Verification and extention of a camera based calibration method for projection displays

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Master's Thesis
Master of Science in Media Technology
30 ECTS
Department of Computer Science and Media Technology
Gjøvik University College, 2007

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1 Abstract

In the everyday use of projection displays devices calibration is rarely a considered issue. This can lead to a projected result that widely diverts from the intended appearance. In 2006 Raja Bala and Karen Braun presented a camera based calibration method for projection displays. This method aims to easily achieve a quick and decent calibration with only the use of a consumer digital photo camera. In this masters thesis the method has been implemented and investigated. The first goal was to investigate the methods performance, and thereby possibly verify and justify the use of this method. Secondly extensions were added to the method with the aim to improve method performance.

Though some factors in the method have been found troublesome, the method is confirmed to work quite well. But experiments show that this calibration approach might be more effective for some projection displays then others. When adding extensions to this method it enhanced performance results even further. And a extended version of the original model gives the best results in the experiments performed. Conclusions have been drawn on the basis of numeric and visual evaluations.

2 Sammendrag

I hverdags bruken av video prosjektører er fargekalibrering sjelden et tema. Dette kan føre til at en video prosjektør viser et bilde som er langt fra det tiltenkte resultatet. I 2006 presenterte Raja Bala og Karen Braun en kamerabasert kalibreringsmetode for video projektører. Denne metoden bruker et vanlig digitalt fotokamera for å oppnå en rask og enkel kalibrering. I denne oppgaven har denne metoden blitt implementert og undersøkt. Ett mål ved å gjøre dette er å teste hvor godt metoden fungerer, og derav muligens verifisere at denne metoden kan være noe å bygge videre på. Et annet mål med oppgaven er å legge til utvidelser til metoden og sjekke om den dette kan forbedre metodens resultater.

Påtross av at noen steg ved metoden kan være problematiske, har det blitt bekreftet at den fungerer godt. Selv om eksperimenter viser at dette ikke nødvendigvis gjelder for alle prosjektører. Å legge til utvidelser til metoden har gitt enda bedre resultater en original metoden. Og det er funnet at en utvidet versjon av den originale metoden vil fungere bedre en originalen. Konklusjoner er basert på numeriske og visuelle evalueringer.

3 Preface

Personal thanks go out to:
Supervisor Jon Y. Hardeberg
co-supervisor Jean Baptiste Thomas
The Norwegian colorlab community
Fellow student Marius Pedersen
Experiment participants
Classmates
Raja Bala

Espen Bårdsnes Mikalsen, 2007/05/30

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4 Introduction

In the day to day use of projection displays calibration is often a non-existing phenomenon. The lack of appearance adjustment often leads to an incorrect presentation of content color. If the projected output widely diverts from the intended appearance both text and graphical output can not only loose their visual appeal, but the contents intended meaning and effect might be lost. Accurate calibration of such displays can be a process that both is technically challenging and requires expensive specialist equipment. In 2006 Raja Bala and Karen Braun[1] presented an alternative method for calibration of projection displays, from now on refered to as the Bala method. The aim of this method is to obtain a good and easy calibration for projectors using a consumer digital camera as a color measurement device. The method focuses only on tone reproduction calibration and does not calculate a 3x3 transformation matrix which is the conventional approach. In this master's thesis Bala and Brauns method has been tested and analysed. And possible extensions to the method have been implemented.

4.1 Research questions

4.1.1 Q1: Verification of the Bala method

Goal

Here the goal is to determine if Bala and Browns presented method does correct digital input to projection displays to a better reproduction then the standard gamma correction used today. This will be an evaluation of the calibration method suggested by Bala and Braun.

Method

The method will be implemented and performance tested with numeric result as a measure of performance. As the method is a correction to projection a visual evaluation of results will also be performed. Separate parts of the method will also be evaluated to identify strengths and weaknesses in the approach.

4.1.2 Q2: Extensions to the Bala method

Goal

Implement extension to the original method in an attempt to improve model performance. This includes steps to enhance estimation of tone response, and examining if a separate estimation of tone response for each of the R, G and B colorchannels improves results.

Method

Use implementation of the original model, and extend it for use with the extensions. Evaluation of extensions will be done in referance to results achieved using the orignial Bala method.

5 State of the art

5.1 Visual matching of color

In display calibration a number of techniques have been used over the years. One of the more dominant of these can be found in use for visual calibration of CRT monitor displays. The approach is to display a pattern of interchanging maximum and minimum luminance to act as a referance stimuli, and match an adjustable luminance to the perceptual luminance of the pattern. Target luminance can be adjusted by changing percentage of pixles containing maximum and minimum luminance. This kind of technique is usually used to determine 50% luminance i.e. matching the adjustable luminance to a pattern consisting of 50% minimum luminance and 50% maximum luminance for eigther a primary channel R, G or B or for overall luminance white channel. Example of this technique can be found in [2] and [1].

5.2 Non-uniformity correction

Explain what non-uniformity is for both camera and projector. Explain techniques used for correction with projectors. Refere to the Hardeberg et al. project here

5.3 Device calibration and characterization

Calibration is used to maintain a devices color response, when knowing the devices characteristics. Calibration can be to simply make sure that the device keeps a fixed setting for color reproduction. In a system, calibration might need to be performed to all devices separately. For a certain device a specific color characteristic often is desired. This typically requires taking color measurements and deriving correction functions to ensure that the device maintains the desired characteristics. The process of measuring and correcting color to specific characteristics is known as a characterization. Characterization is usually done according to a model that suits the device that's being calibrated.

These models are defined in two directions, forward and backward. Forward characterization is defined as devices response to known input. The model thereby describes the devices color characteristics. The backward model tries to calculate these characteristics, and thereby determines required input to obtain desired response. For forward characterization there are two approaches to models. Forward models are divided into physical models and empirical models. These are further discussed by the Digital color imaging handbook[2]. Common for most models is that they try to predict a display devices preferred tone reproduction curve(TRC) for best possible results. This curve represents the luminous output of colorimetric values for a display. Example can be seen in in figure 1.

Example of an empirical model is the PLCC model[3]. This model uses interpolation to predict the function of the TRC curve. This model presumes independency between color channels[2] and constancy in devices color output.

Of the physical models the GoG[4] model is much used. This model presumes that the TRC for the display can be described by a CRT monitor's TRC curve. This model tries to find the optimal gain and gamma for fitting the data along the TRC curve. As

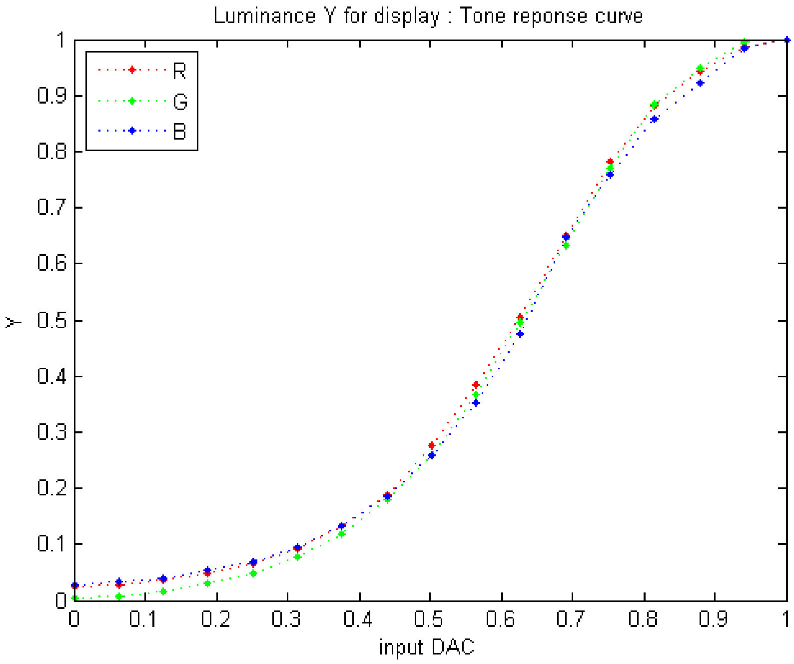


Figure 1: Tone reproduction curve for a DLP projector.

long as this presumption is valid, it enables this model to characterize the display with less data than the PLCC model. The GoG model also presumes channel independency and channel constancy. On implementation Fairchild et. al.[5] found that GoG model was not appropriate for use with lcd technology, because the LCD monitors TRC did not resemble the TRC of an CRT.

5.4 Camera vision

When measuring color luminance on screen with a digital camera, effectively what you do is turning it into a simple spectrophotometer. A spectrophotometer is an advanced and expensive device that has great accuracy. And accordingly cameras accuracy is not expected to be as good when performing same task. Different digital cameras has been implemented in use with projectors, but all have capabilety to operate with fixed.

Raja Bala[1] and Hardeberg et. al. [6] have both performed projects aiming to characterize projectors using digital cameras. In the Hardeberg project a high precision colorimetric camera from Radiant Imaging was used. This was first calibrated using a spectrophotometer, and further used to obtain luminance of onscreen projected colorsamples. Through a modified forward characterization model, that subtracts blacklevels to represent true channel response, projector is characterized. Characterization is further used to compensate for non-uniformity in projected image using a global characterization model and dividing the screen into sectors. Each of these sectors were characterizes individual. Results in this projects characterization of central area with the modified forward model showed promising results for characterization with digital cameras. ΔE[2] difference of 3,66 between original and model calculated colors were measured for central area of screen. And the global model improved average ΔE difference from 5.27 to 2.59.

One of the conclusions in the project was that implementation of the characterization technique in MatLab is not preferable due to calculation time. The authors suggest implementation in C code to improve performance. The authors also proclaim that further improvements probably can be achieved, partially due to additive failure in projectors color reproduction. And that the average ΔE difference can be reduced even more.

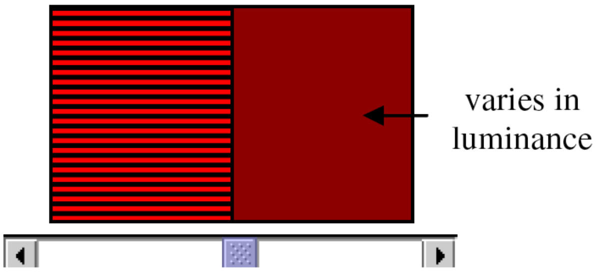


Figure 2: Calibration target with sliderbar for color adjustment[1].

In the before mentioned Bala[1] project characterization using a digital camera is also implemented. His approach differs a bit from[6]. The project suggests a method for projector calibration that does not depend on an already calibrated camera, i.e. a system that can recalibrate itself without the assistance of other equipment. The method is based on both conventional visual calibration techniques investigated earlier by author[7] and a characterization model. In this project a conventional compact digital camera was used.

The key difference is the use of a calibration tool that projects visual patterns, like the one shown in figure 2. The user then performs a visual luminance matching on target to establish the targets 50% luminance point. The calibration tool then displays another target consisting of neutral ramps of known RGB values which includes the 50% luminance point found. An image of these projected ramps are captured with the camera. The resulting RGB values of the target is retrived from image, and used with absolute white and black used with a camera tone response function to create luminance values. i.e. cameras TRC. The camera is the used to calibrate projector through a basic forward characterization model. Also in this project there is used correction for non-uniformity in projected image.

Measurable results from the project show a great improvement from the projectors default settings, to calibration with perposed method. Taking average ΔE from factory settings at17.4, to visually calibrated at 4.6, to final result using persposed method at 1.9 ΔE .

The method does produce good results using a mainstream digital compact camera. Thus a cheap solution as to the use of a spectroradiometer. Digital cameras are also easier to use then advanced measuring devices. And they are capable of capturing the whole screen, which makes it easier using spatial non-uniformity correction functions. The author comments that the function might be further improved by estimate a 3x3 characterization matrix for projector calibration. This would require additional targets of RGB combinations.

Another similar project has also been tested using a common webcam for correcting non-uniformity in projected image[8]. Here the conclusion on camera used was that it produced images of to low quality.

5.5 The Bala method

To efficiently use the camera as a measurement device it is important to determine the relationship between known RGB values and the cameras response to them. This will result in what is called the cameras tone response curve, and is a mapping of the cameras characteristics. Bala and Brauns purposed method uses three obtained points to determine this curve. First of all a well known visual matching technique is used. The approach is to project a colormatch target that consists of one side that is a uniform target with adjustable luminance value, and one side that is a raster or line target consisting of 50% white and 50% black pixels, thus representing the projected 50% luminance point. Adjusting the uniform sides luminance to appear as the raster pattern will result in a known [x y] pair on the cameras tone response curve that represents the 50% luminance point. Further Bala and Braun uses a target consisting of patches of known RGB values from perfect black to perfect white in ramps. The target also includes the 50% luminance point found in the visual calibration. Patches of this luminance value is duplicated in the horizontal and vertical direction for later non-uniformity correction. Taking a picture of this target with the camera and retrieving it's RGB values will reveal the relationship between no luminance, full luminance and 50% luminance for the camera. These three luminance values together with the projectors actual blackpoint is used to map the camera tone response. The projectors actual blackpoint, or flare factor as the authors call it, is the luminance on screen when input luminance value to projector is zero. As to this day there are few or none display technologies that actually reproduce perfect black, and this is especially a problem in projector technology. This flare factor is also affected by surrounding factors like dim room conditions etc. These four points are used through interpolation to determine the full digital camera tone response curve. The interpolation normalizes values to the cameras measurement of perfect white as that is a measurement of full luminance. In the Bala and Braun interpolation spline interpolation was used. The digital camera is then considered calibrated. As before mentioned the target used to retrieve determining points on the cameras tone response curve also included ramps of 15 luminance values. The cameras luminance measurement of these values can now be retrieved and used with their known corresponding digital values to generate a tone response calibration for the projector with the 15 points from the target. This is also done by interpolation. Also here Bala and Braun found spline interpolation to be best suitable. Since the same captured target is used to calibrate both the camera and the projector this becomes a closed system. This means that surrounding factors during image capture, like projection media and camera settings, have little or no effect on the result. Prior to the retrieval of the camera and projector tone response curve, read luminance data from the captured image is corrected for spatial non-uniformity. Spatial non-uniformity is a well known problem with projection displays that results in an uneven luminous output of spatial uniform input data. Bala and Braun corrects for this error by utilising the horizontal and vertical duplications of the 50% graypoint patches in the captured calibration target. As the duplications are spread out over the entire target, their spatial coordinates are used as reference for correction to the various luminance patches in the target. All correction are calculated according to one of the 50% greyscale patches.

6 Implementation and extension of method

6.1 Introduction

In this chapter the implementation of the Bala method is presented. For implementation and testing the Bala method it was chosen to use Mathworks Matlab. Matlab is a high-level language and interactive environment that enables you to perform computationally intensive tasks and is a good tool for experimental implementations. The method have been implemented through a two step approach. Where the first step is basically creating and displaying a colorpatch chart consisting of different luminants, and the second part is the retrieval of information and calculation of correction. The result when running this implementation is a correction curve that can be used to adjust digital input to give a better projected result. This is will be the estimated projector tone response. In this implementation there have been added functionality to test possible improvments to the original model. The original model bases estimation of curves on a visually matched luminance point, and makes a luminance, or grayscale adjustment curve to correct digital input with. In this thesis the original Bala method often is referred to as the gray 1 method. One of the extensions done to the original gray 1 method, is to add two more visually matched luminance level when estimating curves. This method is referred to as the gray 3 method. Functionality has also been added to estimate tone response curves separatly for each of the R, G and B primary channels. When estimating primary channels separatly we get two new methods which is referred to as the RGB 1 method or the RGB 3. The RGB 1 method is separate estimation per primary channel with one visually matched luminance level, and the RGB 3 method is the same but with three visually matched luminance levels. These four versions of the Bala method can be used tested with this projects implementation.

6.1.1 Step 1: Collecting data

As the implementation done in this experiment contains a few extensions to the original method it requires some choices to be made. This is done through a settings dialogue at start-up. In the original method only matching of the 50 % luminance value was used. In this implementation functionality has been added to retrieve the 25, 50 and 75 % luminance points and to retrieve these points separately for each of the red, green and blue color channel. These choices are done in the settings dialog shown in Figure 4. In this parameter setting there is also a possibility to set a custom projector blackpoint, which is of major importance for the later interpolation. Pushing the "‘run'"-button stores necessary settings and closes the settings dialog. From the settings dialog progress follows one of four paths in the main script based on what user chooses. These can be seen in the conceptual model in Figure 3.

Implementation of visual matching

One of the important factors in the Bala method is to visually match projected luminance to determine what input luminance is required to get a preferred output luminance. The value that is found in visual matching is directly influencing how the estimated tone

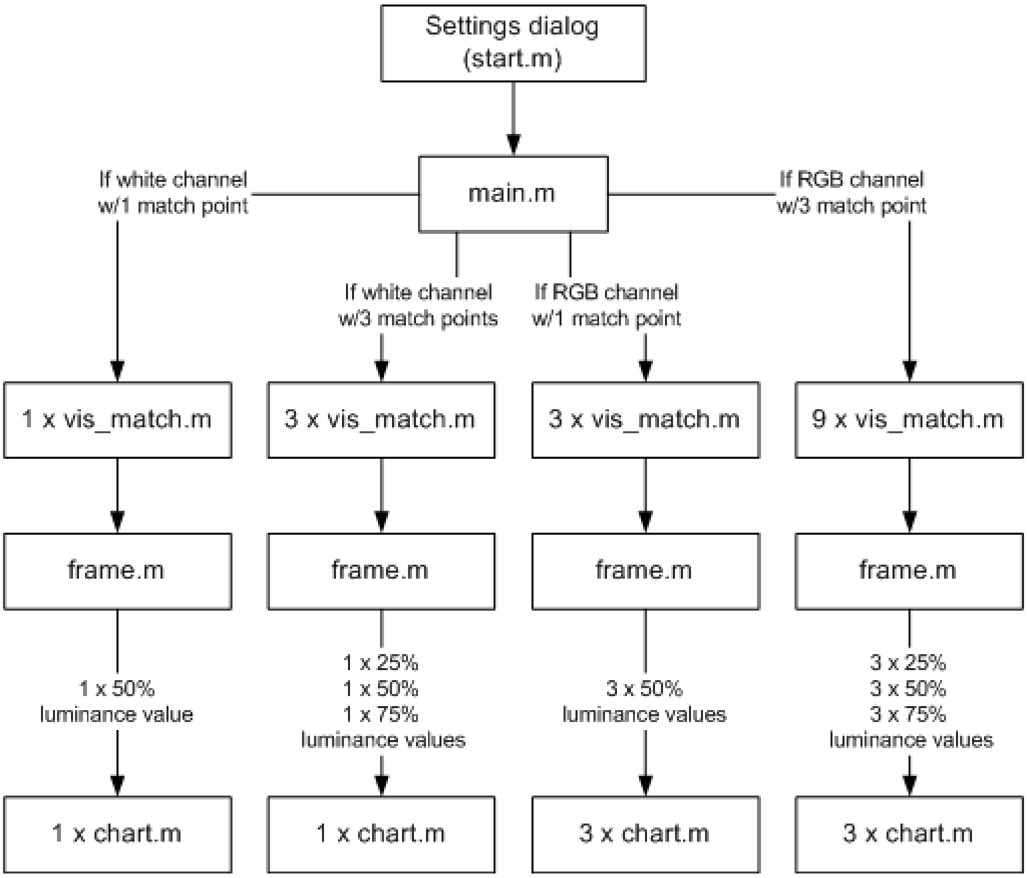
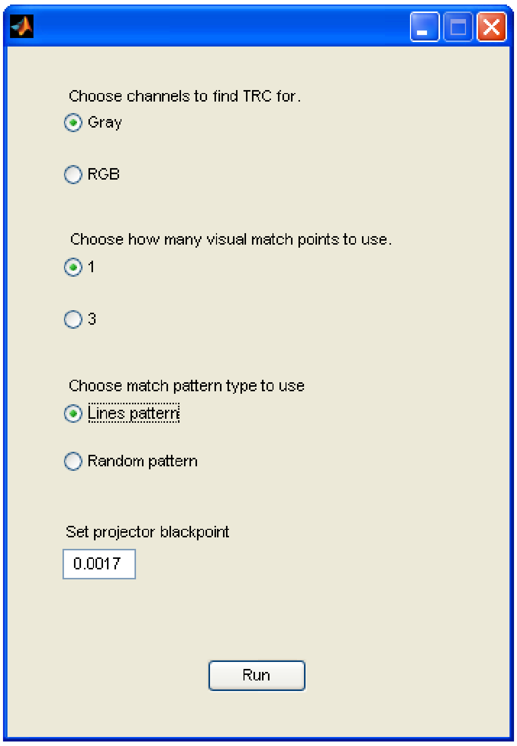


Figure 3: Conseptual diagram of system flow in step 1



Choose channels to find TRC for.

● Gray

○ RGB

Choose how many visual match points to use.

● 1

○ 3

Choose match pattern type to use

● Lines pattern

○ Random pattern

Set projector blackpoint

0.0017

Figure 4: Startup settingsdialog

response curve for the camera will look, and thereby also directly influencing how accurate the camera can be used as a luminance measurment device. In this project the visual matching has been implemented through a full screen figure created with the Matlab GUI editor GUIDE. This figure consists of a pattern in the middle that represents a certain luminance for a certain colorchannel. In figure 5 an illustration of colormatching with a 50% line-rasterpattern in the middle with adjustable gray luminant surronding is shown. When properly adjusted the digital input value to the adjustable background will represent the digital input to projector that gives a 50% luminanse output from projector. Dependent of input parameters the visual matching function is capable of running visual matching for either graylevel or red, green and blue colorchannel, and to display matching targets for these representing 25, 50 and 75% luminance. In this way the visual matching will result in one or several known luminance values. These are stored for in the next step which is a chart of patches. In this implementation it was chosen to cover the whole back area with the adjustable color. Alternativly the back color could be a set luminant, and only a limited area around the pattern could be useed as an adjustable luminant. The reason the whole backarea is used as adjustable is to avoid influance from a set luminant when adjusting to the target.

Displaying referance points and luminance chart

With the necessary visually matched luminances obtained, the system is now ready to display a chart used for calibration of the cameras tone response. Though there is no need for the chart to have a specific shape or number of pathes, it has been choosen to use the approach presented by Bala and Brown in [1]. The advantage found is that all necessary patches can be captured with the camera at once, and one can use the original non-

Figure 5: Visual matchingtarget for overall luminance

uniformity correction. The main point at this stage is to present a recognizable pattern containing separable luminances from minimum to maximum, and the visually matched luminances.

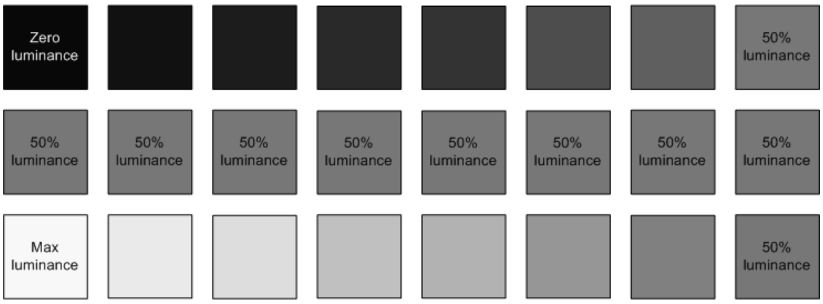


Figure 6: Distribution of luminance on patch chart when using one visually matched luminance value

There are basically two different versions of this chart depending on how many visually matched values have been obtained. Both consists of 3 rows with 8 patches where 14 of these are independant luminance values ranging from zero to maximum luminance of one. The remaining 10 are duplications of the visually matched 50% luminance, and will later be used in a non-uniformity correction. When the system is operating with one visually matched luminance, as in the original method, luminances will be distributed as in Figure 7. In the top row luminance increases in equal steps from left to right from zero luminance to 50% luminance. In the bottom row luminance increases in equal steps from 50% luminance to max luminance of one, from right to left. For camera tone cal-

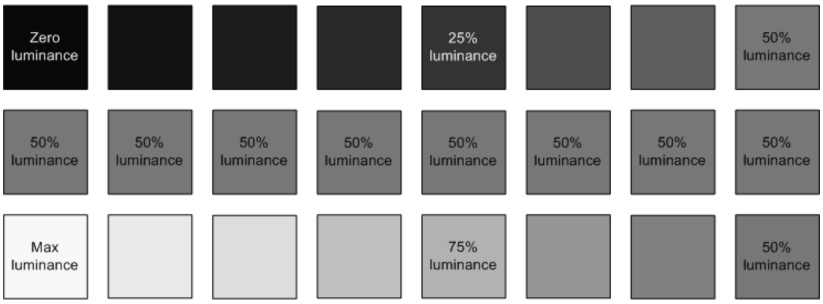


Figure 7: Distribution of luminance on patch chart when using three visually matched luminance value

ibration with 3 visually matched luminances patch five from left in top row has been replaced by the 25% matched luminance and patch five from left in the bottom row has been replaced by the 75% luminance patch. As the original system only operated with one visually matched value, a choice had to be made as to where the two matched luminances should be represented in the system chart. Their placement were chosen so that there would be more patches representing the lower luminant range (0%-25%) and the high luminance range (75%-100%). The chart does now not only contain three referance points (0%, 50% 100%), but five.

Distribution of luminance in chart with three visually matched luminance values can be seen in Figure 7. The chart will be generated in 800 x 600 pixels resolution, but streach to fullscreen with a black backdrop and black border. When displayed the patches cover approximatly 45% of displays width and 40% of displays height. The chart can either display luminance patches for overall luminance in graylevel, or display separate charts for red, green and blue primary channel.

When capturing an image of the projection it is important to keep in mind the purpose of the camera image. The image is captured to later give information about luminances to the system. Therefore it is important that the system is given some sort of referance to what data in the image that is relevant and what is not. In this project an image with cornerpoints was used. This is a pattern of eccactly the same size as the chart, but only containing 3 x 3 pixel size white dots at each cornerpoint of the chart, on a black background.

The approach here is that the system projects the cornerpoints, the camera captures it, the system displays the chart and the camera captures a second image. If system is performing separate tone response calibration for red, green and blue, separate red, green and blue chart is displayed instead of only graylevel. If the images are captured from the excact same location the image containing the four cornerdots will be a good referance to relevant information in the chart image or images. The method of using a separate capture with referance points is not a good solution, but was found aducate for experimental purposes. An edge detection technique could be applied to the chart image to locate relevant data instead of using the referance image. This will is discussed in the further work chapter. Illustration of projected referance cornerpoints and a green luminance chart can be seen in Figures 8 and 9

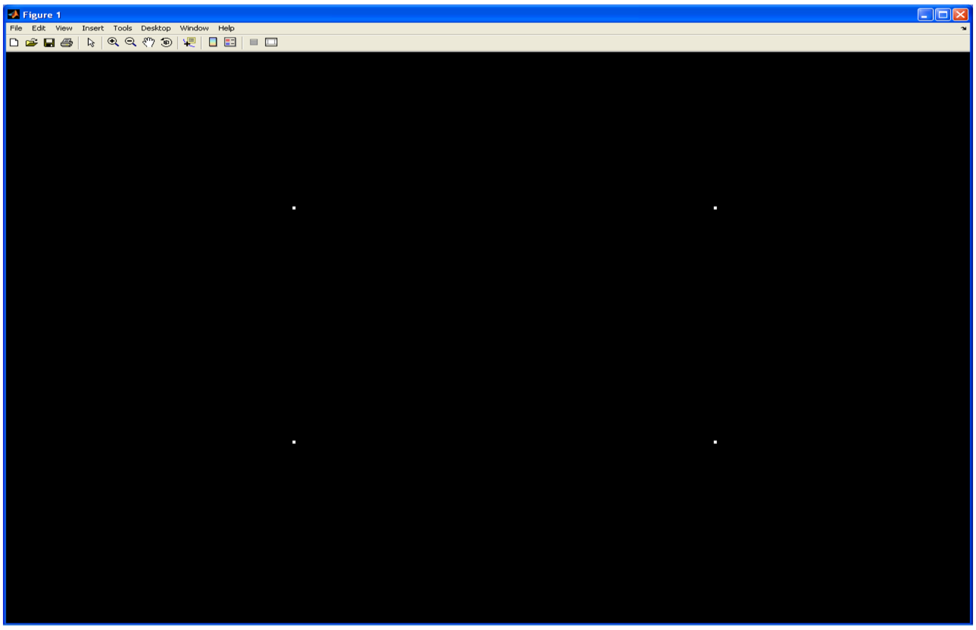


Figure 8: Projected referance cornerpoints

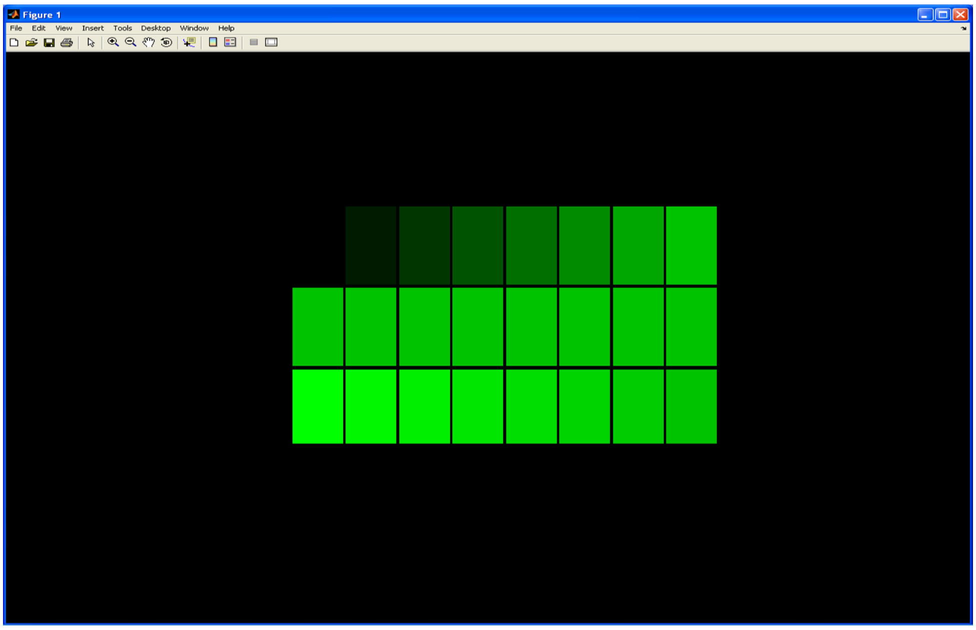


Figure 9: Projected green chart

6.1.2 Step 2: Processing data

Image processing

The second step of the implementation process the captured images and use found data to calculate look up tables(LUT) for correction to digital input values to achieve an accurate output.

First the captured referance points image and the chart image is sent to a process.m. This function starts by calling detect.m **??** which accuratly detects the points in referance image. The function devides the points image into four seperat images by splitting the original equally horizontaly and verticaly. This leaves one referance point in each of the new images. As this image originally contained only a black background and white points the four images can be threshholded to only contain black pixels and white pixels. Where the white pixels represent the referance points. The original output to projector contained 3 x 3 pixels per referance point, this was done to make these points large enough to be registered by the camera. After thresholding the camera image these points will consist of a cluster of white pixels. To get an accurate approximation of the real point in each quadrant a mean of all whitepixel-coordinates in each quadrant is used. This results in one excact point for each quadrant that is returned to process.m. This technique has proven itself to be accurate enough to determine the borders of the chart. These coordinates are then set in referance to the camera captured patch chart(s), and the area inside these points is the area that will be considered as valid image data by the system.

$$Where \;\; Q1y > Q2y \;\; \angle = \arctan(\frac{Q1y - Q2y}{Q2x - Q1x}) \cdot (-1) \tag{6.1}$$

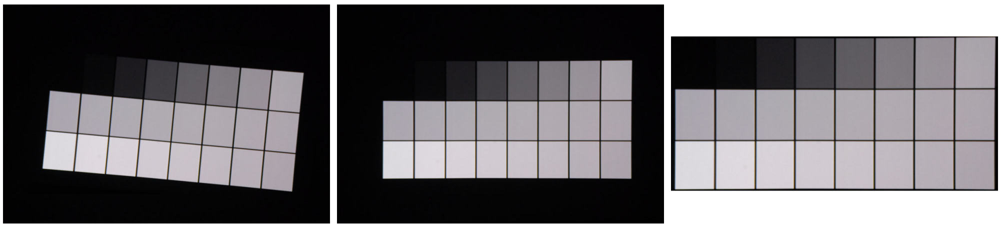
$$Where \;\; Q1y < Q2y \;\; \angle = \arctan(\frac{Q2y - Q1y}{Q2x - Q1x}) \tag{6.2}$$

To easily read luminance information from the chart area the image is rotated. The goal is to rotate the image so that the referancepoints from the top two quadrants aligne in the horizontal direction. This angle is found by using eighter equation 6.1 or 6.2 where $Q1x$ and $Q1y$ is the coordinate pair for the top left quadrant referance point and $Q2x$ and $Q2y$ are coordinates for the top right referance point. This rotation is done to both the original referance point image and the patchchart image, so that the detect.m function can be applied again after rotation to detect new location of the four referance points in the rotated version of the image. The pattern is now alligned horizontally and can be cropped according to the referance points. The image is now ready for data retrival. Example of a image processed can be seen in figure 10.

The image processing used here is not an optimal way of preparing image for data retrival. The rotation operation can be a tedious calculation task for the computer when you use a camera that delivers high resolution images. This is especially aparant when calculating separate LUTs for red, green and blue primary channel where three different chart images are processed. Alternatives will be discussed in the further work chapter.

Collecting data from image

The cropped image is the basesource of information about the cameras response to projected luminance. It is therefore imperative that this data is extracted from the image in a correct way. As the Bala method is only a correction of luminance output and not a cromatic correction the cromatic information can be discarded. This is the first thing



(a) Original chart image (b) After rotation (c) After cropping

Figure 10: Image processing visualized

that is done in the read_values.m **??** function, using predefined function rgb2gray.m [9]. Now the image consists of a grayscale image representing cameras luminous response to known luminous input to the different primary channels of the projector.

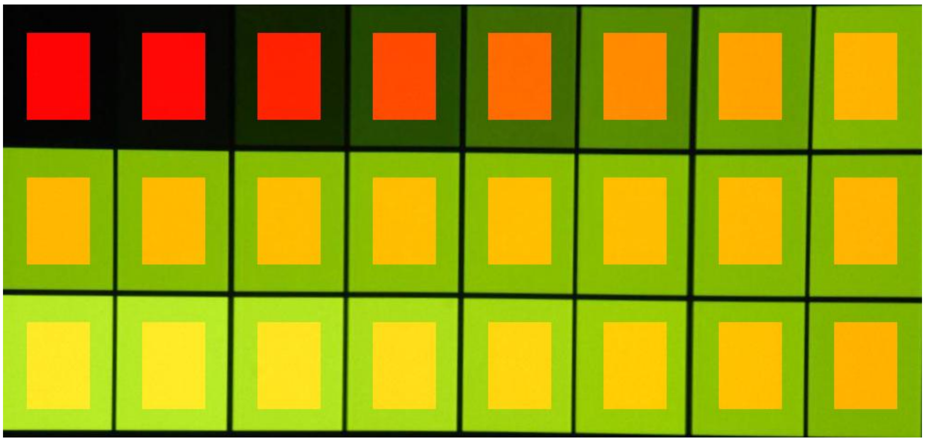


Figure 11: Illustration of read areas on a green chart.

The cropped chart has a known structure of 3 rows with 8 patches in each. Though the cropped chart image may have a small border around it and the rotation might not always be totally perfect, this is sufficiant knowledge to read a mean luminance value from the central area of each patch. The total image is devided into 3 x 8 sectors where approximatly 60% of hight and width of sector is read from the sectors central area. System outputs a image with a visualization of read areas for confirmation of correct read. Such a confirmation image can be seen in figure 11. The area read from each patch is an adjustable factor that can be tuned if necessary. A mean value is now calculated for each patch, this gives a good representation of the cameras captured luminance.

Non-uniformity correction

Hardware containing optics often suffer from non-uniformiy in performance over the devices spatial operating area. For a projector this means that a projection of a spatially uniform input might be displayed with some regions brighter or darker then others. For a camera spatial non-uniformity has the same effect but in the opposite direction when capturing of a uniform surface. When using a camera to capture the displayed image from a projector the potential non-uniformity effect of both the camera and the projector will be part of the resulting image. In the Bala method it is not aimed to correct for non-uniformity in the projected image. But a non-uniformity correction is done to the read data from chart images. This is done so the data used to calculate correction in input to projector will be as correct as possible.

$$M'(x,y) = M(x,y) \cdot C1(x) \cdot C2(y) \tag{6.3}$$

$$C1(x) = G(xo)/G(x) \tag{6.4}$$

Equation 6.3 and 6.4 from Bala and Brauns original paper [1] shows how this is done. M is the original measurment, M' is the corrected measurment, and C1 and C2 are spatial corrections in the y and y directions. Equation 6.4 shows the calculation of correction in the x-direction, where $G(x)$ is the read value of a constant 50% luminance patch at location x. And xo is read luminance value at the referance location. This projects implementation of the non-uniformity correction to read values follows the same method, and can be in appendix **??**

Interpolation of tone response curve for camera

Patch	Luminance	Captured camera luminance
Projector white	$Y_w = 1$	R_1, G_1, B_1
Projector black	Y_b	R_2, G_2, B_2
Mid-gray	$(Y_w + Y_b)/2 = (1 + Y_b)/2$	R_3, G_3, B_3
Perfect black	0	$0, 0, 0$

Table 1: Data used to calibrate the tone response of the digital camera

Using the non-uniformity corrected data the system now has 24 different values of luminance measured on screen with camera, that relate to known projector digital count input values. But at this stage this relation is influenced by both the camera and the projector, so we need to take the cameras characteristics to find the projectors relation to the original input values. This is done thru a simple estimation of camera response. Table 1 show the data that is used to interpolate the estimation of camera response. This represents four x and y pairs in the resulting curve. The perfect black will always be zero luminance Y=0, which means that blacklevel is not taken into account for the cameras estimated tone response curve. Projector white and projector black will be the blackest and the whitest the camera have captured of projection. Mid-gray is the camera capture of a 50% luminance patch from the projected chart. For the camera response curve projector white is set to Y=1 to normalize maximum projected and captured luminance. The projectors black, or blacklevel, is a estimation of how luminant projector black is. No conventional projector as of today can reproduce perfect black, there will always be some luminant output. Raja Bala calls this the flare-factor and estimated it to be 2% i.e. 0.02 in the range 0-1 for the projector he used in his experiment. This flare-factor also inflicts the luminance of the mid-gray. Mid-gray is 50% of the range from projector black to projector white. This means that the projector blackpoint is acounted for in this point. Thus the camera measured luminance of one of the 50% gray patches is set to $0.5 + \mathtt{projectorblack}/2$. Interpolation was performed using a cubic interpolation technique which was found most suitable by Bala. In this experiment spline interpolation was also tested but was not found as suitable as spline interpolation tends to increase errors for deviant points on the curve. This experiments matlab code for estimating camera tone response can be seen in appendix **??**. An example of interpolation result can be seen in Figure 12. When interpolating this graph with three visually matched luminance levels, as is done in the gray 3 method and the RGB 3 method, the number of x and y pairs used in interpolation will increase from four to six. The two new points added are the visually matched 25% and 75% luminance levels.

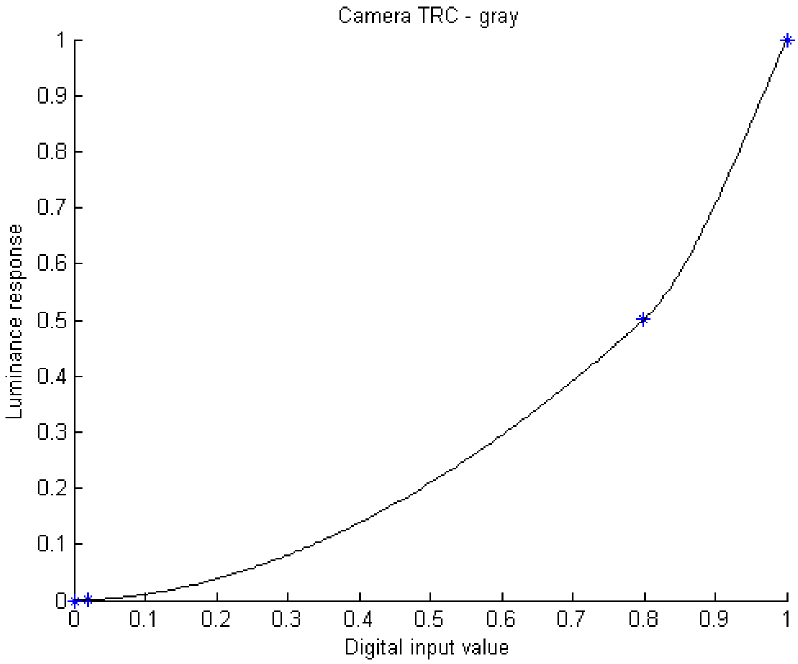


Figure 12: Example of estimated camera tone response curve.

Projector tone response estimation

The cameras tone response estimation describes how the camera responds to input luminance. From the captured chart there already exists 24 different camera measurment values. Using the 50% read luminance values and the 14 read grayscale ramp values we can calculate an estimation of the projectors tone response. This is done by looking up in an inversed approach with this curve we are able to retrieve 15 x and y pairs on an estimated projector tone response curve. This is done by using the 15 normalized camera read luminance values as digital input value to the estimated camera curve, giving 15 new luminances. Using these 15 new luminance values as y, and setting them in relation to the original digital input values to projector as x, we get 15 x and y pairs that is an estimation of points on the projectors tone response. Interpolating over these 15 x,y-pairs gives the estimated projector response. This estimated curve is the one used to correct the input sent to projector. The correction will be the differance between this curve and the sRGB gamma 2.2 curve that most computer displays aim to conform to. An example of a estimated projector tone response curve can be seen in Figure 13.

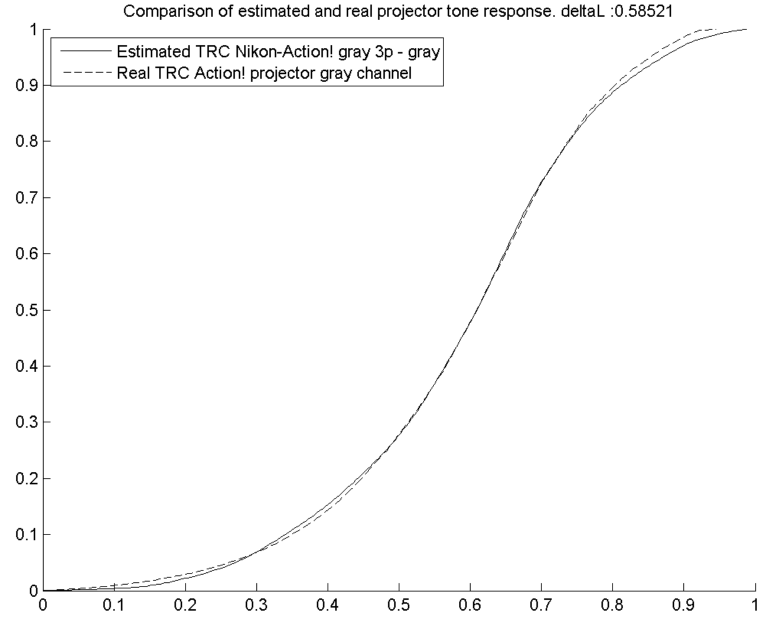


Figure 13: Example of estimated projector tone response curve.

7 Experimental setup

7.1 Hardware and equipment

7.1.1 Panasonic PT-AX100E

The Panasonic LCD projector used in the experiment is a 2006 model 3LCD device, meaning it has separate LCD displays for red, green and blue channel. Though intended for the high definition home cinema market it is a very flexible device with a high contrastration(6000:1). The low throw distance lets this device project a large image at a small distance and the lens shift stick let's user adjust direction of projection by physically adjusting lens angle. This projector also has optional automatic color and brightness correction features. Specifications for the Panasonic PT-AX100E can be seen in Table 2, and further features can be explored in the user manual [10].

7.1.2 Projectiondesign Action! model one

The DLP projector used in this project is a 2003 model from Projectiondesign. For it's time it is a high end device put together from quality parts. It has a high luminous output and a respectible contrast of 3000:1. The Action! Model One has a six segment colorwheel and uses no white segment as is often the case with DLP projectors. This projector has the same native resolution as the Panasonic at 1280 x 720, 16:9 format. The Action! Model one has a significantly longer throw distance then the Panasonic, and a lower zoom range. This results in a smaller projectionsize in this experiment due to space limitations. Overview of this projectors specifications can be seen in Table 3, and full specifications and user guide can be found in the user manual [11].

7.1.3 Projector screen - Euroscreen

7.1.4 Nikon D200

The Nikon D200 was presented on the market in early 2006. It is one of Nikons steps in their range of true digital SLR(Single-lens reflex) cameras. The camera has many of the features found in high-end professional cameras, but is intended for the consumer market. Digital SLR cameras have interchangable objectives, and therefore objectives can be chosen to suit whichever purpous the camera is being used for. In the experiment objective was chosen on account of what was avaliable. A AF-S Nikkor 18-200 mm objective were used. This lens has good zoom capabilities and is therefor versatile as to where the camera can be placed. This is important when the camera is used to capture projection from different projectors that have different projection size. Specifications for Nikon D200 and the Nikkor lense can be seen in Table 4. Further Specifications can be found in the Nikon D200 manual [12]

7.1.5 FujiFilm Finepix S7000

The S7000 is an older camera then the Nikon. It was a high-end consumer camera when it hit the market back in 2003. The S7000 is a compact camera, but has a lot of resembalance with digital SLR cameras. The main differance is that on this camera one can not change lens. It comes with a Fujinon Super EBC Zoom lens which has a range from 35

Panasonic PT-AX100E 	
Brightness(Lumens)	2000 ANSI
Contrast(Full on/off)	6000:1
Audible noise	Not stated
Weight	4.9 kg
Size(HxWxD)	112 x 394 299 mm
Focus	Manual
Zoom	Manual 2.00:1
Throw distance	2.4 - 6.2
Image size	102 - 508 cm
Keystone correction	Digital horizontal and vertical
Lens shift	Yes, horizontal and vertical
HDTV compatibility	1080i, 720p, 1080p/60, 1080p/50, 1080p/24, 525i, 525p, 576i, 576p, 625i, 625p, 1125i
Component video input	Yes
VGA input	Yes
Digital input	HDMI (HDCP)
Display technology	3 LCD 1.8 cm
Native resolution	1280 x 720 pixels
Maximum resolution	1920 x 1080
Aspect ratio	16:9
Lamp type	220 watt UHM
Lamp life	2000 hours

Table 2: Specifications for Panasonic PT-AX100E

Projectiondesign Action! Model one 	
Brightness(Lumens)	1200 ANSI
Contrast(Full on/off)	3000:1
Audible noise	28.0 dB
Weight	2.9 kg
Size(HxWxD)	89 x 277 x 244 mm
Focus	Manual
Zoom	Manual 1.27:1
Throw distance	4.6 - 6.2 m
Image size	234 - 404 cm
Keystone correction	Digital horizontal and vertical
Lens shift	No
HDTV compatibility	1080i, 720p and 576p
Component video input	Yes
VGA input	Yes
Digital input	DVI-D
Display technology	DLP 2.0 cm
Color wheel segments	6
Color wheel speed	5x
Native resolution	1280 x 720 pixels
Maximum resolution	1920 x 1080 pixels
Aspect ratio	16:9
Lamp type	250 watt UHP
Lamp life	2000 hours

Table 3: Specifications for Projectiondesign Action! Model one

Nikon D200 	
Body	Magnesium alloy and high-impact plastic
CCD effective pixels	10.2 million
CCD size	23.6 x 15.8 mm CCD (DX format)
Image size	3872 x 2592, 2896 x 1944, 1936 x 1296, 3008 x 2000, 2240 x 1488, 1504 x 1000
Image format	RAW (compressed / uncompressed) JPEG (3 levels)
Focus modes	Auto, area AF, manual Focus
Auto focus	11/7 area TTL and Mulit-CAM 1000
AF area mode	Single Area AF, Continuous Servo AF, Group Dynamic AF Closest Subject Priority Dynamic AF Single Area AF
Sensitivity	ISO 100 - 1600, up to ISO 3200 with boost, ISO 200 - 1600 (1/3, 1/2 or 1.0 EV steps), ISO 2000, 2500 or 3200 with boost
Image ratio w:h	3:2
Exposure adjustment	+/-5.0 EV (1/3, 1/2 or 1.0 EV steps)
Shutter	30 to 1/8000 sec (1/3, 1/2 or 1.0 EV steps)
White balance	Auto, manual, presets, color temerature adjustment(2500 - 10,000 K, 31 steps)
Full manual operation	Yes
Viewfinder	Optical-type fixed eye-level pentaprism, built-in diopter adjustment (-2 to +1m-1), frame coverage 95%
Built-in flash	Yes, manual pop-up w/button release
Connectivity	USB 2.0, Video out, Remote control 10-pin
Storage	Compact Flash Type I or II, Microdrive supported
Power	Lithium-Ion battery, AC adapter
Tripod mount	Yes, metal
LCD monitor	2.5" TFT LCD (230,000 pixels)
Dimensions	147 x 113 x 74 mm
Weight(inc. battery)	920 g
Operating system	Proprietary
Lens	AF-NIKKOR
Zoom wide	18 mm
Zoom tele	200 mm

Table 4: Specifications for Nikon D200

mm wide to 210 mm telezoom. Specifications for the S7000 can be seen in Table 5, and further specifications can be found in [13]

7.1.6 Konica Minolta CS-1000

The Konica Minolta spectroradiometer shown in Figure 14 is a accurate colormeasurment device ment for industrial and scientific use. It is designed to measure luminance, chromaticity, spectral power ditribution and corolated temperature of objects emitting light. The spectroradiometer usually is used with different display technologies to determine theire charactheristics. This could for example be CRT monitors, flatpanel displays and light sources, or as in this experiments case a projected image. The spectral range of the CS-1000 is from 380-780 nm(± 0.3 nm) and has a spectral bandwidth of 5 nm. Luminance levels can be accuratly measured in the range of 0.01 to 80,000 cd The measurement principle in this device is based on diffraction grating. After grating dispersion, the captured light is focused by the condenser lens, and end up on the array sensor consisting of 512 photo diode elements. Figure 15 shows a schematic model of the device created by Ondrej Panak [14].

Figure 14: Konica Minolta CS-1000 spectroradiometer

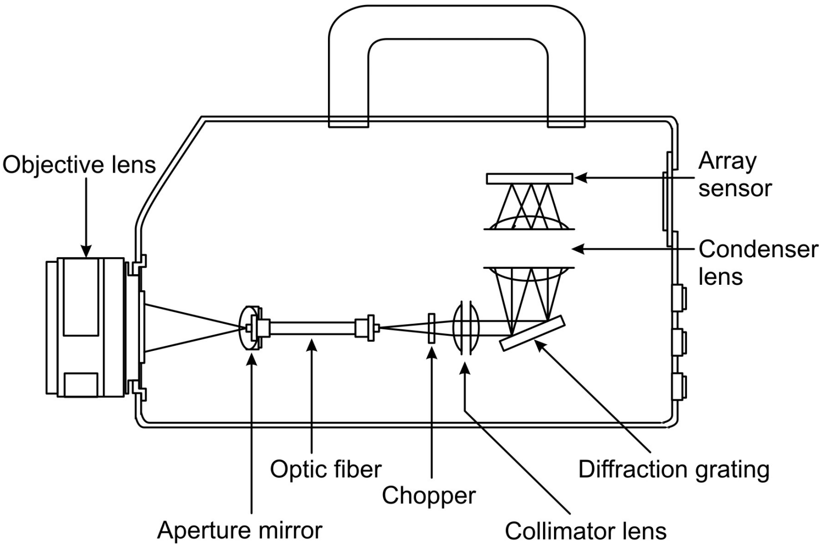


Figure 15: Schematic model of Minolta CS-1000 spectroradiometer.

FujiFilm Finepix S7000 	
Body	Plastic
CCD effective pixels	6.3 million
CCD size	7.6 x 5.7 mm
Image format/size	CCD-RAW, 4048 x 3040 JPEG (interpolated), 2848 x 2136 JPEG, 2016 x 1512 JPEG, 1600 x 1200 JPEG, 1280 x 960 JPEG
Image ratio w:h	4:3
File formats	RAW, JPEG and AVI(Motion JPEG)
Sensitivity equivalents	Automode(ISO 160 - 400), ISO 200, ISO 400, ISO 800
Lens	Fujinon Super EBC Zoom Lens
Zoom wide	35mm
Zoom tele	210mm
Lens Aperture	F2.8 - F3.1
Focus modes	Auto, AF (Center) Focus, area AF, manual Focus
Auto Focus	Passive External AF sensor and CCD AF (TTL)
Auto focus drive	Single AF, continous AF
Normal focus range	50 cm - Infinity (35 - 135 mm zoom), 90 cm - Infinity (135 - 210 mm zoom)
Min shutter	Auto: 1/4 sec, A/S priority: 3 sec, Manual: Bulb, 15 sec
Max shutter	Auto: 1/2000 sec, A/S priority: 1/1000 sec, Manual: 1/10000 sec
Aperture priority	Wide: F2.8 - F8.0, Tele: F3.1 - F8.0
Shutter priority	3 - 1/1000 sec
Exposure adjustment	-2 EV to +2 EV in 1/3 EV steps
Full manual operation	Yes
White balance	Auto, manual, presets
Built-in flash	Yes, manual pop-up
Tripod mount	Yes, metal
Storage media	xD-Picture Card, Compact Flash Type I or Type II (IBM Microdrive compatible)
Viewfinder	TTL EVF, LCD 0.44" (235,000 pixels)
LCD display	1.8" TFT LCD (118,000 pixels)
Operating system	Proprietary
Connectivity	A/V Out, USB 2.0, DC-IN
Power	4 x AA type batteries, AC power adapter
Weight(inc. battery)	597 g
Dimensions	121 x 82 x 97 mm

Table 5: Specifications for FujiFilm Finepix S7000

7.1.7 Computer

Both projectors and spectroradiometer were controlled by a Dell Optiplex GX620 personal computer. This computer uses a Intel Pentium 4 processor, running at 3.2 GHz and has 1 GB of RAM. It connects to displays using a 256 Mb ATI Radeon X600 graphics adapter with a standard windows display profile and all settings set to default. This means that no gamma or color correction is done before output. A 19" LCD Dell 1905FP monitor is connected as main monitor. Projectors were connected using VGA(D-sub 15) cables, while spectroradiometer were connected using RS-232C serial-cable.

7.1.8 Software

Windows XP professional

The computer connected to projectors and spectroradiometer during experimentation was running Windows XP professional operating system. The computer had all updates installed including Windows XP service pack 2. Default settings were used, except the disabling of screensaver and display power off for energy saving to avoid monitor switching off.

Colordisplayer C++

The Konica Minolta CS-1000 spectroradiometer comes with the propriatary software cs-s1w for controlling the device. This software is very good for doing one by one measurment, but does not have suitable functions for measuring sets of colors. For the purpous of measuring larger sets of onscreen colors, PhD student Jean Baptiste Thomas have developed the ColordisplayerC++ software. The software was developed in C++ and takes sets of RGB values that are displayed fullscreen on display device and simultaniously measured by the spectroradiometer. When a measurment is done the program moves on to display and measure the next RGB values in input set. The software stores measurment results in a file as XYZ values. This software was used in the experiment to make measurments with the konica Minolta more efficiantly.

7.2 Hardware settings

When experimenting with equipment with adjustable settings it is important to establish a set of prefered settings and keep these throughout the experiment process. This will ensure that obtained results with a set of devices are not influenced by changes in settings. For the projectors factory defaults were used as this is a predefined versatile adjustment adviced by the manufacturer, and the fact that if settings for some reason were changed the reset function would change settings back to correct values. A common feature with projectors is the keystone correction for image geometry. This is a digital correction of output and will influence the pixel-by-pixel reproduction of the image through interpoled streching and shrinking of image. The Panasonic LCD projector also had internal imageenhancment technology that needed to be disabled. This being Panasonics dynamic iris adjustment that modyfies inputsignals iris and gamma. And the light harmonizer that reduces, or increases power to the projector lamp according to the luminance value of the room.

For cameras experimentation was neccessary to determine suitable settings for image capture. A necessity when capturing image for use with this method is to be in full control of camera settings. Internal image processing, automatic flash and automatic luminance boost are examples of features found in digital cameras that will influence image capture. Such features might be wanted in the day to day use of cameras but when using it as a luminance measurment device such technology might pose a problem. Both cameras used in the experiments give full control over most settings. Both cameras have auto modes where the camera uses settings determined by capture environment factors. This setting, with automatic flash disabled, was used for the FujiFilm S7000. Automatic mode were also tested for the Nikon D200, but experimenting with custom settings gave better results. Settings found to be most suitable was manual mode where both aperture and shutterspeed can be adjusted. Shutterspeed was set to 1/15 secounds and aperture was set to 10 and ISO-setting 100. Both cameras were set to store captures with JPEG compression and sRGB colorspace. Though both cameras can store images in RAW-format, JPEG-format and sRGB-colorspace were chosen because it is what was used in the original method and also what the original method were intended to use. Imagesize used for Nikon D200 3872 x 2592 pixels, and 2848 x 2136 for FujiFilm S7000. Cameras and spectroradiometer were mounted on tripods to secure stability during experimentation.

7.3 Room conditions and equipment setup

Experiments were performed in a laboratory at the norwegian colorlab especially designed for scientific research with displays. This laboratory has no windows and walls are painted with non-reflexive graytone paint. The only light in the room during experiments then came from projection device. This ensured stable and equal conditions during all experiments.

During experiments equipment were set up as shown in Figure 16. The static setup were used to ensure same conditions for projection and measurment equipment for every experiment session. If the distance between the projector and the projectorscreen changes, the luminous intensity onscreen will purtionally change with the projected area. All devices and the position of operator were lined up to be in a perpendicular angle to the screen in the horizontal direction. Vertically projection was adjusted to be perpendicular with operators eyes and with spectroradiometer or camera.

7.4 Visual matching experiment

To determine the accuracy of the visual luminance matching technique an experiment were set up. Six different observers were asked to adjust the luminance of red, green, blue and gray channel to match 25%, 50% and 75% primary color binary patterns. This gives a set of four channels with three different luminance patterns each, a total of 12 matchings in the set. This set were run three times per observer to determine deviations in observer matched luminance. With six observers this added up to a total of 216 matched data values. Observers were also asked five questions to register their experiences when matching luminances. The questiones asked to observers were:

- Are you a professional or non-professional in the field of colorscience?
- Which was the hardest channel to match luminances in?
- Which was the easiest channel to match luminances in?
- Which of the three luminance levels was hardest to match?
- Which of the three luminance levels was easiest to match?

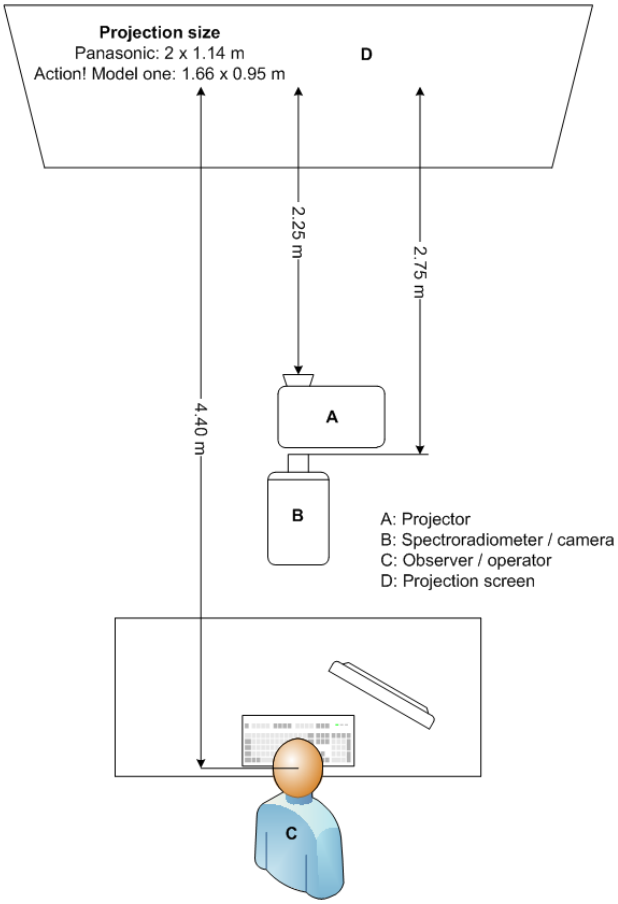


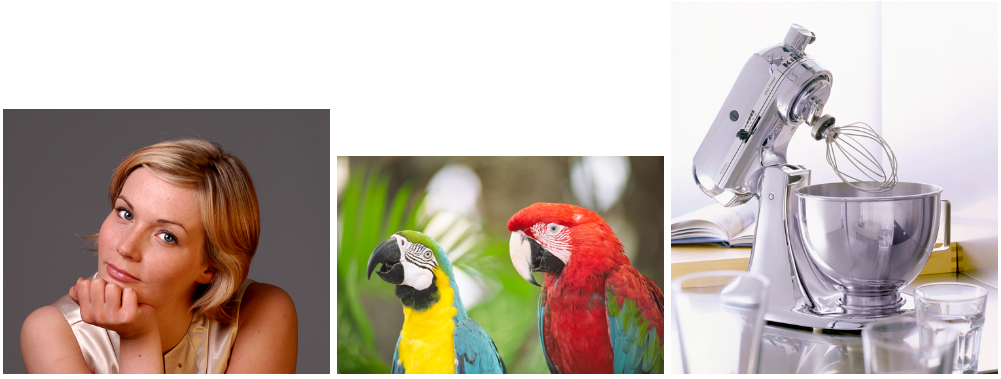
Figure 16: Equipment setup in laboratory

The visual luminance matching experiment was done using the Panasonic projector, and using the projects Matlab implementation of the visual matching target as seen in Figure 5. Equipment was set up as seen in Figure 16.

7.5 Visual pair comparison experiment

Testing the method with a forward and inverse model gives a numerical evaluation of the results. But as this method is a correction to projected output it was also natural to do a human vision based test to determine observers opinion on correction quality. The implementation done in this project tests four different approaches to estimate projector tone response, and thereby gives four different corrected versions of a original image. Three ISO sRGB corrected PNG-format images were chosen to use in the experiment. These three images were chosen for there differance in characteristics. The first image is a portrait that has a good contrastrange, has both a lot of detail and a monotone background and a lot of human skintone representation. The second image has more colorfull contents. The two parrots and the background represent a wide range of colors. And smaller areas of the image, like the beak, also has a wide contrast range. The third image is of a household mixer. This image consist of more light colortones, and though it is not a black and white image it is quite monochromatic. Comparing the original and corrections of this image will be able to reveal any saturation of colors and loss of contrast, while the comparisons when using parrots.png and girl.png also will be determined by color reproduction. The original images can be seen in Figure 17

Images are corrected with the found correction curve according to the difference to the gamma 2.2 curve(sRGB correction). This means that for each pixel in the original image each of the R, G and B values are retrieved, their luminance Y found according to the gamma 2.2 curve, and the found luminance Y is looked up in correction curve to determine the corrected Y' which corresponds in the correction curve to corrected digital input R', G' and B'.



(a) girl.png (b) parrots.png (c) mixer.png

Figure 17: Images used in visual pair comparison experiment

7.6 Evaluation method

7.6.1 Calculated differance

Results in the experiments are calculate as differences in luminance ΔL. The calculation is derived from Equation 7.1, found in [15].

$$\Delta E^{*}_{ab} = \sqrt{(\Delta L*)^2 + (\Delta a*)^2 + (\Delta b*)^2} \tag{7.1}$$

7.6.2 Forward model

As forward comparison model the estimated projector tone response curves are compared with the real projector tone response curves. Both are normalized to max luminance of 100 for calculation of ΔL differance. Real projector response is shown in Figures 18 and 19.

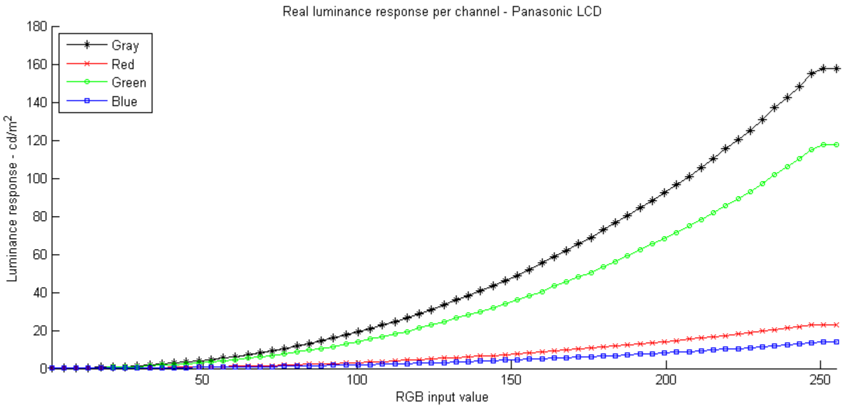


Figure 18: Real luminance response per channel for Panasonic PT-AX100E. Luminance in candela/m^2

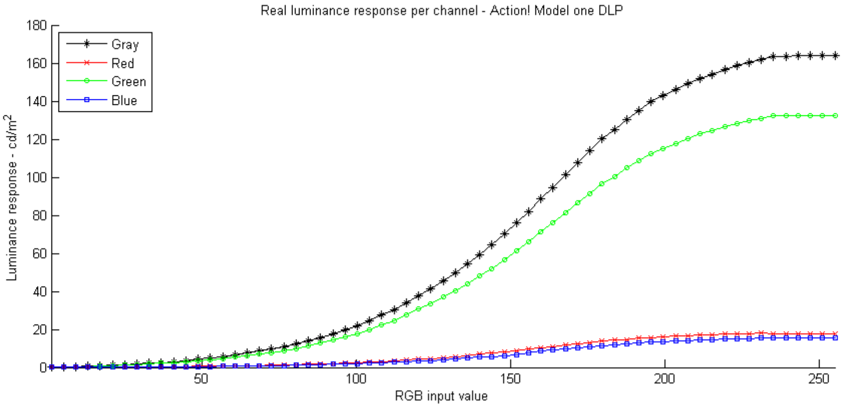


Figure 19: Real luminous response per channel for Projectiondesign Action! Model one. Luminance in candela/m^2

7.6.3 Inverse model

A inverse model is also used to test methods. This is done by estimating starting with a set of 16 XYZ equally increasing grayscale luminances and estimating correction for these 16 luminances as RGB input to projector, with the different methods. The projector output of the corrected RGB input is measured with the spectroradiometer. Then method performance can be estimated as a ΔL differance between intended output values and the methods correction. For comparison max luminance is normalized to 100.

8 Experimental results and analysis

Note: This chapter contains many figures of estimated camera and projector tone response curves. These figures have by mistake been plotted without axis labels. The missing labels are always the same for these figures. This being **Luminance response** for the y-axis and **Digital input value** for x-axis.

8.1 The importance of determining projector blacklevel

The projector black level luminance is one of the four determining luminance's when estimating the cameras tone response curve. This is a factor that the system can not determine by itself, and has to be stated by user. In the original method this luminance was estimated by author to be approximately 2%. It is stated in the original paper[1] that this luminance probably will need to be adjusted for each individual projector. When starting experimentation with this method it was tested with the original black level of 2%. For the Panasonic and the Projectiondesign projector this black level luminance was much to high, resulting in an estimated curve that were far from the truth. On a normalized scale from 0-1, 2% luminance equals a value of 0.02. To determine the real black level for the projectors used in this project, the black level values were determined by five individual luminance measurements with the spectroradiometer where one measurement were done each day during a week of RGB input 0,0,0. A mean value of these five measurements was calculated and used as black level. For the Panasonic LCD projector this value was found to be 0.0017 on a 0-1 range, which in percentage equals to 0.17%. And for the Projectiondesign DLP projector 0.0008, which equals to 0.08%. The projector black level also affects the 50% luminance point as this point is adjusted according to projector black level and 25% and 75% points when estimating curve with 3 Figure 20 shows the effect of using a wrong black level. When testing this it became very clear that one way or another the projectors black level need to be measured or estimated with good accuracy when using this method. This is a weakness in the approach as it moves away from the initial chain of thought on replacing expensive color and luminance measurement equipment with the digital camera.

8.2 Image capture and non-uniformity correction

Camera and projector tone response estimation in the Bala method is largely based on two factors. First of all on how correct the adjustment of visual matching is performed, and secondly the user ability to capture a correct representation of onscreen luminance's in chart with camera. The cameras read of luminance's will be greatly influenced by projector and camera non-uniformity. Typically non-uniformity in projectors have the effect that projection is brighter in the center area of projection and become less bright against the edges of projection[8]. Similar tendencies are seen when capturing an image with a camera, where edges may become less bright in comparison to center area. This is a common way to describe non-uniformity in devices with optics. When capturing an image of projection that suffers from non-uniformity with a device that suffers from non-uniformity, the resulting image will suffer from both devices lack of uniforminty. The

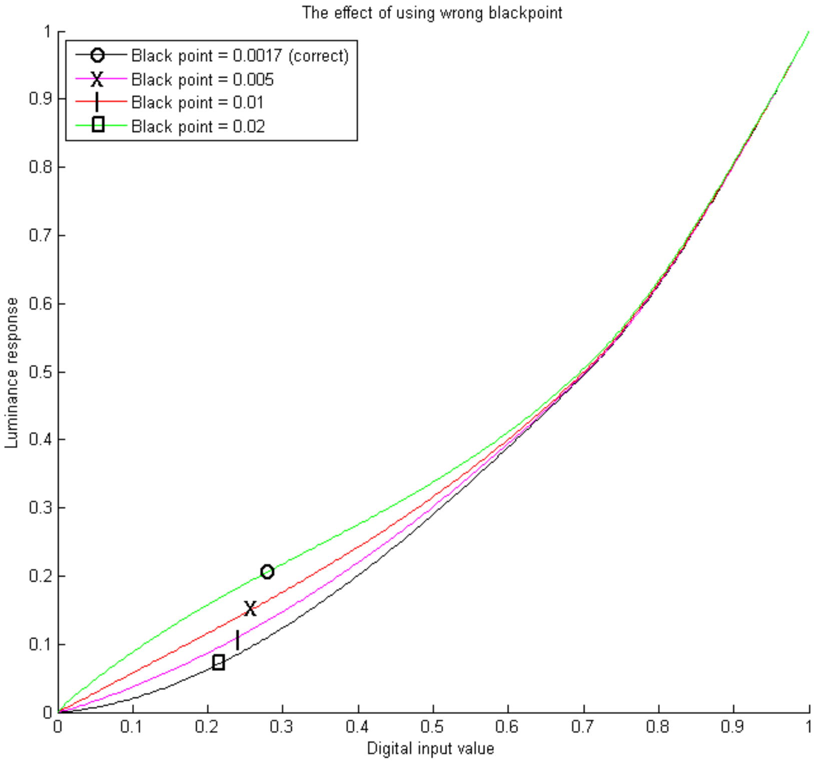


Figure 20: Illustration of differances in estimation of camera TRC when blacklevel value changes

result can be that an when capturing a chart as the one in Figure 9 luminances in image might become more equal then they actually are. On the bottom row of this target the luminances of patches increase from right to left. But because of the non-uniformity in camera and projector the luminance values in the resulting image does not always seem to increase. They might even be decreasing in the left-bottom part of the chart. This is a tendency that has been observed a few times during experimentation. The methods non-uniformity correction is supposed to adjust for this effect in values read from image, but it is not always successfull at adjusting. The reason is that this correction simply is not enough to correct for the error. An example of the result of non-uniformity correction can be seen in Figure 21. In the figure the original read luminance's from camera and the according luminance's after correction are shown. In this curve all of the original 24 patches are represented. luminance's from top row are shown where x is 1-8, luminance's from mid row where x equals 9 to 16 and the bottom row is where x is 17 to 24. The original digital input to projector were a set of equally increasing grayscale values. When the camera captures the target we can clearly see the effect of non-uniformity. The values are no longer increasing, they are actually decreasing in the camera read of the brightest patches. In the luminance's read from the mid row we clearly see the non-uniformity across the screen. Input value to these were equal duplications of the 50% luminance value, and after camera read the patches in the middle of the target are clearly brighter then the ones closer to the sides.

In the corrected luminance's we can see that the non-uniformity correction has evened the values in the mid row, and all values for the 50% luminance patches now have the same luminance value. For patches in the higher range of input brightness we can also see that the correction have adjusted the values to almost continuously increase, but still there is a decrease in the luminance at patch 23. Figure 22 shows the amount of correction done to each of the original patches. The brighter the patch is the more correction has been performed. Here we can also see the bottom row is the one that has been corrected the most.

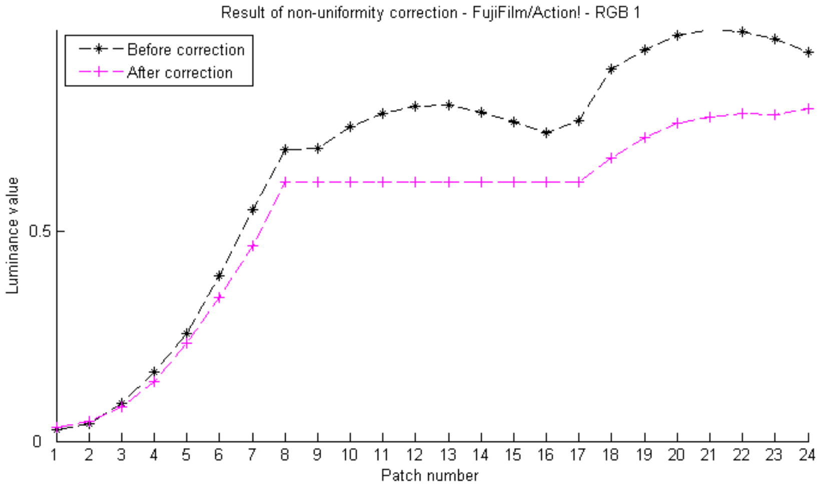


Figure 21: Illustration of non-uniformity correction result according to original read. Values normalized to maximum read luminance = 1.

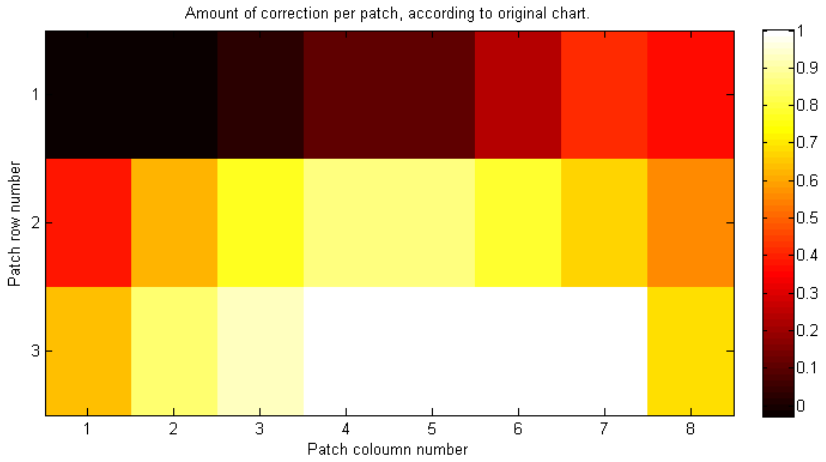


Figure 22: Heatmap of non-uniformity correction according to original chart structure. Values normalized to maximum correction = 1.

Another factor that influences the cameras luminance read is the use of the camera itself. In the original paper the task of image capture is not discussed, and when trying to capture an image in this experiment a few important factors were identified. First of all it is important to position camera correctly. As mentioned in chapter 7.2 a tripod was used this projects setup. This is of course partially because this implementation uses both an image capture of a corner point reference chart shown in Figure 8 and the chart itself shown in figure 9. So it is important that these pictures are taken from the exact same position and that the lens direction does not change.

This projects implementation was done in Matlab, and a problem occurred when it became apparent that Matlab does not have functionality to display figures in true full screen. There will always be a frame around the calibration target as seen in Figure 9. The result is that the camera must only capture the area inside this frame to make sure that the automated calculations is not influenced by other bright areas then the reference points themselves in the captured reference point image. This makes it important to use the cameras zoom capabilities to adjust to the correct area. The correct area will then be inside the frame with enough space to capture the whole target. This task would be easier if the implementation did not demand a capture of the corner reference points and the frame was removed. This is a problem with this projects implementation of the method, and not a problem related to the method itself.

But a more universal problem when using this method is to actually capture the target correctly. The system is dependant of the cameras ability to capture the differences in luminance in the target. Unsuitable settings can be a large source of error to this method. Wrong exposure like to low aperture value that gives to much light to the sensor, and to long exposure time will result in a saturated image which makes it hard to determine differences in the brighter patches. The opposite with high aperture value and short exposure can result in a dark image where the problem is to determine differences in the darker regions of the chart. When luminance's in the different patches of the captured image are close to equal it will affect the estimation of the projector tone response curve. When such a luminance set is looked up in the estimated camera tone response curve the result will be that the estimated projector curve will either have low luminance response for a large area of lower digital count input values. Or the curve will reach max luminance at lower digital input values. This will cause a range of higher digital input values to saturate, and a the higher luminance areas in the curve will be cut off at maximum luminance. Figure 23

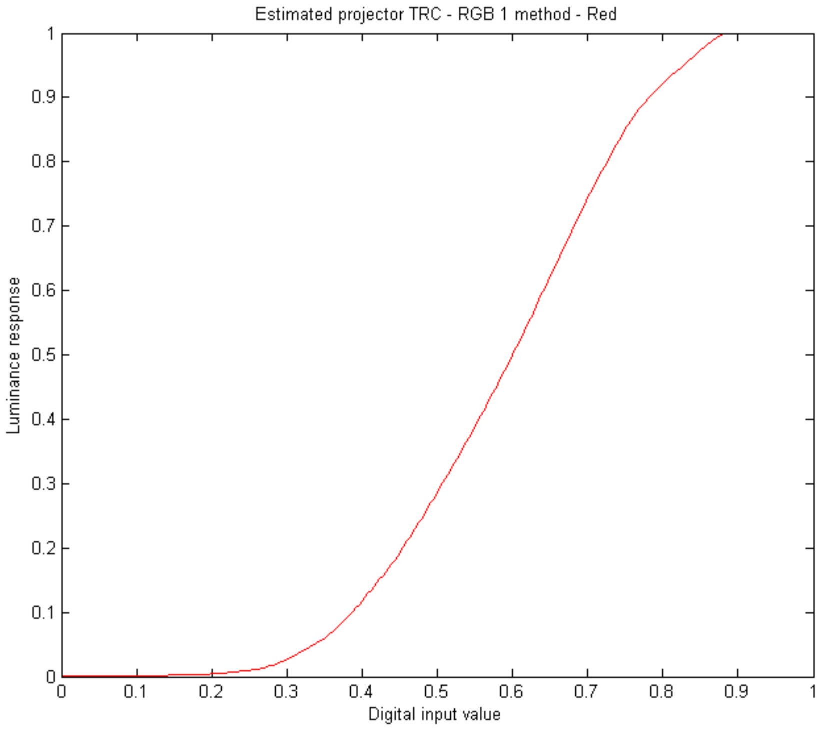


Figure 23: Estimated projector tone response curve for red channel. Using FujiFilm camera and Projectiondesign Action! DLP projector. Saturated in digital input range 0.87 to 1.

When testing the method it became clear that the FujiFilm camera had severe problems with capturing suitable images for use with this method. The captured images seemed to be either saturated in brighter areas or the darker patches were undistinguishable from each other, and the resulting estimated curves after non-uniformity correction were not good. Major efforts were put into experimentation with camera settings to achieve better images, but as mentioned in chapter 7.2 auto mode was found most suitable. Figure 23 is an example of an estimation result using the FujiFilm camera and shows the problematic resulting curve. This type of curve is not a good estimation of the projectors real luminance response.

Using this camera with the Bala method often resulted in this kind of problem. As a consequence the camera was not found suitable for use with this method. The problems when using this camera shows that capturing usable images of the chart might not necessarily be an easy task. But when this is said it needs to be stated that the person operating the camera was not a professional. And the fact that this projects experiments were performed in dark room conditions, while Bala and Brown used dim room conditions. This might influence the cameras capabilities to capture a suitable image. After estimating several tone response curves on basis of the FujiFilm camera it was decided not to use this camera or the results it produced any further. Therefore results from only two hardware combinations will be further discussed in this chapter. This being the Nikon camera with the Projectiondesign DLP projector, and the Nikon with the Panasonic LCD projector.

8.3 Visual matching experiment result

Six participants used the visual matching tool in this projects Bala method implementation. This was done to collect data on how accurate we are able to match a luminance in primaries and the total luminance bray channel. Matching was done to find 25%, 50% and 75% luminance level for R, G, B and gray channel of the Panasonic projector. The resulting data is as shown in Figure 6.

Figure 25 shows the deviations in the matched luminance values per channel and target luminance level. This figure shows that the participants matching of the 25% luminance level has the highest standard deviation. The answers to the questions asked in this experiment, shown in Table 7, confirms that five out of six participants found this level hardest to adjust luminance in. When asked what luminance level participants found it easiest to adjust in, all replyed that the 75% level was the easiest. The standard deviation results in Figure 25 shows that numerically this was not correct, but that the 50% luminance level had the lowest standard deviation for all channels. Some of the participants in the experiment made comments where they stated that they felt it was easier to match luminances as the targets luminance level increased. An explanation for this might be that the participant feels that it is easier to match background luminance to the 75% level, is that a longer range in the adjustment scale percetually matches the binary pattern.

Figure 24 shows the mean values for the different luminance matchings. This figure also show a 95% confidence interval, meaning that based on the collected data one can say with 95% certantie that further performed matchings of luminance with this projector that the results will be inside the confidence interval range. Here it is observed that the confidence interval for the 50% luminance level are significantly smaller then the 25% luminance level, and generally smaller then the 75% luminance level. That the accuracy is better in the 50% matching is also confirmed by the standard deviation plot in Figure 25. Here standard deviation for 50% luminance matching is best for all channels except blue, where it is slightly higher then 75% level.

One point that might cause the mathing at the 50% luminance level more accurate is how the binary line pattern is built. The pattern consists of an equal amount of interchaning channel color maximum luminance and zero luminance lines. The 25% target consists of $\frac{3}{4}$ black and $\frac{1}{4}$ max channel luminance with one maximum line, then followed by three black lines, then the pattern is repeated. The 75% luminance target is the opposit pattern of the 25% target with three max channel luminance lines followed by one black line. The fact that 50% target has equal distribution of these lines might make it easier for the human eye to percive the binary pattern as a uniform color or gray patch that have an unequal distribution where one black or max luminance is repeated over three lines.

As mentioned the participants in the experiment stated that the blue channel was the easiest to adjust luminances in. When studying the standard deviation of the results for blue in Figure 25 you can see that the standard deviation in the blue channel is not especially low, but much more even for the three luminance levels, then the other channels. This represents a more even distribution of error over the three luminance levels in the blue channel. One point that might give advantage to the blue channel in the matching 25% and 75% pattern that have uneven ditribution of lines is that the contrast differances in the pattern are lower then for the other channels, and therefore easier to see as one color. For the gray channel the pattern consists of black and white lines which is the highest contrast difference possible, and this could makes it harder for the human visual system to percieve them as a gray patch them.

Ref to Bala 2005 paper.

Chn.	Target lum.	Y mean	Y min	Y max	Standard dev.	95% conf. interval
Gray	25%	0,5114	0,4748	0,5262	0,0137	0,0068
Red	25%	0,5096	0,4850	0,5377	0,0106	0,0052
Green	25%	0,5099	0,4831	0,5237	0,0100	0,0049
Blue	25%	0,5302	0,5204	0,5622	0,0097	0,0048
Gray	50%	0,6959	0,6889	0,7020	0,0038	0,0019
Red	50%	0,6957	0,6848	0,7076	0,0053	0,0026
Green	50%	0,6939	0,6894	0,7023	0,0039	0,0020
Blue	50%	0,7169	0,7082	0,7308	0,0066	0,0033
Gray	75%	0,8554	0,8419	0,8706	0,0081	0,0040
Red	75%	0,8423	0,8141	0,8594	0,0098	0,0049
Green	75%	0,8521	0,8328	0,8656	0,0082	0,0041
Blue	75%	0,8628	0,8496	0,8748	0,0061	0,0030

Table 6: Results from visual luminance matching experiment

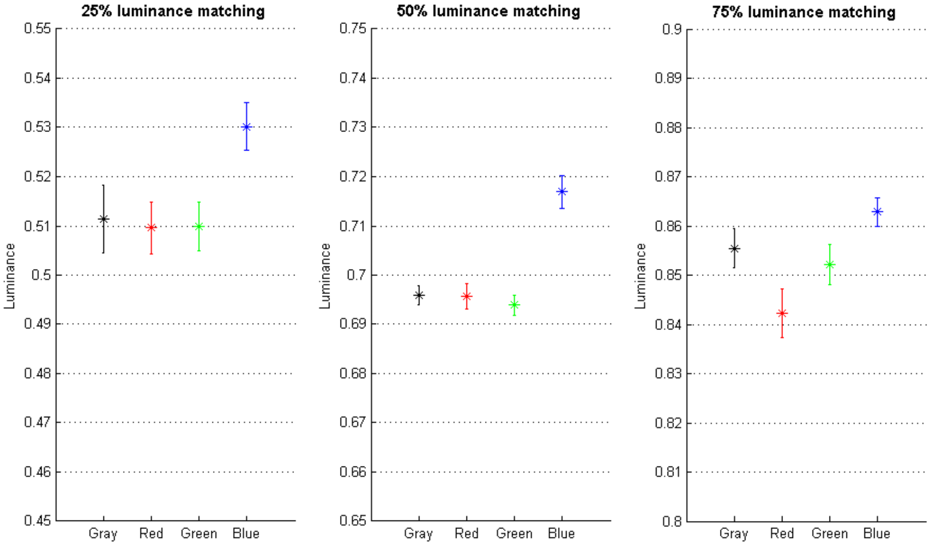


Figure 24: Resulting matched luminance in visual matching experiment. Mean values with 95% confidence interval.

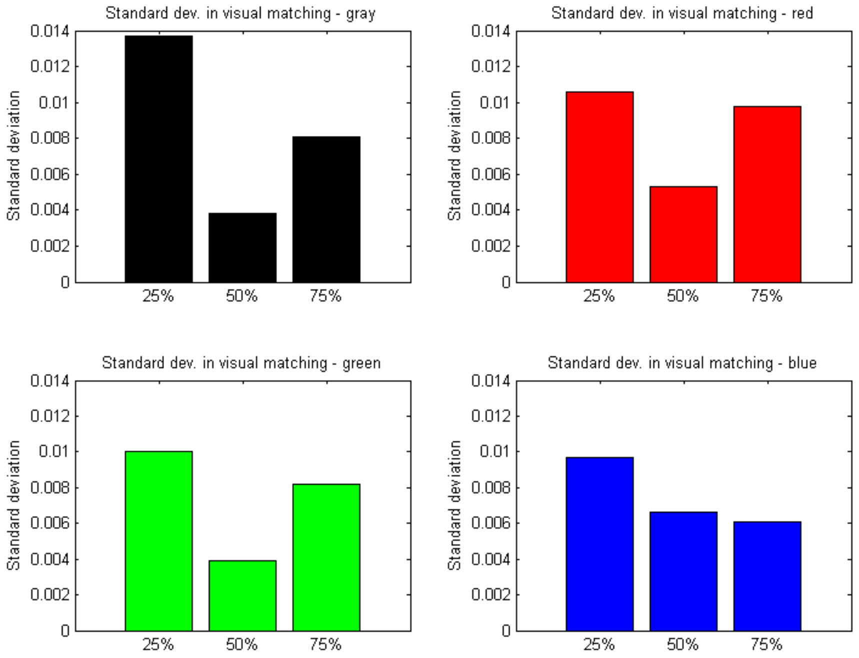


Figure 25: Standard deviation per channel for 25%, 50% and 75% luminance in visual luminance matching experiment.

Observer number	Professional / non-professional	Hardest channel	Easiest channel	Hardest luminance	Easiest luminance
1	Pro	Gray	Blue	25%	75%
2	Pro	Gray	Blue	25%	75%
3	Pro	Gray	Blue	25%	75%
4	Non-pro	Gray	Blue	50%	75%
5	Non-pro	Gray	Red	25%	75%
6	Pro	Gray	Blue	25%	75%

Table 7: Results of visual luminance matching experiment

8.4 Estimation of camera tone response

In this section results of the camera tone response estimations from the project will be presented and analysed. Figures show estimated curves according to the cameras normalized real camera response, with a calculated ΔL mean differance between the two in the figure title. The full set of camera tone response estimations used in the project can be found in Appendix A.

8.4.1 Gray 1 and gray 3 method

The original Bala method is based on using one visually matched point to estimate the cameras tone response for gray channel, in this project refered to as the gray 1 method. Figure 26 and Figure 27 shows the estimated curve achieved when using this method with hardware combinations Nikon camera with Panasonic projector, and Nikon camera with Action! Model one projector. In these curves it is observed that the estimations both conform better to the real curves over the matched 50% luminance. Under this point the estimated curves is higher then the real response and does not follow the real curve well. Figure 26 and Figure 27 shows estimated curve for Nikon camera with Panasonic projector and Nikon with Action! Model one. These curves are estimated using visually matched luminances for 25%, 50% and 75% luminance levels. Here we can see on the estimated curve that the area below the 50% luminace level confirms better with the real camera response then in Figure **??** and 27. So this can then be considered an improvment. Improvments in the area above the 50% luminance level are not that aparent here. But the ΔL differance when using three visual matched points instead of one are considerable. For the Panasonic projector the ΔL was reduced from 5.39 to 3.74, and for the Action! Model one from 3.11 to 1.38.

Looking at the estimated curves for the Panasonic projector we see a bigger gap between estimation and real curve. This is because the digital imput values found during visual matching is not high enough. From looking at Figure 28 we see that the real response curve has a digital input value of about 0.81 while the estimated curve shows a value of about 0.75 for the same luminance level. When looking at same the estimation made with same method for the Action! Model one in Figure 27 we see that the visually matched luminance conform much better with the real response. As mentioned this apperes to be from non-correct visual matching. But throughout experimentation this was discovered and tested. Method was run several times to determine if this mismatch was a temporal coincidance, but this was not the case. When matching luminance for this projector the digital input values always seem to be lower then the real response curve values. A good explanation for this continous mismatch has not been found and could require further investigation. Needless to say the Action! Model one projector therefore gives the best results with methods gray 1 and gray 3 when estimating the cameras tone response. Out of the two methods estimation of curve with three matched luminance values is found to be most accurate.

8.4.2 RGB 1 and RGB 3 method

Figure 30, 31 and 32 show the results from estiamting camera tone response curves separatly for R, G and B color channel, using RGB 3 method with the Action! Model one projector. It is harder to see tendencies and draw conclusions from studying the estimated curves using the RGB 1 and RGB 3 method. There are no obvious repetative

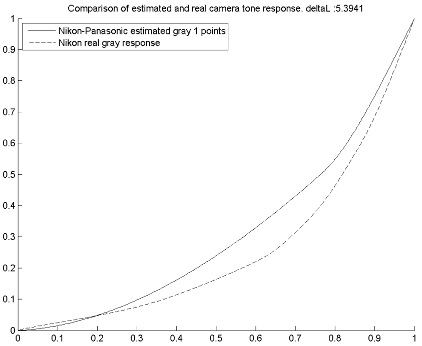


Figure 26: Estimated camera TRC. Gray 1 Panasonic/Nikon

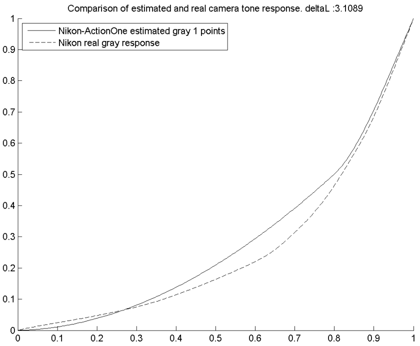


Figure 27: Estimated camera TRC. Gray 1 Action!/Nikon

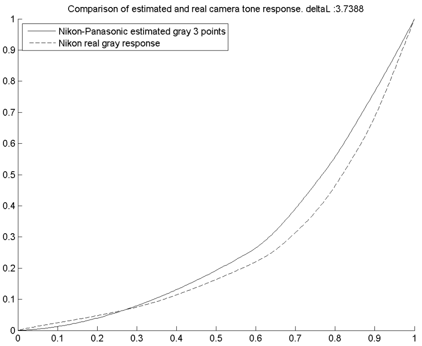


Figure 28: Estimated camera TRC. Gray 3 Panasonic/Nikon

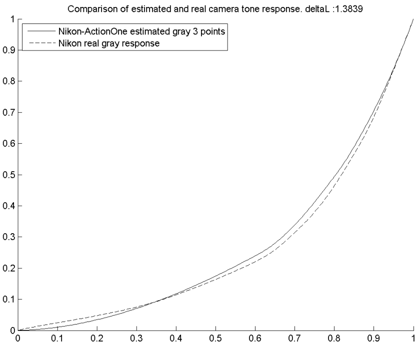


Figure 29: Estimated camera TRC. Gray 3 Action!/Nikon

patterns in these methods graphs. In the example figures we can see that the luminance matching in for the red channel seems to be a bit off, causing the estimation to have a lower curve then the real red channel response. Green and blue estimations conform better to the real response, and show similar ΔL differances as achieved with gray 3 method. One tendencie is apparent though. The estimated curves are all under the real responses in the lower luminance values. This can be explained by the the fact that the estimation is constructed to resemble a gamma shape curve which increases more gradually for lower range digital input. As seen in the example figures 30, 30 and 30 the real luminances response for camera R, G and B channel seem to have a more uniform and higher increase in this digital input range. This effect is more apparent in estimations for red and blue channel, then in the green channel. Considering that the real response curves in the example figures are per channel normalized versions of the curves in Figure 19, This may be becaused the red and blue channels range on the luminance scale is shorter then the green channels range on the projectors real response. Thus these curves characteristics seem flatter.

The results when using RGB 1 and RGB 3 method can be seen in Table 8. Generally these results show that there is a slight ΔL differance improvment when using curves estimated with three visually matched points, but differances are not as noticable and equally uniformly improving as when only estimating curve for the whole system like in methods gray 1 and gray 3.

Method	Projector	ΔL red	ΔL green	ΔL blue
RGB 1	Panasonic	1.73	4.40	2.71
RGB 3	Panasonic	1.60	3.41	1.64
RGB 1	Action!	3.46	1.47	2.49
RGB 3	Action!	4.13	1.07	2.01

Table 8: Mean ΔL differances with RGB 1 and RGB 3 method.

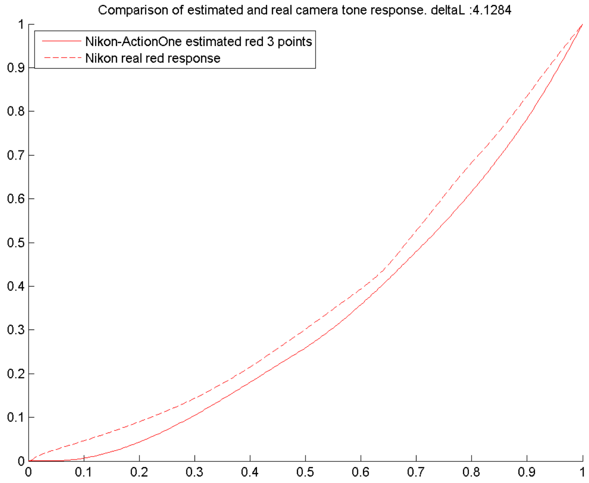


Figure 30: Estimated camera TRC. RGB 3 Action!/Nikon, red channel.

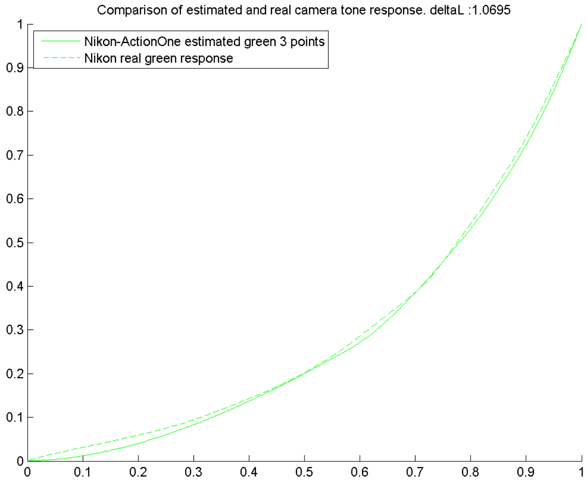


Figure 31: Estimated camera TRC. RGB 3 Action!/Nikon, green channel.

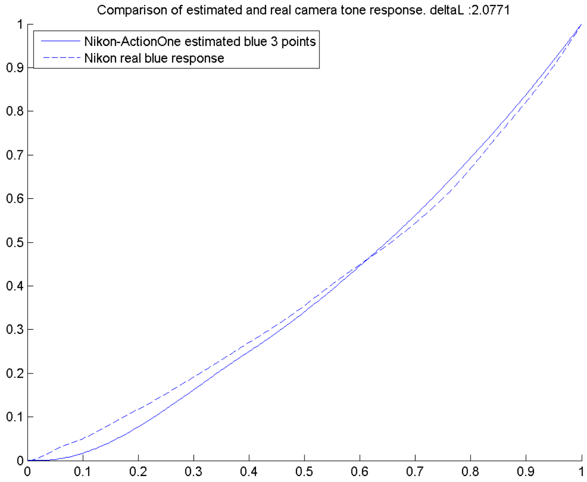


Figure 32: Estimated camera TRC. RGB 3 Action!/Nikon, blue channel.

8.5 Estimation of Projector tone response

In this section estimated projector tone response curves based on camera tone response curves in the previous section will be presented. As explained in Chapter 6.1 these curves are found by looking up the luminance values measured with the camera in the estimated camera response curves, setting these in referance to the original digital input to the projector, and interpolating over the resulting coordinate pairs. These curves accuracy according to projectors real tone response are therefor totally dependant on the quality of the camera tone response estimation. From looking at estimations in Figure 33 and 34 we see that the projector tone response also is influenced by the mismatch under the 50% luminance level. These graphs are based on camera tone response curves estimated with gray 1 method, seen in Figure 26 and 27. By studying the camera curves and the projector curves we clearly see that the problems in the estimation of the cameras curve becomes apparent when estimating the projectors curve. When using gray 3 method this improves. Figure 35 and 36 shows the resulting projector tone response curves when using visually matched values to determine camera tone response. Here we see that the s-shaped real response of the Action! Model one projector has been estimated quite well with a ΔL differance of only 0.59. The shape recemblance using the gray 3 method for the Panasonic projector gives a good shape recemblance. But because of the mysterious continuos mismatch in luminance matching the whole curve is higher then the real response, ΔL differance of 2.14. ΔL differance for estimated projector tone response curves for all methods and hardware combinations can be seen in 9. Of the gray methods, gray 3 shows the best results. So this shows again that the methods using three visually matched luminance levels perform better. This is confirmed by the results in the RGB methods. It seems here that the gray methods perform better then the separate channel estimation RGB methods. One point that could cause this is that while luminance the visual luminance adjustments done to each channel are supposed to increase accuracy, they can also become a factor that can generate more inaccuracy. This caomes from the fact that you visually match more points on the estimated curves and therefor have more oppertunities to make badly adjusted visual matchings. To see the full set of estimated projector tone response curves from the experiment see Appendix B.

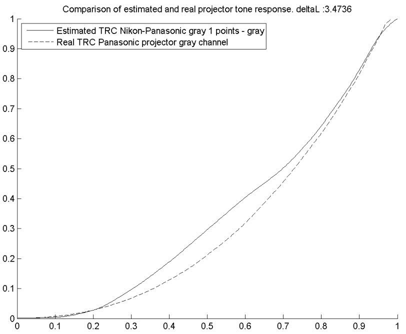


Figure 33: Estimated projector TRC. Gray 1 method with Panasonic/Nikon.

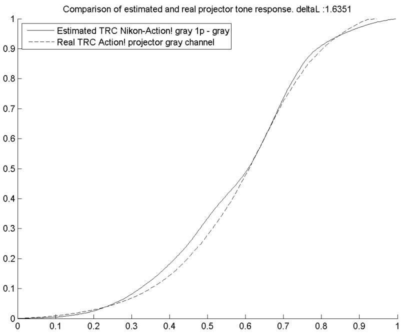


Figure 34: Estimated projector TRC. Gray 1 method with Action!/Nikon.

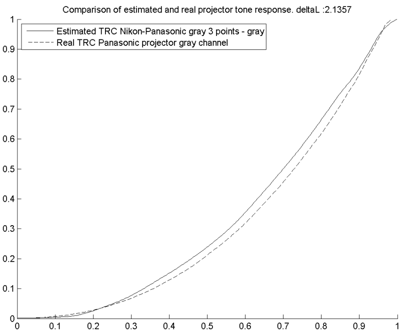


Figure 35: Estimated projector TRC. Gray 3 method with Panasonic/Nikon.

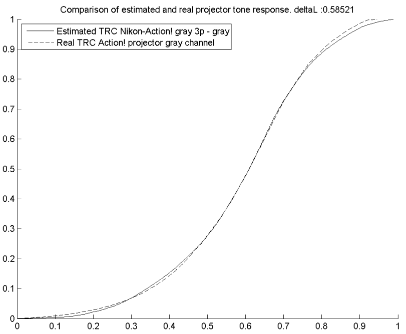


Figure 36: Estimated projector TRC. Gray 3 method with Action!/Nikon.

Method	Projector	ΔL gray	ΔL red	ΔL green	$\Delta Lblue$	RGB mean $\Delta Ldiff$
Gray 1	Panasonic	3.47	—	—	—	—
Gray 3	Panasonic	2.14	—	—	—	—
Gray 1	Action!	1.64	—	—	—	—
Gray 3	Action!	0.59	—	—	—	—
RGB 1	Panasonic	—	1.83	3.03	2.51	2.46
RGB 3	Panasonic	—	1.48	2.30	1.92	1.90
RGB 1	Action!	—	1.90	1.05	2.96	1.97
RGB 3	Action!	—	1.89	0.96	2.01	1.62

Table 9: Mean ΔL differances in real projector response and estimated response curve.

8.6 Inverse model test

The inverse model tests methods with a 16 value gray scale ramp with equally increasing luminance as input. Performance results are measured as to how good the different models are at adjusting digital input to correct displays reproduction of values to achive a linear output. To the results the standard gamma correction of 2.2 has been added to show how the standard correction used in computer displays performes in referance to the corrections done with this projects various methods of the Bala method. Table 10 shows the mean ΔL differance between desired linear projector output and the differant methods corrections. From this table we can see that the standard correction of gamma 2.2 does not perform well for the Action! Model one projector. This projectors real tone response curve has a very s-shaped curve. Correcting it with the standard gamma is not suitable as this curve is most definatly not a s-curve, but a continously increasing curve. The amount of error is shown in figure 38. Figure 37 shows the results of the gray 3 method that was found to be best for this projector in the test. Figure 37 and 40 show the results for gray 3 and gamma 2.2 method with the Panasonic projector. For this projector all method results are very equal. We can see that the standard gamma correction performs almost as good as all the four versions of the Bala method. This is belived to be because the Panasonics real response curves are very equal to a gamma curve. When the projectors tone response curve is equal or close to equal to the gamma 2.2 curve the standard gamma correction will be sufficiant. With the panasonic results are better for the four versions of the Bala method. But if this method was used to actually perform correction for an end users of projectors, one can ask if the effort put into correcting with the Bala method would be worth it to get a correction that performs just slightly better. From these results it is clear that the original Bala method performs well for correction of the Action! Model one projector, reducing ΔL mean from 10.53 to 2.30. But the other three methods perform even better, whereof the gray 1 method performs best with a 0.60 ΔL differance from intended output. The RGB 1 and 3 methods show similar results.

Performing separate visual matching for each channel as in the RGB 1 and RGB 3 method will be take significantly more time then the matching for the gray methods. Gray 1 requires only 1 visual matching at the 50% luminace level, while RGB 1 requires a 50% luminance matching for each channel. When using method gray 3 three luminance levels have to be visually matched, and for RGB 3 this has to be done with all three channels resulting in nine separate visual matchings. The correction result when using RGB 1 and RGB 3 method does not give better results then the gray 3 method in this experiment and it is therefore found unneccessary to do make the extra effort on matching luminance levels separatly for the color channels.

Method	Projector	Mean ΔL	Max ΔL	Standard dev.
Gray 1	Action!	2.2973	6.21	2.00
Gray 3	Action!	0.5970	1.39	0.50
RGB 1	Action!	0.8909	2.77	0.82
RGB 3	Action!	0.8721	1.78	0.65
Gamma 2.2	Action!	10.5293	25.68	9.52
Gray 1	Panasonic	4.1257	9.14	3.02
Gray 3	Panasonic	3.3504	5.70	1.82
RGB 1	Panasonic	3.1100	6.21	2.10
RGB 3	Panasonic	3.0435	5.68	1.85
Gamma 2.2	Panasonic	4.3182	9.31	3.03

Table 10: Mean ΔL differances for differant method in inverse model test.

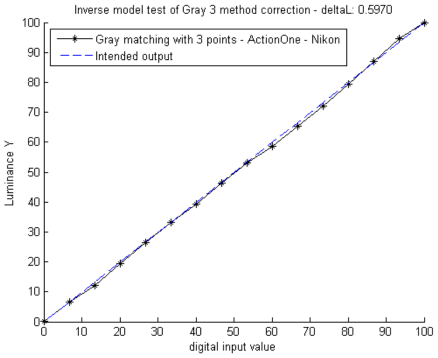


Figure 37: Inverse test result. Gray 3 method with Action!/Nikon.

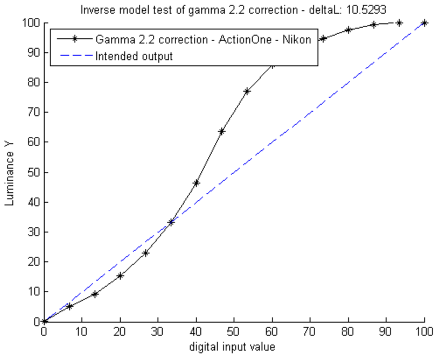


Figure 38: Estimated projector TRC. Gamma 2.2 method with Action!/Nikon.

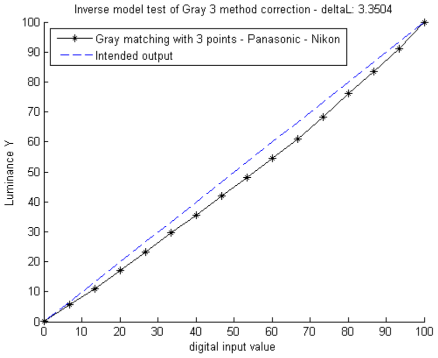


Figure 39: Inverse test result. Gray 3 method with Panasonic/Nikon.

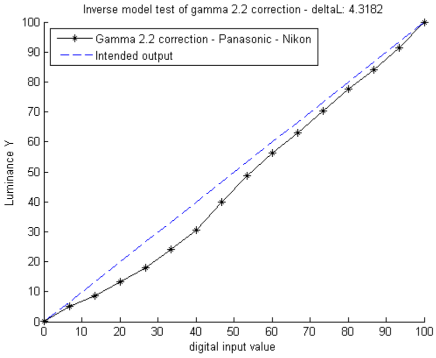


Figure 40: Estimated projector TRC. Gamma 2.2 method with Panasonic/Nikon.

8.7 Visual comparison of correction

In this experiment ten obesrevers were asked to compare original reproductions with reproductions corrected with the four different versions Bala methods. The plot in Figure

41 and 42 show collected data each methods performance with the Action! Model one and the Panasonic projector. These figures show a mean score for each method with a confidence interval of 95%. The higher a method is on the mean score axis, the more the reproductions with this method was perfered by the observers. Some of the methods confidence intervals overlap each other. In these cases it is not possible to say which of the overlapping methods that is better, though one will have a higher mean score then the other.

For the Action! Model one projector Figure 41 shows very clear that the reproductions made with the four Bala methods are very much perferred by observers. The standard sRGB gamma correction scores much lower, something that indicates that the original image was never, or almost never preferred by the observer. The gray 1 method scores the highest mean score, closely followed by gray 3. RGB 1 and RGB 3 methods score lower then the gray methods. For the Panasonic projector the methods have been ranked very equal by the observers. In Figure 42 there is no method that scores especially better then the other. We see that the original image is ranked very equally with the reproductions.

The visual evaluation of reproductions has given results that corrolate well with the numeric results from the inverse model. For the Action! Model one projector the standard gamma correction clearly is not preferrable. And for the Panasonic PT-AX100E projector there no method can be said to perform much better then the other.

Figure 43 shows one pair of reproductions of the girl.png image used in the visual pair comparison experiment. The original image is on the left, and a reproduction corrected according to the gray 3 method for Action! Model one projector is shown on the right.

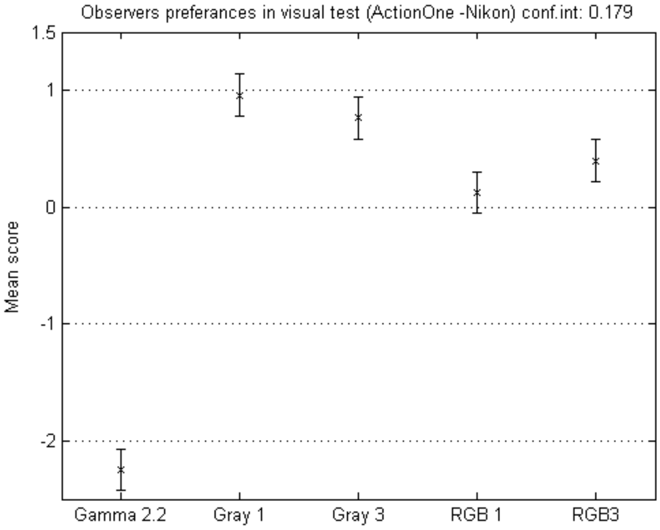


Figure 41: Method score for Action! Model one in of visual pair comparison experiment.

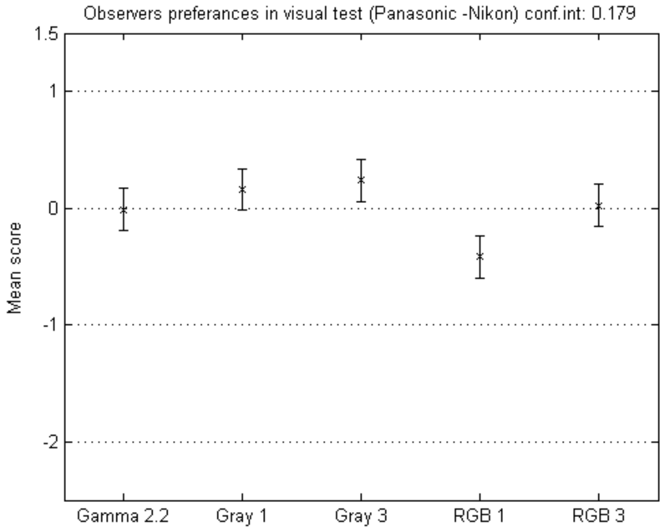


Figure 42: Method score for Panasonic PT-AX100E in of visual pair comparison experiment.

Figure 43: Original girl.png image on the left, corrected image for Action! projector with gray 3 method on the right.

9 Conclusion

This project was aimed to test and possibly enhance a camera based model for projection display calibration. In Chapter 4.1 two research questions were stated.

- Q1: Verification of the Bala method
- Q2: Extensions to the Bala method

The method was tested on two different projectors, a LCD projector and a DLP projector. Using the method with the DLP projector the method gives a much better projector tone correction then what is achieved with the commonly used standard gamma 2.2 correction. For the LCD projector the method does not improve projector output much. It is believed that this is because the projectors tone response is so equal to the gamma 2.2 curve that the correction necessary is minimal. Also there were problems with achieving a good estimation for this projector because of unexplained mismatching in the visual luminance task. It was also discovered that using a camera as a luminance measurement instrument can be a difficult task. As a result one of the cameras originally used in the experiment was found unsuitable for the method. Even though these kinds of difficulties were encountered the final results show that the method works. So the conclusion to research question Q1 is that the model is verified to work.

The experimental extensions added to the Bala method in this project show that adding more visually determined luminance adjustments before estimating tone response curves is an improvement to the method. This has been well documented in experiment results. The extension of separately estimating projector tone response for the primary channels is also found to be an improvement to the to the original method. But as this approach is more time consuming and does not give much better results then using one curve correction it is not found that this is a good approach. The conclusion to research question Q2 is that adding more visually matched luminance points does improve the methods performance considerably. While the estimation of separate channel tone response curves is an improvment to the original model, but not as effective as only adding more visually matched luminance points.

10 Further work

- Implement automated system.
- Automatic image retrival from camera to avoid splitting method in steps.
- Better edge detection to avoid rotation of image.
- Make fullscreen figure representation without frame around it.
- Find a better way to estimate blackpoint without using spectro.
- Store found result in a ICC profile, to put correction curves into good use.

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A Appendix: Estimated camera TRC

In this appendix chapter the projects complete set of estimated camera tone response curves are presented. These have been derived by using the projects implementation of the Bala method with two hardware combinations. A Panasonic PT-AX100E LCD projector with a Nikon D200 digital camera. And a Projectiondesign Action! Model one DLP projector with a Nikon D200 digital camera.

A.1 Method gray 1

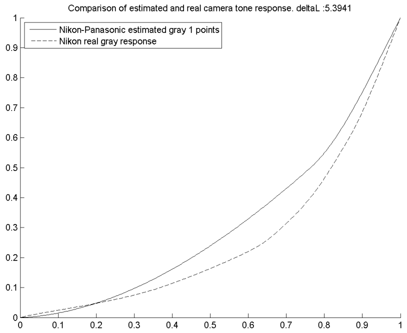

Figure 44: Gray 1 method with Panasonic/Nikon

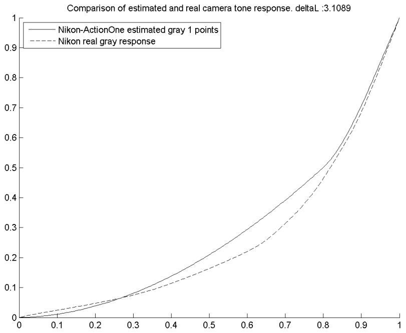

Figure 45: Gray 1 method with Action! Model one/Nikon

A.2 Method gray 3

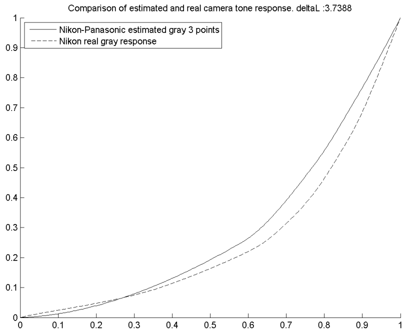

Figure 46: Gray 3 method with Panasonic/Nikon

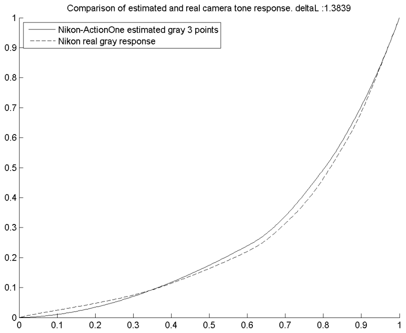

Figure 47: Gray 3 method with Action! Model one/Nikon

A.3 Method RGB 1 for Panasonic projector

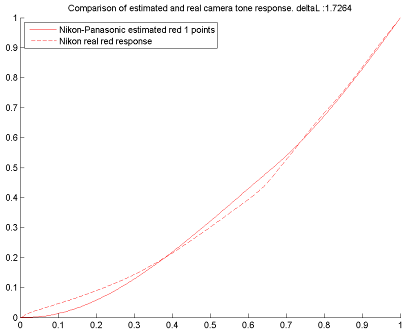

Figure 48: RGB 1 method with Panasonic/Nikon - Red curve

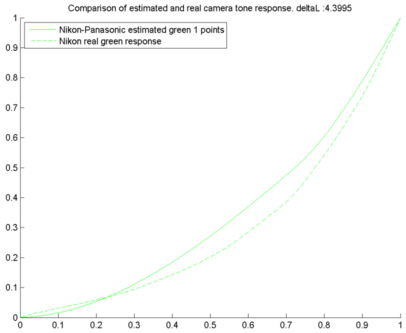

Figure 49: RGB 1 method with Panasonic/Nikon - Green curve

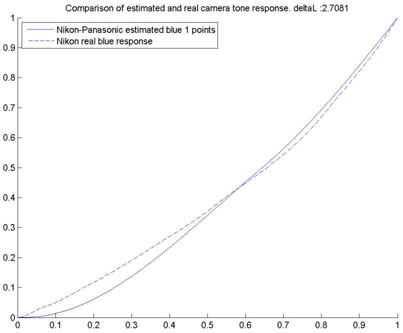

Figure 50: RGB 1 method with Panasonic/Nikon - Blue curve

A.4 Method RGB 3 for Panasonic projector

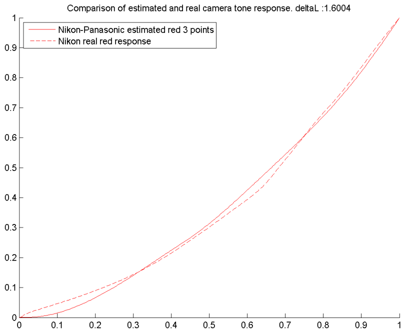

Figure 51: RGB 3 method with Panasonic/Nikon - Red curve

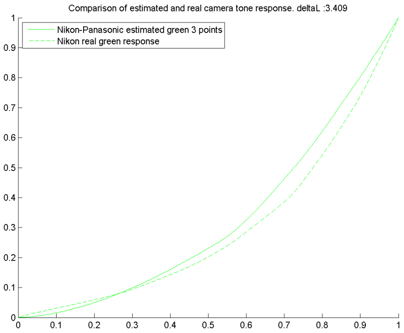

Figure 52: RGB 3 method with Panasonic/Nikon - Green curve

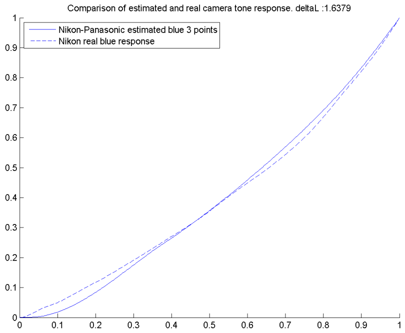

Figure 53: RGB 3 method with Panasonic/Nikon - Blue curve

A.5 Method RGB 1 for Action! Model one projector

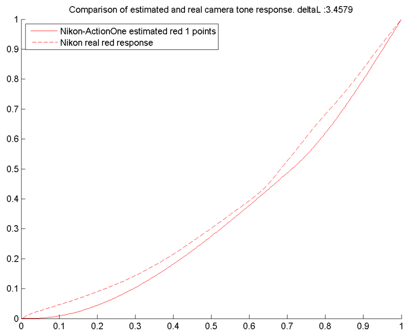

Figure 54: RGB 1 method with Action/Nikon - Red curve

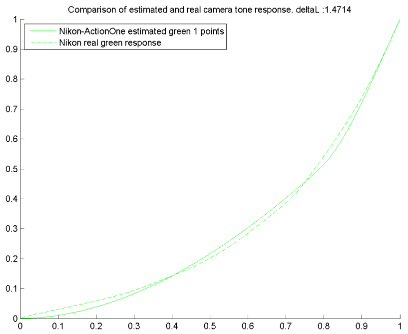

Figure 55: RGB 1 method with Action/Nikon - Green curve

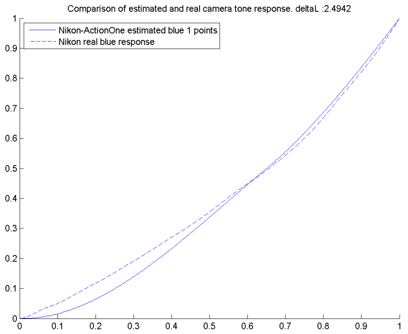

Figure 56: RGB 1 method with Action/Nikon - Blue curve

A.6 Method RGB 3 for Action! Model one projector

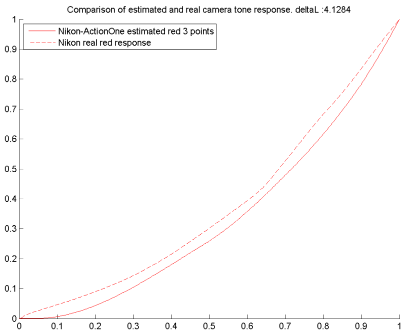

Figure 57: RGB 3 method with Action/Nikon - Red curve

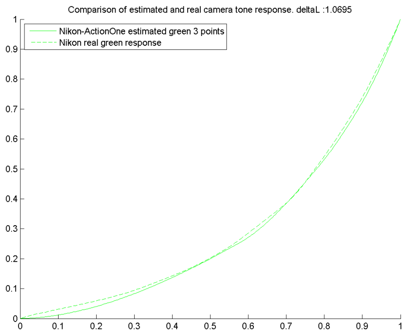

Figure 58: RGB 3 method with Action/Nikon - Green curve

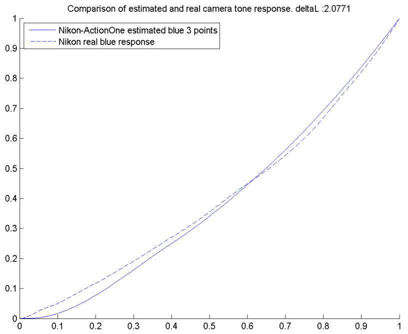

Figure 59: RGB 3 method with Action/Nikon - Blue curve

B Appendix: Estimated projector TRC

In this appendix chapter the projects complete set of estimated projector tone response curves are presented. These have been derived by using the projects implementation of the Bala method with two hardware combinations. A Panasonic PT-AX100E LCD projector with a Nikon D200 digital camera. And a Projectiondesign Action! Model one DLP projector with a Nikon D200 digital camera.

B.1 Method gray 1

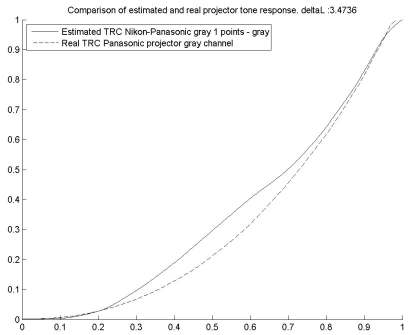

Figure 60: PJ TRC gray 1 method with Panasonic/Nikon

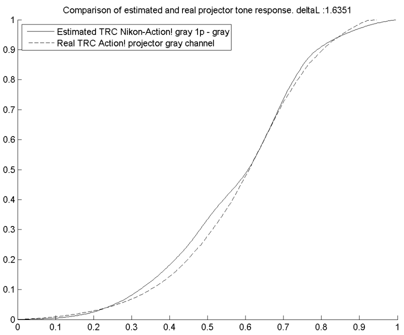

Figure 61: PJ TRC gray 1 method with Action! Model one/Nikon

B.2 Method gray 3

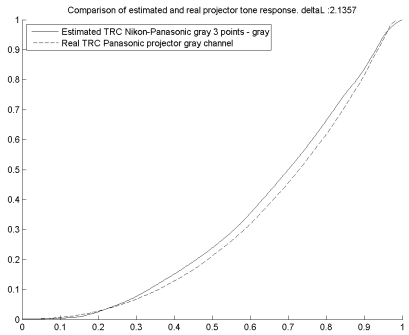

Figure 62: PJ TRC gray 3 method with Panasonic/Nikon

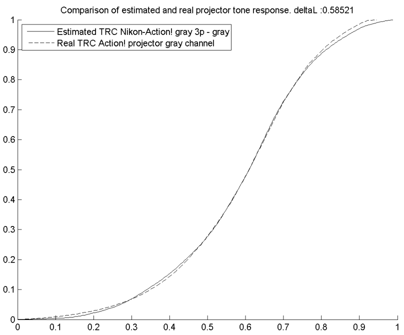

Figure 63: PJ TRC gray 3 method with Action! Model one/Nikon

B.3 Method RGB 1 for Panasonic projector

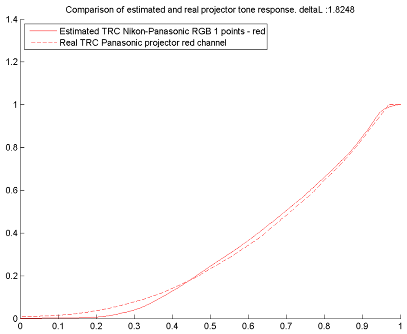

Figure 64: RGB 1 method with Panasonic/Nikon - Red curve

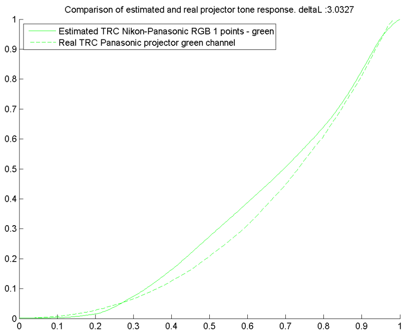

Figure 65: RGB 1 method with Panasonic/Nikon - Green curve

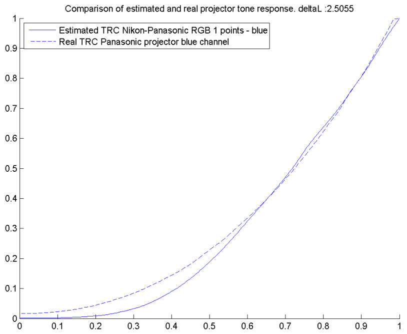

Figure 66: RGB 1 method with Panasonic/Nikon - Blue curve

B.4 Method RGB 3 for Panasonic projector

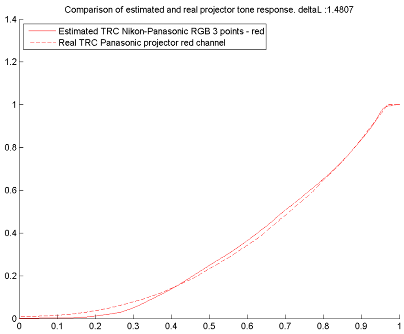

Figure 67: RGB 3 method with Panasonic/Nikon - Red curve

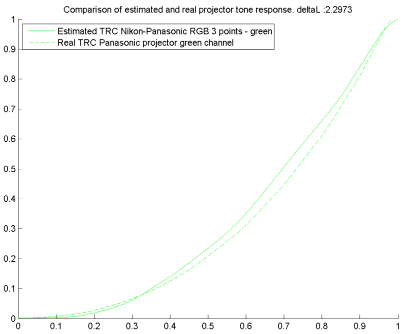

Figure 68: RGB 3 method with Panasonic/Nikon - Green curve

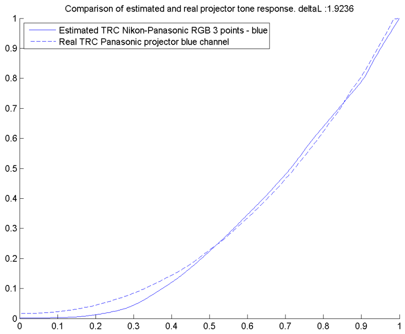

Figure 69: RGB 3 method with Panasonic/Nikon - Blue curve

B.5 Method RGB 1 for Action! Model one projector

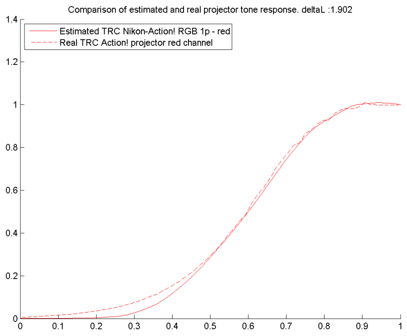

Figure 70: RGB 1 method with Action!/Nikon - Red curve

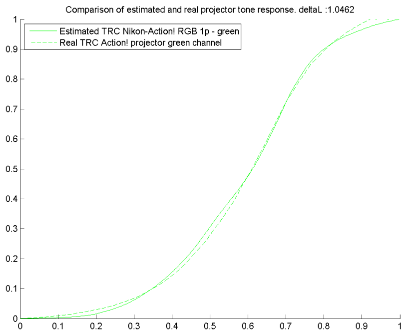

Figure 71: RGB 1 method with Action!/Nikon - Green curve

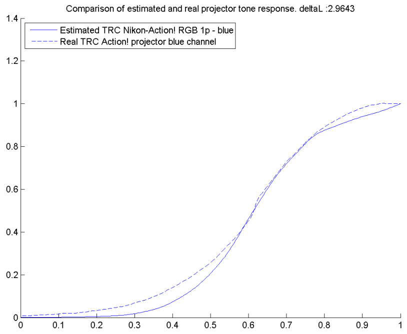

Figure 72: RGB 1 method with Action!/Nikon - Blue curve

B.6 Method RGB 3 for Action! Model one projector

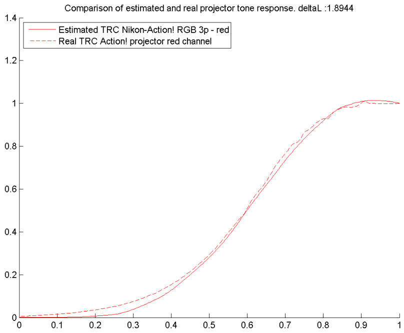

Figure 73: RGB 3 method with Action!/Nikon - Red curve

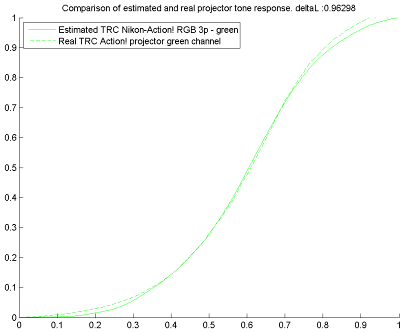

Figure 74: RGB 3 method with Action!/Nikon - Green curve

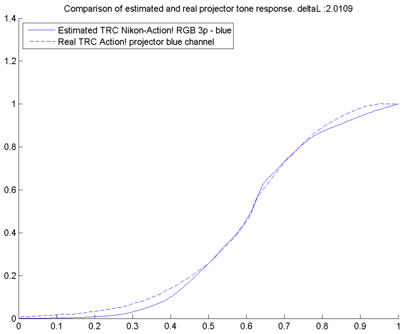

Figure 75: RGB 3 method with Action!/Nikon - Blue curve

C Appendix: Inverse model test results

C.1 Projectiondesign Action! Model one

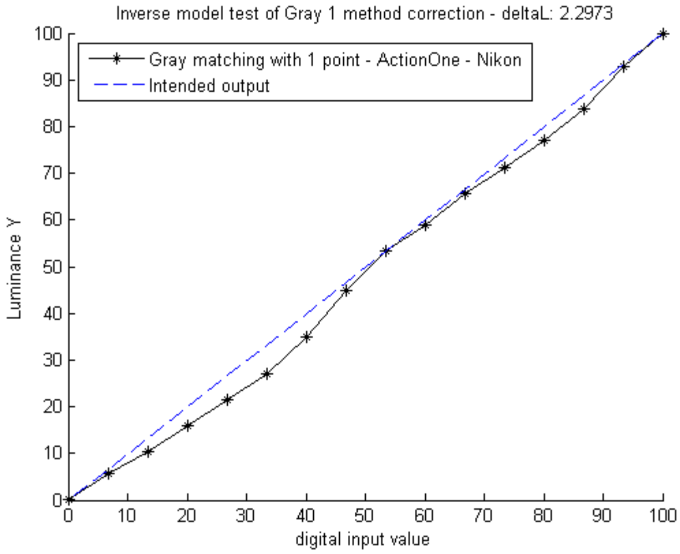

Figure 76: Gray 1 method inverse model test for Action! Model one.

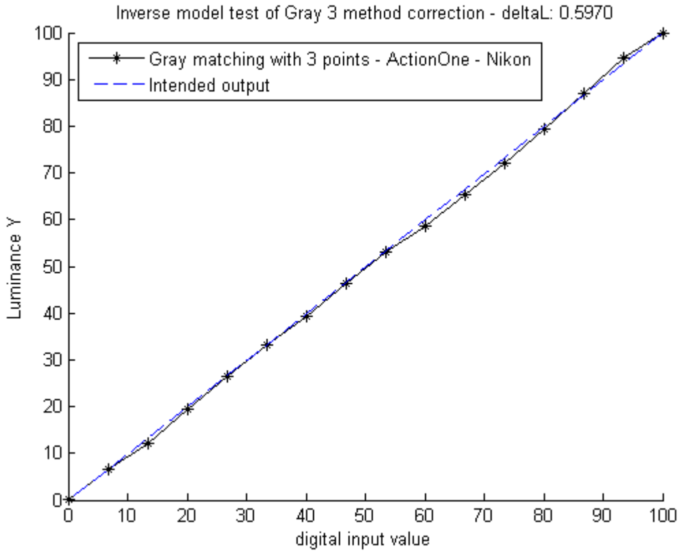

Figure 77: Gray 3 method inverse model test for Action! Model one.

C.2 Panasonic PT-AX100E

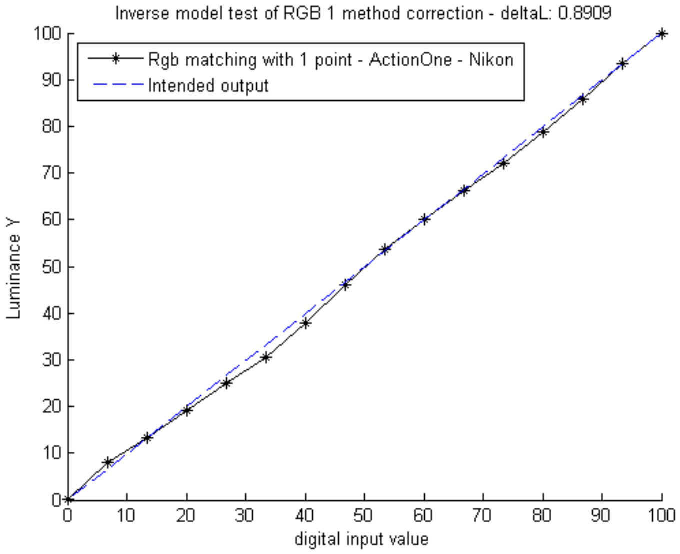

Figure 78: RGB 1 method inverse model test for Action! Model one.

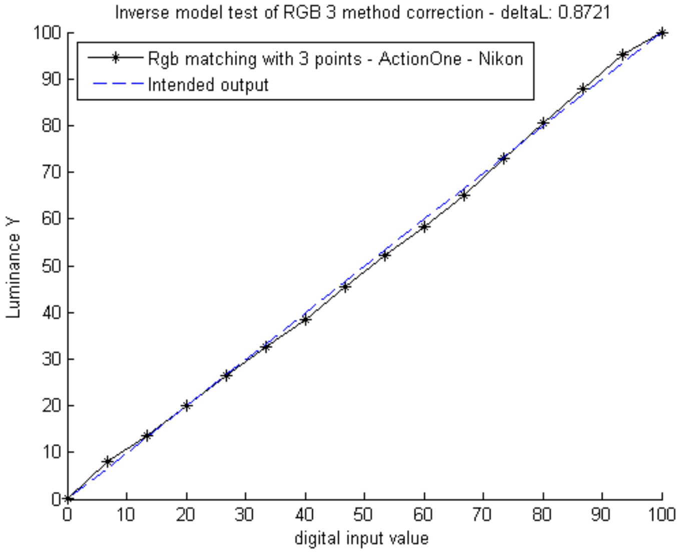

Figure 79: RGB 3 method inverse model test for Action! Model one.

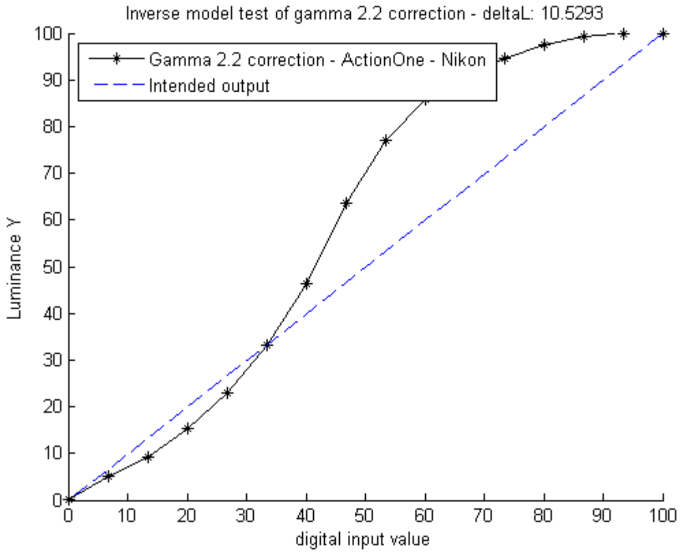

Figure 80: Gamma 2.2 method inverse model test for Action! Model one.

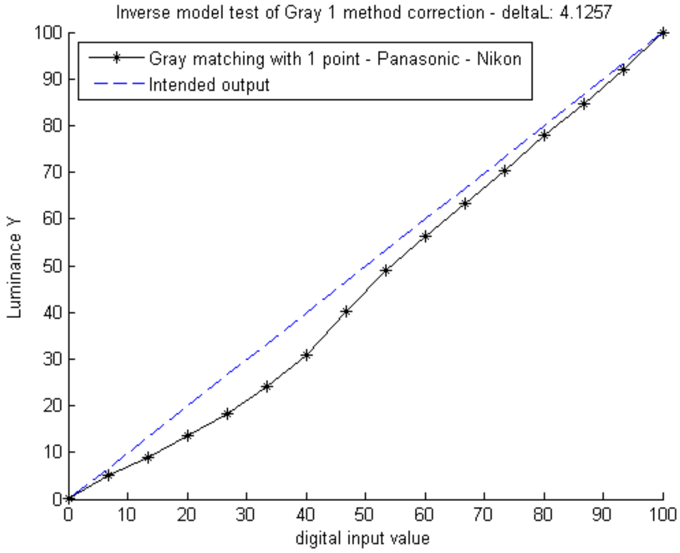

Figure 81: Gray 1 method inverse model test for Action! Panasonic.

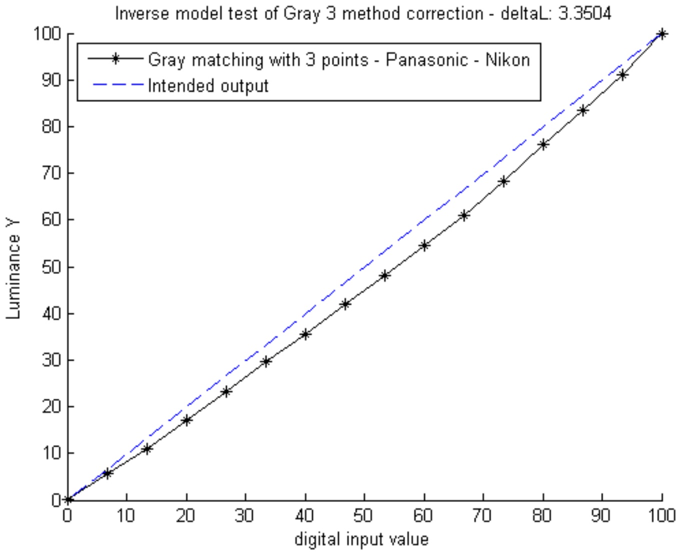

Figure 82: Gray 3 method inverse model test for Action! Panasonic.

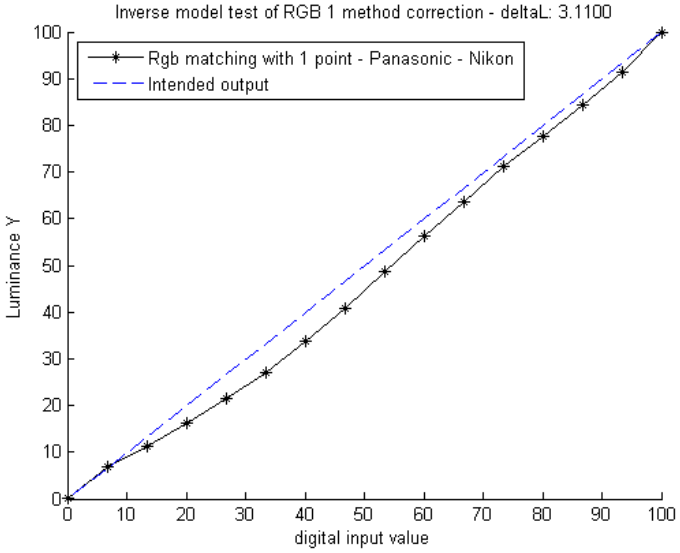

Figure 83: RGB 1 method inverse model test for Action! Panasonic.

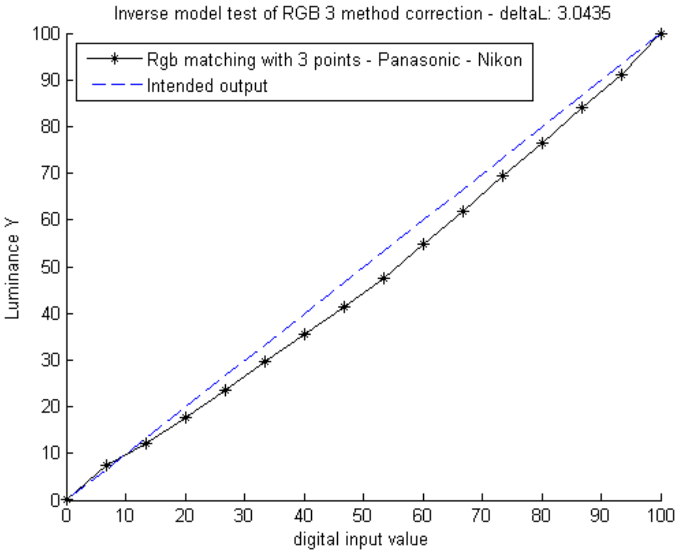

Figure 84: RGB 3 method inverse model test for Action! Panasonic.

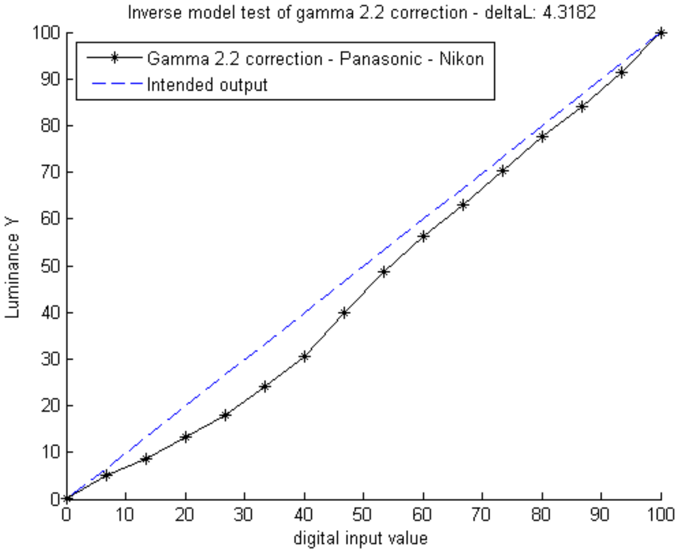

Figure 85: Gamma 2.2 method inverse model test for Panasonic.