total radiation outside the passband to the radiation within the passband. The evaluation of the monochromatic light is performed with the filters used the same way as for the spectral response measurement. This considers the light source, which has a huge influence on the integrated blocking ratio.
First the integration of the spectral distribution of the emitted light is done inside the passband of the interference filters. Although the FWHM is 10 nm (bandwith at 50% of peak transmittance) the allowed passband is the bandwidth at 1% transmittance. An allowed bandpass three times wider than the FWHM (30 nm for the 10 nm FWHM filters) is used for the evaluation. Second the integration is performed for the full area from 350 nm to 950 nm. By subtracting the passband radiation from the full area radiation the radiance outside the passband is calculated. The ratio of these two radiance power values describes the quality of the monochromatic light.

In detail the calculation is done as shown by the example for the 430 nm filter:

$$L_{passband} = \int_{\lambda_{415nm}}^{\lambda_{445nm}} i(\lambda) d\lambda \tag{3.1}$$

The radiance power within the passband of the interference filter.

$$L_{all} = \int_{\lambda_{350nm}}^{\lambda_{950nm}} i(\lambda) d\lambda \tag{3.2}$$

Calculation of the radiance power in the full area.

$$L_{outside\_passband} = L_{all} - L_{passband} \tag{3.3}$$

Radiance power outside of the passband of the interference filter.

$$blocking = \frac{L_{outside\_passband}}{L_{passband}} \tag{3.4}$$

The value "blocking" is the ratio between the radiance power outside the filter bandpass and the radiance inside the filter bandpass. Table 3.2 on page 25 shows the integrated blocking values for all used interference filters. The values vary from 2% up to 10%. The highest error of 10% appears with the 380 nm filter. The radiance power of this filter is quite low, so the ratio between passband radiance and off-passband radiance is high. The validity of this evaluation is highly affected by the signal noise of the spectrometer. It shows a quite high amount of noise, even when a short integration time is used and several measurements are averaged. Figure 3.3 shows the measurement of the 550 nm filter. The graph is scaled to 0% - 10% of the peak of the radiance power to show the noise characteristics. The increased signal towards the limits of the measurement range is not caused by radiation passed by the interference filter. The signal looks the same way for dark current measurements.
Additional to the integrated blocking the actual CWLs are shown in table 3.2. The evaluation shows that there are slight shifts of the CWL. The average shift is 9% of the FWHM, the max shift of this set of filter is 20% of the FWHM. These shifts might be caused by the illumination. More probable is that these are quality variations of the interference filters because the shift varies for each set of filters.

Table 3.2: Quality of the monochromatic light.

CWL normative [nm]	CWL actual [nm]	integrated blocking ratio
380	381.4	10%
390	390.1	9%
400	400.7	7%
410	411.5	3%
420	421.9	6%
430	429.2	4%
440	442.0	4%
450	451.8	4%
460	461.6	3%
470	470.5	4%
480	481.1	5%
490	488.8	4%
500	501.3	3%
510	509.9	5%
520	519.2	4%
530	531.4	5%
540	540.7	5%
550	550.3	3%
560	559.8	4%
570	569.9	4%
580	578.6	5%
590	589.5	5%
600	598.9	5%
610	610.3	7%
620	619.2	5%
630	630.0	6%
640	638.8	7%
650	650.9	6%
660	659.7	8%
670	671.4	8%
680	679.4	6%
690	691.9	6%
700	701.0	9%
710	709.0	8%
720	721.4	7%
750	748.5	2%
800	801.2	4%
850	850.4	2%
906	901.7	2%

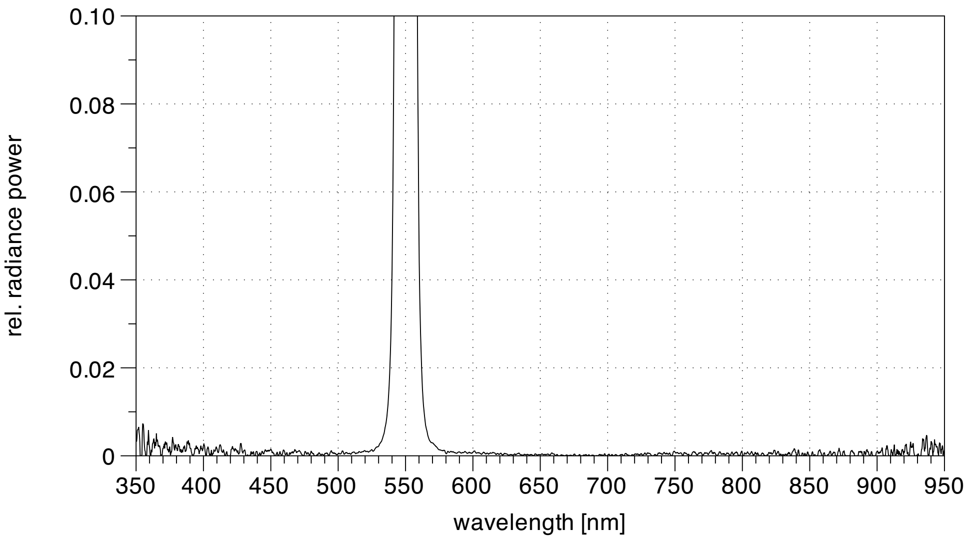

Figure 3.3: Noise of the spectrometer.

3.1.4 Angle dependency of the interference filters

The characteristics of the transmitted light of an interference filter depends on the viewing angle. The viewing angle can cause variations in the radiance power and shifts of the CWL. The changes in radiance power are not critical because the position of the camera is not changed during one series of measurement. The shift of the CWL might be an issue. Generally an increased view angle causes a slight shift of the CWL to a shorter wavelength.

According to the manufacturer of the used interference filters a viewing angle up to 15° does not cause any noticeable shift of the CWL. To verify this statement a comparison of two spectral response measurements of the same camera was performed. One measurement was done with a high viewing angle in respect to the perpendicular of the interference filters. The other measurement was done with the camera perpendicular to the interference filters. The reference channel is blocked for this comparison to avoid any influence of the stray-light. Aside from normal measurement errors the comparison of the data showed no difference. This comparison was done with a Nikon D70. The spectral response measurement of this camera generally suffers from the quite inaccurate exposure control. Since the comparison had to be performed without the reference channel it was not possible to correct the data for exposure inaccuracies. Figure 3.4 on page 28 shows the results of this comparison.

To evaluate the actual shift of the monochromatic light in the image plane of the camera a 35 mm film camera was used. The back of the camera was open to place a spectrometer fiber-optics near to the focal plane. To keep the shutter open during the measurements, the "bulb" mode of the camera was used. Since this evaluation was quite time consuming only the 550 nm filter was used. Two measurements were performed. One with the image of the interference filter placed in the outer corner of the image. This leads to a viewing angle of about 10°. The other with the interference filter placed in the center of the image. The resulting spectral power distribution measurements were compared to each other (see figure 3.5 on page 29). The measurement with the filter placed in the corner of the image had the maximum radiance

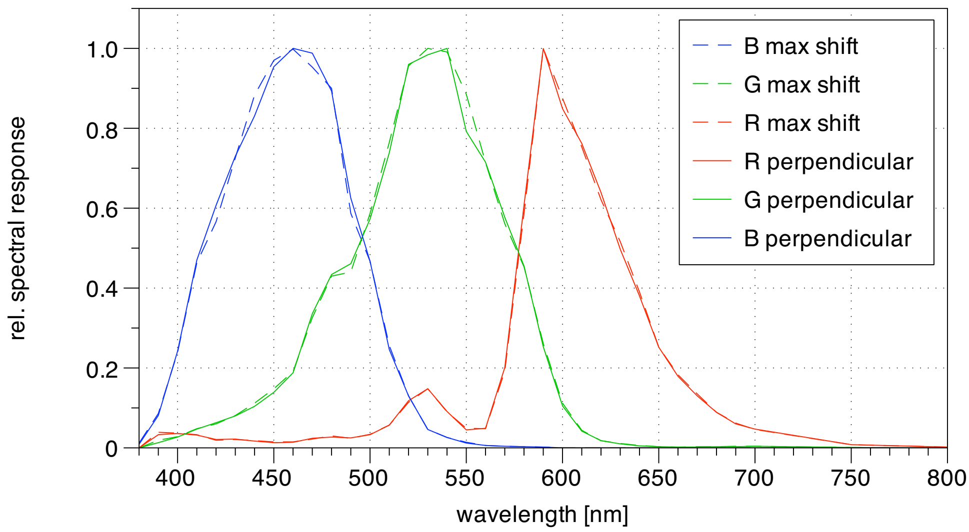

Figure 3.4: The spectral response of the Nikon D70 (scaled to unity) measured with the maximum possible shift (dashed lines) and with the camera mounted perpendicular to the inference filter (solid lines).

power at 549.21 nm. The peak value of the centered interference filter was at 549.74 nm. So there is a small shift to shorter wavelengths of 0.53 nm. For this evaluation a higher than normally used viewing angle was used to get the worst possible error.

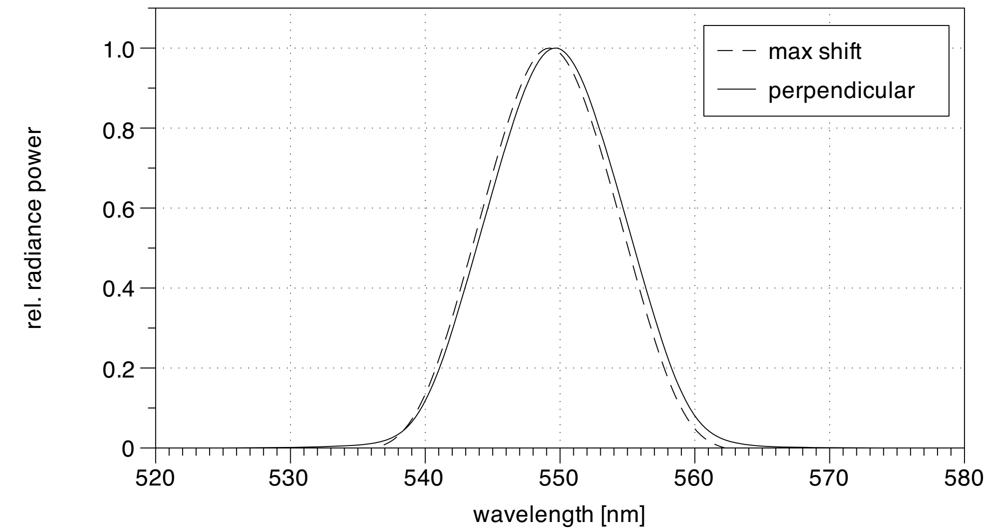

Figure 3.5: Two spectral power distribution measurements of the 550 nm filter. One placed in the corner of the image (dashed line) the other with the filter placed in the center of the image (solid line).

Figure 3.6: The used setup to evaluate the angle dependency of the interference filters. With **A** camSPECS, **B** 35 mm camera with open back, **C** spectrometer fiber-optics.

3.2 Illumination

The camSPECS hardware bases on a modified slide projector. The projector is used as a light-source to illuminate the filters. The slide transportation system is used to move the filters one after another in front of the lamp.

The power supply of the projector is extended with a voltage stabilizer. This device keeps the lamp voltage steady (24 V) even when the line voltage varies. The stabilization factor is about 1 %. This is important, since a change in lamp voltage will have an influence of the spectral power distribution of the lamp.

There are several changes in the lamp house of the projector. A diffuser improves the uniformity of the illumination. To get a more uniform spectral distribution a heat absorbing filter and a color conversion filter are used. The original 250 W lamp of the projector is replaced with a less powerful 55W lamp. So the cooling system is oversized, what helps to protect the interference filters and lamp filters from overheating. Although the heat absorbing filter blocks most of the infrared radiation, the temperature of the filter stays lower than 50° celsius.

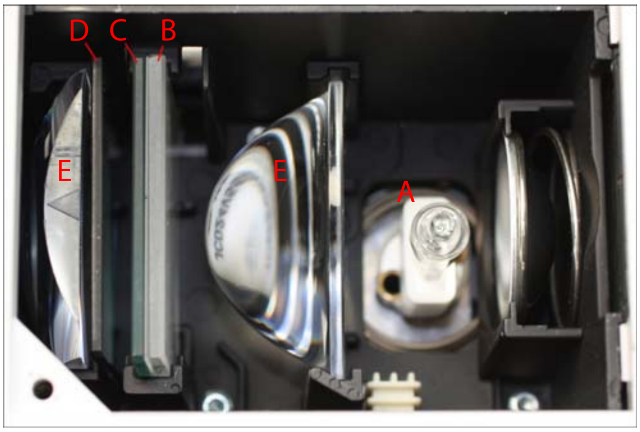

Figure 3.7: The optical system of the projector.

Figure 3.7 shows the modified optical system that is used for the measurement.

A 55W halogen lamp

B diffuser

C heat absorbing filter

D color conversion filter

E lenses

3.2.1 Uniformity of illumination

To evaluate the uniformity a neutral density slide with uniform transmittance is installed in filter plane of the device. A digital SLR camera with a high quality lens is used to photograph the neutral density slide. A large f-stop setting is used and the uniform slide just covers 10 % of the image hight. These measures minimize the influence of the lens shading on this measurement.

Figure 3.8 shows the uniformity of the illumination. The light fall off from the brightest to the darkest spot counts 30 %. This shading is acceptable considering, that the brightness from the center to the corners is monotonic decreasing.

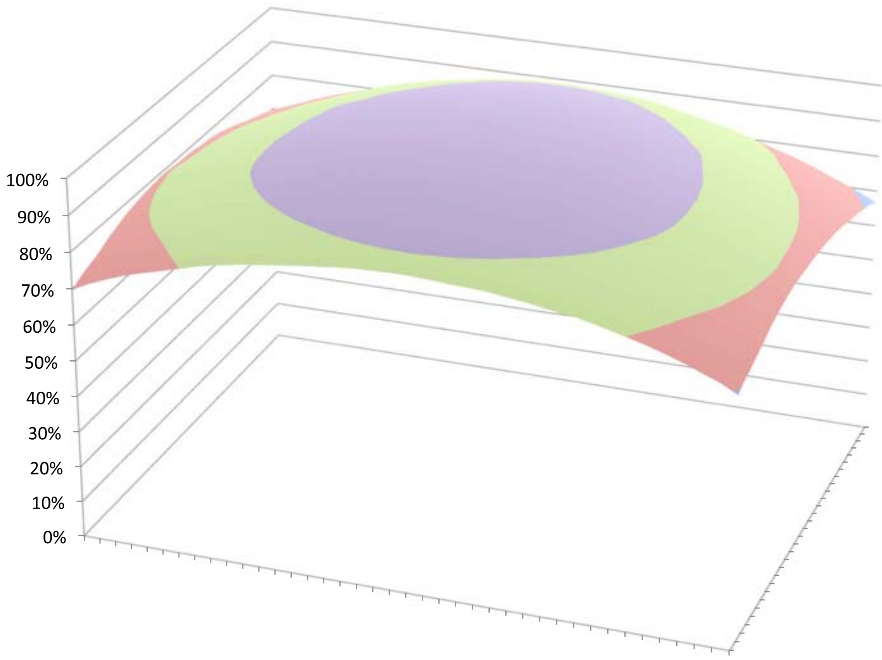

Figure 3.8: Uniformity of the illumination in the filter plane.

3.2.2 Balancing of the spectral distribution of the light source

The planckian radiator like spectral distribution of the halogen lamp causes a huge difference in radiance power passed by the interference filters. The radiance power passed by the shorter wavelength filters is much lower than the radiance power of the longer wavelength filters. Figure 3.9 shows the spectral distribution of the lamp and its influence on the relative radiance power passed by the interference filters.

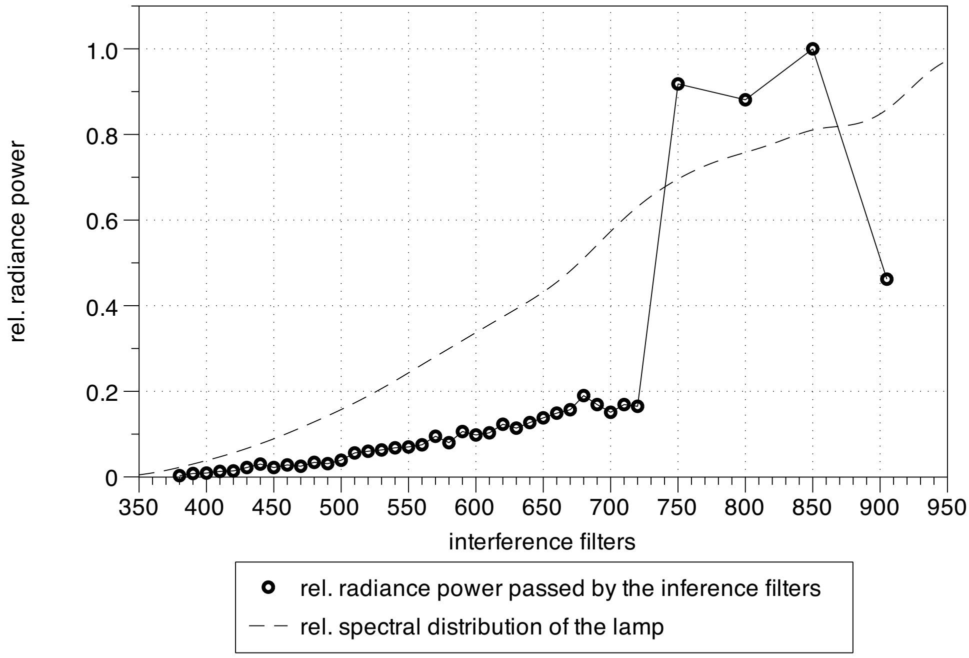

Figure 3.9: The unbalanced light source and relative radiance power passed by the interference filters.

The contrast between the brightest and the darkest filter is very high (see table 3.3). The measurement should be performed with one exposure setting for all sample channels, so the contrast should be as low as possible.

A combination of a heat absorbing filter and a color conversion filter is used to get a better balancing of the light source (see figure 3.10 on page

34). Basically the blue filter alone would be sufficient to balance the light source. To protect it from the infrared radiation the heat absorbing filter is used. The bandwidth of the interference filters at the wavelengths from 750 nm to 905 nm counts 50 nm instead of 10 nm for the rest of the other filters. Thus the radiance power passed by these filter is much higher. The additional attenuation of near infrared radiation of the heat absorbing filter helps to compensate for this issue.

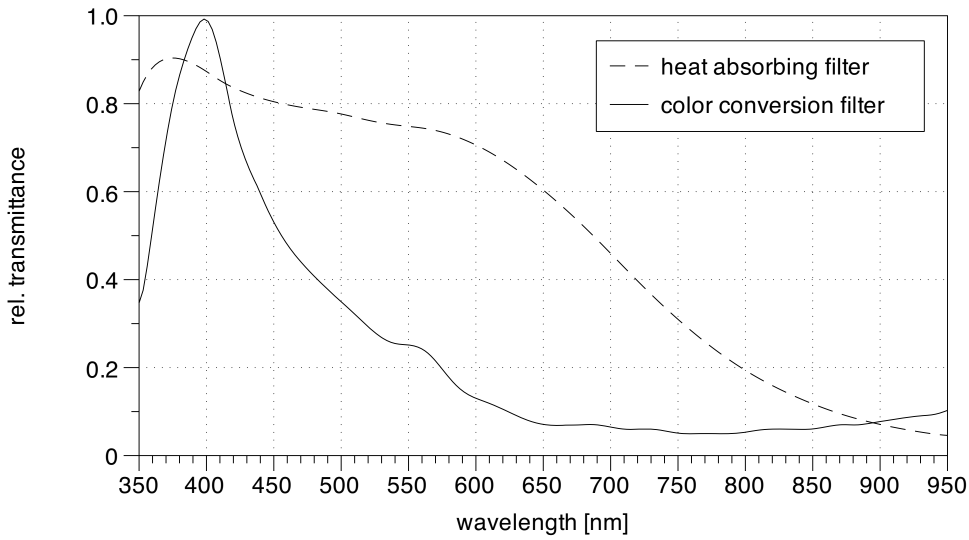

Figure 3.10: Transmittance of the heat absorbing filter (dashed line) and the color conversion filter (solid line).

Figure 3.11 (page 35) shows the multiplication of both filters compared to the light source without any filters. It is obvious, that the combination of the two filters will provide a good balancing of the light source.

The balanced light source that is used for the spectral response measurement is shown in figure 3.12 on page 35 together with the resulting radiance power emitted by the interference filters. The contrast between brightest and darkest filter is now less than 1:10. Table 3.3 on page 36 shows the contrast ratio with and without lamp filters.

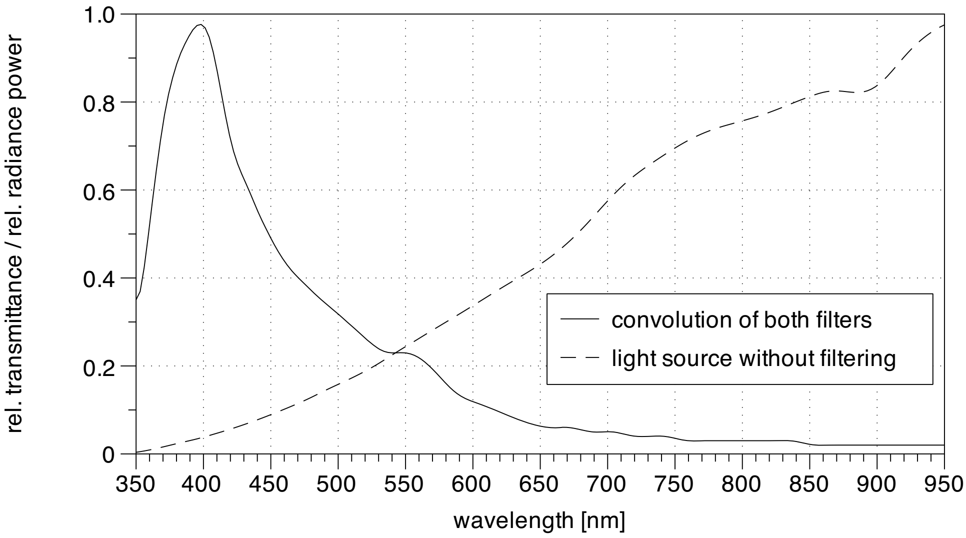

Figure 3.11: Convolution of both filters (solid line) and the light source without filters (dashed line).

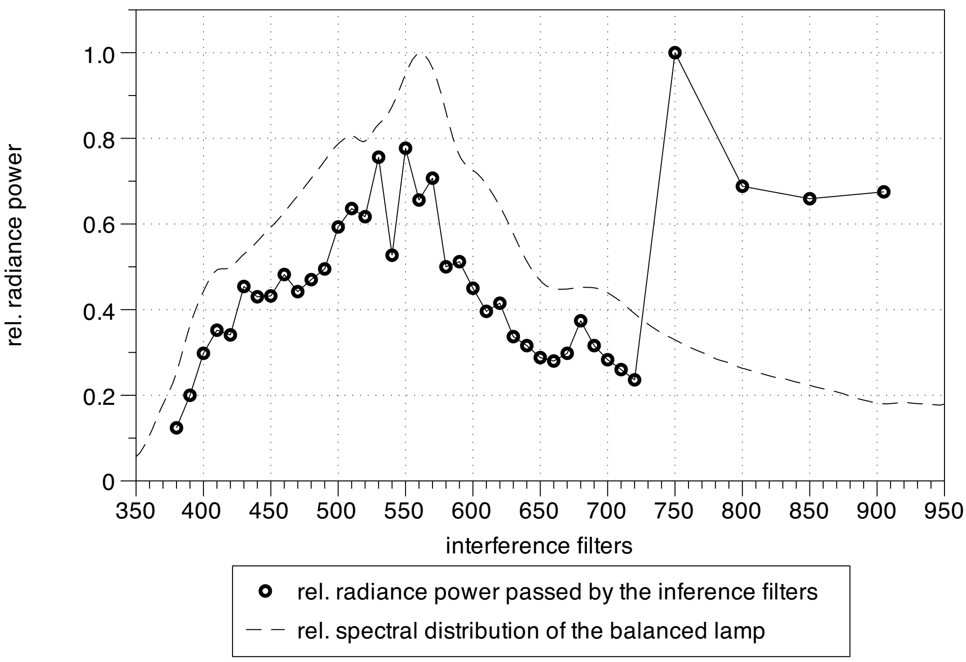

Figure 3.12: The balanced lamp used for the spectral response measurement.

Table 3.3: The contrast ratio of the radiance power with and without balanced light source.

	all filters: 380 - 905 nm	**visual area: 380 - 720 nm**
unbalanced	1:300	1:60
balanced	1:8	1:6

3.2.3 Reference channel

The reference channel is located beside the sample channel and is used as a brightness reference to correct for exposure variations. Even though all filters should have the same transmittance, there might be small variations (0.03 optical density). To compensate for this issue the filters are calibrated to consider the variations during the data processing.

To reduce the contamination of the sample channel by the reference channel, the reference channel is as dark as possible. With an optical density of 1.5 ($\tau = 3\%$) it is just bright enough to allow the camera to get a good reading on it. The signal of the sample channel depends on the spectral response of the camera, so a direct comparison is difficult. On most cameras the reference channel signal counts 40-60% of the peak signal of the sample channel.

The neutral density filters are based on silver halide film, the spectral transmittance is quite uniform. So the spectral power distribution is similar to the original light source. Due to the manufacturing process the neutral density filters show some screening.

3.2.4 Radiance power calibration

The radiance power passed by the interference filters is variable. This is caused by the balanced but not uniform spectral distribution of the light source and the different transmittance and bandwidth of the interference filters.

So a radiance power calibration is needed. The calibration is performed with a high resolution spectrometer (optical resolution about 2 nm).

An optical fiber with a collimator lens is attached to the spectrometer. A collimator is installed in front of the sample channel. To allow free movement of the transportation system the distance between the interference filters and the collimator counts 15 mm (see Figure 3.13). For each sample channel the passed spectral distribution is measured. The position of the optical fiber is not changed during one series of measurement.

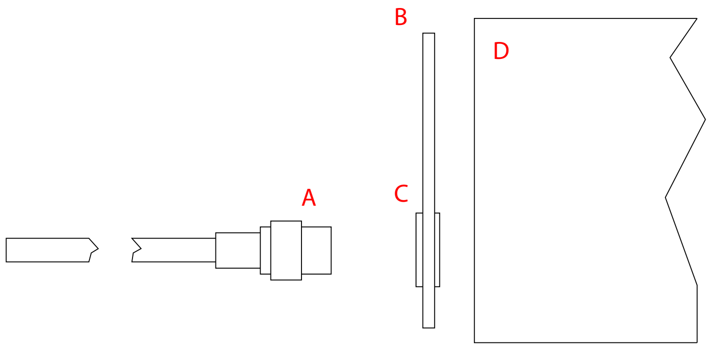

Figure 3.13: Measurement of rel. radiance power

A spectrometer optical fiber with collimator

B filter mounting plate

C interference filter

D illumination system

Figure 3.14 shows the spectral power distribution of the 540 nm filter. The data is normalized to one for this chart.

The relative radiance power of each filter is determined by calculating the integral (see equation 3.5). In practice this is done by summarizing the subtotals. Although the optical resolution of the spectrometer is 1.4 nm the data is provided with 0.27 nm resolution. So the resolution of the subtotals is much higher than the actual optical resolution.

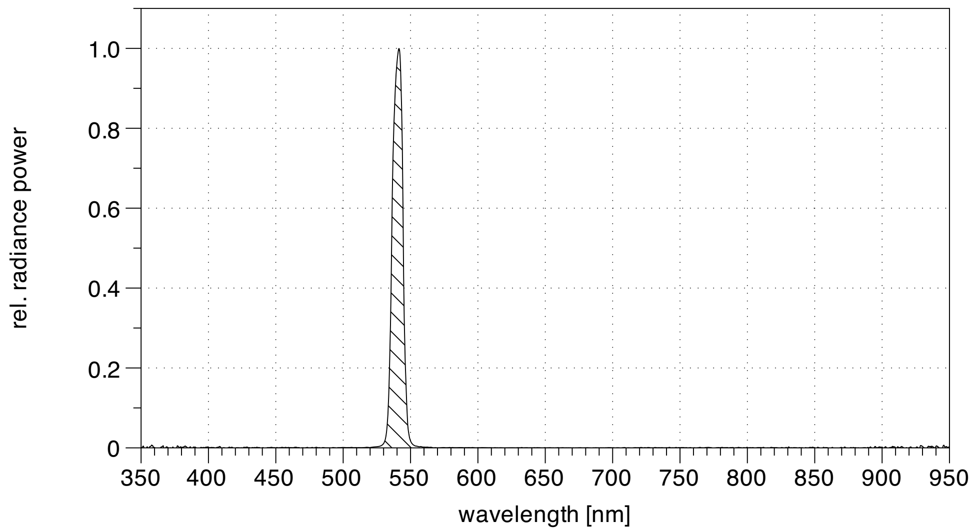

Figure 3.14: Spectral distribution of one filter

$$L_j = \int_{\lambda_l}^{\lambda_h} i(\lambda) d\lambda \tag{3.5}$$

With $\lambda_l = 350nm$ and $\lambda_h = 950nm$.

The relative radiance power is sufficient for the measurement of the relative spectral response. The data is normalized to the radiance power of the 550 nm filter.

3.3 OECF measurement

To check the image data from the camera for linearity the Opto Electronic Conversion Function [4] is measured. To provide a complete solution for the measurement of spectral response an OECF testchart with a size of a regular 35 mm slide illuminated by camSPECS is used.

Figure 3.15 shows the developed testchart for the use in camSPECS. It has a contrast of 1:1000 and is based on black and white film.

To evaluate the linearity of the camera the digital values of the patches are plotted against the transmittance of the testchart patches. Table 3.4 on page 39 shows the optical density of the test chart patches. The circular arrangement of the OECF patches allows the use of this testchart despite the not completely uniform camSPECS illumination.

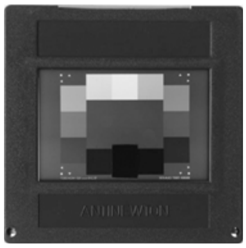

Figure 3.15: 35 mm camSPECS OECF testchart

Table 3.4: OECF testchart optical densities.

patch no.	**optical density**
1	0.22
2	0.33
3	0.54
4	0.62
5	0.84
6	0.96
7	1.16
8	1.29
9	1.62
10	1.91
11	2.43
12	3.41

Chapter 4

Measurement procedure

This chapter describes the procedure to measure the spectral response with the set of interference filters. The process of photographing the monochromatic light and the data processing is discussed.

4.1 Camera setup

4.1.1 Camera settings

Table 4.1 shows the used camera settings. Although using an automatic exposure mode is possible (see 4.3.4 on page 45) it is easier to perform the measurement with one exposure setting for all interference filters. So the manual exposure mode is used. To reduce the influence of noise the lowest possible ISO speed is selected. The measurement must be performed with RAW data, so the camera is set to save RAW-files to the memory card.

Table 4.1: Camera settings

parameter	**setting**
Exposure mode	manual
ISO Speed	lowest
autofocus	off
File type	RAW

4.1.2 Alignment

The camera is placed in front of the projector to photograph the interference filters. The shooting distance can vary from 20 cm up to several meters depending to the focal length of the used lens. The environment must be totally dark to prevent any external light influencing the measurement.

To avoid a direct reflection of the reference channel in the front lens the camera is not placed perpendicularly to the interference filter, but slightly off-center.

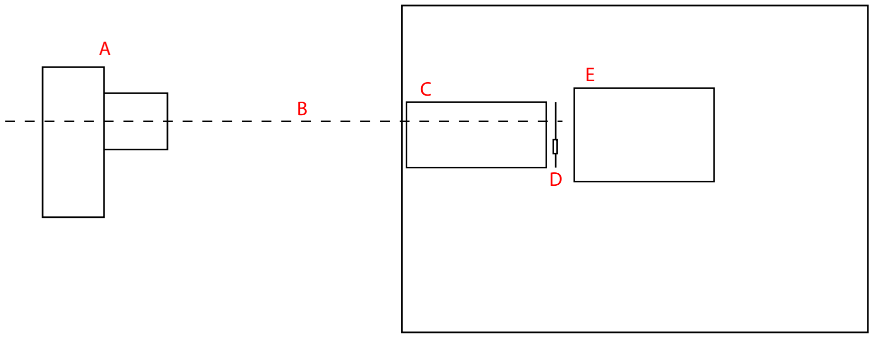

Figure 4.1: Camera mounted slightly off-center in front of camSPECS

A camera

B optical axes of the camera lens

C tube

D filter mounting plate with interference filter

E illumination system

4.1.3 Exposure

An exposure setting is used that allows the highest possible signal, while staying in the linear area of the camera's OECF (see 4.2 on page 42). To evaluate the best exposure setting normally the 550 nm channel is used. This channel has a high radiance power and most cameras have a high sensitivity in this wavelength area.

All filters including the adjustment plate need to be photographed in succession. The adjustment plate is used to setup the camera correctly and to select the positions of the filters in the images for the data processing. This additional plate is used, because on most cameras the 380 nm filter is completely dark, so it is difficult to set the region of interest correctly. The position of the camera is not changed during one series of measurement.

At the time of measurement a dark frame picture is taken with the same exposure settings. This picture is used to perform a dark frame subtraction.

4.2 Linearity

The camera's OECF must be linear to determine the spectral response from the camera's response to the narrowband light. The OECF is measured with the 35 mm OECF-testchart (see 3.3 on page 38). CCDs and CMOSs are working inherently linear, so as expected non of the cameras used for this thesis have a non-linear OECF. However, some cameras showed some kind of highlight-compression. The OECF is linear in an area from 0% up to 80% of the dynamic range, but in the area above 80% it is non-linear. To avoid this problem an exposure setting which keeps the peak signal below this non-linear area is used. Figure 4.2 shows the OECF of a camera witch has a basically linear OECF, except the highlight area.

When the OECF of the camera under test is known, it is easy to linearize the data with the inverse of the OECF. The OECF measured with the 35 mm

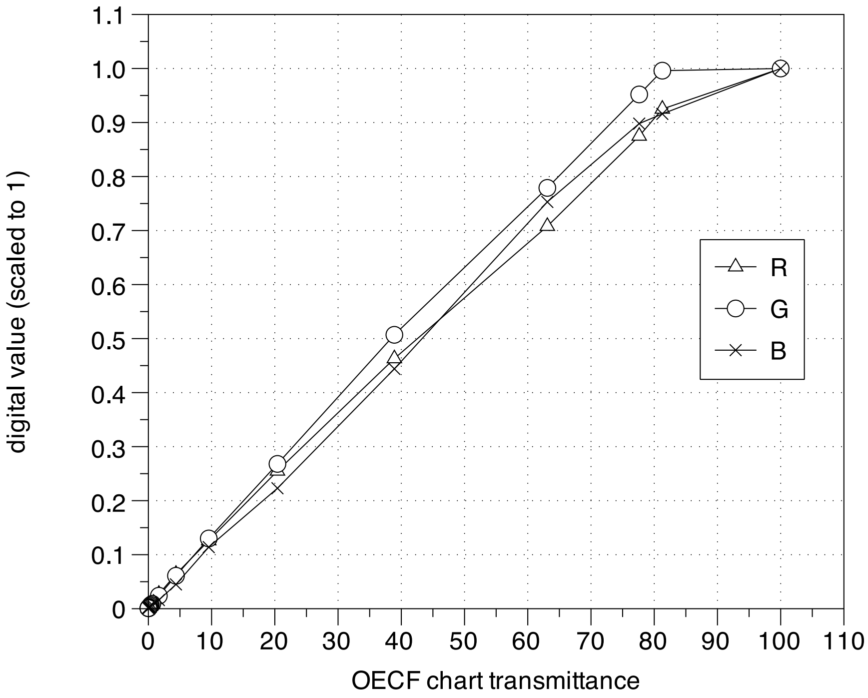

Figure 4.2: An sample OECF showing highlight-compression

test chart is not suitable to linearize the data, because there are measuring errors caused by the not absolutely uniform illumination of the test chart. It is appropriate for a visual evaluation of the linearity.

4.3 Data processing

4.3.1 RAW-file conversion

First the RAW files need to be converted to tiff-files. Dave Coffin's DCRAW [5] is used for most cameras. It offers the possibility to get unprocessed files without demosaicing. Table 4.2 shows the used DCRAW commands.

To correct for a wrong black level and to reduce fixed pattern noise, a dark

Table 4.2: DCRAW settings

command	**effect**
4	16Bit linear, no gamma correction
D	no demosaicing
T	TIFF-file instead of PPM-file

frame subtraction is performed. The dark frame picture is subtracted from all pictures of the interference filters.

4.3.2 Reading the camera's response

The response of the camera to the monochromatic light is determined by accessing an area of the size of 30% of the diameter of the interference filters. The sample and reference channel are processed in this way. The resulting data of each color filter is averaged.

4.3.3 Arrangement of the color filters

The arrangement of the color filters of the image sensor can vary (see 2.4). So there is the need to determine which color filter channel (CF) represents the RGB channels. Usually the two green channels have the same spectral response, so they are averaged.

The brightest color filter in a picture of blue monochromatic light with a CWL of 450 nm for example represents in most cases the blue channel. So it is easy to determine the arrangement of the color filter array. To detect the red color channel the picture of the 600 nm filter is evaluated. The positions of the two green channels are detected with the 540 nm filter.

4.3.4 Exposure correction

To measure the relative spectral response the exposure time must be either the same for all sample channels or the response to the monochromatic light needs to be corrected.

There are two different causes for exposure differences. First: The use of an automatic exposure mode. This might be necessary for cameras which do not feature a manual mode. Second: Shutter and aperture inaccuracies can cause exposure differences.

When different exposure settings are used, the exposure value (EV, see 2.3) is used for the correction.

Anyway the reference channel is used as a brightness reference to correct for smaller exposure variances. The reference channel itself can have small variations in transmittance. To provide a consistent reference these variations are considered by using a calibration of the reference channel.

Reference channel correction

In the following equations the index i means the i^{th} color channel, index j represents the j^{th} monochromatic color channel. "RAW" means the unprocessed response of the camera to the sample and reference channel. "SR" means the spectral response of the camera.

First the response to the reference channel is corrected with the reference channel calibration:

$$REF\_COR_j = \frac{REF\_RAW_j}{REF\_CAL_j} \tag{4.1}$$

The brightness of the reference channel is standardized to the mean value of the reference channel brightness of the i^{th} color channel. This value is the nominal brightness.

$$REF\_COR\_NOM_{ij} = \frac{REF\_COR_j}{meanvalue\_REF\_COR} \tag{4.2}$$

Correction of the camera response with the reference channel nominal brightness. The result is the cameras response to the sample channels corrected for exposure variations.

$$S\_RAW\_COR_{ij} = \frac{S\_RAW_{ij}}{REF\_COR\_NOMij} \tag{4.3}$$

Exposure value correction

Calculation of the correction value. With ISO_REF the reference ISO speed setting (100), EV_REF is the mean value of all exposure values of one series of measurement.

$$COR\_EV_j = 2^{EV_j - EV\_REF} * \frac{ISO\_REF}{ISO_j} \tag{4.4}$$

The next step is the correction of the camera response with the nominal exposure value. $S\_RAW\_COR_{ij}$ is the camera's response to the monochromatic light, corrected with the reference channel.

$$S\_RAW\_COR\_EV_{ij} = \frac{S\_RAW\_COR_{ij}}{COR\_EV_j} \tag{4.5}$$

4.3.5 Radiance power processing

As shown in chapter 3.2.2 on page 33 the radiance power L_j is not equal. So the response to the monochromatic light $S\_RAW\_COR_{ij}$ needs to be corrected with the relative radiance power L_j (see 3.2.4 on page 36).

The relative spectral response is:

$$S(\lambda)_{rel,i} = S_{ij} = \frac{S\_RAW_{ij}}{L_j} \tag{4.6}$$

4.3.6 Further processing

The spectral response is scaled depending on the further usage. A common way to scale the data is to normalize the data to the response of the green channel at 550 nm. Another possibility is the scaling to unity, so that all channels have a maximum of 1.

The sampling of the spectral response is 10 nm in an area of 380 nm to 720 nm. From 750 nm up to 905 nm it varies between 35 nm and 50 nm. The data can be interpolated to a sampling rate of 5 nm, for example.

4.4 Evaluation of the measurement

There are several ways to evaluate the quality of a spectral response measurement. The most apparent one is to compare the measurement data to the sensor data sheet. Unfortunately it is hard to get this data in most cases. Another problem is that there might be differences from device to device and important information about the test procedure is missing.

A better approach would be a comparison of one device with two different measurement procedures. For this thesis a Leica M8 was measured with camSPECS and a monochromator. The only drawback is, that the monochromator measurement was performed without a lens attached to the camera, while the camSPECS measurement requests a lens.

The most meaningful evaluation is the comparison of predicted and actual camera RGB values. With the camera response model proposed in [2] it is possible to use the spectral response data, sample spectra and illumination to predict the camera's response to these sample colors. For this test a color reproduction test chart with known spectral reflectance illuminated by a known light source is used. The predicted RGB values can be compared to the actual RGB values in an image of the test taken with camera under evaluation. The better the accuracy of the spectral response measurement, the smaller will be the difference between the predicted and the measured RGB values.

4.4.1 Comparison to the data sheet

As mentioned earlier most sensor data sheets are not published. The Kodak sensor used in the Leica M8 is an exception. A detailed data sheet is published by Kodak [6]. Figure 4.3 on page 49 shows the relative spectral response published in the data sheet and the results of a camSPECS measurement. The shapes of the curves do match quite well, while the balance of the color channels shows a difference.

Possible reasons for the differences are:

image sensor: There are no detailed information about the sensor cover glass and additional filters like the anti-aliasing lowpass. It is probable, that a slightly modified sensor is used for the final camera.

device depending spectral response: Although not very probable for a high end camera, the spectral response might vary from device to device.

camera lens: The data sheet of a sensor will not consider the spectral transmittance $\tau(\lambda)$ of the camera lenses. Figure 4.4 on page 49 shows the spectral transmittance of an example lens. It is obvious, that the lens has a huge impact on the spectral response of the camera. Unfortunately the spectral transmittance of the lens used for the camSPECS measurement is not available. So it was not possible to correct the camSPECS spectral response data for the spectral transmittance of the lens.

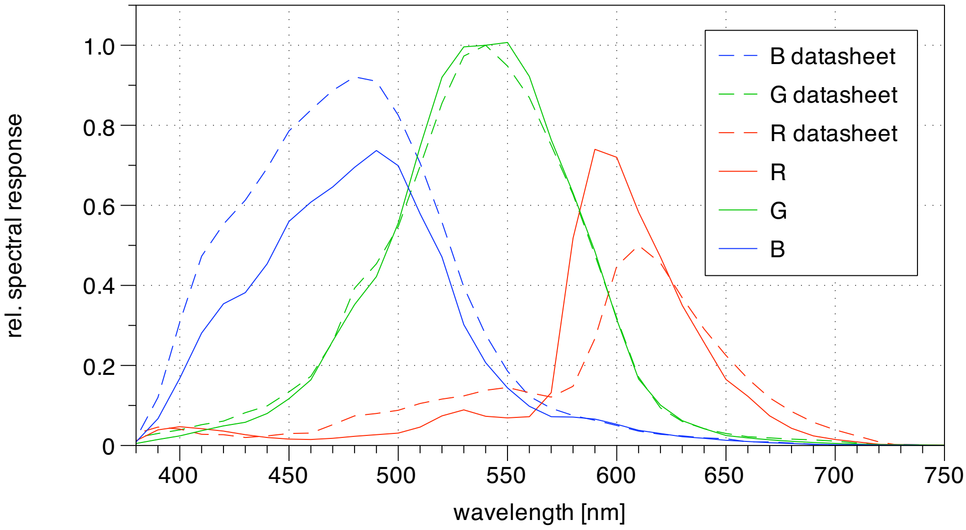

Figure 4.3: Kodak KAF-10500 sensor data sheet spectral response (dashed lines) and camSPECS measurement (solid lines).

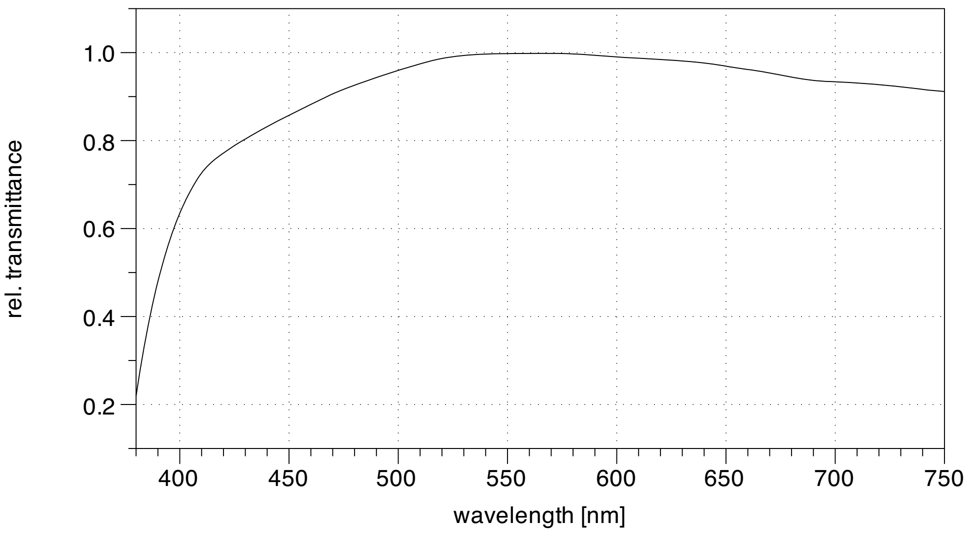

Figure 4.4: The spectral transmittance of a typical camera lens.

4.4.2 Comparison to a monochromator measurement

The standard equipment for a spectral response measurement is a monochromator. So the comparison of the measurement data from camSPECS to the data from a monochromator measurement is very interesting. Unfortunately for this thesis no monochromator was available. Using published data from other sources is not an option, because only very few data is published and there are the same drawbacks as the comparison to the sensor data sheet. The lens transmittance is not known and the spectral response might vary from device to device. Much more expressive is the measurement of *one* camera with different measurement equipment. With the support of the Leica Camera AG it was possible to measure the same Leica M8 with camSPECS and a monochromator. Figure 4.5 on page 50 shows the relative spectral response measurement with a monochromator and camSPECS. For the camSPECS measurement a lens was used, the monochromator measurement was performed without a lens attached to the camera. To make the data comparable the data from camSPECS was corrected for the influence of the lens. The comparison shows that camSPECS is able to provide similar results to the monochromator measurement.

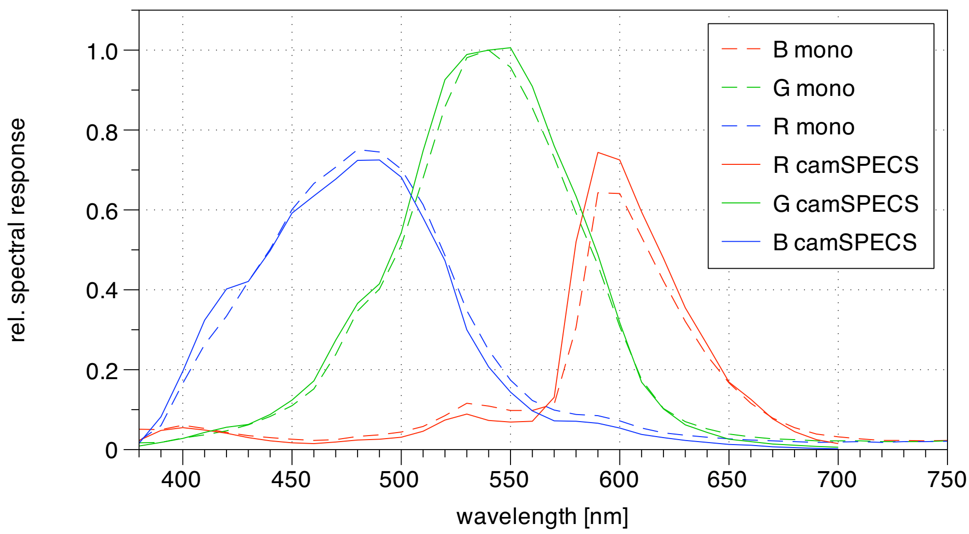

Figure 4.5: The rel. spectral response of the Leica M8 measured with a monochromator (dashed lines) and camSPECS (solid lines).

4.4.3 Evaluation with camera response models

The most expressive way to evaluate the accuracy of a spectral response measurement is to use the data for what it is normally used: The prediction of the camera response to sample colors. By using the digital camera response model proposed in [2] it is possible to simulate how the camera will react to any spectral power distribution.

Camera response model

The linear response model is described as:

$$r_i = e \int_{\lambda_l}^{\lambda_h} s_i(\lambda) i(\lambda) d\lambda + n_i \tag{4.7}$$

With i for the i^{th} color channel, e the exposure time, $s_i(\lambda)$ the spectral response of the i^{th} color channel, $i(\lambda)$ for the spectral incident power and n_i as a random variable.

The evaluation is performed with linear RAW data, so the linear response model is adequate. Due to a later discussed scaling of the value, the exposure time e is negligible. The noise value n can be ignored, too. So equation 4.7 is simplified to:

$$r_i = \int_{\lambda_l}^{\lambda_h} s_i(\lambda) i(\lambda) d\lambda \tag{4.8}$$

In the following the camera response is called r_pre_i with "pre" for predicted.

Color stimulus

For this test a color reproduction test chart (e.g. X-Rite Color Checker SG) is used. To calculate the spectral incident power i the spectral reflectance $\rho_j(\lambda)$ of the patches (index j) is measured with an X-Rite Eye One spectrometer or is taken from the data sheet of the Color Checker. The spectral power distribution of the used illumination $S(\lambda)$ is measured, too.

The color stimulus of the single test chart patches is calculated as follows:

$$i_j = \rho_j(\lambda)S(\lambda) \tag{4.9}$$

A better way to get i_j is the use of a "telescopic" spectroradiometer. These spectrometers have a viewfinder which allows measurements from a distance. So it is possible to measure the spectral incident power at the camera position. Additionally a separate measurement of the light source is not necessary. Another way to simplify the procedure is the use of transmittance color reproduction charts illuminated from the back by an integrating sphere.

Predicted camera response to the color stimulus

With the camera response model and the color stimulus the camera responses to the test colors are predicted. In the following the resulting values for the three color channels are called "predicted RGB" values. They are only expressive for the actual camera and are not comparable to other devices, because they are in the cameras "RAW RGB" color space. The predicted RGB values are normalised to one separately for all color channels. Due to this scaling the exposure time e in equation 4.7 can be neglected.

Actual RGB values

The predicted RGB values are compared to actual RGB values taken from an image of the color reproduction chart. A testchart with known spectral reflectance $\rho(\lambda)$ (see 4.4.3) is photographed with the camera under test. The spectral power distribution of the used illumination $S(\lambda)$ is measured with a spectralphotometer after a heating period of about 15 minutes. Two lamps in a reprographic arrangement are used to get a uniform illumination of the color reproduction chart.

The camera is mounted perpendicularly in front of the test chart with a distance of at least 1.5 m. The testchart is photographed with the camera set to "RAW" mode. The exposure is set in a way, so that the signal is as high as possible without getting values outside of the non-linear area of the cameras OECF (see 4.2 on page 42). To judge the exposure for unprocessed RAW-files is not easy, so an exposure bracketing is performed. For all exposure settings a black image is taken, too. The pictures are processed the same way as the RAW-files for the spectral response measurement (see 4.3.1 on page 43). The appropriate exposed picture is selected for further processing. The camera response to the sample colors is extracted from each patch of the color reproduction chart. An area with the size of 25% of each color patch is used. The amount of used pixels varies with the framing of the picture. For cameras with a low pixel count the images are taken in a way, so that the color reproduction test chart covers the complete image. The values for each color channel is averaged.
The arrangement of the color filters is detected with a similar method used for the spectral response measurement (see 4.3.3 on page 44). Since the arrangement of the color-patches of the test chart is known, it is easy to detect the red- and blue-channel. In most cases the two green color channels are equal. So they are averaged. The resulting actual RGB values r_act_i are scaled to 1 for each color channel i separately.

Comparison

The predicted r_pre_i and the actual camera response r_act_i are plotted against each other to show the results graphically. Figure 4.6 shows the camera response comparison for a Hasselblad H3d. The white patches of the used X-Rite Color Checker SG are saturated in the evaluated image. That causes a slightly bigger error in this area.

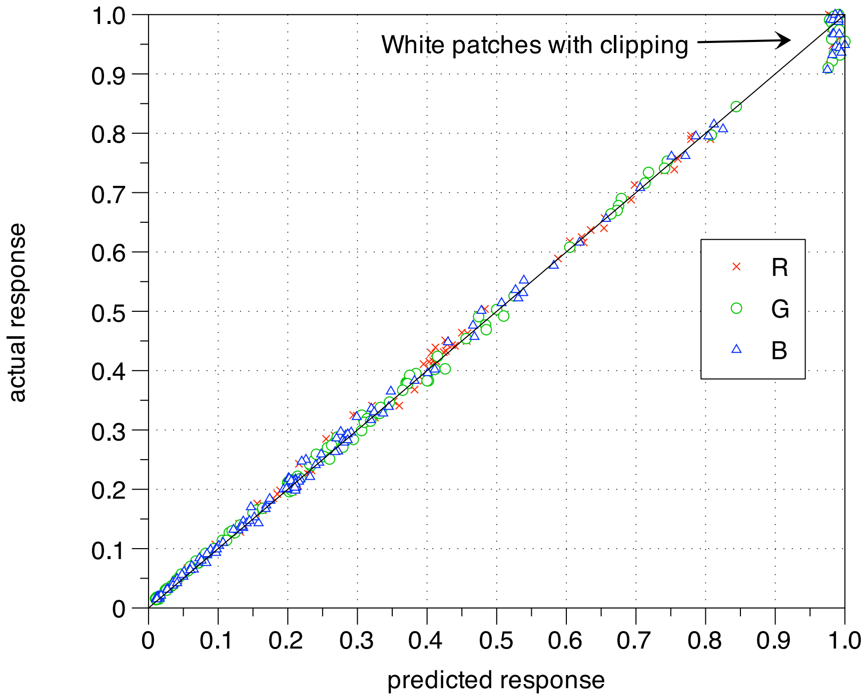

Figure 4.6: The comparison of the predicted and actual camera response.

Table 4.3 shows the relative error between the predicted and measured camera response. The average error is reasonable while the maximum error is quite high. A more detailed evaluation of the errors show, that the high errors occur at bright color patches where the camera's signal is already clipped or near to clipping. On dark patches the error is quite high, too. In the area from 5% up to 95% of the range of values the error is reasonable. The reason for the high error at dark patches might be noise from the camera and stray-light.

The evaluation with the camera response model might be more expressive when the color stimulus is measured near to the camera position. This will eliminate the influence of direct reflections of the light sources used to illuminate the color test chart. Another approach to improve the evaluation might be the use of transmittance light test charts illuminated by an integrating sphere. A spot spectrometer was not available at the time of measurement. Due to limited amount of time for this thesis it was not possible to investigate if the camera response model evaluation can be improved with the introduced measures.

Table 4.3: The relative error between the predicted and the measured camera response.

all Color Checker patches			
	R	G	B
max	35.6%	35.4%	33.8%
mean	6.5%	7.0%	6.5%

inside 5%-95% range of values			
	R	G	B
max	16.5%	15.1%	15.9%
mean	3.5%	3.5%	3.6%

4.5 Expenditure of time

An important goal of this thesis is to provide a solution that offers a fast and accurate measurement of the spectral response.

The average time used to calibrate a regular digital SLR camera is about 15 minutes. Table 4.4 shows the amount of time (minutes) that is usually necessary to perform the steps of the measurement procedure. The values depend on several factors such as the shot-to-shot time of the camera, ease of use of the camera and the used computer system. A radiance power calibration is not necessary for each measurement. The developed software (see chapter 5) greatly reduces the expenditure of time for the data processing. So the camSPECS measurement is much faster than using a complicated monochromator.

Table 4.4: Expenditure of time

	task	**time exposure**
1.	camera setup	3
2.	determination of the exposure setting	5
3.	photographing all filters	3
4.	data procssing	4

Chapter 5

Software

To reduce the expenditure of time to perform the measurement a software written with Mathworks Matlab was developed. The software performs all the former introduced tasks of data processing.

5.1 RAW processing

The RAW processing module is a batch processing tool that controls DCRAW. It is a fast and convenient way to convert RAW-files to undemosaiced tiff-files (see 4.3.1 on page 43).

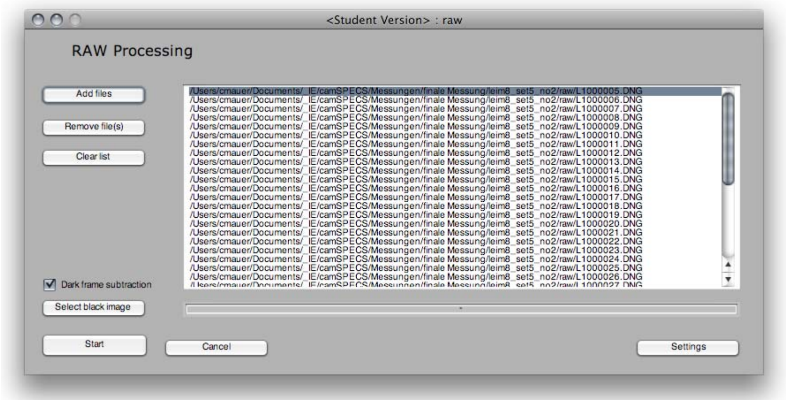

Figure 5.1: RAW processing.

5.2 Spectral response

The spectral response module performs the data processing as described (see 4.3.2 on page 44). The arrangement of the color filter array is detected automatically (see 4.3.3). A step not introduced before is that the software saves the results in a txt-file to the hard drive. The file is saved to the same directory as the tiff-files used for the evaluation. Figure 5.2 on page 59 shows the layout of the txt-file.

A: The CWLs of the interference filters.

B The final relative spectral response.

C The digital values of the reference channel.

D The exposure value of each picture.

E The unprocessed response of the camera to the monochromatic light.

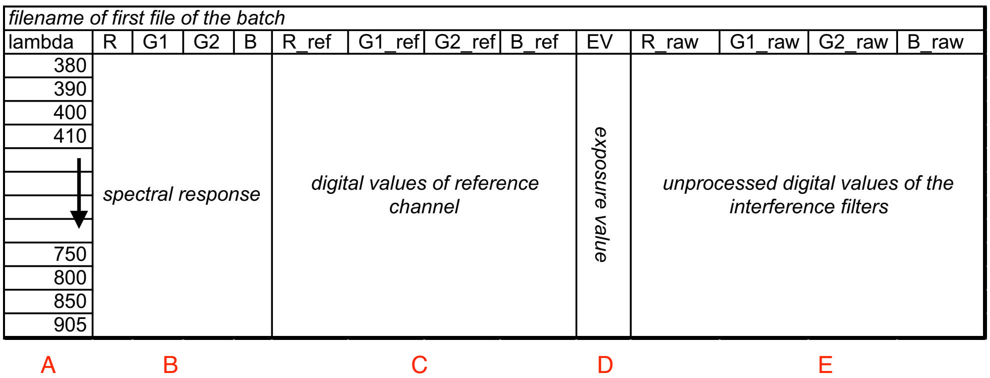

Figure 5.2: The results txt-file of the spectral response modul.

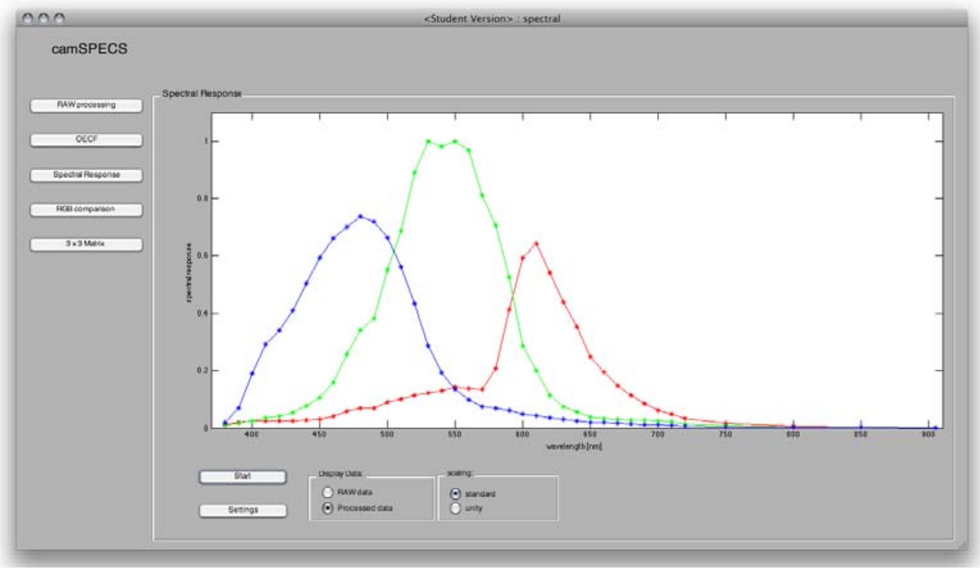

Figure 5.3: Spectral response.

5.3 OECF

The OECF module is designed to analyze the OECF test chart pictures (see 4.2 on page 42. To get a better idea of the camera's behavior it is possible to evaluate multiple pictures of an exposure bracketing. There are buttons to scroll through all evaluated files. The maximum allowed digital number can be entered in a user editable input field. The spectral response module will warn the user, if this threshold is passed.

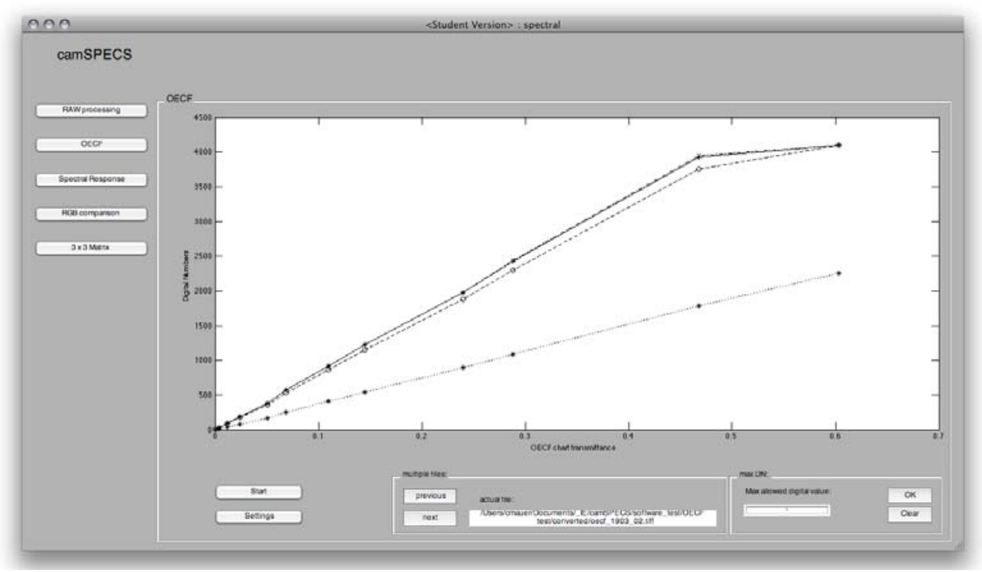

Figure 5.4: The OECF module of the camSPECS software.

5.4 RGB comparison

This module is a tool to access the quality of the spectral response measurement. A picture of a color testchart (e.g. an X-Rite Color Checker SG) is loaded to the software. The spectral reflectance of the chart is provided as a txt-file. The spectral distribution of the light source used to illuminate the test chart is loaded, too. The software performs the steps described in 4.4.3 on page 51.

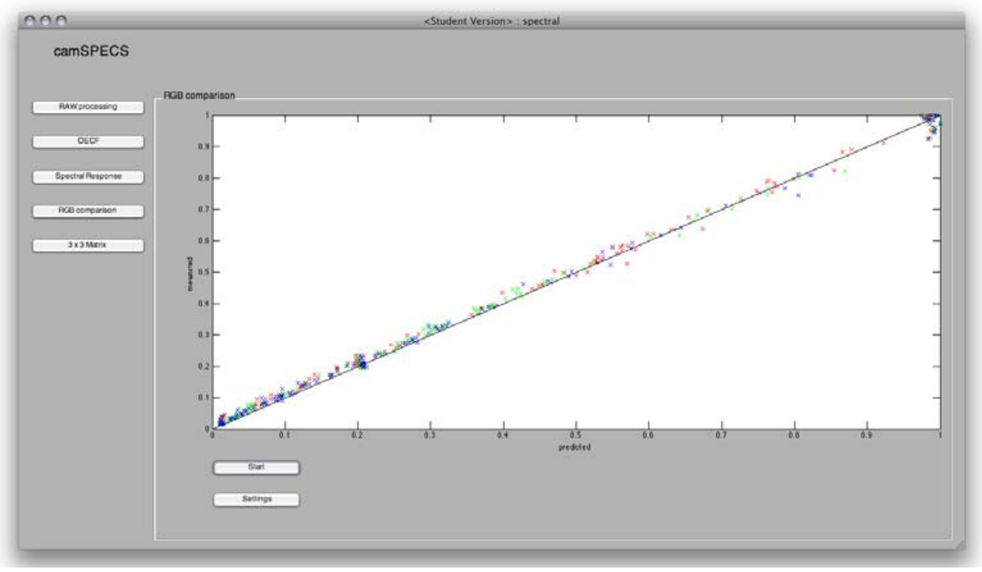

Figure 5.5: The OECF module of the camSPECS software.

Chapter 6

Conclusion

The goal of this thesis was to develop a device to measure the spectral response of a digital camera. A set of interference filters should be used together with the modified slide projector. To make the measurement convenient an evaluation software is necessary.

The advantages against a monochromator setup should be:

- Ease of use.
- Less expenditure of time.
- Affordability.

As shown, the stated goals are achieved. The system, based on a set of interference filters, is much easier to use than a monochromator and provides similiar accuracy. The complete procedure takes much less time. The cost of production of camSPECS are much lower than those of a monochromator, because much less optical parts are necessary. A monochromator setup is usually at least 3 times more expensive than camSPECS.

Further investigations

There are some points which might need further investigation.

User calibration device

To calibrate the device a spectrometer or radiometer is necessary. A easy to use and affordable calibration device based on a photodiode might be useful. It has to be investigated, if such a device offers the necessary accuracy and is easy enough to use.

One Shot device

Photographing the interference filters one after another is more accurate than using an array of interference filters. With such an array flare could cause a pollution of the light of the separate sample channels. Lens shading and the different viewing angles need to be controlled. The obvious advantage of such a device is, that only one exposure is necessary. So the measurement is very fast and even cameras without a manual exposure setting can be used easily. For cameras with a high quality lens and a high pixel count an array of interference filters might be appropriate.

Color correction matrix and training data

A feature which could be added to the software is the generation of the 3x3 color transformation matrix. This is the most important application of the spectral response data, so it seems to be natural to offer this function in the camSPECS software. The generate the matrix a set of sample spectra called training data is needed. It is planed to gather as much as possible spectral reflectance data of different objects.

Appendix A

Results

In this chapter the measurement results of several cameras used for this thesis are shown graphically and numerically. Some of the measurements were performed with former hard- and software versions of camSPECS. They are not suitable to judge the quality of the final device.

A.1 Production-model results

The spectral response of following cameras were measured with the final or near to final camSPECS hard- and software.

A.1.1 Leica M8

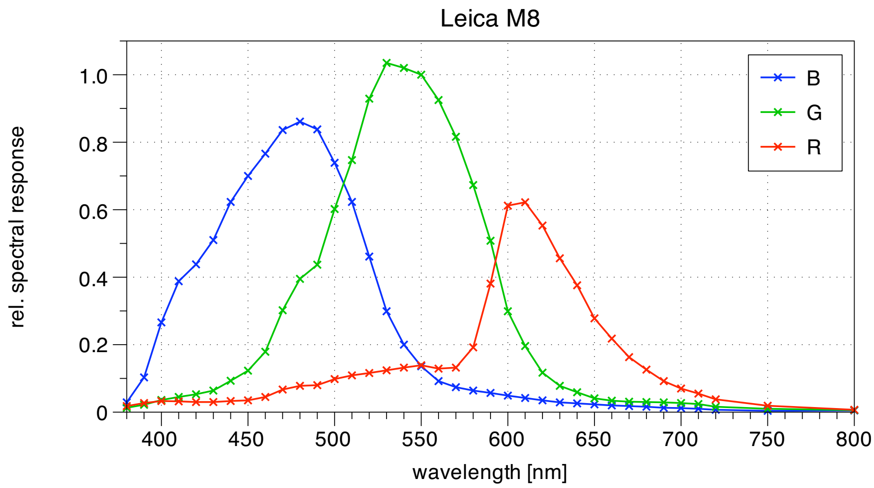

Figure A.1: Leica M8

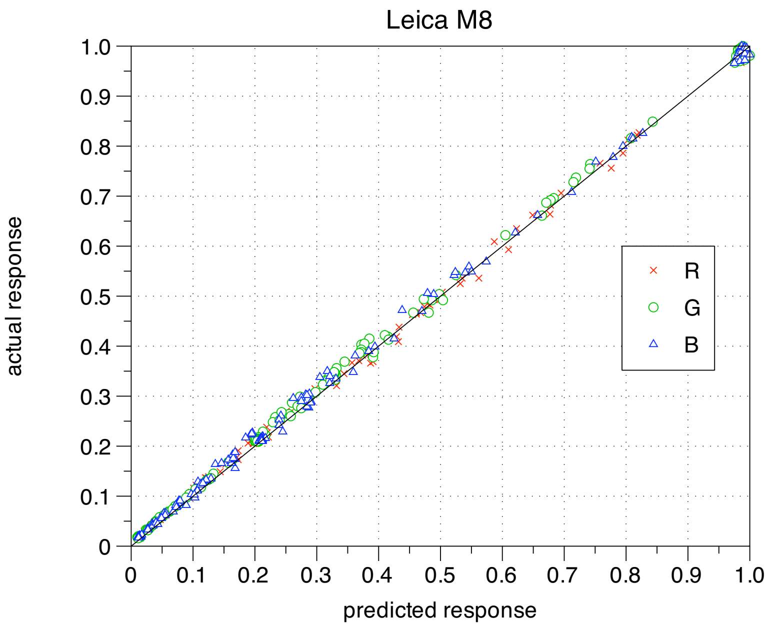

Figure A.2: Leica M8 RGB comparison

all Color Checker patches			
	R	G	B
max	45.3%	44.8%	43.5%
mean	8.0%	8.9%	8.8%

inside 5%-95% range of values			
	R	G	B
max	13.9%	15.4%	18.8%
mean	3.9%	5.0%	5.4%

(a) Leica M8 relative error.

	R	**G**	**B**
380	0.02	0.01	0.03
390	0.03	0.02	0.10
400	0.03	0.04	0.27
410	0.03	0.04	0.39
420	0.03	0.05	0.44
430	0.03	0.06	0.51
440	0.03	0.09	0.62
450	0.04	0.12	0.70
460	0.05	0.18	0.77
470	0.07	0.30	0.84
480	0.08	0.40	0.86
490	0.08	0.44	0.84
500	0.10	0.60	0.74
510	0.11	0.75	0.62
520	0.12	0.93	0.46
530	0.12	1.03	0.30
540	0.13	1.02	0.20
550	0.14	1.00	0.14
560	0.13	0.92	0.09
570	0.13	0.82	0.07
580	0.19	0.67	0.06
590	0.38	0.51	0.06
600	0.61	0.30	0.05
610	0.62	0.20	0.04
620	0.55	0.12	0.04
630	0.46	0.08	0.03
640	0.38	0.06	0.03
650	0.28	0.04	0.02
660	0.22	0.03	0.02
670	0.16	0.03	0.02
680	0.13	0.03	0.02
690	0.09	0.03	0.01
700	0.07	0.03	0.01
710	0.06	0.02	0.01
720	0.04	0.02	0.01
750	0.02	0.01	0.00
800	0.01	0.01	0.00
850	0.00	0.00	0.00
905	0.00	0.00	0.00

(b) Leica M8 spectral response

Table A.1: Leica M8 results.

A.1.2 Nikon D700

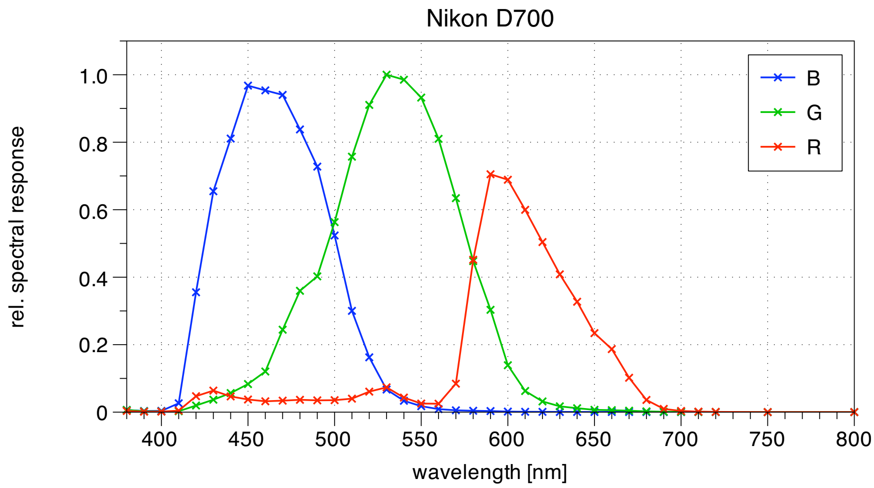

Figure A.3: Nikon D700

Table A.2: Spectral response of the Nikon D700.

	R	**G**	**B**
380	0.00	0.01	0.01
390	0.00	0.00	0.00
400	0.00	0.00	0.00
410	0.00	0.00	0.03
420	0.05	0.02	0.38
430	0.07	0.04	0.70
440	0.05	0.06	0.87
450	0.04	0.09	1.04
460	0.03	0.13	1.02
470	0.04	0.26	1.01
480	0.04	0.39	0.90
490	0.04	0.43	0.78
500	0.04	0.60	0.56
510	0.04	0.81	0.32
520	0.07	0.98	0.17
530	0.08	1.07	0.07
540	0.05	1.06	0.04
550	0.03	1.00	0.02
560	0.03	0.87	0.01
570	0.09	0.68	0.01
580	0.48	0.48	0.00
590	0.76	0.33	0.00
600	0.74	0.15	0.00
610	0.64	0.07	0.00
620	0.54	0.03	0.00
630	0.44	0.02	0.00
640	0.35	0.01	0.00
650	0.25	0.01	0.00
660	0.20	0.01	0.00
670	0.11	0.00	0.00
680	0.04	0.00	0.00
690	0.01	0.00	0.00
700	0.00	0.00	0.00
710	0.00	0.00	0.00
720	0.00	0.00	0.00
750	0.00	0.00	0.00
800	0.00	0.00	0.00
850	0.00	0.00	0.00
905	0.00	0.00	0.00

A.1.3 Canon EOS 40D

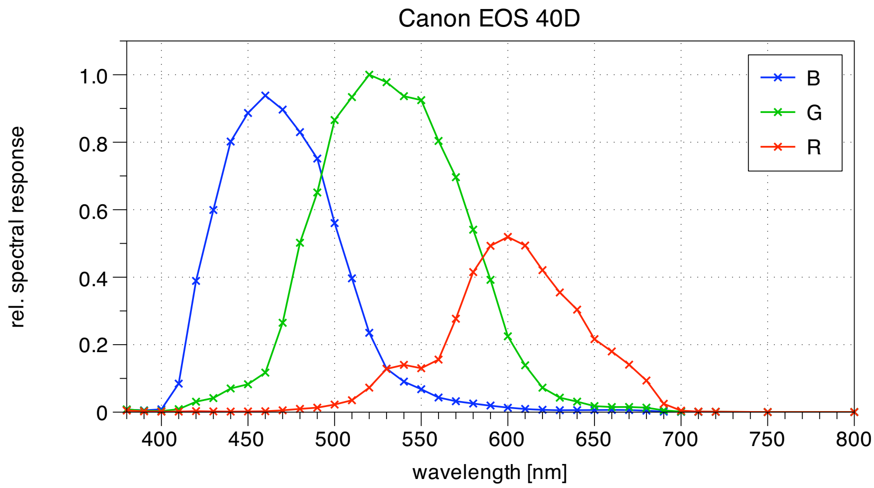

Figure A.4: Canon EOS 40D

Table A.3: Canon EOS 40D

	R	**G**	**B**
380	0.01	0.01	0.01
390	0.00	0.00	0.01
400	0.00	0.00	0.01
410	0.00	0.01	0.09
420	0.00	0.03	0.42
430	0.00	0.05	0.65
440	0.00	0.08	0.87
450	0.00	0.09	0.96
460	0.00	0.13	1.01
470	0.01	0.29	0.97
480	0.01	0.54	0.90
490	0.01	0.70	0.81
500	0.02	0.94	0.61
510	0.04	1.01	0.43
520	0.08	1.08	0.25
530	0.14	1.06	0.14
540	0.15	1.01	0.10
550	0.14	1.00	0.07
560	0.17	0.87	0.05
570	0.30	0.75	0.04
580	0.45	0.58	0.03
590	0.53	0.42	0.02
600	0.56	0.24	0.01
610	0.53	0.15	0.01
620	0.46	0.08	0.01
630	0.38	0.05	0.01
640	0.33	0.03	0.01
650	0.23	0.02	0.01
660	0.19	0.02	0.01
670	0.15	0.02	0.01
680	0.10	0.01	0.00
690	0.03	0.01	0.00
700	0.00	0.00	0.00
710	0.00	0.00	0.00
720	0.00	0.00	0.00
750	0.00	0.00	0.00
800	0.00	0.00	0.00
850	0.00	0.00	0.00
905	0.00	0.00	0.00

A.1.4 Fuji S5 Pro

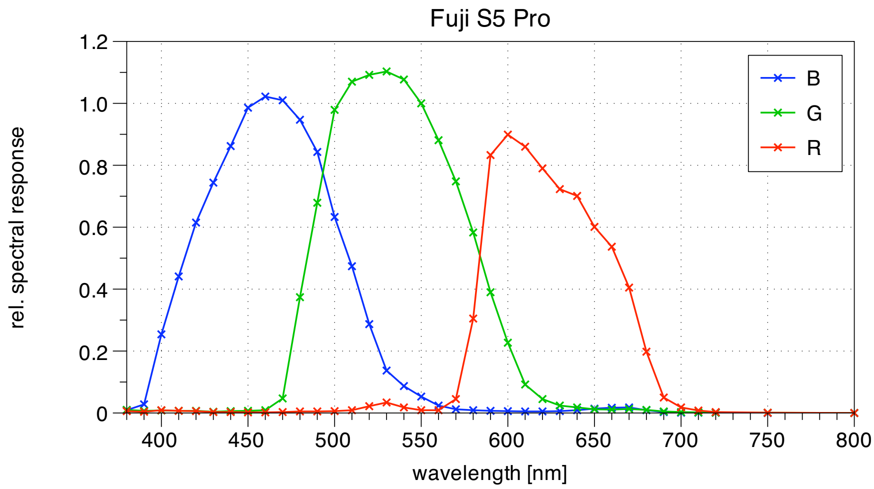

Figure A.5: Fuji S5 Pro

Table A.4: Fuji S5 Pro

	R	**G**	**B**
380	0.01	0.01	0.01
390	0.00	0.01	0.03
400	0.01	0.01	0.25
410	0.01	0.01	0.44
420	0.01	0.01	0.62
430	0.00	0.00	0.74
440	0.00	0.01	0.86
450	0.00	0.01	0.99
460	0.00	0.01	1.02
470	0.00	0.05	1.01
480	0.01	0.37	0.95
490	0.01	0.68	0.84
500	0.01	0.98	0.63
510	0.01	1.07	0.47
520	0.02	1.09	0.29
530	0.03	1.10	0.14
540	0.02	1.08	0.09
550	0.01	1.00	0.05
560	0.01	0.88	0.02
570	0.05	0.75	0.01
580	0.31	0.58	0.01
590	0.83	0.39	0.01
600	0.90	0.23	0.01
610	0.86	0.09	0.01
620	0.79	0.05	0.01
630	0.72	0.02	0.01
640	0.70	0.02	0.01
650	0.60	0.01	0.01
660	0.54	0.01	0.02
670	0.41	0.01	0.02
680	0.20	0.01	0.01
690	0.05	0.01	0.00
700	0.02	0.00	0.00
710	0.01	0.00	0.00
720	0.00	0.00	0.00
750	0.00	0.00	0.00
800	0.00	0.00	0.00
850	0.00	0.00	0.00
900	0.00	0.00	0.00

A.1.5 Panasonic DMC-LX3

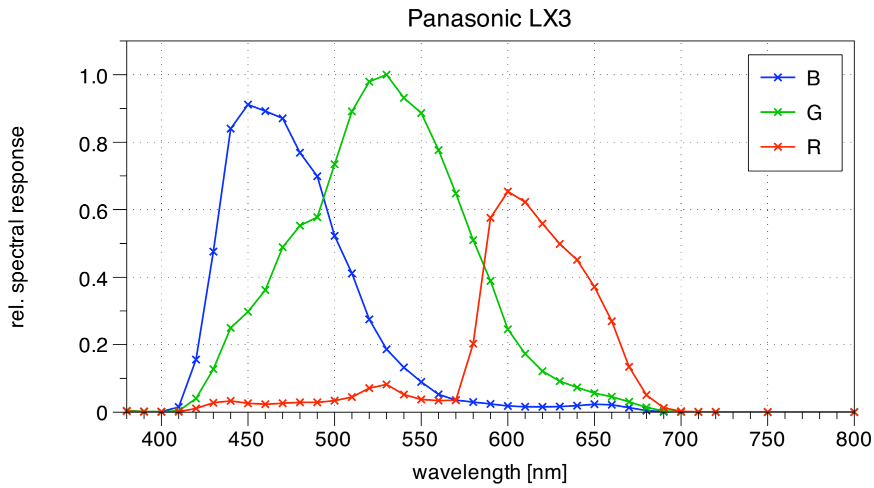

Figure A.6: Panasonic DMC-LX3

Table A.5: Panasonic DMC-LX3

	R	**G**	**B**
380	0.00	0.00	0.00
390	0.00	0.00	0.00
400	0.00	0.00	0.00
410	0.00	0.00	0.02
420	0.01	0.05	0.18
430	0.03	0.14	0.54
440	0.04	0.28	0.95
450	0.03	0.34	1.03
460	0.03	0.41	1.01
470	0.03	0.55	0.98
480	0.03	0.62	0.87
490	0.03	0.65	0.79
500	0.04	0.83	0.59
510	0.05	1.01	0.46
520	0.08	1.10	0.31
530	0.09	1.13	0.21
540	0.06	1.05	0.15
550	0.04	1.00	0.10
560	0.04	0.88	0.06
570	0.04	0.73	0.04
580	0.23	0.58	0.03
590	0.65	0.44	0.03
600	0.74	0.28	0.02
610	0.70	0.20	0.02
620	0.63	0.14	0.02
630	0.56	0.10	0.02
640	0.51	0.08	0.02
650	0.42	0.06	0.03
660	0.30	0.05	0.02
670	0.15	0.03	0.02
680	0.06	0.02	0.01
690	0.01	0.00	0.00
700	0.00	0.00	0.00
710	0.00	0.00	0.00
720	0.00	0.00	0.00
750	0.00	0.00	0.00
800	0.00	0.00	0.00
850	0.00	0.00	0.00
905	0.00	0.00	0.00

A.1.6 Arriflex D-21

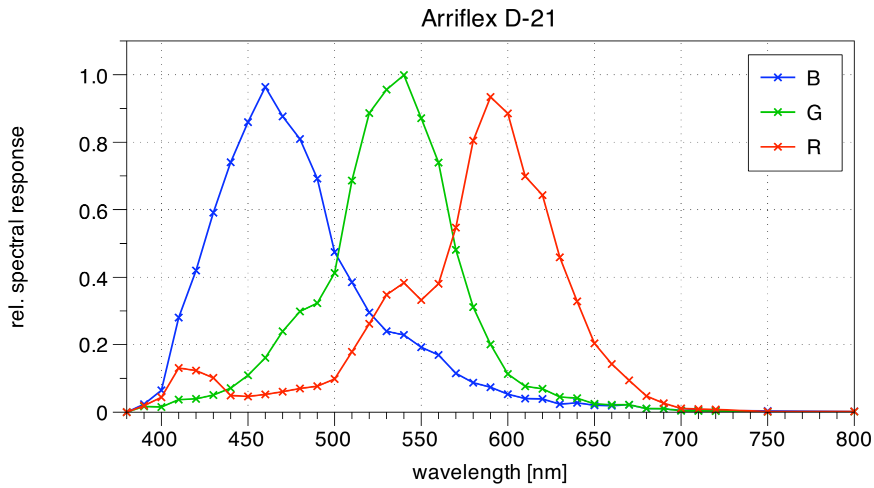

Figure A.7: Arriflex D-21

Table A.6: Arriflex D-21

	R	**G**	**B**
380	0.00	0.00	0.00
390	0.02	0.02	0.03
400	0.05	0.02	0.07
410	0.15	0.04	0.32
420	0.14	0.05	0.48
430	0.12	0.06	0.68
440	0.06	0.08	0.85
450	0.05	0.13	0.99
460	0.06	0.18	1.11
470	0.07	0.27	1.01
480	0.08	0.34	0.93
490	0.09	0.37	0.79
500	0.11	0.47	0.54
510	0.21	0.79	0.44
520	0.30	1.02	0.34
530	0.40	1.10	0.28
540	0.44	1.15	0.26
550	0.38	1.00	0.22
560	0.44	0.85	0.19
570	0.63	0.55	0.13
580	0.92	0.36	0.10
590	1.07	0.23	0.08
600	1.02	0.13	0.06
610	0.80	0.09	0.05
620	0.74	0.08	0.04
630	0.53	0.05	0.03
640	0.38	0.05	0.03
650	0.23	0.03	0.02
660	0.16	0.03	0.02
670	0.11	0.03	0.02
680	0.05	0.01	0.01
690	0.03	0.01	0.01
700	0.01	0.00	0.01
710	0.01	0.00	0.01
720	0.01	0.00	0.01
750	0.00	0.00	0.00
800	0.00	0.00	0.00
850	0.01	0.01	0.01
905	0.00	0.00	0.00

A.1.7 Canon EOS 450D no IR filter

It was possible to measure the spectral response of a modified Canon EOS 450D without IR blocking filter. A camera without infrared blocking filter is commonly used for astronomy or the reproduction of artwork.

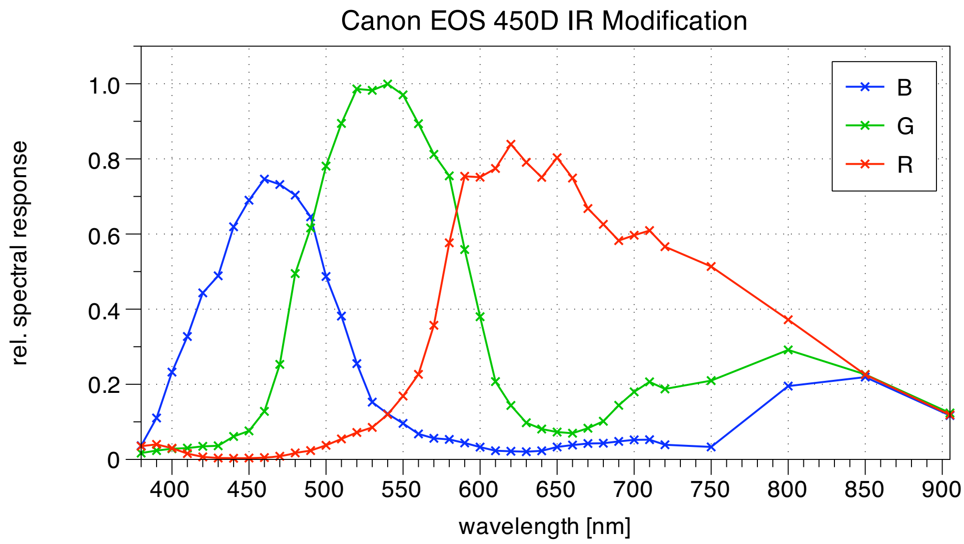

Figure A.8: Canon EOS 450D IR Modification

Table A.7: Canon EOS 450D IR Modification

	R	**G**	**B**
380	0.04	0.02	0.04
390	0.04	0.02	0.11
400	0.03	0.03	0.24
410	0.02	0.03	0.34
420	0.01	0.04	0.46
430	0.00	0.04	0.50
440	0.00	0.06	0.64
450	0.00	0.08	0.71
460	0.01	0.13	0.77
470	0.01	0.26	0.75
480	0.02	0.51	0.73
490	0.02	0.64	0.67
500	0.04	0.81	0.50
510	0.06	0.92	0.39
520	0.07	1.02	0.26
530	0.09	1.01	0.16
540	0.12	1.03	0.13
550	0.17	1.00	0.10
560	0.23	0.92	0.07
570	0.37	0.84	0.06
580	0.59	0.78	0.06
590	0.78	0.58	0.05
600	0.77	0.39	0.03
610	0.80	0.21	0.02
620	0.87	0.15	0.02
630	0.82	0.10	0.02
640	0.77	0.08	0.02
650	0.83	0.08	0.03
660	0.77	0.07	0.04
670	0.69	0.09	0.04
680	0.65	0.11	0.04
690	0.60	0.15	0.05
700	0.62	0.19	0.05
710	0.63	0.21	0.05
720	0.58	0.19	0.04
750	0.53	0.22	0.03
800	0.38	0.30	0.20
850	0.23	0.23	0.23
905	0.12	0.13	0.12

A.2 Pre-production-model results

The data shown in this section was measured with a pre-production-model of camSPECS. The accuracy might be lower than on the final product.

A.2.1 Hasselblad H3D

Although measured with pre-production hardware the evaluation of the measurement shows that the accuracy is comparable to the production-model.

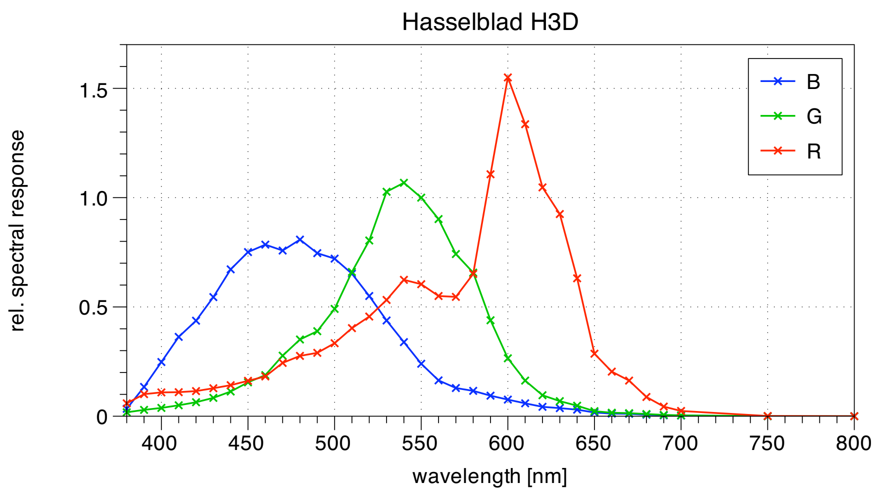

Figure A.9: Hasselblad H3D

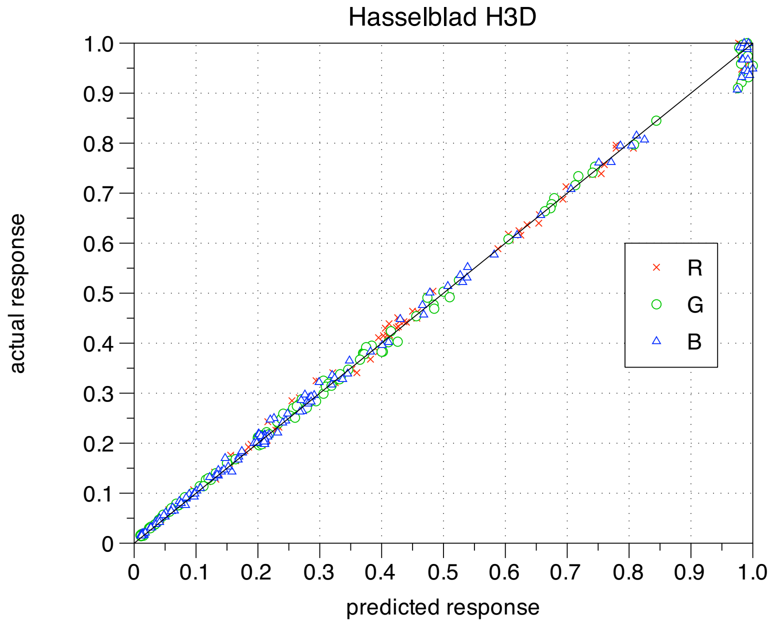

Figure A.10: Hasselblad H3D

all Color Checker patches			
	R	G	B
max	35.6%	35.4%	33.8%
mean	6.5%	7.0%	6.5%

inside 5%-95% range of values			
	R	G	B
max	16.5%	15.1%	15.9%
mean	3.5%	3.5%	3.6%

(a) Hasselblad H3D relative error.

	R	**G**	**B**
380	0.06	0.02	0.03
390	0.10	0.03	0.13
400	0.11	0.04	0.25
410	0.11	0.05	0.36
420	0.12	0.06	0.44
430	0.13	0.08	0.55
440	0.14	0.11	0.67
450	0.16	0.16	0.75
460	0.18	0.19	0.79
470	0.24	0.28	0.76
480	0.28	0.35	0.81
490	0.29	0.39	0.75
500	0.33	0.49	0.72
510	0.40	0.66	0.65
520	0.46	0.80	0.55
530	0.53	1.03	0.44
540	0.62	1.07	0.34
550	0.60	1.00	0.24
560	0.55	0.90	0.16
570	0.55	0.74	0.13
580	0.65	0.66	0.12
590	1.11	0.44	0.09
600	1.55	0.27	0.08
610	1.34	0.16	0.06
620	1.05	0.10	0.04
630	0.93	0.07	0.04
640	0.63	0.05	0.03
650	0.29	0.02	0.02
660	0.20	0.02	0.01
670	0.16	0.01	0.01
680	0.09	0.01	0.01
690	0.04	0.01	0.00
700	0.02	0.00	0.00
750	0.00	0.00	0.00
800	0.00	0.00	0.00
850	0.00	0.00	0.00
906	0.00	0.00	0.00

(b) Hasselblad H3D spectral response.

Table A.8: Hasselblad H3D results.

A.2.2 Nikon D200

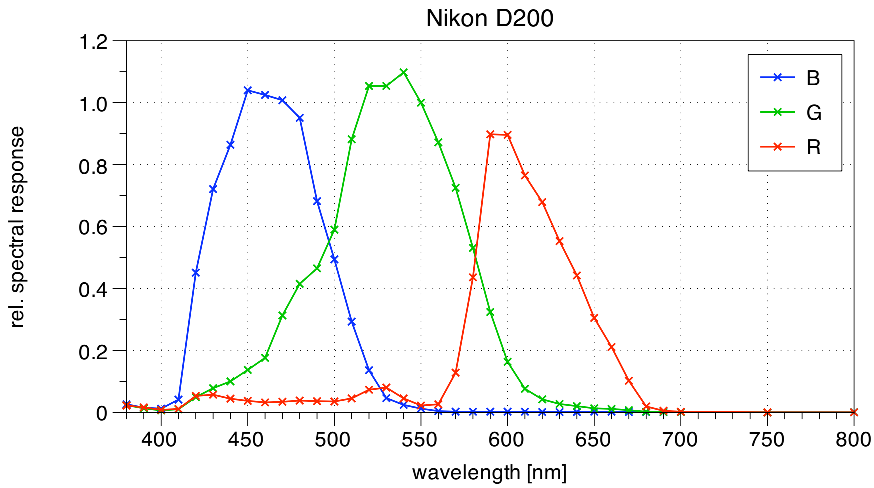

Figure A.11: Nikon D200

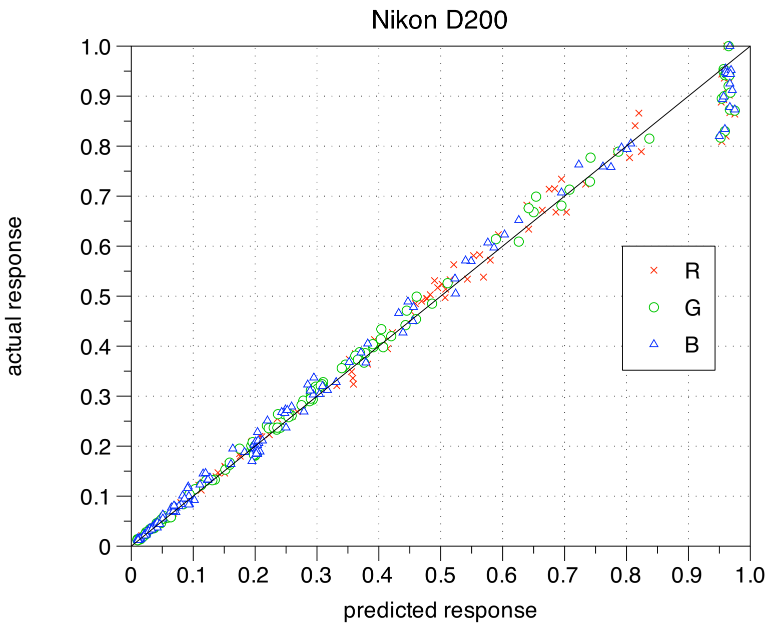

Figure A.12: Nikon D200

all Color Checker patches			
	R	G	B
max	36.9%	30.6%	30.9%
mean	6.2%	5.6%	7.4%

inside 5%-95% range of values			
	R	G	B
max	13.0%	12.0%	22.5%
mean	4.1%	4.3%	6.6%

(a) Nikon D200 relative error.

	R	**G**	**B**
380	0.02	0.02	0.03
390	0.02	0.01	0.02
400	0.01	0.01	0.01
410	0.01	0.01	0.04
420	0.05	0.05	0.45
430	0.06	0.08	0.72
440	0.04	0.10	0.86
450	0.04	0.14	1.04
460	0.03	0.18	1.03
470	0.03	0.31	1.01
480	0.04	0.42	0.95
490	0.04	0.47	0.68
500	0.03	0.59	0.49
510	0.05	0.88	0.29
520	0.07	1.05	0.14
530	0.08	1.05	0.05
540	0.04	1.10	0.02
550	0.02	1.00	0.01
560	0.03	0.87	0.00
570	0.13	0.72	0.00
580	0.44	0.53	0.00
590	0.90	0.32	0.00
600	0.90	0.16	0.00
610	0.77	0.08	0.00
620	0.68	0.04	0.00
630	0.55	0.03	0.00
640	0.44	0.02	0.00
650	0.31	0.01	0.00
660	0.21	0.01	0.00
670	0.10	0.01	0.00
680	0.02	0.00	0.00
690	0.00	0.00	0.00
700	0.00	0.00	0.00
750	0.00	0.00	0.00
800	0.00	0.00	0.00
850	0.00	0.00	0.00
906	0.00	0.00	0.00

(b) Nikon D200 spectral response.

Table A.9: Nikon D200 results.

Appendix B

Acknowledgment

I would like to thank the team of Image Engineering Dietmar Wüller. Special thanks go to Eric Walowit for his expertise and the Leica Camera AG for suppling cameras and comparison data.

Appendix C

Remarks

Affirmation / 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, den 14. Januar 2009

Unterschrift
(Vorname, Nachname)

Remark of closure / Sperrvermerk

This thesis is not closed.
Die vorgelegte Arbeit unterliegt keinem Sperrvermerk.

Declaration of publication / Weitergabeerklärung

I declare, that this thesis and / or a copy of it may be used for scientific purposes.

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

Köln, den 14. Januar 2009

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