Kubelka Munk Theory for Efficient Spectral Printer Modelling

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Abstract

In Spectral colour reproduction, we reproduce a colour using its spectrum rather than using its trichromatic values. This increases the colour fidelity quality of the reproduction under different illumination conditions and gives higher colour accuracy. Our work particularly focuses on the quality of spectral colour image reproduction of the printing world, more specifically on the spectral printer modeling.

Negebauer model (NG) and Yule-Nielsen modified spectral Neugebauer (YNSN) model are the most frequently used spectral printer models. In these models the reflectance of the colorant combinations estimated as a convex combination of reflectances of Neugebauer Primaries (NPs). Getting the way to print out NPs will be tedious work for printers with high number of channels. One of the reasons is the number of patches that one needs to print. It increases exponentially with the number of colorants of the printer. Printing and measuring all those Neugebauer Primaries consumes lots of time and materials. The other reason is that finding out the way to really print out all possible combinations is very difficult for printers with more than 5 channels. In this case, one needs to have the SDK of the printer and find out some sort of way to communicate with the printer driver directly.

The Kubelka-Munk theory has been tested in order to estimate those Neugebauer Primaries so that we could save our resources, power and time. We used different kinds of papers for test and for recommending more cheapest and accurate way of using this theory. Then we spectrally model the CMYK HP Deskjet 1220C printer and Xerox phaser 7760 laser printer using spectral Neugebauer model (NG) and Yule-Nielsen modified spectral Neugebauer (YNSN) model. Using these models we show that how much more improvements we could actually get by estimating Neugebauer Primaries using Kubelka-munk theory rather than using real measurements of the Neugebauer Primaries. We also tested mixed NPs, half measured and half estimated. We also tried to see whether using DORT2002 model for Neugebauer primary estimation improve Kubelka-Munk estimation or not.

Our results show us the reasonability of the kubelka-munk theory for spectral printer modeling. The results differ from printer to printer and from paper to paper. The spectral estimations of both NG and YNSN models in laser printers perform much better than inkjet printers. We also see that using simple and very cheap copy paper will give us even better performances than using some expensive photo papers. It is the opacity which is a very good criterion for choosing good paper for KM theory. The higher the opacity the higher the performance of the KM theory will be. On the other hand, the very big spectral and colorimetric differences between DORT2002 estimated Neugebauer Primaries and measured Neugebauer Primaries show us that it will not be a good idea to use the way that we followed for using DORT2002 model for NP estimation of spectral printer modeling. Based on our results, we finally give lists of suggestions which are related with spectral printer modeling.

Keywords: Spectral color reproduction, Spectral printer modeling, Kubelaka-Munk theory, DORT2002 model, reflectance estimation.

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1. Introduction

High-fidelity color image reproduction is one of the key issues for different industries these days. For this purpose, spectral color image reproduction is considerably effective. It enables to obtain the spectral reflectance, to greatly improve the colorimetric accuracy, and to reproduce colors under different illuminations. That is why essential technologies for high-fidelity color reproduction such as multi-spectral and hyper-spectral cameras, scanners and printers have been developed for various industries.

The user expectation for quality image reproduction increases with the rapid growth of technology. Users will expect the images reproduced to be as close as possible with the original ones both spectrally and perceptually. The previous printing devices able to print more and more colors which are spectrally different but appears identical to the original one using the phenomenon called metamerism, in which two objects having different spectral power distribution match in color under one illumination.

Unfortunately, these printers have some serious limitations. These include the difficulty of finding pigments, which have perfect spectra of the primaries, and color mismatches during changes of illuminations. It is impossible to find pigments with perfect combination of spectra of the primaries. For example, the subtractive mixture of CMY primaries is theoretically considered to be black. But actually it is dark brown. We also know that the colorimetric measure of a particular object is a function of spectral power distribution of the illuminant, spectral power distribution of the reflectance of the object, and color matching functions of the observer. There will be number of objects with different reflectance which will give color match under some illumination conditions. But this match will no longer hold if we change the illumination.

Spectral color reproduction will be the remedy for the above problems. Here we are going to reproduce a color using its spectrum not its trichromatic values. This will increase the color fidelity quality of the reproduction under different illumination conditions and gives higher color accuracy.

Spectral color image reproduction is very wide and complicated problem. Here we are going to consider problems in spectral color reproduction. Our original goal was to consider colorant selection problem and to contribute some work on this area. We were trying to answer questions like how many colorants will be required for more accurate spectral colour reproduction; which of the currently available inks will be those perfect inks for the intended task? We were planning to follow the paper "Optimal colorant design for spectral colour reproduction" by Ali Alsam and Professor Jon Y.Hardeberg which is based on the ideas that since a very large number of reflectances can be well reconstructed using 6 to 8 basis functions, the colorants for the best spectral reproduction are very much related with those basis functions. To get those basis functions they used Nonnegative matrix factorization (NMF) algorithm with some modification in order to satisfy Neugebauer printing model area coverage constraint. We were also planning to improve their method by considering optical and mechanical dot gain effects and incorporating them in to the NMF.

We were planning to use HP 12 channel inkjet printer for colorant selection but it took us (color lab) a long time to get the printer from HP. Once we get the printer we had a problem to communicate with the printer driver. It was mandatory for us to have the SDK of the printer. The process to get the printer's SDK was very lengthy, that we couldn't make it till now. For that reason, we were forced to change our direction of study and we focussed on evaluation of Kubelka-Munk model for estimating

Neugebauer Primaries and use it with Neugebauer model and Yule-Nielsen modified spectral Neugebauer (YNSN) model for spectral printer modeling.

One of the most important issue we faced here, is the problem occurs during spectral printer modeling. We used the spectral Neugebauer model and Yule-Nielsen modified spectral Neugebauer (YNSN) model. For the sake of these models we need to print and measure patches of Neugebauer primaries. The number of patches we need to print increases exponentially with the number of colorants of the printer. This is because of the number of possible combination of '**n**' colorants which is given by $\mathbf{2^n}$. For Spectral printer with more than 7 or 8 colorants, printing all those Neugebauer Primaries and measure them will consume lots of time and materials. Not only the large number of Neugebauer Primeries, the process of finding and printing them for printer with more than 7 or 8 colorants is not an easy job as well. There might be some charts which include all Neugebauer Primaries of CMYK printers. What if we want to model printer with higher number of channels, for example for our printer with 12 colorants? There are no charts which actually incorporate Neugebauer Primaries of, let us say, more than 8 channel printers. In this case we are forced to have the SDK of the printer and find out some way to be able to order the printer to print anything we want which we found out as complex work.

One of the solutions for the above problems will be printing only the primary colorants and estimating the rest of the reflectances of NPs. In order to estimate the NPs, some use very complicated version of Kubelka-Munk theory, some use Neugebauer model and reflectances of the primaries. Here we test the simple and the first Kubelka-Munk theory without any modification. We tested it on different types of papers and for two types of printers and we show the kinds of papers and the process of measurements which will lead us to a good and accurate estimation of Neugebauer primeries for good spectral printer modeling.

We used Spectral Neugebauer model and Yule-Nielsen modified spectral Neugebauer (YNSN) model combined with the measured NPs alone, the estimated NPs using simple Kubelka-Munk theory alone and the mixture of those primaries in order to model the printers. This helped us to evaluate the performance of this simple Kubelka-Munk theory on different papers and on different printers. We were able to see significant difference in the performance of this theory among those papers and printers type. Finally, we tried DORT2002 software of Mid Sweden University for spectral modeling and we check if it yields some improvements over KM model.

We could notice from our results that using the kubelka-munk theory for estimating NPs for spectral printer modeling is logical. The results we found for the two printers are different. They also differ from paper to paper. The spectral estimations of both NG and YNSN models in laser printers perform much better than inkjet printers. We also see that using simple and very inexpensive copy paper will give us better if not same performances with expensive photo papers. It is not the type of paper we used. It is the opacity which is a very good criterion for choosing good paper for KM theory. The performance of the KM theory increases with the opacity. On the other hand, we found the difference between DORT2002 estimated NPs and measured NPs being very high that we can't use DORT2002 for spectral printer modeling and we stick to KM model.

Finally, we give lists of recommendations for setting spectral printer model. Given a printer with n-channels, we recommend which of Neugebauer Primaries to print and to estimate, what type of paper to use, and things to be done during printing and measurement process.

In the following chapter we explain some basic words and concepts we used in this thesis report. We describe the models, theories and formulas we used and short summery of previous work results using Kubelka-Munk theory. In chapter three we performed comparison between one Hyper-Spectral camera and the two Spectrophotometers for selecting a measurement instrument for our experiment. In Chapter four the experimental methods we used will be described in detail. In chapter five our experiment results with their detail discussions and list of recommendations for spectral printer modeling will be given. Finally, in the last chapter, we summarized our results.

2. Literature review

In order to help understand the whole thesis and avoid confusions, in this chapter some essential vocabularies, definitions and formulas will be given. Then Kubelka-Munk Theory, Spectral Printer Models, Spectral difference metrics and perceptual color difference matrices used in this work will be described. Finally, a concise summery of previous work results of the same model will be shown.

2.1 Useful vocabularies

- *NPs:* is a short form for Neugebauer primaries. These are the collections of reflectances which include the reflectances of the primary colorants of the printer, the reflectance of the paper and the reflectances of the possible combinations of the primary colorants.
- *YNSN:* is a short form of Yule-Nielsen modified Spectral Neugebauer model. It is a modification of the spectral Neugebauer model using the Yule-Nielsen n-factor.
- *Sample backing:* The papers we used for printing are not 100% opaque. For these reason, the property of the material behind the paper during measurement can change the spectral reflectance of the measurement. We can minimize this impact by using sample backing. Here are some common options for backing materials.
    - *Self-backing:* using the number of same unprinted paper
    - *White backing:* using White material that possess all the characteristics mentioned in ISO TC 130/SC N 1055.
    - *Black backing:* using black material also conforms with ISO 5-4
- *Opacity:* is the measure of impenetrability to the illuminant in to the specimen and is given by the following formula.

$$\mathrm{OS} = \left(\frac{\mathrm{Yb}}{\mathrm{Yw}}\right) x100,$$

where OS is opacity under 0/45 geometry, D50 illuminant and two degree observer. Y_b is the Y tristimulus value computed from measurements made using black backing. Y_w is the Y tristimulus value computed from measurement made using white backing.

- *Grammage*: is a metric measure of paper weight based on the same square meter sheet of paper. It is the term which describes the density of the paper and expressed in grams per square meter (g/m^2).
- *Metamerism:* is a psychophysical phenomenon commonly defined as "two samples which match when illuminated by a particular light source and then do not match when illuminated by a different light source." There are different types of metamerism. [47]
    - *Sample metamerism:* is when two colour samples appear to match under a particular light source, and then do not match under a different light source.
    - *Illuminant metamerism*: is witnessed when you have a number of spectrally matched samples, but appears to be different when each is independently, yet simultaneously illuminated and viewed under lights whose spectral power distributions differ.
    - *Observer metamerism:* Every individual perceives color slightly differently. Samples which are exactly similar for one observer might not match for the other observer. That is why there were 31 individuals tested to derive the 1931 "standard observer" values

    adopted by the ISO and are still used as the basis for the majority of colour science study today.
  - *Geometric metamerism*: Identical colours appear different when viewed at different angles, distances, light positions, etc.
  - *Graphic arts and color reproduction considerations***:** In the printing industry, metamerism is the biggest problem. If metamerism did not exist the problem will be illuminated. Different hardware has different color channels with different spectral reflectances. Natural scene contains various natural colors each has unique spectral reflectance curves but the majority of color reproductions utilize cyan, magenta, yellow, and black inks or colorants. These days' printers incorporate a few additional colors to expand their gamut. But none of these inks are exact spectral matches to the media originally used to produce the original art. Therefore, a printed reproduction of an original artwork reproduction is a metameric match to the original. Inks used to create a color reproduction can be combined to simulate an artwork, but can only be made to accurately match the reproduction under only one light source. Because of metamerism it is impossible to generate a color reproduction that can match under every light source. But without the phenomenon of metamerism, mass color reproductions would not be possible and the color reproduction industry as we know it simply would not exist.
- *Measurement uncertainty:* [59] can be divided into two categories, precision and accuracy. *Precision* illustrates the dispersion of the measurements taken whereas *Accuracy* describes the difference between the measurements taken by the instruments and the actual value. Precision further divided into repeatability and reproducibility. *Repeatability* is the closeness of agreement between the results of successive measurement of the same test specimen, or test specimens taken at random from a homogeneous supply, carried out in a single laboratory, by the same method of measurement, operator, and measurement instrument with a repetition over a specified period of time. *Reproducibility* is then closeness of the measurements by changing conditions such as the operator, measuring instrument, laboratory, or time.

  Repeatability can be short term, medium term or long term. The *short-term* repeatability is based on measurements made in succession. The *medium-term* repeatability can be based on measurements made over a period of hours and finally the *long-term* repeatability is based on measurements made over weeks or longer.

- *The image reproduction pipeline:* Different types of imaging devices form some kind of communication channel for the sake of having an enormous image reproduction [7,17,46]. As it can be seen in figure 2.1 the original scene will be captured and passes through different computational process.

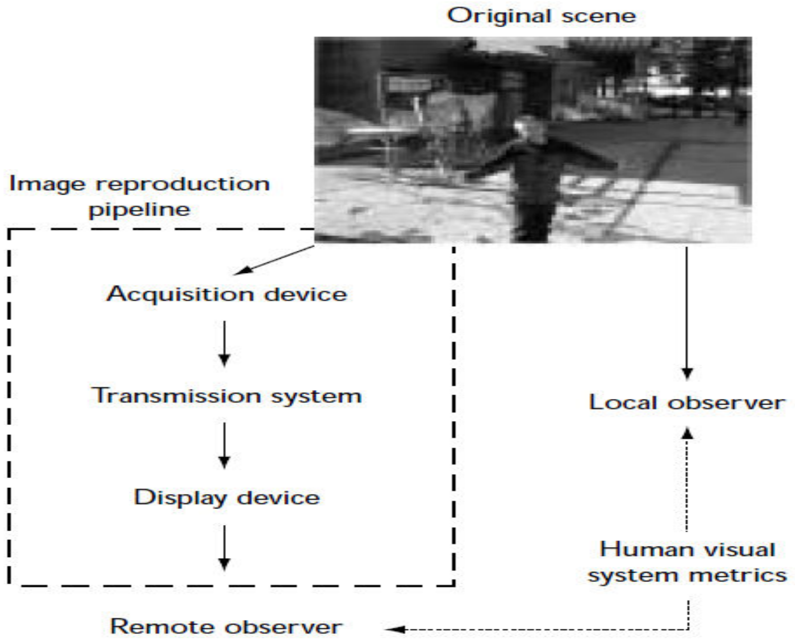


Figure 2.1: Image reproduction pipeline (Source: (LouisD.Silverstein, 2003))

These operations will help making the inter-device communication better and facilitating transmission and storage. The transmitted image is then converted to a form which will be rendered by a display device. Finally the display device will display the scene in understandable form for a human observer.

In order to get a match between the visual experience of seeing the original image and seeing the reproduction the communication channel should work well. For this reason, there will be several requirements of the devices in the pipeline.

Image capturing devices must measure the original scene as close as possible with the human visual system. The signals captured by both systems must match. Display devices also have to display accurate signals for the human visual system. The precise signal captured by the capturing devices should not be changed throughout the communication channel and should be delivered exactly.

- *Dot gain:* Dot gain is a phenomenon that causes printed material to look darker than intended. This happens because the diameter of halftone dots increases during the prepress and printing process. The optical and physical properties of the media and machines used both in preparing the job for print and the printing process itself causes this behavior. [6,35]

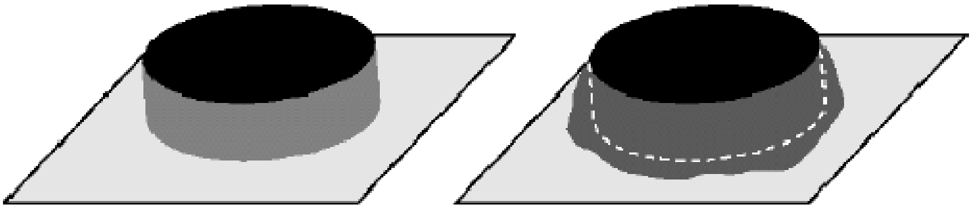


Figure 2.2: Dot gain (Source: (Lawler, 1994-1997))

The left one, the theoretical halftone dot, does not print as it is with its true value. In practice there is a tiny amount of ink surrounding the dot and causes the dot size to increase slightly. The spreading of the ink on the paper increases the area of the dot and the ink absorbed into the paper also adds additional area to the dots, and causes the measured and illusory dot gain to be greater. There are two types of dot gain, Mechanical and Optical dot gain.

- *Mechanical dot gain:* is the physical ink spread. A more fluid ink would spread more, and, thus, the dot gain would be higher. The absorbency of the substrate also affects dot gain, with more absorbent substrates having more dot gain, since they allow the ink to spread more through their pores.
- *Optical dot gain:* is a dot gain resulted by the interaction of light with the ink and paper. As the light penetrates the ink and reaches the substrate, a certain amount of it is diffused. The diffused light may exit the edge of the dot in such a way as to reflect some light beyond the dot's physical dimensions or it gets trapped underneath the dot. As such, the dot appears bigger, even if it physically isn't.

2.2 Printers

A printer is an output device that produces text and graphics on paper. It is a hardware which produces a hard copy of electronic documents on physical print media such as paper and transparencies. There are different types of printers. They can be divided into groups based on different criteria. [8,14]

One, they can be divided in to two main groups, impact printer and non-impact printer. Impact printer produces text and images when tiny wire pins on print head strike the ink ribbon by physically contacting the paper. Non-impact printer produces text and graphics on paper without actually striking the paper.

Two, they just can be named based on the specific function they are designed for such as photo printers, portable printers and all-in-one / multifunction printers. Photo printers and portable printers usually use inkjet print method whereas multifunction printers may use inkjet or laser print method.

Three, they can also be categorized based on the print method or print technology such as inkjet printer, laser printer, dot-matrix printer and thermal printer. Among these, only dot-matrix printer is impact printer and the others are non-impact printers. Among them Inkjet printers and laser printers are the most popular printer types for home and business use. Dot matrix printer was popular in 70's and 80's but has been gradually replaced by inkjet printers and thermal printers are limited to ATM, cash registers and point-of-sales terminals use.

2.2.1 Inkjet Printers

Inkjet printers are most popular printers for a home use. They print text and images by spraying little droplets of liquid ink onto paper. They use either thermal inkjet or piezoelectric inkjet technology. Thermal inkjet printer uses heating element to heat liquid ink to form vapor bubble, which forces the ink droplets onto the paper through the nozzle. Piezoelectric inkjet technology uses a piezoelectric crystal in each nozzle instead of using heating element. The piezoelectric crystal and forces little droplets of ink onto the paper from the nozzle by changing its shape and size based on the electric current received.

Thermal inkjet printers use aqueous ink which is a mixture of water, glycol and dyes. These inks are inexpensive but they can only be used on paper or specially coated materials. Piezoelectric inkjet printers allow the use of a wider range of inks, such as solvent inks, UV-curable inks, dye sublimation inks, and can print text and graphics on different uncoated materials.

The inkjet head design is also divided into two main groups: fixed-head and disposable head. Fixed-head is built into the printer and should last for the whole life of the printer. It produces more accurate output than cheap disposable head. The ink cartridges for fixed head printers are also cheaper as the print head does not need to be replaced. However, if the head is damaged, the entire printer has to be replaced. Disposable head is included in replacement ink cartridge. It is replaced each time an ink cartridge runs out of ink. This increases the cost of ink cartridges and also limits the use of high quality print head in these cartridges. However, a damaged print head is not a problem as one can easily replace it with a new ink cartridge.

The papers we use for printing vary from printers to printers. Inkjet papers are custom designed for inkjet applications, particularly full color applications. They should be the once which have been surface-treated to ensure good text definition, low color mottle (non-uniformity in the image color), and minimal feathering. The surface treatment also helps to control ink drop penetration which maximizes the brightness of the colors and enhances the sheet's smoothness, which affects image quality as well.

Inkjet printers are capable of printing fine and smooth details with higher quality of output. They are cheap, easy to use and have no warming up time. On the other hand their print head is less durable and they are prone to clogging and damage. They are reasonably fast but not as fast as laser printers. The main problem of these types of printers is that there is an ink bleeding and the ink carried sideways causes blurred effects on some papers.

2.2.2 Laser Printer

A laser printer consists of these major components: drum cartridge, rotating mirror, toner cartridge and roller. They operate by shining a laser beam to produce an image on a drum. The drum is then rolled through a pool, or reservoir, or toner (black or colored powder), and the electrically charged portions of the drum pick up ink. Finally, using a combination of heat and pressure, the ink on the drum is transferred onto the page of the paper. Color laser printers use the same toner-based printing process as black and white laser printers, except that they combine four different toner colors. They add colored toner in three additional passes.

The papers we use for printing with laser printers should be selected carefully. Laser papers feature a number of unique qualities. First, laser paper must be able to withstand the high heat and toner formulations associated with the electro-photographic process. Paper performance can also be affected by the equipment's paper path, the path through which the paper passes during the imaging process. It should have anti-jamming and anti-curling qualities. Mostly laser papers have higher brightness and heavier basis weight ranges than less expensive multipurpose sheets.

Laser Printers can print text and images in high speed and high quality resolution. They have no smearing effect and are very good for high volume printing. On the contrary, they are more expensive than inkjet printers and they are less capable of printing high quality images like photographs. They need worming up time and they have larger size than inkjet printers.

2.2.3 Printing

Printing is a process of making different graphics or art by placing ink on paper or other substrates (any objects). It is not a process of drawing directly on the substrate. It is somewhat indirect transfer process. Reflection prints are the most common once. Since the print itself is light, they are very flexible and very suitable ways of viewing and reproducing images.

> "Improvements in printing come from three basic sources: the ability to create papers and inks with improved ink absorption properties; the ability to control the placement of the inks on the page; and the ability to predict the perceptual consequences of the first two processes." (LouisD.Silverstein, 2003)

Researchers have been working in these three areas for past 2 decades. There have been positive advances. Especially, the biggest improvements have been seen in the area of controlling the placement of ink on the paper.

2.2.4 Color mixing models

Subtractive color mixing: Subtractive color mixing is the kind of mixing we get if we illuminate colored filters with white light from behind, as illustrated in figure 4. The commonly used subtractive primary colors are cyan, magenta and yellow, and if we overlap all three in effectively equal mixture, all the light is subtracted giving black. Subtractive color mixing is more complex than the additive color mixing we get with colored spotlights. We get this type of mixing with in paints and pigments and devices like Printers. [24]

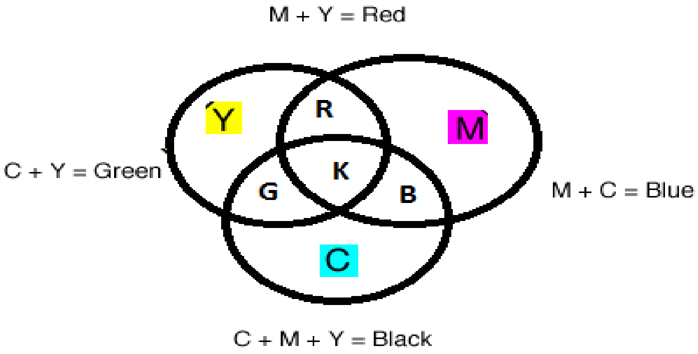


Figure 2.3: Subtractive color mixing

Additive Color Mixing: is the kind of mixing you get if you overlap spotlights in a dark room (see figure 5). The commonly used additive primary colors are red, green and blue. The mixture of all three in effectively equal amount, you get white light. Additive color mixing is conceptually simpler than the subtractive color mixing. It is mainly applied in devices like CRT display and RGB cameras.

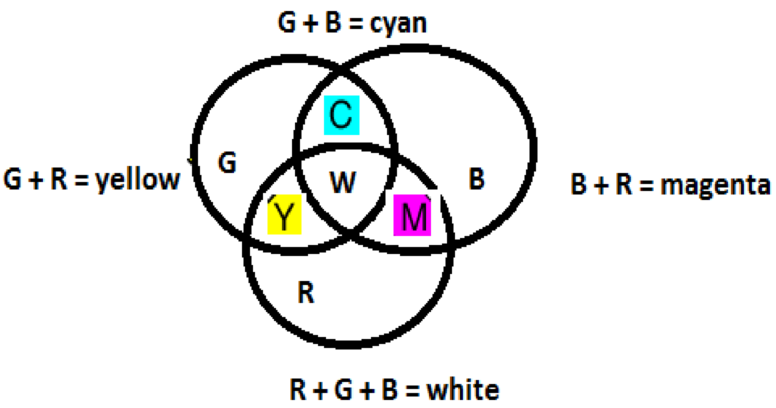


Figure 2.4: Additive color mixing

2.3 Kubelka-Munk Model (two-flux model)

Let us assume we have a paper with reflectance P_g with optical contact with a light absorbing and scattering ink of thickness X. [10,15,18,20,26]

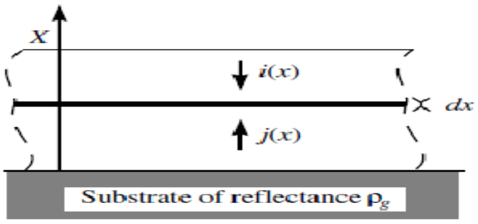


Figure 2.5: Kubelka-Munk two-flux model
(Source: Digital Color Imaging Hand Book)

Let us also suppose that the scattering is isometric as if it results from multiple scattering and that K is a phenomenological absorption coefficient which is the fraction of the light flux absorbed by the infinitesimal layer and S is phenomenological scattering coefficient analogous to the fraction of the light flux that is scattered backward by the infinitesimal layer.

This reflection model is based on the two diffused light fluxes (Figure 2.5). The variation of the two fluxes when they cross the layer is given by the following linear differential equation:

$$\left\{ \begin{array}{l} \frac{\mathrm{di}(x)}{\mathrm{dx}} = (\mathrm{K} + \mathrm{S})\mathrm{i}(\mathrm{x}) - \mathrm{Sj}(\mathrm{x}) \\ \frac{\mathrm{dj}(x)}{\mathrm{dx}} = -(\mathrm{K} + \mathrm{S})\mathrm{j}(\mathrm{x}) + \mathrm{Si}(\mathrm{x}) \end{array} \right.$$

, Since the flux *j(x)* is reduced in amount *(K +S)j(x)dx* due to absorption and the backscattering within the layer and is increased in *Si(x)dx* by the backscattered light when it crosses the same layer. The reverse is true for the incidence flux *i(x)*.

It is possible to use a matrix algebra based method for solving the above equation. After writing the equation in the following matrix form,

$$\begin{pmatrix} \frac{di(x)}{dx} \\ \frac{dj(x)}{dx} \end{pmatrix} = \begin{pmatrix} K+S & -S \\ S & -(K+S) \end{pmatrix} \cdot \begin{pmatrix} i(x) \\ j(x) \end{pmatrix}$$

and applying different integration, exponential lows and boundary conditions one can able to drive all known results of kubelka-Munk theory.

2.3.1 The hyperbolic solution of Kubelka-Monk model

The hyperbolic solution is one of the solutions of Kubelka-Monk theory. It computes the body or true reflectance of the sample as follows. (Sharma, 2003)

$$R = \frac{1 - R_g.(a - b.\coth(\mathrm{bSX}))}{a - R_g + b.\coth(\mathrm{bSX})}$$

where R, R_g, S, K and X are true reflectance, reflectance of the substrate or paper, scattering coefficient, absorption coefficient and thickness of the sample respectively and a and b are given as follows.

$$a = \frac{(S+K)}{S}$$

$$b = \sqrt{a^2 - 1}$$

In order to use this equation, we need to find the values of K and S of the medium or the ink in our case. One way of determining these coefficients is using $\mathbf{R_0}$ (Reflectance of a layer with ideal black background), $\mathbf{R_1}$ (Reflectance of a layer with ideal white background) and X of the medium.

$$R_0 = \frac{1}{a + b.\coth(\mathrm{bSX})}$$

$$R_1 = \frac{1 - (a - b.\coth(\mathrm{cSX}))}{a + b.\coth(\mathrm{bSX})}$$

'a' can be extract from the above equations and can be computed using the following formula.

$$a = 0.5(1 - \frac{R_1 - 1}{R_0})$$

Then **'b'** can be found as follows.

$$b = \sqrt{a^2 - 1}$$

Once we calculate **a** and **b**, expression for **S** can be derived from equation we used for $\boldsymbol{\rho_0}$ computation.

$$S = \frac{1}{\mathrm{bX}}\mathrm{acoth}\frac{1 - \mathrm{aR_0}}{\mathrm{bR_0}}$$

Finally, K can be calculated as

$$K = S(a - 1)$$

2.3.2 Computing the absorption and reflectance coefficients of KM theory

Li Young uses the following method in order to compute the K and S coefficients of printing inks. [12]

First we need to find the way to print different levels of the ink we want to measure K and S's for. The ink shouldn't be penetrating in to the substrate we used for printing on. Using ink-jet films will prevent the ink from penetrating in to the substrate. Then by changing the ink-level specification in the printer driving software one can print samples in increasing level from 1 up to 5 ink levels. In order to have a high reflection during spectral reflectance measurements putting a white and opaque background under the samples will help a lot.

As we described in the section 2.3 the spectral reflectance value of an ink layer is a function of its absorption and reflectance coefficients.

$$R(\lambda, Z) = f(S(\lambda)Z, K(\lambda)Z)$$

While, $S(\lambda)$ and $K(\lambda)$ are the spectral scattering and absorption coefficients and Z is the thickness of the ink layer. It is for colors like cyan, magenta; yellow … When the interface reflection is negligible the spectral reflectance function f will be given by the following formula.

$$f(\mathrm{SZ}, \mathrm{KZ}) = \frac{(R_\infty - R_g)e^{-(1/R_\infty - R_\infty)\mathrm{SZ}} - R(1 - R_g R_\infty)}{R_\infty(R_\infty - R_g)e^{-(1/R_\infty - R_\infty)\mathrm{SZ}} - (1 - R_g R_\infty)}$$

While R_g is the spectral reflectance of the blank substrate or paper and R_∞ which is the reflectance of infinitely think ink layer is given by

$$R_\infty(\lambda) = 1 + \frac{K(\lambda)}{S(\lambda)} - \sqrt{(\frac{K(\lambda)}{S(\lambda)})^2 + 2\frac{K(\lambda)}{S(\lambda)}}$$

Therefore, one can print a sample by specifying one ink level (from 1 to 5) once. Then again by print the same sample with the same ink level twice one will have two sets of samples. Finally by measuring and fitting the reflectances of the two same samples from the two sets, it is possible to find the scattering and absorption coefficients.

Li young himself [11] showed that this Kubelaka- Munk theory is not enough to describe the absorption and scattering behavior of printed colorants perfectly in all conditions. They add one more concept called the scattering induced-path-variation (SIPV) factor in order to revise and correct this basic theory of Kubelka and Munk.

In the contrary, other researches show [2] their favors towards the basic Kubelka-Munk model. They pointed out that the problems of KM two-flux model are mainly because of the low resolution of the model and this problem can be solved by using radiative transfer model of higher resolution. The basic Kubelka-Monk should be used where its accuracy is sufficient, and the radiative transfer software like DORT2002 should be used where higher accuracy is needed.

2.3.3 Kubelka-Munk theory and K/S

The Kubelka-Munk equation [54] defines a relationship between spectral reflectances of the sample and its absorption and scattering characteristics of the samples with Opacities greater than 75% using the equation:

$$\frac{K(\lambda)}{S(\lambda)} = \frac{(1-0.01R(\lambda))^2}{2(0.01R(\lambda))}$$

Where R is the reflectance given in percent (%) and K and S are the absorption and scattering coefficients of the colorant.

These ratios for individual colorants are then stored and can be used for computing the K/S ratio of the mixture where those colorants are used in. This can be done just by extending the above Kubelka-Munk theory. K/S of the mixture is given by the sum of the K/S values of the individual colorants.

$$(\frac{K(\lambda)}{S(\lambda)})_{\text{mixture}} = a(\frac{K(\lambda)}{S(\lambda)})_{\text{colorant1}} + b(\frac{K(\lambda)}{S(\lambda)})_{\text{colorant2}} + \ldots + (\frac{K(\lambda)}{S(\lambda)})_{\text{paper}}$$

where *a,b,c, …* are the concentration of the colorants in the mixture.

Once one has *K/S* for all colorants and their combinations, he/she can compute the reflectances of the primaries and their combinations as follows.

$$R_\infty(\lambda) = 1 + \frac{K(\lambda)}{S(\lambda)} - \sqrt{(\frac{K(\lambda)}{S(\lambda)})^2 + 2\frac{K(\lambda)}{S(\lambda)}}$$

Because of its simplicity we prefer to use this method as our main algorithm for predicting NPs for spectral printer modeling as shown in the next chapters.

2.4 Using *DORT2002*

DORT2002 is software developed by Mid Sweden University for calculating the light intensity given medium parameters and boundary conditions. It is a model which takes care of a radiative transfer problem formulation and solution. It is implemented in MATLAB [56].

Detail information about the software like installation, input and output parameters is given in the manual [56]. DORT2002 can perform forward and inverse problems, and different fields in p are required for different cases. In the forward problem, we need to give the medium parameters like absorption and scattering coefficients and boundary conditions and the software will compute the light intensity including, reflectance factors.

We can run the software just by calling the function dort2002(). Calling the function as

$$r = \text{dort2002()}$$

and

$$r = \text{dort2002(default\_parameters(), 'forward', 'angle} - \text{resolved')}$$

have the same effect, since the forward mode is the default mode of the software. The software finally returns the structure variable r with the following variables and values.

```
total_transmittance: 0.0456
total_absorptance: 0.4602
total_reflectance: 0.4942
ABSDF: [90x1 double]
BSDF: [90x72 double]
I_ac _ 1: [90x72 double]
beam_ 1: 0
```

It also has a module to do the inverse, given the reflectance factors of the measured data, the geometry and other information about the paper it will give us the absorption and scattering coefficients of the medium.

Assuming we measured the spectral reflectance factor with a d/0 instrument and stored the measurement data in vectors Ro(31,1) and Roo(31,1) for spectral reflectance of the printed ink and the spectral reflectance of the paper respectively, we create fields in the input struct as:

$$p.\mathrm{Ro} = \mathrm{Ro}$$
$$p.\mathrm{Roo} = \mathrm{Roo}$$

We then need to set the grammage of the paper used, for example Color copy paper, to 0.194Kg/m^2 and spectral values of the asymmetry factor to be constant to 0.8 since the developers suggest that g=0.8 as a good guess. Thus, the input struct is sated as:

$$p.g = 0.8 \times \mathrm{ones}(\mathrm{size}(p.\mathrm{Ro}));$$
$$p.w = 0.194;$$

Finally we can run the simulation by writing the following command in MATLAB window

$$r = \mathrm{dort2002}(p, '\mathrm{inverse}', 'd/0')$$

The software will give us the structure r with the following variables and values.

```
sigma_s: [31x1 double]
sigma_a: [31x1 double]
F: 2.6983e-011
N_iter: 133
N_func: 495
```

, Where r.sigma_s and r.sigma_a are the estimated scattering and absorption coefficients, respectively. F, N_iter and N_func stands for objective function, the number of iterations and the number of function evaluations.

Per Edström in his report [55] described DORT2002 as the natural generalization of Kubelka-Munk model. He also shows that DORT2002 model is more accurate than Kubelka-Munk and it can be applicable in a wider range of areas than KM model. He also shows that under the conditions like perfectly diffused light, perfectly isotropic scattering and only two channels in DORT2002 model, the exact translation between the scattering and absorption coefficients of KM and DORT2002 models can be given as follows.

$$K = 2 \times \sigma_a$$
$$S = \sigma_s$$

2.5 Spectral Printer modeling

2.5.1 Murray Davies model

The Murray Davies equation [5,42] is used to predict the reflectance of a given colorant with a given area coverage and it is given as follows.

$$r(\lambda) = (1 - c) \times r_{\text{paper}}(\lambda) + c \times r_{\text{maxcol}}(\lambda)$$

where $r_{\text{paper}}(\lambda)$, $r_{\text{maxcol}}(\lambda)$, C and $r(\lambda)$ are the paper measured spectral reflectance, the measured spectral reflectance of the paper covered by the colorant at maximum coverage(100%), given colorant coverage and the predicted spectral reflectance, respectively.

The Murray Davies model, which predicts the reflectance of a single colorant coverage, will not be enough for printer characterization of more than one ink because of the overlapping of different colorant droplets by the time of printing process. It will be very important to estimate all the different colorant overlaps in addition to estimating each colorants independently. For a good estimation of colorant combination, it should include all NPs (the Neugebauer primaries) which are reflectances of all colorants of the printer, all possible combinations of them and reflectance of the paper.

2.5.2 Spectral Neugebauer (NG) printer model

The Neugebauer model[1,16,40,34] is the extension of Murray-Davis model which could handle all the above mentioned issues. In this model the estimated reflectance *c* can be written as the convex combination of *n* reflectances of NPs *ci*; *i*=1, . . . ,*n*:

$$r(\lambda) = \sum_{i=0}^{2^m-1} w_i r_{i,\max}(\lambda)$$

while,

$$w_i \in [0,1], \sum_{i=0}^{2^m-1} w_i = 1$$

where w_i is the area coverage of the i^{th} primaries.

This Neugebauer model will not give good results in real practical situation. In practice there are a lot more facts which need to be included in the model in order to get more accurate results. Among these critical facts the dot gain effect is one of them.

There is a dot gain effect in real printer systems. We need to take in to consideration both types of dot gain effects, Mechanical and optical dot gain. The colorant coverage without considering the dot gain effect is the theoretical colorant coverage [4,31,32,22] and the one with the dot gain is the effective colorant coverage. Here we need some sort of relationship between them in order to handle the dot gain effect. The inverse of the Murray Davies model will give us the way to do that (Figure 2.6 and 2.7).

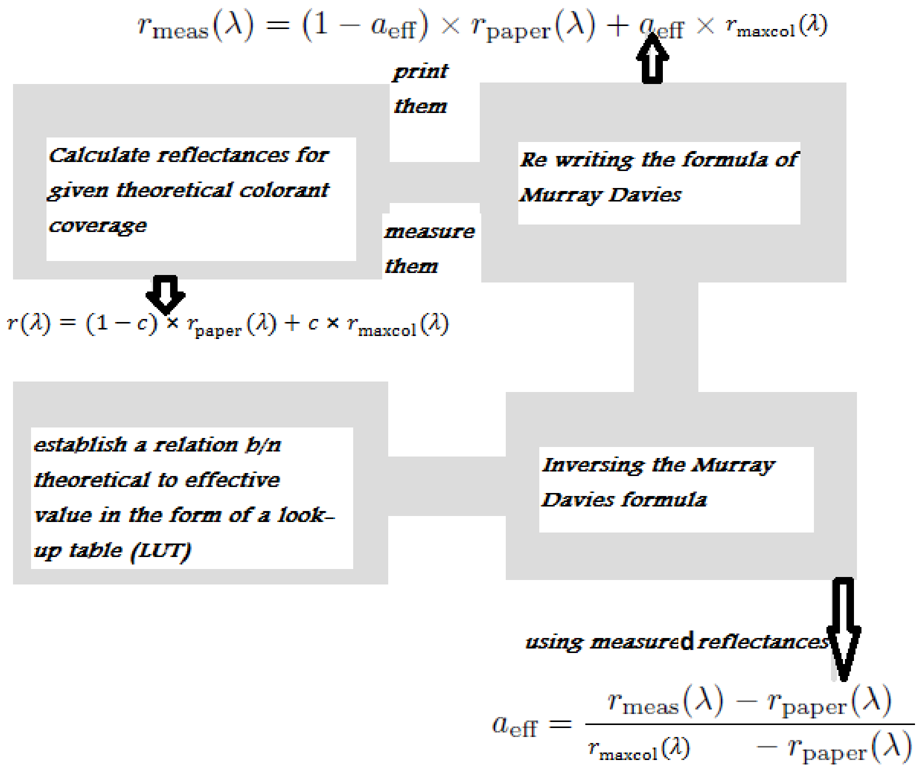


Figure 2.6: Forming Look up Table for effective colorant coverage

In order to estimate the effective area covered by the colorant of a known input value, value called theoretical value, first we need to print out and measure the reflectances corresponding to our theoretical colorant coverage. Then rewrite the Murray Davies equation as follows:

$$r_{\mathrm{meas}}(\lambda) = (1 - a_{\mathrm{eff}}) \times r_{\mathrm{paper}}(\lambda) + a_{\mathrm{eff}} \times r_{\mathrm{maxcol}}(\lambda)$$

We just need to replace the measured reflectance in place of estimated reflectance and effective colorant coverage in place of theoretical colorant coverage. Then inverting this equation will give us the following way to compute the effective dot area.

$$a_{\mathrm{eff}} = \frac{r_{\mathrm{meas}}(\lambda) - r_{\mathrm{paper}}(\lambda)}{r_{\mathrm{maxcol}}(\lambda) - r_{\mathrm{paper}}(\lambda)}$$

Finally, using different interpolation methods we can build some sort of LUT which will have the corresponding effective dot area for a given theoretical dot area. This same process can be repeated in order to build LUTs for each primary colorant of our printers (Figure 4).

The corresponding weights for NPs are then going to be computed using these effective colorant coverage's. They are computed with the statistical Demichel model by assuming the dot placement independence and independence between the colorant screens. [16,30] Demichel for M colorants is given by:

$$w_i = \prod_{j=1\to m} \begin{cases} c_j; \text{ if colorant } j \text{ is part of the } i\text{th NP} \\ (1-c_j); \text{ else} \end{cases}$$

for a given colorant combination

$$c_j \in [0,1] \text{ for } j \in \{1,2,\ldots,m\}$$

where $c_j = 0$ if there is no inks for the jth colorant and $c_j = 1$ for full coverage of the jth colorant. w_i is the weights for the NPs with the following property:

$$w_i \in [0,1] \text{ and } \sum_{i=0}^{2^m-1} w_i = 1$$

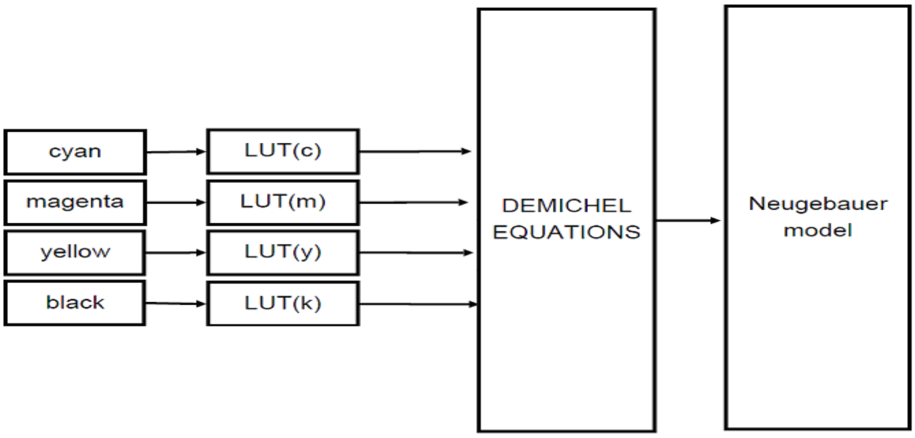


Figure 2.7: Process of scheming Neugebauer model for 4 colorant printer (Source: (Jeremie Gerhardt, 2007))

2.5.3 The Yule-Nielsen modified spectral Neugebauer model

This model incorporate everything which is in spectral Neugebauer model but in addition to the mechanical dot gain, this model also tries to incorporate the optical dot gain effect. [1,5,11,13,22,43,32,42] This is done by adding Yules-Nielsen *n* factor to the previous Neugebauer model as follows:

$$r^{1/n}(\lambda) = \sum_{i=0}^{2^m-1} w_i {r^{1/n}}_{i,\max}(\lambda)$$

To find the n factor, we can use methods with an iterative process which estimates the spectral reflectances for various n factor values. Then by comparing the estimated spectral reflectances with the measured spectral reflectances, we can choose the *n* value which gives the smallest colorimetric differences or smallest spectral difference.

2.5.4 Cellular Neugebauer Model

In the Normal Neugebauer Model we consider only NPs obtained from combinations of two colorant concentrations (0% and 100%). We think this set can represent all the intermediate area coverage.

If 50% coverage of each channels of our printer is included, then each colorant will have three states and there will be **n3** NPs. The name cellular is given because geometrically, it is like partitioning the n dimensional space in to a grid of rectangular cells which are formed by three nodes at 0%, 50% and 100%.

For example, in the case of two channel printer (cyan and magenta) the 2D diagram in figure 2.8 illustrates the cellular NG model. [28,34]

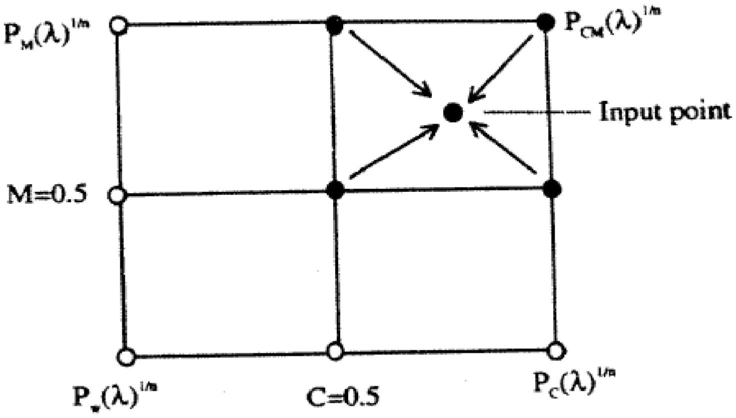


Figure 2.8: Illustration of cellular NG model.

Solid circles denote spectral primaries interpolated to obtain reflectance at the input C and M values.(Source: (Balasubramanian, 1999))

While P_m, P_w, P_c, P_{cm} are reflectances of Magenta, White, Cyan and combination of Cyan and Magenta at a full coverage (100%).

The NG equation then can be applied within each cell.

> "One can think of a cellular model as a physical characterization of an M-ary printer, where M is the number of true "gray levels" reproducible by the printer for each separation. From a mathematical point standpoint, however, the sub division of cmy space in to cells affords a finer interpolation, hence presumably greater accuracy, even for the case of binary devices. " (Balasubramanian, 1999) [1]

2.6 Spectral Curves Difference Metrics

Spectral Metrics are metrics which we used to compare spectral curves based on computation of spectral curve differences [3]. The two commonly used metrics are Root mean square error and Goodness of Fit Coefficient.

2.6.1 Root mean square error

The root mean square error of two vectors X1 and X2 is given by:

$$\text{RMSE} = \sqrt{\frac{\sum_{i=1}^{n} \quad (x_{1i} - x_{2i})^2}{n}}$$

,where n represents the length of the vectors.

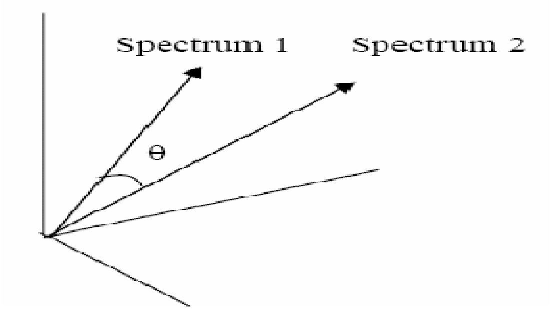
For the Perfect matched vectors RMSE is equal to zero and for the worst match RMSE extends to infinity. This metric is not affected by absolute values of the spectra (light versus dark).

2.6.2 Goodness of Fit Coefficient

GFC [9] is based on the inequality of Schwartz and given two vectors X1 and X2 each with length n, it is described by the equation:

$$\mathrm{GFC} = \frac{\left| \sum_{i=1}^{n} (x_{1i} x_{2i}) \right|}{\sqrt{\left| \sum_{i=1}^{n} (x_{1i})^2 \right|} \sqrt{\left| \sum_{i=1}^{n} (x_{2i})^2 \right|}}$$

It is the cosine of the angle between two spectra if these are intended to be vectors in a Hilbert space.



Goodness of Fit Coefficient (Source: (Romero, 2001))

GFC ranges from 0 to 1, where 1 indicates a perfect match between the two vectors or spectra.

2.7 Perceptual metrics

Color-difference equations which are developed by CIE committees such as CIELUV, CIELAB and CIE94, are for getting good evidence about the colour matching not for evaluating spectral curves matches. They can be used as a cost functions or to evaluate spectral estimation accuracy. But it is well known that colour difference equations produce bad correlation to spectral matches, particularly for metameric pairs.

2.7.1 CIE XYZ

The colour coordinate system CIE XYZ is created in 1931 by CIE [23,47,29,33]. The CIE accept a set of colour matching functions to define the Standard Colorimetric 2 degree Observer, x(λ), y(λ), z(λ) as functions of the wavelength (Figure 2.9).

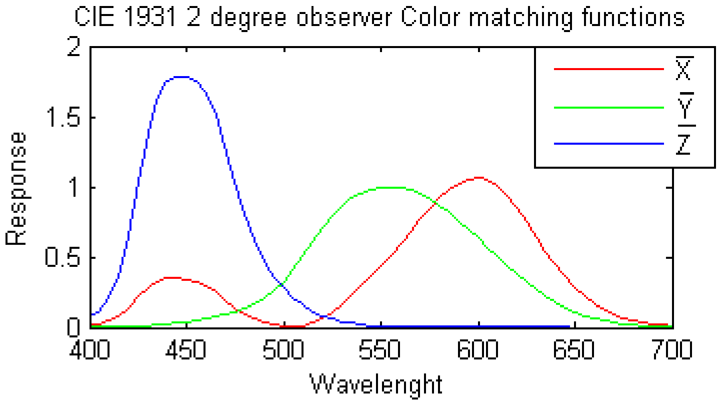


Figure 2.9: 2 degree observer Colour matching functions

These colour matching functions then can be used to compute CIE tristimulus values X, Y, Z .The following are the formulas which have been used for computing the tristimulus values of the reflecting objects.

$$X = k\int_{\text{vis}} R(\lambda)P(\lambda)\bar{x}(\lambda)\,\mathrm{d}\lambda$$
$$Y = k\int_{\text{vis}} R(\lambda)P(\lambda)\bar{y}(\lambda)\,\mathrm{d}\lambda$$
$$Z = k\int_{\text{vis}} R(\lambda)P(\lambda)\bar{z}(\lambda)\,\mathrm{d}\lambda$$

where K is a constant given by

$$k = \frac{100}{\int_{\text{vis}} P(\lambda)\bar{y}(\lambda)\,\mathrm{d}\lambda}$$

And R(λ) and P(λ) are object spectral reflectance and Spectral power distributions of the illuminant respectively. The integral is taken in the visible wavelength region in 10nm interval [400nm:10:700nm].

2.7.2 CIE 1976 Uniform Colour Spaces (CIELAB)

The CIELAB [29,47] colour space is the most frequently used colour space in different industries especially, in the applications involving subtractive colour mixing. It incorporates the following three axis.

- L*: the lightness axis ranges from zero to 100 corresponds to black and white respectively.
- a*: axis from negative a* to positive a* is the colour corresponds from green to red
- b*: axis from negative b* to positive b* are the colours representing blue to yellow.

Once we have the XYZ values of the patches, the corresponding L*a*b* values can be calculated as follows:

$$L^* = (116 \times \text{fy}) - 16$$
$$a^* = 500(\text{fx} - \text{fy})$$
$$b^* = 200(\text{fy} - \text{fz})$$

while,

$$\text{fx} = \sqrt[3]{(\frac{X}{\text{Xn}})},\quad \text{fy} = \sqrt[3]{(\frac{Y}{\text{Yn}})} \text{ and } \text{fz} = \sqrt[3]{(\frac{Z}{\text{Zn}})}$$

but

If $(\frac{X}{\text{Xn}})$ is less than or equal to $(24/116)^3$ then

$$\text{fx} = \frac{841}{108} \times (\frac{X}{\text{Xn}}) + (\frac{16}{116})$$

$$\text{fy} = \frac{841}{108} \times (\frac{Y}{\text{Yn}}) + (\frac{16}{116})$$

$$\mathrm{fz} = \frac{841}{108} \times (\frac{Z}{\mathrm{Zn}}) + (\frac{16}{116})$$

where, X_n, Y_n and Z_n are the normalized CIE XYZ tristimulus values of the reference white point.

2.7.3 CIELAB color difference formula

After the CIE recommendation of common colour difference formulas in 1976, the CIELAB formula has been widely used by achieving an important uniformity of use amongst different researchers and industries.

If we have two colours with Lab values $L^*_a a^*_a b^*_a$ and $L^*_b a^*_b b^*_b$, the color difference between them is then given by the following formula:

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

While,$\Delta \mathrm{L}^*_{\mathrm{ab}} = L^*_a - L^*_b$, $\Delta \mathrm{a}^*_{\mathrm{ab}} = a^*_a - a^*_b$ and $\Delta \mathrm{b}^*_{\mathrm{ab}} = b^*_a - b^*_b$

2.7.4 CIE94 color difference formula

The CIE94 formula was a very conservative approach accounting for most robust effects in reliable experimental datasets. CIE94 included positional corrections to CIELAB and influence of the experimental observation conditions thorough the so-called “parametric factors”.

$$\Delta \mathrm{E}^*_{94} = \sqrt{(\frac{\Delta \mathrm{L}^*_{\mathrm{ab}}}{K_L S_L})^2 + (\frac{\Delta \mathrm{C}^*_{\mathrm{ab}}}{K_C S_C})^2 + (\frac{\Delta \mathrm{H}^*_{\mathrm{ab}}}{K_H S_H})^2}$$

While, $S_L = 1,\ S_C = 1 + 0.045 C^*_{\mathrm{ab}}$, $S_H = 1 + 0.015 C^*_{\mathrm{ab}}$ and

$$\mathrm{HD} = s * \sqrt{2 * ((C^*_a \times C^*_b) - (a^*_a \times a^*_b) - (b^*_a \times b^*_b))}$$

If $(a^*_a \times b^*_b)$ is greater than $(a^*_b \times b^*_a)$ then $s = -1$. Otherwise, $s = 1$.

where C* is the value of standard's Chroma. If neither can be reasonably termed the standard, the geometric mean of the C values is used.

$$C^*_{\mathrm{ab}} = \sqrt{C^*_a \times C^*_b}$$

and chroma is given by

$$C^* = \sqrt{a^{*2} + b^{*2}}$$

The variables k_L, k_C and k_H are the 'parametric factors' and are included in the formula to allow for adjustments to be made independently to each colour-difference term to account for any deviations from the reference viewing conditions, that cause component specific variations in the visual tolerances. Under the reference conditions, they are set to **$k_L = k_C = k_H = 1$.**

2.8 Previous uses of Kubelka-Munk for Printer Modelling

In this part of the chapter, we are going to mention, briefly, some of the previous works which uses Kubelka-Munk theory for estimating NPs in order to model a printer. We will also show some of their results in order to give some insight about what have been done and to give some previous results in order to have something to compare our results with.

2.8.1 Extending Printing Color Gamut by Optimizing the Spectral Reflectance of Inks

In this work [54] the authors (Yongda Chen, Roy S. Berns, Lawrence A. Taplin) created the virtual printing model for their ink optimization in their exploration of the optimum combinations of three- and four-chromatic inks in order to maximize the color gamut for halftone printing. The model was created based on the Yule- Nielsen spectral-Neugebauer equations and the spectral reflectances of prints were estimated using Kubelka-Munk turbid media theory.

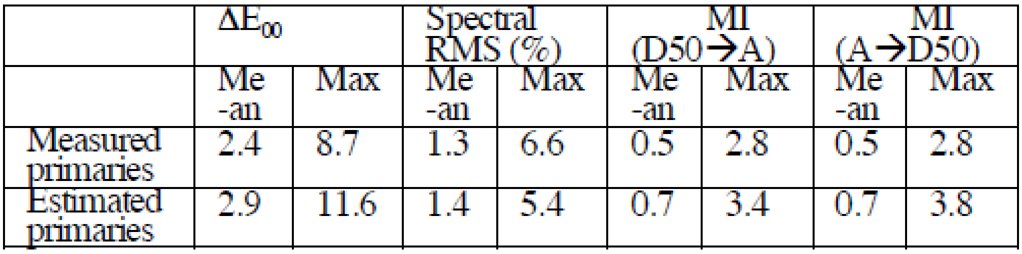
In this research they assumed that transparent ink-jet inks would penetrate the paper support, yielding a homogenous colored layer. For this reason they used the opaque K-M equations (see section 2.3.2). Using those NPs predicted by KM theory they created YNSN model of their printer. Then using these models they predicted the spectral reflectances of over prints with different inks (see section 2.5).

The virtual printing model were built based on a modified Epson Pro 5500 ink-jet printer by replacing light cyan and magenta with pigmented orange and green inks yielding a CMYKGO ink set. They used Epson photo quality ink jet glossy paper for printing on the samples.

According to Epson Pro printer and its CMTKGO ink set, they evaluated the performance of their virtual printer model. They used 600 printed test patches. They used GretagMacbeth Spectrolino spectrophotometer for reflectance measurments and they also used illuminant D50 and the CIE 1931 2° standard observer color matching function for colorimetric values calculations.

In order to perform the reasonability of the KM theory for NPs estimation, they also used YNSN model with measured NPs to predict the test samples. The color difference and spectral differences between the estimated reflectances of the test samples using measured NPs and using estimated NPs are computed. They also perform a parametric correction on predicted spectra such that a perfect match can be obtained for illuminant D50 and A and they computed their ΔE for illuminant A and D50, respectively, and these values can be used as a metameric index. The results were acceptable and very similar to actual measurements (see table 2.1).

Table 2.1: Performance comparison between YNSN model and Virtual Printer [54]



	ΔE_{00}		Spectral RMS (%)		MI (D50→A)		MI (A→D50)	
	Mean	Max	Mean	Max	Mean	Max	Mean	Max
Measured primaries	2.4	8.7	1.3	6.6	0.5	2.8	0.5	2.8
Estimated primaries	2.9	11.6	1.4	5.4	0.7	3.4	0.7	3.8

2.8.2 Spectral printer characterization

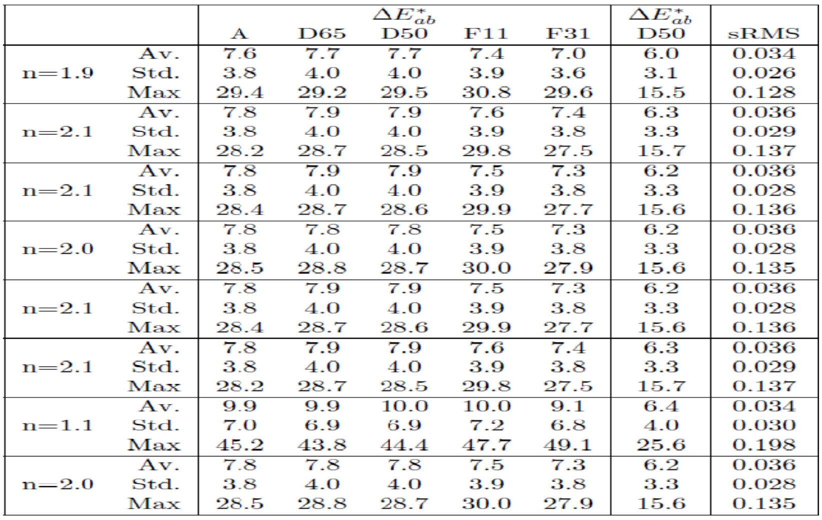
Jeremie Gerhardt, in his PhD thesis [4], performs spectral printer characterization for a multi-colorant inkjet printer with seven inks. He used the Epson 2100 Photo Stylus inkjet printer by replacing the original set of inks by a cyan, magenta, yellow, black, red, green and blue (CMYKRGB) set of inks.

He used both the spectral Neugebauer (NG) printer model and the Yule-Nielsen modified Spectral Neugebauer (YNSN) model for the characterization. As I already described in section 2.3, it is important to print out or estimate NPs of the primaries for spectral printer modeling. In this particular thesis, he used the combination of them. He estimated some of the NPs using KM theory and he printed the rest of colorant combinations on Epson photo paper and measured them.

To build the spectral Neugebauer model he used those spectral reflectances of the NPs and the spectral reflectances of each single colorant ramps which are made of 16 linearly spaced steps from 0% to 100% to create look-up tables (LUTs) for their respective effective colorant coverage. The spectral reflectances are estimated from the colorant combination of each patch by following the workflow shown in Figure 4 and the effective colorant coverage values are obtained by interpolation using the LUTs and the theoretical colorant coverage values of each patch.

The test chart they used to evaluate the performance of the spectral model of this 7 ink printer is made of 4175 patches which have been divided in several smaller grids in order to print it on A4 paper. Finally, he measured the printed test chart and compared them with the estimated once using YNSN Spectral printer model both spectrally and perceptually. The resulted spectral and colorimetric differences between the measured and estimated spectral reflectances for different n values are shown in table 2.2.

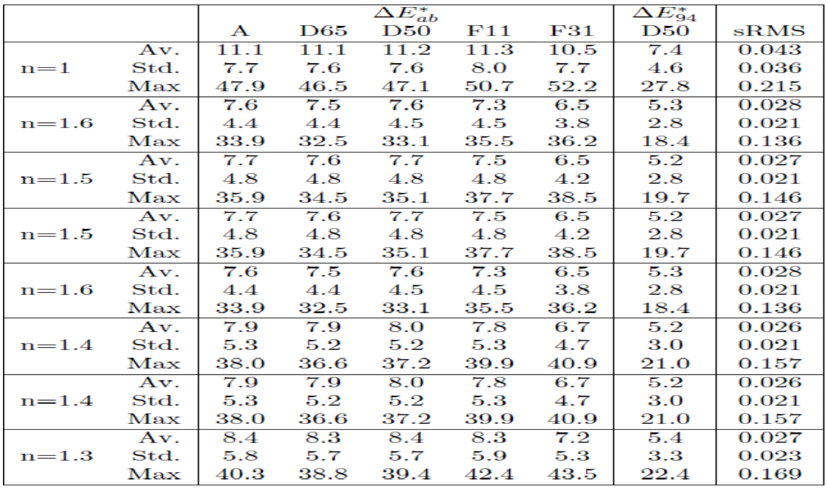
Table 2.2: Performance of the YNSN model for the best n factor values obtained by optimization on the single colorant ramps. [4]



		ΔE^*_{ab}					ΔE^*_{ab}	
		A	D65	D50	F11	F31	D50	sRMS
n=1.9	Av.	7.6	7.7	7.7	7.4	7.0	6.0	0.034
	Std.	3.8	4.0	4.0	3.9	3.6	3.1	0.026
	Max	29.4	29.2	29.5	30.8	29.6	15.5	0.128
n=2.1	Av.	7.8	7.9	7.9	7.6	7.4	6.3	0.036
	Std.	3.8	4.0	4.0	3.9	3.8	3.3	0.029
	Max	28.2	28.7	28.5	29.8	27.5	15.7	0.137
n=2.1	Av.	7.8	7.9	7.9	7.5	7.3	6.2	0.036
	Std.	3.8	4.0	4.0	3.9	3.8	3.3	0.028
	Max	28.4	28.7	28.6	29.9	27.7	15.6	0.136
n=2.0	Av.	7.8	7.8	7.8	7.5	7.3	6.2	0.036
	Std.	3.8	4.0	4.0	3.9	3.8	3.3	0.028
	Max	28.5	28.8	28.7	30.0	27.9	15.6	0.135
n=2.1	Av.	7.8	7.9	7.9	7.5	7.3	6.2	0.036
	Std.	3.8	4.0	4.0	3.9	3.8	3.3	0.028
	Max	28.4	28.7	28.6	29.9	27.7	15.6	0.136
n=2.1	Av.	7.8	7.9	7.9	7.6	7.4	6.3	0.036
	Std.	3.8	4.0	4.0	3.9	3.8	3.3	0.029
	Max	28.2	28.7	28.5	29.8	27.5	15.7	0.137
n=1.1	Av.	9.9	9.9	10.0	10.0	9.1	6.4	0.034
	Std.	7.0	6.9	6.9	7.2	6.8	4.0	0.030
	Max	45.2	43.8	44.4	47.7	49.1	25.6	0.198
n=2.0	Av.	7.8	7.8	7.8	7.5	7.3	6.2	0.036
	Std.	3.8	4.0	4.0	3.9	3.8	3.3	0.028
	Max	28.5	28.8	28.7	30.0	27.9	15.6	0.135

They also tried a second approach to select a suitable n factor value using single colorant ramps and they performed spectral reflectance estimation with the YNSN model for those different n values. The respective results for spectral and colorimetric differences, after performing this optimization on approximately 10% of their patches, are shown in Table 2.3.

Table 2.3: Performance of the YNSN model for the best n factor values obtained by optimization on approximatively 10% of the printed test chart. [4]



		ΔE^*_{ab}					ΔE^*_{94}	
		A	D65	D50	F11	F31	D50	sRMS
n=1	Av.	11.1	11.1	11.2	11.3	10.5	7.4	0.043
	Std.	7.7	7.6	7.6	8.0	7.7	4.6	0.036
	Max	47.9	46.5	47.1	50.7	52.2	27.8	0.215
n=1.6	Av.	7.6	7.5	7.6	7.3	6.5	5.3	0.028
	Std.	4.4	4.4	4.5	4.5	3.8	2.8	0.021
	Max	33.9	32.5	33.1	35.5	36.2	18.4	0.136
n=1.5	Av.	7.7	7.6	7.7	7.5	6.5	5.2	0.027
	Std.	4.8	4.8	4.8	4.8	4.2	2.8	0.021
	Max	35.9	34.5	35.1	37.7	38.5	19.7	0.146
n=1.5	Av.	7.7	7.6	7.7	7.5	6.5	5.2	0.027
	Std.	4.8	4.8	4.8	4.8	4.2	2.8	0.021
	Max	35.9	34.5	35.1	37.7	38.5	19.7	0.146
n=1.6	Av.	7.6	7.5	7.6	7.3	6.5	5.3	0.028
	Std.	4.4	4.4	4.5	4.5	3.8	2.8	0.021
	Max	33.9	32.5	33.1	35.5	36.2	18.4	0.136
n=1.4	Av.	7.9	7.9	8.0	7.8	6.7	5.2	0.026
	Std.	5.3	5.2	5.2	5.3	4.7	3.0	0.021
	Max	38.0	36.6	37.2	39.9	40.9	21.0	0.157
n=1.4	Av.	7.9	7.9	8.0	7.8	6.7	5.2	0.026
	Std.	5.3	5.2	5.2	5.3	4.7	3.0	0.021
	Max	38.0	36.6	37.2	39.9	40.9	21.0	0.157
n=1.3	Av.	8.4	8.3	8.4	8.3	7.2	5.4	0.027
	Std.	5.8	5.7	5.7	5.9	5.3	3.3	0.023
	Max	40.3	38.8	39.4	42.4	43.5	22.4	0.169

He showed that performing optimization on the measured spectral reflectances of the test chart and their estimated spectral reflectances by the YNSN gives a small improvement. The introduction of the Yule-Nielsen *n* factor in to spectral Neugebauer printer model for the YNSN improves the spectral Neugebauer printer model's performance. Not only using YNSN models, using effective colorant coverage instead of theoretical once also handles the mechanical dot gain effect and improves the performance.

He also pointed out that looking at the dot gain for the NP's and creating additional LUTs for various inks superposition, knowing that the printer is always performing the same order to lay down the inks will increase the performance even more. The disposition of more NPs using cellular Neugebauer model has also its own advantages for giving a better estimation.

3. Spectrophotometers vs. hyper-spectral cameras

Hyper-spectral Imager sensors collect image data in hundreds of very narrow spectral bands simultaneously. This helps to derive the spectrum for each pixel in the image. They actually contain a great amount of information from across the electromagnetic spectrum (Figure 3.1).

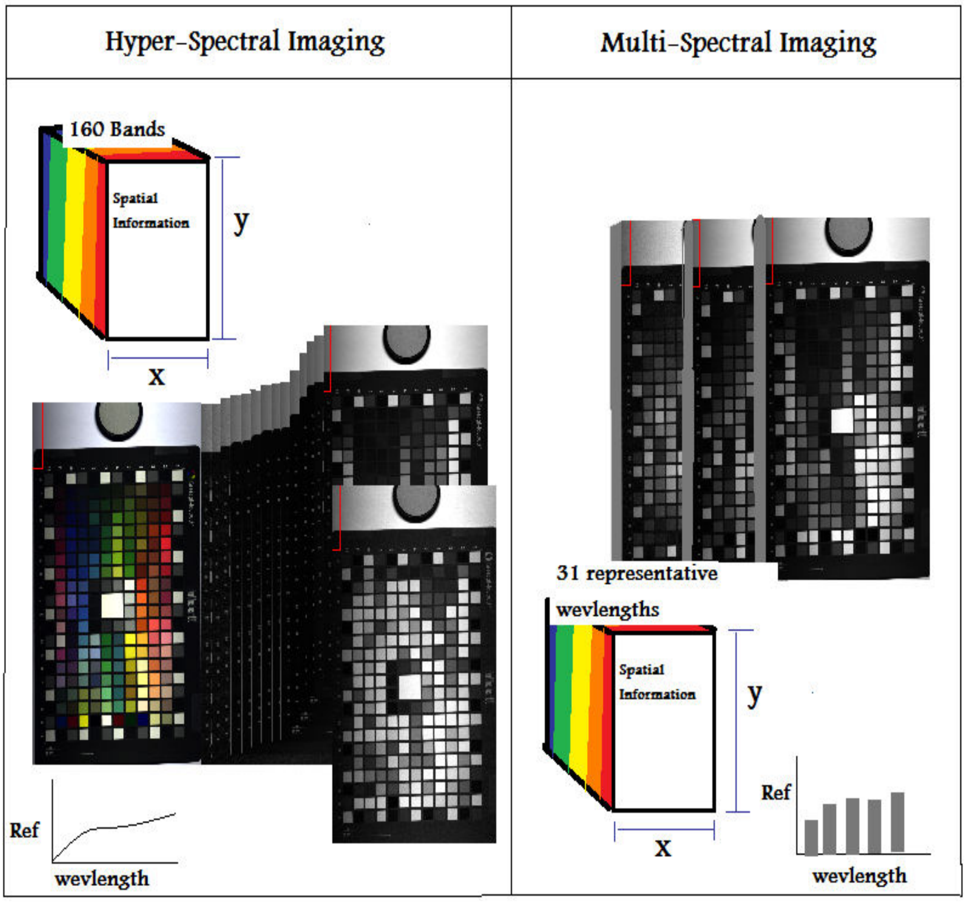


Figure 3.1: Hyper-Spectral vs. Multi-Spectral imaging

Hyper-Spectral imaging is much related to the field multi-Spectral imaging. Their main difference is mostly in the number of spectral bands. Multi-spectral data contains from tens to hundreds of bands where as Hyper-spectral data contains hundreds to thousands of bands. If we consider the manner in which the data is collected, Hyper-Spectral data is a set of contiguous bands usually by one sensor where as Multi-spectral is a set of optimally chosen spectral bands which is not contiguous and can be collected from multiple sensors.

Here we performed comparison of one of the spectrophotometers found in the color lab (BARBIERI Spectro LFP RT) with the HySpex Hyper-spectral camera [51] from NEO (Norsk Electro Optisk) research and development oriented company. The comparison made for the purpose of selecting one instrument for measuring spectral reflectance during our experiment. Here we present the experimental method we followed and experimental results briefly.

3.1 Experiment

We used Gretag Macbeth Color Checker DC color chart. We took the Hyper-Spectral image of it using HySpex and we extracted the reflectances of each patch from the Hyper-Spectral image using special software. We also measure the reflectance of the chart using BARBIERI spectrophotometer.

We used Root mean square error and Goodness of Fit Coefficient for comparing the measurements using the two instruments (Spectral reflectance from HySpex and Spectral reflectances from BARBIERI Spectro LFP RT spectrophotometer) spectrally. For the case of Perceptual differences we used CIELAB and CIE94 colour differences.

As mentioned in the manual of Gretag Macbeth Color Checker DC CD, the reference values on the CD are averages with a tolerance of deltaE <1.0, which are based on the processes used in the Munsell Lab according to ISO 9001. The standard colour values (XYZ and L*a*b* values) refers to the CIE colour measuring system of the International Commission on Illumination, D50, 2°.

In order to do any comparisons with this reference values we should calculate the XYZ and L*a*b* values of the spectra from HySpex under illumination D50 and for 2° observer (Section 2.6). We also used the D50 illuminant and 2° observer for BARBIERI Spectro LFP RT spectrophotometer measurements as well.

For the calculation of L*a*b* values, we used the same reference white values for both BARBIERI measurements and the spectral data extracted from Hyper-Spectral Image. First, we calculated the [XnYnZn] reference white values from the resulted XYZ and L*a*b* values of BARBIERI. Then we used the same reference white for computing L*a*b* values for HySpex data.

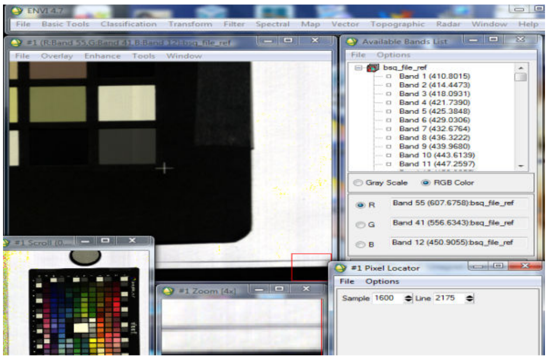
Our perceptual difference calculation is just like evaluating the accuracy of the two instruments. We are measuring the distance between the measurements taken by two instruments and the actual target values of the Gretag Macbeth Colour checker DC.

3.1.1 Spectrum extraction from Hyspex

Since the data we found from HySpex was just Hyper-Spectral Image of the color checker DC, we were supposed to find a way to extract spectral reflectances of all the patches. In order to extract the average spectrum of each patches from the Hyper-spectral image of Gretag Macbeth color checker DC, we used ENVI 4.6 software [52]. In this software we have different tools for reading, visualizing and analyzing of hyper-spectral data.

Using pixel locator tool (Figure 3.2) from the display window we were able to find out the dimensions of the entire image as well as the patches. The Dimensions of the hyper-spectral image and the patches are shown in Figure 3.3.

The BARBIERI Spectro LFP RT spectrophotometer measures the 10mm by 10mm area of the Gretac Macbeth color checker DC patches using BARBIERI Profile_Xpert Gateway software. This area covers 83.3% of those 12mm by 12mm patches. For this reason we need to take the average spectra of number of pixels which cover about 83.3 % of the 60x60 pixels patches of the Hyper-spectral image of the same colour checker DC.



bsq_file_ref
Band 1 (410.8015)
Band 2 (414.4473)
Band 3 (418.0931)
Band 4 (421.7390)
Band 5 (425.3848)
Band 6 (429.0306)
Band 7 (432.6764)
Band 8 (436.3222)
Band 9 (439.9680)
Band 10 (443.6139)
Band 11 (447.2597)

○ Gray Scale ● RGB Color

● R Band 55 (607.6758):bsq_file_ref
○ G Band 41 (556.6343):bsq_file_ref
○ B Band 12 (450.9055):bsq_file_ref

Sample 1600 Line 2175

Figure 3.2: Pixel locator tool from the display window of ENVI 4.6

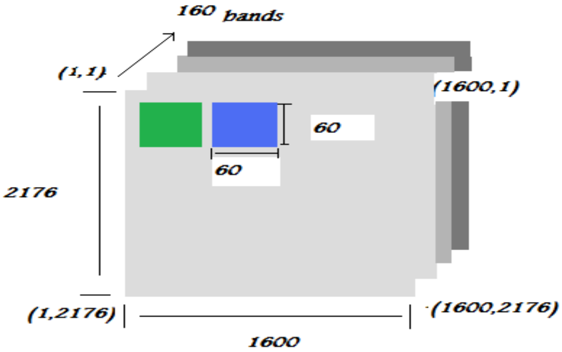
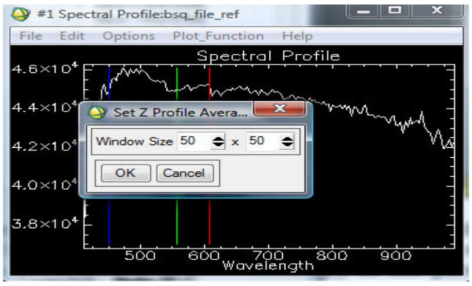


Figure 3.3: dimensions of the patches in the Hyper-Spectral images

We use the Z profile (spectrum) tool (Figure 3.4) of the display window for collecting spectral reflectance of each patch in the hyper-spectral image. We use the set Z profile average window size option of this tool in order to take the average spectra of pixels in the area of the patches which covers 83.3% of them.



Window Size 50 x 50

Figure 3.4: Z profile spectrum tool

Choosing the average window size above 60 will include spectrum of pixels outside the patch which will result error in our results. For minimizing the risk of passing the boundary of the patches and for covering as large area as BARBIERI spectrophotometers able to cover, we choose 50x50pixels average window sizes. This area will cover approximately 83.3% of them.

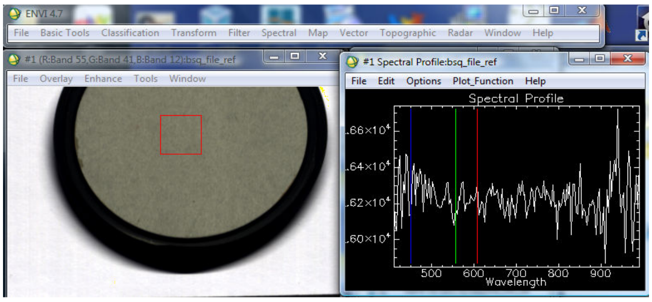


Figure 3.5: 70x70 window size

3.1.2 Normalization

Finally, we need to normalize the resulted average spectra in order to get values in the range [0,1] . For this purpose, I used the average SPD of gray circle in 70x70 pixels window (the red box in the Figure 3.5) as follows.

Normalized SPD of the patch = (Average SPD of the patch / Average gray circle SPD) * 0.4

The number 0.4 is the reflectance factor for the diffuse gray standard of Spectralon (gray circle) used during measurement. That means the gray target reflects 40% of the light across the whole spectral range.

Using 70x70 pixels window for average spectral reflectance data of gray circle didn't cause any problem because the gray circle has much more width than 60x60 pixels of other patches.

3.1.3 Re-sampling

Since the spectral power distribution found from other spectrophotometers is sampled by 10nm interval and since it is more accustomed in colorimetry, we need to resample the normalized spectra in to 10nm interval. As we can see above, the SPD of the patch is not spiky. Therefore, there will not be any problem if we resample it in 10nm interval.

Most Importantly, In order to directly compare two spectra, it is necessary to resample one of them so that both are on the same wavelength scale. There are several re-sampling routines available. We found out the following interpolation functions with the listed methods in Matlab.

yi = *interp1*(x,Y,xi,method)
    'nearest' : Nearest neighbour interpolation
    'linear' : Linear interpolation (default)
    'spline': Cubic spline interpolation
    'pchip' : Piecewise cubic Hermite interpolation
    'cubic': (Same as 'pchip')
    'v5cubic': Cubic interpolation used in MATLAB 5. This method does not extrapolate. Also, if x is not equally spaced, 'spline' is used/
y = *resample*(x,p,q)

Our average spectra are regularly sampled in 3.64582nm interval. But here, the resample function forces that its arguments p and q must be positive integers. For this reason, we rather prefer to use the *interp1* function with a method 'spline' since it allows extrapolation for out of range wavelengths. This method also gives negative values during extrapolation for some wavelengths which are out of the given range. We just forced all negative values to be zero.

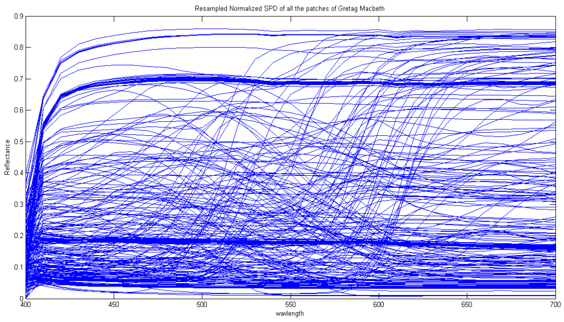


Figure 3.6: Re-sampled and Normalized SPDs of Color checker DC reflectances

Once the spectra have the same wavelength scale (Figure 3.6), then comparing them will be an easy task.

3.2 Experimental Results and Discussion

The spectral differences between the BARBIERI and HySpex are displayed in figure 3.7 and 3.8.

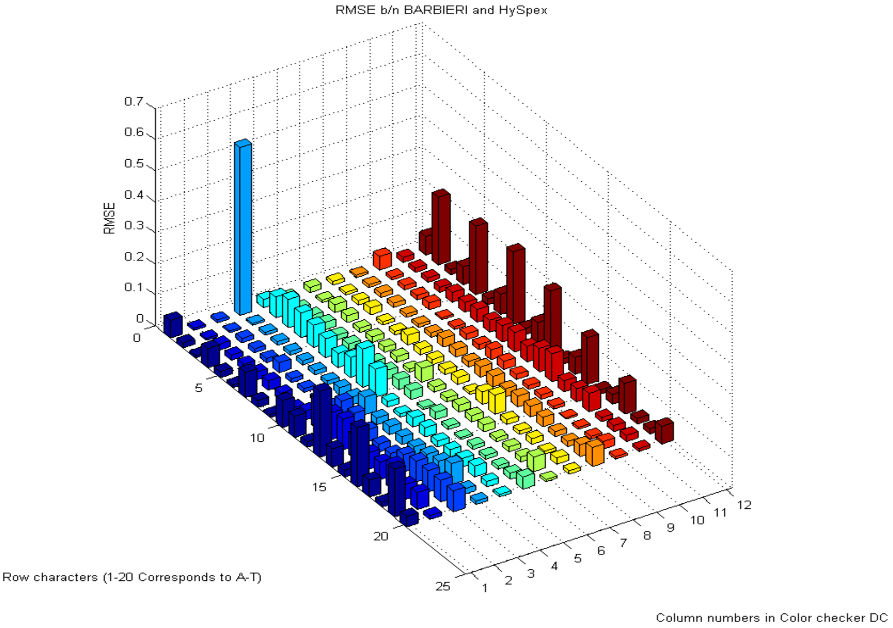


Figure 3.7: RMSE for BARBIERI and HySpex measurments

As displayed in the above bar graphs, RMSE and CGFC(1-GFC) results of the Spectral reflectance of all the patches from HySpex and Spectral reflectances from BARBIERI Spectro LFP RT spectrophotometer show a higher differences between them in particular areas.

The RMSE of the patch (A4) = 0.5407 which is much larger than the others. We can also see that the RMSE values for the patches in column 12 of color checker DC being very high. In general RMSE shows us there is a big mismatch between BARBIERI and HySpex in the following patches (A4,S1,P1,M1,B12,E12,H12,k12, and N12) of color checker DC colour chart.

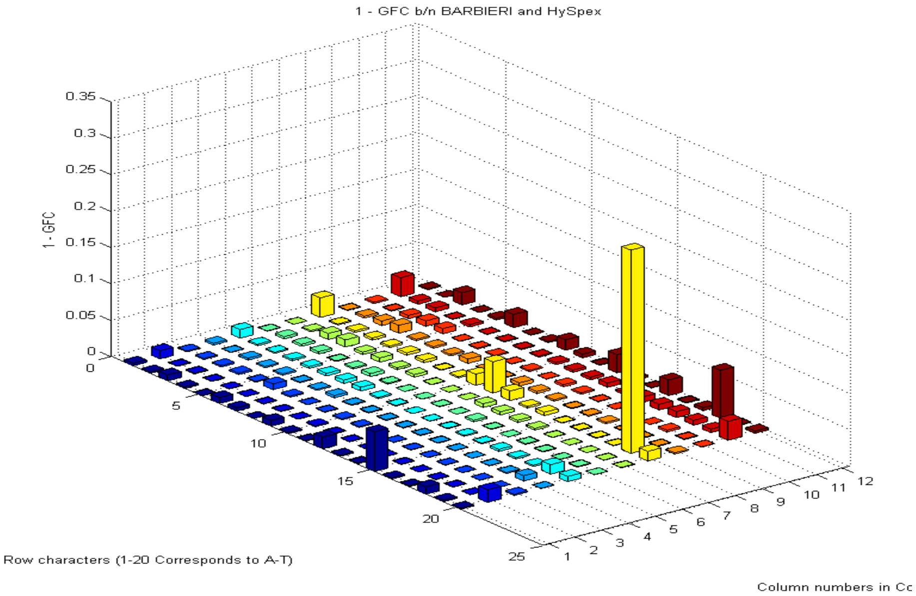


Figure 3.8: CGFC for BARBIERI and HySpex measurements

The bar graphs in Figure 3.9-3.11 show the colorimetric differences between the two measurements.

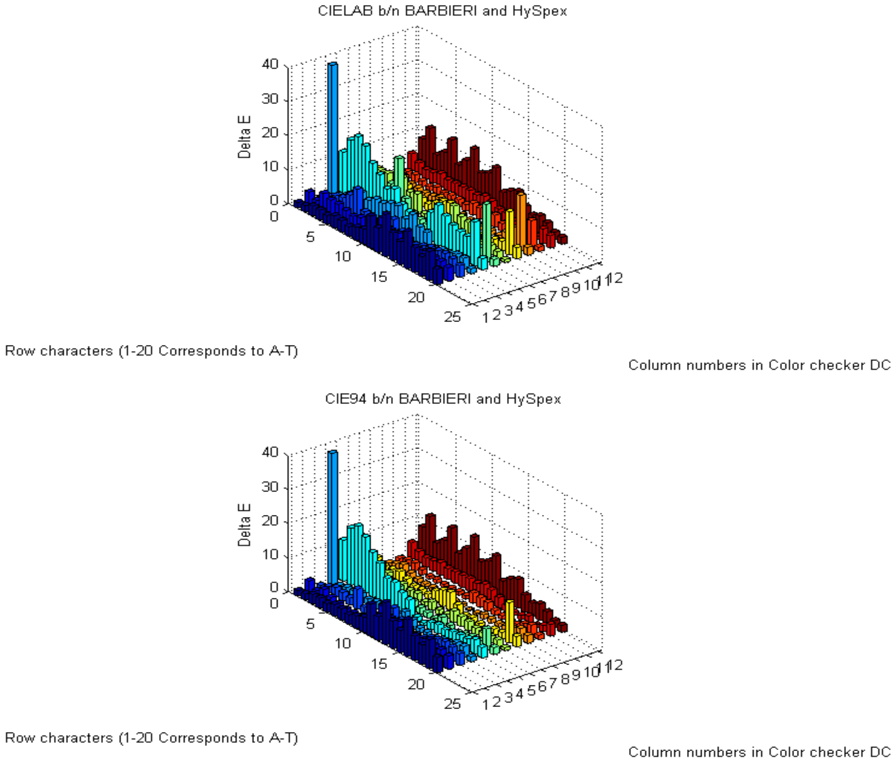


Figure3.9: ΔE_{ab} and ΔE_{94} between BARBIERI and HySpex measurements

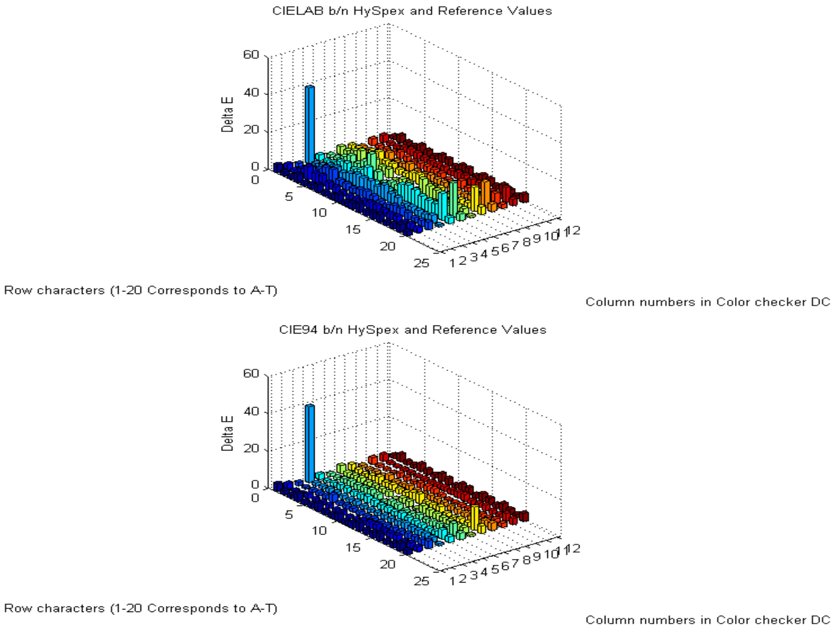


Figure 3.10: ΔE_{ab} and ΔE_{94} between HySpex measurements and Reference values

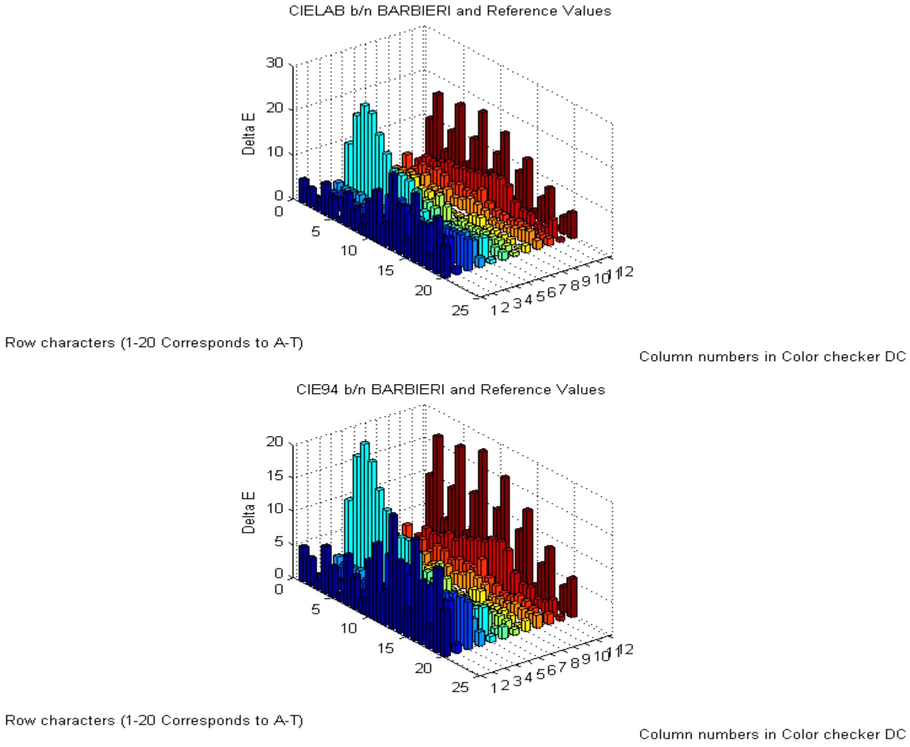


Figure 3.11: ΔE_{ab} and ΔE_{94} between BARBIERI measurements and Reference values

As it can be seen from the bar graphs (figure 3.9-3.11), HySpex resulted more accurate measurements than BARIBERIE for all patches in color checker DC except for the A4 patch (ΔE_{ab} = 40.7187). Whereas, BARIBERIE measurements gives colour difference values which are $\Delta E_{ab} < 20$ for all the patches of colour checker DC.

The same thing can be said about HySpex and BARIBERIE measurements in the case of CIE94 too. The HySpex measurements show more accurate results than BARIBERIE once. Again the patch (A4) gives (ΔE_{94} = 40.7181) value which is much more than the rest of the patches in HySpex measurements but all the colour difference values are under $\Delta E_{94} = 20$ for the BARIBERIE measurements.

In general, The HySpex Hyper-Spectral camera and BARIBERIE performs almost equally spectrally with the exception of the gray patches specially the patch A4. There is a large discrepancy between them in the time of perceptual difference. HySpex agrees with the references values given from the Gretag Macbeth while BARIBERIE gives higher ΔE values. Still Hyspex gives a very large Delta E value for patch A4, more than twice that of BARIBERIE.

The higher values of the RMSE between HySpex and BARBIERI are shown for white patches. We also have seen that HySpex perceptual difference with the reference values is very small for those white patches except patch A4, which is still very high. In the other direction, the ΔE for those white patches is still high in case of BARBIERI and Reference values. These show us that the reason for higher RMSE value for those white patches is BARBIERI except the patch A4, which is obviously the problem of HySpex.

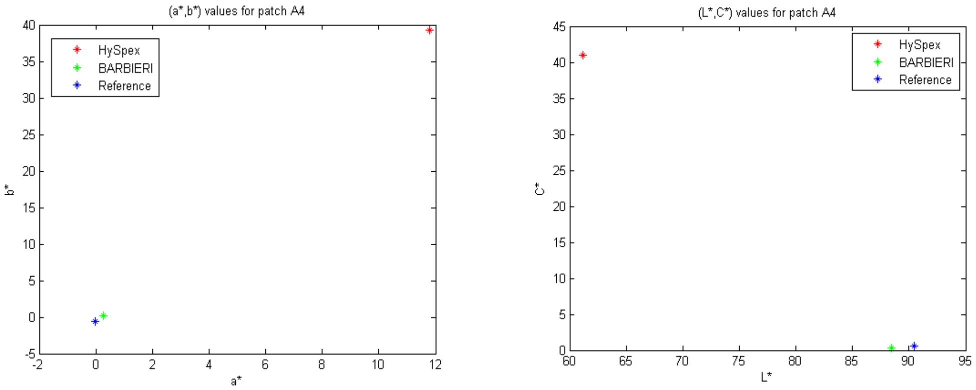


Figure 3.12: Three measurement values of color checker DC patch A4 in a*,b* space(left one) and in L*,C* space (right one).

As we see from the plots in figure 3.12, HySpex measurement for A4 is very different both in lightness and chroma. “Why is HySpex giving us such a high difference particularly for patch A4?” This is an important question that we need to raise this time.

In order to answer this question and to proof the above problems of BARBIERI on the white grey patches, we measure some of the patches of the same colour chart using Eye One Spectrolino (figure 3.13).

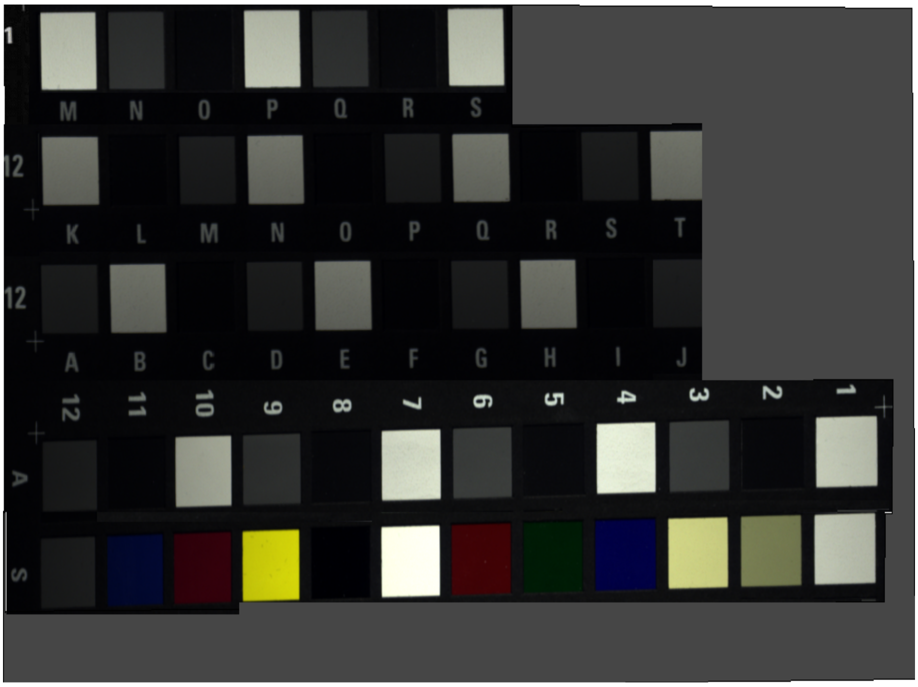


Figure 3.13: Patches which gives higher perceptual difference during HySpex comparisons.

The Spectral and Colorimetric differences among Eye One, HySpex, BARBIERI and Reference values for the colour checker DC are given in the appendix E.

Based on these measurements we can't get any clear cut information about the source of the problem that HySpex is giving us large differences particularly for patch A4. Eye One spectrolino also has high spectral and perceptual differences for patch A4.

In the mean time, the RMSE, GFC and the Perceptual differences show us some kind of trend for Eye One Spectrolino too. As we can see from the figures, the distances or RMSE and GFC values are very high for row "A" in the chart, especially for black patches. The CIELAB and CIE94 perceptual differences also show us same kind of trend.

3.3 Conclusion

We have compared one Hyperspectral camera and one Spectrophotometer spectrally and perceptually. We also added one more spectrophotometer later for more assessment of our results.

We were able to see that, each spectrophotometer has its own problem in certain special fashion. BARBIERI shows poor performances on the grey patches, especially on the white once. Eye One on the other hand has a problem on black patches.

According to our results, HySpex gives the more accurate measurements except patch A4. This high spectral and perceptual difference for patch A4 is the result of some specular reflections since the lighting/viewing geometry was not close to the ideal during the Hyper-Spectral imaging of color checker DC patches using HySpex camera. We were unable to take the Hyper-Spectral image again under the appropriate and correct condition because of lots of problems. Since the camera was already mounted in NEO we can't borrow and bring it to HIG and we had very limited time to do so. The license we had for the ENVI software was also expired. The most important thing we need to realize here is that the problem of HySpex on this patch A4 was a measurement error due to wrong illumination and viewing geometry not the problem of the camera.

These results might point us that using Hyper-spectral cameras for color Image reproduction will be preferable than spectrophotometers in terms of accuracy. Researchers who need more accurate spectral measurements for their research should use Hyper-Spectral Imaging Cameras in place of Spectrophotometers.

In the contrary, extraction of spectral reflectances from the Hyper-Spectral Images might need another extra time and specialized software. In the case of Spectrophotometers, data retrieval is very easy. They even provide the already calculated Lab and XYZ values. It is like spoon feeding. Researchers who do not need a strongly accurate spectral measurements and who needs very easy and fast way of finding spectral data can use Spectrophotometers than Hyper-Spectral Imaging cameras.

As described above, we had a problem of borrowing the HySpex camera; we didn’t have the license for ENVI 4.6 for longer time and also the time and effort which we need to spend for the extraction of spectral reflectance data from the Hyper-Spectral Image was not negligible. Since we need to measure lots of printed charts for a number of times, using HySpex will be very time consuming and very tedious work. For this and some other reasons we choose to use Eye one Spectrolino spectro photometer with UV cut for spectral reflectance measurements of our experiment.

4. Experimental methods

For our experiment we have used two CMYK printers for spectral modeling, Xerox Phaser 7760 color laser printer and HP 1220C DeskJet printer**.** Both printers are a 4 channel (CMYK) printers. Figure 4.1 a and b, shows the spectral reflectances of their primary colorants. Also, Figure 4.2 a and b shows their respective reflectances of NPs.

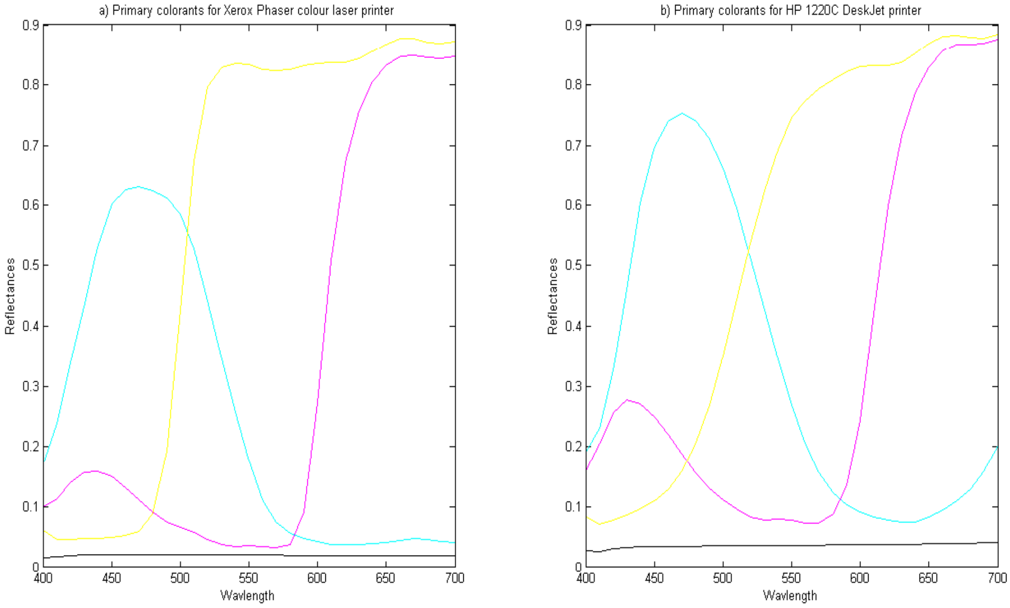


Figure 4.1: Primary colorants of the Laser and Inkjet CMYK printers which are printed and measured on color copy paper

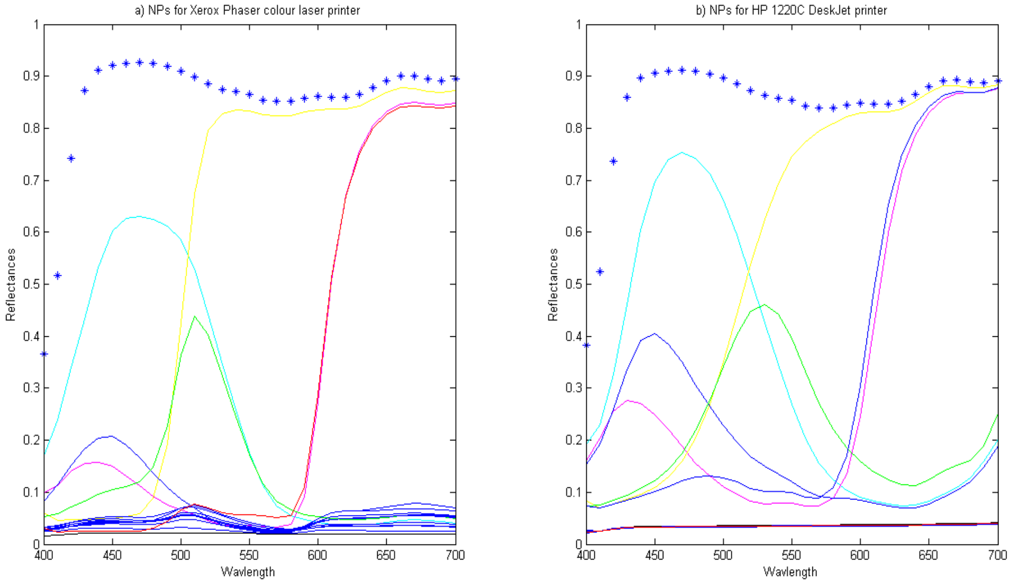


Figure 4.2: NPs of the Laser and Inkjet CMYK printers which are printed and measured on color copy paper

The colorant combinations have been printed on three types of papers (Figure 4.3 and table 4.1). All papers are made in A4 size.

Table 4.1: The three papers we used for our experiment

Papers	Grammage	Opacity
Staple copy paper	80 g/m²	94.1126
Color Copy paper	250 g/m²	99.5077
HP advanced Photo paper	250 g/m²	96.2078

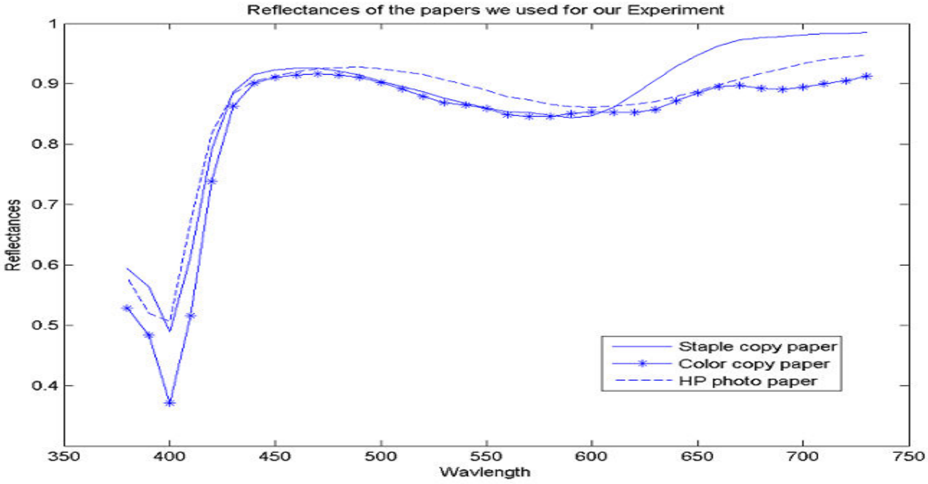


Figure 4.3: Reflectances of the three papers we used

As mentioned in section 2.2 the characteristics of papers that we should use for different printers differ a lot. Because of the high heat and toner formulation during leaser printing, we could not use HP photo paper for a print using our Xerox Phaser color laser printer. We used only staple copy paper and color copy paper. But for the case of our HP Inkjet printer, we used HP photo paper in addition to those used for the Xerox Laser printer.

We calculated the opacity of the papers using the methods mentioned in section 2.1.

$$\mathrm{OS} = \left(\frac{\mathrm{Yn}}{\mathrm{Yw}}\right)x100$$

We used the ECI2002 CMYK iCColor chart as a main source for CMYK primaries and NPs. It is a very big chart which includes the four primaries (CMYK) and all possible combinations of them. For visualizing and printing the chart we used Adobe Photoshop CS4.

As we described more clearly in section three, we performed a little comparison between Hyper-Spectral cameras of NEO (Norsk Electro Optics) with two of spectrophotometers in our lab. Even if we get a good performance of measurement from HySpex, the accessibility of the HySpex camera was very difficult. We choose Gretagmacbeth Eye one pro UV cut spectrophotometer for our measurement because it has more close measurement with HySpex and it has UV filter for removing effects of optical brightness of the papers. In our experiment we used this spectrophotometer (Figure 4.5) with measure tool software of Profile Maker pro 5.0.9 for measuring the NPs (Figure 4.4) and the test charts.

Figure 4.4: NPs from the chart (paper,CMYK,...)

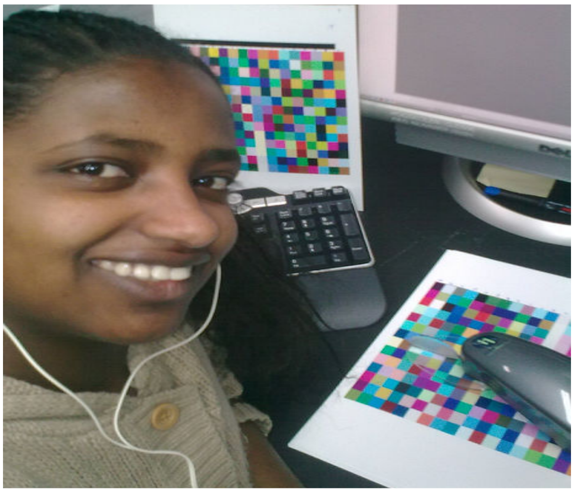


Figure 4.5: Mekides with Eye One Pro and some part of ECI2002 CMYK iCColor chart

We measure the NPs and the test chart printed on the three papers two times in a two months interval. We computed long term repeatability of our measurement in terms of Spectral and Color differences. We computed the average RMSE and GFC between the two measurements of spectral reflectances of NPs and two measurements of the test chart. We also computed the average ΔE_{ab} and ΔE_{94} , under D50 illuminant and for two degree observer, between the two measurements.

4.1 NP Estimation

The first part of our experiment was to estimate the reflectances of NPs (Figure 4.4) using our KM theory mentioned in section 2.3.3. We used the measured reflectances of the primary colorants of the printers as a starting point for the estimation of the reflectance of the rest of the NPs. First, we calculate the K/S ratios for these primaries. Then we used these ratios in order to compute the K/S ratios for the possible combinations among these primaries. Finally, we computed the reflectance of each NPs from their resulted K/S ratios.

We printed out the 16 NPs (2^4) of each printer from ECI2002 CMYK chart on the mentioned three types of papers. We checked over and printed the chart using Adobe Photoshop CS4 software. The chart was opened in CMYK mode and since it is a CMYK TIFF file and since we have CMYK printers, we were able to find pure and independent primary prints by putting off both monitor and printer color management, except the dot-gain effect. Only the dot-gain correction was not off. We set the color management policies RGB, CMYK and Gray options to be off and we set the color handling option to no color management. For example, Cyan patch of the chart contains only Cyan ink after a print out using both our printers. We were also able to print Magenta, Yellow and Black patches independently like Cyan. These verify for us that the primaries of our printers are independent of each other and there will not be any unnecessary mixing of colorants.

During the measurement of the patches we used the self backing. We measured the patches by placing them on the 20 similar but blank papers. We measured the reflectance of printed NPs and compare them with the estimated once. We used both

Spectral and colorimetric distance metrics so that we can notice how much diverse they can be both spectrally and perceptually.

Finally, we tried to see if there is a change in the performance of Kubelka-Munk theory in the process of NP estimation after two months. We measure the NPs, estimate the NPs and compared them again. We computed the Spectral and Color differences between measured and Estimated NPs for our new measurements. Finally, we see the difference between Spectral and color differences of our first measurement and those of our second measurement.

4.4.1 DORT2002 for NP estimation

Hoping more improvements over the KM model, we also tried DORT2002 for estimating NPs for spectral printer modeling. We follow the following steps for using DORT2002 software and estimate NPs of our printers.

- We modified the default parameter of structure variable P by assigning the spectral reflectances of the printed primaries, asymmetric factor, grammage in kg/m^2 and reflectance of the paper we used for print.
- We used this modified P, inverse mode and d/0 measurement geometry of the software input arguments in order to compute the scattering and absorption coefficients of the primary colorants of the two printers.
- Using the σa and σs of the primary colorants we calculated the σa and σs for all possible combinations of them as follows.

$$\sigma_{a,\mathrm{comb}} = \mathrm{a}\sigma_{\mathrm{acol1}} + \mathrm{b}\sigma_{\mathrm{acol2}} + \mathrm{c}\sigma_{\mathrm{acol3}} + \ldots + \mathrm{n}\sigma_{\mathrm{acoln}}$$

$$\sigma_{s,\mathrm{comb}} = \mathrm{a}\sigma_{\mathrm{scol1}} + \mathrm{b}\sigma_{\mathrm{scol2}} + \mathrm{c}\sigma_{\mathrm{scol3}} + \ldots + \mathrm{n}\sigma_{\mathrm{scoln}}$$

While, $\sigma_{a,\mathrm{comb}}$ and $\sigma_{s,\mathrm{comb}}$ are the scattering and absorption coefficients of the combination of primary colorants with their respective colorant concentrations a,b, ... of DORT2002 model.

- Using the resulted σ_a and σ_s of NPS, forward mode and d/0 measurement geometry of DORT2002, we can compute the reflectance values of the NPs and the paper.

Finally, we compare the estimated spectral reflectances and measured once both spectrally and colorimetrically.

4.2 Spectral Modeling

The difference between the estimated NPs and measured NPs is not the only important result for us. The main question that we are trying to solve here is that is it possible that we use KM theory to estimate NPs for spectral printer modeling and how much more advantage does it have over the measured NPs? In this part of the experiment we model both of our printers using both the spectral Neugebauer (NG) printer model and the Yule-Nielsen modified spectral Neugebauer (YNSN) model.

For the sake of computing LUTs of colorant coverage for our printers, we prepared and print pure ramps for each colorant on mentioned three papers. They are a series of patches with equally spaced colorant coverage values range from 0% to 100% in 5% interval (Figure 4.6).

Figure 4.6: Ramps of single colorants

We measured the reflectances of these ramps using Eye One pro Spectrophotometer (Figure 4.7-4.11).

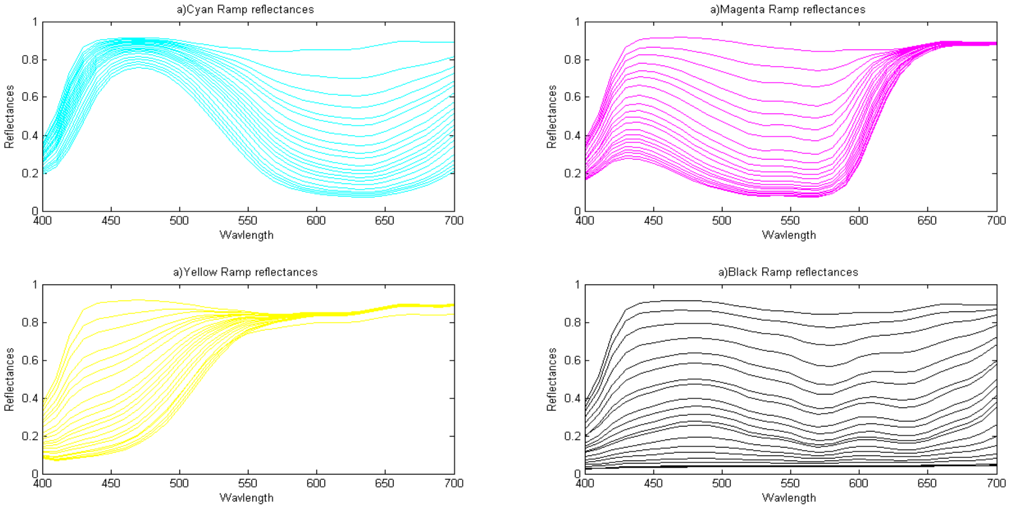


Figure 4.7: Measured spectral reflectances of equally spaced ramps of our InkJet printer primaries on color copy paper.

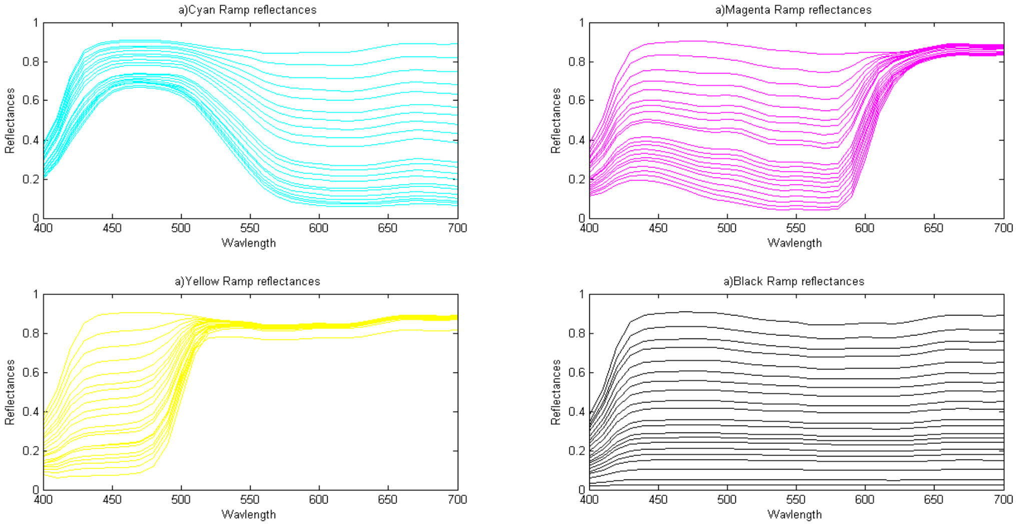


Figure 4.8: Measured spectral reflectances of equally spaced ramps of our Xerox Laser printer primaries on color copy paper.

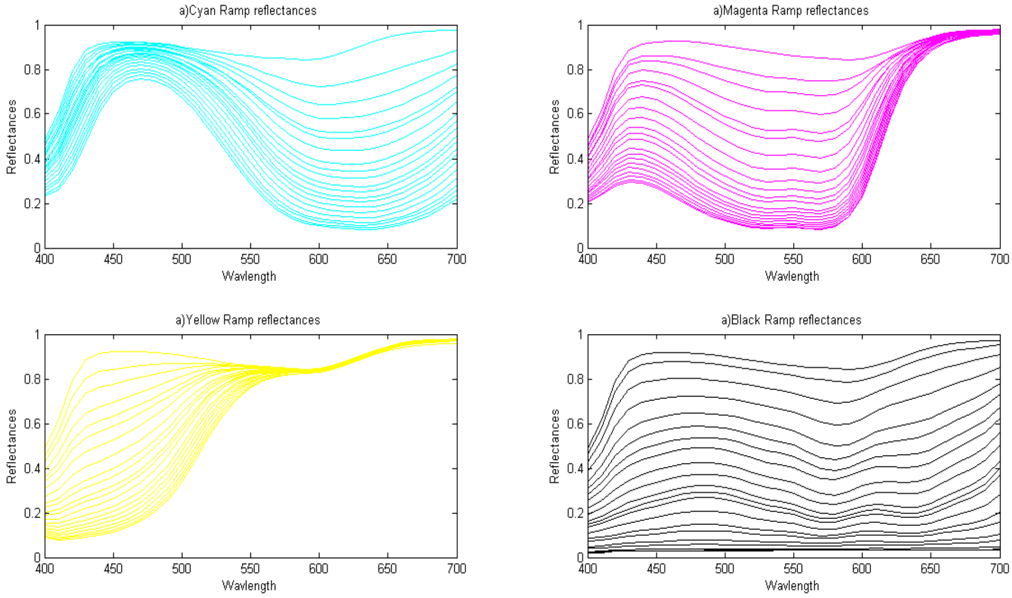


Figure 4.9: Measured spectral reflectances of equally spaced ramps of our InkJet printer primaries on staple paper.

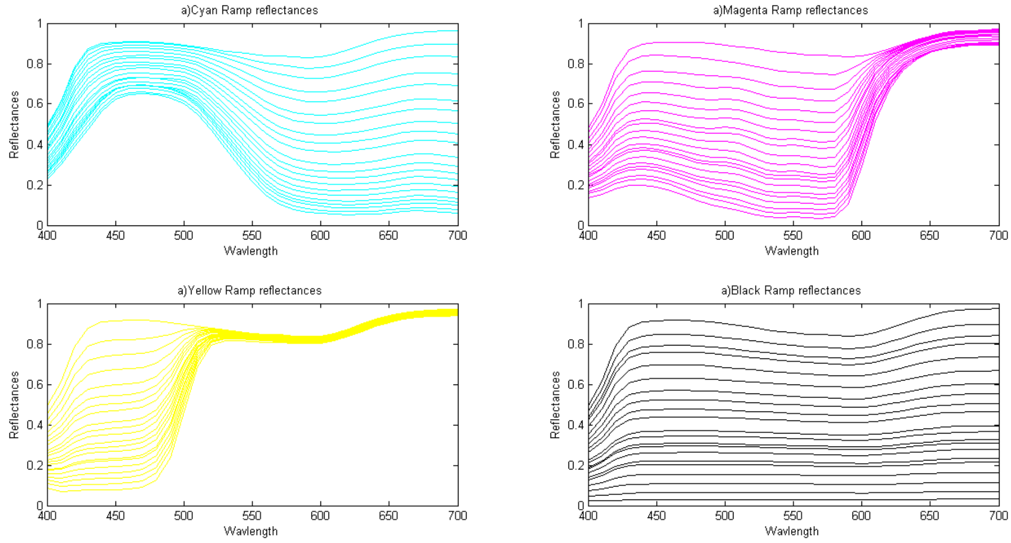


Figure 4.10: Measured spectral reflectances of equally spaced ramps of our Xerox Laser printer primaries on staple paper.

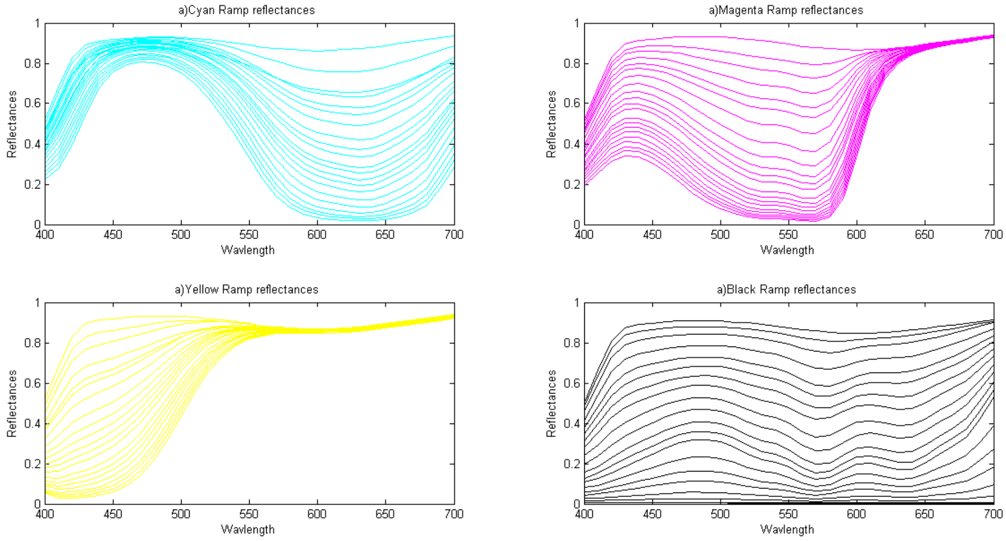


Figure 4.11: Measured spectral reflectances of equally spaced ramps of our InkJet printer primaries on HP photo paper.

Then we used these measurements for computing effective colorant coverage for the patches of the ramp as described in section 2.5 and to build LUTs. Once we had these LUTs we were able to compute effective colorant coverage of our test chart by interpolating them.

As we mentioned in section 2.5, we need reflectances of NPs in order to spectrally model a printer. We model both of our printers three times, once using measured NPs, once using estimated NPs and once using the mixture of them. For the modeling we follow all the steps in figure 2.7.

Once we have the model we can compute or estimate reflectances of any colorant combinations of the primaries. As explained in section 2.5.2 and 2.5.3, for the case of spectral Neugebauer (NG) printer model and the Yule-Nielsen modified spectral Neugebauer (YNSN) model, we used the following formulas respectively.

$$r(\lambda) = \sum_{i=0}^{2^m-1} w_i r_{i,\max}(\lambda)$$

And

$$r^{1/n}(\lambda) = \sum_{i=0}^{2^m-1} w_i {r^{1/n}}_{i,\max}(\lambda)$$

while,

$$w_i \in [0,1], \sum_{i=0}^{2^m-1} \quad w_i = 1$$

The test chart has been designed by extracting it from the ECI2002 CMYK test chart. We were using handheld Eye one Pro for measuring the patches and it will take a long time to measure all patches of the ECI2002 CMYK iCColor chart. That is why we did not use the entire chart as our test chart and we only used 108 patches of them (Figure 4.12).

Figure 4.12: Test chart from ECI2002 CMYK test chart

During the measurement of the patches we used the self backing similarly like our NP measurements. We also estimated the reflectances of the same chart using our printer models, both NG model and YNSN model. First, we estimate the reflectance of our test chart by the spectral model which is built by estimated NPs. Again we estimated the same chart using the spectral model built by measured NPs and mixed NPs. We used the effective colorant coverage for all estimation of reflectances. Finally, we computed the difference between the three estimated and combined spectral reflectance values of our test chart and the measured reflectances of the test chart both spectrally and perceptually.

5. Experimental Results and Discussions

First we want to show the long term repeatability of our measurements. The following bar graphs display the mean spectral and colorimetric difference between the two measurements we have done for NPs in two month interval. The long term repeatability for our test chart measurements is given in the Appendix G.

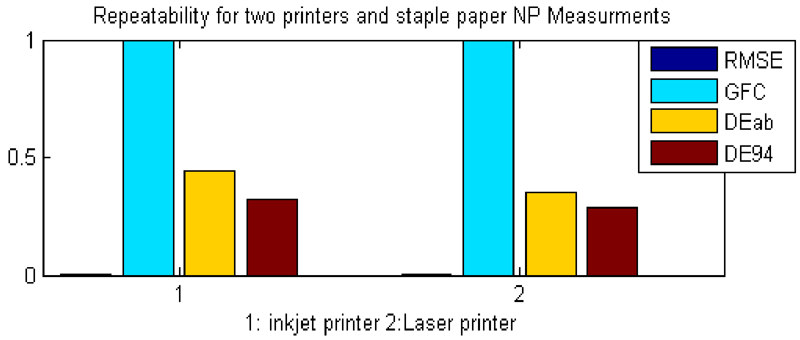


Figure 5.1: Repeatability of NP measurements for inkjet left) and laser printer (right) using staple paper. The RMSE,GFC,ΔE_{ab} and ΔE_{94} values are the average values of those of individual Patches of NPs.

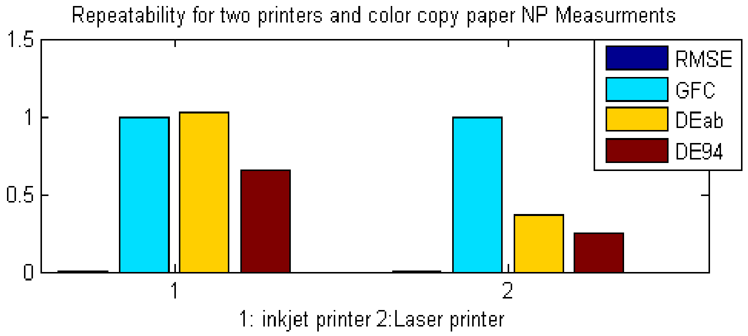


Figure 5.2: Repeatability of NP measurements for inkjet (left) and laser printer (right) using color copy paper. The RMSE,GFC,ΔE_{ab} and ΔE_{94} values are the average values of those of individual Patches of NPs.

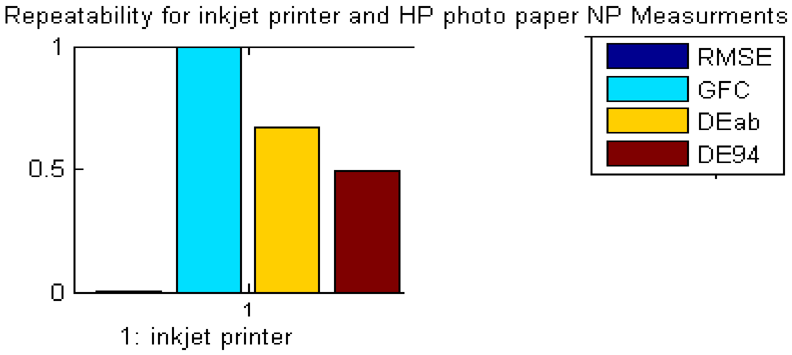


Figure 5.3: Repeatability of NP measurements for inkjet printer using HP photo paper**.** The RMSE,GFC,ΔE_{ab} and ΔE_{94} values are the average values of those of individual Patches of NPs.

As we can see from figure 5.1-5.3 and figures in Appendix G, all Spectral differences show as the tolerability of our measurements. In these two months there will be different changes including the fading of the colors of our prints. Color difference of average $\Delta E_{94} < 2$ is a good value and tolerable for long term repeatability. As we can see our results for both ΔE_{ab} and ΔE_{94} are below 0.5 for Laser printer and less than 1 for inkjet printer. The only exception was ΔE value of inkjet printer and color copy paper but still the values are below 2 and they are acceptable.

5.1 NP Estimation

Then, in the first part of our experiment we compare the estimated and computed reflectances of NPs both spectrally and perceptually. We did the comparison for both our printers (Laser and Inkjet printers). The resulted mean and standard deviation of spectral and colorimetric differences for all types of papers are listed in table 5.1. Full lists of the colorimetric and spectral differences for each NP on three different papers are given in the Appendix B.

Table 5.1: Average spectral and colorimetric difference between measured and estimated NPs

	Staple copy paper (80g/m^2)			
Laser Printer	RMSE	GFC	ΔE	ΔE94
Mean	0.0153	0.9876	**6.4653**	4.9102
Std.	0.0131	0.0133	5.5108	3.9201
Ink Jet printer				
Mean	0.0190	0.9845	**4.7043**	4.1043
Std.	0.0329	0.0325	5.2501	4.3531
	Color copy paper (250g/m^2)			
Laser Printer	RMSE	GFC	ΔE	ΔE94
Mean	0.0194	0.9838	**8.0119**	6.377
Std.	0.016	0.0207	6.2939	5.1163
Ink Jet printer				
Mean	0.0192	0.9845	**5.1893**	4.5134
Std.	0.0311	0.0315	5.1741	4.1921
	HP Photo paper (250g/m^2)			
	RMSE	GFC	ΔE	ΔE94
Ink Jet printer				
Mean	0.0241	0.8946	**6.1282**	4.1370
Std.	0.0454	0.1486	10.9297	7.2655

The difference between the two NPs (measured and estimated once) in our Laser printer is a bit higher than their difference in our InkJet printer for all three paper types. Their difference is also higher for the papers with higher Opacity or grammage in both types of Printers. This is true both spectrally and perceptually. Using a photo paper for inkjet printer also doesn't increase the performance both spectrally and colorimetrically. These high mean colorimetric and spectral differences for the case of photo paper are the results of very high differences in only three patches, especially blue patch (6th) of the NPs. The complete listings of the individual spectral and color differences are given in the Appendix B.

In Figure (5.4-5.8) we plotted the measured and estimated spectral reflectances. Mostly their difference is in scale. For the case of laser printer the estimated reflectances of NPs are darker than the measured once. Whereas, inkjet printer NPs have negligible differences on staple paper and some of the estimated NPs are a little darker on the color copy paper. The estimated reflectances of the NPs, using the HP photo papers as a base substrate, gives a good match in the range [400:700], except for the 6th patch of them.

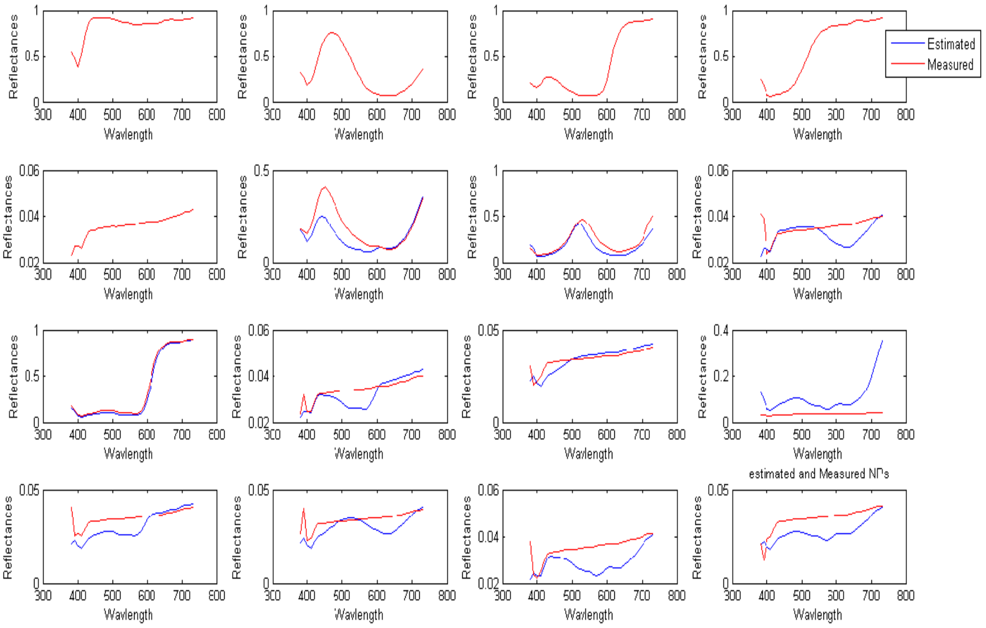


Figure 5.4: Estimated and Measured reflectances of NPs for our color copy paper and DeskJet Printer. (Note: scales in the y-axis are different for some of the plots)

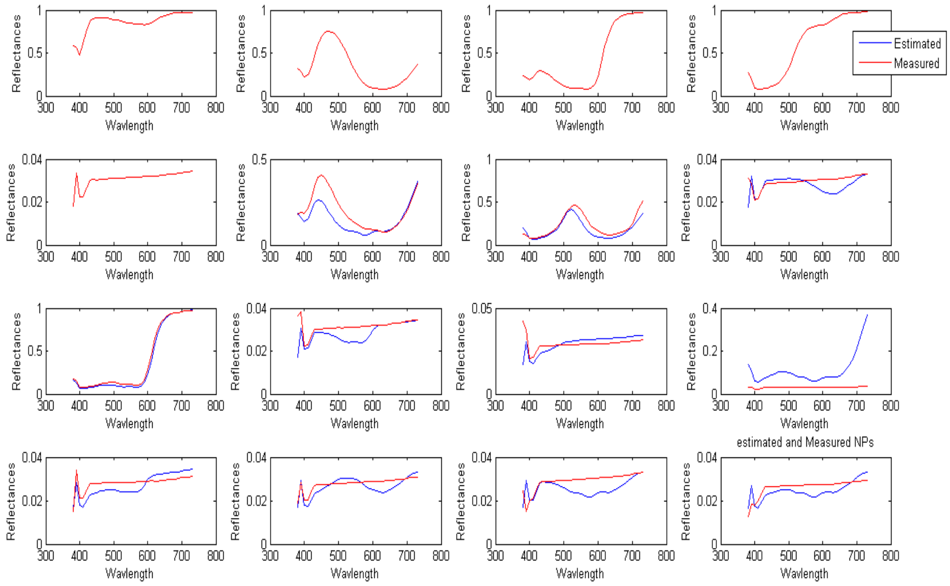


Figure 5.5: Estimated and Measured reflectances of NPs for the staple paper and DeskJet Printer. (Note: scales in the y-axis are different for some of the plots)

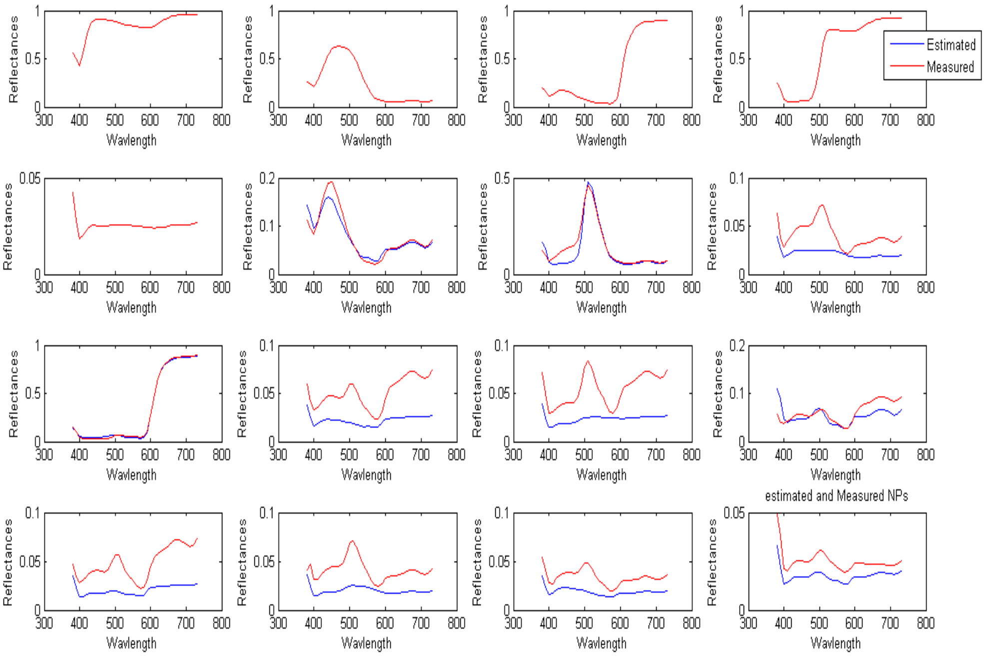


Figure 5.6: Estimated and Measured reflectances of NPs for the staple paper and Xerox Laser Printer. (Note: scales in the y-axis are different for some of the plots)

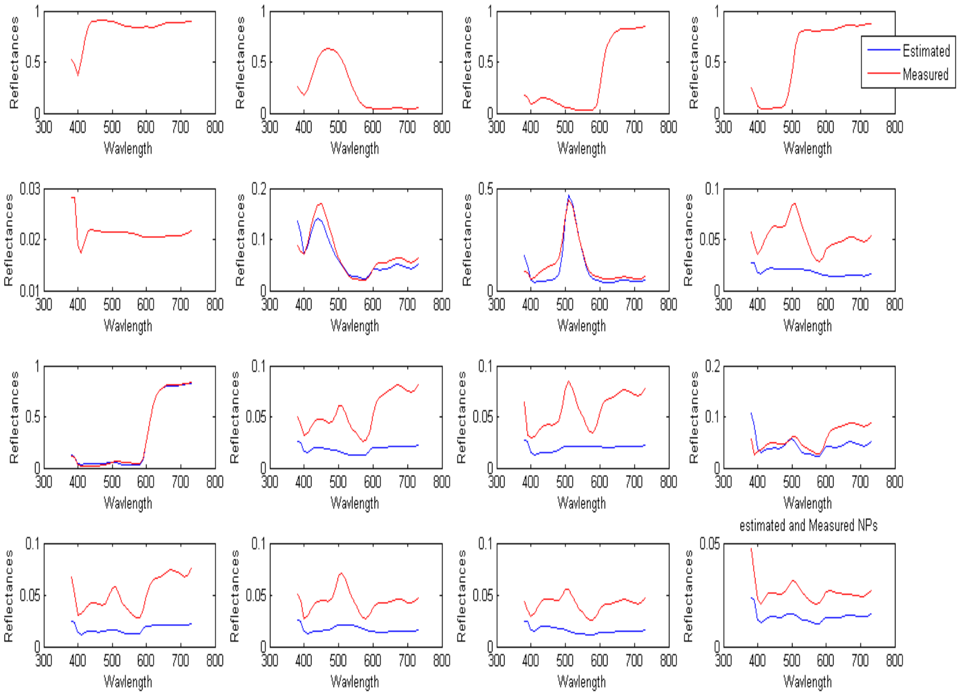


Figure 5.7: Estimated and Measured reflectances of NPs for the color copy paper and Xerox Laser Printer. (Note: scales in the y-axis are different for some of the plots)

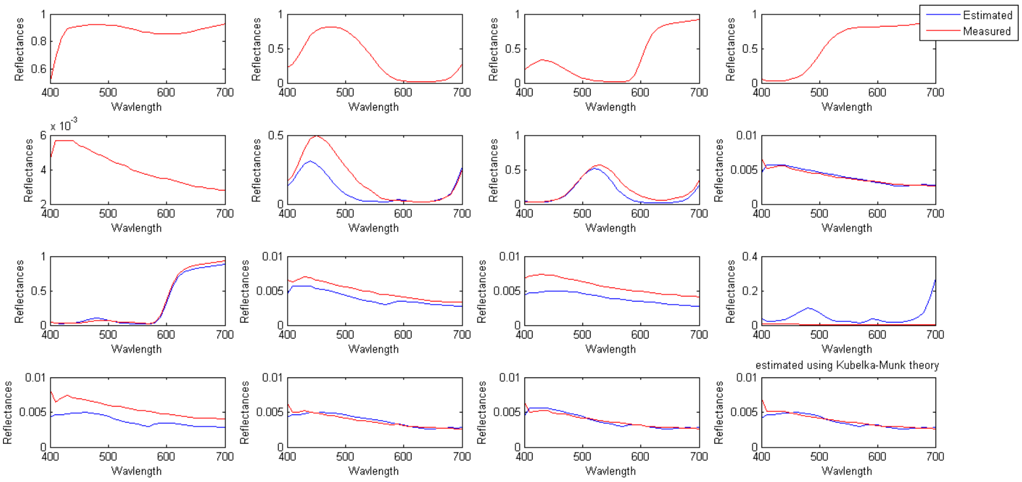


Figure 5.8: Estimated and Measured reflectances of NPs for the photo paper and DeskJet Printer. (Note: scales in the y-axis are different for some of the plots)

As explained in section 4, we computed long term repeatability of our measurements and we calculated the differences between the Spectral and Colorimetric differences between estimated and measured NPs twice in two months interval. Here we present the difference between our two results (Table 5.2).

Table 5.2: The absolute value of the difference between Average spectral and colorimetric difference between measured and estimated NPs of first measurement and those of second measurement (two months later)

	Staple copy paper (80g/m^2)			
Laser Printer	*RMSE1-RMSE2*	*GFC1-GFC2*	*ΔEab1-ΔEab2*	*ΔE941-ΔE942*
Mean	0.0008	0.0003	0.3405	0.3148
Std.	0.0004	0.0004	0.111	0.2874
Ink Jet printer				
Mean	0.0005	0	0.0695	0.0669
Std.	0.0006	0.0002	0.0552	0.0156
	Color copy paper (250g/m^2)			
Laser Printer	*RMSE1-RMSE2*	*GFC1-GFC2*	*ΔEab1-ΔEab2*	*ΔE941-ΔE942*
Mean	0.0003	0.0004	0.1867	0.1537
Std.	0.0001	0.0007	0.1093	0.0582
Ink Jet printer				
Mean	0.0004	0.001	0.0275	0.0668
Std.	0.0005	0.0012	0.1569	0.055
	HP Photo paper (250g/m^2)			
	RMSE1-RMSE2	*GFC1-GFC2*	*ΔEab1-ΔEab2*	*ΔE941-ΔE942*
Ink Jet printer				
Mean	0.0002	0.0009	0.313	0.1592
Std.	0.0003	0.002	0.1896	0.0109

As we can see from the results in table 5.2 the spectral and color differences between the two NP estimation experiments are very small. Since we perform the second experiment after two months, there are different factors which will affect our second result and which makes the difference between the two experiment results very high.

But, still our results are consistent. From this we can conclude that our first measurement was correct and reliable. This will help us to develop much stronger confidence in our overall results.

5.1.1 DORT2002 for NP Estimation

We also tested DORT2002 for estimation of NPs for spectral printer modeling. We follow the steps described in section 2.4 and 4.1.1. The mean and standard deviations of spectral and colorimetric differences between measured spectral reflectances of NPs and DORT2002 estimated reflectances of NPs are given in table 5.2. The plots of reflectance for our inkjet printer and Laser printer with the color copy paper without reflectance of the paper will be given in figure 5.6 and 5.7. The rest of the plots for both printers with the other types of papers are given in the Appendix F.

Table 5.3: Average spectral and colorimetric difference between measured and DORT2002 estimated NPs

	Staple copy paper (80g/m^2)			
Laser Printer	RMSE	GFC	ΔE	ΔE94
Mean	0.3974	0.9274	**47.7633**	40.1240
Std.	0.2983	0.0764	30.9514	30.0742
Ink Jet printer				
Mean	0.4280	0.9247	**53.5295**	45.5753
Std.	0.2853	0.0859	30.9514	30.0742
	Color copy paper (250g/m^2)			
Laser Printer	RMSE	GFC	ΔE	ΔE94
Mean	0.3844	0.9273	**47.6769**	39.3937
Std.	0.2901	0.0776	35.9201	30.1313
Ink Jet printer				
Mean	0.3933	0.9397	**44.2066**	39.5625
Std.	0.2953	0.0715	32.7449	30.1058
	HP Photo paper (250g/m^2)			
	RMSE	GFC	ΔE	ΔE94
Ink Jet printer				
Mean	0.4275	0.8788	**58.6735**	50.2810
Std.	0.3177	0.1127	43.0598	38.6632

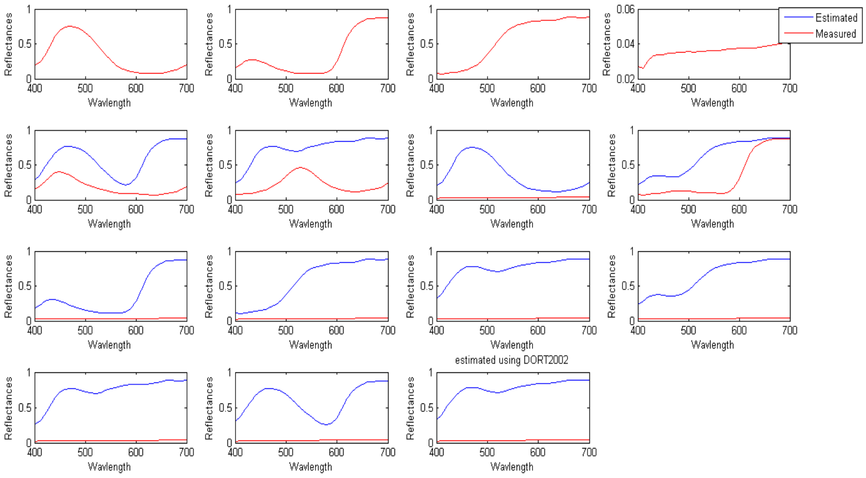


Figure 5.9: DORT2002 Estimated reflectances and Measured reflectances of NPs for the Color copy paper and Inkjet Printer(Note: scales in the y-axis are different for some of the plots)

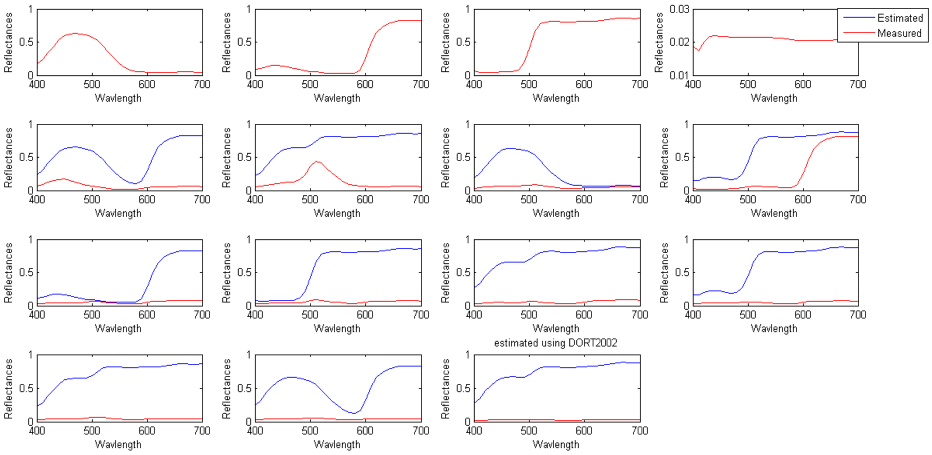


Figure 5.10: DORT2002 Estimated reflectances and Measured reflectances of NPs for the Color copy paper and Laser Printer(Note: scales in the y-axis are different for some of the plots)

The results given in the above table and plots show us the very big spectral and perceptual difference between the measured and DORT2002 estimated NPs. As we can see from the first four reflectance plots of each figure, we get exact match for primaries. The bigger difference is then only for the computed NPs from those primary colorants.

As we described already in section 2.3, KM theory can be further extended to mixture of colorants stating that the K/S values for a mixture of colorants are the sum of the K/S values of the individual colorants multiplied by concentrations of the corresponding colorants. This is actually very basic concept in color formulation and color matching. We just need to determine the K /S values of the individual colorants of the printer and store them. Later we can use these values every time these colorants are included in the mixture.

We assume this additive theory also works for DORT2002. Watching at the results, one can understand simple additive model doesn't hold for DORT2002 as it does for KM. we actually use default settings most of the time. We just set the grammage of the paper, the reflectance of the paper, the reflectance of the colorant and measurement geometry but for the other parameters we used their default values. This might have effect on the overall results but for this thesis work we didn't use DORT2002 for spectral printer modeling. The estimation of NPs is already bad and there is no need to use it for spectral printer modeling. We are not saying that the problem is from the software. The problem is the way how we used it for estimating NPs. Probably we need to measure S and K of each colorant and paper independently, which is a little difficult in terms of time and complication of the work. Since we were not so confident by our results we asked the developers of the software and we get similar responses.

> "… When doing these kinds of simulations, it is crucial to use the right input. Scattering and absorption parameters of the paper may be reasonably easy to obtain, whereas the ink parameters are sometimes not uniquely determined as easily. The absorption depth of the ink into the ink-receiving layer is also both important and perhaps hard to estimate and the same holds for any ink absorption gradient …" Prof. Per Edström

We suggested this idea, as a future work at the conclusion of our work.

5.2 NG Modeling

As explained in section 2.5.2 to take mechanical dot gain effect in to consideration, we computed colorant coverage LUTs for each colorant of the two printers. We computed them exactly as described in section 2.5. Since effective colorant coverage differs in wavelength, we take the average of values throughout the range of the wavelength. The LUTs computed from ramps, printed on the three different papers, are plotted as Figure (5.11-5.15):

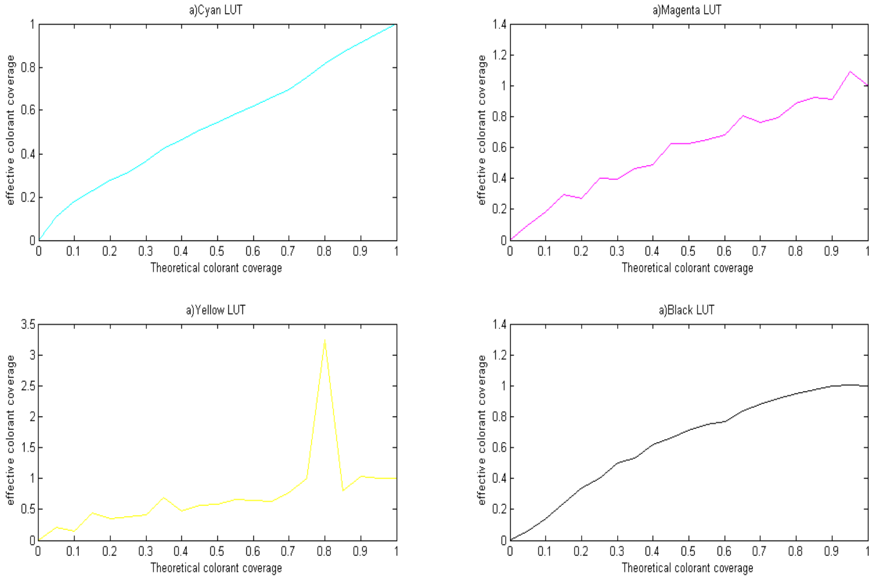


Figure 5.11: Computed LUTs for Deskjet Printer using simple NG model averaged by wavelength. Mid paper

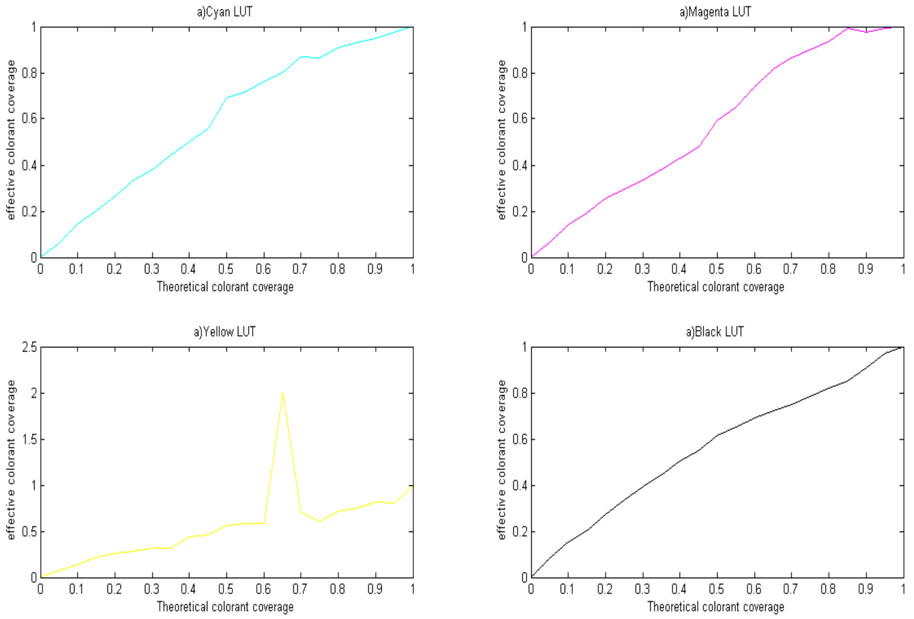


Figure 5.12: Computed LUTs for Xerox Laser printer using simple NG model averaged by wavelength. Mid paper

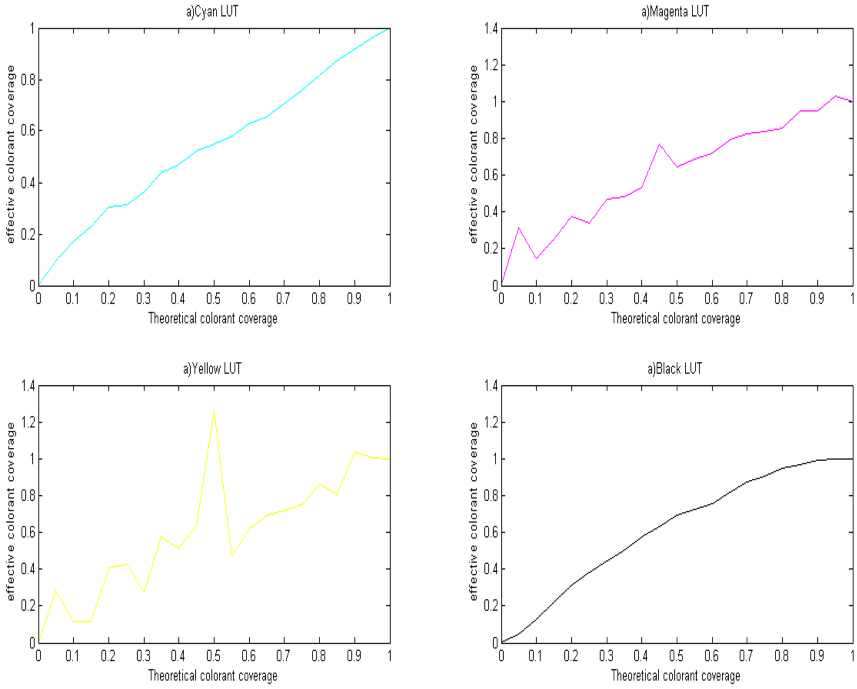


Figure 5.13: Computed LUTs for Deskjet Printer using simple NG model averaged by wavelength. Staple paper

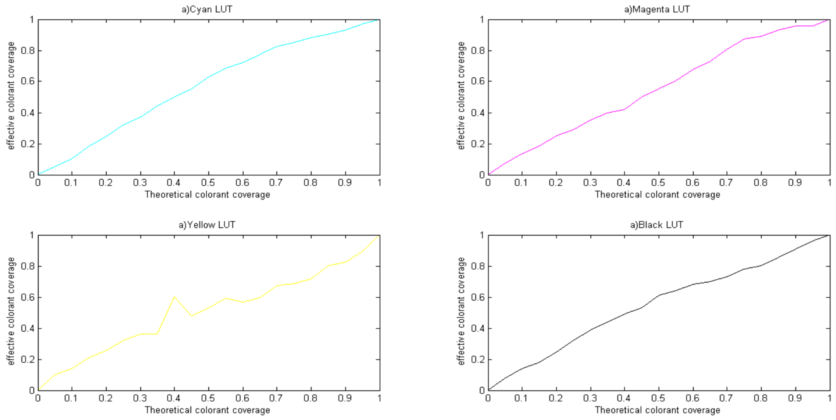


Figure 5.14: Computed LUTs for Xerox Laser printer using simple NG model averaged by wavelength. Staple paper

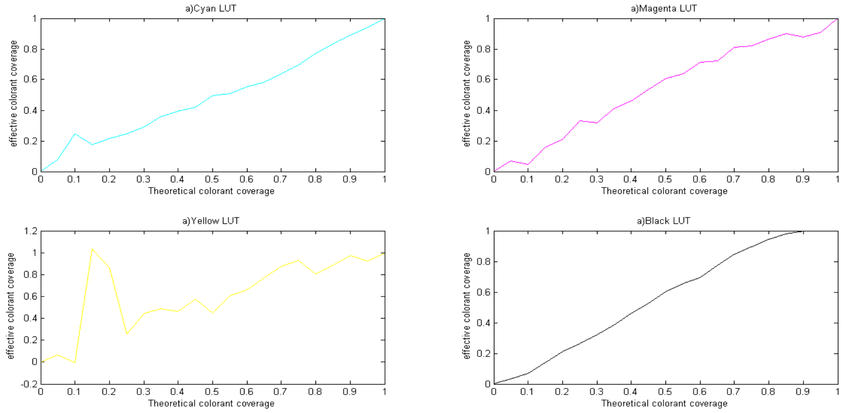


Figure 5.15: Computed LUTs for Inkjet printer and HP photo paper using simple NG model averaged by wavelength.

Magenta and Yellow channels of the inkjet printer have somewhat spiky LUTs. The LUTs for laser printer are all almost linear except the yellow channel. In the contrary, cyan and black channels have effective colorant coverage which is almost linearly related with theoretical coverage, in both printers. This shows us that cyan and black colorants of both printers have less probability of ink spreading than the yellow and magenta colorants. Since we didn't make dot-gain correction to be off the LUTs should all be linear. Some of the spikes must be from ink spreading on the paper and measurement errors. We can also see that the prints from Laser printer were more linear than the prints from inkjet printer.

In the second part of our experiment we estimated the reflectance of our test chart using NG model and YNSN model of our laser and inkjet printers. We also printed out the test chart on the three papers using both printers and measured their spectral reflectances. Finally, we compared the estimated and measured reflectances of our test chart.

We show the mean and standard deviation of spectral and colorimetric differences of the estimated and measured reflectances of the test chart using NG model built by estimated, measured and mixed NPs in Table 5.4-5.6. The whole listings of the spectral and color differences for each patch of our test chart are given in the Appendix B.

Table 5.4: Spectral and colorimetric difference for NG model for staple paper

	NG with estimated NPs			
Laser Printer	RMSE	GFC	ΔE	ΔE94
Mean	0.0440	0.9938	**7.3355**	5.3190
Std.	0.0285	0.0071	3.6225	2.6678
Ink Jet printer				
Mean	0.0772	0.9709	**15.5631**	9.8445
Std.	0.0406	0.0296	8.9199	5.2557
	NG with measured NPs			
Laser Printer	RMSE	GFC	ΔE	ΔE94
Mean	0.0481	0.9941	**8.0296**	5.8180
Std.	0.0288	0.0069	4.3240	2.6455
Ink Jet printer				
Mean	0.0720	0.9780	**14.1894**	8.8044
Std.	0.0411	0.0230	8.6107	5.0322
	NG with mixed NPs			
Laser Printer	RMSE	GFC	ΔE	ΔE94
Mean	0.0459	0.9944	**7.3243**	5.4450
Std.	0.0288	0.0065	3.4332	2.6230
Ink Jet printer				
Mean	0.0760	0.9731	**15.4543**	9.7992
Std.	0.0401	0.0293	9.0634	5.3896

Spectral NG printer model for the inkjet printer resulted higher spectral and colorimetric difference than the laser printer. Using estimated NPs or mixed NPs for NG modeling of the laser printer resulted less than 4% of spectral error which is almost half of the 8% spectral error resulted for the inkjet printer. The same is true for colorimetric difference too. Spectral NG printer modeling works more accurately for the laser printer than inkjet printer.

Using estimated and mixed NPs for Spectral NG modeling of laser printer gives smaller spectral and colorimetric differences. That means using estimated NPs by this less complicated Kubelka-Munk theory for laser printer modeling improves print estimation than using measured NPs.

We saw that, NG model has less accurate performance on inkjet printer than laser printer. Whereas using estimated NPs has not much effect on the modeling of the inkjet printer. It doesn’t improve it nor make it worse. Mixing the estimated NPs and measured NPs for NG modeling improves a little the result of spectral NG model of the inkjet printer but it doesn’t have much influence on laser printer. It almost works equally like using just estimated NPs for NG model of the laser printer. The performance of the method for the inkjet printer with HP photo paper was very poor. These errors were almost double of the errors which have been found using the other two papers on the same printer.

Table 5.5: Spectral and colorimetric difference for NG model for color copy paper

	NG with estimated NPs			
Laser Printer	RMSE	GFC	ΔE	ΔE94
Mean	0.0358	0.9930	**7.3620**	5.0476
Std.	0.0233	0.0096	4.1586	2.7372
Ink Jet printer				
Mean	0.0749	0.9718	**16.0265**	9.9521
Std.	0.0394	0.0291	9.0443	4.9305
	NG with measured NPs			
Laser Printer	RMSE	GFC	ΔE	ΔE94
Mean	0.0390	0.9942	**7.8647**	5.3988
Std.	0.0252	0.0073	4.9943	2.8342
Ink Jet printer				
Mean	0.0708	0.9777	**14.7690**	9.0236
Std.	0.0404	0.0233	8.9696	4.9683
	NG with mixed NPs			
Laser Printer	RMSE	GFC	ΔE	ΔE94
	0.0361	0.9947	**6.9254**	4.781
Mean	0.0251	0.0065	4.1005	2.6841
Std.				
Ink Jet printer				
Mean	0.0735	0.9736	**15.8245**	9.7646
Std.	0.0393	0.0294	9.2825	5.1346

Table 5.6: Spectral and colorimetric difference for NG model for HP photo paper

	NG with estimated NPs			
Inkjet printer	RMSE	GFC	ΔE	ΔE94
Mean	0.094	0.947	**22.085**	12.334
Std.	0.0572	0.0758	15.1384	8.524
	NG with measured NPs			
Inkjet printer	RMSE	GFC	ΔE	ΔE94
Mean	0.089	0.957	**21.391**	11.958
Std.	0.0602	0.0613	15.8066	9.1387
	NG with mixed NPs			
Inkjet printer	RMSE	GFC	ΔE	ΔE94
Mean	0.093	0.953	**21.960**	12.289
Std.	0.0583	0.0628	15.6034	8.819

5.3 YNSN Modeling

We also examine the results of the spectral and perceptual differences between the measured and estimated reflectance of our test chart using YNSN model for various *n* values. We list the mean and standard deviations of the spectral and perceptual differences for various ‘n’ values in the table 5.7-5.11 and we give all lists of values for each patches of the test chart in Appendix D.

Table 5.7: Spectral and colorimetric difference for YNSN model for Laser printer and Staple paper

	SRMSE							
	n=0.5	n=1	n=1.5	n=2	n=2.5	n=3	n=3.5	n=4
	Measured NPs							
Mean	0.132	0.048	**0.028**	0.029	0.033	0.0369	0.040	0.043
Std.	0.064	0.029	0.019	0.019	0.023	0.0263	0.029	0.030
	Estimated NPs							
Mean	0.130	0.044	**0.029**	0.034	0.041	0.046	0.050	0.053
Std.	0.064	0.029	0.016	0.019	0.025	0.028	0.029	0.032
	Mixed NPs							
Mean	0.131	0.046	**0.027**	0.030	0.035	0.040	0.043	0.046
Std.	0.064	0.029	0.018	0.020	0.024	0.027	0.029	0.031
	ΔE_{ab} D50							
	n=0.5	n=1	n=1.5	n=2	n=2.5	n=3	n=3.5	n=4
	Measured NPs							
Mean	17.967	8.030	**6.637**	7.406	8.298	9.029	9.607	10.058
Std.	7.933	4.324	4.106	4.527	4.857	5.065	5.192	5.287
	Estimated NPs							
Mean	18.452	7.335	**5.958**	7.148	8.363	9.314	10.032	10.583
Std.	8.072	3.623	2.740	3.426	3.944	4.263	4.487	4.660
	Mixed NPs							
Mean	17.955	7.324	**5.842**	6.778	7.819	8.653	9.289	9.779
Std.	8.063	3.433	2.739	3.357	3.810	4.084	4.277	4.427
	ΔE_{94} D50							
	n=0.5	n=1	n=1.5	n=2	n=2.5	n=3	n=3.5	n=4
	Measured NPs							
Mean	13.724	5.818	**4.314**	4.671	5.273	5.804	6.227	6.561
Std.	5.881	2.646	2.224	2.600	2.910	3.103	3.238	3.342
	Estimated NPs							
Mean	13.757	5.319	**4.136**	4.936	5.807	6.506	7.039	7.449
Std.	5.867	2.668	2.106	2.632	3.042	3.290	3.469	3.605
	Mixed NPs							
Mean	13.673	5.445	**3.908**	4.424	5.148	5.747	6.208	6.567
Std.	5.964	2.623	1.997	2.340	2.647	2.861	3.027	3.156

Table 5.8 : Spectral and colorimetric difference for YNSN model for Inkjet printer and Staple paper

	sRMSE							
	n=0.5	n=1	n=1.5	n=2	n=2.5	n=3	n=3.5	n=4
	Measured NPs							
Mean	0.118	**0.072**	0.075	0.081	0.085	0.089	0.092	0.094
Std.	0.070	0.041	0.041	0.047	0.052	0.056	0.058	0.060
	Estimated NPs							
Mean	0.120	**0.077**	0.080	0.085	0.088	0.091	0.093	0.095
Std.	0.066	0.041	0.040	0.045	0.049	0.052	0.054	0.056
	Mixed NPs							
Mean	0.117	**0.076**	0.081	0.088	0.093	0.097	0.100	0.102
Std.	0.068	0.040	0.042	0.048	0.052	0.056	0.058	0.060
	ΔE_{ab} D50							
	n=0.5	n=1	n=1.5	n=2	n=2.5	n=3	n=3.5	n=4
	Measured NPs							
Mean	20.643	14.189	**13.798**	14.224	14.644	14.985	15.258	15.478
Std.	11.439	8.611	7.658	7.550	7.695	7.878	8.045	8.187
	Estimated NPs							
Mean	21.515	15.563	**15.149**	15.477	15.806	16.076	16.293	16.468
Std.	11.781	8.920	7.939	7.719	7.761	7.859	7.957	8.044
	Mixed NPs							
Mean	21.595	15.454	**15.109**	15.543	15.985	16.338	16.619	16.843
Std.	11.885	9.063	8.147	7.992	8.041	8.151	8.263	8.364
	ΔE_{94} D50							
	n=0.5	n=1	n=1.5	n=2	n=2.5	n=3	n=3.5	n=4
	Measured NPs							
Mean	13.656	**8.804**	8.810	9.336	9.790	10.147	10.426	10.649
Std.	7.480	5.032	4.768	5.052	5.369	5.622	5.816	5.966
	Estimated NPs							
Mean	14.243	**9.844**	9.934	10.443	10.860	11.178	11.424	11.617
Std.	7.432	5.256	4.955	5.127	5.360	5.555	5.709	5.829
	Mixed NPs							
Mean	14.144	**9.799**	10.045	10.678	11.197	11.588	11.888	12.124
Std.	7.572	5.390	5.181	5.410	5.646	5.842	5.997	6.118

For the case of laser printer and staple copy paper using the estimated and mixed NPs gives better perceptual results than using measured NPs for n equals to 1-1.5 both spectrally and colorimetrically. When it comes to the color copy paper, using mixed NPs for spectral modeling gives improved spectral results than using estimated NPs only. Their color difference also shows the improvement resulted from using mixed NPs for a number of different n values.

In the other case, for the inkjet printer with all papers we see very poor performance. For the staple copy paper using measured or mixed NPs doesn’t have any influence on the performance. For HP photo paper the performance become even worse. Using estimated or mixed NPs also doesn’t improve the performance or it doesn’t make it worse for all types of papers. Using mixed NPs or only Estimated NPS has almost similar effect for overall performance of the spectral printer model.

Table 5.9 : Spectral and colorimetric difference for YNSN model for Laser printer and color copy paper

	sRMSE							
	n=0.5	n=1	n=1.5	n=2	n=2.5	n=3	n=3.5	n=4
	Measured NPs							
Mean	0.117	0.039	**0.024**	0.029	0.035	0.041	0.045	0.048
Std.	0.062	0.025	0.015	0.020	0.023	0.026	0.028	0.030
	Estimated NPs							
Mean	0.116	0.036	**0.031**	0.041	0.050	0.056	0.061	0.064
Std.	0.062	0.023	0.014	0.021	0.025	0.028	0.030	0.032
	Mixed NPs							
Mean	0.116	0.036	**0.026**	0.033	0.041	0.046	0.051	0.054
Std.	0.062	0.025	0.014	0.020	0.024	0.027	0.029	0.031
	ΔE_{ab} D50							
	n=0.5	n=1	n=1.5	n=2	n=2.5	n=3	n=3.5	n=4
	Measured NPs							
Mean	16.898	7.865	**7.179**	8.161	9.123	9.887	10.472	10.924
Std.	7.956	4.994	4.915	5.234	5.438	5.545	5.612	5.667
	Estimated NPs							
Mean	17.883	7.362	**6.977**	8.600	10.007	11.067	11.856	12.455
Std.	7.996	4.159	3.736	4.330	4.731	4.961	5.126	5.256
	Mixed NPs							
Mean	16.960	6.925	**6.415**	7.715	8.897	9.807	10.487	11.006
Std.	7.971	4.101	3.658	4.161	4.483	4.654	4.775	4.874
	ΔE_{94} D50							
	n=0.5	n=1	n=1.5	n=2	n=2.5	n=3	n=3.5	n=4
	Measured NPs							
Mean	12.486	5.399	**4.634**	5.337	6.091	6.693	7.149	7.500
Std.	5.634	2.834	2.827	3.180	3.379	3.490	3.575	3.646
	Estimated NPs							
Mean	12.559	5.048	**5.147**	6.466	7.600	8.428	9.033	9.491
Std.	5.526	2.737	2.847	3.420	3.667	3.820	3.945	4.048
	Mixed NPs							
Mean	12.367	4.781	**4.326**	5.317	6.251	6.958	7.480	7.876
Std.	5.696	2.684	2.429	2.879	3.115	3.257	3.375	3.475

Table 5.10: Spectral and colorimetric difference for YNSN model for Inkjet printer and color paper

	sRMSE							
	n=0.5	n=1	n=1.5	n=2	n=2.5	n=3	n=3.5	n=4
	Measured NPs							
Mean	0.118	**0.071**	0.071	0.076	0.079	0.082	0.085	0.086
Std.	0.068	0.040	0.040	0.045	0.049	0.052	0.054	0.056
	Estimated NPs							
Mean	0.118	**0.075**	0.076	0.080	0.083	0.086	0.088	0.089
Std.	0.065	0.039	0.039	0.043	0.046	0.049	0.051	0.052
	Mixed NPs							
Mean	0.116	**0.074**	0.076	0.082	0.086	0.090	0.092	0.094
Std.	0.066	0.039	0.040	0.046	0.050	0.053	0.055	0.057
	ΔE_{ab} D50							
	n=0.5	n=1	n=1.5	n=2	n=2.5	n=3	n=3.5	n=4
	Measured NPs							
Mean	21.703	14.769	**13.982**	14.166	14.452	14.709	14.922	15.098
Std.	12.071	8.970	7.614	7.264	7.247	7.329	7.431	7.530
	Estimated NPs							
Mean	22.624	16.026	**15.148**	15.245	15.452	15.647	15.813	15.952
Std.	12.289	9.044	7.740	7.329	7.260	7.292	7.352	7.415
	Mixed NPs							
Mean	22.631	15.825	**14.969**	15.132	15.422	15.686	15.906	16.087
Std.	12.435	9.282	8.021	7.652	7.578	7.602	7.659	7.723
	ΔE_{94} D50							
	n=0.5	n=1	n=1.5	n=2	n=2.5	n=3	n=3.5	n=4
	Measured NPs							
Mean	14.521	9.024	**8.592**	8.894	9.221	9.496	9.718	9.898
Std.	7.938	4.968	4.238	4.291	4.505	4.711	4.883	5.023
	Estimated NPs							
Mean	15.139	9.952	**9.606**	9.921	10.236	10.493	10.699	10.864
Std.	7.861	4.930	4.340	4.396	4.591	4.774	4.924	5.044
	Mixed NPs							
Mean	15.003	9.765	**9.491**	9.886	10.273	10.588	10.838	11.039
Std.	8.046	5.135	4.582	4.652	4.834	4.998	5.134	5.243

Table 5.11: Spectral and colorimetric difference for YNSN model for Inkjet printer and photo paper

	sRMSE							
	n=0.5	n=1	n=1.5	n=2	n=2.5	n=3	n=3.5	n=4
	Measured NPs							
Mean	0.137	**0.089**	0.096	0.108	0.118	0.125	0.131	0.135
Std.	0.078	0.060	0.063	0.070	0.076	0.080	0.084	0.087
	Estimated NPs							
Mean	0.137	**0.094**	0.100	0.111	0.119	0.125	0.129	0.133
Std.	0.075	0.057	0.060	0.065	0.070	0.074	0.076	0.079
	Mixed NPs							
Mean	0.134	**0.093**	0.103	0.116	0.127	0.135	0.141	0.146
Std.	0.076	0.058	0.062	0.069	0.075	0.079	0.083	0.086
	ΔE_{ab} D50							
	n=0.5	n=1	n=1.5	n=2	n=2.5	n=3	n=3.5	n=4
	Measured NPs							
Mean	28.962	21.391	**20.504**	21.436	22.550	23.529	24.333	24.984
Std.	16.750	15.807	15.371	15.266	15.308	15.388	15.481	15.575
	Estimated NPs							
Mean	29.978	22.085	**21.189**	22.087	23.155	24.082	24.837	25.447
Std.	16.934	15.138	14.252	13.951	13.883	13.891	13.926	13.969
	Mixed NPs							
Mean	30.143	21.960	**21.085**	22.181	23.449	24.544	25.436	26.156
Std.	17.022	15.603	14.720	14.353	14.251	14.250	14.288	14.341
	ΔE_{94} D50							
	n=0.5	n=1	n=1.5	n=2	n=2.5	n=3	n=3.5	n=4
	Measured NPs							
Mean	18.096	11.958	**11.623**	12.706	13.808	14.714	15.433	16.005
Std.	10.686	9.139	8.732	8.833	9.075	9.327	9.551	9.744
	Estimated NPs							
Mean	18.283	12.334	**12.175**	13.332	14.439	15.320	16.007	16.548
Std.	10.681	8.524	7.999	8.012	8.188	8.395	8.587	8.754
	Mixed NPs							
Mean	18.177	**12.289**	12.386	13.770	15.063	16.089	16.889	17.521
Std.	10.841	8.819	8.323	8.371	8.559	8.771	8.968	9.141

As explained before using the YNSN model improves the performance of NG model. The improvement is a lot more visible for laser printer than inkjet printer. From the results, we are able to see that it is difficult to choose one specific *n* value for a good improvement of estimation of the model. As it can be seen from the figures in Appendix D and the above table of results the best n value for Laser printer with staple and color copy paper are 1.3 and 1.2 respectively. Also, for the case of Inkjet printer with staple, color copy and HP photo papers the best n values are (1.3 and 1.4) and (1.2 and 1.3) respectively.

As we see here, all improvements over NG model are found for n values in the range [1,1.4], particularly around n=1.3. In order to see these improvements more clearly we re-run the YNSN model for the n value with a finer step [1:0.1:2]. As an example we show the resulted plot for Laser printer and color copy paper in figure 5.16. The results for all types of papers and the two printers are shown in the Appendix D (figure D6-D10).

As explained in section 2.7, Jeremie Gerhardt [4] found the best n value for his spectral printer model of 7 channel inkjet printer to be around 2. He performed optimization for each channel in order to get a best n values which gives less spectral and colorimetric differences and during his experiment all color management was off, including dot-gain correction. In the contrary, in our experiment, we didn't perform any optimization independently. We just tested a number of n-values and we didn't make the dot-gain correction to be off. That is why the look up tables (Figure 5.11-5.15) are somewhat linear and that is why our result for n value is closer to 1 than Gerhardt's result (n=2). In our case YNSN improvement over NG performance is less than that of Gerhardt's work and that is because of the dot gain correction.

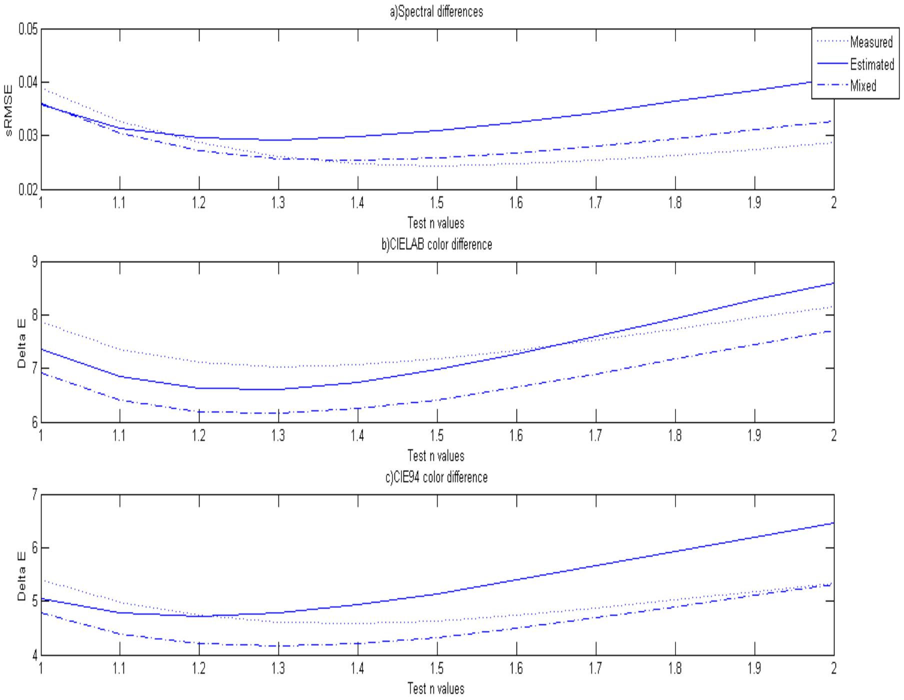


Figure 5.16: Spectral and color differences for the Laser printer and color copy paper A)spectral root mean square error B) CIELAB color difference C) CIE94 color difference

5.4 Suggestions

We focus mainly on evaluation of KM model for estimating NPs. We don't do much work on improving NG spectral printer model and YNSN model because of time shortage. But we want to mention important issues we need to consider for further enhancement of the two models accuracy. As Prof. Hersch's group described in their work [58], mechanical Dot gain is different when dots are printed alone on a paper; when they are printed in superposition with one other ink or printed in superposition with two other inks. The dot gain is also dependent on which solid ink the considered halftone layer is superposed. Based on this, they developed a model for computing the effective surface coverage of a dot according to its superposition conditions and they propose a model EYNSN (enhanced YNSN model) by improving the Yule-Nielsen modified Neugebauer model. Using ENYSN minimizes the difference between the measured spectral reflectances of the test chart and the EYNSN estimated reflectances of the test chart.

And also as described in Romain Rossier and Roger D. Hersch recent work [57] different inks have different properties. They have their own mechanical and optical properties. The mechanical and optical dot gain for different inks will be different. There for, the Yule-Nielsen spectral printer model should be extended in order to account for the different optical and possibly mechanical properties of the inks. They consider for each colorants of the printer a specific Yule-Nielsen n-factor. Optimal n-factors are calculated for halftones composed of several inks by weighting the inks best n-factors with a parabolic function of their surface coverages. This way, they show that it will be possible to get more improvements over simple YNNM.

Finally, given a printer with n-colorants, here we give some of our recommendation on different issues related with spectral printer modeling including, Which Neugebauer Primaries to print and to estimate, types of paper to use, and things to be done during printing and measurement process.

- Print and measure primary colorants of the printer
- Estimate the rest of the NPs
- If possible making half of the NPs to be measured and half of the NPs to be estimated will give a little bit better results sometimes. We need to make sure that the cost of printing and measuring half of the NPs should not be greater than the improvements we get over only estimated NPs.
- During printing colorants, make sure there is no mixing of color from the other channels. This can be done by having direct access to the printer driver or by using Adobe photo shop software with all types of color managements being off.
- Kubelka-Munk gives an accurate prediction for more opaque papers. While choosing a paper, no matter how cheap it is just focus on the opacity of the paper. The higher the opacity of the paper the more accurate will be the model.
- Optical brightness of the paper might affect the overall result of the model. Using UV filter during measurement will solve this problem.
- During measuring spectral reflectances of the patches always make sure that you are using white backing. Using more than 20 blank paper of the same type, as the one we are measuring, as a background will be enough.
- Incorporating mechanical dot gain effect and optical dot gain effect through effective colorant coverage LUTs and YN n factor will increase the performance of the spectral printer model.
- Treating each channels of the printer independently for computing the best YN n factor will be recommended since different inks has different mechanical and optical properties.
- By the time of calculating effective colorant coverage, considering effective colorant coverage in every superposition condition might help enhancing the model accuracy.

6. Conclusion

In this study we evaluated the Kubelka-Munk theory for estimating NPs for spectral printer characterization. We tested the theory on three types of papers and two types of printers. We also mix the measured and estimated NPs in order to see if there will be a change in the overall performance and we tested DORT2002 software of Mid Sweden University for getting some improvements over Kubelka-Munk model.

For the case of choosing measurement devices, we performed the comparison between Hyper-Spectral camera and multispectral spectrophotometers. We used the NEO's Hyper-Spectral camera and the two color lab spectrophotometers. The accuracy of the Hyper-Spectral camera was very interesting but the time we have was not enough to borrow the camera from NEO. Even if we could borrow it, the time required for extraction of reflectance for all our experimental measurements will be a problem for us. We choose Gretag Macbeth Eye One spectrolino for our experimental measurements because we can't use HySpex for the mentioned reasons, for its UV-filter and since the performance of Eye one pro is much closer to HySpex.

Our comparisons between the measured reflectances of the patches of our test chart and the estimated reflectances of the patches of the test chart using the three types of NPs (measured, estimated and mixed) shows us the reasonability of the kubelka-munk theory for spectral printer modeling. Sometimes the spectral printer model gives very poor estimation but it is for all types of NPs. The model performance differs from printer to printer and from paper to paper.

We have showed that the spectral estimations of both NG and YNSN models in laser printers perform much better than inkjet printers. We also see that using any kind of photo paper will not assure us to get a good estimation. Using simple and very cheap copy paper will give us even better estimation than using some expensive photo papers. Of course the opacity is still a very good criterion for choosing good paper for KM theory. The higher the opacity the higher the performance of the KM theory will be. The way we used DORT2002 doesn't give us the expected improvement. Instead, the differences between the estimated and measured NPs were much larger than those differences found for KM theory. We finally give some suggestions on different issues related to spectral printer modeling.

As future work, we have to find some other way of improving our Spectral printer models. There have been lots of researches done in this area. Among them using cellular NG model, taking care of the effective dot sizes of NPs and EYNSN are included.

In the future, the kubelka-Munk theory we used for this thesis should be evaluated so that we could get better performance. For example, we can consider adding more paper, ink and light interaction properties to this simple KM theory. There are also numbers of works done for improving KM theory. DORT2002, with careful measurements of scattering and absorption coefficient measurements, should give improved performance. May be using appropriate values for all parameters of the software in place of those default values might give us the expected improvement.

Here we did this thesis work based on CMYK printers but the estimating spectral reflectances of NPs will be more important for printers with higher number of channels. We were trying to characterize HP 12 channel printer and performing colorant selection. Because of time delay to get the printer and its SDK, we couldn't finish our job as planned. Applying and testing the KM theory for estimating NPs for these types of printers, with higher number of colorants, and using their spectral printer models for colorant selection will be a good idea for future work.

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Appendix A: NPs and their colorant coverage information

Here are the NPs names in the ECI2002 CMYK chart and the area coverage given by percentage divided by 100.

Table A1: NPs

C	M	Y	B	Patch names
0	0	0	0	R75-83
1	0	0	0	I22
0	1	0	0	J63
0	0	1	0	K70
0	0	0	1	L77
1	1	0	0	L2
1	0	1	0	D21
1	0	0	1	N59
0	1	1	0	F5
0	1	0	1	O64
0	0	1	1	Q26
1	1	1	0	C74
0	1	1	1	Q28
1	0	1	1	R33
1	1	0	1	N57
1	1	1	1	R35

Table A2: The test chart names in ECI2002 CMYK chart and their colorant concentration.

patch names	C	M	Y	K
A14	0.00	70.00	0.00	0.00
A28	0.00	40.00	0.00	20.00
A42	20.00	0.00	100.00	60.00
A56	70.00	0.00	70.00	60.00
A70	0.00	3.00	40.00	3.00
A83	20.00	40.00	55.00	0.00
B14	55.00	0.00	10.00	0.00
B28	100.00	85.00	85.00	100.00
B42	100.00	40.00	70.00	0.00
B56	55.00	20.00	40.00	0.00
B70	40.00	20.00	100.00	40.00
B83	100.00	20.00	20.00	0.00
C14	0.00	20.00	100.00	60.00
C28	100.00	70.00	0.00	0.00
C42	100.00	40.00	0.00	20.00
C56	20.00	100.00	100.00	60.00
C70	100.00	0.00	100.00	0.00

C83	0.00	40.00	0.00	3.00
D14	40.00	0.00	40.00	60.00
D28	70.00	40.00	70.00	20.00
D42	0.00	100.00	100.00	70.00
D56	70.00	100.00	85.00	0.00
D70	40.00	55.00	40.00	0.00
D83	70.00	40.00	20.00	40.00
E14	40.00	100.00	10.00	0.00
E28	40.00	0.00	85.00	0.00
E42	70.00	70.00	20.00	60.00
E56	70.00	40.00	10.00	20.00
E70	70.00	20.00	85.00	0.00
E83	100.00	10.00	10.00	0.00
F14	3.00	40.00	3.00	40.00
F28	40.00	100.00	40.00	60.00
F42	10.00	10.00	10.00	0.00
F56	100.00	0.00	100.00	20.00
F70	100.00	100.00	100.00	60.00
F83	20.00	20.00	40.00	40.00
G14	30.00	30.00	40.00	0.00
G28	100.00	70.00	0.00	60.00
G42	0.00	70.00	70.00	0.00
G56	40.00	70.00	40.00	0.00
G70	40.00	85.00	85.00	0.00
G83	0.00	40.00	20.00	0.00
H14	70.00	40.00	40.00	20.00
H28	100.00	55.00	100.00	0.00
H42	70.00	40.00	30.00	0.00
H56	100.00	10.00	20.00	0.00
H70	0.00	0.00	100.00	20.00
H83	70.00	100.00	0.00	60.00
I14	100.00	85.00	100.00	0.00
I28	100.00	70.00	70.00	40.00
I42	100.00	40.00	40.00	20.00
I56	100.00	0.00	0.00	0.00
I70	20.00	70.00	70.00	60.00
I83	100.00	10.00	0.00	20.00
J14	0.00	0.00	0.00	10.00
J28	55.00	0.00	20.00	0.00
J42	10.00	0.00	0.00	0.00
J56	0.00	0.00	0.00	70.00
J70	70.00	10.00	85.00	0.00
J83	55.00	100.00	30.00	0.00
K14	40.00	40.00	0.00	3.00
K28	10.00	70.00	55.00	0.00
K42	0.00	70.00	70.00	40.00
K56	0.00	40.00	40.00	20.00

K70	0.00	0.00	100.00	0.00
K83	100.00	40.00	70.00	60.00
L14	85.00	55.00	0.00	0.00
L28	0.00	10.00	0.00	0.00
L42	20.00	10.00	20.00	0.00
L56	10.00	0.00	70.00	0.00
L70	0.00	70.00	0.00	0.00
L83	20.00	85.00	55.00	0.00
M14	40.00	100.00	100.00	40.00
M28	40.00	3.00	0.00	40.00
M42	70.00	55.00	20.00	0.00
M56	0.00	55.00	55.00	0.00
M70	85.00	0.00	85.00	0.00
M83	40.00	27.00	27.00	0.00
N14	0.00	40.00	70.00	60.00
N28	85.00	55.00	30.00	0.00
N42	40.00	0.00	3.00	0.00
N56	10.00	10.00	20.00	0.00
N70	10.00	30.00	70.00	0.00
N83	100.00	0.00	100.00	80.00
O14	30.00	85.00	55.00	0.00
O28	30.00	100.00	70.00	0.00
O42	55.00	10.00	100.00	0.00
O56	0.00	40.00	0.00	100.00
O70	30.00	70.00	85.00	0.00
O83	55.00	70.00	70.00	0.00
P14	55.00	20.00	0.00	0.00
P28	10.00	40.00	100.00	20.00
P42	70.00	30.00	70.00	0.00
P56	70.00	85.00	0.00	0.00
P70	0.00	10.00	20.00	20.00
P83	100.00	70.00	0.00	80.00
Q14	100.00	0.00	70.00	80.00
Q28	0.00	100.00	100.00	100.00
Q42	30.00	100.00	10.00	0.00
Q56	55.00	10.00	70.00	0.00
Q70	30.00	55.00	55.00	0.00
Q83	55.00	100.00	85.00	0.00
R14	55.00	70.00	100.00	0.00
R28	55.00	20.00	30.00	0.00
R42	10.00	55.00	85.00	0.00
R56	70.00	30.00	100.00	0.00
R70	70.00	85.00	30.00	0.00
R83	0.00	0.00	0.00	0.00

Table A3: Test charts effective colorant coverage (percentage/100)

	C	M	Y	K
A14	0	0,762208	0	0
A28	0	0,490335	0	0,336882
A42	0,278129	0	1	0,769735
A56	0,696733	0	0,764483	0,769735
A70	0	0,067244	0,475336	0,03432
A83	0,278129	0,490335	0,66594	0
B14	0,585794	0	0,144075	0
B28	1	0,924027	0,802905	1
B42	1	0,490335	0,764483	0
B56	0,585794	0,269789	0,475336	0
B70	0,465168	0,269789	1	0,619409
B83	1	0,269789	0,345421	0
C14	0	0,269789	1	0,769735
C28	1	0,762208	0	0
C42	1	0,490335	0	0,336882
C56	0,278129	1	1	0,769735
C70	1	0	1	0
C83	0	0,490335	0	0,03432
D14	0,465168	0	0,475336	0,769735
D28	0,696733	0,490335	0,764483	0,336882
D42	0	1	1	0,882299
D56	0,696733	1	0,802905	0
D70	0,465168	0,649729	0,475336	0
D83	0,696733	0,490335	0,345421	0,619409
E14	0,465168	1	0,144075	0
E28	0,465168	0	0,802905	0
E42	0,696733	0,762208	0,345421	0,769735
E56	0,696733	0,490335	0,144075	0,336882
E70	0,696733	0,269789	0,802905	0
E83	1	0,180595	0,144075	0
F14	0,070027	0,490335	0,216675	0,619409
F28	0,465168	1	0,475336	0,769735
F42	0,179706	0,180595	0,144075	0
F56	1	0	1	0,336882
F70	1	1	1	0,769735
F83	0,278129	0,269789	0,475336	0,619409
G14	0,367926	0,392854	0,475336	0
G28	1	0,762208	0	0,769735
G42	0	0,762208	0,764483	0

G56	0,465168	0,762208	0,475336	0
G70	0,465168	0,924027	0,802905	0
G83	0	0,490335	0,345421	0
H14	0,696733	0,490335	0,475336	0,336882
H28	1	0,649729	1	0
H42	0,696733	0,490335	0,413213	0
H56	1	0,180595	0,345421	0
H70	0	0	1	0,336882
H83	0,696733	1	0	0,769735
I14	1	0,924027	1	0
I28	1	0,762208	0,764483	0,619409
I42	1	0,490335	0,475336	0,336882
I56	1	0	0	0
I70	0,278129	0,762208	0,764483	0,769735
I83	1	0,180595	0	0,336882
J14	0	0	0	0,137358
J28	0,585794	0	0,345421	0
J42	0,179706	0	0	0
J56	0	0	0	0,882299
J70	0,696733	0,180595	0,802905	0
J83	0,585794	1	0,413213	0
K14	0,465168	0,490335	0	0,03432
K28	0,179706	0,762208	0,66594	0
K42	0	0,762208	0,764483	0,619409
K56	0	0,490335	0,475336	0,336882
K70	0	0	1	0
K83	1	0,490335	0,764483	0,769735
L14	0,869271	0,649729	0	0
L28	0	0,180595	0	0
L42	0,278129	0,180595	0,345421	0
L56	0,179706	0	0,764483	0
L70	0	0,762208	0	0
L83	0,278129	0,924027	0,66594	0
M14	0,465168	1	1	0,619409
M28	0,465168	0,067244	0	0,619409
M42	0,696733	0,649729	0,345421	0
M56	0	0,649729	0,66594	0
M70	0,869271	0	0,802905	0
M83	0,465168	0,406216	0,368873	0
N14	0	0,490335	0,764483	0,769735

N28	0,869271	0,649729	0,413213	0
N42	0,465168	0	0,216675	0
N56	0,179706	0,180595	0,345421	0
N70	0,179706	0,392854	0,764483	0
N83	1	0	1	0,951303
O14	0,367926	0,924027	0,66594	0
O28	0,367926	1	0,764483	0
O42	0,585794	0,180595	1	0
O56	0	0,490335	0	1
O70	0,367926	0,762208	0,802905	0
O83	0,585794	0,762208	0,764483	0
P14	0,585794	0,269789	0	0
P28	0,179706	0,490335	1	0,336882
P42	0,696733	0,392854	0,764483	0
P56	0,696733	0,924027	0	0
P70	0	0,180595	0,345421	0,336882
P83	1	0,762208	0	0,951303
Q14	1	0	0,764483	0,951303
Q28	0	1	1	1
Q42	0,367926	1	0,144075	0
Q56	0,585794	0,180595	0,764483	0
Q70	0,367926	0,649729	0,66594	0
Q83	0,585794	1	0,802905	0
R14	0,585794	0,762208	1	0
R28	0,585794	0,269789	0,413213	0
R42	0,179706	0,649729	0,802905	0
R56	0,696733	0,392854	1	0
R70	0,696733	0,924027	0,413213	0
R83	0	0	0	0

Appendix B: Spectral and Color differences between estimated and measured NPs

Table B1: Spectral and color differences of NPs for Laser printer and color copy paper

C	M	Y	B		RMSE	GFC	DElab	DE94
0	0	0	0	R75-83	0.0000	1.0000	0.0000	0 .0000
1	0	0	0	I22	0.0000	1.0000	0.0000	0.0000
0	1	0	0	J63	0.0000	1.0000	0.0000	0.0000
0	0	1	0	K70	0.0000	1.0000	0.0000	0.0000
0	0	0	1	L77	0.0000	1.0000	0.0000	0.0000
1	1	0	0	L2	0.0173	0.9815	9.4801	3.8636
1	0	1	0	D21	0.0357	0.9762	20.4084	7.5806
1	0	0	1	N59	0.0359	0.9753	12.6621	12.3598
0	1	1	0	F5	0.0120	0.9997	12.5876	6.0314
0	1	0	1	O64	0.0396	0.9711	12.3847	12.3472
0	0	1	1	Q26	0.0405	0.9704	12.3522	12.3216
1	1	1	0	C74	0.0265	0.9193	7.5809	6.9675
0	1	1	1	Q28	0.0368	0.9890	11.8606	11.8458
1	0	1	1	R33	0.0284	0.9813	10.7453	10.6634
1	1	0	1	N57	0.0262	0.9800	11.5356	11.4744
1	1	1	1	R35	0.0120	0.9974	6.5926	6.5872
			mean		0,0194	0,9838	8,0119	6,3770
			std		0,0160	0,0207	6,2939	5,1163

Table B2: Spectral and color differences of NPs for Laser printer and staple paper

C	M	Y	K		RMSE	GFC	Delab	DE94
0	0	0	0	R75-83	0.0000	1.0000	0.0000	0.0000
1	0	0	0	I22	0.0000	1.0000	0.0000	0.0000
0	1	0	0	J63	0.0000	1.0000	0.0000	0.0000
0	0	1	0	K70	0.0000	1.0000	0.0000	0.0000
0	0	0	1	L77	0.0000	1.0000	0.0000	0.0000
1	1	0	0	L2	0.0143	0.9898	9.1852	3.4803
1	0	1	0	D21	0.0347	0.9803	19.4005	8.2828
1	0	0	1	N59	0.0216	0.9787	9.1893	8.2260
0	1	1	0	F5	0.0113	0.9998	10.8727	5.1402
0	1	0	1	O64	0.0313	0.9816	9.3198	9.3072
0	0	1	1	Q26	0.0339	0.9762	9.6586	9.5754
1	1	1	0	C74	0.0203	0.9541	4.4858	3.9707
0	1	1	1	Q28	0.0300	0.9799	8.9949	8.9621
1	0	1	1	R33	0.0229	0.9749	9.4992	9.0053

1	1	0	1	N57	0.0158	0.9903	8.3035	8.0985
1	1	1	1	R35	0.0079	0.9955	4.5351	4.5140
			mean		0.0153	0.9876	6,4653	4,9102
			Std		0.0131	0.0133	5,5108	3,9201

Table B3: Spectral and color differences of NPs for inkjet printer and color copy paper

C	M	Y	B		RMSE	GFC	Delab	DE94
0	0	0	0	R75-83	0.0000	1.0000	0.0000	0.0000
1	0	0	0	I22	0.0000	1.0000	0.0000	0.0000
0	1	0	0	J63	0.0000	1.0000	0.0000	0.0000
0	0	1	0	K70	0.0000	1.0000	0.0000	0.0000
0	0	0	1	L77	0.0000	1.0000	0.0000	0.0000
1	1	0	0	L2	0.0771	0.9593	17.1320	12.7588
1	0	1	0	D21	0.0657	0.9851	13.2379	9.7593
1	0	0	1	N59	0.0060	0.9888	4.8295	4.6120
0	1	1	0	F5	0.0263	0.9990	4.3352	3.6053
0	1	0	1	O64	0.0044	0.9925	6.1267	5.7087
0	0	1	1	Q26	0.0032	0.9958	3.7798	3.3755
1	1	1	0	C74	0.0957	0.8726	12.4787	12.1881
0	1	1	1	Q28	0.0066	0.9865	4.9074	4.5884
1	0	1	1	R33	0.0055	0.9921	4.9937	4.6252
1	1	0	1	N57	0.0080	0.9897	6.6513	6.4539
1	1	1	1	R35	0.0084	0.9907	4.5572	4.5384
			mean		0.0192	0.9845	5,18930	4,5134
			Std		0.0311	0.0315	5,1741	4,1921

Table B4: Spectral and color differences of NPs for inkjet printer and staple paper

C	M	Y	K		RMSE	GFC	DElab	DE94
0	0	0	0	R75-83	0.0000	1.0000	0.0000	0.0000
1	0	0	0	I22	0.0000	1.0000	0.0000	0.0000
0	1	0	0	J63	0.0000	1.0000	0.0000	0.0000
0	0	1	0	K70	0.0000	1.0000	0.0000	0.0000
0	0	0	1	L77	0.0000	1.0000	0.0000	0.0000
1	1	0	0	L2	0.0754	0.9644	15.8859	12.1005
1	0	1	0	D21	0.0657	0.9837	13.7025	9.9837
1	0	0	1	N59	0.0040	0.9921	3.9614	3.8001
0	1	1	0	F5	0.0280	0.9988	4.5040	3.7655
0	1	0	1	O64	0.0051	0.9910	4.9497	4.7234
0	0	1	1	Q26	0.0051	0.9855	3.5072	3.2626
1	1	1	0	C74	0.1052	0.8674	13.9728	13.8369

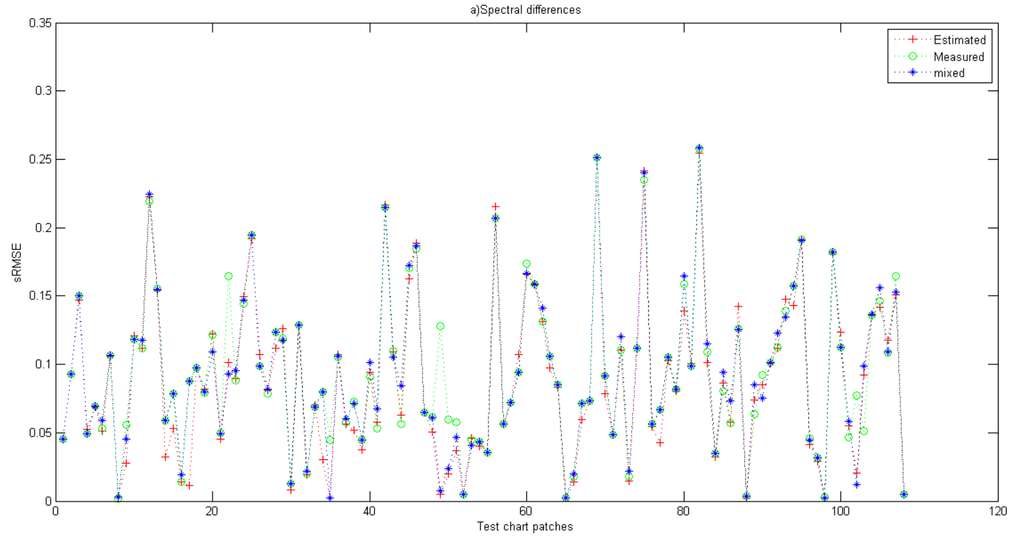
0	1	1	1	Q28	0.0037	0.9919	3.4967	3.3134
1	0	1	1	R33	0.0028	0.9957	4.1175	3.8603
1	1	0	1	N57	0.0054	0.9883	5.0860	4.9427
1	1	1	1	R35	0.0036	0.9926	2.0853	2.0802
			mean		0.0190	0.9845	4,7043	4,1043
			Std		0.0329	0.0325	5,2501	4,3531

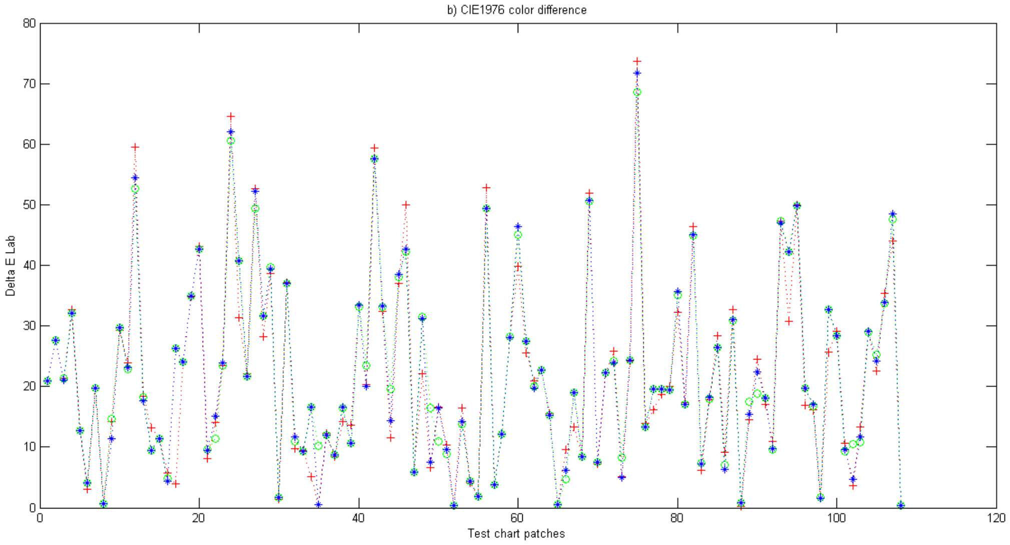
Table B5: Spectral and color differences of NPs for inkjet printer and HP photo paper

C	M	Y	K		RMSE	GFC	DElab	DE94
0	0	0	0	R75-83	0.0000	1.0000	0.0000	0.0000
1	0	0	0	I22	0.0000	1.0000	0.0000	0.0000
0	1	0	0	J63	0.0000	1.0000	0.0000	0.0000
0	0	1	0	K70	0.0000	1.0000	0.0000	0.0000
0	0	0	1	L77	0.0000	1.0000	0.0000	0.0000
1	1	0	0	L2	0.1065	0.9312	36.1224	22.5318
1	0	1	0	D21	0.0784	0.9788	22.6169	11.9471
1	0	0	1	N59	0.0006	0.9890	0.4125	0.3890
0	1	1	0	F5	0.0293	0.9996	10.8857	5.2151
0	1	0	1	O64	0.0027	0.9314	1.3960	1.3705
0	0	1	1	Q26	0.0025	0.9542	1.6563	1.6186
1	1	1	0	C74	0.1473	0.4846	21.1738	19.4661
0	1	1	1	Q28	0.0051	0.7419	1.7938	1.7760
1	0	1	1	R33	0.0042	0.7979	0.7049	0.6863
1	1	0	1	N57	0.0039	0.7770	0.9240	0.8488
1	1	1	1	R35	0.0050	0.7283	0.3641	0.3425
			mean		0.0241	0.8946	6.1282	4.1370
			std		0.0454	0.1486	10,9297	7,2655

Appendix C: Spectral and Color differences between estimated and measured reflectances of test chart using NG model

Here we plot the spectral and color difference between the estimated spectral reflectances using our NG Spectral printer model and the measured spectral reflectances of our test chart for all types of papers and printers. In one plot we provide the differences for the NG spectral model designed by measured, estimated and mixed NPs.





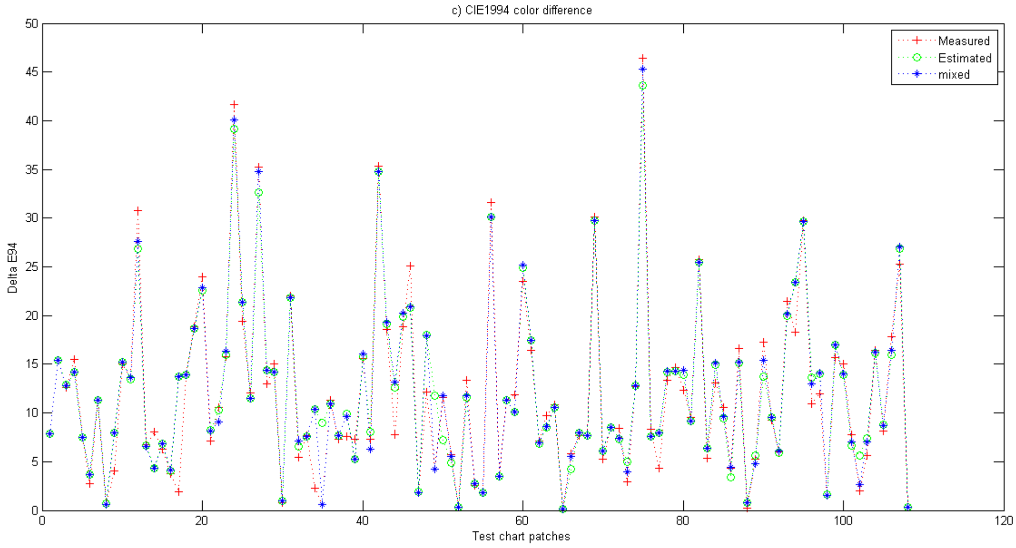
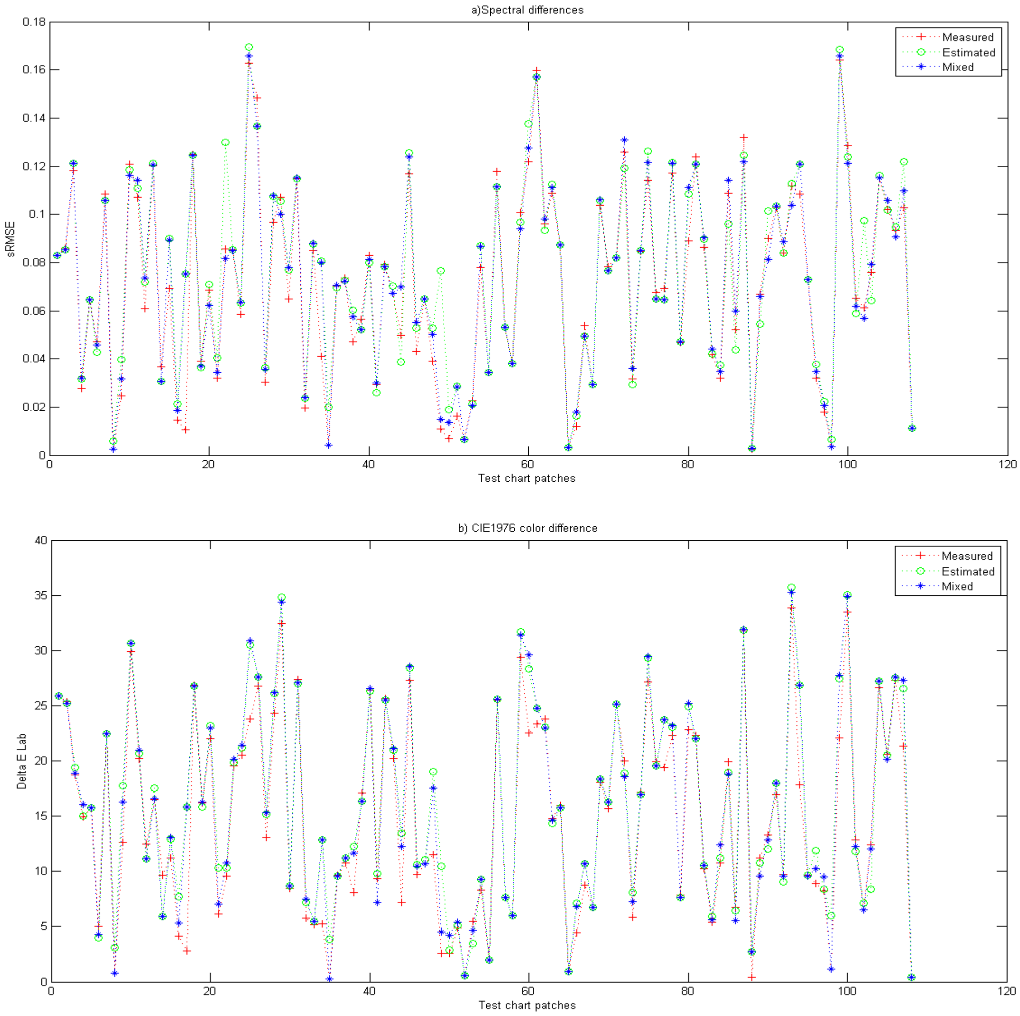


Figure c1: Spectral and color differences for the inkjet printer and HP photo paper. A)spectral root mean square error B) CIELAB color difference C) CIE94 color difference



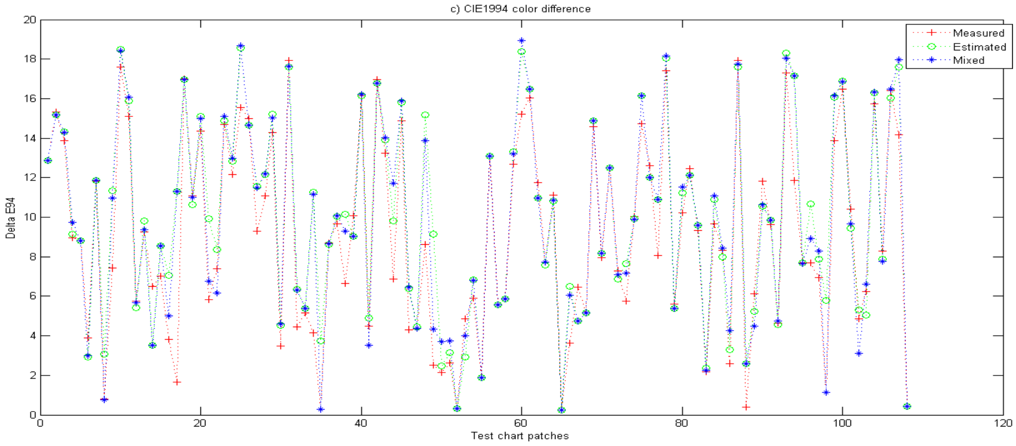
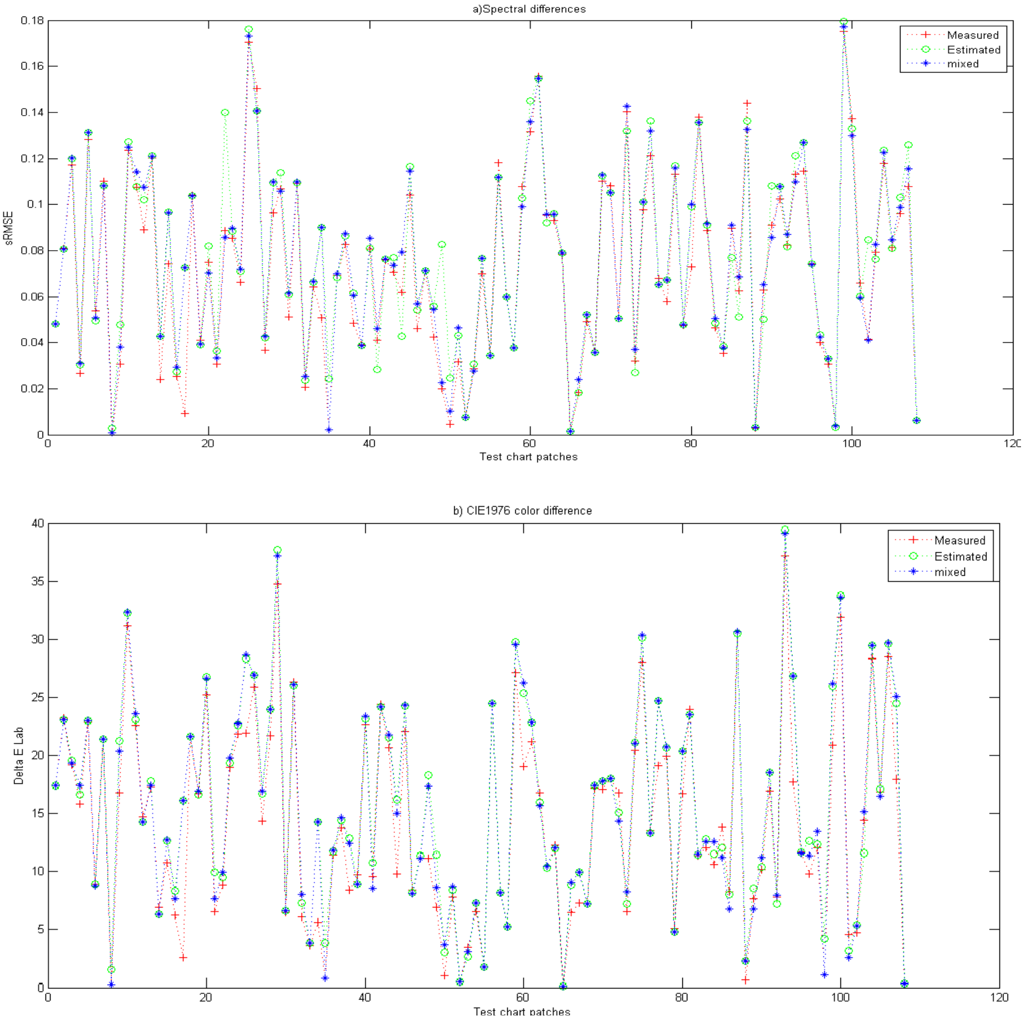


Figure c2: Spectral and color differences for the inkjet printer and color copy paper A)spectral root mean square error B) CIELAB color difference C) CIE94 color difference



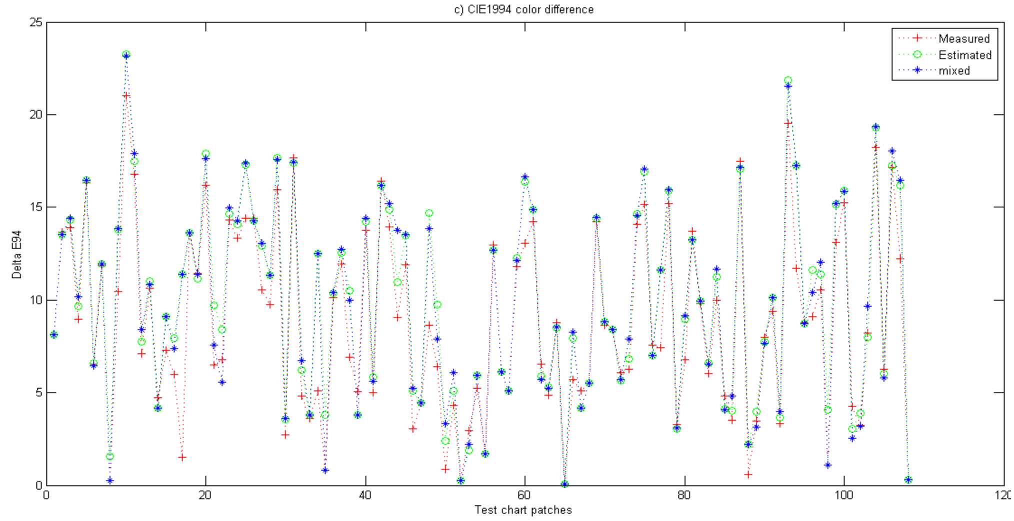
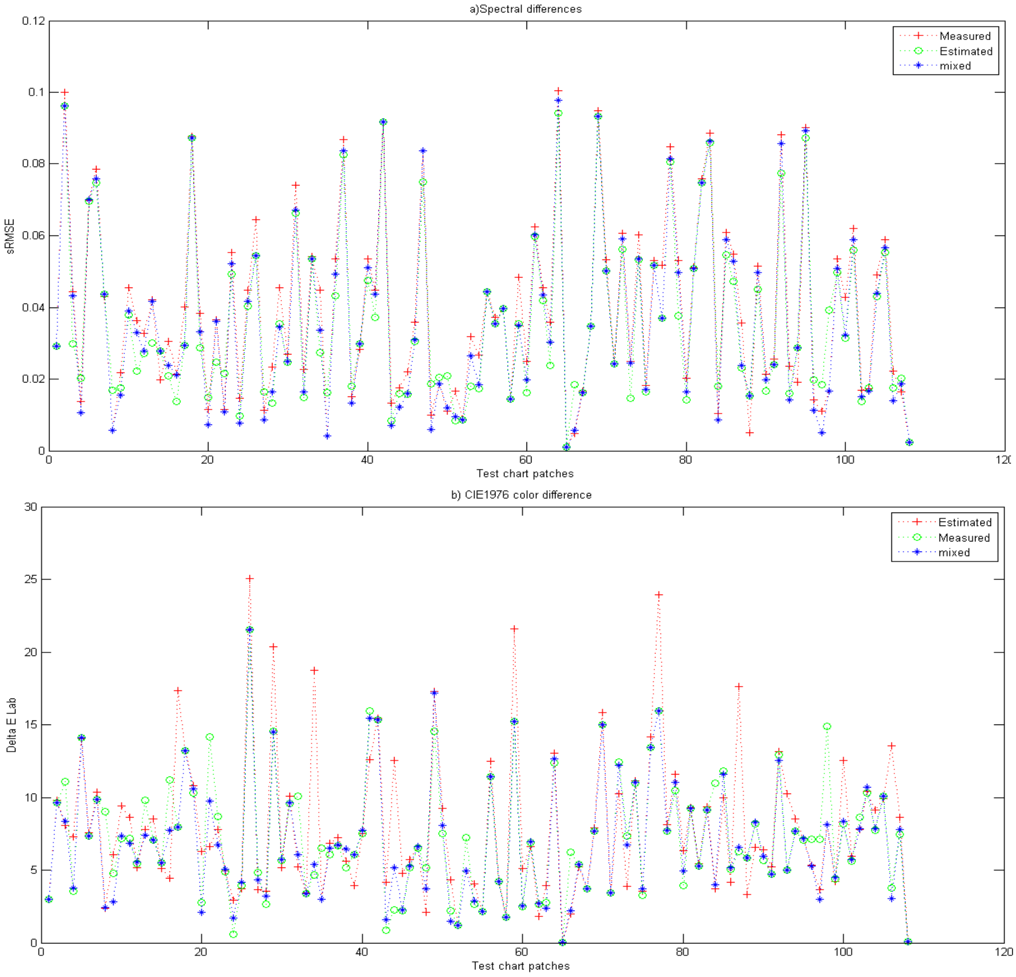


Figure c3: Spectral and color differences for the inkjet printer and staple copy paper A)spectral root mean square error B) CIELAB color difference C) CIE94 color difference



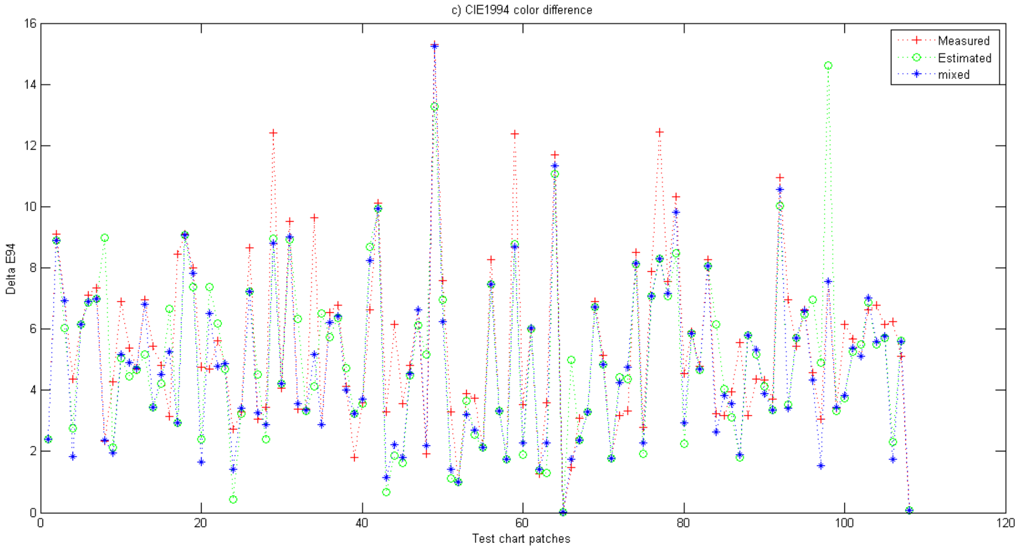
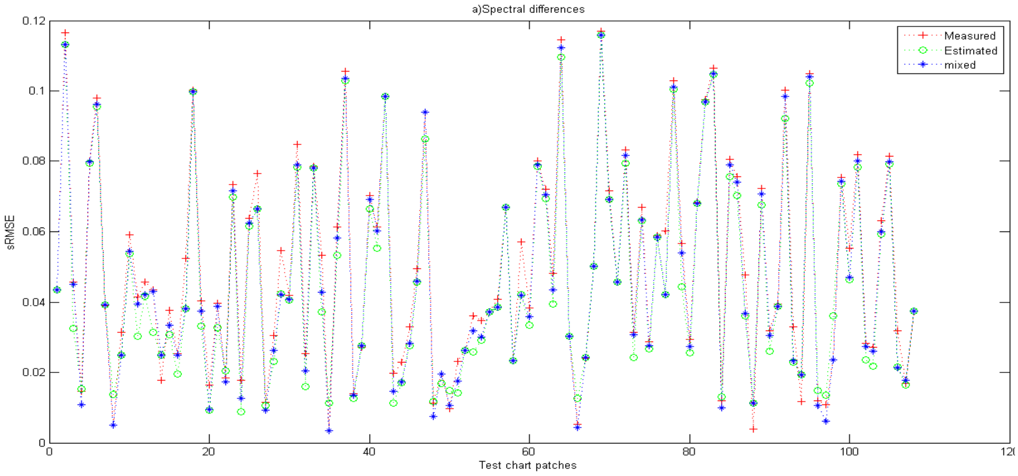
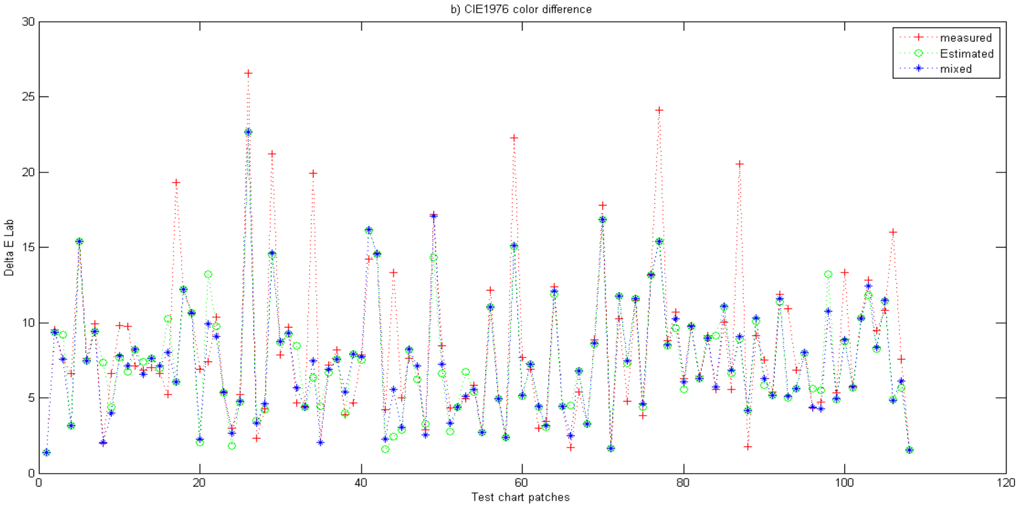


Figure c4: Spectral and color differences for the Laser printer and color copy paper A)spectral root mean square error B) CIELAB color difference C) CIE94 color difference





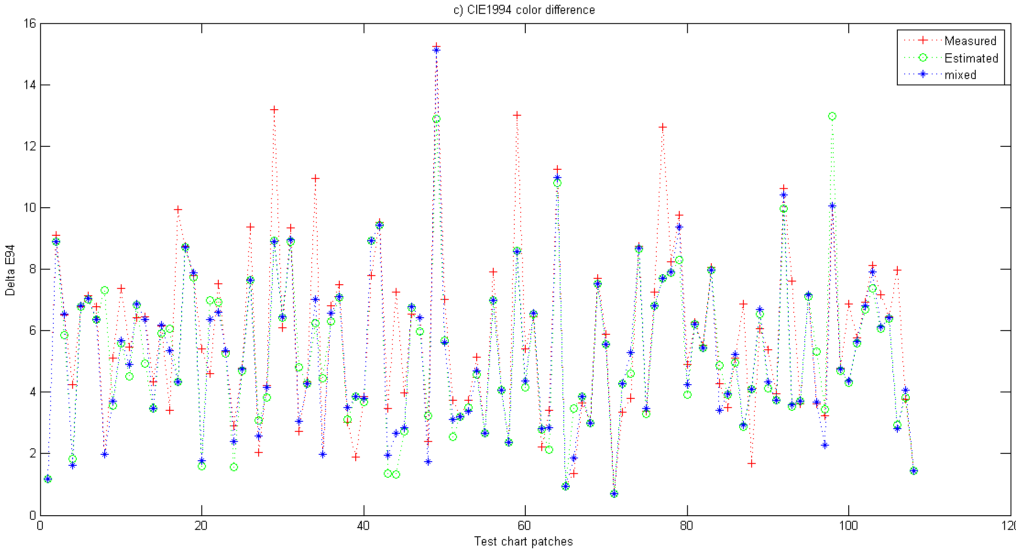


Figure c5: Spectral and color differences for the Laser printer and staple paper A)spectral root mean square error B) CIELAB color difference C) CIE94 color difference

Appendix D: Spectral and Color differences between estimated and measured reflectances of the test chart using YNSN model

In this part we present the mean spectral and color difference plots for the test chart. We plotted the errors for estimations of YNSM using estimated, measured and mixed NPs. We tested several values of n in the range [0.5:0.5:4].

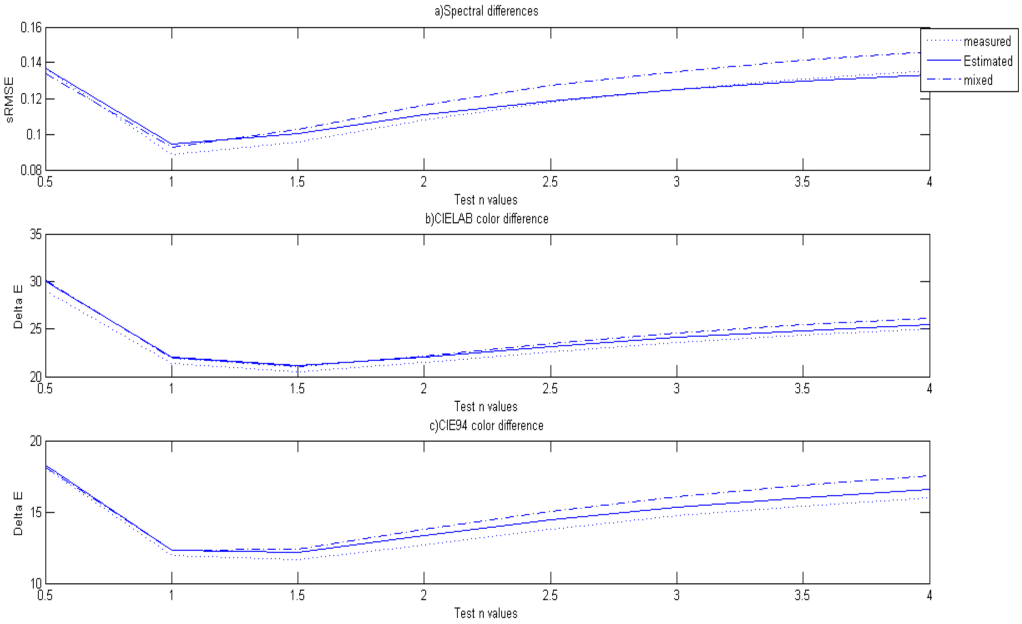


Figure D1: Spectral and color differences for the inkjet printer and HP photo paper A)spectral root mean square error B) CIELAB color difference C) CIE94 color difference

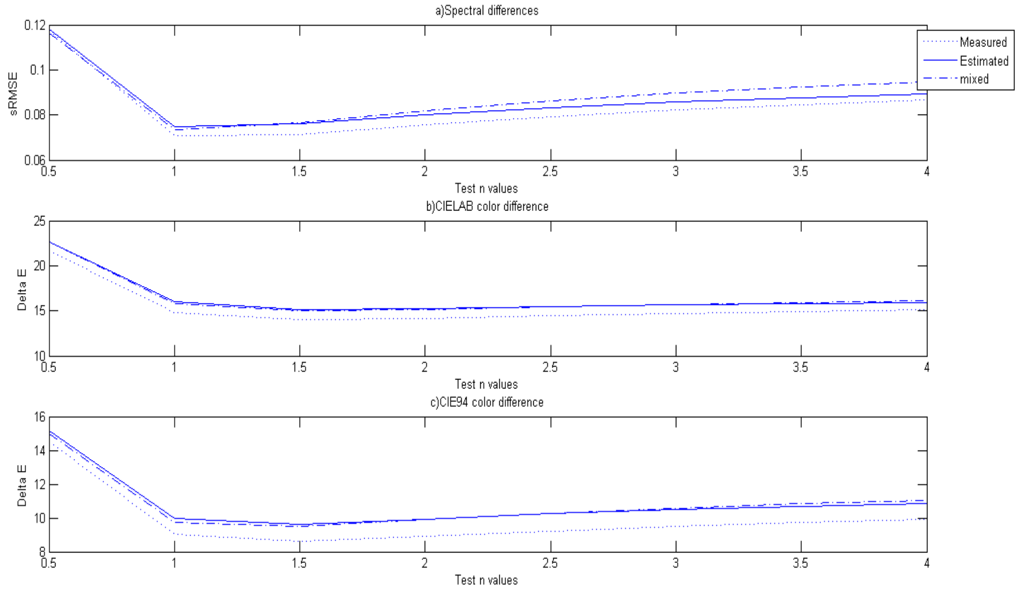


Figure D2: Spectral and color differences for the inkjet printer and color copy paper A)spectral root mean square error B) CIELAB color difference C) CIE94 color difference

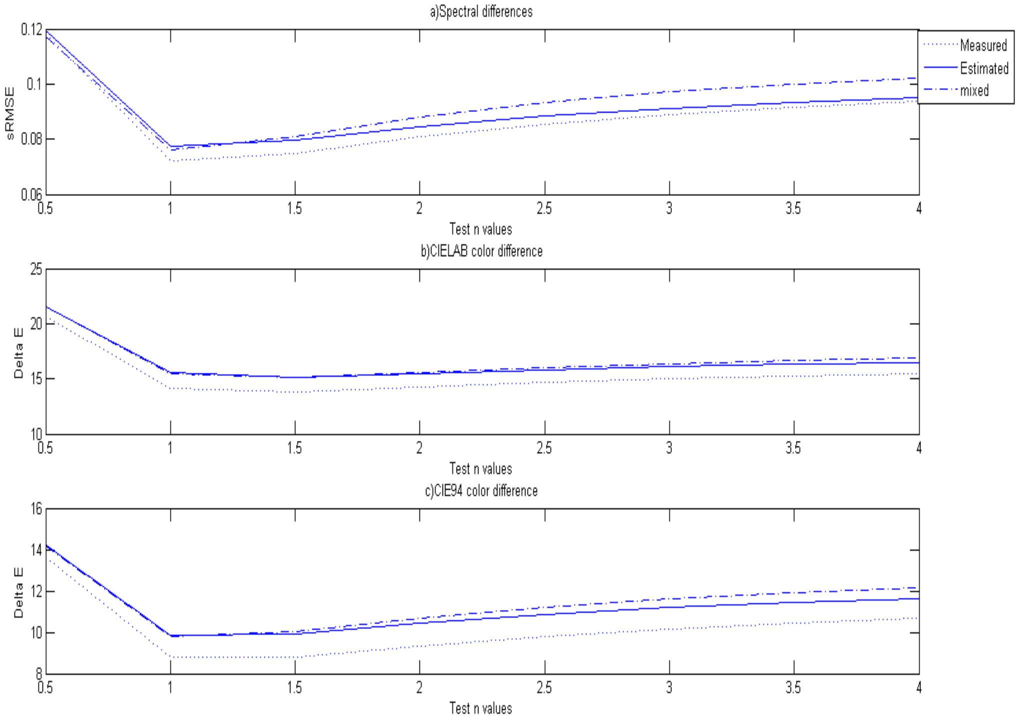


Figure D3: Spectral and color differences for the inkjet printer and staple paper A)spectral root mean square error B) CIELAB color difference C) CIE94 color difference

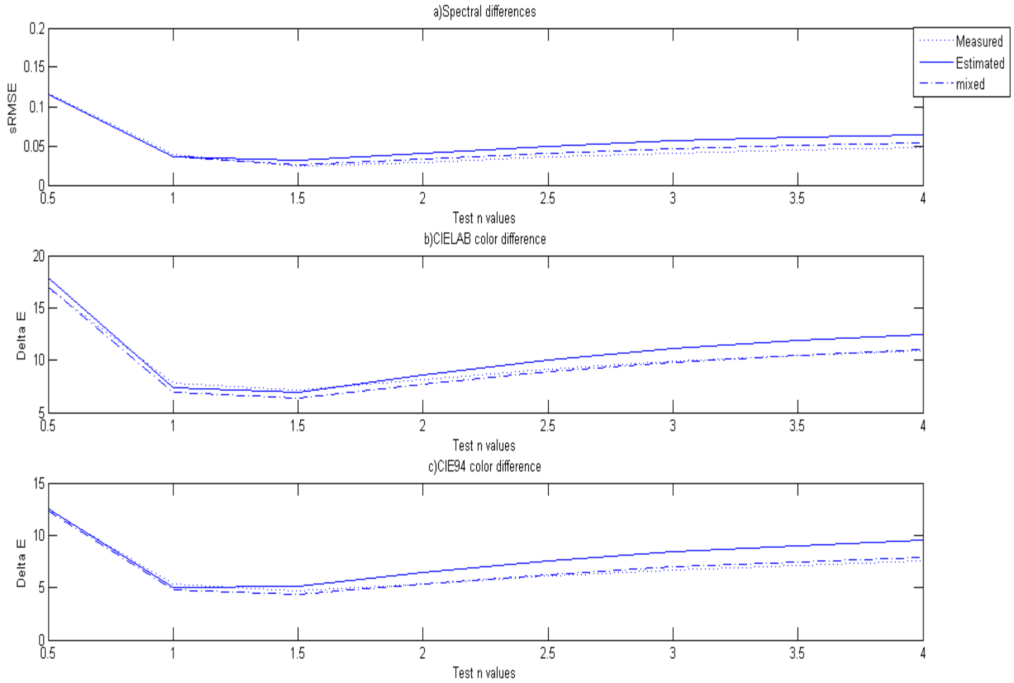


Figure D4: Spectral and color differences for the Laser printer and color copy paper A)spectral root mean square error B) CIELAB color difference C) CIE94 color difference

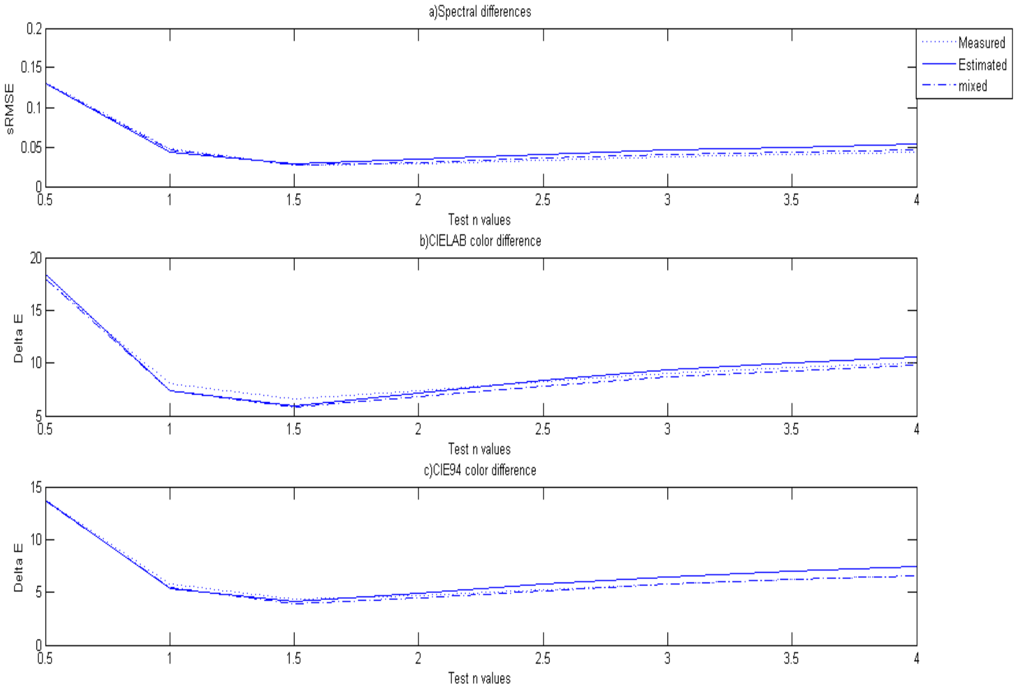


Figure D5: Spectral and color differences for the Laser printer and staple paper A)spectral root mean square error B) CIELAB color difference C) CIE94 color difference

We re-run the YNSN model for n values in the interval [1,2] in 0.1 step. It is for the purpose of watching the best n value which improves the results of NG model more clearly. Here we plot the results as follows:

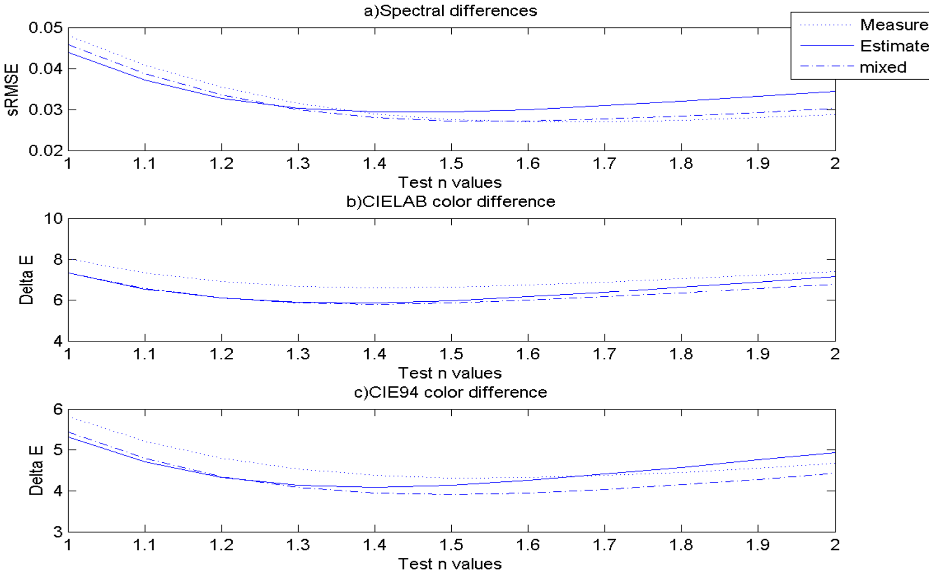


Figure D6: Spectral and color differences for the Laser printer and staple paper A)spectral root mean square error B) CIELAB color difference C) CIE94 color difference

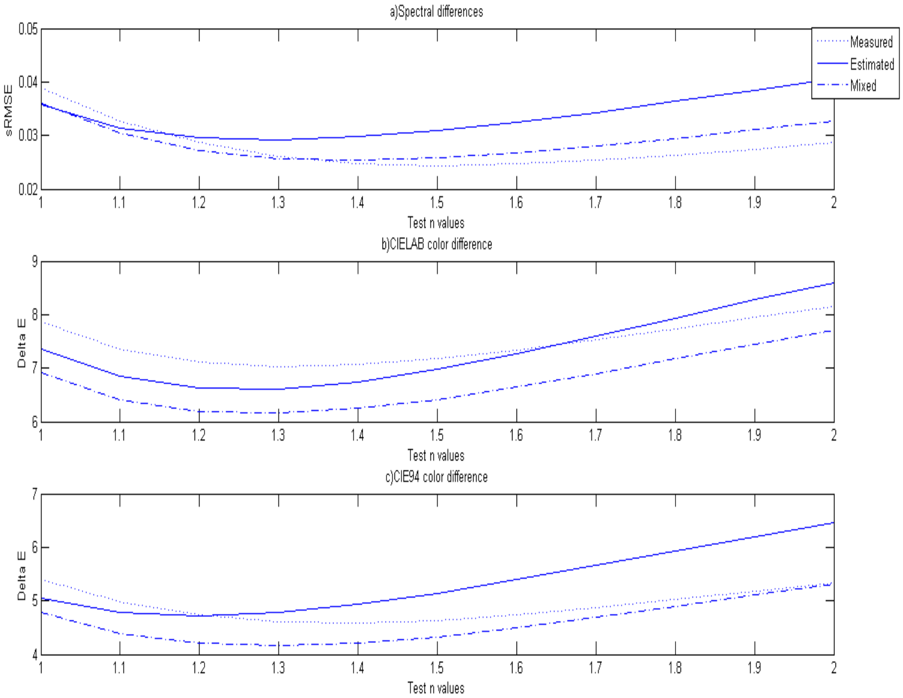


Figure D7: spectral and color differences for the Laser printer and color copy paper A)spectral root mean square error B) CIELAB color difference C) CIE94 color difference

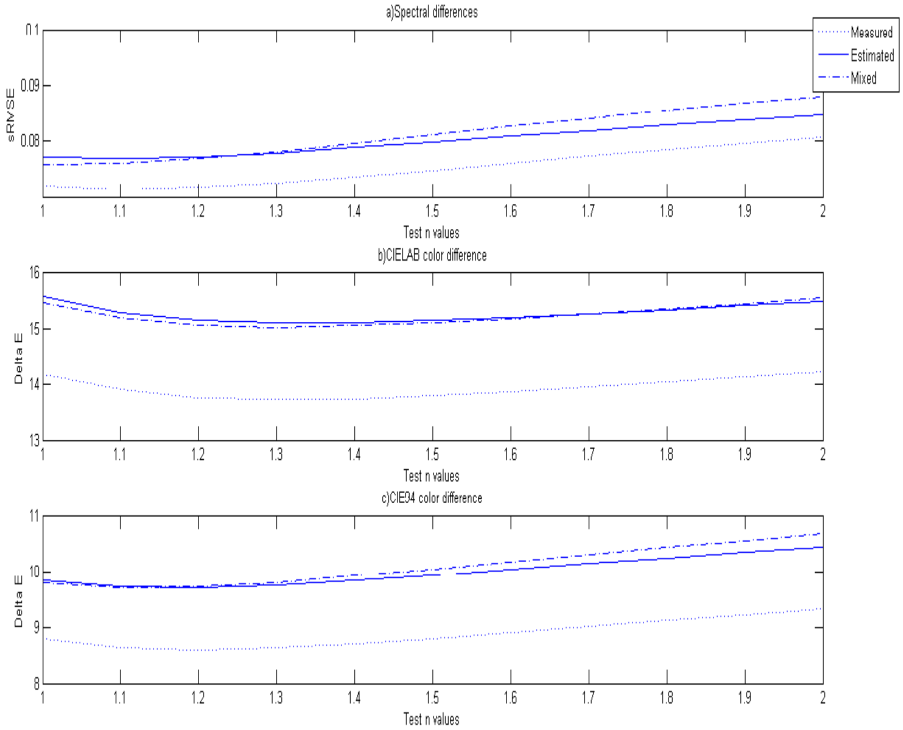


Figure D8: spectral and color differences for the Inkjet printer and staple copy paper A)spectral root mean square error B) CIELAB color difference C) CIE94 color difference

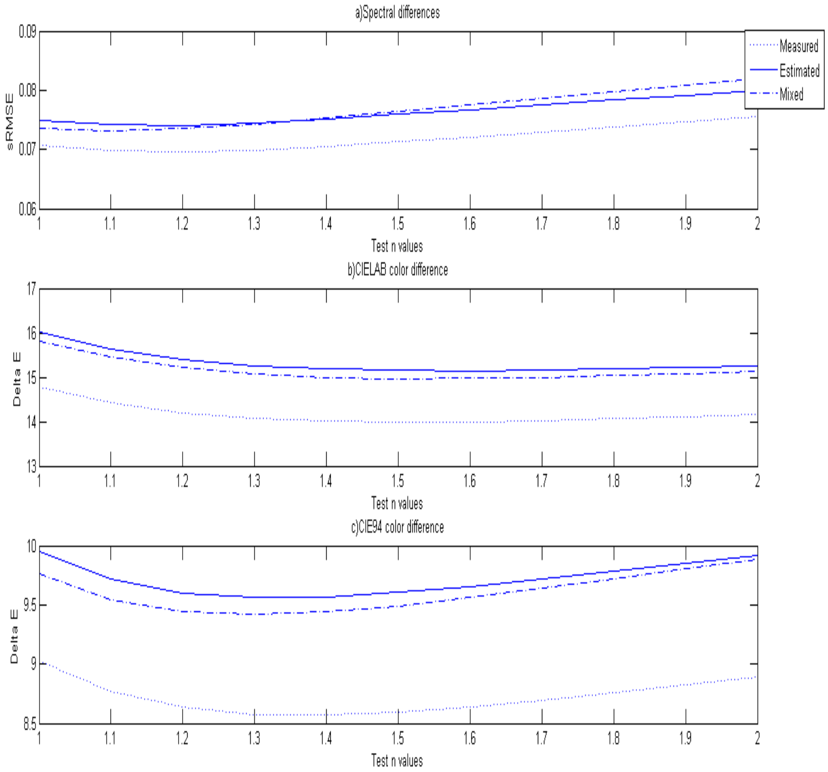


Figure D9: spectral and color differences for the Inkjet printer and color copy paper A)spectral root mean square error B) CIELAB color difference C) CIE94 color difference

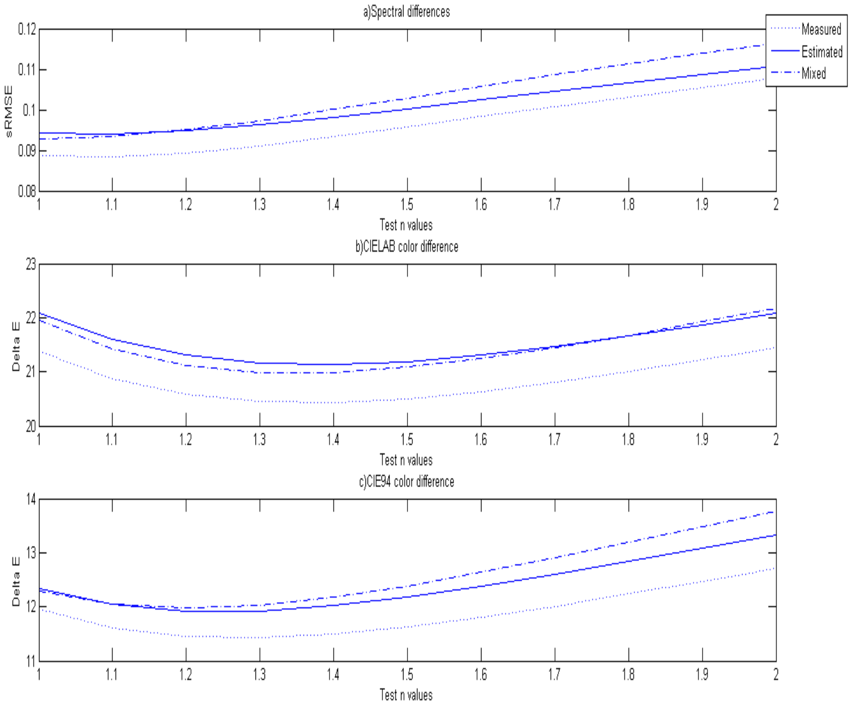


Figure D10: spectral and color differences for the Inkjet printer and HP photo paper A)spectral root mean square error B) CIELAB color difference C) CIE94 color difference

Appendix E: Spectral and Color differences between Eye One, HySpex and Reference values

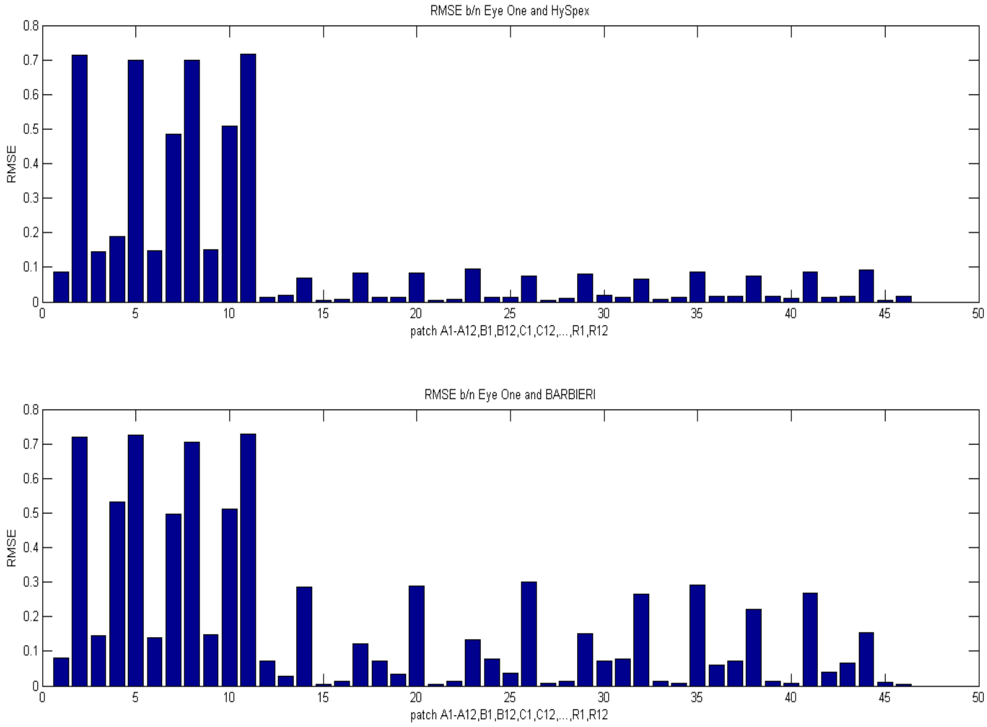


Figure E1: RMSE between Eye one, HySpex and BARBIERI

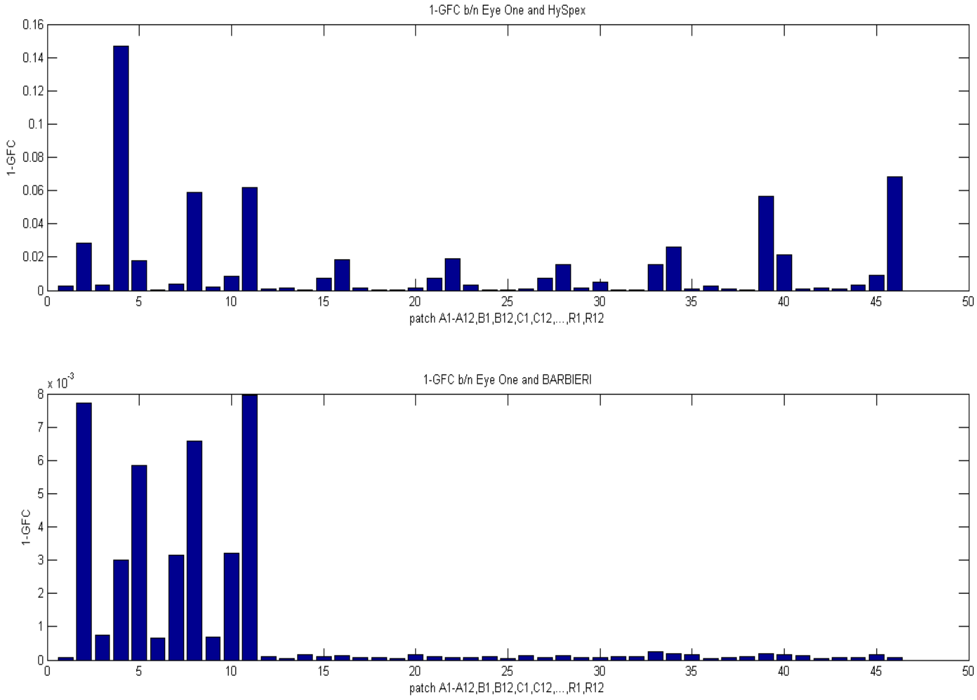


Figure E2: CGFC between Eye one and HySpex and BARBIERI

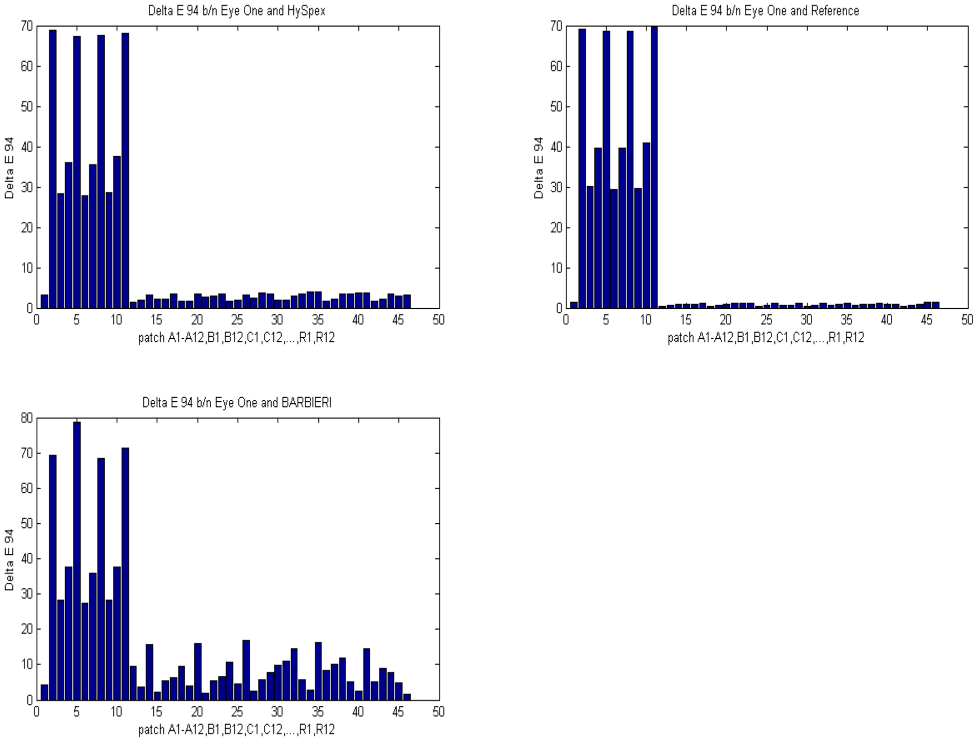


Figure E3: CIE94 color difference values between Eye one, HySpex, BARBIERI and Reference values

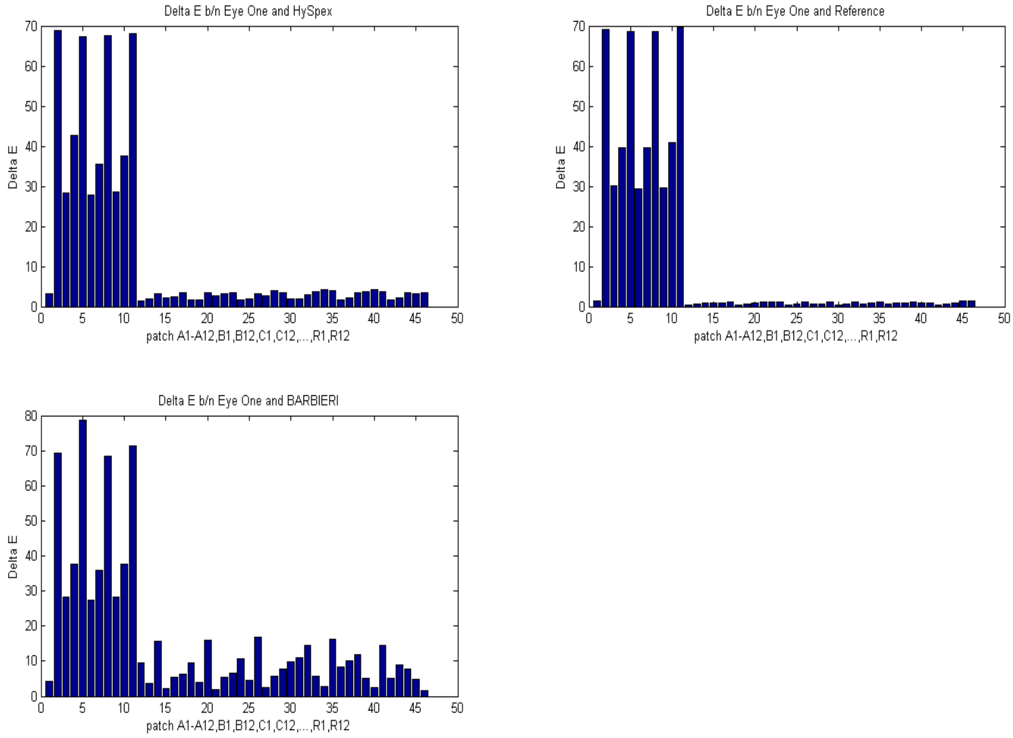


Figure E4: CIELab color difference values between Eye one, HySpex, BARBIERI and Reference values

Appendix F: Spectral Reflectances of DORT2002 estimated NPs

Here we present the spectral reflectance plots for NPs which are estimated by using DORT2002 software. The measured spectral reflectances of those NPs are also plotted with their respective estimated once.

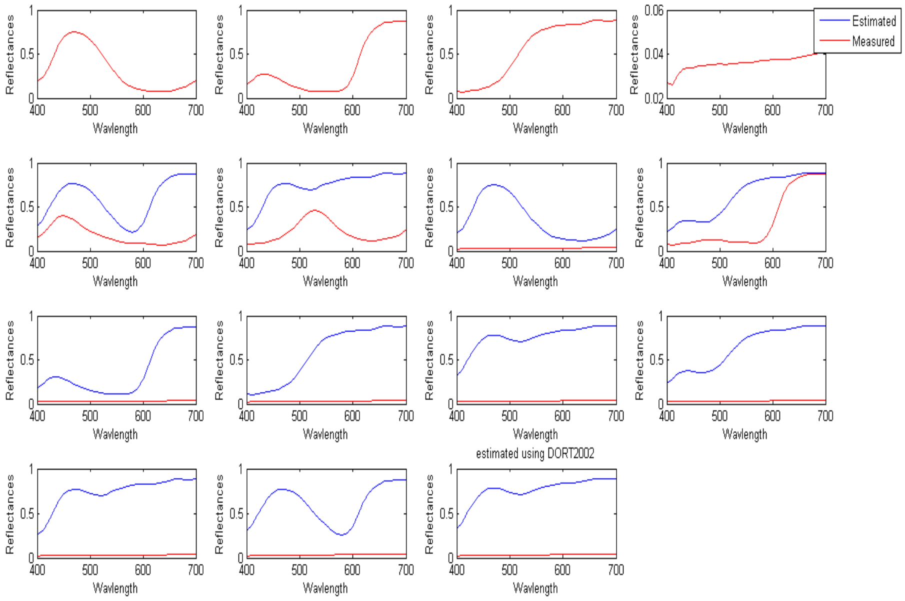


Figure F1: DORT2002 Estimated reflectances and Measured reflectances of NPs for the Color copy paper and Inkjet Printer. (Note: scales in the y-axis are different for some of the plots)

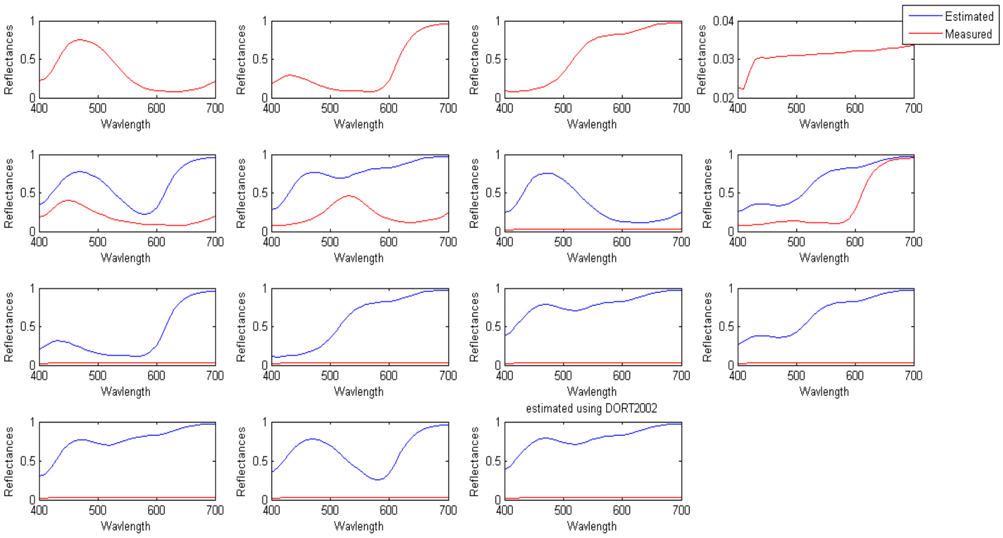


Figure F2: DORT2002 Estimated reflectances and Measured reflectances of NPs for the Staple copy paper and Inkjet Printer. (Note: scales in the y-axis are different for some of the plots)

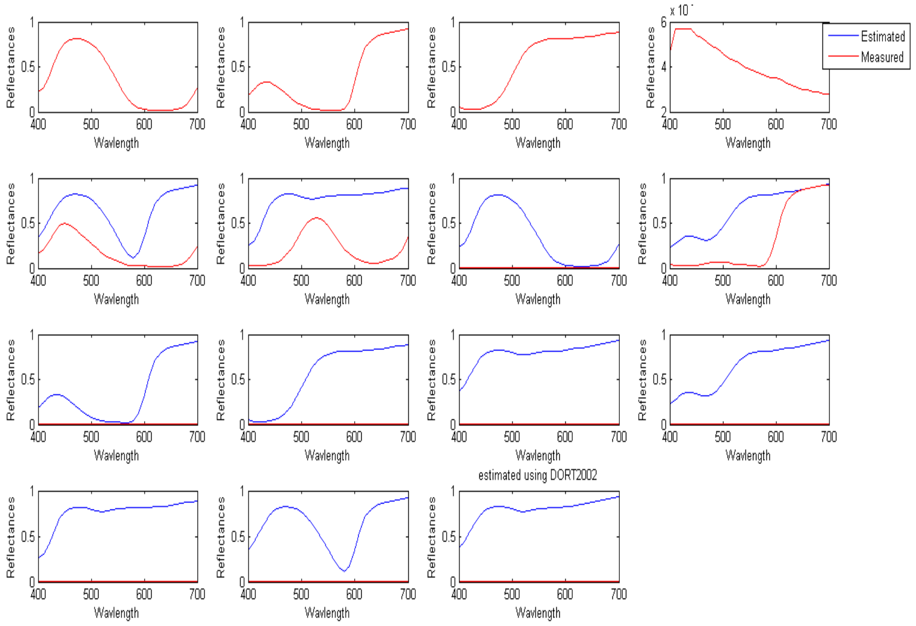


Figure F3: DORT2002 Estimated reflectances and Measured reflectances of NPs for the HP Photo paper and Inkjet Printer. (Note: scales in the y-axis are different for some of the plots)

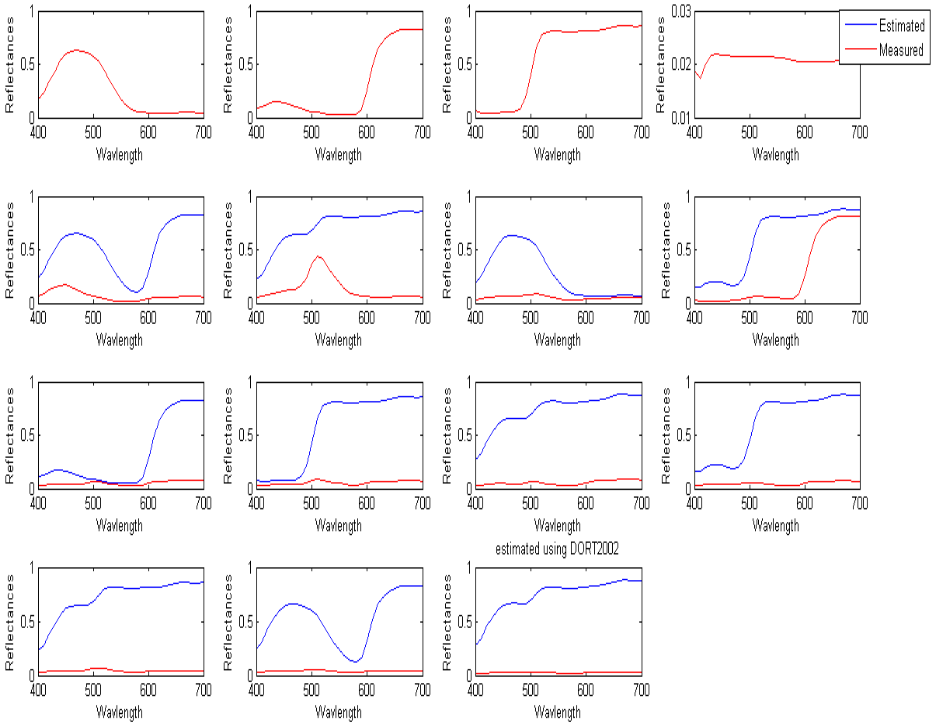


Figure F4: DORT2002 Estimated reflectances and Measured reflectances of NPs for the Color copy paper and Laser Printer. (Note: scales in the y-axis are different for some of the plots)

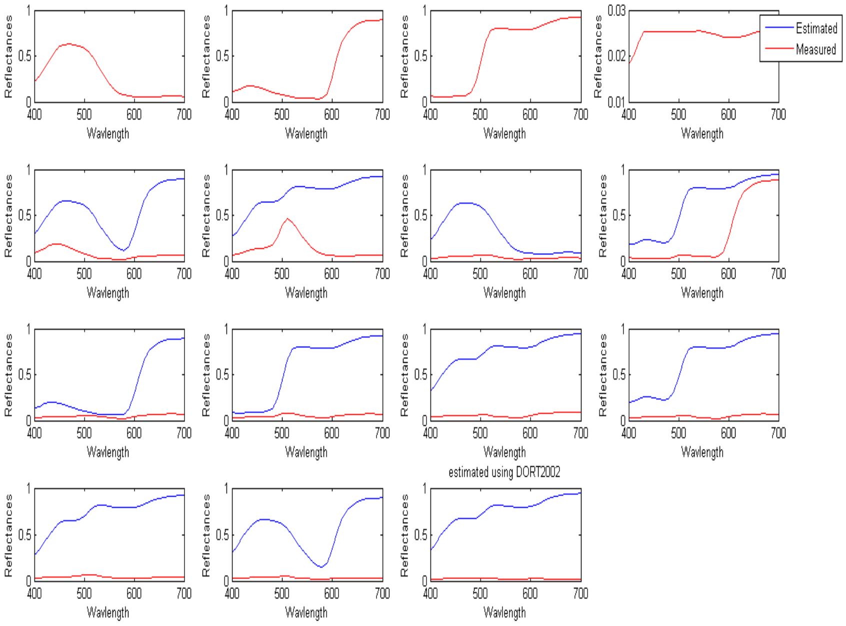


Figure F5: DORT2002 Estimated reflectances and Measured reflectances of NPs for the Staple copy paper and Laser Printer. (Note: scales in the y-axis are different for some of the plots)

Appendix G: Repeatability Measures

We measured the test charts and the ramps for CMYK colorants twice in two months interval. We analyzed the long term repeatability of our measurements in terms of spectral and color differences. Here we show the bar graphs for the mean RMSE, GFC, $\Delta E_{ab,\ and}$ ΔE_{94} between the two measurements of test charts.

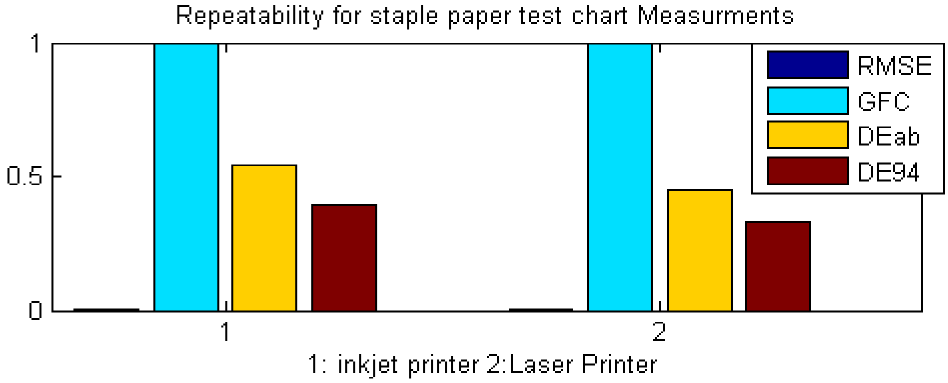


Figure G1: Repeatability measurements for test charts printed on staple paper by our inkjet and laser printer. The RMSE,GFC,ΔE_{ab} and ΔE_{94} values are the averages values of those of individual Patches of the test chart.

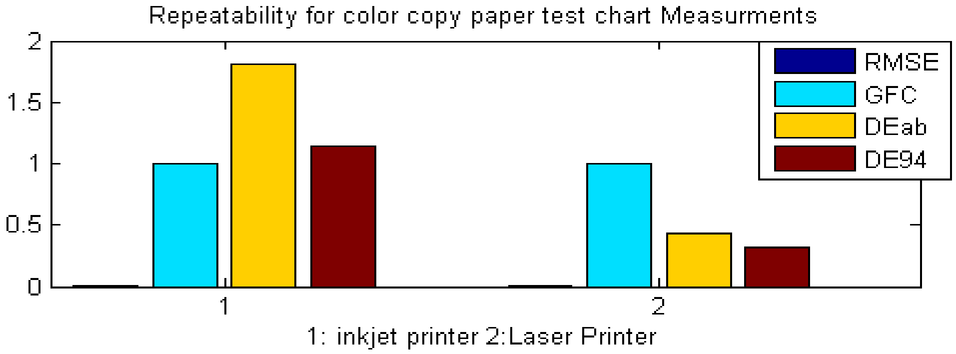


Figure G2: Repeatability measurements for test charts printed on color copy paper by our inkjet and laser printer. The RMSE,GFC,ΔE_{ab} and ΔE_{94} values are the average values of those of individual Patches of the test chart.

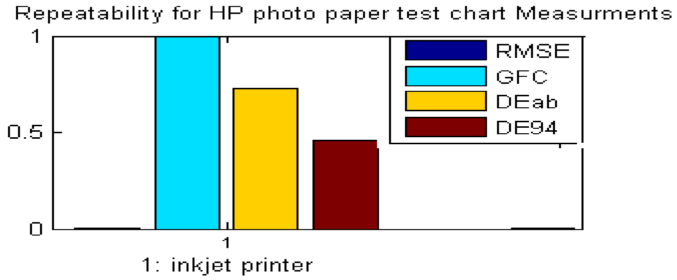


Figure G3: Repeatability measurements for test charts printed on HP photo paper by our inkjet printer. The RMSE,GFC,ΔE_{ab} and ΔE_{94} values are the average values of those of individual Patches of the test chart.