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PERFORMANCE EVALUATION OF IMAGING SYSTEMS

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ABSTRACT

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Performance Evaluation of Imaging Systems

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Imaging systems have developed latest years and developing is still continuing following years. Manufacturers of imaging systems give promises for the quality of the performance of imaging systems to advertise their products. Promises for the quality of the performance are often so good that they will not be tested in normal usage.

The main target in this research is to evaluate the quality of the performance of two imaging systems: Scanner and CCD color camera. Optical measurement procedures were planned to evaluate the quality of imaging performances. Other target in this research is to evaluate calibration programs for the camera and the scanner.

Measuring targets had to choose to evaluate the quality of imaging performances. Manufacturers have given definitions for targets. The third task in this research is to evaluate and consider how good measuring targets are.

TIIVISTELMÄ

Lappeenrannan teknillinen yliopisto
Sähkötekniikan osasto
Matematiikan ja fysiikan laitos
Ismo Ruohela

Kuvantamisjärjestelmien kuvan laadun arviointi

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62 sivua, 37 kuvaa, 10 taulukkoa, 4 liitettä
Tarkastajat: Professori Erik Vartiainen
TkT Lasse Lensu
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Kuvantamisjärjestelmät ovat kehittyneet paljon menneinä vuosina ja niiden kehitys jatkuu edelleen. Valmistajat antavat lupauksia omien laitteistojensa suorituskyvyn hyvyydestä saadakseen mainostettua laitteita paremmin. Valmistajien, laitteidensa suorituskyvylle antamat lupaukset eivät usein joudu koetukselle normaaleissa käyttötarkoituksissa.

Tässä diplomityössä keskityttiin arvioimaan kahta erilaista kuvantamisjärjestelmää: skanneri ja CCD-värikamera. Järjestelmien suorituskyvyn arviointia varten pyrittiin kehittämään optiset mittausjärjestelyt, joiden avulla on mahdollista todentaa laitteiden hyvyyttä. Tutkimuksissa toisena tarkoituksena oli arvioida kameralle ja skannerille tarkoitettua kalibrointi ohjelmistoa.

Järjestelmien arvioinnin suorittamista varten valittiin mittausvälineitä, joiden avulla laitteiden hyvyyttä tutkittiin. Mittausvälineille eli ”targeteille” on valmistajan toimesta annettu määritteitä, joiden paikkansa pitävyyden arviointi ja pohdinta olivat kolmas tämän työn tärkeä tavoite.

FOREWORD

This research has done for the Department of Information Technology as a part of Digiq project at the Department of Mathematics and Physics. Professor Erik Vartiainen and Dr. Lasse Lensu have been examiners and Dr. Pertti Silfsten has been supervisor in this research. I want to thank all of them for the help I have got to my master's thesis.

TABLE OF CONTENTS

SYMBOLS AND ABREVIATIONS

CCD	Charge-coupled device
MTF	Modulated transfer function
CIE	Commission Internationale de l'Eclairage
AD	Actual distance
PD	Predicted distance
L^*	Lightness
a^*	Proportion of red and green
b^*	Proportion of yellow and blue
ΔE	Color difference
dpi	Dots per inch
V	The luminous sensitivity for cones
V'	The luminous sensitivity for rods
S	For short wavelengths sensitive cone
M	For middle wavelengths sensitive cone
L	For long wavelengths sensitive cone
I_{MAX}	Maximum intensity
I_{MIN}	Minimum intensity
M_{mod}	Modulation
D_{50}	CIE standard illuminant with color temperature 5000 K
λ	Wavelength
r	Resolution
R	Resolving power
D	Distortion

1. INTRODUCTION

Nowadays insistences for imaging systems have become greater than ever. The quality of imaging systems performance has been developing better and better by year to year. Insistences for imaging quality are not going to decrease following years but they continue increasing during the growth of the technology.

Imaging devices, such as cameras, scanners, printers etc., has the maximum accuracy for the quality of the imaging performance. The maximum accuracy is manufacturer’s promise for the best accuracy that an imaging system is able to repeat. Imaging systems are also planned to repeat colors as proper as possible, which means that original and repeated color should look same for human eye at the same lightning condition. This research is one part of DigiQ, Fusion of Digital and Visual Print Quality, research project. The purpose of the research is to develop a procedure to evaluate the performance quality of two imaging systems from viewpoint of physics and optics. Two chosen imaging systems to the research are CCD camera with light system and a high-resolution scanner.

The research started by thinking possible characteristics, which would describe imaging systems’ ability to repeat details. The sharpness of an image and image’s colors are details, which affect most to the view that humans see. Due to that resolution was chosen to evaluate images’ sharpness and color to evaluate the preserving of colors. Three other chosen characteristics to the evaluating of the imaging performance were distortion, MTF and depth of field. Distortion describes how much the lens in imaging device changes the geometry of the repeated image compared to the original image. MTF is modulation transfer function, which describes imaging systems’ contrast between white and black lines in different spatial resolutions. Depth of field describes how big area in an image around the focus point stay sharp. Each one of chosen characteristics needed own test target, which details and characteristics were known.

Imaging performance evaluation was done by evaluating photographed and scanned test targets and comparing them and their results to test targets’ details and characteristics or to the promised quality of the imaging system. Manufacturers have given details and characteristics for test targets and in this research was evaluated the validity of them.

The third main task in this research was to evaluate GretacMacbeth's method to calibrate scanner and camera. Spectrophotometer's software contains a program, which is planned to calibrate different devices. Program's ability to calibrate correctly was analyzed to find out if it is useful and worthwhile to calibrate devices using the program.

2. BACKGROUND KNOWLEDGE

Quality of an image is dependent on characteristics of an imaging system. Many other circumstances also cause needs to adjust the characteristics of an imaging system. This chapter contains information about characteristics, which are related to image's quality and its transitions. There are also characteristic which are related to human capability to observer color and its shades.

2.1 Spatial resolution

Spatial Resolution refers to the number of pixels are used in construction of a digital image. Spatial resolution is defined as pixels per inch (dpi). The higher the spatial resolution of an image is the more pixels are used in the image. The spatial resolution of a digital image is related to the spatial density of the image and optical resolution of the imaging system. Spatial density defines the mount of pixels in image and distances between them. Optical resolution is defined by the characteristics of imaging system and it is imaging system's ability to resolve details from original image. Spatial resolution is commonly called output resolution and worse from spatial density or optical resolution is limiting the quality of the final image. [12]

2.2 Response linearity

Sensors are meant to receive light as photons, which are carrying image information. Sensor converts photons into electronic signal and digitizes the information. After digitization, the response of the signal output should be linearly proportional to the amount of received light (Figure 2.2.1). In other words if a mount of arriving photons increase it should have a linear affect to the response. The response should increase also proportionally as much as the mount of photons on the sensor. [10]

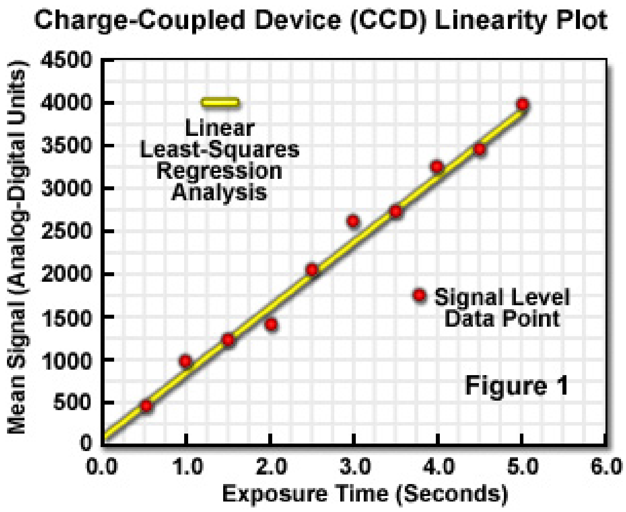

Figure 2.2.1 Response linearity in CCD sensor.

In figure 2.2.1 is an example from CCD linearity. Mean signal describes the mount of received light and it is reported by help of exposure time. It is one common way how manufactures assess linearity. The technique is based on a graphical plot of measured output signal as a function of exposure time, extending to the full well capacity of the device. Full well capacity means the maximum number of electrons that can be stored in each pixel. [9]

2.3 Imaging noise

Imaging systems include a sensor which idea is to detect light at the moment when the system saves a view. Sensor is able to detect light by collecting coming photons because it is very sensitive and able to count individual photons. Sensor has divided to small pieces called pixels. Every pixel on the sensor collects photons, which arrive on to it and convert them into electrons. Storing these electrons causes a charge, which is possible to measure and convert into a digital form. Both of these conversions produce noise to digital image. Main imaging noises are dark noise read noise, photon noise and reset noise, which are caused during operations mentioned ahead. Other possible sources of noise can be for different electronic circuits and their components and disturbances. [10]

2.3.1 Dark noise

Detected photons donate their energy to sensor and it converts energy into electrons. Energy causes heat at the sensor. The heat is able to generate new electrons. Dark noise is accumulation of these new electrons, which means dark current. Dark noise appears in image as small spots. [10]

The mount of dark noise is dependent on temperature. The lower temperature is the less dark noise is disturbing CCD sensors. A common way to reduce dark noise is to cool the CCD when the dark current is decreasing.

2.3.2 Read noise

Read noise is combination of changing CCD charge to signal, converting analog signal to digital and amplifying the charge before measuring and converting. The charge from each sensor’s pixel has to measure and convert to digital value to construct an image. Amplifier is needed to amplify the signal because the charge is too low to measure without amplifying. Unfortunately amplifiers are never ideal which causes some noise. The major part of read noise is the noise, which adds during the amplifying the low charge before converting it to digital value. That noise is added uniformly to every image pixel. [10]

Read noise can be independent of frequency (white noise) or depended of frequency (flicker noise). Output amplifier has output resistance, which causes read noise called white noise and its magnitude is independent of frequency. Flicker noise has an inverse depended to frequency. Flicker noise reduces when the read-out frequency increases.

2.3.3 Photon noise

Photons do not arrive constant to the sensor by the reason of the statistical nature of photons production. In a given time different amount of photons hit to pixels. Consequence of that is the difference in values at pixels. Pixels with lower value come out from image as obscure quality. Photon noise cannot be reduced from imaging systems but photon noise forms as a minimum noise level for a system. In minimum noise level dark noise and read noise are reduced to their minimum levels. [10]

2.3.4 Reset noise

Reset noise is induced when CCD sensors collect charge from pixels. It is employing a sense capacitor and source-follower amplifier. Before CCD sensors are able to measure the charge from pixel, sense capacitors have to be reset to a reference level. Reset noise is varying from pixel to pixel because it is generated uncertainly in the reference voltage level due to thermal variations in the channel resistance of reset transistor. [10]

2.3.5 Random noise

Imaging systems contains many electronic components and circuits. These components can produce noise as an effect from disturbance in current or voltage. Clocking noise is example from random noise. Many clocking circuits, under control of a master clock, are needed to process and transfer signals. Clocking noise is result from operations in these circuits. [10]

2.4 Dynamic range

Sensors have maximum and minimum limits for signals they can generate. The maximum signal is largest possible signal, which is proportional to maximum capacity of pixel. The minimum signal is lowest possible signal, which means noise level. Noise level is formed signal when the sensor is not exposed to any light. Noise level's signal is formed as a sum of dark and read noises. The dynamic range of sensor is defined by the largest signal divided the lowest signal. Largest possible signal means devices the full well capacity of the sensor. Imaging systems with high dynamic range are able to get an image with better quality than systems with lower dynamic range.

Every pixel on the sensor collects photons but some of them capture photons from bright part and other from dark part. All pixels convert the energy of photons to discrete value. Pixels which are operating at bright part, get much more photons than pixels which are operating at dark part. Pixels, which capture photons from the bright, get filled up very quickly. In the other words, the measuring time is too long for those pixels and they loose some information. Making the measuring time shorter does not help either because then pixels, which are operating at dark part, cannot collect enough photons. Conclusion to the problem is changing the size of pixels. If pixels are larger they can collect more photons during shorter measuring time. [8]

2.5 Geometric image distortion

Geometric distortion is the departure of image points from the original locations by projective transformation. Two fundamental distortions are barrel distortion (Figure 2.5.1 right) and pincushion distortion (Figure 2.5.1 middle).

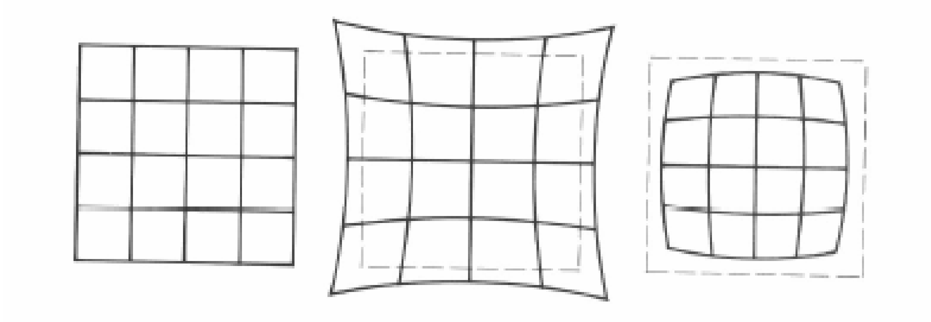

Figure 2.5.1 Undistorted grid left, pincushion distortion in middle and barrel distortion right.

Barrel distortion is called positive distortion because image points are too close to the optical axis (Figure 2.5.3). Pincushion distortion is called negative distortion and then image points are too far from the optical axis (Figure 2.5.4). Distortion is proportional to the cube of the height of the image point. Main reason to image distortion is curved lens.

Curved lens is not able to form image for flat plane but for curved surface. Image cannot be in focus in the middle of it and in the margins at the same time. Different areas of the lens have different focal lengths and magnifications. Distortion does not displace any information but it locates some part of information onto a wrong place. [11]

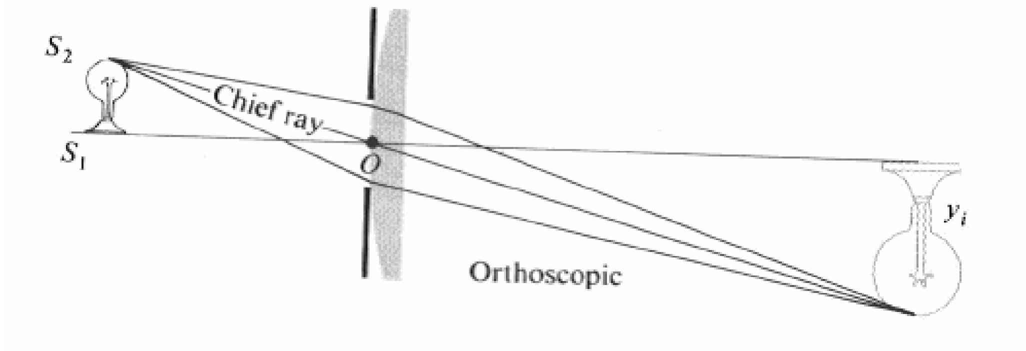

Figure 2.5.2 Undistorted.

Distortions can be seen by help of a stop located in front of lens and behind lens. Chief ray goes through the principal point when the stop is at the lens (Figure 2.5.2) and does not cause distortion. In figure 2.5.2 y_i describes an object in real form and size.

When the stop is in front of the lens, the lens turns the chief ray so that object will look smaller than original object (Figure 2.5.3). The stop behind the lens causes opposite result. Then the lens turns the chief ray so that object will looks bigger than original object (Figure 2.5.4). Original size of object is able to see by help of the broken line, which goes through zero point (Figure 2.5.3 and figure 2.5.4). [11]

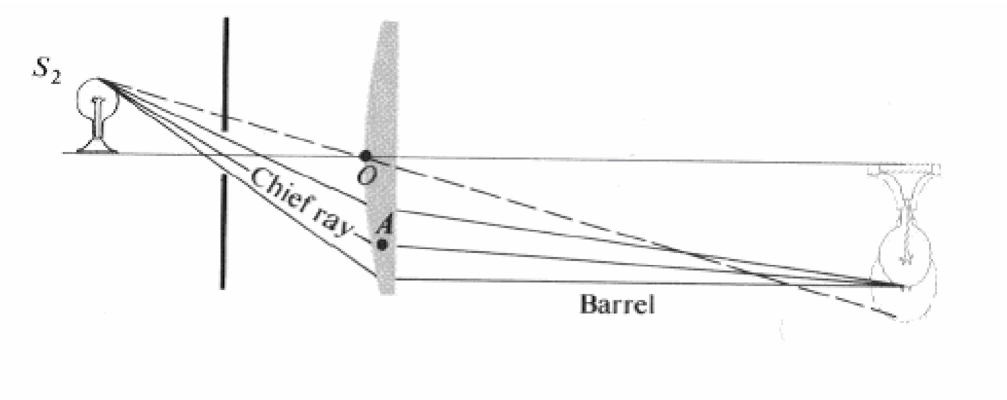

Figure 2.5.3 Barrel distortion.

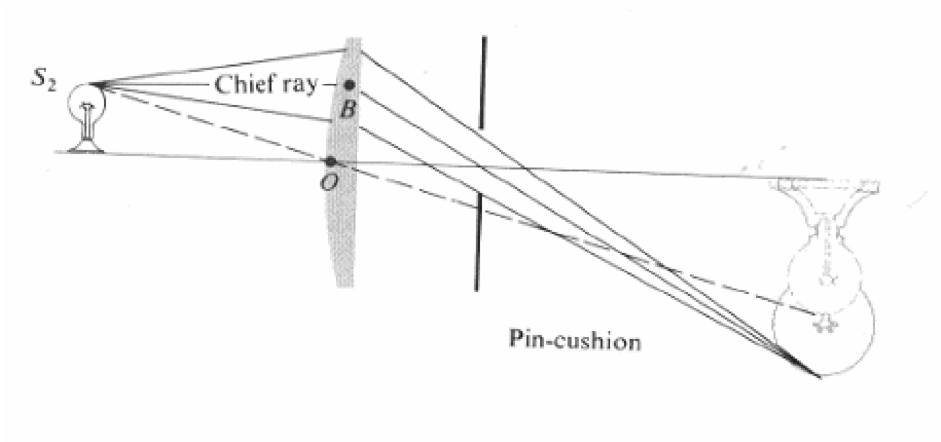

Figure 2.5.4 Pincushion distortion.

2.6 Focus and depth of field

Focus is an image point at the mirror's axle where light rays, which come parallel with mirror's axle to mirror, converge. In figure 2.6.1 image point is on the right side of the lens, where black arrows reach the mirror's axle. If light rays converge well a forming image is sharp and looks like original view. When light rays do not converge well an image is obscure.

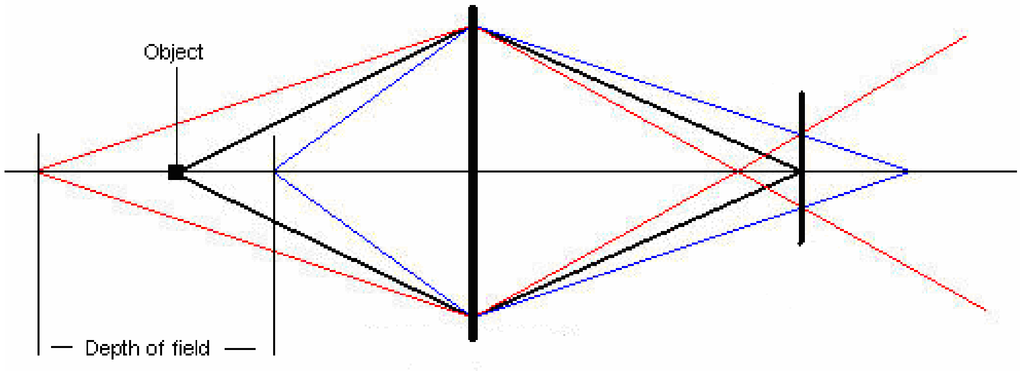

Figure 2.6.1 *Light ray gone trough the lens and focused on the surface behind the lens. Depth of field is the area in front of the lens.*

Depth of field is distance that an object can be moved from focus before the recorded subjects are not sharp anymore (Figure 2.6.1). Depth of field is commonly defined as the range both in front of and behind the subject. When a lens focuses on a subject, all other subjects at the same distance are also in focus. Subjects, at the different distance, are out of focus. Human eye cannot distinguish small differences in distance but see subjects sharp. The zone, where human eye can see subjects sharp, is referred to as a depth of field. The limit when subject is not acceptable or sharp anymore is changing in accordance to applications.

2.7 Color sensitivity

Color is psychophysical measurement. People are able to see colors differently. The light arrives to human's eye at the retina and is absorbed by the photopicments located at the tips of the rods and cones. Rods and cones are sensitive differently to the light with different wavelength. There are two different luminous sensitivities for low and high illumination levels (Figure 2.7.1). In figure 2.7.1 the luminous sensitivity on the left, *V'*, corresponds to the sensitivity of the rods and the luminous sensitivity on the right, *V*, and corresponds to the combination of the sensitivity of the three type cones. [5] [4] [6]

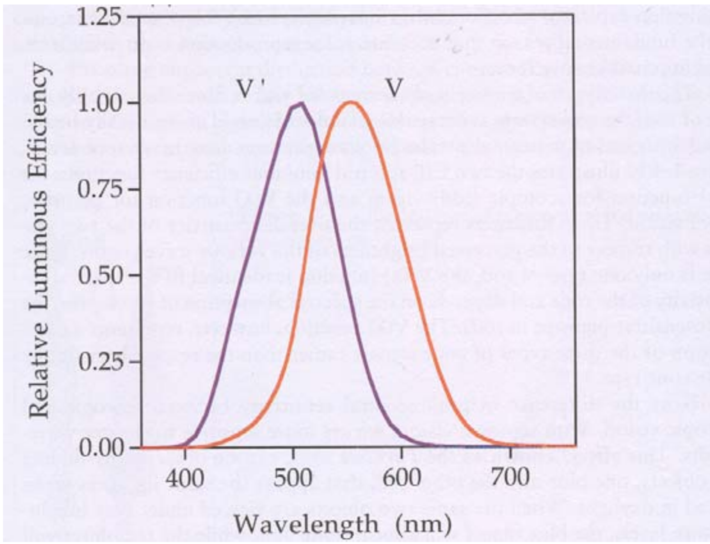

Figure 2.7.1 Luminous sensitivities of the rods (V') and the cones (V).

Three different cone types mentioned earlier are all sensitive for light in different wavelength. In figure 2.7.2, find spectral responses for *S*, *M* and *L* cones. Letters refer to the wavelengths cones are sensitive. *S* means short-wavelengths, *M* means middle-wavelengths and *L* means long-wavelengths. Instead of *S*, *M* and *L* letters are used blue, green and red sensitivities for cones. Blue sensitive cone is same as *S* cone, green cone is same as *M* cone and red cone is same as *L* cone. [6]

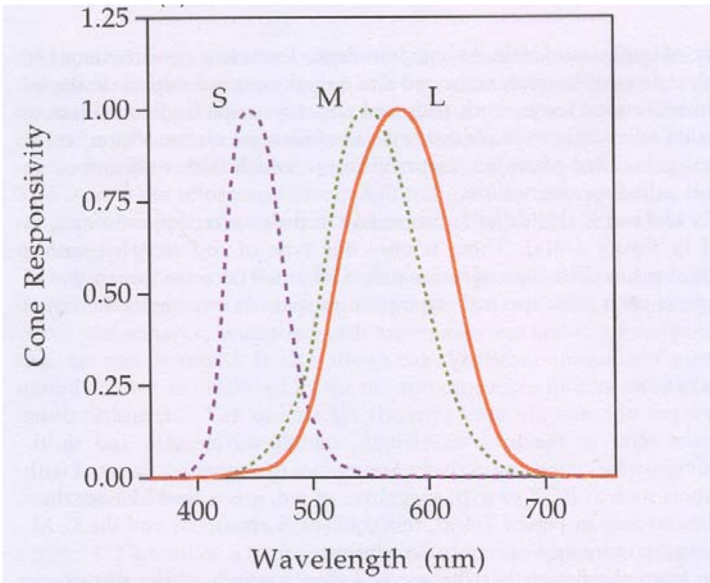

Figure 2.7.2 Spectral response of the S, M and L cones.

2.8 White balance

White balance is commonly used in digital imaging devices. Its intention is to define colors look like human eye sees them. Adjusting the white balance proper has performed by help of the color temperature of the present light. Imaging systems are able to choose proper settings for white balance when the color temperature of present light is measured.

Digital CCD cameras are often able to define white balance automatically as well as it can be done manually. CCD camera defines white balance automatically from whitest part in photographed image. However, automatically defined white balance can become faulty if there are not any white parts in the image. White balance settings for CCD camera can be defined manually with white object. Photographing conditions are able to cause problems when white balance is defined manually. Then have to be sure that conditions will keep on similarly.

3. STANDARDS FOR CALIBRATION AND CALCULATIONS

Standard colorimetric observers and standard light sources are needed in color definition, because all people see colors differently. CIE (Commission Internationale de l'Eclairage) has defined and standardized the CIE colorimetric system. It is based on standard color-matching functions and tristimulus values. Next there are introduced CIE standards, needed in this research, for the evaluation of color.

3.1 CIE Standard Illuminant D_{50}

CIE standard illuminant D_{50} is destined to represent a phase of lightning conditions inside where the lightning is artificial produced, with correlated color temperature 5000 K. Its spectral power distribution goes from wavelength 380 nm to 730 nm at 10 mm intervals.

The relative spectral power distribution of D_{50} artificial lightning simulator shows in figure 3.1.1. [3]

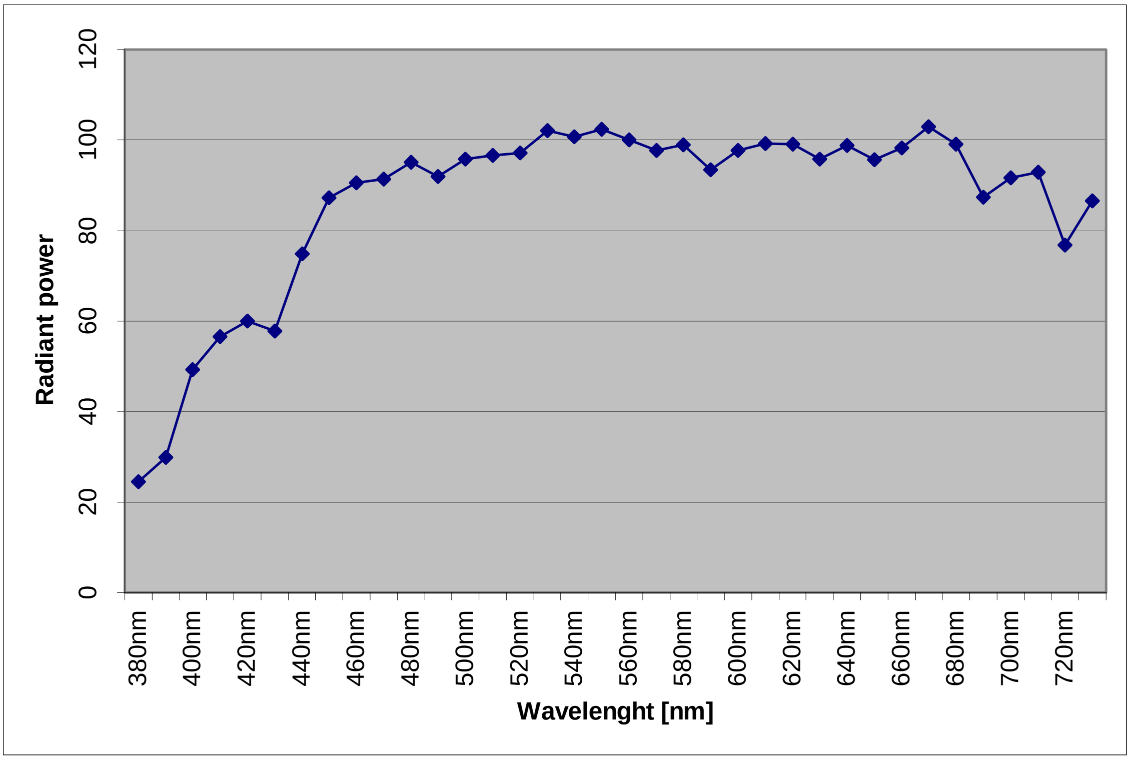

Figure 3.1.1 Relative spectral power distribution of D_{50} light source.

Standard source D_{50} is used to calculate lightness L^* and color coordinates a^* and b^*. D_{50} source has X_N, Y_N and Z_N tristimulus values for reference white. [3]

3.2 The CIE Standard Colorimetric Observers

There are defined color sensitivity curves for standard observer for three pigments $\bar{x}(\lambda), \bar{y}(\lambda), \bar{z}(\lambda)$. The CIE 1931 Standard Colorimetric Observer was defined in 1931. It contains color-matching functions $\bar{x}(\lambda), \bar{y}(\lambda), \bar{z}(\lambda)$ (Figure 3.2.1), which are defined in wavelength range λ=380 nm to λ=780 nm at wavelength intervals $\Delta\lambda$=5 nm. Color-matching functions' values are given with four decimals. Color-matching functions are defined for two degrees bipartite matching field. [3]

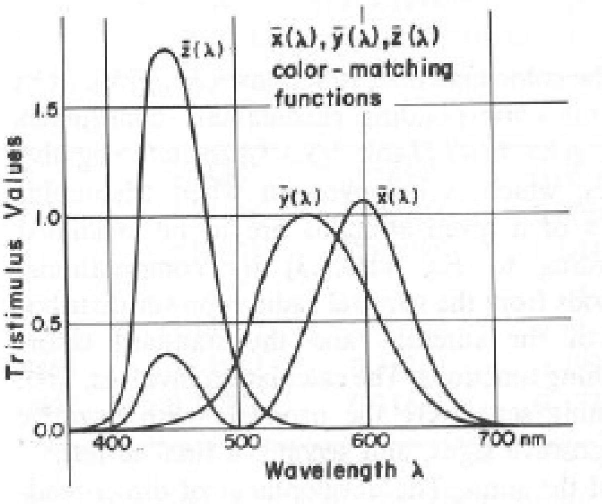

Figure 3.2.1 Color-matching functions in CIE 1931 standard.

The CIE 1964 Standard is an alternative set of standard color-matching functions to the CIE 1931 Standard. The values of color-matching functions $\bar{x}_{10}(\lambda), \bar{y}_{10}(\lambda), \bar{z}_{10}(\lambda)$ (Figure 3.2.2) are given for wavelengths ranging from λ=360 nm to λ=830 nm at wavelength intervals $\Delta\lambda$=1 nm. The color-matching functions are given by six significant figures and the corresponding chromaticity coordinates by five decimals. Color-matching functions are used in fields of large angular subtense, over four degrees, is desired. [3]

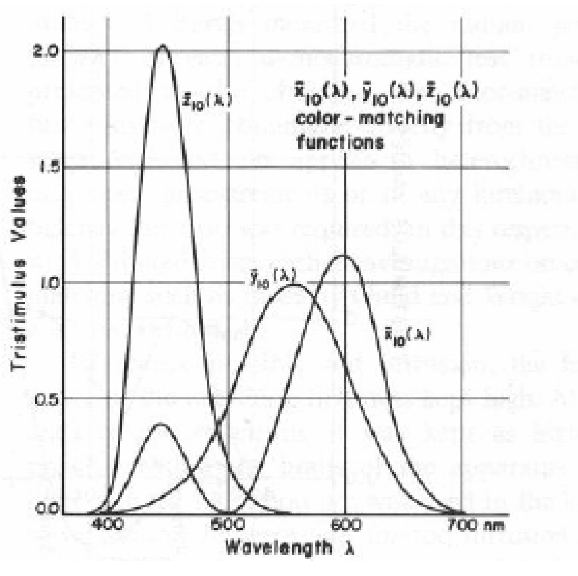

Figure 3.2.2 Color-matching functions in CIE 1964 standard.

Chromaticity coordinates are defined by help of tristimulus values X, Y and Z, given by

$$X = \int_0^\infty I(\lambda)\bar{x}(\lambda)d\lambda\,, \tag{3.2.1}$$

$$Y = \int_0^\infty I(\lambda)\bar{y}(\lambda)d\lambda\,, \tag{3.2.2}$$

$$Z = \int_0^\infty I(\lambda)\bar{z}(\lambda)d\lambda\,, \tag{3.2.3}$$

which are responses of image's intensity *I(λ)* as a function of wavelength *λ*.

Color sensitivity curves are described with help of chromaticity coordinates x, y and z, given by

$$x = \frac{X}{X+Y+Z}\,, \tag{3.2.4}$$

$$y = \frac{Y}{X+Y+Z}\,, \tag{3.2.5}$$

$$z = 1-(x+y)\,. \tag{3.2.6}$$

The collection of chromaticity coordinates, which are generated by changing wavelength, is shown in figure 3.2.3. The figure is chromaticity diagram of CIE 1931 standard colorimetric observer. [3]

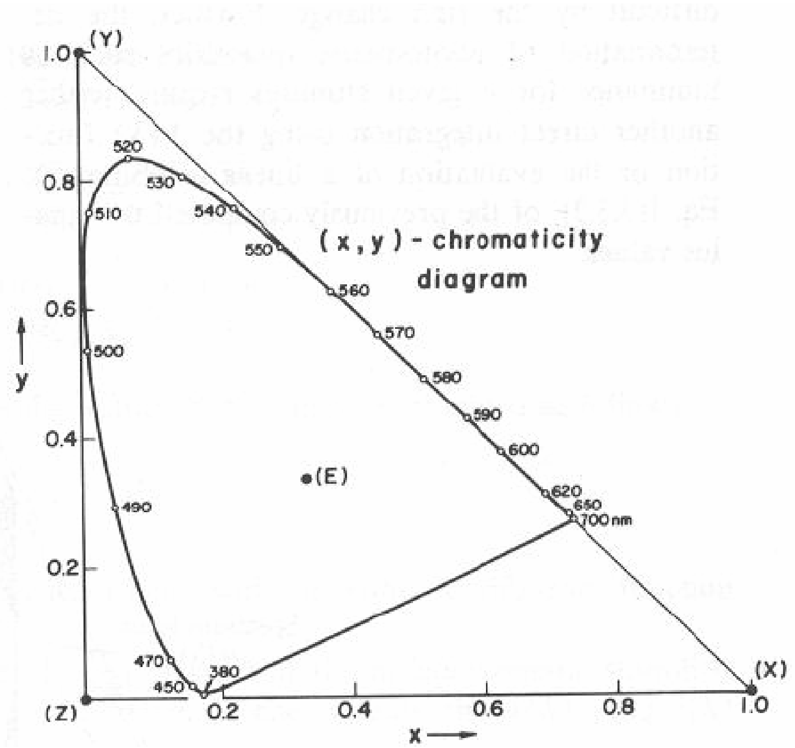

Figure 3.2.3 Chromaticity diagram of CIE 1931 standard colorimetric observer.

In table 3.2.1 are introduced CIE 1931 standard color-matching functions for wavelengths ranging from λ=400 nm to λ=700 nm with intervals $\Delta\lambda$=10 nm.

Table 3.2.1 Color-matching functions in CIE 1931 standard with intervals $\Delta\lambda$=10 nm.

λ[nm]	X(λ)	Y(λ)	Z(λ)	λ[nm]	X(λ)	Y(λ)	Z(λ)
400	0,0143	0,0004	0,0679	560	0,5945	0,9950	0,0039
410	0,0435	0,0012	0,2074	570	0,7621	0,9520	0,0021
420	0,1344	0,0040	0,6456	580	0,9163	0,8700	0,0017
430	0,2839	0,0116	1,3856	590	1,0263	0,7570	0,0011
440	0,3483	0,0230	1,7471	600	1,0622	0,6310	0,0008
450	0,3362	0,0380	1,7721	610	1,0026	0,5030	0,0003
460	0,2908	0,0600	1,6692	620	0,8544	0,3810	0,0002
470	0,1954	0,0910	1,2876	630	0,6424	0,2650	0,0001
480	0,0956	0,1390	0,8130	640	0,4479	0,1750	0,00002
490	0,0320	0,2080	0,4652	650	0,2835	0,1070	0
500	0,0049	0,3230	0,2720	660	0,1649	0,0610	0
510	0,0093	0,5030	0,1582	670	0,0874	0,0320	0
520	0,0633	0,7100	0,0783	680	0,0468	0,0170	0
530	0,1655	0,8620	0,0422	690	0,0227	0,0082	0
540	0,2904	0,9540	0,0203	700	0,0114	0,0041	0
550	0,4334	0,9950	0,0087				

3.3 CIE 1976 ($L^*a^*b^*$) color space

CIE $L^*a^*b^*$ color space is perceptually uniform. $L^*a^*b^*$ coordinates are defined with tristimulus values of spectrum X, Y, Z and tristimulus values of reference white X_N, Y_N, Z_N. Tristimulus values of reference white depend on light source. Y_N is 100 for all sources but X_N and Z_N varies between different light sources.

$L^*a^*b^*$ color space build up from three coordinate. L^* is lightness, a^* is proportion of red and green and b^* is proportion of yellow and blue. L^* varies from 0 to 100 such, that 0 is ideally black and 100 is white, a^* varies from -100 to 100 such, that green is -100 and red is 100 and b^* varies from -100 to 100 such, that blue is -100 and yellow is 100 (Figure 3.3.1).

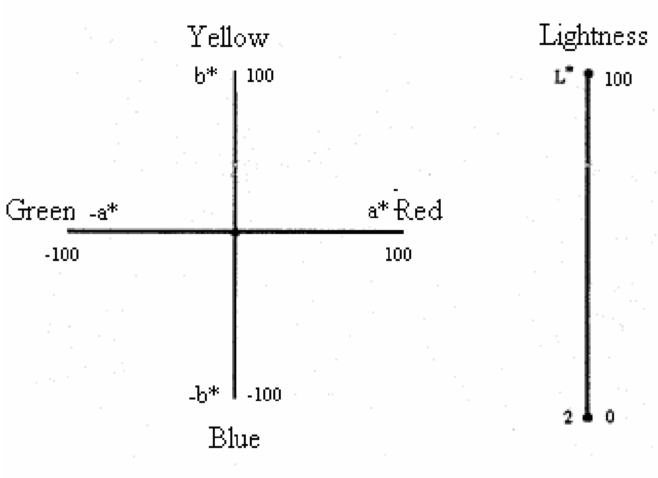

*Figure 3.3.1 L*a*b*- coordinates*

In calculation of coordinates L^*, a^* and b^* have to use three equations. First lightness L^* is calculated from equation 3.3.1, a^* is calculated from equation 3.3.2 and b^* is calculated from equation 3.3.3.

$$L^* = 116\left(\frac{Y}{Y_N}\right)^{\frac{1}{3}} - 16\,. \tag{3.3.1}$$

$$a^* = 500\left[\left(\frac{X}{X_N}\right)^{\frac{1}{3}} - \left(\frac{Y}{Y_N}\right)^{\frac{1}{3}}\right]. \quad (3.3.2)$$

$$b^* = 200\left[\left(\frac{Y}{Y_N}\right)^{\frac{1}{3}} - \left(\frac{Z}{Z_N}\right)^{\frac{1}{3}}\right]. \quad (3.3.3)$$

The coordinates can be defined from equation 3.3.1 to 3.3.3 if $\frac{Y}{Y_N}, \frac{X}{X_N}$ and $\frac{Z}{Z_N}$ are greater than 0,01. If $\frac{Y}{Y_N}, \frac{X}{X_N}$ and $\frac{Z}{Z_N}$ are less than 0,01 have to normal equations 3.3.1, 3.3.2 and 3.3.3 replace by modified equations 3.3.4, 3.3.5 and 3.3.6.

$$L^* = 903{,}3\left(\frac{Y}{Y_N}\right), \quad (3.3.4)$$

where $\frac{Y}{Y_n} \leq 0{,}008856$.

$$a^* = 500\left[f\left(\frac{X}{X_N}\right) - f\left(\frac{Y}{Y_N}\right)\right], \quad (3.3.5)$$

$$b^* = 200\left[f\left(\frac{Y}{Y_N}\right) - f\left(\frac{Z}{Z_N}\right)\right], \quad (3.3.6)$$

where

$$f\left(\frac{X}{X_N}\right) = 7{,}787 \cdot \left(\frac{X}{X_N}\right) + \frac{16}{116}, \quad (3.3.7)$$

$$f\left(\frac{Y}{Y_N}\right) = 7{,}787 \cdot \left(\frac{Y}{Y_N}\right) + \frac{16}{116}, \quad (3.3.8)$$

$$f\left(\frac{Z}{Z_N}\right) = 7{,}787 \cdot \left(\frac{Z}{Z_N}\right) + \frac{16}{116}, \tag{3.3.9}$$

if $\frac{Y}{Y_N} \leq 0{,}008856, \frac{X}{X_N} \leq 0{,}008856$ and $\frac{Z}{Z_N} \leq 0{,}008856$. If they are greater than 0,008856, a^* and b^* are calculated from equations 3.3.2 and 3.3.3. [3]

3.4 CIE 1976 ($L^*a^*b^*$) color-difference equation

The color difference, ΔE^*, given by

$$\Delta E^* = \sqrt{\left(\Delta L^*\right)^2 + \left(\Delta a^*\right)^2 + \left(\Delta b^*\right)^2}, \tag{3.4.1}$$

is distance between two points in 3-dimensional-coordinates. In equation 3.4.1 ΔL^* is difference in lightness and Δa^* and Δb^* are differences in a^*- and b^*-coordinates. [3]

4. REFERENCES

This research was focused to sort out characteristics in two different imaging systems. Imaging systems were scanner and CCD camera system. Scanner, used in the research, is Microtek ArtixScan 2500f and CCD camera system contains AVT Oscar F-510C CCD color camera and halogen ring light source. Microtek ArtixScan uses also CCD sensors to perform images.

Manufacturers give some specifications for imaging devices. Specifications are possible to try to ensure truthful by measuring characteristics with measurement targets. Chosen measurement targets to this research will be introduced later on in chapter 4.1. Knowledge about targets' characteristics makes it possible to compare and evaluate imaging systems performance. The characteristics of images are analyzed and compared to the original characteristics of targets.

The evaluation of colors is more complicated to perform. Used color coordinates are calculated mathematically from measured specks and calculations need always some standard light source. Manufacturer has not given coordinates for 140 colors target. Color differences have to be calculated by trusting to the results of the used GretagMacbeth's spectrophotometer.

4.1 Measurement instruments, software and targets

This chapter contains explanations of targets, which were used in the research, as well as information about used spectrophotometer and software used for color evaluation and software to the exertion of the CCD camera system.

4.1.1 GretagMacbeth EyeOne

GretagMacbeth EyeOne is spectrophotometer, which intention in this research was to evaluate colors in images. Spectrophotometer is feasible to connect directly to computer via USB port. GretagMacbeth contains three different software. Match software calibrates monitors, scanners and digital cameras, Diagnostics software calibrates the spectrophotometer to operate properly and Share software makes possible to measure color coordinates from different subjects and to measure incident light.

Spectrophotometer contains light source. To measure color coordinates from subjects spectrophotometer uses own light source. It measures light, which is reflected from a subject. GretagMacbeth package contain also cosine-corrected diffuse light measurement head to measure incident light.

In the evaluate mode's accuracy procedure the Share software is able to calculate color coordinates $L^*a^*b^*$ from measuring results and color-difference ΔE between two different coordinates. In the accuracy procedure, the spectrophotometer measures reflected light and gives it as a speck of radiance furthermore calculated $L^*a^*b^*$-coordinates. Share software uses CIE standard illuminant D_{50} in color coordinates calculations. In the evaluate mode's light procedure the Share software is able to measure the incident light. In light procedure the spectrophotometer has to be equipped with cosine-corrected diffuse light measurement head. It operates as a sensor by collecting receiving photons. The light mode gives a speck of irradiance.

4.1.2 Color checker target

EyeOne color management package, used in research, was XT, which included GretagMacbeth color checker targets. Smaller color checker target contained 24 different color squares (Figure 4.1.2.1 left) and another contains 140 different color squares (Figure 4.1.2.1 right). [13]

Figure 4.1.2.1 Color checker targets with 24 - and 140 colored squares.

4.1.3 Depth of field target

Depth of field target (Figure 4.1.3.1) is used to evaluate the possible amount of object shift in CCD camera before image's quality becomes obscure. Depth of field target defines an area where bars of the target are clear and sharp. The target contains vertical and horizontal bars. On the surface of the target lies measuring tape where the depth of field is possible to read in millimeters. [13]

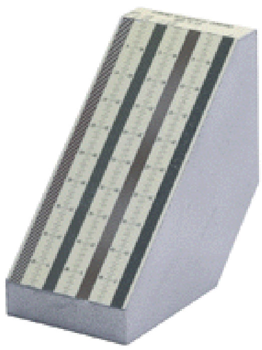

Figure 4.1.3.1   Depth of field target

4.1.4   Multi-Frequency Grid Distortion Target

Multi-frequency distortion target (Figure 4.1.4.1) is used to evaluate geometric distortion in images of imaging systems. There are different kinds of multi-frequency distortion targets but chrome on glass target is used in this research. Distortion target contains variable frequency. The denser the dot pattern is the higher the frequency is. [13]

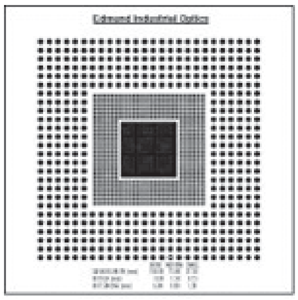

Figure 4.1.4.1   Multi-frequency grid distortion target

4.1.5   Coriander and FirePackage

Coriander is possible software to use in Linux to control CCD camera. Coriander enables to change camera’s settings to get better quality to photographed images. Wanted resolution and white balance have to define manually before photographing. Coriander can define white color true if the white balance setting is done separately with white paper before first photograph. Coriander's settings contain possibility to define resolution to the wanted value.

FirePackage is software, which was used in this research to control CCD camera. This software is developed for camera controlling in windows environment. The software contains same possible to control camera and change its settings than coriander.

4.1.6 USAF resolution target

USAF resolution target (Figure 4.1.6.1) is needed to establish the resolution of image. By resolution target it is possible to define lp/mm values for image. Lp/mm means line pairs in millimeter. The resolution of image is the better the more line pairs lie in millimeter. Resolution target contains elements, which are composed of vertical and horizontal equally spaced bars. Resolution target can be positive or negative. In positive resolution target chrome pattern lies on clear background (Figure 4.1.6.1 upper) and in negative target clear pattern lies on chrome background (Figure 4.1.6.1 lower). [13]

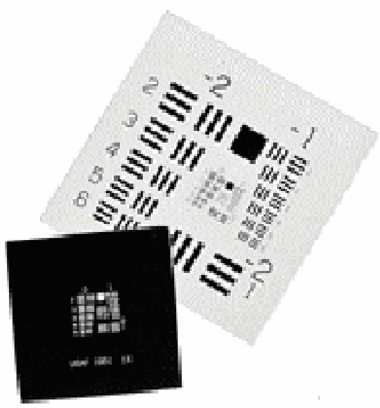

Figure 4.1.6.1 USAF Resolution targets.

Value for resolution is possible to read from the table of the resolution target (Table 4.1.6.1). Group numbers mean the values in the top part of the resolution target and elements mean values at sides of the resolution target (Figure 4.1.6.1)(Table 4.1.6.1).

Table 4.1.6.1 The table of the USAF resolution target.

Number of Line Pairs / mm in USAF Resolving Power Test Target 1951											
Group Number										For High Res only	
Element	-2	-1	0	1	2	3	4	5	6	7	8	9
1	0.250	0.500	1.00	2.00	4.00	8.00	16.00	32.0	64.0	128.0	256.0	512.0
2	0.280	0.561	1.12	2.24	4.49	8.98	17.95	36.0	71.8	144.0	287.0	575.0
3	0.315	0.630	1.26	2.52	5.04	10.10	20.16	40.3	80.6	161.0	323.0	645.0
4	0.353	0.707	1.41	2.83	5.66	11.30	22.62	45.3	90.5	181.0	362.0	-----
5	0.397	0.793	1.59	3.17	6.35	12.70	25.39	50.8	102.0	203.0	406.0	-----
6	0.445	0.891	1.78	3.56	7.13	14.30	28.50	57.0	114.0	228.0	456.0	-----

4.1.7 Sinusoidal target

Sinusoidal target (Figure 4.1.7.1) is used to evaluate imaging systems' ability to reproduce the contrast of image. There are two types of sinusoidal targets, reflected and transmitted, but in this research is used reflected type of target, which frequency range is from 0,25 lp/mm to 20 lp/mm. [13]

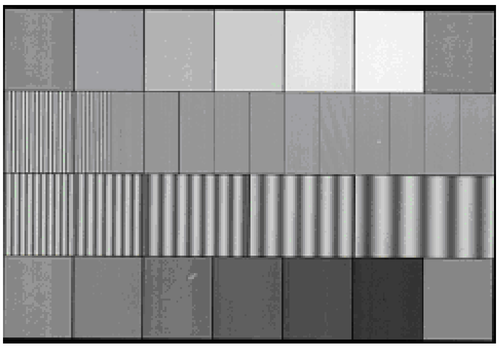

Figure 4.1.7.1 Sinusoidal target

Sinusoidal target contains two gray scale rows. In table 4.1.7.1, grey scale squares contain letters. The numbers indicate their nominal density values. Inner rows contain the sinusoidal areas and the numbers indicate the spatial frequencies from 0,25 to 20 in cycles per millimeter.

Table 4.1.7.1 Sinusoidal target's spatial frequencies.

4.2 Optical reference measurements

Color, resolution, depth of field, distortion and MTF was chosen for characteristics to evaluate imaging quality. Resolution and color are visually the most important characteristics because they define image's quality for spectators. Depth of field is important characteristic in photographing that enough details are possible to perform sharp. The ability of imaging systems to preserve details and geometry is also important characteristic to get an image to seem as an original image. In this chapter there are introduced chosen characteristics and measure procedures.

4.2.1 Color

The ability of an imaging system to copy colors from original image is evaluated by help of differences ΔL^*, Δa^* and Δb^* and color-difference ΔE between original target's and copied image's colors in L^*, a^* and b^* coordinates.

Evaluating color has to do by help of color checker targets. Color checker target has to be scanned and photographed to define images for color evaluation. Color checker target can be scanned as a one image but photographed as four color square groups. CCD camera and scanner both have imaging programs, which can define settings to get images quality good. Scanner uses own light source and make own fixing calculation for images. Camera system has halogen ring light source system with adjustable intensity and program, which can change camera's settings. White balance has to be defined manually before photographing, because automatic white balance setting causes problems if there is not any white square on the photographed part of the color checker target. The gain setting is defined automatically. Halogen light source's intensity was set to its maximum in preference measurements.

GretagMacbeth contains the Share software, which is able to measure the spectral irradiance of light and illuminance from monitor. The monitor, used in this research, is ColorEdge CG19. The ambient light is measured with cosine-corrected diffuse light measurement head. The spectral irradiance of the light on monitor is measured from color palettes and photographed and scanned images.

Scanned images are saved in tif-form and images have to be opened in Adobe Photoshop C5 program because it can handle tif-formed images. In this research it has to be expected that Adobe's program does not try to change the image. The incident light can be measured from every squares of the color checker target from the image in Adobe Photoshop C5.

Reference color palettes are measured from color checker target's squares in the accuracy procedure in evaluate mode in the Share software. Accuracy procedure shows the measured color in a circle, which makes it possible to measure that measured color as incident light from monitor. Measured colors of the color checker target have to be measured as an incident light to make result comparing with other measurements possible and to avoid the characteristics of the monitor to affect to results. Two Share software have to be opened to measure incident light from color palettes and copied images. Another of the Share software uses light procedure and measures incident light from other Share software, which is in accuracy procedure and shows reference color palette, and from scanned or photographed image. Measurements have to be done for all squares in color checker targets.

The color difference evaluating between scanned or photographed color targets and reference color palettes is done, by calculating $L^*a^*b^*$-coordinates from the results of irradiances. Calculations are done for light sources and it is expected that tristimulus value Y for light source is always 100. $L^*a^*b^*$- coordinates are calculated by using standard illuminant D_{50}. Color-matching functions to color calculations are introduced in table 3.2.1. X, x and y can be calculated

4.2.2 Resolution

Resolution refers to the sharpness and clarity of an image. The resolution term is often used to describe devices or images quality. Resolution is usually notified as dots per inch (dpi) in a line one inch long or as a mount of dots on every line.

Resolution, *r*, is defined in this research as a line pairs in millimeter by help of USAF resolution target. The resolution is possible to resolve by scanning and photographing the resolution target. From the scanned image, have to sort out the smallest pattern that scanner or camera has been able to perform. Sorting out is done by means of Matlab program's "improfile" command (Attachment 3). Value for resolution is possible to define from peeks of the resolution target's image profile. One pattern on resolution target consists of three black lines. Image profile shows a peek for every black line. Last acceptable pattern is the group of peeks where is possible to notice three peeks and resolution can be read from the resolution target as a line pairs in millimeter, when the last acceptable group number and element is known. Line pairs can be changed into resolving power.

The resolving power, *R*, given by

$$R = \frac{1}{2r}, \tag{4.4.2.1}$$

describes how small details a device is able to separate. [13]

4.2.3 Distortion

Distortion, D, is an amount of misplaced information. Distortion has introduced in chapter 2.5 (Figure 2.5.1). Evaluating the distortion of imaging system is accomplished using multi-frequency distortion target. By help of target is possible to evaluate if produced image has expanded or contracted.

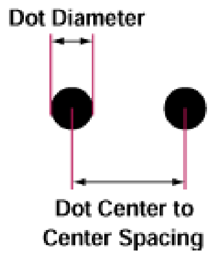

Figure 4.2.3.1 Dots of the multi-frequency distortion target.

Distortion target contains dots (Figure 4.1.4.1 and figure 4.2.3.1). In table 4.2.3.1 are distances for dots with different frequencies as well as lengths for diameters. Square A (Table 4.2.3.1) is area in figure 4.1.4.1, where distance between dots is longest. Square B is the area in the middle and square C is area where the distance is shortest. [13]

Table 4.2.3.1 Distances for dots of the multi-frequency distortion target.

Square	A (mm)	B (mm)	C (mm)
Square Size (measured center to center of dots)	50.00	25.00	12.50
Dot Diameter	1.00	0.50	0.25
Dot Center Spacing	2.00	1.00	0.50

Distortion, D, given by

$$D = \frac{AD - PD}{PD} \cdot 100\% , \qquad (4.2.3.1)$$

defines a percentage of distortion. In equation 4.2.3.1 AD (actual distance) is distance from the center of the distorted image to its corner. PD (predicted distance) is distance from the center of the non-distorted image to its corner.

Windows Paint program is used in analyzing images to solve the predicted distance. The number of pixels needed to form a dot can be measured in Paint program. The diameter of dot is known and the amount of millimeters, which one pixel is showing can be calculated by dividing the diameter to the number of pixels. The distance from middle of the image can be calculated by multiplying the amount of millimeters in one pixel to the number of pixels needed between middle point and border. Predicted distance can be calculated as the hypotenuse of rectangular triangle. Actual distance can be calculated also as the hypotenuse of rectangular triangle from given square sizes (Table 4.2.3.1).

4.2.4 Depth of field

Depth of field is defined for CCD camera by taking photograph from depth of field target. The angle between camera and target's scale is 45 degrees. Camera has to place above the depth of field target and so high that the level in top of target is in focus. Depth of field describes the amount of shift from focus point before image becomes obscure. There is also another way to sort out the depth of field of the camera. Camera can be focused in the middle of depth of field target when angle between target's scale and camera is 45 degrees. That makes possible to sort out depth of fields for both sides of focus point. [13]

4.2.5 MTF

MTF (Equation 4.2.5.2) is modulation transfer function. MTF measurement assesses contrast between white and black lines. It describes how much contrast remains between white and black lines after projection through a lens. MTF value has to be defined for every spatial frequency and those results form a figure for MTF.

Modulation, M_{mod}, given by

$$M_{\text{mod}} = \frac{I_{MAX} - I_{MIN}}{I_{MAX} + I_{MIN}}, \qquad (4.2.5.1)$$

for individual spatial resolutions. In equation 4.2.5.1 I_{MAX} is maximum intensity in printed or photographed image and I_{MIN} is minimum intensity. I_{MAX} and I_{MIN} can be solved out by means of matlab's image profile (Attachment 3). I_{MAX} is maximum value and I_{MIN} is minimum value in image profile figure.

Modulation transfer function, MTF, given by

$$MTF = \frac{M_1}{M_0}, \qquad (4.2.5.2)$$

can be defined for individual spatial resolutions. In equation 4.2.5.2 M_1 is the modulation of scanned or photographed image and M_0 is the modulation of the original image. MTF target's ideal MTF function can be calculated by dividing target's peak-to-peak modulation values by compensated modulation values. In figure 4.2.5.1 is ideal MTF function for MTF target.

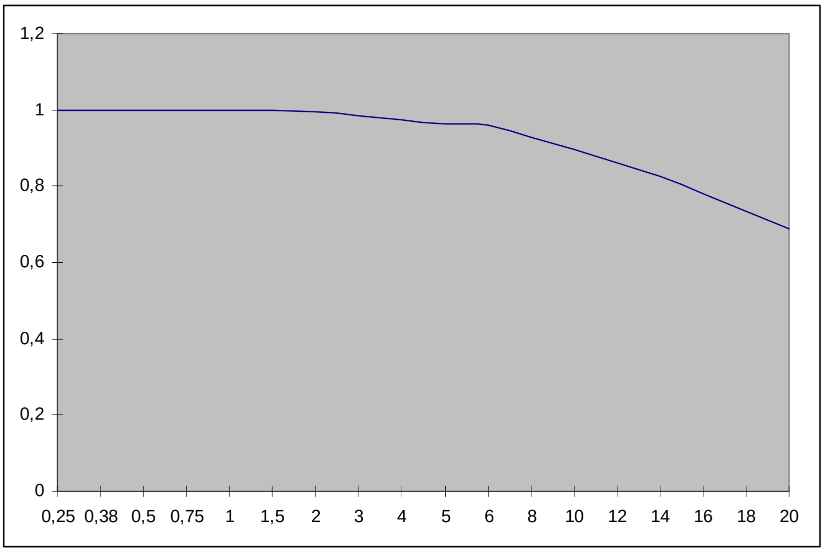

Figure 4.2.5.1 Ideal MTF function for MTF target.

4.3 Measurement results

This chapter contains information and results from first measurements. Measurement targets were scanned and photographed and images analyzed. All five characteristics were analyzed for camera but depth of field was not for scanner. Depth of field target is not suitable for measuring the depth of field of the scanner.

4.3.1 Scanner

Table 4.3.1.1 Color differences between measured and scanned color checker targets' squares.

	Measured			Scanned			
	L*	a*	b*	L*	a*	b*	ΔE
A1	100,0000	-3,0248	-8,5388	100,0000	-4,0948	-7,7239	**1,34**
A2	100,0000	29,9213	6,1126	100,0000	23,2648	12,8034	**9,44**
A3	100,0000	9,4184	-6,0736	100,0000	-5,0950	-1,6287	**15,18**
A4	100,0000	-1,0738	-7,4208	100,0000	-4,3812	-7,3020	**3,31**
A5	100,0000	31,3780	8,7312	100,0000	18,1480	14,1243	**14,29**
A6	100,0000	11,2541	-4,9510	100,0000	-5,2077	-2,5391	**16,64**
A7	100,0000	-0,6798	-6,5817	100,0000	-4,1265	-5,8225	**3,53**
A8	100,0000	32,7685	12,6136	100,0000	22,2043	14,8252	**10,79**
A9	100,0000	11,5771	-3,6056	100,0000	-3,7156	-0,4560	**15,61**
A10	100,0000	0,5091	-6,5427	100,0000	-3,2822	-5,3652	**3,97**
B1	100,0000	12,1197	-3,8851	100,0000	-0,5598	-0,4190	**13,14**
B2	100,0000	75,3721	-11,5492	100,0000	73,2543	-9,5482	**2,91**
B3	100,0000	37,6303	-27,8994	100,0000	34,6458	-29,4677	**3,37**
B4	100,0000	70,7994	-48,1394	100,0000	70,7493	-49,9614	**1,82**
B5	100,0000	-13,6541	-85,2791	100,0000	0,9713	-72,9083	**19,16**
B6	100,0000	-37,9225	-46,2933	100,0000	-27,5880	-38,3968	**13,01**
B7	100,0000	-0,8301	-10,8615	100,0000	9,2371	-4,9176	**11,69**
B8	100,0000	-48,6388	-24,7032	100,0000	-39,6837	-23,6092	**9,02**
B9	100,0000	21,7350	12,8828	100,0000	12,5416	18,0118	**10,53**
B10	100,0000	7,4946	-8,0899	100,0000	-1,0961	-0,4315	**11,51**
C1	100,0000	32,9769	9,9544	100,0000	26,3618	13,9824	**7,74**
C2	100,0000	43,0920	-20,1923	100,0000	32,6687	-14,8819	**11,70**
C3	100,0000	37,8612	-60,8022	100,0000	33,2470	-55,0338	**7,39**
C4	100,0000	27,9847	-50,6681	100,0000	25,6347	-46,5283	**4,76**
C5	100,0000	-14,1436	-47,5487	100,0000	-10,2918	-45,4200	**4,40**
C6	100,0000	17,5622	-18,7568	100,0000	13,3319	-24,9666	**7,51**
C7	100,0000	0,8265	-47,9037	100,0000	-1,1481	-45,2778	**3,29**

C8	100,0000	-32,9160	-13,8896	100,0000	-38,5256	-19,8959	**8,22**
C9	100,0000	-36,6333	18,1569	100,0000	-45,9279	17,3672	**9,33**
C10	100,0000	33,5546	12,5357	100,0000	24,5142	14,2261	**9,20**
D1	100,0000	0,2321	-6,5332	100,0000	-2,5418	-7,3136	**2,88**
D2	100,0000	1,5221	-15,8986	100,0000	-3,7208	-15,7825	**5,24**
D3	100,0000	17,0302	-6,5401	100,0000	11,7351	-7,4407	**5,37**
D4	100,0000	-16,6050	-8,4272	100,0000	-23,4965	-8,4016	**6,89**
D5	100,0000	14,2488	-1,2701	100,0000	8,2161	-0,4661	**6,09**
D6	100,0000	-13,0755	20,7435	100,0000	-14,5959	18,8512	**2,43**
D7	100,0000	40,9364	39,0519	100,0000	28,4322	37,5175	**12,60**
D8	100,0000	27,4766	16,1630	100,0000	25,3719	14,1432	**2,92**
D9	100,0000	-47,1892	16,0921	100,0000	-50,5113	14,9880	**3,50**
D10	100,0000	-1,1889	-7,0372	100,0000	-5,5432	-6,5936	**4,38**
E1	100,0000	3,1861	-10,4053	100,0000	-16,2034	-8,3880	**19,49**
E2	100,0000	41,0218	46,7493	100,0000	14,2673	31,7255	**30,68**
E3	100,0000	55,5927	124,3528	100,0000	40,2516	93,0451	**34,86**
E4	100,0000	95,0059	-270,0378	100,0000	51,9011	-179,9891	**99,83**
E5	100,0000	-5,1567	-9,1848	100,0000	-7,6132	-8,9935	**2,46**
E6	100,0000	12,6045	-6,6438	100,0000	-124,7657	-29,1246	**139,20**
E7	100,0000	21,8793	18,0329	100,0000	13,2002	13,8082	**9,65**
E8	100,0000	33,9970	20,7245	100,0000	26,4804	14,9326	**9,49**
E9	100,0000	-36,8096	6,1226	100,0000	-76,4545	5,9520	**39,65**
E10	100,0000	0,3731	-10,7447	100,0000	-15,4965	-6,5707	**16,41**
F1	100,0000	28,4013	6,5400	100,0000	0,9819	-1,4904	**28,57**
F2	100,0000	27,2437	16,1983	100,0000	23,7486	13,1703	**4,62**
F3	100,0000	32,4305	-102,2696	100,0000	28,2416	-97,0821	**6,67**
F4	100,0000	-63,7758	47,2398	100,0000	-70,5712	44,2877	**7,41**
F5	100,0000	0,2421	-9,4264	100,0000	-7,8396	-9,3921	**8,08**
F6	100,0000	14,9340	-3,3079	100,0000	-11,1726	-3,8464	**26,11**
F7	100,0000	18,4960	24,7908	100,0000	9,3069	25,9157	**9,26**
F8	100,0000	19,4047	13,6163	100,0000	10,1714	14,3105	**9,26**
F9	100,0000	-53,3318	3,3490	100,0000	-65,4173	0,0311	**12,53**
F10	100,0000	28,2260	7,3740	100,0000	3,2151	-2,5959	**26,92**
G1	100,0000	-2,0784	-8,1378	100,0000	-4,9552	-8,8253	**2,96**
G2	100,0000	1,4816	-45,6377	100,0000	-7,4085	-43,3139	**9,19**
G3	100,0000	80,1645	23,0533	100,0000	70,3824	22,9779	**9,78**
G4	100,0000	98,2538	47,3001	100,0000	91,5722	49,7574	**7,12**
G5	100,0000	2,0345	-8,3433	100,0000	-6,9878	-8,5894	**9,03**
G6	100,0000	4,5592	-9,9944	100,0000	-5,5034	-4,6601	**11,39**
G7	100,0000	28,1413	34,2622	100,0000	16,1517	34,2413	**11,99**
G8	100,0000	21,8221	12,1775	100,0000	14,5230	13,1352	**7,36**
G9	100,0000	-41,8546	46,5598	100,0000	-57,7971	48,3401	**16,04**
G10	100,0000	-2,6187	-8,4537	100,0000	-4,4448	-6,6090	**2,60**
H1	100,0000	3,9001	-10,6051	100,0000	-11,5167	-6,8281	**15,87**
H2	100,0000	-29,0568	44,3203	100,0000	-44,7754	45,8570	**15,79**
H3	100,0000	74,2296	-79,5661	100,0000	42,4057	-51,6472	**42,33**
H4	100,0000	0,0287	98,5662	100,0000	-5,4019	97,6020	**5,52**

H5	100,0000	-1,2675	-12,3055	100,0000	-12,4939	-6,0826	**12,84**
H6	100,0000	-1,3188	-11,0275	100,0000	-9,4089	-8,6475	**8,43**
H7	100,0000	18,0173	12,9499	100,0000	9,8014	11,8547	**8,29**
H8	100,0000	20,3532	15,9890	100,0000	14,7306	13,4980	**6,15**
H9	100,0000	-78,7992	57,5128	100,0000	-90,1911	59,6394	**11,59**
H10	100,0000	4,7238	-9,1586	100,0000	-11,8304	-5,7158	**16,91**
I1	100,0000	26,9068	14,8943	100,0000	-3,2386	5,0119	**31,72**
I2	100,0000	19,3491	-49,4951	100,0000	9,5763	-47,3284	**10,01**
I3	100,0000	-31,4116	70,0835	100,0000	-37,9963	68,3449	**6,81**
I4	100,0000	86,8429	-30,1499	100,0000	76,8410	-28,3403	**10,16**
I5	100,0000	10,4602	-4,6105	100,0000	-8,3766	-1,5542	**19,08**
I6	100,0000	1,6120	-7,6643	100,0000	-6,4292	-8,6227	**8,10**
I7	100,0000	45,3143	47,8736	100,0000	32,6849	49,1091	**12,69**
I8	100,0000	34,9358	32,5805	100,0000	14,6229	40,0189	**21,63**
I9	100,0000	-60,5290	51,0262	100,0000	-73,3035	52,2395	**12,83**
I10	100,0000	30,8952	12,6027	100,0000	13,5720	9,8321	**17,54**
J1	100,0000	-3,3269	-7,7454	100,0000	-3,3345	-7,5984	**0,15**
J2	100,0000	-45,3414	-10,5680	100,0000	-38,2666	-8,5307	**7,36**
J3	100,0000	24,2779	90,5816	100,0000	10,0293	85,8547	**15,01**
J4	100,0000	-32,3497	-54,7098	100,0000	-20,6174	-48,5097	**13,27**
J5	100,0000	17,5043	-0,1444	100,0000	12,7555	5,5893	**7,44**
J6	100,0000	-1,2091	-8,4486	100,0000	-5,0617	-7,9062	**3,89**
J7	100,0000	34,4514	26,7077	100,0000	26,0366	22,3033	**9,50**
J8	100,0000	29,0548	28,3599	100,0000	22,0774	22,5769	**9,06**
J9	100,0000	24,0500	58,1590	100,0000	6,6393	53,0684	**18,14**
J10	100,0000	-1,0062	-7,0750	100,0000	-2,9030	-5,1925	**2,67**
K1	100,0000	9,9110	-6,1571	100,0000	-0,0803	-2,3687	**10,69**
K2	100,0000	11,7848	9,9879	100,0000	4,2459	9,3116	**7,57**
K3	100,0000	-16,1994	-1,3333	100,0000	-16,9707	-4,6711	**3,43**
K4	100,0000	7,6631	-13,5304	100,0000	2,5598	-13,7082	**5,11**
K5	100,0000	-12,5008	-17,0599	100,0000	-15,6935	-14,8043	**3,91**
K6	100,0000	3,9631	-6,9660	100,0000	-4,1086	-6,4479	**8,09**
K7	100,0000	11,9878	-2,4824	100,0000	0,6874	-0,5026	**11,47**
K8	100,0000	29,4394	6,9274	100,0000	11,6119	6,4484	**17,83**
K9	100,0000	-9,5111	55,2515	100,0000	-27,7030	60,5293	**18,94**
K10	100,0000	12,7949	-3,0859	100,0000	-0,2496	-0,5602	**13,29**
L1	100,0000	31,7569	12,2329	100,0000	26,9769	15,0106	**5,53**
L2	100,0000	56,1415	15,3105	100,0000	46,8653	16,9345	**9,42**
L3	100,0000	91,5976	45,9452	100,0000	82,9831	51,6071	**10,31**
L4	100,0000	48,5627	-0,3851	100,0000	42,3050	1,8358	**6,64**
L5	100,0000	47,4452	14,7744	100,0000	39,2543	18,3427	**8,93**
L6	100,0000	63,4997	68,8465	100,0000	56,3006	71,7483	**7,76**
L7	100,0000	-6,2408	71,1277	100,0000	-25,2678	77,4223	**20,04**
L8	100,0000	10,0369	53,9896	100,0000	-3,8310	60,7397	**15,42**
L9	100,0000	-23,3975	65,3713	100,0000	-36,2233	66,9184	**12,92**
L10	100,0000	33,6429	12,4603	100,0000	26,6045	11,7125	**7,08**
M1	100,0000	18,7074	0,8394	100,0000	-10,7640	-4,0647	**29,88**

M2	100,0000	80,7212	11,9123	100,0000	90,9121	12,4032	**10,20**
M3	100,0000	48,0454	2,4085	100,0000	41,0480	-9,9321	**14,19**
M4	100,0000	83,7922	33,4443	100,0000	95,7501	50,4887	**20,82**
M5	100,0000	86,8141	46,7723	100,0000	93,5317	59,2365	**14,16**
M6	100,0000	22,9056	73,5159	100,0000	4,3526	97,1642	**30,06**
M7	100,0000	8,8858	77,0786	100,0000	-7,7138	96,7089	**25,71**
M8	100,0000	-12,0881	67,7418	100,0000	-35,6010	80,7226	**26,86**
M9	100,0000	37,4333	19,8614	100,0000	16,2801	21,9597	**21,26**
M10	100,0000	13,1390	-1,8357	100,0000	-8,4158	-2,7297	**21,57**
N1	100,0000	-1,7206	-7,2069	100,0000	-4,6317	-8,4352	**3,16**
N2	100,0000	6,0486	-6,5435	100,0000	-7,6045	-3,0887	**14,08**
N3	100,0000	28,7151	9,8353	100,0000	12,4191	6,9999	**16,54**
N4	100,0000	-1,8142	-6,8592	100,0000	-4,3482	-7,5221	**2,62**
N5	100,0000	7,5749	-5,6045	100,0000	-6,2936	-3,0734	**14,10**
N6	100,0000	31,0599	9,8068	100,0000	9,7851	8,1571	**21,34**
N7	100,0000	-0,7718	-6,7052	100,0000	-4,2659	-6,3398	**3,51**
N8	100,0000	9,1466	-5,2101	100,0000	-5,3518	-3,4062	**14,61**
N9	100,0000	25,0898	23,5534	100,0000	16,0369	6,9217	**18,94**
N10	100,0000	-2,8135	-6,8989	100,0000	-3,4168	-5,4398	**1,58**

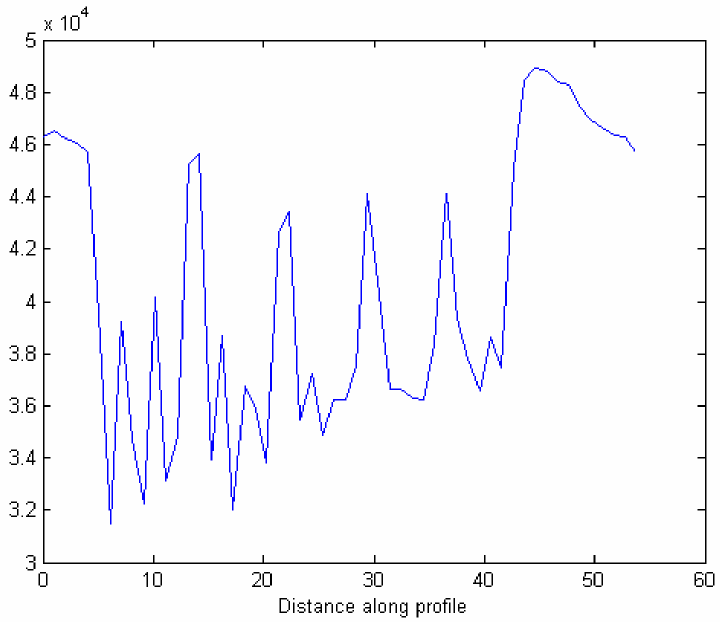

Figure 4.3.1.1 Resolution target's fourth group's profile for elements from 2 to 6. Resolution target has scanned with 1250 dpi resolution.

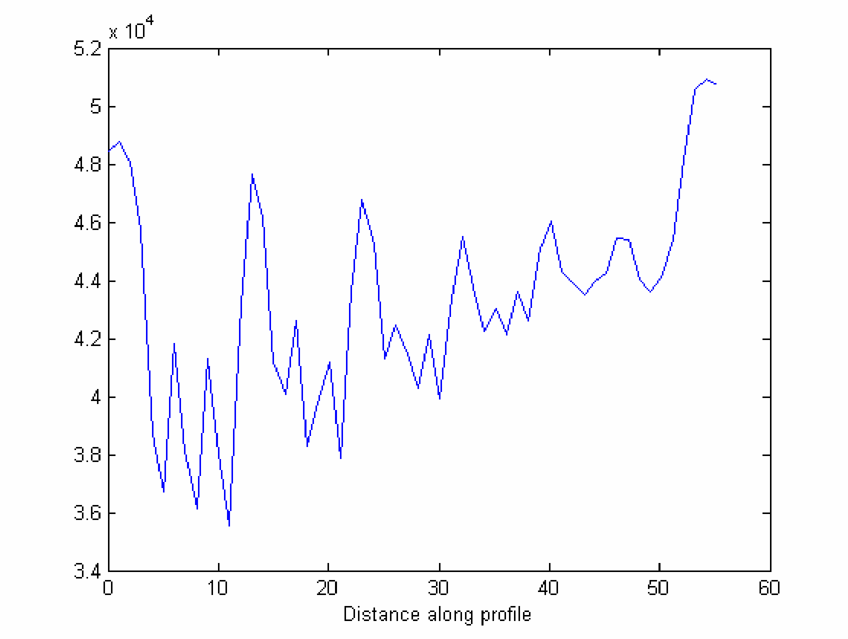

Figure 4.3.1.2 *Resolution target's fifth group's profile for elements from 1 to 6. Resolution target has scanned with 2500 dpi resolution.*

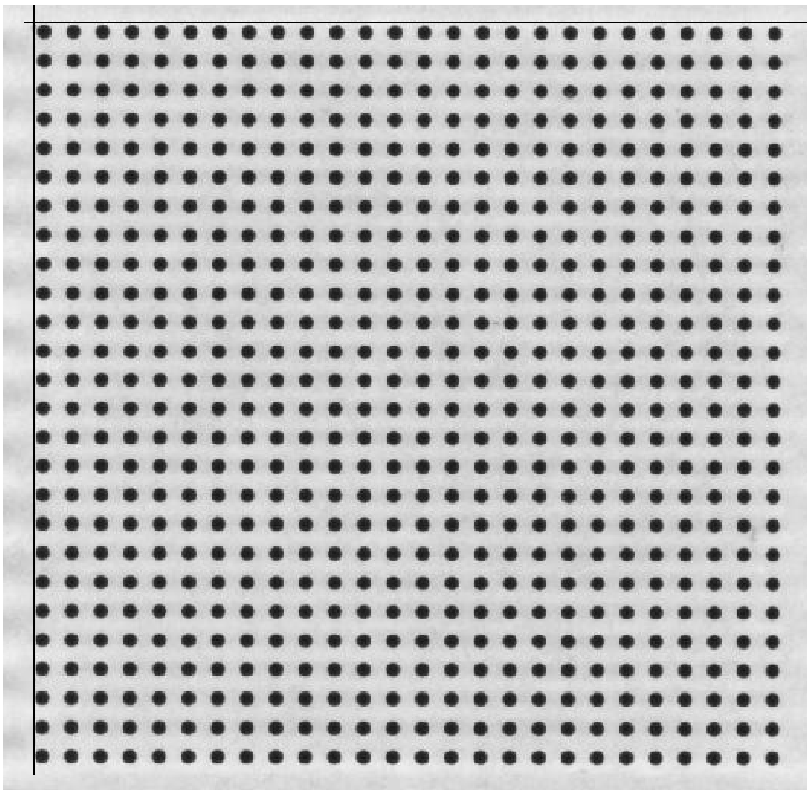

Figure 4.3.1.3 *Distortion target's C square scanned with 1250 dpi resolution. Lines above and left are helping to notice the amount of distortion.*

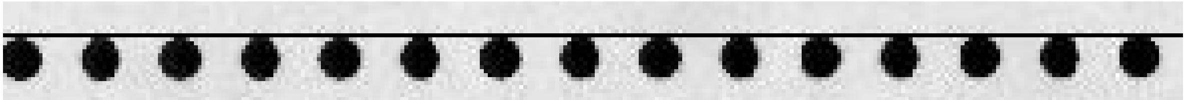

Figure 4.3.1.4 Distortion target's A square's scanned with 2500 dpi resolution and first line has zoomed. Line above is helping to notice the amount of distortion.

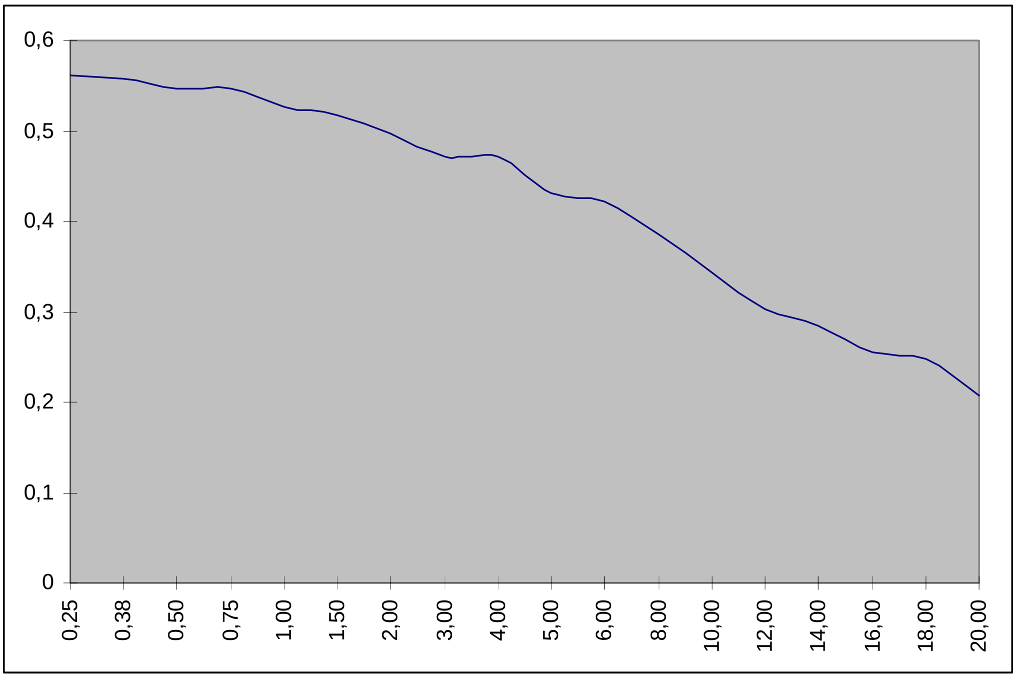

Figure 4.3.1.5 MTF function for scanner with 1250 dpi resolution.

4.3.2 Camera

Table 4.3.2.1 Color differences between measured and photographed color checker targets' squares.

	Measured			Photographed			
	L*	a*	b*	L*	a*	b*	**E**
A1	100,0000	-3,0248	-8,5388	100,0000	-3,0248	-8,5388	**2,4192**
A2	100,0000	29,9213	6,1126	100,0000	-1,6824	-9,9624	**35,4570**
A3	100,0000	9,4184	-6,0736	100,0000	2,4937	-10,6759	**8,3146**
A4	100,0000	-1,0738	-7,4208	100,0000	-2,1309	-5,8169	**1,9210**
A5	100,0000	31,3780	8,7312	100,0000	25,0818	7,5279	**6,4102**
A6	100,0000	11,2541	-4,9510	100,0000	3,3517	-6,5998	**8,0726**
A7	100,0000	-0,6798	-6,5817	100,0000	2,1260	-6,7958	**2,8140**
A8	100,0000	32,7685	12,6136	100,0000	-22,2411	-40,8261	**76,6933**

A9	100,0000	11,5771	-3,6056	100,0000	8,5328	-11,7126	**8,6598**
A10	100,0000	0,5091	-6,5427	100,0000	-0,6253	-5,7071	**1,4089**
B1	100,0000	12,1197	-3,8851	100,0000	-2,4476	-12,9281	**17,1460**
B2	100,0000	75,3721	-11,5492	100,0000	99,8139	-7,5892	**24,7605**
B3	100,0000	37,6303	-27,8994	100,0000	73,6032	-57,8705	**46,8222**
B4	100,0000	70,7994	-48,1394	100,0000	74,9630	-58,1604	**10,8516**
B5	100,0000	-13,6541	-85,2791	100,0000	22,0339	-102,237	**39,5122**
B6	100,0000	-37,9225	-46,2933	100,0000	-28,9179	-41,7628	**10,0801**
B7	100,0000	-0,8301	-10,8615	100,0000	-9,1910	-17,6677	**10,7810**
B8	100,0000	-48,6388	-24,7032	100,0000	30,7862	10,1012	**86,7161**
B9	100,0000	21,7350	12,8828	100,0000	27,0260	6,6983	**8,1390**
B10	100,0000	7,4946	-8,0899	100,0000	11,9744	-12,0647	**5,9889**
C1	100,0000	32,9769	9,9544	100,0000	29,7740	6,0687	**5,0355**
C2	100,0000	43,0920	-20,1923	100,0000	38,6273	-23,2717	**5,4237**
C3	100,0000	37,8612	-60,8022	100,0000	44,1927	-54,1158	**9,2084**
C4	100,0000	27,9847	-50,6681	100,0000	34,4672	-11,5864	**39,6157**
C5	100,0000	-14,1436	-47,5487	100,0000	19,9843	-77,1628	**45,1852**
C6	100,0000	17,5622	-18,7568	100,0000	31,2999	-4,2388	**19,9875**
C7	100,0000	0,8265	-47,9037	100,0000	24,7750	-69,3173	**32,1259**
C8	100,0000	-32,9160	-13,8896	100,0000	-1,7425	-25,9660	**33,4309**
C9	100,0000	-36,6333	18,1569	100,0000	-25,0879	14,6539	**12,0651**
C10	100,0000	33,5546	12,5357	100,0000	-1,7888	-4,9298	**39,4233**
D1	100,0000	0,2321	-6,5332	100,0000	-2,0724	-6,7198	**2,3120**
D2	100,0000	1,5221	-15,8986	100,0000	-0,6292	-7,3039	**8,8598**
D3	100,0000	17,0302	-6,5401	100,0000	7,5833	0,0181	**11,5002**
D4	100,0000	-16,6050	-8,4272	100,0000	-21,0478	-4,9346	**5,6513**
D5	100,0000	14,2488	-1,2701	100,0000	2,3343	12,5549	**18,2507**
D6	100,0000	-13,0755	20,7435	100,0000	-16,0030	38,1353	**17,6364**
D7	100,0000	40,9364	39,0519	100,0000	61,7233	49,0917	**23,0845**
D8	100,0000	27,4766	16,1630	100,0000	55,9123	21,6332	**28,9571**
D9	100,0000	-47,1892	16,0921	100,0000	-9,3585	0,4713	**40,9289**
D10	100,0000	-1,1889	-7,0372	100,0000	31,6344	11,6577	**37,7740**
E1	100,0000	3,1861	-10,4053	100,0000	0,3611	-17,7560	**7,8748**
E2	100,0000	41,0218	46,7493	100,0000	40,6154	5,1429	**41,6084**
E3	100,0000	55,5927	124,3528	100,0000	48,0469	88,5352	**36,6038**
E4	100,0000	95,0059	-270,038	100,0000	113,2653	-240,395	**34,8154**
E5	100,0000	-5,1567	-9,1848	100,0000	-5,8117	-7,2920	**2,0029**
E6	100,0000	12,6045	-6,6438	100,0000	-819,250	-172,062	**848,1419**
E7	100,0000	21,8793	18,0329	100,0000	-0,3641	36,2617	**28,7586**
E8	100,0000	33,9970	20,7245	100,0000	29,1696	38,1502	**18,0820**
E9	100,0000	-36,8096	6,1226	100,0000	13,9994	-14,8151	**54,9540**
E10	100,0000	0,3731	-10,7447	100,0000	4,5017	-12,3793	**4,4404**
F1	100,0000	28,4013	6,5400	100,0000	19,5367	-16,4819	**24,6696**
F2	100,0000	27,2437	16,1983	100,0000	46,0291	-0,4992	**25,1336**
F3	100,0000	32,4305	-102,270	100,0000	84,4784	-190,132	**102,1217**
F4	100,0000	-63,7758	47,2398	100,0000	-76,8305	39,0915	**15,3889**
F5	100,0000	0,2421	-9,4264	100,0000	-5,9904	-8,8364	**6,2604**
F6	100,0000	14,9340	-3,3079	100,0000	-10,5190	-44,5841	**48,4931**

F7	100,0000	18,4960	24,7908	100,0000	39,8509	31,8092	**22,4786**
F8	100,0000	19,4047	13,6163	100,0000	38,7149	23,5122	**21,6983**
F9	100,0000	-53,3318	3,3490	100,0000	-49,1639	-10,3553	**14,3241**
F10	100,0000	28,2260	7,3740	100,0000	32,9835	9,2792	**5,1248**
G1	100,0000	-2,0784	-8,1378	100,0000	-3,7967	-6,1144	**2,6546**
G2	100,0000	1,4816	-45,6377	100,0000	11,8592	-53,4115	**12,9663**
G3	100,0000	80,1645	23,0533	100,0000	109,2660	37,9906	**32,7112**
G4	100,0000	98,2538	47,3001	100,0000	100,1322	37,6989	**9,7832**
G5	100,0000	2,0345	-8,3433	100,0000	6,8021	-1,4394	**8,3901**
G6	100,0000	4,5592	-9,9944	100,0000	26,3263	-3,3330	**22,7636**
G7	100,0000	28,1413	34,2622	100,0000	45,1728	16,3704	**24,7020**
G8	100,0000	21,8221	12,1775	100,0000	50,5119	17,3363	**29,1499**
G9	100,0000	-41,8546	46,5598	100,0000	-37,1073	48,1720	**5,0137**
G10	100,0000	-2,6187	-8,4537	100,0000	0,3105	-5,2108	**4,3700**
H1	100,0000	3,9001	-10,6051	100,0000	4,4725	-2,7046	**7,9212**
H2	100,0000	-29,0568	44,3203	100,0000	-3,9882	29,6400	**29,0507**
H3	100,0000	74,2296	-79,5661	100,0000	39,0045	-7,8454	**79,9041**
H4	100,0000	0,0287	98,5662	100,0000	5,7365	79,9846	**19,4385**
H5	100,0000	-1,2675	-12,3055	100,0000	15,1320	2,3763	**22,0113**
H6	100,0000	-1,3188	-11,0275	100,0000	9,0272	4,4710	**18,6344**
H7	100,0000	18,0173	12,9499	100,0000	45,8605	17,7071	**28,2467**
H8	100,0000	20,3532	15,9890	100,0000	54,3381	21,3757	**34,4092**
H9	100,0000	-78,7992	57,5128	100,0000	-30,4409	37,8798	**52,1918**
H10	100,0000	4,7238	-9,1586	100,0000	21,7268	-2,0504	**18,4290**
I1	100,0000	26,9068	14,8943	100,0000	37,7024	10,7020	**11,5810**
I2	100,0000	19,3491	-49,4951	100,0000	38,6606	-39,9855	**21,5259**
I3	100,0000	-31,4116	70,0835	100,0000	-27,8562	54,3852	**16,0959**
I4	100,0000	86,8429	-30,1499	100,0000	82,9679	-0,3972	**30,0040**
I5	100,0000	10,4602	-4,6105	100,0000	34,1950	4,9991	**25,6063**
I6	100,0000	1,6120	-7,6643	100,0000	11,3344	-2,7390	**10,8988**
I7	100,0000	45,3143	47,8736	100,0000	48,0235	23,5331	**24,4908**
I8	100,0000	34,9358	32,5805	100,0000	39,8031	14,2854	**18,9315**
I9	100,0000	-60,5290	51,0262	100,0000	-37,6462	41,0229	**24,9737**
I10	100,0000	30,8952	12,6027	100,0000	38,4574	13,3731	**7,6013**
J1	100,0000	-3,3269	-7,7454	100,0000	0,0223	-6,1737	**3,6996**
J2	100,0000	-45,3414	-10,5680	100,0000	-21,7793	-12,4760	**23,6392**
J3	100,0000	24,2779	90,5816	100,0000	45,7626	64,4318	**33,8438**
J4	100,0000	-32,3497	-54,7098	100,0000	25,6791	-53,4075	**58,0435**
J5	100,0000	17,5043	-0,1444	100,0000	37,0958	10,9028	**22,4915**
J6	100,0000	-1,2091	-8,4486	100,0000	2,2456	-1,4132	**7,8379**
J7	100,0000	34,4514	26,7077	100,0000	52,0374	37,3775	**20,5697**
J8	100,0000	29,0548	28,3599	100,0000	50,5898	36,5077	**23,0248**
J9	100,0000	24,0500	58,1590	100,0000	35,1604	46,3198	**16,2360**
J10	100,0000	-1,0062	-7,0750	100,0000	2,3119	-5,8638	**3,5323**
K1	100,0000	9,9110	-6,1571	100,0000	4,8102	-8,1557	**5,4784**
K2	100,0000	11,7848	9,9879	100,0000	0,6085	28,1383	**21,3154**
K3	100,0000	-16,1994	-1,3333	100,0000	-6,1366	-5,2523	**10,7991**
K4	100,0000	7,6631	-13,5304	100,0000	11,9600	-12,4497	**4,4307**

K5	100,0000	-12,5008	-17,0599	100,0000	-16,0433	-10,6230	**7,3473**
K6	100,0000	3,9631	-6,9660	100,0000	5,4286	-3,3670	**3,8860**
K7	100,0000	11,9878	-2,4824	100,0000	13,0331	-4,3843	**2,1702**
K8	100,0000	29,4394	6,9274	100,0000	29,4255	0,8725	**6,0548**
K9	100,0000	-9,5111	55,2515	100,0000	-44,1605	70,4060	**37,8185**
K10	100,0000	12,7949	-3,0859	100,0000	0,6374	-2,3808	**12,1779**
L1	100,0000	31,7569	12,2329	100,0000	25,3210	-14,4300	**27,4286**
L2	100,0000	56,1415	15,3105	100,0000	47,5505	-3,1174	**20,3320**
L3	100,0000	91,5976	45,9452	100,0000	120,4358	66,1713	**35,2241**
L4	100,0000	48,5627	-0,3851	100,0000	93,9949	15,8984	**48,2621**
L5	100,0000	47,4452	14,7744	100,0000	96,2463	34,0930	**52,4857**
L6	100,0000	63,4997	68,8465	100,0000	108,4380	81,6149	**46,7170**
L7	100,0000	-6,2408	71,1277	100,0000	-37,5775	75,6007	**31,6543**
L8	100,0000	10,0369	53,9896	100,0000	5,6283	59,1439	**6,7825**
L9	100,0000	-23,3975	65,3713	100,0000	-60,3784	75,1540	**38,2529**
L10	100,0000	33,6429	12,4603	100,0000	21,7597	16,6696	**12,6067**
M1	100,0000	18,7074	0,8394	100,0000	9,5039	-5,9743	**11,4513**
M2	100,0000	80,7212	11,9123	100,0000	104,0715	33,7925	**31,9996**
M3	100,0000	48,0454	2,4085	100,0000	34,9383	-2,6564	**14,0517**
M4	100,0000	83,7922	33,4443	100,0000	99,0154	47,7064	**20,8603**
M5	100,0000	86,8141	46,7723	100,0000	115,8151	70,7026	**37,5994**
M6	100,0000	22,9056	73,5159	100,0000	5,8082	81,2919	**18,7826**
M7	100,0000	8,8858	77,0786	100,0000	-12,9389	81,1722	**22,2053**
M8	100,0000	-12,0881	67,7418	100,0000	-36,9766	72,5423	**25,3472**
M9	100,0000	37,4333	19,8614	100,0000	26,2708	16,6451	**11,6166**
M10	100,0000	13,1390	-1,8357	100,0000	10,3686	1,1447	**4,0692**
N1	100,0000	-1,7206	-7,2069	100,0000	-3,1015	-7,2729	**1,3824**
N2	100,0000	6,0486	-6,5435	100,0000	10,1365	1,3473	**8,8867**
N3	100,0000	28,7151	9,8353	100,0000	26,9877	7,9678	**2,5439**
N4	100,0000	-1,8142	-6,8592	100,0000	-1,3119	-7,8968	**1,1528**
N5	100,0000	7,5749	-5,6045	100,0000	9,1047	5,2637	**10,9753**
N6	100,0000	31,0599	9,8068	100,0000	25,9525	15,3779	**7,5580**
N7	100,0000	-0,7718	-6,7052	100,0000	-2,4046	-7,1954	**1,7048**
N8	100,0000	9,1466	-5,2101	100,0000	13,2788	1,9865	**8,2986**
N9	100,0000	25,0898	23,5534	100,0000	28,8476	11,8443	**12,2973**
N10	100,0000	-2,8135	-6,8989	100,0000	-1,5016	-7,0476	**1,3203**

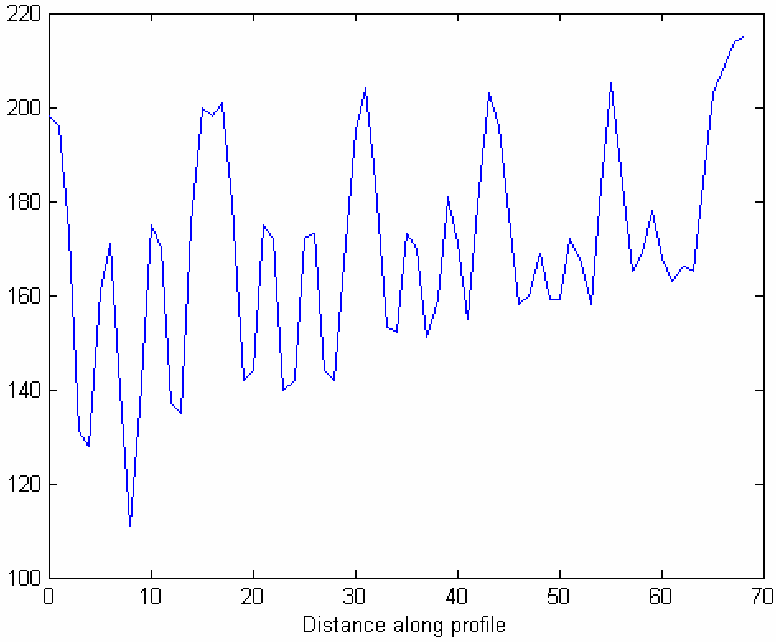

Figure 4.3.2.1 Resolution target's fourth group's profile from vertical element 2 to 6.

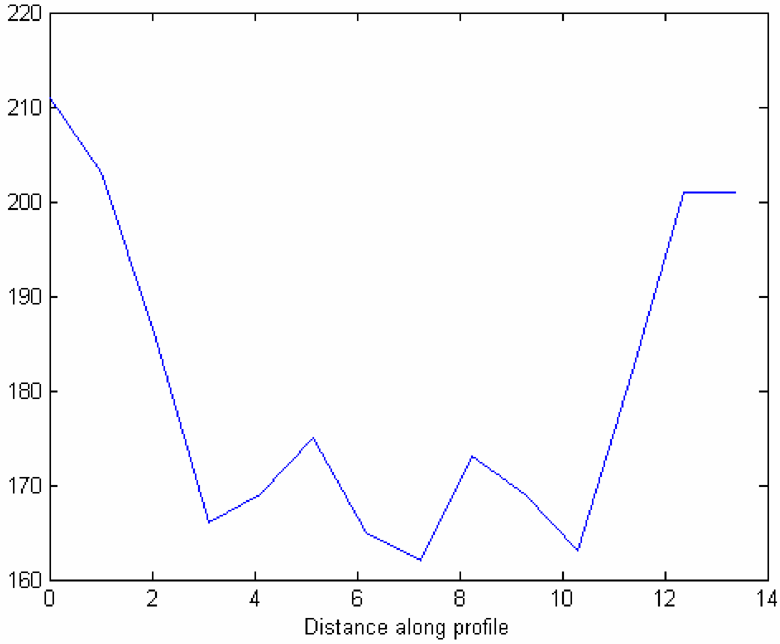

Figure 4.3.2.2 Resolution target's fourth group's profile from horizontal element 5.

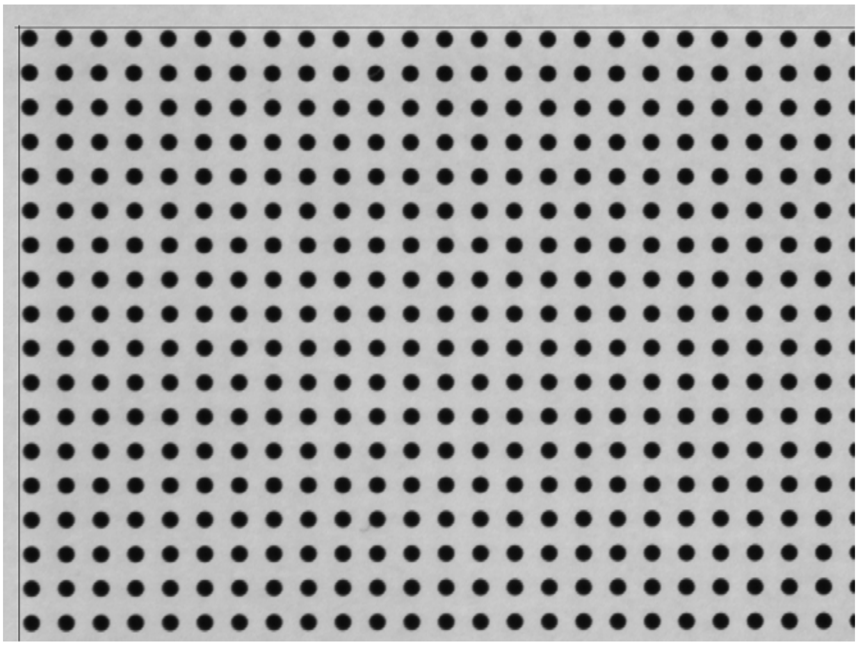

Figure 4.3.2.3 *Distortion target's C square photographed with highest resolution. Lines above and left are helping to notice the amount of distortion.*

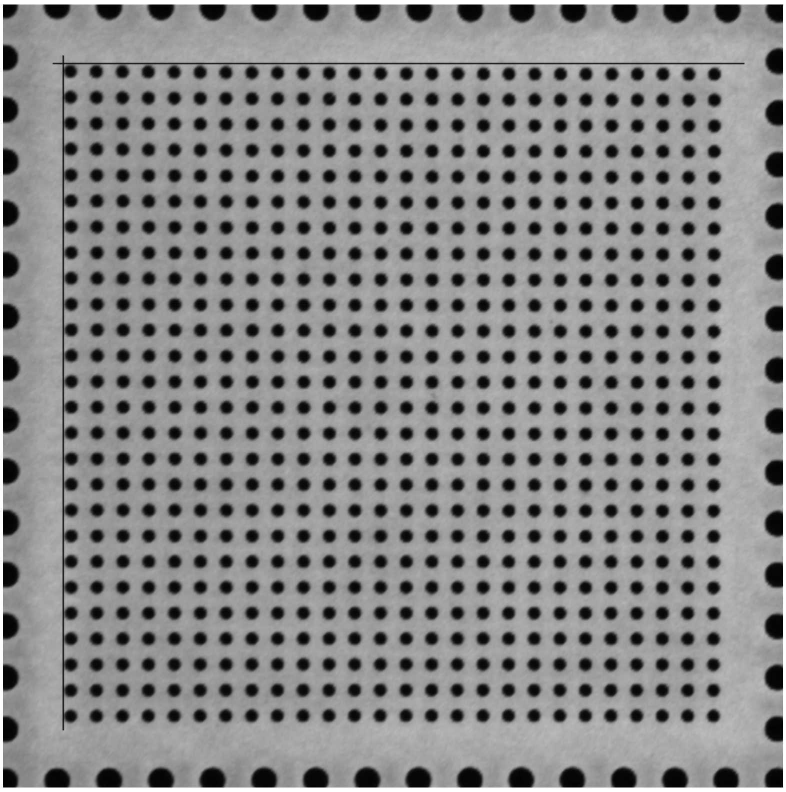

Figure 4.3.2.4 *Distortion target's C square photographed with lower resolution. Lines above and left are helping to notice the amount of distortion.*

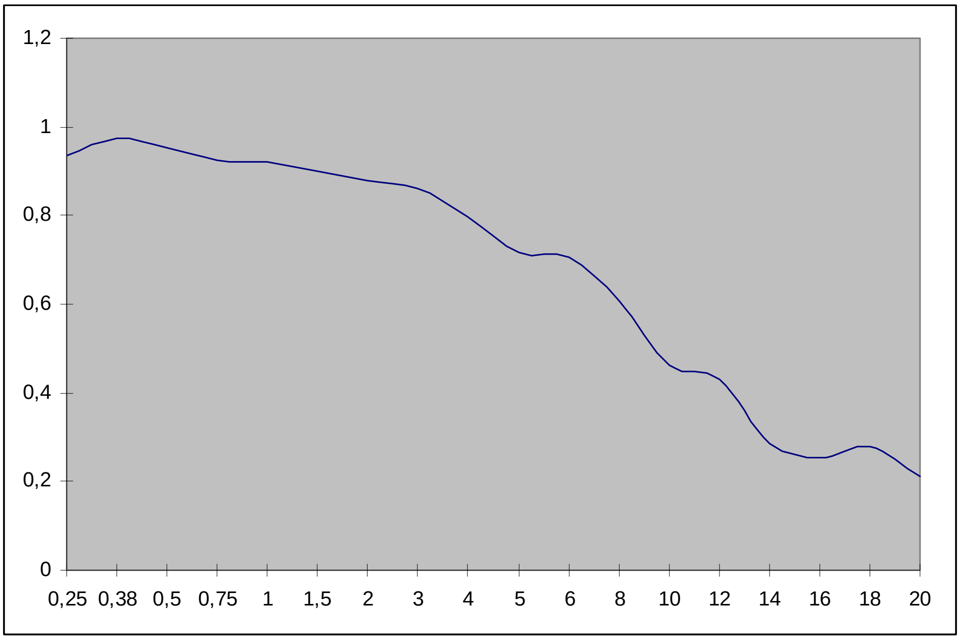

Figure 4.3.2.5 MTF function for CCD camera with highest resolution.

4.4 Tests for spectrophotometer

GretagMacbeth was able to measure the mount of light from light colors well but with darker colors it had problems to measure reliably. The effect of surrounding color to measurement results was analyzed by means of squares of the test chart in figure 4.4.1.

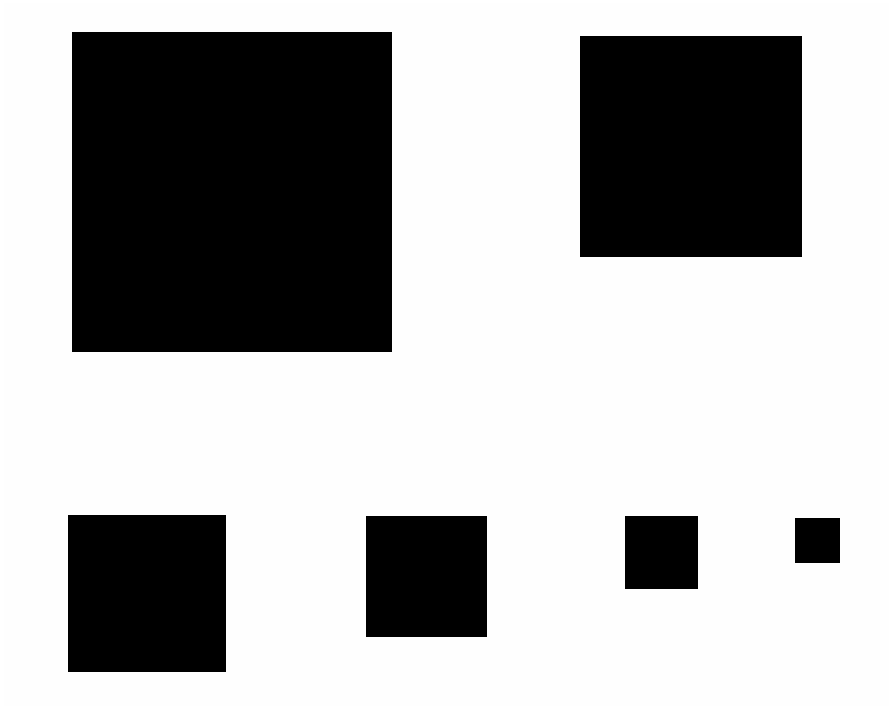

Figure 4.4.1 Test chart for background color's effect in light measuring.

Six squares with different size were drawn on the white background. From all squares (Figure 4.4.1) were measured light and in figure 4.4.2 is shown results. From results can see that white background has affected to results of four smallest squares (Figure 4.4.2, series 3-6) but only from two smallest squares measured results are bad (Figure 4.4.2, series 5 and 6). Surrounding white causes mistakes to incident light measuring and makes black color lighter. Background color is not affecting into measurements from two biggest squares (Figure 4.4.2, series 1 and 2).

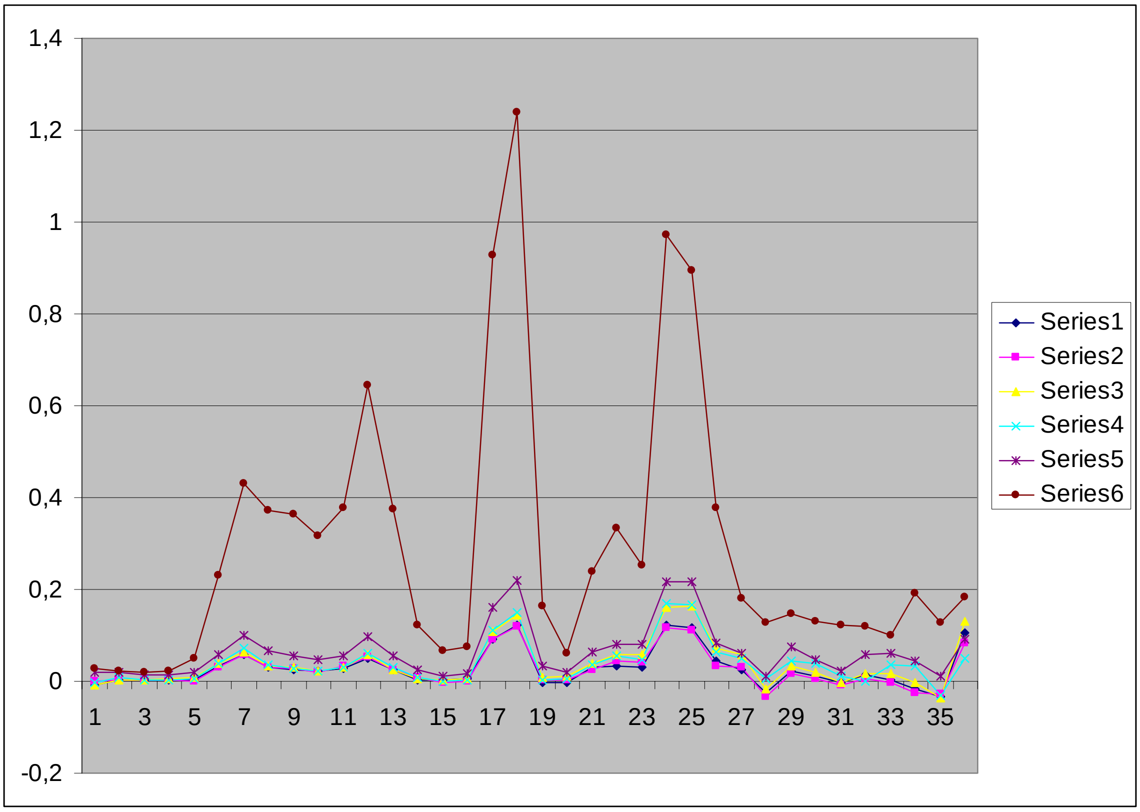

Figure 4.4.2 *Measurement results for test charts in figure 4.5.1. Series 1 is irradiance for biggest test chart and series 6 for smallest test chart.*

Forming dark color to the screen needs less light than lighter color. The screen does not have to send almost any light to form black color but white color needs a lot of green, blue and red light. Screens contain three different kinds of pixels, which all receives green, blue or red colored light. The effect of surrounding colors is greater in dark colors because changes in smaller values are relatively much bigger than changes in bigger values.

Spectrophotometers calibration is also problematic in the incident light-measuring mode. Calibrations have differences, which affect much to results. In figure 4.4.3 are shown five different measurement results for dark. Measuring has done with black calibration cap by measuring irradiance from calibration cap. Spectrophotometer was calibrated over again before all measurements and irradiances were measured with all calibrations. In figure is shown that irradiances are varying from minus to plus irregularly.

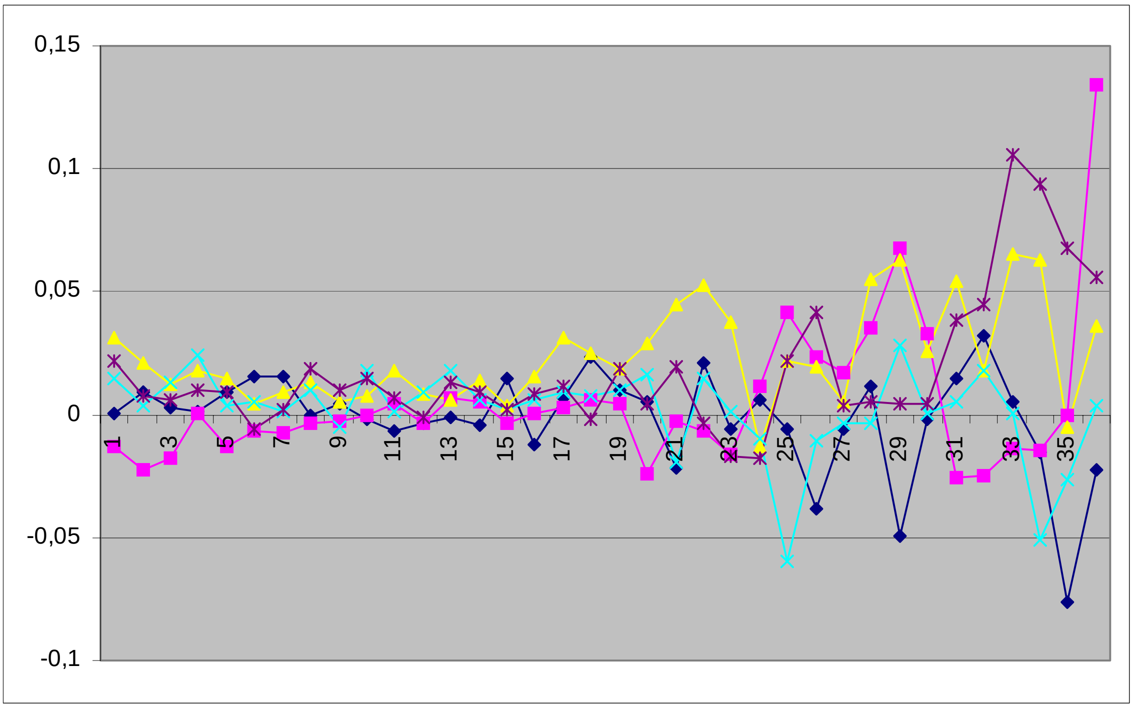

Figure 4.4.3 Five different measurements to dark with five different dark calibrations.

The error between white and black was solved to make clear the uncertainty of the measuring. Error percent are calculated for all wavelengths in table 4.4.1. Error percent should stay lower than 1 or the uncertainty of the measuring will be faithless. Especially with shortest and longest wavelengths error results are very bad.

Table 4.4.1 Errors between white and black in percents.

	380nm	390nm	400nm	410nm	420nm	430nm	440nm	450nm	460nm	470nm
Black	0,0033	-0,01	-0,008	-0,012	-0,007	0,0028	0,0081	-0,014	0,0112	0,0009
White	0,0104	-0,003	0,0015	0,0314	0,2437	1,2447	2,424	2,1311	2,1627	1,8565
Error [%]	32,09	355,53	-494,90	-37,98	-2,95	0,22	0,33	-0,65	0,52	0,05
	480nm	**490nm**	**500nm**	**510nm**	**520nm**	**530nm**	**540nm**	**550nm**	**560nm**	**570nm**
Black	0,006	-0,006	0,0046	-0,01	-0,003	-5E-04	-0,011	0,0042	0,0184	0,0196
White	2,1659	3,6333	2,1234	0,6371	0,3058	0,3516	4,8333	6,4848	0,8578	0,2372
Error [%]	0,28	-0,16	0,21	-1,51	-0,91	-0,13	-0,24	0,06	2,15	8,26
	580nm	**590nm**	**600nm**	**610nm**	**620nm**	**630nm**	**640nm**	**650nm**	**660nm**	**670nm**
Black	0,0126	0,0082	0,0115	-0,027	-0,012	0,0098	-0,026	-0,016	-0,019	-0,019
White	1,0535	1,4939	0,9777	4,0742	3,6252	1,4621	0,444	0,3733	0,2921	0,2523
Error [%]	1,19	0,55	1,17	-0,66	-0,32	0,67	-5,82	-4,42	-6,55	-7,51

	680nm	690nm	700nm	710nm	720nm	730nm				
Black	-0,015	-0,033	-0,012	-1E-04	0,005	-0,045				
White	0,2165	0,1975	0,2113	0,6136	0,2427	0,0064				
Error [%]	-6,74	-16,80	-5,85	-0,02	2,06	-705,81				

4.5 Analyses

Color differences between measured color checker target and scanned or photographed color checker target is done by means of the CIE 1976 (L*a*b*) color-difference equation (Chapter 3.4). Color differences between measured and scanned color checker target is shown in table 4.3.1.1 and between measured and photographed is shown in table 4.3.2.1. Color differences should stay minimal but calculation from reference measurements gives very big values for color difference. The problem is the amount of measured light in reference measurements. Reference measurements have measured from the monitor. Monitor has to send a lot of light to show white color but close to nothing to show black color. Color differences stay lower than 10 for light colors but for darker colors color differences increase too big. E6 is a square in the color checker target with 140 squares, which is impossible as well for scanner as for camera to repeat properly.

Scanner is not able to repeat darkest colors properly. Scanner changes dark colors lighter. Scanner uses own light source and the scanning program is able to fix scanning results and try to make colors look proper. Instead of own light source, CCD camera system contains halogen ring light source with adjustable intensity. The program, used with camera, tries to define gain setting automatically to make colors look proper. However the program is able to define dark colors proper if the maximum intensity of the light source and lighter colors proper if the intensity of the light source is lower.

4.5.1 Scanner

In figure 4.3.1.1 is shown scanners image profile from group four, when image was scanned with 1250 dpi resolution. The first element of the group four is under group three and it is not shown in the image profile of the group four. Scanner is able to repeat element three, which is the second three peeks group in figure 4.3.1.1. From table 4.1.6.1 can read that scanner is able to repeat 20,16 line pairs for millimeter. In figure 4.3.1.2 is shown scanner image profile for 2500 dpi scanning resolution. Image profile is for group five and scanner has been able to repeat four first elements and it means that scanner is able to repeat 40,3 line pairs in millimeter (Table 4.1.6.1).

The amount of distortion is evaluated by means of multi-frequency distortion target. From the target scanned images are shown in figures 4.3.1.3 with 1250 dpi resolution and in figure 4.3.1.4 with 2500 dpi resolution. Scanner causes barrel distortion. It is possible to notify from figures 4.3.1.3 and 4.3.1.4 by means of lines above and on the left of the square. The space between line and circles means that figure has distorted. In figure 4.3.1.4 the distortion is possible to notice from the right side of the figure, where dots start to go under the line above dots. The mount of distortion is possible to calculate by using equation 18. Distortion with 1250 dpi resolution (Figure 4.3.1.3) is about –10,9 % and with 2500 dpi resolution (Figure 4.3.1.4) is about –6,6 % (Attachment 1).

The shape of the MTF function for the scanner seems to decrease smoothly, which might be similar to the MTF target’s ideal function. The graph of the MTF function has set up on the low level.

4.5.2 Camera

Resolution is evaluated by means of image profiles from groups’ line patters. In figure 4.3.2.1 is shown that camera is able to repeat fifth vertical element in the group number four. Element six do not contain three evident peaks anymore. In figure 4.3.2.2 is the image profile of the fifth horizontal element in the group four. It is last pattern, which is possible to perceive. From table 4.1.6.1 can read that camera is able to repeat vertically 11,30 line pairs for millimeter and horizontally 20,16 line pairs for millimeter.

The amount of distortion is evaluated by means of multi-frequency distortion target. Photographs from the target are shown in figures 4.3.2.3 with high resolution and 4.3.2.4

with lower resolution. Camera causes pincushion distortion. It is possible to notify from figures 4.3.2.3 and 4.3.2.4 by means of lines above and on the left of the square. The space between line and circles means that figure has distorted. The mount of distortion is possible to calculate by using equation 18. Distortion with lower resolution (Figure 4.3.2.4) is about –13,6 % and with high resolution (Figure 4.3.2.3) is about –9,5 % (Attachment 2).

The shape of the MTF function for the CCD camera seems to be changing uncertainly. Despite of the worse shape of the MTF function, the level of the graph of the MTF function has set up closer to one with low spatial resolutions.

5. CALIBRATION

In chapter 3 was chosen five different characteristics. One of them, color, is used in calibration. Color is a characteristic, which is dependent of light. Imaging systems have to define settings to find proper colors from figure to the formed image.

GretagMacbeth software contains Match programs, which can be used to calibrate scanners and cameras. Both programs need measured color palettes, which it can compare to the same scanned or photographed palette. Ideally palettes should get to look same to calibrate scanner or camera to repeat colors correctly. Spectrophotometer has to calibrate before making reference palette and comparing measurements. Measured palette is measured from color checker target by square to square and reference chart is scanned or photographed image.

Match program causes a problem in calibration because it does not accept all scanned images as a reference chart. Microtek’s scanning program is able to use different color types but Match program cannot use all color types. Match program is not very accurate software for calibration either. Differences between measured and scanned or photographed color palettes have to be evaluated without spectrophotometer or anything else measuring equipment. Match program is able to calculate profile for scanner if human, who is calibrating, thinks that both of the images look same and continue calibration.

GretagMacbeth's Match program is not recommended to use in calibration if there is some other method for calibration. In this research was noticed that Microtek's own profile-making program was more accurate than Match program. Making profile by Match program is recommended only when it is only way to calibrate some device.

6. PERFORMANCE EVALUATION

This chapter contains evaluation for some targets, which are used in performance evaluation of imaging systems. Chapter contains also results for the performance evaluation of scanner and camera.

6.1 Evaluation for targets

6.1.1 Color checker target

The manufacture of the color checker target with 24 squares gives values for L*a*b*-coordinates. The validity of given coordinates were tested by two different spectrophotometer, GretachMacbeth and Minolta CM-2002. Both spectrophotometers used reflective measuring. Color differences between manufacturer's values and by GretagMacbeth measured values is shown in table 6.1.1.1 and the differences between manufacturer's values and by Minolta measured values is shown in table 6.1.1.2.

Table 6.1.1.1 Color differences between manufacturer's values and values measured by GretagMacbeth.

	Manufacture			GretagMacbeth			
Square	L*	a*	b*	L*	a*	b*	ΔE
1	37,986	13,555	14,059	37,800	13,700	14,700	**0,6830**
2	65,711	18,130	17,810	65,200	18,700	17,800	**0,7656**
3	49,927	-4,880	-21,925	50,100	-5,100	-21,900	**0,2810**
4	43,139	-13,095	21,905	43,100	-13,100	22,900	**0,9958**
5	55,112	8,844	-25,399	55,600	8,200	-24,600	**1,1363**
6	70,719	-33,397	-0,199	71,200	-33,100	0,100	**0,6395**

7	62,661	36,067	57,096	62,500	36,600	57,400	**0,6344**
8	40,020	10,410	-45,964	40,300	10,500	-46,200	**0,3771**
9	51,124	48,239	16,248	51,700	48,000	16,500	**0,6726**
10	30,325	22,976	-21,587	31,100	19,100	-20,500	**4,0995**
11	72,532	-23,709	57,255	72,700	-23,200	57,600	**0,6374**
12	71,941	19,363	67,857	71,700	19,700	68,400	**0,6830**
13	28,778	14,179	-50,297	28,900	12,200	-49,900	**2,0221**
14	55,261	-38,342	31,370	54,800	-38,700	32,000	**0,8588**
15	42,101	53,378	28,190	42,600	52,100	28,100	**1,3749**
16	81,733	4,039	79,819	83,400	3,200	82,200	**3,0252**
17	51,935	49,986	-14,574	52,800	51,100	-13,400	**1,8351**
18	51,038	-28,631	-28,638	51,000	-27,800	-28,800	**0,8475**
19	96,539	-0,425	1,186	95,400	-0,700	2,300	**1,6168**
20	81,257	-0,638	-0,335	80,800	-0,700	-0,100	**0,5176**
21	66,766	-0,734	-0,504	65,300	-0,600	-0,300	**1,4862**
22	50,867	-0,153	-0,270	50,800	-0,400	0,000	**0,3720**
23	35,656	-0,421	-1,231	36,200	-0,500	-0,800	**0,6985**
24	20,461	-0,079	-0,973	21,400	0,000	-0,400	**1,1029**

Table 6.1.1.2 Color differences between manufacturer's values and values measured by Minolta CM-2002.

	Manufacture			Minolta CM-2002			
Square	L*	a*	b*	L*	a*	b*	ΔE
1	37,986	13,555	14,059	39,330	12,760	13,970	**1,5641**
2	65,711	18,130	17,810	65,380	19,140	17,270	**1,1922**
3	49,927	-4,880	-21,925	49,280	-4,080	-21,330	**1,1885**
4	43,139	-13,095	21,905	43,330	-12,990	20,700	**1,2246**
5	55,112	8,844	-25,399	54,410	8,770	-23,410	**2,1105**
6	70,719	-33,397	-0,199	69,030	-31,410	-1,190	**2,7898**
7	62,661	36,067	57,096	62,850	34,640	56,560	**1,5360**
8	40,020	10,410	-45,964	40,140	11,240	-44,360	**1,8100**
9	51,124	48,239	16,248	51,420	46,430	16,970	**1,9701**
10	30,325	22,976	-21,587	31,210	18,780	-18,860	**5,0819**
11	72,532	-23,709	57,255	70,380	-23,480	52,990	**4,7827**
12	71,941	19,363	67,857	70,530	17,000	65,490	**3,6301**
13	28,778	14,179	-50,297	29,780	13,170	-48,360	**2,4029**
14	55,261	-38,342	31,370	54,020	-37,170	28,580	**3,2707**
15	42,101	53,378	28,190	42,910	50,350	27,760	**3,1636**
16	81,733	4,039	79,819	80,710	1,700	77,780	**3,2673**
17	51,935	49,986	-14,574	52,030	49,710	-11,240	**3,3468**
18	51,038	-28,631	-28,638	49,200	-24,210	-29,000	**4,8015**
19	96,539	-0,425	1,186	93,440	-0,380	2,360	**3,3142**
20	81,257	-0,638	-0,335	79,330	-0,520	0,060	**1,9706**
21	66,766	-0,734	-0,504	65,230	-0,550	-0,420	**1,5493**

22	50,867	-0,153	-0,270	49,660	-0,360	-0,170	**1,2287**
23	35,656	-0,421	-1,231	36,520	-0,340	-0,850	**0,9477**
24	20,461	-0,079	-0,973	22,170	0,000	-0,230	**1,8652**

GretagMacbeth's measurement results show that colors in 24 colors color checker target fill the bill of manufacturer's promises. Minolta's spectrophotometer CM-2002 is not as reliable as GretagMacbeth because the diameter of measuring head in Minolta is as long as the length of color squares in 24 colors color checker target. Only square 10, in the 24 colors color checker target, gives bigger color-difference value for both spectrophotometers.

Manufacturer has not given any L^*, a^* and b^*-coordinates for 140 colors color checker target. Color squares look better in 140 colors target. Especially black squares look darker than in 24 colors target. In attachment IIII is shown table where are measured L^*, a^* and b^*-coordinates for 140 colors target with GretagMacbeth and Minolta and color difference between results. GretagMacbeth is able to measure dark colors better and it causes big color difference in dark colors. Other colors give small color difference values (Attachment 4).

140 colors target is better to use in color evaluation because it contains more different colors and black color is very dark. In 24 colors target the last square looks black, but when it is compared to the black square of the140 colors target, it turns out as a dark gray square. Both color checker targets are very disposed for dirt. Targets have to be preserving out of light in their cover boxes. Targets also have to be used very carefully to keep color squares clean.

6.1.2 Depth of field target

Depth of field target is planned to define the distance that photographed object can be moved forward and behind from the place where it is in focus. On the measurement surface of the depth of field target is a plastic cover. The plastic cover does not lie on the surface smoothly. Some air has stayed between measurement surface and the plastic cover. The uneven plastic cover causes some noise to photographed depth of field target images. The noise is shown in images as obscure areas amongst the measuring bars.

6.1.3 Distortion target and resolution target

Distortion target and resolution target were analyzed by means of microscope and ruler. Diameters of dots of the depth of field target turned out to be as long as the producer has informed. Also the distances between dots were informed correctly.

Producer has informed the amount of line pairs in millimeter in resolution target. The number of line pairs were analyzed by calculated the number of black and white lines on the area of one millimeter. Producer's information about line pairs in millimeter seems to be valid.

Distortion target's and resolution target's tests are not most reliable because the scale in ruler can be inaccurate. However results for biggest lines and dots are quite accurate.

6.1.4 MTF target

MTF target has reflecting surface, which might cause disturbances. Especially in scanning the reflective surface turned out as a problem. Scanner's effective lightning caused much worse results than producer's reference results. Producer has informed peak-to-peak modulation values and compensated modulation values for target with every spatial frequency but those values can not be tested without as good testing machines as the producer has used.

6.2 The performance evaluation of scanner

6.2.1 Resolution evaluation

The Microtek Artixscan 2500f scanner has two different high-resolution changes. One possibility is to use resolution 2500 dpi and use smaller area from scanner or 1250 dpi and whole area of scanner. Theoretically 2500 dpi means that scanner is able to repeat 98 line pairs in millimeter and its resolution power is 10 μm. 1250 dpi means that it is able to repeat only 49 line pairs in millimeter and resolution power is 20 μm.

From the results of analyzed reference measurements is possible to calculate scanner's resolution power. When scanning resolution was set to 1250 dpi scanner was able to repeat 20,16 line pairs in millimeter, which means its resolution power was 24,8 μm (Equation 17). With the scanning resolution 2500 dpi scanner was able to repeat 40,3 line pairs in millimeter. That means value 12,4 μm for resolution power.

6.2.2 MTF evaluation

MTF function for scanner is shown in figure 6.2.2.1 with 1250 dpi and 2500 dpi resolution. Scanner spreads lines in test patterns, which is shown in figure 6.2.2.1 as decreased MTF value compared to reference MTF function. Forms of the MTF functions of the scanner remind the form of reference MTF function. Changes in white and black colors affect to MTF functions of the scanner. In scanned MTF target image, black lines are not as dark as in original target and white lines are also darker than in original target. MTF target has also reflecting surface, which might cause disturbances during scanning.

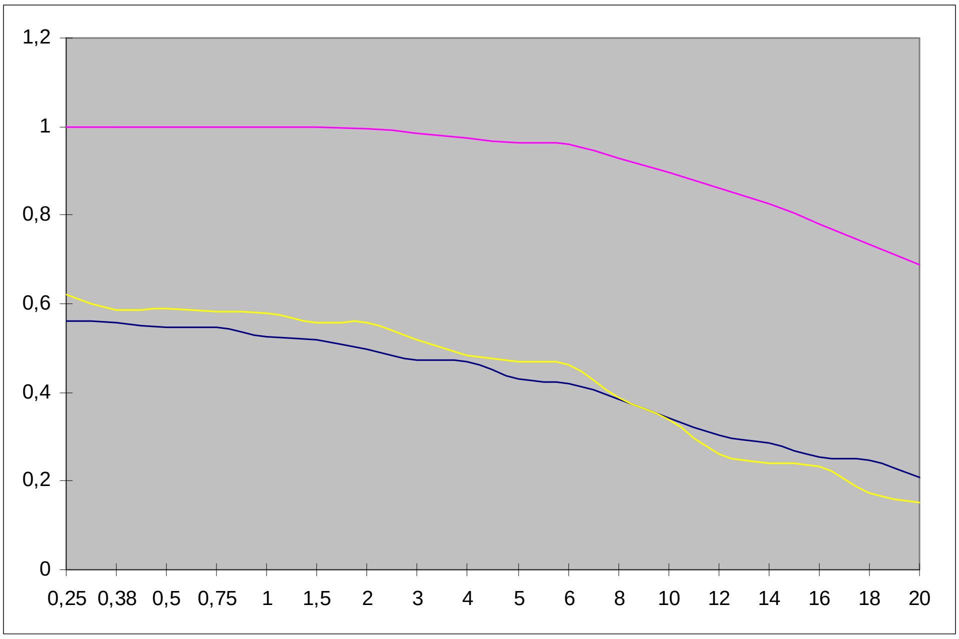

Figure 6.2.2.1 Ideal MTF function (red line) and MTF function for scanned target with 1250 dpi resolution (blue line) and with 2500 dpi resolution (yellow line).

6.3 The performance evaluation of camera system

6.3.1 Resolution evaluation

AVT Oscar F-510C CCD camera was used with 7th format and mode 0. That mode uses smaller area from cameras lens, about one quarter, and is able to get accurate images. The FireView software contains possibility to define X- and Y-offset, which are used to get photographed area moved in the middle of the lens. The ideal maximum resolution power for CCD camera was solved by measuring the mount of pixels used in the group zero in element two, to form a line pair. 75 pixels were needed to form that line pairs, which means that camera shows 11,8 µm/pixel. Ideally camera's resolution power is that 11,8 µm, but in practice the camera does not reach that accuracy.

6.3.2 MTF evaluation

MTF function for CCD camera is shown in figure 6.3.2.1 with high resolution. Scanner spreads lines in test patterns, which is shown in figure 6.3.2.1 as decreased MTF value compared to reference MTF function. Form of the MTF function of the camera does not remind the form of reference MTF function as well as forms of the MTF function of the scanner. In photographed MTF target image, black lines are darker and white lines lighter than in scanned images. It causes increased MTF function with lower spatial resolutions. With higher spatial resolutions cameras ability to repeat lines is decreased and MTF function goes as low as in the MTF function of the scanner.

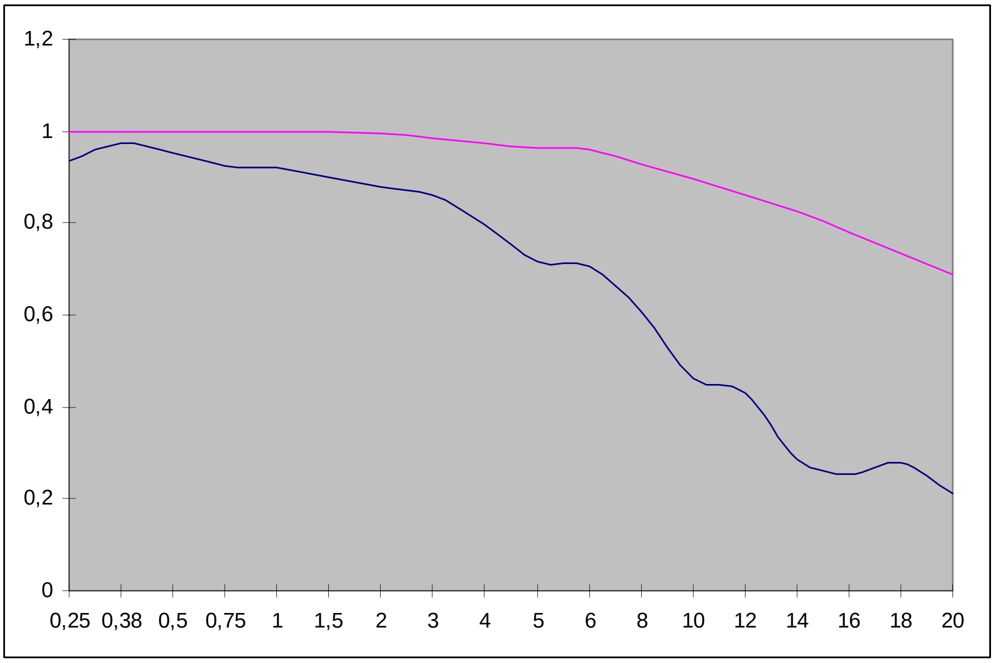

Figure 6.3.2.1 Ideal MTF function (red line) and MTF function for scanned target (blue line).

6.3.3 Depth of Field

Depth of field target was photographed in 45° angle. In figure 6.3.3.1 is shown depth of field target, which top surface, is in focus. The photograph has been taken with minimum aperture, which means that evaluated depth of field is minimum value for camera. With the biggest aperture, the scale of target is not long enough and the depth of field is over 50 mm. The evaluated depth of field is a sum of depth of field behind and in front of the focus point.

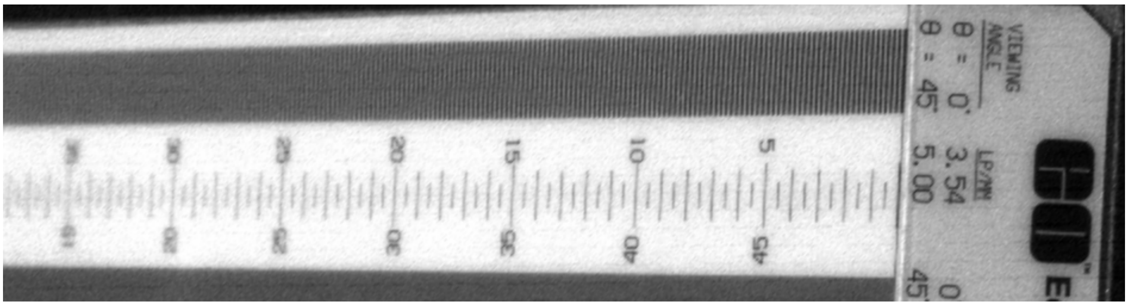

Figure 6.3.3.1 Photographed depth of field target.

Figure 6.3.3.2 helps to evaluate last acceptable line pair to define the minimum depth of field for camera. From figure 6.3.3.2 can evaluate that last line pairs can be separated from the position of 25 or 26 millimeter. It means that cameras minimum depth of field is about 25 millimeter.

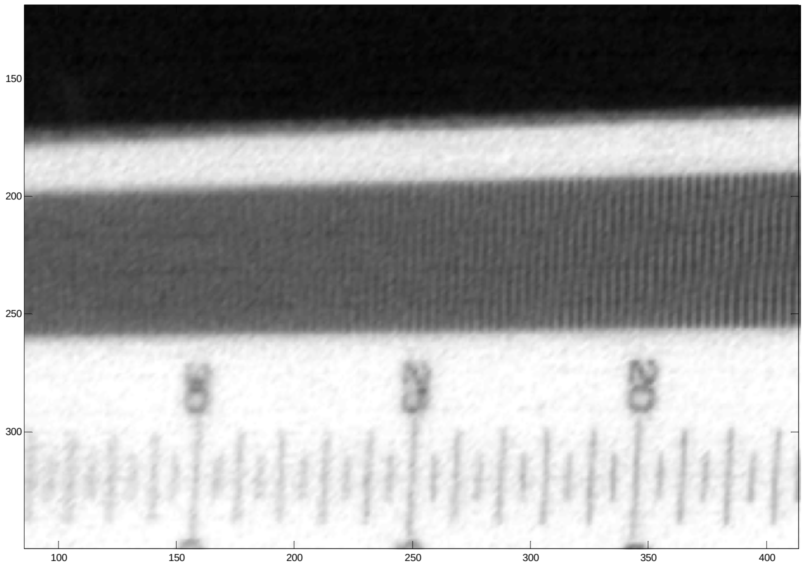

Figure 6.3.3.2 Line pairs in 5 lp/mm category in figure 6.3.3.1.

7. CONCLUSIONS

The research contained three main tasks: performance evaluation, calibration and targets' evaluation. Performance evaluation was proceeding with good results. Calibration and targets' evaluation gave also bad results.

Calibration modes in GretagMacbeth's Match programs are problematic. The Diagnostic program is able to calibrate measuring device if settings of the monitor are proper. Instead of it the Match program is able to calibrate monitor settings if settings of the measuring device are proper. Calibration modes for scanner and camera are inexact for calibration. Calibration modes are able to produce profiles for scanner and camera but the correct profile might be something else. Scanners' own profile-making programs might be better to use for calibration but if some scanner has not got profiling program, making profile by Match program is better than nothing.

Chosen measurement targets included good targets and a little bit worse targets. Resolution target and distortion target were as good as manufacturers promised. Measures for details in targets were same than in datasheet. Color checker targets had differences in the quality of colored squares. The quality of the 140 colors target squares seemed to be higher than in mini color checker target. Colors in the mini checker target squares seemed to be easier to copy. The depth of field target were difficult to use because putting the top surface of the target in focus was first problem and another problem were to define the last non-obscure line pair from the scale. Depth of field target was possible use only in photographing because getting the top surface of the target in focus was impossible with scanner. The quality of the surface of the depth of field target was also weak. Sinusoidal target was used to define MTF functions for imaging systems. Sinusoidal target seemed to work properly because the shape of scanner's MTF function was same than theoretical. Target's shining surface may cause weaker results.

Performance evaluations for scanner show that scanner is able to repeat as small details as manufacturer has promised. However the smallest details are looking a little obscure in images. Scanner causes barrel distortion but the amount of distortion is not too significant.

Scanner is able to repeat almost every color in color checker target quite well. Only darkest colors are converted lighter. Scanning program is able to fix scanned images to get their colors look like original colors. Scanner uses always own light source and the scanning program knows the specks of the light and it is the reason why the program is able to fix results.

The shape of The MTF function for scanner reminds theoretical MTF function, but it has set up lower level than theoretical function. Effective light source probably make lines in MTF target to look wider. Wider lines in MTF target and converted dark lines cause worse function than theoretical function.

Performance evaluations for CCD camera system show problems in photographing. The camera is able to repeat almost as small details than it theoretically can. Instead of it MTF function for the camera and colors are changing quite much from theoretical values. The program, used with the camera, is able to define white balance setting to get the most light color look white and gain setting to make camera's view to look bright enough. Manually once done white balance setting and automatic gain setting cause that the quality of white color and its hues are correct. Therefore the MTF function appears to be near theoretical MTF function with lower spatial frequencies but changing more variable and its quality gets poorer.

The biggest problem with camera is color repeating. The program, used with the camera, defines gain setting automatically to try to get colors look like original, but the program does not know the specks of used lightning. Used lightning conditions affect to colors, which camera is able to see. Changing the intensity of used light source or adjusting the gain setting manually, makes it possible to get all colors look proper. But automatic gain setting with halogen light source caused big differences to results. Automatic gain setting probably notices the amount of received photons from different parts of the photographed area and defines the gain setting bigger that all signals from sensors are big enough. Bigger gain causes problems for light colors, because light colors change to look a lot of lighter or even white. It might make dark colors look too light also.

The depth of field ability in the camera is very good. The minimal depth of field value is very good and with bigger depth of field values the depth of field target's measuring scale ends. Photographed object can be out of focus and still it is impossible for human eye to notice obscure details from photographed images. The lens used with CCD camera causes some barrel distortion but the amount of distortion is not too significant.

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ATTACHMENT 1 Resolution calculations

Square A	[mm]	Square C	[mm]
Pattern Length X	50,00	Pattern Length X	12,50
Pattern Length Y	50,00	Pattern Length Y	12,50
Dot Diameter	1,00	Dot Diameter	0,25

$$PD_{high} = \sqrt{25^2 + 25^2} = 35,35534$$

$$PD_{low} = \sqrt{6,25^2 + 6,25^2} = 8,838835$$

$$\frac{0,25mm}{11,\ pixels} = 0,022727$$

$$\frac{1,00mm}{11pixels} = 0,090909$$

$$AD_{lowresolution} = \sqrt{(248 * 0,022727)^2 + (248 * 0,022727)^2} = 8,458085$$

$$AD_{highresolution} = \sqrt{(258 * 0,090909)^2 + (258 * 0,090909)^2} = 33,16974$$

$$\%_{low} = \frac{AD_{lowresolution} - PD}{AD_{lowresolution}} * 100 = \frac{8,458085 - 8,838835}{8,458085} * 100\% = -10,887\%$$

$$\%_{high} = \frac{AD_{highresolution} - PD}{AD_{highresolution}} * 100 = \frac{33,16974 - 35,35534}{33,16974} * 100\% = -6,589\%$$

ATTACHMENT 2 **Distortion calculations**

	[mm]
Dot diameter	0,25
Dot center spacing	0,5

$$PD = 12{,}5 * \sqrt{0{,}5^2 + 0{,}5^2} = 8{,}838835$$

$$\frac{0{,}25mm}{23\,pixels} = 0{,}010869565$$

$$\frac{0{,}25mm}{12\,pixels} = 0{,}020833333$$

$$AD_{lowresolution} = \sqrt{(264 * 0{,}02083)^2 + (264 * 0{,}02083)^2} = 7{,}778174593$$

$$AD_{highresolution} = \sqrt{(336 * 0{,}01087)^2 + (336 * 0{,}01087)^2} = 5{,}16495388$$

$$\%_{low} = \frac{AD_{lowresolution} - PD}{AD_{lowresolution}} * 100 = \frac{7{,}778174593 - 8{,}838835}{7{,}778174593} * 100\% = -13{,}6364\%$$

$$\%_{high} = \frac{AD_{highresolution} - PD}{AD_{highresolution}} * 100 = \frac{5{,}16495388 - 8{,}838835}{5{,}16495388} * 100\% = -9{,}5238\%$$

ATTACHMENT 3 Matlab codes

```
picture=imread('FILENAME');     /* open an image to matlab */

figure;                         /* forms figure from the image */
imagesc(picture(:,:,1));
colormap gray;
axis image

improfile                       /*command forms an image profile */
```

ATTACHMENT 4 **Color difference in 140 colors color checker target**

GretagMacbeth			Minolta CM-2002			Difference in coordinates			Color-difference	
L*	a*	b*	L*	a*	b*	ΔL*	Δa*	Δb*	**ΔE**	
96,6	0,2	3,5	95,12	-0,58	1,01	1,48	0,78	2,49	**3**	A1
5,4	0,1	-0,2	18,93	0,03	-0,37	-13,53	0,07	0,17	**13,531**	A2
49,8	-0,4	0,2	51,71	-0,34	-0,24	-1,91	-0,06	0,44	**1,961**	A3
96,7	-1,2	0,9	95,18	-0,8	1,05	1,52	-0,4	-0,15	**1,579**	A4
6,3	0,1	-0,5	19,04	0,11	-0,27	-12,74	-0,01	-0,23	**12,742**	A5
49,7	-1,1	0,2	51,72	-0,34	-0,21	-2,02	-0,76	0,41	**2,197**	A6
96,5	-1,1	1,1	95,03	-0,75	1,15	1,47	-0,35	-0,05	**1,512**	A7
5,2	0,1	-0,2	18,91	0,02	-0,28	-13,71	0,08	0,08	**13,71**	A8
49,8	-0,4	0,1	51,73	-0,36	-0,25	-1,93	-0,04	0,35	**1,962**	A9
96,7	-1,1	1	95,19	-0,8	1	1,51	-0,3	0	**1,54**	A10
49,6	-0,4	0,1	51,68	-0,36	-0,24	-2,08	-0,04	0,34	**2,108**	B1
32,8	52,4	-10,2	37,36	45,58	-8	-4,56	6,82	-2,2	**8,494**	B2
61	26	-18,3	62,18	24,94	-16,87	-1,18	1,06	-1,43	**2,136**	B3
30,5	48,4	-38,4	36,12	40,28	-31,97	-5,62	8,12	-6,43	**11,784**	B4
49,5	-15,7	-48,1	50,76	-12,17	-46,16	-1,26	-3,53	-1,94	**4,22**	B5
60,7	-30,8	-26,2	61,11	-27,19	-25,93	-0,41	-3,61	-0,27	**3,643**	B6
18,6	-27,7	-6,6	26,11	-15,64	-6	-7,51	-12,06	-0,6	**14,22**	B7
60,2	-41,8	-12,8	60,67	-37,22	-13,45	-0,47	-4,58	0,65	**4,65**	B8
20,6	1,7	9,8	27,25	0,88	5,5	-6,65	0,82	4,3	**7,961**	B9
49,8	-0,4	0,2	51,75	-0,35	-0,21	-1,95	-0,05	0,41	**1,993**	B10
5,3	0,1	-0,1	19,26	0,04	-0,14	-13,96	0,06	0,04	**13,96**	C1
21,3	18	-18,6	28,1	13,63	-14,42	-6,8	4,37	-4,18	**9,1**	C2
41,6	18,2	-36,8	44,88	16,62	-33,38	-3,28	1,58	-3,42	**4,995**	C3
19,4	-0,2	-36,6	26,17	0,87	-30,75	-6,77	-1,07	-5,85	**9,011**	C4
60,3	-18,6	-31,3	60,86	-15,53	-30,39	-0,56	-3,07	-0,91	**3,251**	C5
19,7	-18	-21,4	26,62	-10,58	-17,63	-6,92	-7,42	-3,77	**10,824**	C6
60,7	-6,2	-32,4	61,49	-4,47	-31,11	-0,79	-1,73	-1,29	**2,298**	C7
50,8	-49,8	-10	51,84	-42,92	-11,16	-1,04	-6,88	1,16	**7,054**	C8
60,7	-39,9	20,6	61,51	-37,14	17,34	-0,81	-2,76	3,26	**4,348**	C9
5,6	0,1	-0,1	19,38	0,03	-0,15	-13,78	0,07	0,05	**13,78**	C10
96,7	-1,2	0,9	95,32	-0,82	0,96	1,38	-0,38	-0,06	**1,433**	D1
84,3	-2,2	-7,6	83,94	-1,43	-7,57	0,36	-0,77	-0,03	**0,851**	D2
84,9	14,2	0,7	84,7	13,86	0,83	0,2	0,34	-0,13	**0,415**	D3
85,1	-19,2	-0,8	84,12	-18,12	-1,2	0,98	-1,08	0,4	**1,512**	D4
85,3	13,1	7	84,97	12,74	7,07	0,33	0,36	-0,07	**0,493**	D5
84,4	-10,7	26,9	83,95	-10,47	24,95	0,45	-0,23	1,95	**2,014**	D6
61,9	30,6	36,9	63,47	28,01	33,63	-1,57	2,59	3,27	**4,457**	D7
64,5	20,7	19,1	65,57	20	17,19	-1,07	0,7	1,91	**2,298**	D8
50,5	-53,7	14,3	52,12	-47,21	11,01	-1,62	-6,49	3,29	**7,454**	D9

(Continue)

(Attachment 4 continues)

96,3	-1,1	1	95,18	-0,78	1,03	1,12	-0,32	-0,03	**1,165**	D10
49,7	-0,4	0,2	51,69	-0,38	-0,24	-1,99	-0,02	0,44	**2,038**	E1
32,1	18,3	21,7	37,07	14,97	16,3	-4,97	3,33	5,4	**8,059**	E2
60,7	38,2	72,2	62,37	34,69	61,92	-1,67	3,51	10,28	**10,99**	E3
19,8	21,5	-58,6	26,8	16,38	-49,14	-7	5,12	-9,46	**12,834**	E4
96,6	-1,2	1	95,27	-0,8	0,99	1,33	-0,4	0,01	**1,389**	E5
5,5	0,2	-0,1	19,26	0,06	-0,23	-13,76	0,14	0,13	**13,761**	E6
76,9	20,2	22,9	77,51	19,03	22,02	-0,61	1,17	0,88	**1,586**	E7
73,1	28,8	24,5	74,36	27,37	23,37	-1,26	1,43	1,13	**2,216**	E8
20	-24,9	6,9	27,57	-15,39	3,35	-7,57	-9,51	3,55	**12,663**	E9
49,8	-0,4	0,3	51,68	-0,36	-0,21	-1,88	-0,04	0,51	**1,948**	E10
5,7	0,1	-0,4	19,14	0,03	-0,29	-13,44	0,07	-0,11	**13,441**	F1
63,6	20	19,4	64,81	19,46	17,49	-1,21	0,54	1,91	**2,325**	F2
35,2	10,9	-49,6	39,28	10,16	-44,88	-4,08	0,74	-4,72	**6,283**	F3
52	-43,9	38,6	53,12	-40,07	31,71	-1,12	-3,83	6,89	**7,962**	F4
79,7	0	0,2	79,69	0,19	0,07	0,01	-0,19	0,13	**0,23**	F5
30,8	-0,3	-0,5	35,22	-0,28	-0,85	-4,42	-0,02	0,35	**4,434**	F6
63,7	14,2	26,2	64,96	13,41	23,57	-1,26	0,79	2,63	**3,021**	F7
64,6	14,3	17,5	65,53	13,61	15,98	-0,93	0,69	1,52	**1,911**	F8
60,1	-44,4	8,2	60,65	-40,56	5,98	-0,55	-3,84	2,22	**4,47**	F9
5,5	0,1	0	19,25	0,03	-0,14	-13,75	0,07	0,14	**13,751**	F10
96,7	-1,1	1	95,22	-0,8	0,96	1,48	-0,3	0,04	**1,511**	G1
46,5	-5,3	-24,1	48,7	-4,13	-22,68	-2,2	-1,17	-1,42	**2,868**	G2
47,2	52,3	20,8	50,38	48,34	19,02	-3,18	3,96	1,78	**5,382**	G3
36,3	64,8	38,7	40,99	58,35	30,14	-4,69	6,45	8,56	**11,699**	G4
65,5	-0,2	0	66,25	-0,08	-0,3	-0,75	-0,12	0,3	**0,817**	G5
40,4	-0,4	-0,3	43,5	-0,31	-0,68	-3,1	-0,09	0,38	**3,124**	G6
43,9	16,6	27,5	47,07	14,65	22,8	-3,17	1,95	4,7	**5,995**	G7
64,6	16,6	16,8	65,81	16,14	15,35	-1,21	0,46	1,45	**1,944**	G8
60,8	-29,7	41,5	61,93	-29,77	36,45	-1,13	0,07	5,05	**5,175**	G9
96,7	-1,1	1,1	95,19	-0,79	0,99	1,51	-0,31	0,11	**1,545**	G10
49,7	-0,4	0,2	51,66	-0,035	-0,25	-1,96	-0,365	0,45	**2,044**	H1
38,2	-16,7	30,6	41,16	-15,46	23,79	-2,96	-1,24	6,81	**7,528**	H2
21,4	29,1	-27	28,41	22,1	-21,06	-7,01	7	-5,94	**11,551**	H3
80,6	3,9	89,5	80,69	2,32	79,75	-0,09	1,58	9,75	**9,878**	H4
49,8	-0,4	0,3	51,8	-0,34	-0,16	-2	-0,06	0,46	**2,053**	H5
60,6	-0,2	-0,3	61,73	-0,06	-0,55	-1,13	-0,14	0,25	**1,166**	H6
67,6	14,2	17,2	68,47	13,66	15,65	-0,87	0,54	1,55	**1,858**	H7
64,9	16,7	18,8	65,99	16,06	17,03	-1,09	0,64	1,77	**2,175**	H8
51,5	-49,8	44,8	53,1	-46,52	36,93	-1,6	-3,28	7,87	**8,675**	H9
49,8	-0,4	0,3	51,72	-0,37	-0,21	-1,92	-0,03	0,51	**1,987**	H10
5,7	0,1	-0,2	19,13	0,1	-0,29	-13,43	0	0,09	**13,43**	I1

(Continue)

(Attachment 4 continues)

51,7	9	-26,6	53,39	8,86	-24,73	-1,69	0,14	-1,87	**2,524**	I2
70,9	-24,1	64,8	70,99	-24,19	57,59	-0,09	0,09	7,21	**7,211**	I3
48,4	55	-15	51,04	51,23	-12,75	-2,64	3,77	-2,25	**5,123**	I4
35,7	-0,3	-0,2	39,24	-0,19	-0,45	-3,54	-0,11	0,25	**3,551**	I5
75,5	0	0,2	75,59	0,15	-0,01	-0,09	-0,15	0,21	**0,273**	I6
44,8	26,5	39,7	48,2	23,33	32,6	-3,4	3,17	7,1	**8,486**	I7
35,8	16,7	27,7	39,74	14,08	20,96	-3,94	2,62	6,74	**8,235**	I8
61,4	-52,6	47,3	62,03	-49,6	40,29	-0,63	-3	7,01	**7,651**	I9
5,6	0	0,1	19,07	0,02	-0,12	-13,47	-0,02	0,22	**13,472**	I10
96,7	-1,2	1,1	95,2	-0,81	1	1,5	-0,39	0,1	**1,553**	J1
69,1	-34,3	-0,4	69,25	-31,72	-1,56	-0,15	-2,58	1,16	**2,833**	J2
69,6	20	79,2	70,56	17,13	70,27	-0,96	2,87	8,93	**9,429**	J3
47,8	-32,8	-30	49,57	-27,31	-29,24	-1,77	-5,49	-0,76	**5,818**	J4
16,3	-0,4	-1,1	25,52	-0,36	-1,23	-9,22	-0,04	0,13	**9,221**	J5
89,1	-0,7	0	88,32	-0,37	-0,07	0,78	-0,33	0,07	**0,85**	J6
63,5	25,1	26,6	65,15	23,28	24,92	-1,65	1,82	1,68	**2,976**	J7
65,9	21,7	27,9	67,44	20,3	25,99	-1,54	1,4	1,91	**2,825**	J8
61,7	17	51,4	63,14	14,51	45,35	-1,44	2,49	6,05	**6,699**	J9
96,7	-1,1	1	95,23	-0,8	0,95	1,47	-0,3	0,05	**1,501**	J10
49,7	-0,4	0,2	51,69	-0,36	-0,24	-1,99	-0,04	0,44	**2,038**	K1
85,4	10,6	17,5	84,87	9,72	16,77	0,53	0,88	0,73	**1,26**	K2
89,8	-16,7	6,3	88,68	-15,63	5,62	1,12	-1,07	0,68	**1,692**	K3
84,9	4,8	-5,4	84,38	5,18	-5,37	0,52	-0,38	-0,03	**0,645**	K4
84,1	-14	-8,5	83,2	-12,64	-8,57	0,9	-1,36	0,07	**1,632**	K5
71	-0,2	0	71,47	-0,04	-0,22	-0,47	-0,16	0,22	**0,543**	K6
45,8	-0,3	0,3	48,12	-0,21	-0,13	-2,32	-0,09	0,43	**2,361**	K7
20,8	0	-0,2	27,8	-0,09	-0,64	-7	0,09	0,44	**7,014**	K8
61,9	-13,2	56	62,84	-14,89	48,95	-0,94	1,69	7,05	**7,31**	K9
49,8	-0,4	0,3	51,74	-0,36	-0,22	-1,94	-0,04	0,52	**2,009**	K10
5,4	0	-0,1	19,13	0,05	-0,22	-13,73	-0,05	0,12	**13,731**	L1
21,4	35,3	8,6	28,41	27,42	5,97	-7,01	7,88	2,63	**10,87**	L2
43	67,3	48,9	46,53	61,69	40,2	-3,53	5,61	8,7	**10,937**	L3
60,6	36,2	4	61,96	34,28	4,07	-1,36	1,92	-0,07	**2,354**	L4
61,6	36,5	17,8	62,98	34,47	16,73	-1,38	2,03	1,07	**2,678**	L5
62,2	52,4	78,8	63,54	48,63	67,59	-1,34	3,77	11,21	**11,903**	L6
72,3	-9,5	89,1	72,91	-12,39	77,55	-0,61	2,89	11,55	**11,922**	L7
62,2	3,7	57,7	63,22	1,66	50,64	-1,02	2,04	7,06	**7,419**	L8
72	-27,2	74,1	72,21	-28,07	65,23	-0,21	0,87	8,87	**8,915**	L9
5,4	0,1	-0,1	19,05	0,07	-0,22	-13,65	0,03	0,12	**13,651**	L10
49,7	-0,4	0,3	51,66	-0,35	-0,2	-1,96	-0,05	0,5	**2,023**	M1
41,8	62,2	10,6	45,44	57,06	10,11	-3,64	5,14	0,49	**6,317**	M2
19	30,6	-7,7	26,56	22,67	-5,51	-7,56	7,93	-2,19	**11,173**	M3

(Continue)

(Attachment 4 continues)

39,6	66,1	34,7	43,29	60,45	28,04	-3,69	5,65	6,66	**9,481**	M4
52,5	68,2	48,9	55,06	63,39	42,82	-2,56	4,81	6,08	**8,164**	M5
81,3	24	87,8	81,38	20,63	79,62	-0,08	3,37	8,18	**8,847**	M6
81,8	6,8	96,3	81,67	4,24	86,45	0,13	2,56	9,85	**10,178**	M7
72	-16,1	76,6	72,12	-17,72	67,98	-0,12	1,62	8,62	**8,772**	M8
19,8	14,8	18,2	26,7	10,38	10,38	-6,9	4,42	7,82	**11,327**	M9
49,8	-0,4	0,2	51,72	-0,37	-0,2	-1,92	-0,03	0,4	**1,961**	M10
96,8	-1,1	1,2	95,05	-0,38	1,04	1,75	-0,72	0,16	**1,899**	N1
49,6	-0,3	0,4	51,72	-0,36	-0,25	-2,12	0,06	0,65	**2,218**	N2
5,8	0	-0,2	20,12	0,03	-0,2	-14,32	-0,03	0	**14,32**	N3
96,5	-1,1	1,2	95,04	-0,8	1,05	1,46	-0,3	0,15	**1,498**	N4
49,8	-0,4	0,2	51,77	-0,35	-0,24	-1,97	-0,05	0,44	**2,019**	N5
5,9	0,1	-0,3	19,91	0,04	-0,42	-14,01	0,06	0,12	**14,011**	N6
96,8	-1,1	1,1	95,13	-0,8	1,03	1,67	-0,3	0,07	**1,698**	N7
49,8	-0,4	0,3	51,73	-0,36	-0,22	-1,93	-0,04	0,52	**1,999**	N8
6,3	0	-0,1	19,97	0,07	-0,22	-13,67	-0,07	0,12	**13,671**	N9
96,7	-1,1	1,1	95,14	-0,79	1,01	1,56	-0,31	0,09	**1,593**	N10