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Self-Generated Absorption Filter Based Optical Densitometry Calculations for Expanded Gamut and Spot Color Printing on Paperboard for Packaging Applications and Proposed OBA Index

Awadhoot Vijaykant Shendye
Western Michigan University, ashendye@gmail.com

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by

Awadhoot Vijaykant Shendye

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Doctoral Committee:

Paul D. Fleming III, Ph.D., Chair
Alexandra Pekarovicova, Ph.D.
Veronika Husovska Ph.D.
Kiran Deshapande Ph.D.

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In the printing industry, process color printing is a very common way of reproduction of color photographic images. As continuous tone reproduction is not possible, images are converted to halftone format. Process control of a halftone image quality is carried out by measuring optical density of solid patches. ISO 5 defines measurement of optical density, formula, filters and requirements. As per ISO document optical density can be calculated only for the 4 colors cyan, magenta, yellow and black, known as process colors. To enhance quality of color reproduction of images, the number of reproducible colors are increased by gamut expansion. The color gamut of this process color is expanded by adding orange, green and violet along with CMYK. This process is known as CMYKOGV expanded color gamut process. For measurement and control of ink film on substrate, a spectrophotometer is used to measure reflected light from an ink patch and related to its opacity. The range of sensitivity of these instruments is usually from 400 nm to 700 nm. Each color has its own reflection spectrum. The spectrum of each color can be divided in two parts known as reflection and absorption regions. When a color is printed in tonal gradation, then the reflectance spectrum shows change in the absorption region. The optical density is calculated by using data from the change in the absorption region. This change in the absorption region is selected by using a filter in the density calculation. For CMYK inks, this filter is defined in the ISO document, but for orange, green and violet, no filter is available, so optical density calculations

are not possible. This research focuses on generation of absorption filters for orange, green violet and other spot inks to measure optical density. Also, it recommends modifications in the ISO 20654 SCTV formula.

In the paper industry, one dimensional scales are widely used for determining optical properties of paper and paperboard. Whiteness, tint, brightness, yellowness and opacity are most common optical properties of paper and paper board. Most papers have a blue cast generated by addition of OBA (Optical Brightening Agent) or blue dye. This blue cast is given because of human perception that bluer is whiter up to certain limit. It is necessary to determine how much blue cast paper and paperboard has. As printing industry follows ISO 3664 standard for viewing, which has a D_{50} light source, this also plays a very important role in showing blue cast. Color perception is based on light source and light reflected from object. D50 has UV component in it and this interacts with OBAs and provides a blue cast as emission caused by OBA is in blue region. Use of a UV blocking filter results in measurements without effect of emission in blue region. This difference is used in determining the blue cast of the paper. This equation is known as Shendye-Fleming OBA Index.

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Awadhoot Shendye

Dedicated to My Father
Mr. Vijaykant Narayan Shendye

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CHAPTER 1

INTRODUCTION

1.1 Usefulness of research

As expanded gamut printing is gaining popularity in the printing industry, then the necessity of having process control is getting even more important than ever. Currently, no methodology is available for measurement of optical density for orange, green and violet or other spot colors. This research focuses on developing methodology for measuring optical density for orange, green and violet, and other spot colors. This will benefit all expanded gamut printers, irrespective of printing process, to measure optical density of inks for control of ink film thickness amount on substrate. Optical density measurement will help in color management to achieve close match of proof to press.

The paper industry uses one dimensional color scales like whiteness, yellowness and brightness for determining optical properties of paper. While determining whiteness of paper it is considered as bluer is whiter up to certain limit. OBAs are added in paper to give a blue cast. Currently, there is no method available to determine blue cast of the paper, which can account whole blue region of the spectrum. This research provides a method for determining blue cast of the paper and paperboard, known as Shendye-Fleming OBA index. This index is useful in comparing the blue cast of papers and can be used as a quality control tool for controlled addition of OBA.

1.2 Background

In the printing industry, process color printing is a very common way of reproducing color photographic images. Process control of halftone images is carried out by measuring the optical density of solid patches, because a picture in halftone form cannot be measured, so measurement is carried out on patches of the target[1]. Optical density helps to control the correct ink film thickness, which governs quality of the printed picture. ISO 5 defines measurement of optical density, formula, filters and other requirements[2]. As per the ISO 5-3 document, optical density is defined only for cyan, magenta, yellow and black, known as process colors. Once optical density of ink is calculated, then it is used in other densitometry functions, such as the Murray-Davies[3] optical dot area calculation, trapping, print contrast, hue error and grayness of process colors[4]. These densitometry functions are used for analysis of various print qualities and represent important tools of process control. Red, green and blue filters are used for calculation of density of cyan, magenta and yellow colors respectively. This is based on the subtractive color theory[5]. The usual formulation of the subtractive color theory is limited to process colors only. The color gamut of this process color set can be expanded by adding additional colors, such as orange, green and violet along with CMYK inks[6,7]. This is known as CMYKOGV expanded color gamut process. As there are no filters available for orange, green and violet, optical density measurement of these colors is not possible and density measurement of any other color beyond process color is not possible to calculate under current ISO 5-3 method of densitometry[1]. This limits process control of OGV inks and even any other inks used in expanded gamut colors. For measurement and control of ink films on substrates, a spectrophotometer is used[8]. Each color has its own reflection spectrum. The spectrum of each color can be divided in two parts known as reflection and absorption regions[9]. When a color is printed in tonal gradation, then the reflectance spectrum shows changes in the absorption region. The optical density is calculated by using data from the change in the absorption region[9]. This change in the absorption region is selected by using a filter in optical density calculation. Expanded gamut has been recently commercialized by companies such as Esko Graphics[10]. A tonal gradation is printed with various dot shapes and sizes along with different screen resolution. This is carried out to make analysis of the tonal gradation in order to calculate optical density, which is used to make analysis of various print and image quality parameters[11]. In expanded gamut printing, an image is separated into orange, green and violet and it is necessary to measure tonal gradations of those inks for analyses[12]. Once the density is calculated, it can be used for further analysis of different components of an image or print. This gives importance to calculations of density for expanded gamut printing[13].

1.3 Industrial application and significance

The purpose of this project is to replace conventional densitometry of ISO 5-3 by a universal self-generating floating filter based on new densitometry. A new formula, developed in our research is universal and can be applied to any printing process for reproducing any dot shape on any screen ruling for any inks including process colors, spot colors and extended gamut colors on any substrate. The robustness of this formula makes it universal for optical density calculations and further densitometry calculations of Murray-Davies optical dot area calculation, trapping, print contrast, hue error and grayness of any color for the purpose of process control. Due to the benefit of cost savings and better color reproduction, expanded gamut printing has become popular in the industry, and the necessity of having process control has become even more important than ever. Currently, no methodology is available for measurement of optical density for orange, green, violet and other spot colors. This research focuses on developing methodology for calculating optical density by using spectral data as the input function for orange, green and violet extended gamut colors and spot colors to control ink amount on substrate. Self-generation of the absorption filter for optical density calculation is a universal method, as it can be applicable to all colors and shows the same results as ISO status –T densitometry for process colors. Tonal gradations of expanded gamut colors and spot colors will be printed by offset litho printing with different dot shapes and screen ruling on different substrates, then spectral measurements will be used to apply the method. This new method will allow all expanded gamut printers, irrespective of printing process, to measure density of inks for control of ink amount on a substrate. Optical density measurement will help in color management to achieve closer match to proof. Also, it can be used to adjust 1-dimensional lookup table curves in raster image processing for adjustment of machine dot gain. The new method will be used with spectrophotometers and process control software. Conformation about successful development will be carried out by comparing results of the new method versus the old method for process colors under ISO Status-T calculations. A developed technology can be licensed to instrument manufacturers to embed in their software used with spectrophotometers. With the constantly growing expanded color printing market, we believe that this will help in solving many problems in controlling ink on substrate and apparent dot area measurement of expanded gamut colors and spot colors for process control.

The human visible range is from 400 to 700 nm of electromagnetic spectrum and it works as a low pass filter[14]. This spectral range is used for color measurements. Color matching and color management is important in printing. For achieving color management, the desired ink film thickness should be achieved. Measurement of color does not provide direction to increase ink or decrease ink film thickness. A single number scale is very important to make decisions about increasing or decreasing of ink film on substrate. Printing inks are classified as process colors or spot colors. Cyan, Magenta, Yellow and Black are known as process colors. Inks other than process colors are known as spot colors. Process colors are transparent in thin film nature, and this property is used in measuring and controlling ink on substrate. Optical density is directly related to ink film thickness. The nature of the spectrum in the absorption region changes as the amount of ink increases. This property is used in research to develop the new formula. A region of spectrum is selected as bandpass filter. This research will help measuring density of spot and expanded gamut colors and can be used to measure apparent dot area.

1.5 Dissertation overview

The outline of the dissertation is as follows. Chapter 2 is a literature review. This explains basic concepts of densitometry required in this dissertation. It explains about color filters used in calculating density, densitometry calculations and applications. It also explains concepts required in the proposed equation. It explains how density and apparent dot area are calculated in the ISO 5-3 method and what are its limitations. Chapter 3 explains about methods used in the research. It provides problem statement, proposed solution and applications. This chapter has newly proposed mathematical equation for calculating optical density for any given color. Also, it has equation for measuring OBA index on dimensional color scale and explains its applications. Chapter 4 is about implementation of the proposed equations. These provide methods used in experiments and implementation of formulas. This explains how the test chart was designed, printed and measured. It also provides guidelines for selecting bandwidth of bandpass filters generated by the equation. Chapter 5 explains results and analysis. It has comparison of Shendye-Fleming universal density to ISO status E density for process colors and dot area calculated by using the Murray-Davies equation by using ISO density and Shendye-Fleming density. It also compares results of ISO Spot Color Tone Value (SCTV) formula for dot area with the Murray-Davies[3] equation. Chapter 6 discusses conclusion of research and future work.

1.6 Key contributions

This study explores many facets of Shendye-Fleming universal density equation and Shendye-Fleming OBA index.

- Two methods of density calculation were implemented and evaluated for expanded gamut and spot color printing processes.
- New universal self-generating filter based density calculation method was developed and implemented for process color and for beyond process color inks.
- Different methods such as Murray-Davies and SCTV for calculating apparent dot area were implemented and evaluated for process colors and beyond process colors.
- Application of the method was evaluated for different dot shapes, different substrates, different halftoning techniques and different resolution of halftoning.
- A band pass filter range for many spot colors is provided as a starting point.
- A set of guidelines and method for selecting range for band pass filter is defined and provided along with a few examples.
- Effects of different measuring conditions on density and dot area was evaluated.
- Shendye-Fleming OBA index, as a one-dimensional color scale was introduced and evaluated for application.
- OBA of several papers was calculated and provided as reference for comparison.

1.7 Terminology

AM- Amplitude modulation screening, where distance between center of two dots remains constant and size of dot changes.

CMYK- a set of 4 inks- cyan, magenta, yellow, black- used traditionally as set of process inks.

CMYKOGV- A printing process used as an example of the n-color printing process that uses 7 inks- cyan, magenta, yellow, black, orange, green and violet.

Color Separation- a process by which an original artwork or image is decomposed into individual single color components for printing using primary inks for example CMYK or CMYKOGV inks.

Density- negative logarithm to the base 10 of the reflectance factor.

Densitometry- Study and analysis of changes in the amount or density.

Dot area (apparent)- an area of individual element of a halftone expressed in percentage. A dot area measurement is the ratio between the amount of light reflected back, or transmitted, through a given halftone versus the amount of light collected back from or through a solid of the same color.

Dot gain or tone value increase- is an increase in diameter of the halftone dot or increase in apparent tonal value.

Expanded/Extended Gamut- a printing processes in which color separation of image is carried out in more than 4 process colors for reproduction.

FM- a halftoning technique in which is a halftone process based on pseudo-random distribution of halftone dots, using frequency modulation (FM) to change the density of dots according to the gray level desired.

Halftoning-the transformation from a con-tone image to a binary one.

Screening- a combination of AM and FM halftoning technique in the same image. Highlight area is AM halftoning and midtone area is FM halftoning.

Kubelka-Munk- a set of mathematical equations defining a relationship between spectral reflectance of sample and its absorption and scattering characteristics.

OBA- Optical brighteners, optical brightening agents (OBAs), fluorescent brightening agents (FBAs), or fluorescent whitening agents (FWAs), are chemical compounds that absorb light in the ultraviolet and violet region (usually 340-370 nm) of the electromagnetic spectrum, and re-emit light in the blue region (typically 420-470 nm) by fluorescence.

Printing Process -a process of reproducing visual information including text and images by using colorant onto substrate.

Printing system - a set of printing conditions including device, imaging method, substrate, inks and consumables.

Printing Technology- different techniques of reproducing visual information by placing a colorant on to a substrate in controlled manner.

Process colors -a set of 4 transparent inks – cyan, magenta yellow black is known process colors. It is also known as CMYK.

Saunderson's Correction- a method for making this correction was proposed by Saunderson in terms of two parameters, k_1 and k_2. It was derived for spectrophotometer measurements made with integrating sphere geometry.

Scattering is a general physical process where light is forced to deviate from a straight trajectory by one or more paths due to localized non-uniformities in the medium through which they pass.

Screen Ruling- number of image elements, such as dots or lines, per unit of length in the direction which produces the highest value.

Spectrophotometer- an apparatus for measuring the intensity of light in a part of the spectrum, especially as transmitted, reflected or emitted by particular substances.

Spectral reflectance factor- ratio of the reflected flux to the absolute reference reflected flux under the same geometrical and spectral conditions of measurement, as a function of wavelength.

Spot colors or Brand Colors- a color printed with its own premixed ink instead of the process inks. These are usually critical colors may be outside or inside the gamut of process colors or expanded gamut colors.

Tone Value- a percentage of the surface that appears to be covered by colorant of a single color.

CHAPTER 2

LITERATURE REVIEW

2.1 Color separations filters and density measurement

The additive color theory is for addition of components of light. Applications of additive color theory is found in television, or computer monitors, i.e. light emitting devices. Red, green and blue primary colors are applied in the additive color theory. The additive color theory[15] starts with black and when all primary colors are added then it reaches white. The subtractive color theory is used in printing inks and paints, where dyes or pigments are added together. Cyan, magenta and yellow are primary colors in the subtractive theory[5]. The subtractive theory starts with white and when all colors are added then they generate black. The color reproduction gamut of cyan, magenta and yellow is dependent on purity of color pigments and halftone technique along with whiteness and smoothness of the substrate[16]. These color theories are used in color separation for printing images. A red filter is used to separate the cyan plate. A green filter is used to separate the magenta plate and a blue filter is used to separate the yellow plate.

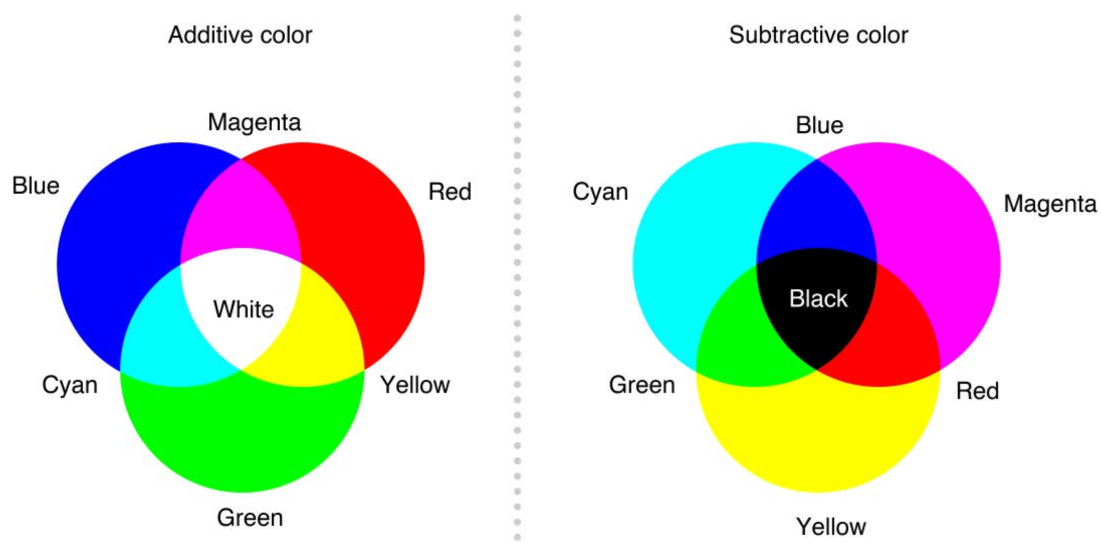


Figure 1: Additive and subtractive theory.

If one observes cyan ink through a red filter, it will appear as black. When magenta ink is viewed through a green filter, then it is seen as black. The same way when yellow ink is viewed through a blue filter then it appears black. This theory is used when density is measured for process control.

2.2 Optical density

Optical density of process color is indirectly related to ink film thickness. Optical density is the logarithm of opacity[17]. For any solid patch of process color, the higher the ink film thickness is, higher the optical density is. When the optical density of any halftone is measured, then the smaller the dot area or dot size is, the smaller the optical density value is. The method of calculation and requirements for the optical density formulae are described in the ISO 5 document[18]. Densitometry functions are only for process colors and they cannot be used for spot colors. Process colors are transparent at low ink film thickness[19]. The correct amount of ink film thickness is required to print cast free pictures. Also, when press characterization is carried out, then optical density should be measured and the same optical density numbers should be targeted while matching a proof. Density plays an important role in color management to match proof to press, as controlling uniform density across the sheet and reproducing it to target density is one of the important steps in color management. Without density control, color management is not possible. A picture in halftone form cannot be measured, so measurement is done on patches of a target[20]. Optical density can be used for calculating other process control parameters[17]. As the IFT (Ink Film Thickness) increases, the color patch becomes more opaque. So, optical density helps to control the correct IFT, which governs the quality of a picture.

The following formula is given in the ISO standard for calculating optical density.[18]

$$\text{ISO standard density } = log_{10}\left[\sum_{\lambda}\frac{W_{\lambda}R_{\lambda}}{100}\right] \quad (1)$$

where W_{λ} is the spectral weighting factor at wavelength λ as defined in the files 10nmWgts.csv or 20nmWgt.csv, and R_{λ} is the spectral reflectance factor at wavelength λ.

The denominator 100 is the sum of the spectra weighting factors of the range 340 nm to 770 nm (by construction).

This formula shows that optical density is a logarithmic function. The logarithm has a more linear relationship to ink film thickness than the reflectance itself. It has better correlation with visual perception of lightness difference[21]. The logarithmic scale provides increased measurement sensitivity for low reflectance of light. Density is based on two types measurements, and they are:

- Reflection- Reflected light from object is used for optical density calculation.
- Transmission –Light transmitted through the object is used for transmission density calculation.

The ISO 5 document defines a light source as follows

- Light Source: For reflection ISO density, ISO 5 defines as *"the relative spectral power distribution of the flux incident on a specimen surface should confirm to CIE illuminant A (corresponding to distribution temperature of 2856° K)"*. In practice, instruments used to measure reflection ISO density, the relative spectral power distribution of the flux incident on color specimen surface should be of same distribution temperature of 2856 K ± 100° K.

When the light source was added to the ISO standard, at that time all color measuring instruments used an incandescent bulb. When ISO 15336[22] was developed, then it added M0, M1 and M2 measurement conditions. This new measurement allows using a white LED light with a UV component for measurement of color. Although this part is not as per ISO 5, many instruments are available in the market that allow measuring density by using a white LED light with an UV component.

When optical density is measured, then sampling conditions are recommended. The optical density of some materials change with variation in temperature and relative humidity, therefore in order to avoid ambiguity, such materials should be measured at 23 ± 2° C and 50 ± 5% relative humidity.

The ISO 5 standard defines various sets of filters with different bandwidths and absorption ranges. This set of filters is known as “Densitometric status[18]”. ISO 5-3 defines various status responses. This concept comes from traditionally selecting a set of filters for color selection:

- **T, A, E, Ax, Tx, Ex, I HIFI, DIN, DIN NB, SPI.**
- **Status T / ANSI T**: wide band color reflection densitometer response, used mainly in the United States.
- **Status E / DIN 16536**: wide band color reflection densitometer response, used mainly in Europe. The main difference from Status T: higher values for yellow as status E blue filter has lower bandwidth.

  Difference between status T and E is Blue (yellow ink) filter only and it has no impact on dot area calculation. In case of yellow my method can match to Status E only and has no impact on dot area measurement.
- **Status A / ANSI A**: wide band color reflection and transmission densitometer response, used mainly in the photographic industry to measure positive prints. This response, like the Status T response, is found in both transmission and reflection densitometers.
- **Status M**: wide band color transmission densitometer response, used in the photographic industry for measurements of negatives.

- ***Status I / SPI, DIN NB***: Status I density is applicable for the evaluation of graphic arts materials such as process ink on paper. It is a special case of the narrow-band densitometry defined in ISO 5-3 with spectral bandwidth and sideband rejection as defined in that document, with peak wavelengths as follows:
    - blue: 430 nm (± 5 nm)
    - green: 535 nm (± 5 nm)
    - red: 625 nm (± 5 nm).
- ***Status Ax, Ex, Tx***: Old classic densitometers used filters made out of glass or gelatin. The new generation of densitometers are spectrally based. This means that modern devices measure a spectral curve and use exact mathematical filters to calculate the optical density. For example, the status T spectral curves are shown in Figure 2: Status T filter response ISO 5.. This differs from the responses of classic devices.
- Traditional densitometers have slight deviations from the responses defined by ANSI/DIN/ISO, because the accuracy in manufacturing glass or gelatin filters is limited. It is known that the difference between the old and the new densitometers is that the latter are spectrally based. For those users who have to use both series, manufacturers provide the Ax/Ex/Tx response to get density values out of a new Series instruments, which correspond with the densities of the old Series.

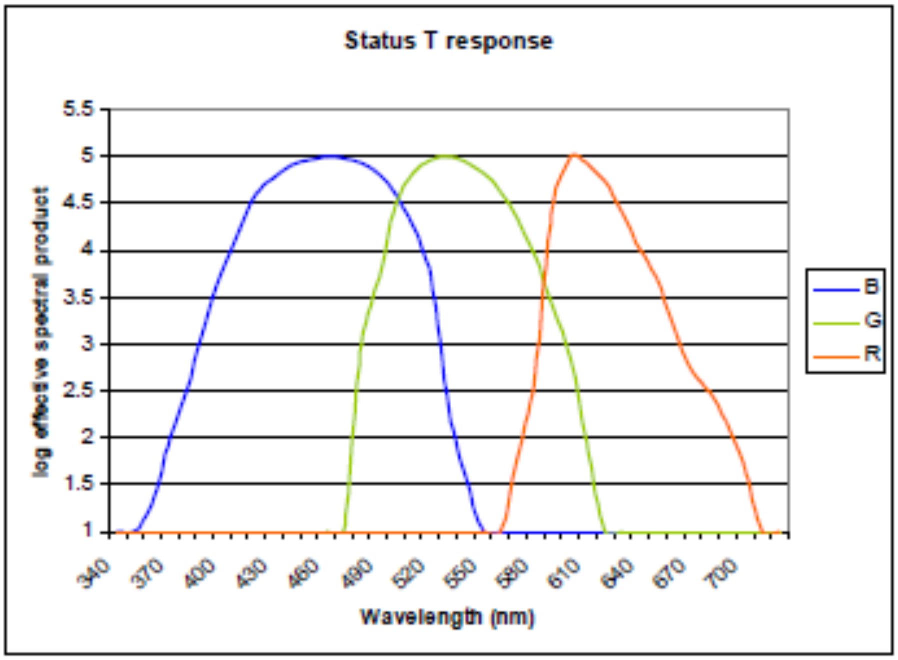


Figure 2: Status T filter response ISO 5.[23]

The calculation of density is logarithmic in nature, because such measurements have a more linear relationship with IFT. As a logarithmic function, it also correlates better with visual perception of lightness difference.

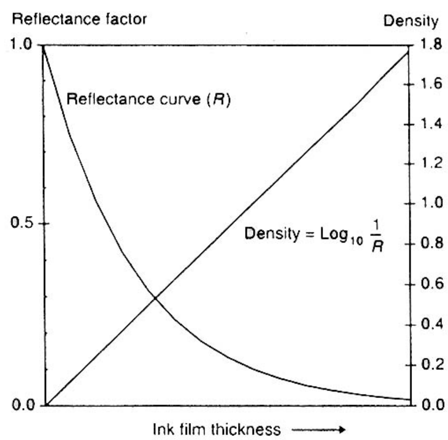


Figure 3: Comparison of IFT and density.

The logarithmic function provides increased measurement sensitivity for small reflectance differences.

2.3 Densitometry

Densitometry is the method of using optical density of half tone and solid inks to calculate different parameters for image quality control. As an image is printed with multiple dots, it is necessary to control the amount of inks on those dots. These dots could be of same sizes with different population density or of different sizes with the same population density. So, in the printing density of solid, density of halftone dot and density of paper is used to calculate different printing parameters. Dot area is calculated using the Murray- Davies equation[21], which uses density. Also, ink trapping, print contrast, hue error and grayness values are calculated by using density of process inks, halftone dots and paper. As per ISO 5-3, densitometry is applicable for process colors cyan, magenta, yellow and black only. Densitometry depends on ink amount, meaning that when ink is printed with tonal gradation, then reflectance spectrum changes in the absorption spectrum area depending on ink amount. A representation of a cyan tonal gradation is shown in Figure 4.

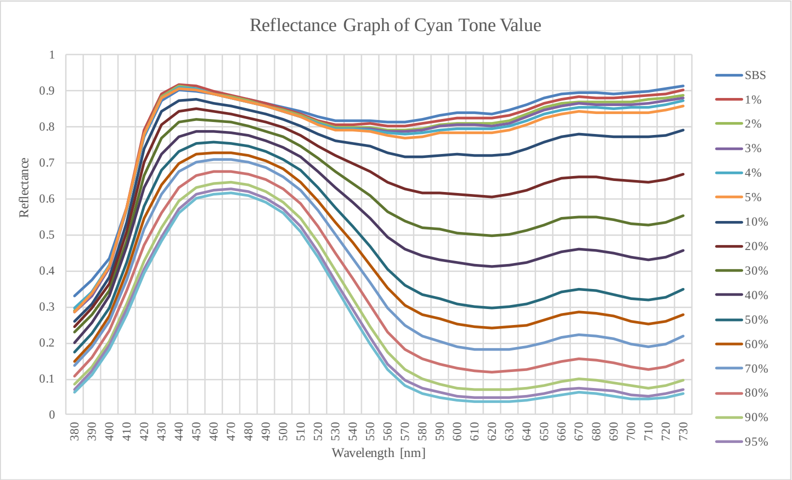


Figure 4: Reflectance of tonal gradation of cyan.

2.4 Halftoning

Printing originals could be of two types, one continuous tone and second halftone. Limitation of any printing process is that it cannot print continuous tone images, simply because the image carrier would not be able to carry ink to the substrate, thus the image needs to be organized into discrete dots, reproduced differently by various printing processes. Halftoning is method of dithering and thresholding where some spatial information is lost.[24] It is method of deleting pixels from image. Thus, halftoning is a method of creating an illusion of continuous tone imagery by converting an image into small dots. Dots could be of different shapes such as round, elliptical, diamond, etc. Two major halftoning techniques are generally used 1) AM screening 2) FM screening.

1) AM screening[25] - in AM screening, the area of a halftone dot is changed but distance between center of two dots remains constant. The size of the dot is decided by amount of color information in that area, showing percent of area covered.
2) FM screening[25] - in FM screening the area of a dot remains the same. The number of dots in an area changes based on amount of colorant in that area.

When a digital image is processed through a RIP (for Raster Image Processing), it uses output resolution for calculation of dot area. Generally, output resolution is 2400 or 2540 pixels per inch. At 2400 resolution, one square inch area has 2400 x 2400 pixels. When we want 50% dot in that area, then RIP will delete every alternative pixel for FM screening, and for AM screening it will delete 600 pixels from four edges and dot will be made up of 1200 pixels as one square. So, half of the pixels will be black and half of the pixels will be white. By deleting pixels, the dot area is calculated in the RIP. So, in a digital file, the dot area calculations are actually image area based calculations. These dot areas are expressed as percentage. An entire area covered with ink, also known as solids, is known as 100% tone. Substrate without any ink is 0%. So, all dots lie between 0% to 100% area. Digital dot area can be less than 1% or greater than 99%, depending on resolution of the output device e.g. a platesetter. For example, a 150 LPI (Lines Per Inch) halftone can be obtained with 2400 dpi plate setter with a 16 x 16 grid of pixels. This simulates 257 shades of ink (16^2 +1 for no ink) at 150 LPI, which is generally considered good print.

2.5 Dot area and density on paper

When these dots are printed on a substrate, area based calculations don't work. Capturing the area and calculating exact area occupied by ink is not possible, because of reflection of light from borders of dot area. As a result, an indirect method to calculate dot area is used. Different amounts of ink on a substrate reflect light with different intensity, and this property was used by Murray-Davies[3] to calculate dot area. Various models were developed over time, such as Demichel/Neugebauer equations, Yule-Nielsen equation, which is a modification of the Murray-Davies equation, Clapper-Yule equation, and the Huntsman model[26]. Currently, the most popular equation, used in densitometers is the Murray-Davies equation. For the same reflectance data as input, different formulas show different results, so when Dot area/TVI is communicated, specifying formula and its parameters are necessary.

2.6 Optical dot area and Murray- Davies equation

The Murray–Davies equation shows gray levels can be controlled as controlling the dot area function. The Murray- Davies equation uses density of solid, density of halftone area and density of paper for calculation of dot area. Dot area calculation is one of the widely-used applications of optical density[327].

$$\text{D}=100* \left[\frac{1-10^{(D_0-D_n)}}{1-10^{(D_0-D_{100})}}\right] \tag{2}$$

where D=Dot percentage, D_0 = density of paper, D_{100} = solid density and D_n = density of specified dot area.

When measuring of the reflectance of the paper, the solid, and the halftone, plugging the densities into the Murray-Davies equation, an indirect measurement of the size of the dots is received. The difference between dot area calculated by measurement of printed sample and the area on the printing plate is called dot gain or tone value increase. Murray-Davies equation can fail due to variation in reflectance of ink and paper.

2.7 Physical dot area and Yule-Nielsen equation[28]

The Murray-Davies equation gives optical dot area calculations. Due to the light reflected from boundary of the dot, it appears to be larger than actual size and it is called optical dot gain, which can be eliminated by the Yule-Nielsen equation. The Yule-Nielsen equation is the same as the Murray/Davies equation with modification carried out to estimate the physical dot area. In modification factor “n” is included to calculate physical dot area by an equation that is an approximation of physical dot area as a result of raw materials like ink, paper, substrate, printing pressure and other process variables in the printing process[29]. The Yule-Nielsen[28] equation is not a description of the physical mechanism of halftone imaging, but it is a useful approximation technique. The Yule-Neilson even works for physical dot area of inkjet inks as measured by image analysis[30]. The Noffke-Seymour formula[31] uses Beer's law but Beer’s law is for transparent liquids so it is not considered here. Birkett/Spontelli is CTV (Colorimetric Tonal Value) equation and it was compared with SCTV by the SCHMOO committee and found SCTV is better than CTV[32]. A camera based method of calculating optical dot area and dot gain was assessed by Stefan Gustavson in his thesis “Dot Gain in color halftones”[33] this process requires large aperture for taking photographs of images by camera and it can’t be used on press for quick measurement.

2.8 Kubelka-Munk theory and absorption[34]

A Kubelka-Munk conversion is applied to a diffuse reflectance spectrum. The Kubelka-Munk theory is based upon a model in which the radiation field is approximated by two fluxes, the one, traveling from the illuminated sample surface, and the other, traveling toward the illuminated surface[35]. Kubelka–Munk (K-M) theory appears to be a rather simple approximation to describe the optical properties of a light-absorbing and scattering medium. The K-M theory is derived with certain assumptions and hence has several limitations. The most significant assumption is the isotropic scattering within the sample. The film is assumed to have plane parallel surfaces, sufficient in extent to ensure that edge effects can be ignored[36]. No generation of light within the film is assumed (no fluorescence and related processes). The illuminating and viewing light has to be diffuse. We chose this case of radiative transfer theory because of its simplicity. Kubelka Munk theory provides the ratio of absorption (K) to scattering (S) by using reflection of light[37]. Most important, it is based on the laws of physics and contains no empiricism.

Equation 3 shows calculation ratio of the absorption to scattering by using reflection.

$$\frac{(1-R)^2}{2R} = \frac{K}{S} \tag{3}$$

where, R = reflectance; K = absorption coefficient; S = scattering coefficient

K/S is calculated for the reflectance sample only for each wavelength read. In the Kubelka-Munk assumption, reflected light from the surface of the material depends on the factors such as thickness of the film, absorption and scattering coefficients of the ink film, and the reflectance of the background, which is paper on which ink is printed. Thin translucent films over a moderately scattering substrate is a known limitation of the straight Kubelka-Munk equation. One of the assumptions of the K-M model is that the light flux is completely diffuse (equal fluxes up and down) within the film. This is clearly not the situation in an almost but not quite fully transparent ink film over a dull substrate. It also does not describe ink on metal foils. K-M does a good job on very transparent inks on opaque, non-absorbing (chemically), white substrates. Predictions will be 75% to 85% accurate within experimental errors. This was derived by Hofmann[38] for 45/0 geometry of measurement instruments and then simplified somewhat by Schmelzer[39]. For spherical geometry, the first derivation was developed by Mudgett and Richards[40]. Figure 5 shows K/S calculation of cyan inks tonal gradation. Apart from spot color mixing, Kubelka-Munk is used for over print color prediction and characterization of ink jet printers.[41]

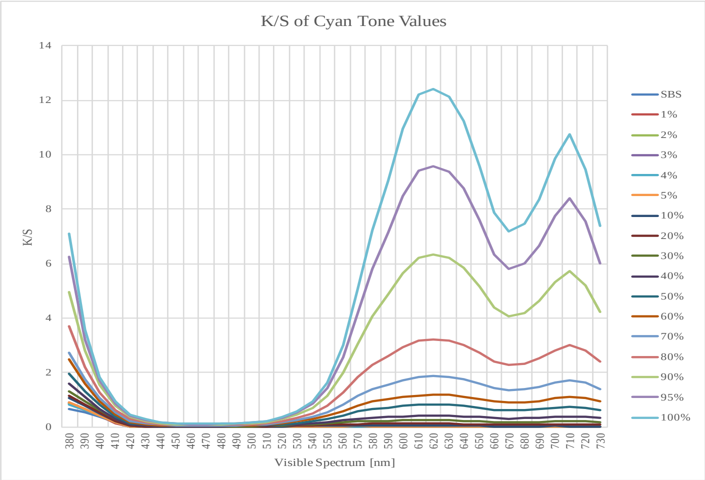


Figure 5: K/S of tonal gradation of cyan ink.

2.9 Saunderson correction[42]

The equation was developed by Saunderson in his work on computational color recipe prediction development, it dates back many years[43]. Before the Kubelka-Munk model can be applied, a correction has to be made for reflections at the sample surface[44]. The Saunderson correction factor for different measurement geometry instruments and the solutions of the Kubelka-Munk equation for opaque and transparent layers is specified in the ISO 18314-2:2015 standard document[45].

Surface reflection, also known as the Fresnel reflectance Equation, which is used in Saunderson Correction, is given in Equation 4.

$$R_c = \frac{R_0 - k_1}{\{1 - k_1 - k_2(1 - R_0)\}} \tag{4}$$

where R_c is the corrected reflectance factor at complete opacity and k_2 is the Fresnel reflection coefficient. k_1 is the surface reflectance occurring as light enters a medium of higher refractive index. The value of k_1 depends on the refractive index relative to air and on the angle of incident light.

$$k_1 = \frac{(n_1-1)^2}{(n_2-1)^2} \tag{5}$$

k_2 is the surface reflectance occurring when light enters a medium of lower refractive index. Thus, k_2 is the diffuse internal coefficient[40]. Mostly k_2 value in Saunderson equation is 0.4, but sometimes replaced by 0.6 based on refractive index of 1.5 for ink film. R_0 = total light reflected, including the contribution from the surface reflectance.

When the refractive index of ink varnish is 1.5 with ink surface smooth and glossy then k_1 is 0.04 (4%) and k_2 is 0.60 (60%). If it is considered that incident light beam falls on the surface of ink film to the normal to surface. The value of the refractive index of varnish is changed because of the resins or extenders used. The correction should be carried out to k_1 and k_2 factors.

In this work, the Saunderson's correction is not used. As a 0/45 geometry instrument is used for measurement of inks on paperboard, Saunderson correction is not required. 0/45 geometry instrument eliminates gloss at the time of measurement when inks are printed on paperboard and gloss is reduced and it is expected that paper board has lower gloss than coated or glazed paper.

2.10 Expanded gamut

The word expanded gamut is interchangeably used with extended gamut. Also, CMYKOGV is often used to define the ink set employed in expanded gamut, but violet may be interchangeably applied with blue and orange is may be used interchangeably used with red[46].

Traditionally cyan, magenta, yellow and black are considered as process colors. To increase gamut of CMYK process, many attempts have been made[47]. Multichannel profiling was an attempt to increase the gamut of process colors[12,48] by using ICC based color separation. Before introducing 7 color process, 6 color process was popular with adding orange and green to extend gamut.[49] Due to mixing of opponent colors, the actual characterization generates a large number of black patches and 7 color profiling may not be successful. GMG color and Esko Graphics has provided successful solutions for expanded gamut separations and some successful commercial solutions are available to separate colors in 7 channels. When the multi-channel test chart is generated, then ICC based software selects color with opponent colors. As an example, orange is mixed with cyan, and this combination results into generation of large number of gray patches. These are not useful interpolation based color conversion techniques[50]. Due to this reason, Esko Graphics used CMYK, OMYK, CGYK and CMVK to avoid mixing of opponent in their commercial solution. Also, when screening is done, then only 3 screen angles are available to avoid moiré pattern. In ICC profile based color separation it assigns 4 to 7 values to each pixel, which makes screening difficult. Due to this, Esko makes all color separations with not more than 3 colors and no pixels has opponent colors[51]. When the ICC profile is used to make color separations, then RIP tools are available to push colors of image towards gamut boundary to make them vibrant.

As ICC V4 was not successful beyond 4 color process, ICC introduced ICCMAX spectral based profiling[52]. Till today ICCMAX profiling is not commercially available for implementation.

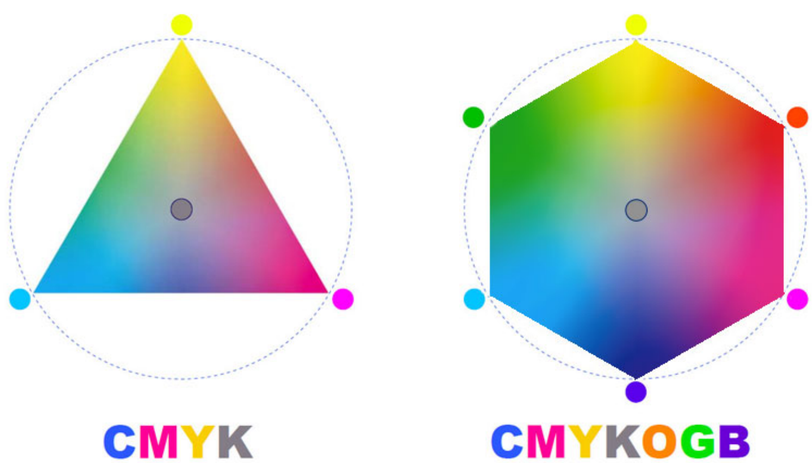


Figure 6: Gamut expansion by OGB/V colors.

Courtesy[53]:- http://www.i-i.com/new-technologies-in-a-printing-world-extended-gamut-printing/

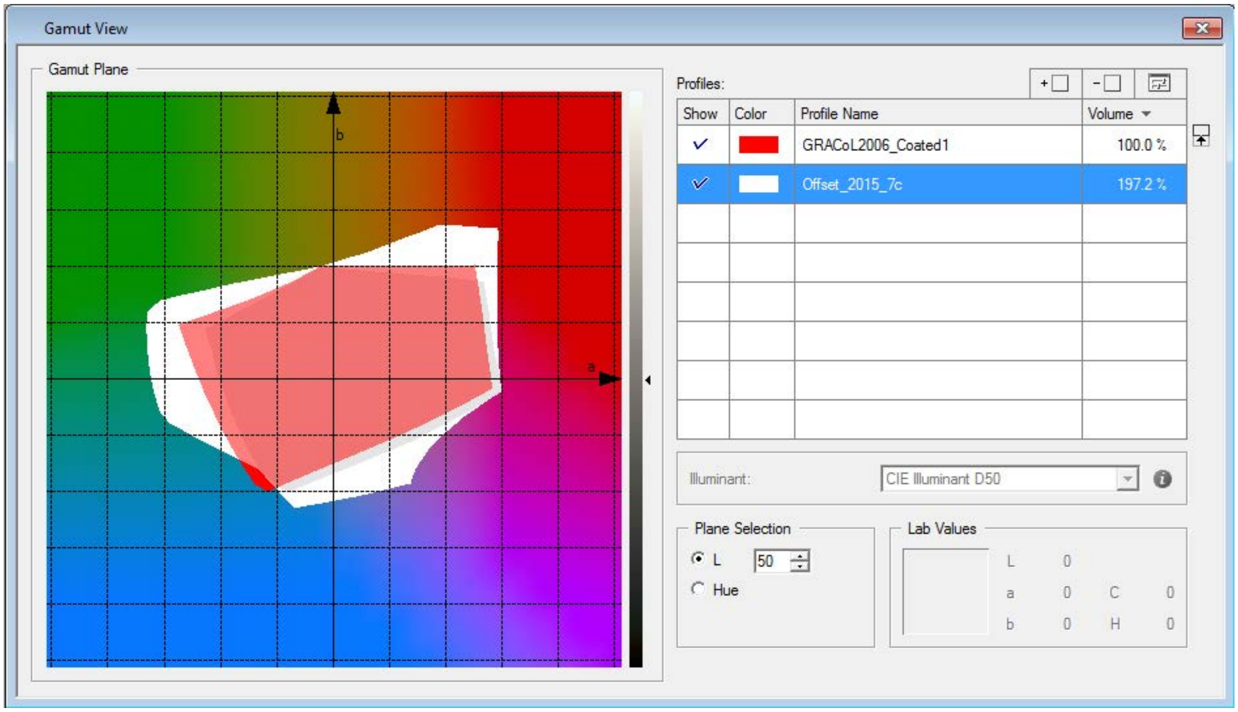


Figure 7: Comparison of process color gamut vs 7c gamut.

Image Courtesy- Mark Samworth, Esko Graphics USA

Figure 6 shows how addition of orange, green and blue colors increases gamut reference. Extended gamut covers around 80% of Pantone coated spot colors with $\Delta E<3$ by the ΔE_{2000} formula. Figure 7 shows comparison of gamut of GRACoL 2006 coated profile and expanded gamut profile of offset process reference. It shows how by expanding colors CMYK gamut can be doubled in its size. In halftone reproduction, vibrant and saturated colors can be reproduced by converting images to an extended gamut color space[10]. For reproduction of images in extended gamut mode, a moiré free separation is needed[54]. Due to restricted number of screen angles, no color has combination of more than 3 colors and opponent colors are not mixed with each other[55]. A gamut comparison of CMYK and expanded gamut inks can be done in various color spaces. Input data for color characterization play an important role in deciding accuracy of color conversion.[56]

As spot colors can be converted into a combination of expanded gamut inks, it offers many advantages such as[57] :

1) Reduction in printing press wash-up time,

2) Lower spot colors inventory,

3) Cost of formulation of spot color is less,

4) Combination run is possible for small jobs,

5) Make ready time is reduced.

In printing with extended gamut inks, it is very important to implement press characterization and maintain stability by adjusting the 1-D LUT (Look Up Table) constantly. When color management workflow for extended gamut is setup, target densities are given to the press operator to match, so print will match with the proof. For process color target densities can be setup, but for OGV no method is available and the press operator has to rely on color difference numbers. But color difference numbers do not provide clear direction to press operator to decide whether to increase or decrease ink amount to create the match. So, having a method for calculating optical density of orange, green and violet will help press operators to make decisions about controlling ink film on substrates for process and even more for spot colors, it is critical to have accurate pigment selection for expanded gamut.

2.11 Spot colors

Custom inks are used for reproduction of color images, but they are not considered as spot colors.[58] A spot color or brand standard color is a color made by an ink (mono pigmented or mixed pigmented) that is printed using a single print station. A spot color is a special ink in which color is achieved without overprinting CMYK inks, and a spot color is printed on a separate unit with its own image carrier. A spot color provides consistency in color reproduction and out of CMYK gamut colors can be printed with spot color by using other pigments[59]. By using a single ink as a spot color, it provides stability in color reproduction. Two spot colors can be over printed to achieve a 3rd color and colorimetric value[60,61] of overprint of spot colors can be predicted so spot colors are printed in tonal steps. A spot color can fall inside the process color gamut or outside the gamut[62]. Spot color inks can reproduce colors with a close match to the original when it is outside the gamut of CMYK colors. Because a single plate is needed for the spot color and tints of that color, it is usually more economical to print an extended color gamut job. A spot color is a specific color of ink. A tint is a lighter version of a color. Tints of spot colors use a percentage of ink, such as 80% or 50% or 10%. Again, spot color inks could be single pigmented inks or could be mixture of 2 or more pigments. Also, spot color inks could be transparent or opaque, usually they have larger particle size, which make them more opaque. Mostly Kubelka-Munk two- constant or multiflux mode is used for mixing spot colors in printing[63].

When a spot color is printed in 100% solid, then it can be controlled by using a color difference equation as a process control parameter[64]. But there is no method available to calculate dot area of a spot color, when it is printed in tonal value steps, because there is no specific filter in densitometers available to calculate density of spot color ink. Since density is not calculated, it is not possible to use the Murray-Davies equation to calculate dot area of printed tonal steps of spot colors. This leads to bigger problems in process control.

2.12 SCTV dot area calculations

Spot Color Tone Value (SCTV) is proposed in the ISO 20654:2017 standard. Its status was 60.00 (International standard under publication) when accessed on July 16, 2017 for research. When published standard was used in August 2017, a typo error was found in equation (6) from the document. Based on logic of CIELAB, the correct number was used in the draft. It is proposed for measuring dot area of spot color. SCTV is based on CIE XYZ values specified in ISO 13655. CIE XYZ values are calculated for D50/2.

From CIE XYZ value components are defined

$$SCTV = 100 \times \sqrt{\frac{(V_{xt} - V_{xp})^2 + (V_{yt} - V_{yp})^2 + (V_{zt} - V_{zp})^2}{(V_{xs} - V_{xp})^2 + (V_{yt} - V_{yp})^2 + (V_{zs} - V_{zp})^2}} \tag{6}$$

Value components are defined to have functional form similar to that of CIE L*

$$V_x = f\left(\frac{X}{X_n}\right) \times 116 - 16$$

$$V_y = f\left(\frac{Y}{Y_n}\right) \times 116 - 16$$

$$V_z = f\left(\frac{Z}{Z_n}\right) \times 116 - 16$$

$V_{xs}\, V_{ys}\, V_{zs}$ *are* $V_x\, V_y\, V_z$ *values calculated for spot solid ink,*

$V_{xp}\, V_{yp}\, V_{zp}$ *are* $V_x\, V_y\, V_z$ *values calculated for substrate and*

$V_{xt}\, V_{yt}\, V_{zt}$ *are* $V_x\, V_y\, V_z$ *values calculated for spot tone.*

$$f(u) = (u)^{1/3} \qquad if\ u > \left(\frac{6}{29}\right)^3$$

$$f(u) = \left(\frac{941}{108}\right).(u) + \left(\frac{4}{29}\right) \qquad if\ u \le \left(\frac{6}{29}\right)^3$$

Error in ISO 20654:2017[E]: - The published ISO standard has 941/108. The correct number as per CIELAB is 841/108. So, with correction we used below equation.

$$f(u) = \left(\frac{841}{108}\right).(u) + \left(\frac{4}{29}\right) \qquad if\ u \le \left(\frac{6}{29}\right)^3$$

The typo has been corrected in the most recent draft. SCTV provides dot area, but no density is provided for process control. This standard expects linear reproduction for adjusting 1-D LUT.

SCTV can be calculated from CIELAB values also, in that case CIE XYZ values are calculated from CIELAB and then SCTV calculations are carried out.

2.13 Shendye-Fleming correction to SCTV

A cube root function in SCTV is replaced by linear equation. This function is call g(d). Shendye-Fleming correction is shown as follows.

$$V_x = g\left(\frac{X}{X_n}\right) \times 100 \tag{7a}$$

$$V_y = g\left(\frac{Y}{Y_n}\right) \times 100 \tag{7b}$$

$$V_z = g\left(\frac{Z}{Z_n}\right) \times 100 \tag{7c}$$

Where;

$$g(d) = d \qquad for\ all\ d.$$

This function can provide dot areas closer to the Murray-Davies equation. This is a semi empirical model that has better correlation with observer data. Physical or optical mechanisms of the printing process are described by a mechanistic model.

2.14 Measurement of reflectance spectrum of light

In any printing process, it is important to control the amount of ink on substrate. This is carried out by measurement of reflected light. The basic principle is that the lower the amount of light reflected, the lower is the ink film thickness. So, measurement of reflected light is carried out as a part of process control. For measurement of reflectance of light, an X-rite i1 pro2 instrument is used. An i1 Pro2 instrument has a range from 380 nm to 730 nm, and it has 0/45 ring illumination geometry. The 45°:0° measuring geometry used in the spectrophotometer, which has directional illumination. A light source incident angle is 45° and observer/detector is placed at 0°. Spectrophotometer having 0/45° geometry illuminates the sample at an incident angle of 90°

because this angle is same as 0° angle and while the detector views the sample at a 45° angle. In the spectrophotometry when, the light source is placed at 45°, then it gives ring illumination. It has been observed in the printing industry that 0/45° or 45/0° geometry spectrophotometric data closely simulate the visual experience, as human eye eliminates gloss, while viewing the same way a 0/45 instrument eliminates gloss while measuring[65]. 0/45 geometry instruments are generally used for any flat, non-fluorescent, color specimen. It is especially recommended for measuring specimens of intermediate gloss like ink on paper.

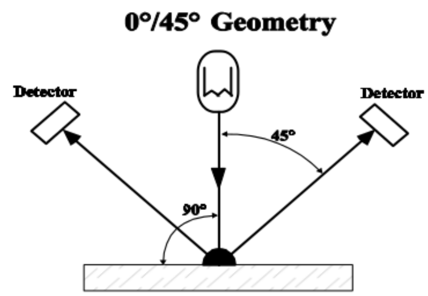


Figure 8: Illustration of 0/45 geometry.
Image Courtesy[66]- https://stephenstuff.wordpress.com/2012/01/07/an-introduction-to-digital-camera-profiling/

In ISO 13655, measurement conditions are defined for measurement of color. Reference needed Measurement illumination condition M0 has very little UV content. ISO 13655 standard specifies that M0 mode is not recommended when substrate used in printing has OBA and it is observed under ISO 3664 viewing condition. The old UV-cut method with using UV cut filter of measuring is now called M2 in ISO 13655. Measurement illumination condition M1, which is D50, was introduced to reduce variations in measurement results between instruments caused by OBAs and to give better visual simulation under ISO 3664 viewing conditions. M1 is the best choice for the printing industry for measurement of color. Measurements taken with M1 mode measure the colors with a D50 illuminant, so the UV component in the measurement light source is similar as the amount of UV present in the D50 light booth. M3 uses a polarization filter for measuring wet ink applications and is not available on current i1 Pro2 spectrophotometers. Polarization filters must be mounted separately and are not used for measurement of color. The polarization filter is used to avoid density drop caused by ink drying. Wet ink density is always higher than dry ink density for the same patch. This is known as dry back. Use of polarization filter avoids this dry back effect. For measurement of high gloss colors and metallic colors, d/8 geometry with specular component included is used.

2.15 CIE colorimetry[67]

In 1931, the International Commission on Illumination (CIE -Commission Internationale de l'Eclairage), established a color specification system. The CIE system provides the recommendations for basic colorimetry. The CIE provides the standard illuminants and the standard colorimetric observer data, the reference standard for reflectance sample calibration and the illuminating and viewing conditions, the method for calculation of tristimulus values, chromaticity coordinates, color spaces and color differences; and the various other colorimetric practices and formulae. The CIE system is accepted as the standard method across the various platforms for various industry and standardization. CIE allows a user to select various illuminants according to its application. The graphic printing industry uses the D50 illuminant.

Illuminants [68]

"An illuminant is set of numbers defined by the relative spectral power distribution that may or may not be physically realizable as a source"[69]. All illuminant data are published by CIE. In this work, CIE D illuminant D50 is used with 2° observer color matching functions.

CIE 'D' series of illuminants[70] –The method of calculation for this series is based on a correlated color temperature. D65 is recommended by CIE as a standard illuminant. It represents day light at noon with a color temperature of 6504 °K. D50 has been adopted by the graphic arts industry in the USA as a standard illuminant, and it represents horizon sun light with a color temperature of 5000 °K. Illuminant and light source are distinct concepts. An illuminant is defined by mathematical data, which are used in colorimetric calculations and a light source is a physical source, which emits electromagnetic radiation in the visible region. Not all illuminants have physical light sources. Light sources are made by targeting illuminant data and the difference between target (illuminant) and light source is characterized by the color-rendering index

2.16 Optical brightening agents

Paper manufacturers add optical brightening agents in paper to make paper appear brighter. Fluorescence is a phenomenon where the molecules of a fluorescent substance become electronically excited by absorbing light energy and then emit this energy at a higher wavelength. Fluorescence phenomenon can take place with compounds having large conjugated systems which contains π-electrons. The light source must contain a UV component to work with OBA[71]. "*OBAs absorb ultraviolet radiant energy at 300–360 nm and reemit the energy in the visible range, mainly in the blue wavelength region*"[72]. OBA's are used in textile and paper industries. There are three main types popular in the paper industry and they are based on the stilbene molecule. The main difference among these groups is the number of solubilizing sulfonic groups[73]. Di-sulfonated OBAs have two sulfonic groups; the two other substituents are hydrophilic groups[74]. Di-sulfonated OBAs have a very good affinity, but they have very limited solubility and are mostly used in the wet-end side of paper chemistry. The most commonly used OBAs are the tetrasulfonated types. Medium affinity and good solubility of Tetra-sulfonated OBAs give them versatile characteristics. They are widely used in most applications in the paper industry from wet-end, size-press, and coating applications[75]. The hexa-sulfonated OBAs are specialties used mostly in coatings where high brightness is required like gloss coated paper and packaging board[76]. Most of the OBAs on the market are derivatives of bis(triazinylamino)stilbene[77]. Only the trans-isomer exhibits strong fluorescence, the cis-isomer is non-fluorescent. The OBAs used in the paper industry are natrium salts and these saults are water soluble. Water solubility is important as it works as carrier for pulp. Not all types of papers contain OBA. OBA is added while making paper for printing and writing only. Tissue papers, napkins do not require OBA.

OBA and color reproduction:

Brightness, whiteness, color, lightness are optical properties of paper and they have impact on color reproduction capabilities of paper. Mechanical properties such as smoothness, permeability and porosity also have impact on image quality reproduction. Process color inks are transparent and light is reflected from paper. The color gamut[78] is based on ink and substrate combination. For a given ink/substrate combination, the color gamut volume in Lab space is the number of colors that can be reproduced with a ΔE tolerance of √3[78]. The International Color Consortium (ICC) White Paper 14 (2005) summarizes CIE Publication 163 (2004), which indicates and quantifies that the fluorescence of the substrate can be found in both solid ink areas and halftone ink area with different papers[79]. Colors reproduced by papers with and without OBA are different[80] and the methods to predict or correct the OBA effects are important for color reproduction. While setting up color management workflows, reference print conditions[81] are always used as benchmarks. The concept of reference printing conditions is organization of such characterization data sets into a minimum logical family that covers the full range of printable color gamut. ANSI CGATS TR 001 is an example of a characterization data set, which is a logical candidate for this type of family of reference printing conditions[82]. The G7 method[83] is one of the methods to achieve targets defined in ISO 12647-2 for offset printing. Brikett and Spontelli have suggested to blend M1 and M2 measurement for reducing problems in color management caused by OBA.[84] X-Rite™ has patented a technology for color measurement of printed samples including brighteners by weighting spectral correction factor on spectrum with UV component.[85]

2.17 One dimensional color scales

In assessment of optical properties of color of the material, many one dimensional color scales are used. Brightness, whiteness, and yellowness are common one-dimensional scales used to specify optical properties of paper or another white substrate. These one dimensional color scales are for comparison, so they don't have units. Optical Brightening Agents (OBAs) also known as Fluorescent Whitening Agents (FWA) are widely used in paper to provide A blue cast, but there is no index available to measure effects of OBAs in the blue region. When you consider a sample of white paper you may see it as having a bluish tint or a creamy tinge to it, this is because it is very difficult to create a cast free white. A cast free white paper will reflect all the colors of the spectrum equally, whereas a blue white shade reflects more in shorter wavelength than in red and green region of light. A creamy white or yellowish white shade absorbs more light in the blue region. So, this change in absorption in the blue region of paper requires new one-dimensional color scale.

Brightness of paper; Bleaching of pulp not only gives whiteness, but it also affects brightness of paper[86]. Higher pulp bleaching increases brightness of paper[87]. TAPPI test method T452 is given for Brightness of Pulp, Paper, and Paperboard (Directional Reflectance at 457 nm)[88]. TAPPI test method T 525 provides diffuse brightness of pulp by d/0 geometry instrument[89]. TAPPI test method T 534 provides brightness of clay and other mineral pigments by d/0 geometry instrument[90]. T 646 provides Brightness of Clay and Other Mineral Pigments (45/0)[91]. As brightness is measured at 457 nm, which is in the blue region, OBAs are added in the paper to increase reflection in that region. Addition of OBAs helps to increase the measured brightness of paper.

Whiteness of paper; Whiteness of paper mainly comes from bleaching of pulp and whiteness of clay used in paper coatings[92]. TAPPI test method T 560 refers to CIE Whiteness and Tint of Paper and Paperboard (Using d/0), Diffuse Illumination and Normal Viewing)[93]. Method T 562 method CIE Whiteness and Tint of Paper and Paperboard (Using 45/0 Directional Illumination and Normal Viewing)[94]. Both have equivalent method as ASTM E313[95]. TAPPI uses illuminant C, which has correlated color temperature of 6774 K. CIE has discontinued illuminant C and recommended to replace it with D_{65}. TAPPI standards have not been updated and illuminant C is still used. Many other whiteness formulas have been derived[96]. The Fleming-Aksoy whiteness formula[96] covers some limitations of the CIE formula. The method for calculating CIE whiteness is given below.

CIE Whiteness; First Calculate CIE XYZ values for illuminant observer combination, and then calculate CIE chromaticity coordinates.

To calculate CIE XYZ the values, following equations are used:

$$X = K\int_{380}^{730}\left(S(\lambda)R(\lambda)\overline{X}(\lambda)\right) \tag{8a}$$

$$Y = K\int_{380}^{730}\left(S(\lambda)R(\lambda)\overline{Y}(\lambda)\right) \tag{8b}$$

$$Z = K\int_{380}^{730}\left(S(\lambda)R(\lambda)\overline{Z}(\lambda)\right) \tag{8c}$$

Where

XYZ- Tristimulus values

$X_{n,}$ Y_n Z_{n-} Chromaticity coordinates of illuminant

$S(\lambda)$ – Illuminant emission data

$R(\lambda)$ – Reflectance data

$\bar{X}(\lambda), \bar{Y}(\lambda), \bar{Z}(\lambda)$ - Color matching functions for 1931 or 1964 CIE observer

The constant K is calculated for normalization.

$$K = \left[\frac{100}{\int S(\lambda)\, \bar{y}(\lambda)\, d\lambda} \right]$$

$x = X / (X + Y + Z)$

$y = Y / (X + Y + Z)$ and finally

$$\text{CIE whiteness} = Y + 800\,(x_n - x) + 1700\,(y_n - y) \quad (9a)$$

$$\text{CIE tint } T = 1000\,(x_n - x) - 650\,(y_n - y) \text{ for a } 2° \text{ observer} \quad (9b)$$

$$T = 900(x_n - x) - 650(y_n - y), \text{ for a } 10° \text{ observer} \quad (9c)$$

Where x_n and y_n are color coordinates of the achromatic point.

Positive tint indicates greenishness. Negative tint indicates reddishness. For achromatic points ASTM E313 mentions as *"The CIE gave coefficients for both standard observer and illuminant* D_{65}*; those for standard observer and illuminant C were taken from AATCC; and those for 1964 observer and illuminant C and illuminant* D_{50} *were established by subcommittee E12.04. Those for illuminant C and illuminant D50 and both observers are unofficial and should be used for in-house comparison only."* As guidelines, the following limits are recommended:

$5Y - 280 > W > 40$

$-3 < T < 3$

where

W = CIE whiteness; T = CIE tint

Fleming-Aksoy whiteness[97,96]; W_{FA} is based on the assumption that observers prefer more 'Blue' white but only if it is not too blue. Reference W_{FA} formula uses the CIELAB color space. The coefficients were determined from the CIE formula by requiring that two formulas have the same values and derivatives with respect to a* and b* at zero Chroma for given Y or L* value.

N_{FA} corresponds to a maximum whiteness at the perfectly reflecting diffuser, i.e. zero Chroma in the CIE L*a*b* space.

$$W_{FA} = Y(1/2)^{[a^*(a^*-2a1^*)+b^*(b^*-2b1^*)]/C_2^2} \tag{10}$$

$C = (a^{*2}+b^{*2})^{1/2}$ is the Chroma and C_0 and C_2 are characteristic Chroma values determined from the boundary region defined. a1* and b1* are the coordinates for the local maximum whiteness at constant lightness Y (or L*). They are determined by equating the corresponding derivatives of W_{FA} and W_{CIE} with respect to a_1^* and b_1^* to one another.

The expressions are:

$$a_1^* = \alpha(Y_n/Y)^{4/3}C_2^2/(200\ln 2) \text{ and} \tag{11a}$$

$$b_1^* = -\beta(Y_n/Y)^{4/3}C_2^2/(200\ln 2) \tag{11b}$$

where, $\alpha = 3x_n(900y_n – 800z_n)/500$ and

$\beta = 3z_n(800x_n + 1700y_n)/200$,

with Y_n, x_n and y_n being the illuminant luminance and chromaticity values.

2.18 ISO Standards and OBA

ISO 3664:2009 viewing condition[98] and OBA

The perception of color depends on spectral properties of the light source. Light source spectra and intensity play an important role in ISO 3664 specification using D50 illuminant as reference to make light sources and viewing conditions for viewing printed images. These new light sources used in viewing booths are much closer to the amount of UV energy present in a reference D50 viewing conditions mentioned in the standard and thus results are closer to M1 measuring devices so that getting a better match between visual assessment and measurement is possible. In ISO 3664, when paper contains OBA and it is viewed under ISO 3664 viewing condition, then the UV component of the D50 light source interacts with OBA and increases apparent reflection of light in the blue region. This causes the substrate to look bluer. ISO 3664:2009 specifies increased levels UV activity in D50 graphics arts lighting, and gives a standard that is closer to daylight, but at the same time exposes even more strongly some of the problems resulting by the mismatch between OBA-free proofing papers and OBA-loaded printing paper. In FOGRA research report 60.055 *"Method to compensate the differences between proofing and production stock"*[99] recommends to use ΔB method, which determines the OBA amount through the difference between CIE b* value of M2 and M0 or M1 measurement. The drawback of this method it is a one dimensional scale based on three dimensional color space values.

ISO 13655:2009 spectral measurement[100] and OBA

The latest version of ISO 13655 for spectrophotometer measuring standards was released around 2010. The ISO 13655:2009 standard defined the measurement standards for papers with high OBA content. This standard defines four color measurement modes.

M0-This measurement condition uses the tungsten lamp as per old spectrophotometers. This light source contents less UV and doesn't show much impact due to OBA in measurements

M1-The new mode based on D50 lighting. This light source used in spectrophotometer contains UV and it is designed to consider for having better visual-numerical correlation under ISO 3664-2009 as the illuminate to accurately measure printed results on papers with high OBAs.

M2-This is measurement uses a UV cut filter. This is a replacement for the current 'UV' instruments. By adding all these modes in a single instrument, it eliminates the need of keeping different instruments.

M3- To avoid dry back effect in measurement of density, a polarization filter is used. This measurement mode defines use of polarization filter for measurement of wet printed sheets.

Selection of correct measurement condition for measurement is important. Also, selection of measurement condition for measurement of optical properties of paper play an important role in visual-numerical correlation.

ISO 15397:2014 communication of paper properties[101] and OBA

ISO 15397:2014 specifies the list of relevant properties of paper substrates to be communicated between the paper and printing industries. This standard recommends specifying brightness, CIE whiteness, gloss, color measurement and fluorescence along with mechanical properties of paper. Here, the Fluorescence component is calculated as the difference between the whiteness/brightness measured with a source of light having a UV-content corresponding to the chosen illuminant and the whiteness/brightness measured with a source without radiation of the excitation band. Specification of OBA as a one dimensional scale will help specifying blue cast of paper.

ISO 2470-1:2016 Blue reflectance factor[102] and OBA

This standard specifies a method for measuring the diffuse blue reflectance factor (ISO brightness) of pulps, papers and boards. This is an indication of the amount of present Optical Brightening Agents (OBA's) in the substrate, expressed as a percentage. As per this standard Brightness is measured using a D65/10° light source and a second time on wavelength 420 nm (total UV blockage). The Delta UV is the difference between both values. f, in the case of fluorescent samples, measurements are made with a filter with a cut-off wavelength of 420 nm placed in the light beam, it is possible to determine the ISO brightness of the non-fluorescent substrate and thus to calculate the contribution of the fluorescent whitening agent to the ISO brightness:

$$\Delta UV\ (\%) = R457 - R420 \tag{12}$$

Where:

R457 = brightness at 457 nm (red/green cut-off)

R420 = brightness at 420 nm (UV cut-off)

The biggest limitation of this standard is that UV affects sample measurement from 400 nm to 550 nm region. This entire region effect is not considered as effect of fluorescence. The amount of fluorescence affect in this region has visual impact. So, calculation method of ISO 2470 has poor visual numerical correlation for ISO 3664 viewing condition.

CHAPTER 3

METHODS

3.1 Problem statement

The process color gamut is now extended by adding Orange, Green and Violet as extended process colors. Because of RGB and Visual filters, existing densitometry is only limited to CMYK process colors. Due to lack of availability of filters for OGV, a new method is necessary to calculate optical density of OGV inks and spot colors.

Human eye perception is that “bluer is whiter” up to a certain limit when whiteness of material is considered. Light has impact on perception of whiteness. It is necessary to determine OBA on paper as an optical property for comparison with reference to ISO 3664 viewing condition.

3.2 Proposed equation for universal density measurement

The proposed Shendye-Fleming universal density equation for calculating optical density beyond process colors for non-fluorescent, non-metallic inks is given in Equation 13.

$$D_{S-F} = -\log_{10}\left[\frac{\sum_{\lambda=a}^{\lambda=b}\left(\left(\mathrm{R}\right)*\left[\frac{(1-R)^2}{2\mathrm{R}}\right]\right)}{\sum_{\lambda=a}^{\lambda=b}\left(\frac{(1-R)^2}{2\mathrm{R}}\right)}\right] \tag{13}$$

Where; R: reflectance value of color.

In equation 6, the Kubelka-Munk equation is used to generate the filter set. The absorption region of Kubelka-Munk spectrum is used to filter the absorption region of the reflectance spectrum. This equation uses a band-width of the reflectance spectrum for calculation of density. The band-width region of spectrum measurement is multiplied with the same band-width region as its absorption spectrum and then it is normalized. After normalization, a negative logarithmic value at base 10 of the calculated value is taken as output. Verification of this equation is carried out by comparing to results for CMY ink densities calculated by Status E filter sets, which is a fixed set of filters. The behavior of equation 13 is the same for any color spectrum measured, even beyond process color sets. As there is no method available to verify equation beyond process colors its results are not compared, but are analyzed. Output of this equation is a single positive density number. As this number is similar to ISO status density, it can be used for further densitometry calculations. By inputting density value of extended process colors and spot colors into the Murray-Davies equation, apparent dot areas can be calculated. As the equation is spectral based, it can be used for any printed process on any substrate for any screen ruling and any dot shape.

Following are the characteristics of Equation 13:

1) The equation is spectral based.
2) The equation generates a filter from its input reflectance spectrum data.
3) As the filter is generated from reflectance data, each calculation has its own filter, so filter values change and they are not fixed, so it is a floating filter.
4) This allows calculation of density beyond process colors.
5) Being spectral based, this technique can be used for any printing process and for any screen ruling, AM or FM, and also for any dot shape.
6) The user has freedom for selection of band-width for absorption region.
7) Density can be used for Murray-Davies equation for apparent dot area.
8) As 0/45 geometry is used since it eliminates gloss in measurement, there is no need of correcting measurement values by Saunderson’s correction.
9) When compared to ISO 5: -3 status E for CMY, the results are close.

3.3 Print quality analysis

During printing, it is very important to analyze the quality of print. Print quality analysis is carried out by analyzing elements of prints[103]. For that, the density of the print is one of the important and basic characteristics of print. Other measurements are based on densitometry, such as dot area, print contrast and trapping. When a large solid area is printed, then evenness of printed film is measured by measuring density at various locations. Various print elements such as media wedge are used for assessment of print quality for different quality parameters. Controlling density of individual cyan, magenta and yellows helps in achieving gray balance in an image[83,104]. The quality of an image depends upon various factors such as dot area, dot shape, or smoothness of tonal gradient. There are several automated computerized print quality assessment tools available[105]. If the dot is round in shape, then roundness and dot area can be measured for calculating dot fidelity and this can't be done using spectral measurement[30]. Also, apart from round dots, many more dot shapes are available. Frequency modulated screenings can be used where dot shape changes as tonal step changes in image.

3.4 Print process control

Due to process variables in printing, measurement and control of these variables is necessary. Print process control is important for maintaining consistent quality. To control the quality of image and print, it is important to control basic elements. This is carried out by using reference print conditions as target[106]. A constant comparison between reference and current results are necessary to take correction during process. Density is one of the important tools in print process control. Tighter controls give consistency in reproduction for longer run in printing.

3.5 Proposed equation for OBA index

$$\text{Shendye} - \text{Fleming OBA Index} = 100 * \left[\frac{\sum_{\lambda=400nm}^{\lambda=550\text{nm}}\big((\text{ R(M1)}-\text{R(M2)})*\text{D50}\big)}{\sum_{\lambda=400nm}^{\lambda=550\text{nm}}(\text{D50})}\right] \tag{14}$$

Where;

R(M1): - Reflectance of paper by M1 measurement condition

R(M2): - Reflectance of paper by M2 measurement condition

D50: - D50 illuminant

The Shendye-Fleming OBA index can be used with any spectrophotometer with ISO 15339 M1 and M2 measurements. It uses illuminant data of D50. A constant is derived from illuminant data from beginning of blue region to 550 nm.

3.6 Applications of Shendye-Fleming OBA index

Application of OBA index is for the paper and paperboard industry as a quality control tool. The Shendye-Fleming OBA index can be used to compare blue cast between two papers in production. It can be also used for comparing the amount of OBA added between two papers. As the Shendye-Fleming OBA index uses D50 illuminant along with M1 and M2 measurement conditions, it gives better visual-numerical correlation under ISO 3664 viewing condition for comparing OBA of the paper. Blue cast of paper plays a very important role in color reproduction as it has an impact on color appearance. The Shendye-Fleming OBA index can help in color management to determine impact of OBA on blue and yellow cast of white substrates.

CHAPTER 4

IMPLEMENTATION OF MODEL

4.1 Methodology

Part 1 – Printing and data gathering

Part 2 – Model development and robustness testing

1. Materials required
    a. Spectrophotometer with 0/45 geometry
    b. Inks- CMYKOGV + spots
    c. 2 different substrates: SBS and Recycled coated board
    d. Lithography printing press
    e. Test target: RIT target with tonal steps
2. Experimental sequence
    a. Prepare test target
    b. Print test target on 2 different stocks by CMYKOGV inks
    c. Measure spectral reflectance data of target
3. Obtaining data: - Use i1 Pro 2 instrument for obtaining spectral reflectance data. All calculations for determining optical density will be carried out based on spectral reflectance data.
4. Calculate optical density for CMYK by ISO 5-3 method.
5. Develop new filter generating model for calculating optical density.
6. Compare new model with status E filter response set of ISO density.
7. Develop filter for orange, green and violet inks and calculate optical densities.

8. Compare optical densities with tonal gradation range of OGV inks.

9. Compare new model for different stocks.

4.2 Reproduction workflow

A normal production workflow in the packaging industry was used in this testing. The G7 method was used to calculate RIP curves. Target densities were set by using RPC 006[107] reference print conditions. An X-rite i1 Pro2 device was used for measuring spectral reflectance data for M0, M1 and M2 measurement conditions. Custom built software was used for measuring density on press.

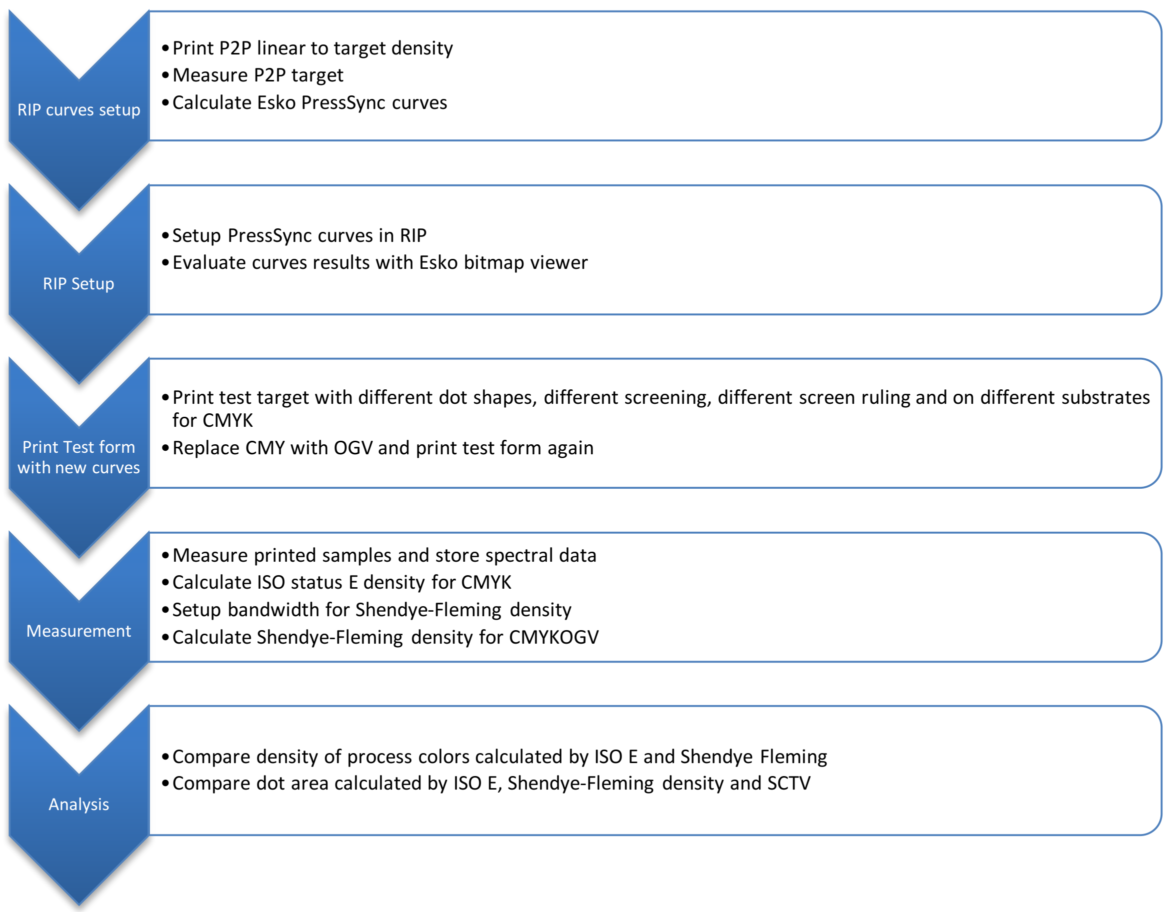


Figure 9: Workflow of the experiment.[83]

Printing to target density is very important. If the image is printed with low density, then it results in dot loss and results in loss of detail and smooth reproduction of tonal gradation. Images printed with low density look like faded images. If image is printed with high density, then it results in high dot gain or tone value increase, which results in loss of details in shadow areas. High dot gain also shows an image that is printed darker. So, printing to target density is critical part of color management.

Figure 10 shows the workflow sequence for color management with G7 method to target ISO 12647-2 data set by using GRACoL method.

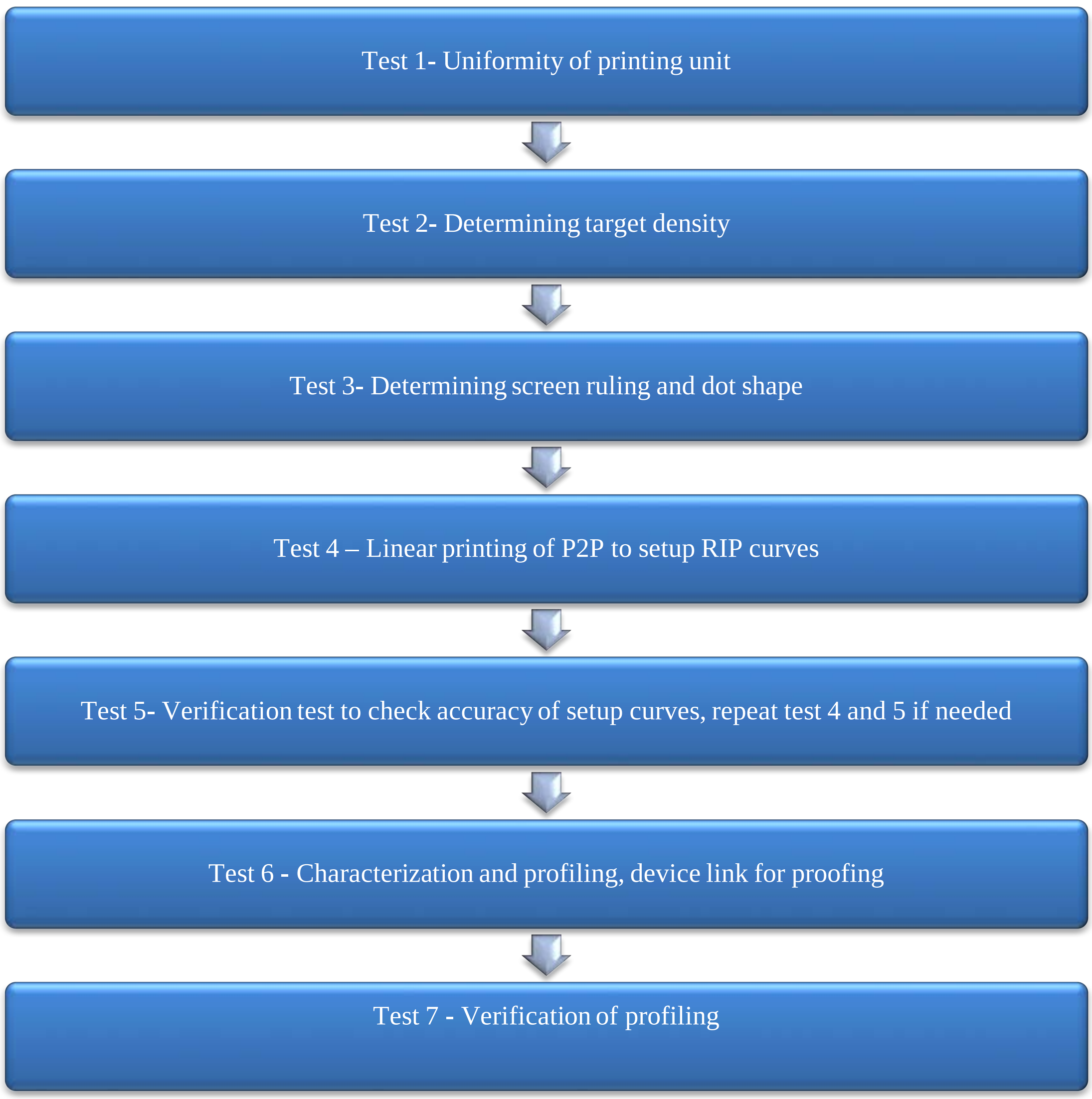


Figure 10: Workflow for press characterization.

4.3 Test targets

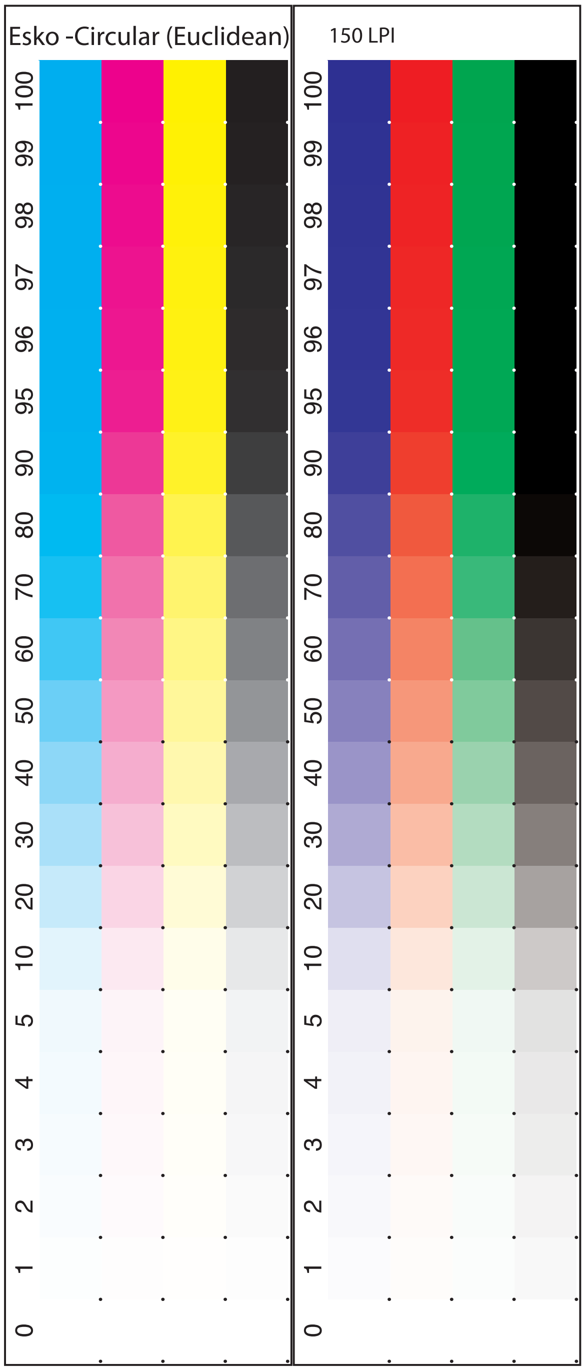


Figure 11: RIT tone value measurement target.

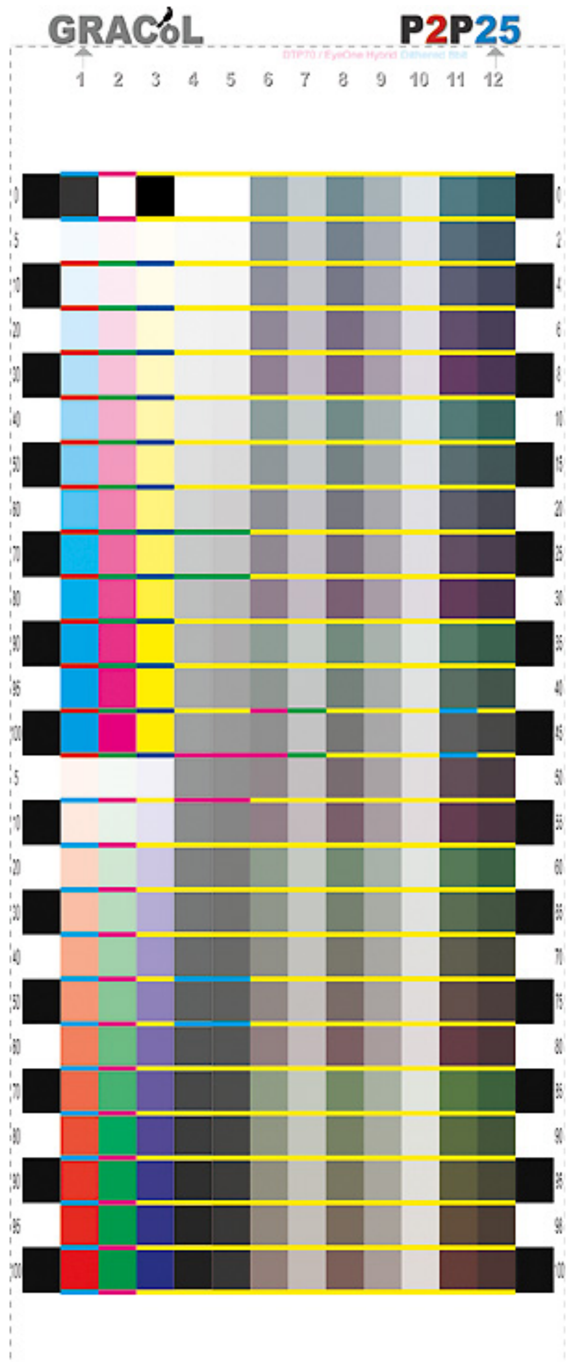


Figure 12: G7 P2P target.

The RIT dot area scale was used for measurement and calculation of dot area. P2P is the target design for G7 method to calculate RIP curves. This plays a crucial role in targeting certain standard data sets.

In G7 implementation, the first step is determining RIP curves by printing P2P linear. The test form (Figure 13) shows that different elements were used in the test form for evaluating quality of print. Column number 4 and 5 from P2P helps in determining gray balance of inks. As target is printed, it shows dot gain of respective printing units.

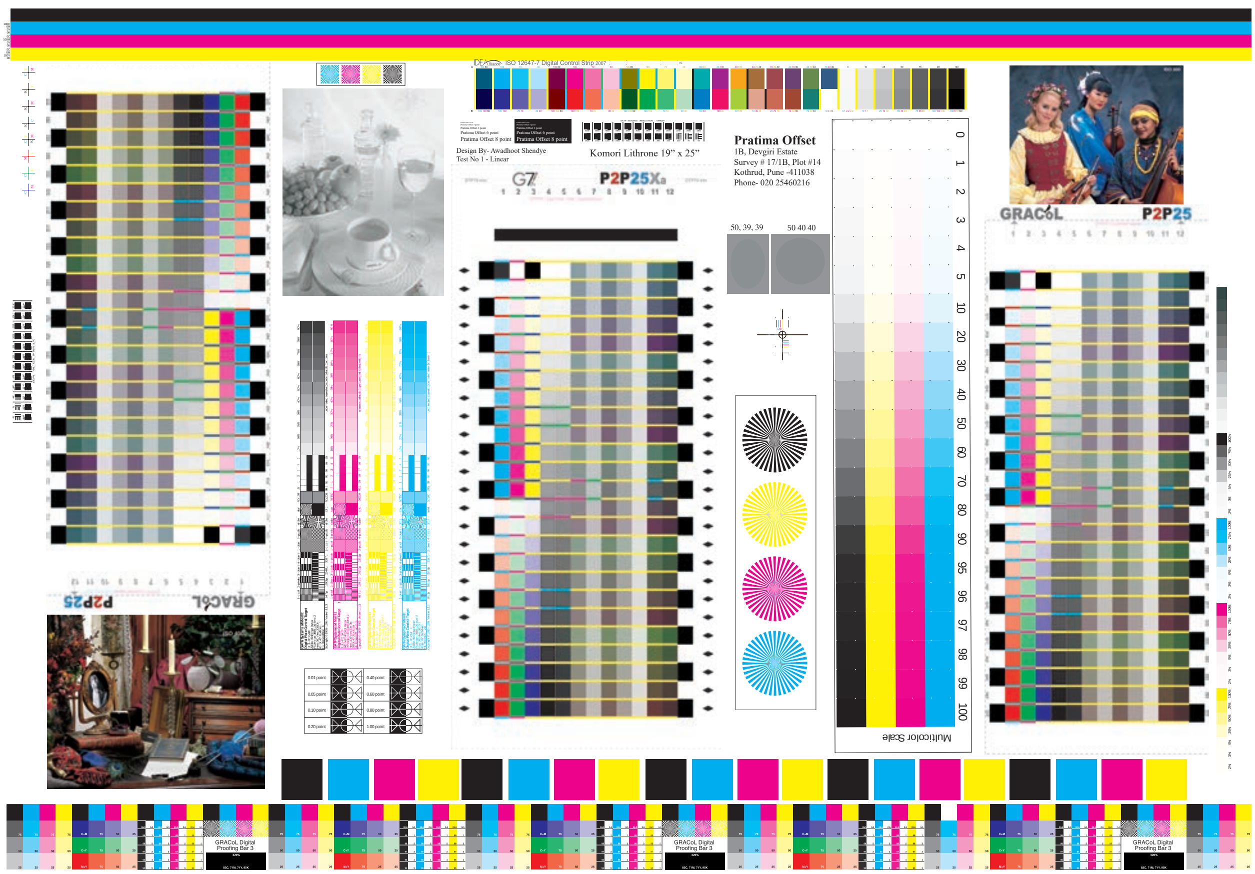


Figure 13: Test form used for press calibration.

4.3 Computation process

In this experiment, all tests in color managements are not required. If information from press about densities or previous RIP curves is available, then a few steps can be reduced to reduce time spent on running tests. Technically this should be carried out for each press, paper and ink combination. This will result in a large number of profiles and RIP curves in the data set. Due to the large number of substrates available, this is not feasible in press so grouping of substrates is carried out and the closest data set and RIP curve combination are used. The same approach was used in this experiment.

Figure 14 shows how target densities were calculated and then the same data from P2P were used for setting to Esko Press Sync curves in RIP.

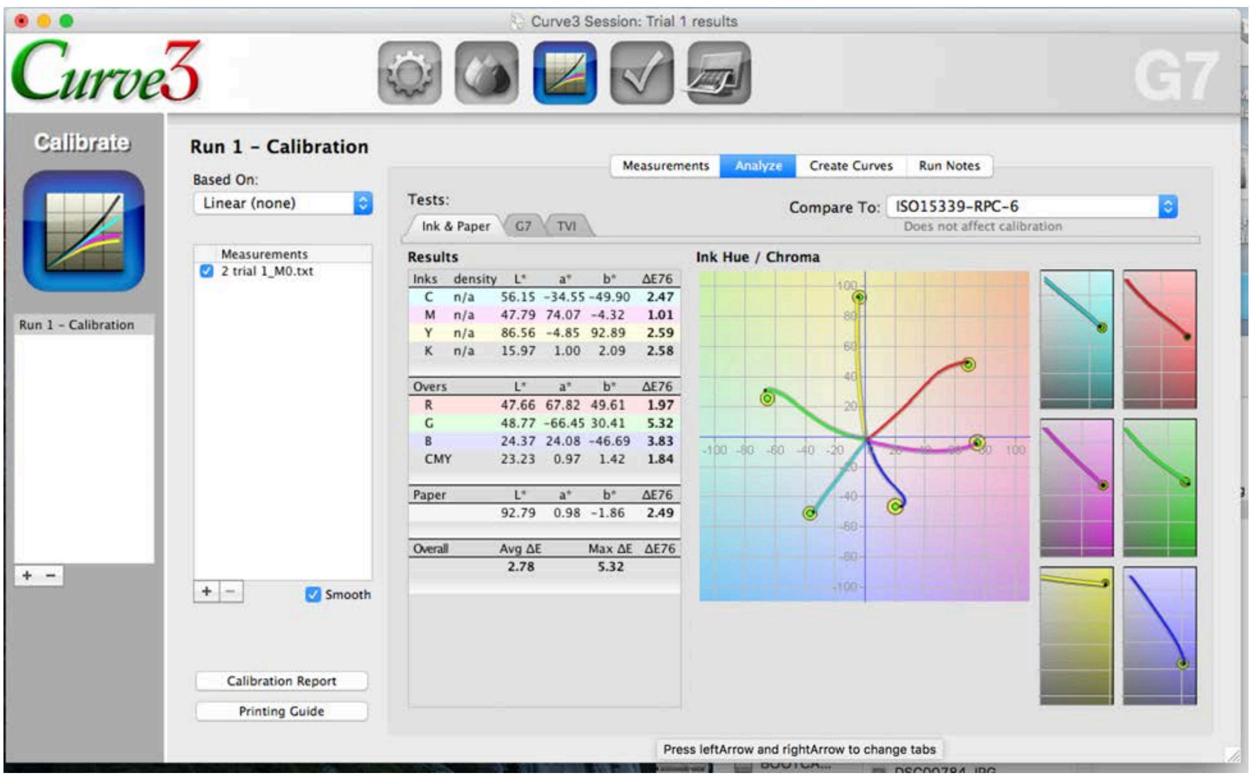


Figure 14 :Analysis of linear P2P.

The closest results were achieved for ISO 15339 –RPC-6 data set. Then those P2P measurements were used for calculating RIP curves. Current ISO 12647-2 does not provide a target for available packaging boards, so the closest data set has to be selected for setting up RIP curves. An outlier weighting method was used. Default screen angles were used with Fogra Round dot at 150 LPI.

This also provided node based curve data for manual curve entry in the RIP. Table 1 shows Esko Rip curves.

Table 1: Target RIP curves for Esko Press Sync

Inks	Esko PressSync Curves	Screen Angles [degrees]
Cyan	E 49	15
Magenta	E 48	75
Yellow	B 51	90
Black	B 42	45

Figure 15 shows node based data to setup RIP curves. Esko PressSync curves is set of preset curves from A to H and number after that shows its cutback at 50% dot. It has magnitude from 20% to 70% so it gives set of 400 curves.

Control Points: "wanted" values

Entry	C	M	Y	K
0.0	0.00	0.00	0.00	0.00
2.0	2.84	3.01	4.30	2.94
4.0	4.92	5.02	6.81	5.10
6.0	6.74	7.12	9.75	7.06
8.0	8.49	8.80	12.02	8.80
10.0	10.16	10.32	13.72	10.39
15.0	14.12	14.26	18.20	14.51
20.0	18.27	18.47	24.40	18.74
30.0	28.42	28.30	34.24	26.76
40.0	38.35	37.72	42.32	34.85
50.0	49.47	47.47	50.46	42.54
60.0	58.11	57.52	57.59	49.34
70.0	69.32	68.54	67.85	57.49
80.0	80.18	80.24	79.07	68.05
85.0	85.45	86.01	85.39	73.65
90.0	90.79	90.55	90.35	80.15
95.0	95.29	95.35	95.31	88.08
100.0	100.00	100.00	100.00	100.00

+ − Harlequin-based RIP

Figure 15: Wanted RIP curve data by nodes.

Table 2 shows printing process parameters of the experiment.

Table 2: Press run process parameters

Press Run	
Press	Komori Lithrone 19” x 25”
Substrate	SBS and CRB
Substrate type	Packaging board
Substrate grammage	300 gsm
Ink sequence	K-C-M-Y-O-G-V
Fountain solution pH	5.4
Fountain solution Conductivity	2300 mS
Fountain solution temperature	11.7° C
Fountain dosage	6%
IPA dosage	4%
Run length	1000 sheets each
Press speed	8000 SPH
Press maintenance verified	Yes

Abbreviations:
SBS- Sulphate Bleached board
CRB- Coated Recycled Board
IPA-Iso Propyl Alcohol
SPH- Sheets Per Hour

A 4 unit/color offset lithographic machine has print sequence was KCMY as 7 colors need to be printed on the 4 color machine, ink changing is carried out as Orange in cyan unit, Green in magenta unit and Violet in Yellow unit as they have same plates as it requires same screen angle. Although printing sequence does not matter because any overprints or trapping is not under consideration. Only individual tonal scales are under consideration for measurement as element of image so printing sequence has no impact on process.

In prepress, object oriented screening from Esko was used. This allows user to make different screen angles, screen ruling and dot shapes on plate in one set of exposures. Table 3: Measurement parameters shows measurement conditions.

Table 3: Measurement parameters

Measurement Conditions	
Instrument	X-Rite i1 Pro 2
Geometry	0/45
Measurement Conditions	Dual spot M0, M1 and M2
Measurement range	380 to 730 nm
Interval	10 nm
Aperture	4 mm
Calibration	Yes

Measurements were taken in spot mode and reflectance data were stored in *.csv format by custom software built in C++ for this project. Then, Microsoft Excel was used for computation and plotting graphs. Repeatability, reproducibility and accuracy of instrument is important. In this experiment X-Rite i1 pro2 instrument was used and as per manufacturer it has Short-term repeatability: 0.1 $\Delta E94^*$ on white (D50, 2°, mean of 10 measurements every 3 seconds on white) and Inter-instrument agreement: 0.4 $\Delta E94^*$ average, 1.0 $\Delta E94^*$ max. (deviation from X-Rite manufacturing standard at a temperature of 23ºC on 12 BCRA tiles (D50, 2º)).

Each ink used in expanded gamut must be mono-pigmented. Usually pigments with highest purity are selected for expanded gamut inks to get maximum gamut volume. Selection of pigments for expanded gamut is outside the scope of this research.

Table 4 shows pigments used in CMYKOGV inks in this experiment. CMYK inks were as per specification of ISO 2846.

Table 4: Pigments used in CMYKOGV inks

Ink Colors	Pigments
Cyan	PB 15:3
Magenta	PR 57:1
Yellow	Y 13
Black	Black 7
Orange	PO-64
Green	PG-7
Violet	PV-23

4.4 Prepress settings

Prepress settings plays very important role in image quality. Table 5 shows prepress parameters set while making file and plates.

Table 5: Prepress parameters

Prepress Parameter	
Screening Techniques	AM, FM Hybrid
AM dot shapes	Euclidian, Elliptical, Square, Round Fogra
AM Screen Ruling	100, 133, 150, 175, 225 LPI
FM screening	Esko organic stochastic 20 micron
Hybrid Screening	Esko Samba Flex 9H
CTP output resolution	2400 DPI
RIP	Esko color Engine
1-D LUT	Esko PressSync
Plates	Kodak

Table 5 shows the prepress parameters used in the experiment. Different dot shapes, screen ruling and screening techniques were covered and 1-bit tiff files were evaluated before exposing plates. Platesetter and developer were linearized as per manufacturers recommendation before plates were made. To verify application of 1-D LUT to plates dot area was measured by X-Rite iC plate instrument.

4.5 DOE- Design of experiments

Shendye-Fleming method for expanded gamut

Substrates- 2 SBS and CRB

Inks- CMYKOGV

Dot Shapes for AM screening- Square, Elliptical, Circular Euclidean

Screen Techniques- Esko Organic Stochastic and Esko Samba Flex 9H

Screen Ruling AM- Round Fogra dot 100, 133, 150 ,175, 225 LPI

Tonal steps 100%, 95%, 90%, 80%, 70%, 60%, 50%, 40%, 30%, 20% 10%, 5%, 4%, 3%, 2%, 1%

Measurement mode- M0, M1 and M2

Analysis- Density: Comparison of for ISO Status E and Shendye-Fleming for CMYK.

Dot area- Murray-Davies by ISO E, Shendye-Fleming and SCTV.

The total number of measurements for expanded gamut is 6720, total graphs are 840. All graphs are plotted, but partial DOE is reported to cover all variables. All graphs will be available upon request.

Shendye-Fleming method for Spot colors

Substrate: SBS

Spot colors- 12

Measurement mode – M0, M1 and M2

Tonal steps- 10%, 20%, 30%, 40%, 50%, 60%, 70%, 80%, 90%, 100%

Graphs- Density plot of tonal steps and Dot area plot of tonal steps

Total number of graphs- 820 (Remaining graphs available on request)

Shendye-Fleming OBA index - Total number of substrates 10, total 10 graphs.

CHAPTER 5

RESULTS AND DISCUSSION

5.1 Results

After printing, reflectance data of all printed patches were measured by specially developed software in C++ and C#. Then data were imported into Microsoft Excel for calculation and analysis. Reflectance data and K/S of tonal gradation were plotted. Then, based on both the graphs, the bandwidth for filter for Shendye-Fleming density was selected. ISO Status E density was calculated and apparent dot area was calculated by using the Murray-Davies equation. Dot area calculated by SCTV, and Murray-Davies from ISO status E density and Shendye-Fleming density were calculated and plotted for comparison for cyan, magenta, yellow and black inks. As no filter is available for orange, green, violet and spot colors, ISO density can't be calculated. So, only Shendye-Fleming density was calculated and dot area by Murray-Davies with Shendye-Fleming density and SCTV were compared. Based on data from CMYK, bandwidth for other inks were selected.

Table 6: Filter bandwidth comparison for density measurement

Filter bandwidth comparison		
Filter	ISO E	Shendye-Fleming Manual
Red	540 nm to 730 nm 540, 550, 720, 730 ~0 and 560, 570 are negative	580 nm to 700 nm
Green	460 nm to 630 nm 460, 470 are negative, 620, 630 ~0	480 nm to 630 nm
Blue	380 nm to 540 nm 510 is negative 520, 530, 540~0	430 nm to 470 nm
Visual	380 to 730 nm 380, 390, 400 ~0	430 nm to 700 nm

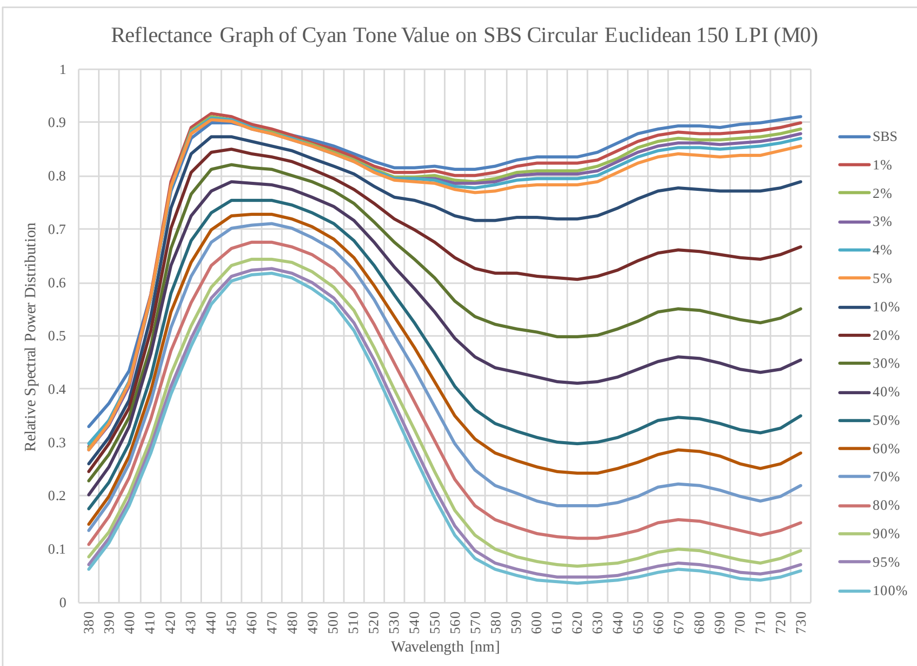


Figure 16: Reflectance data of cyan tonal gradation.

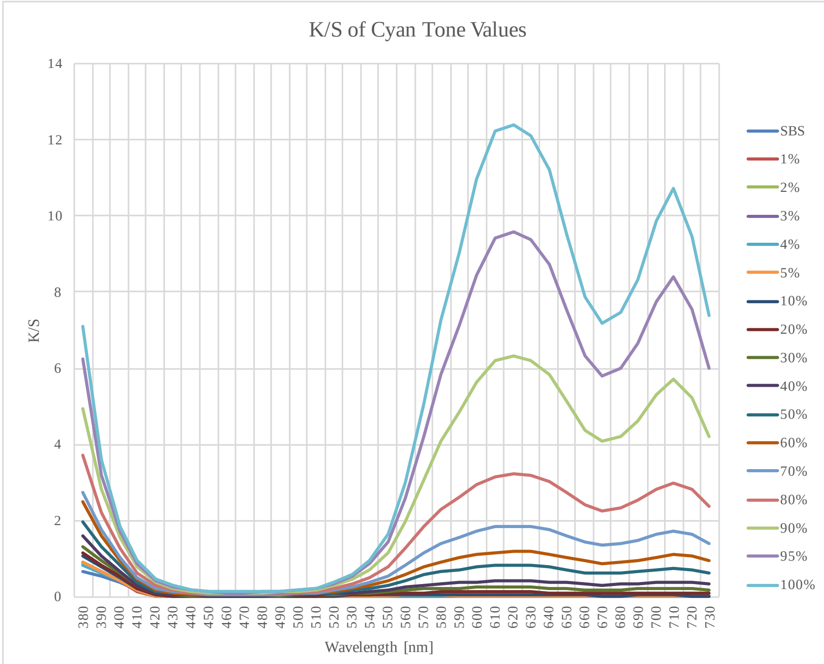


Figure 17: K/S of cyan tonal gradation.

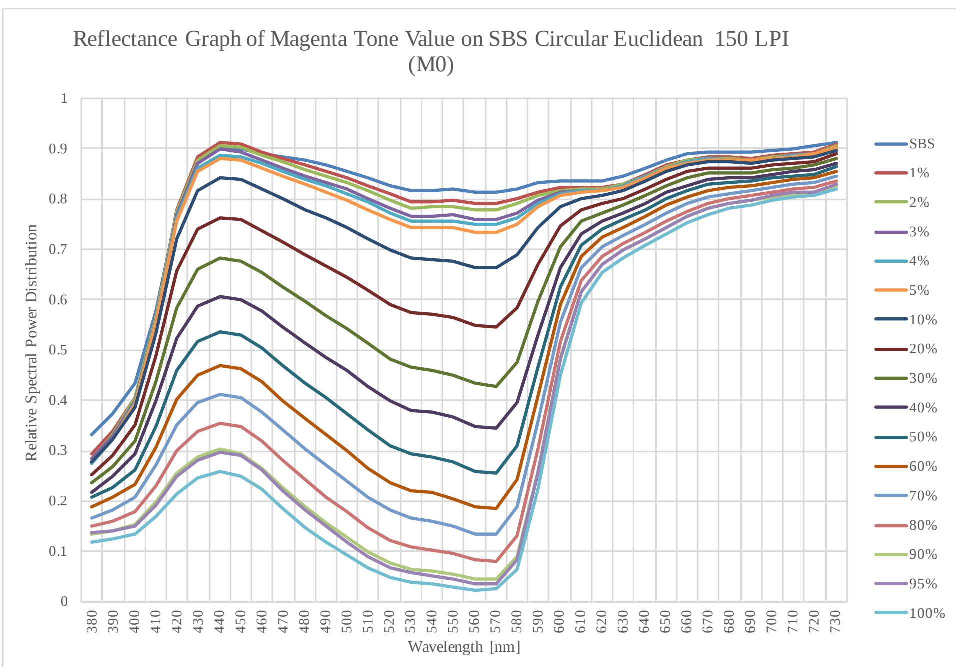


Figure 18: Reflectance data of magenta tonal gradation.

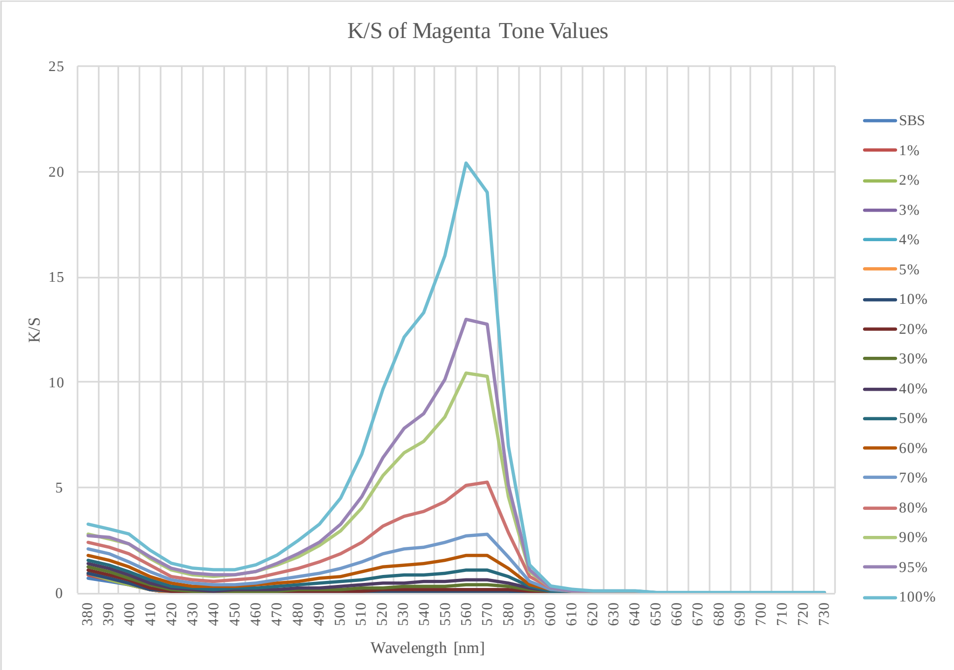


Figure 19: K/S of magenta tonal gradation.

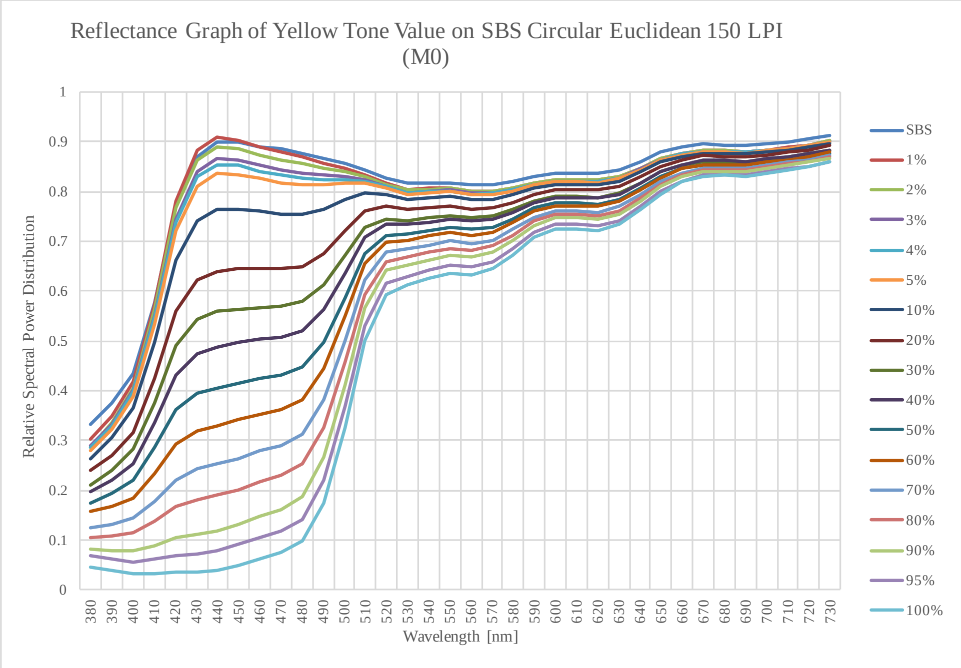


Figure 20: Reflectance data of yellow tonal gradation.

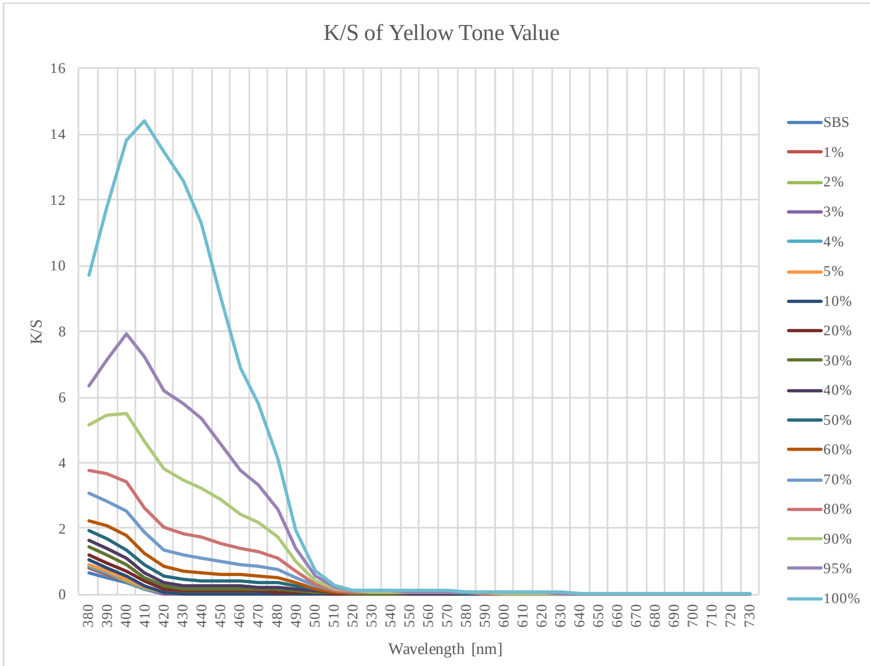


Figure 21: K/S of yellow tonal gradation.

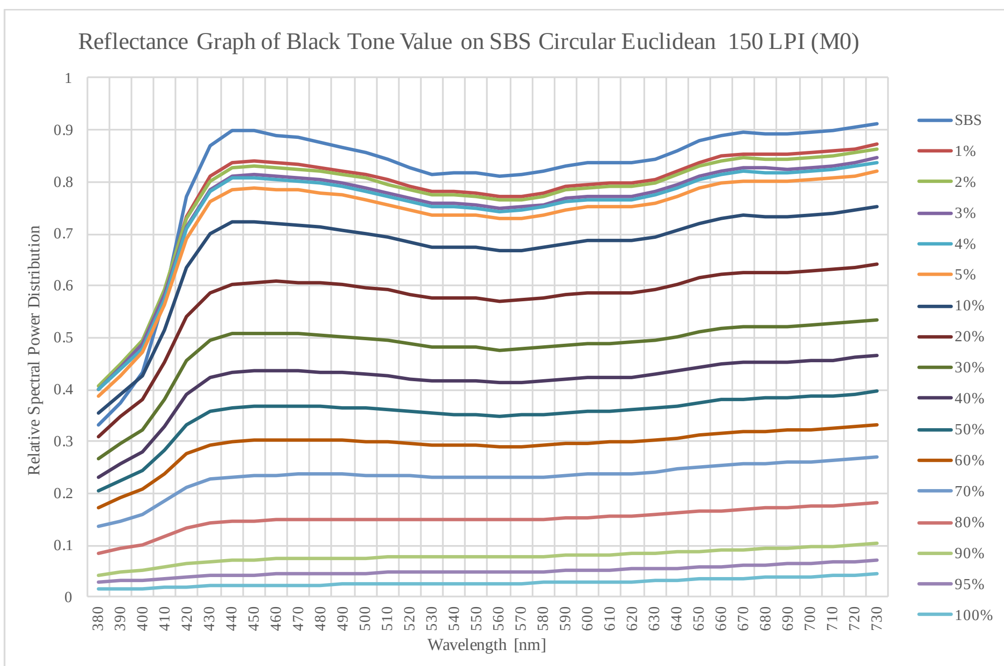


Figure 22: Reflectance data of black tonal gradation.

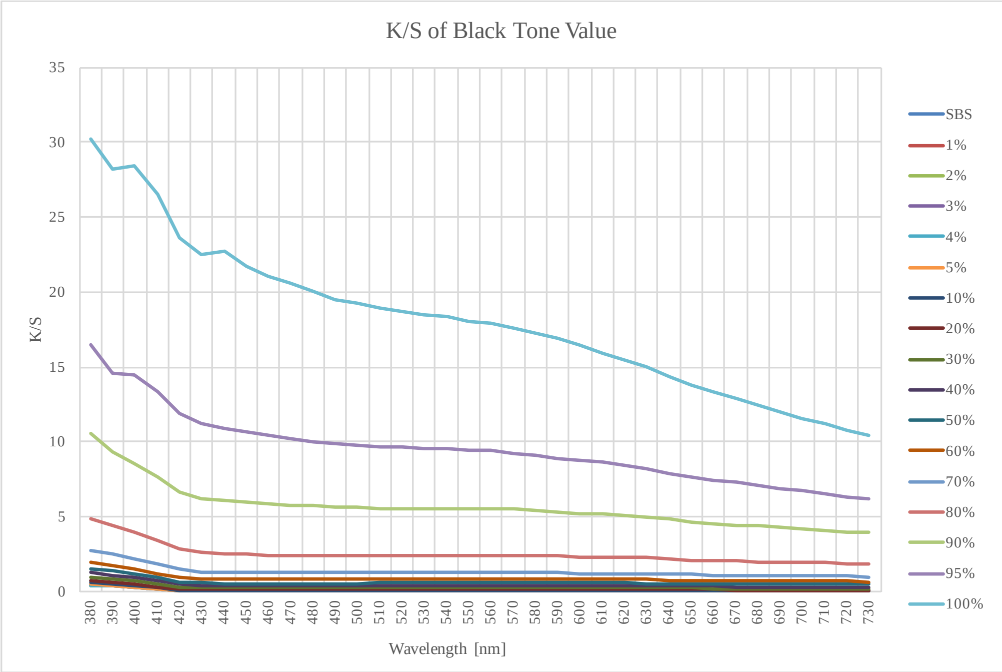


Figure 23: K/S of black tonal gradation.

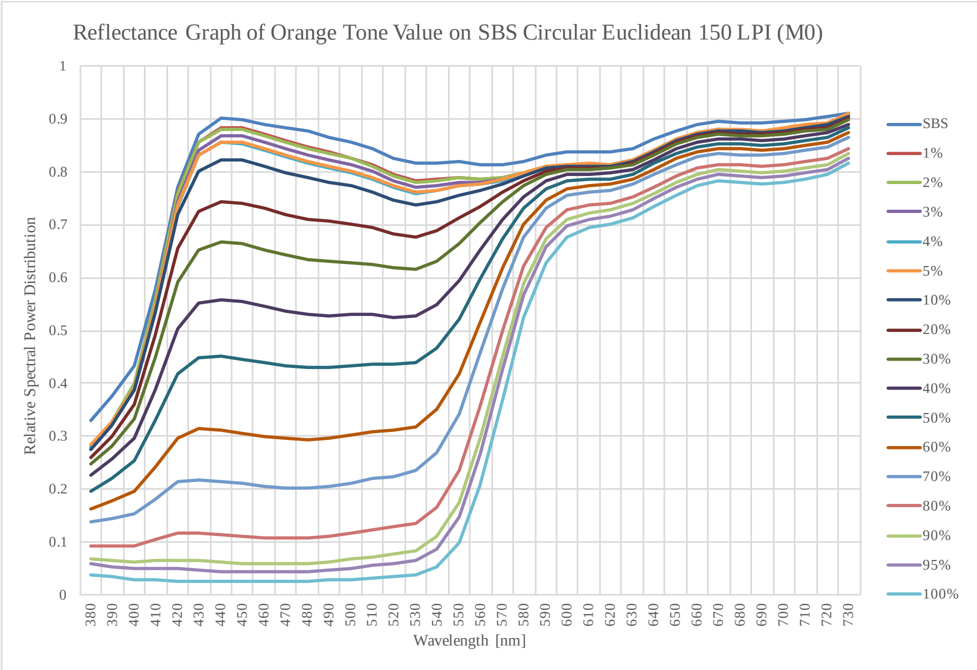


Figure 24: Reflectance data of orange tonal gradation.

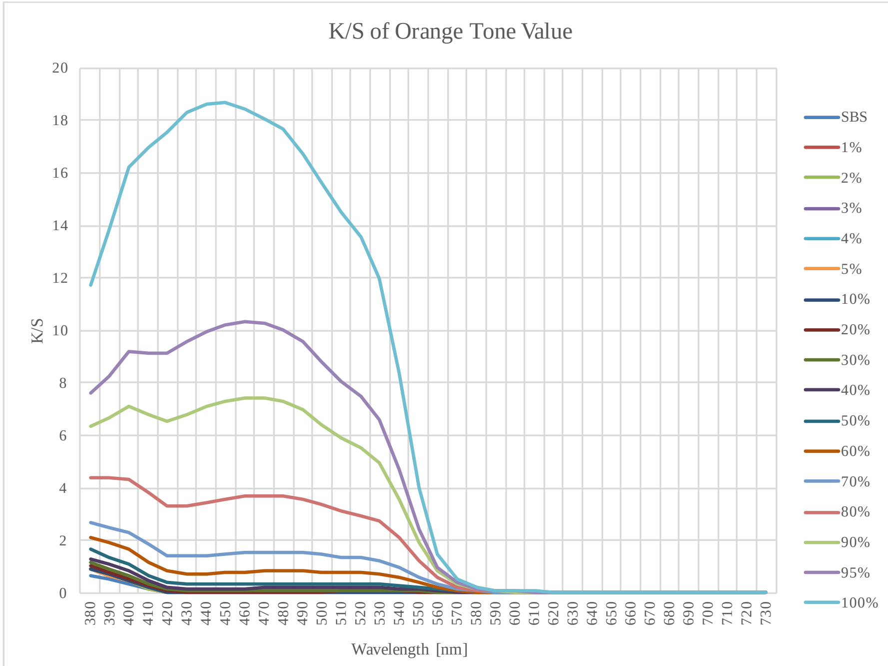


Figure 25: K/S of orange tonal gradation.

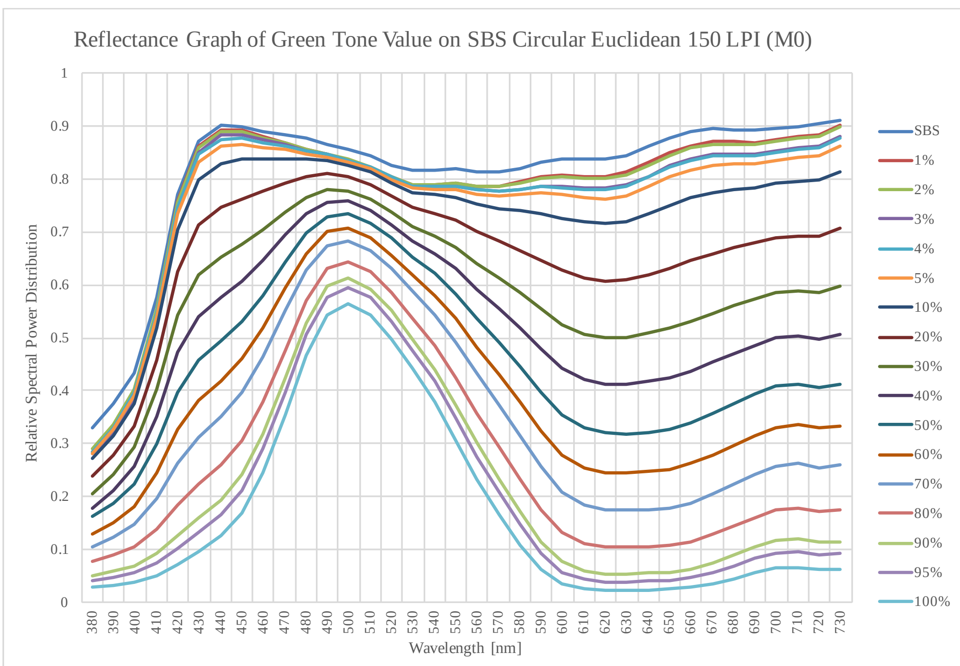


Figure 26: Reflectance data of green tonal gradation.

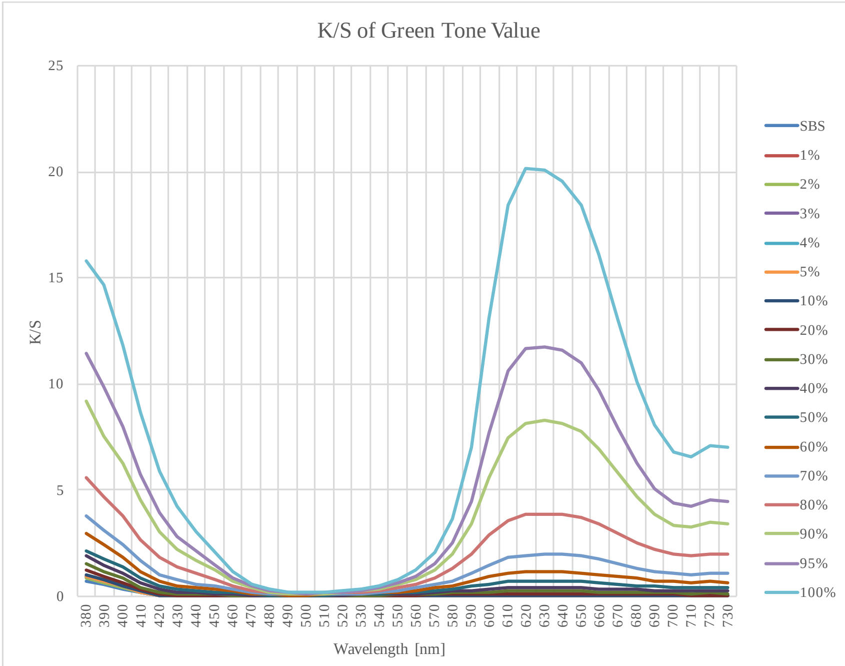


Figure 27: K/S of green tonal gradation.

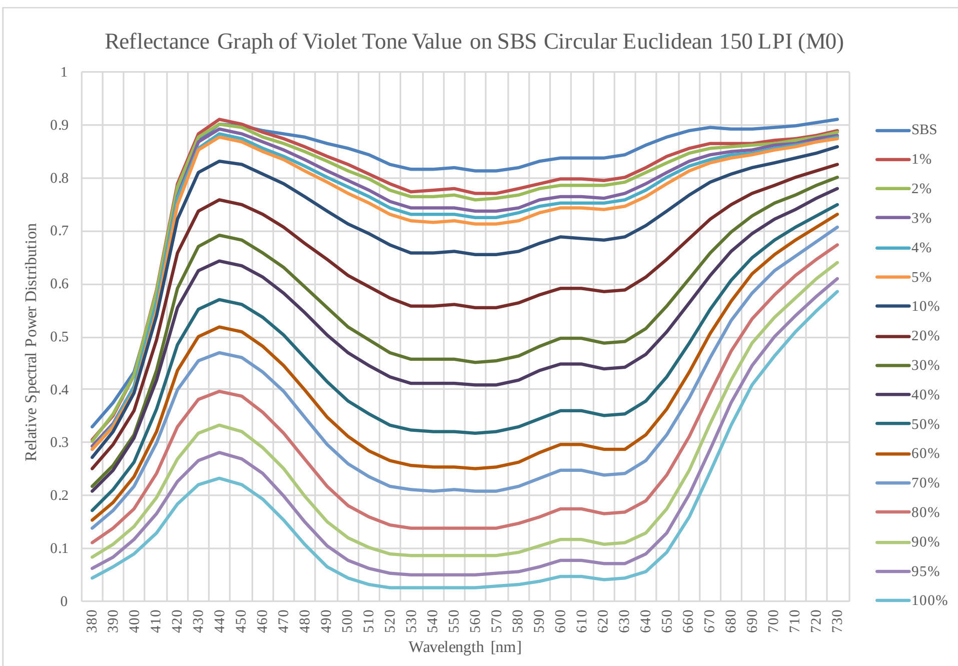


Figure 28: Reflectance data of violet tonal gradation.

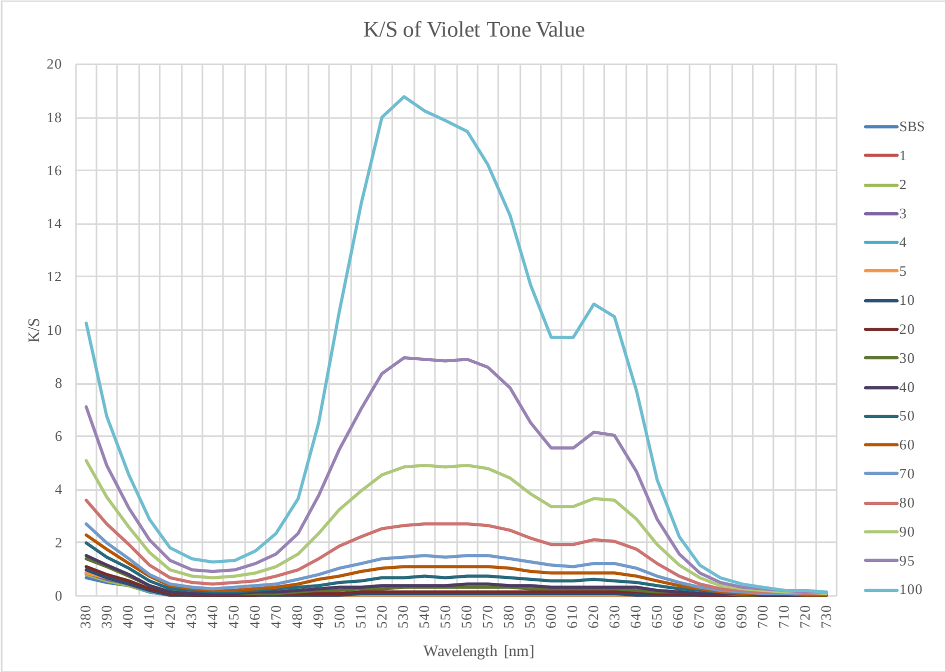


Figure 29: K/S of violet tonal gradation.

A plot of reflectance data and K/S of tonal gradation of expanded gamut inks shows that due to addition of white from paper with ink color part of reflectance graph is not affected, but a change in absorption region of reflectance graph is observed. When a red filter is used for cyan color separation, then it gives negative image and when a positive image/plate is made then it gives cyan separation because red filter allows color part of the magenta and yellow (which is red) spectrum to pass and blocks absorption part of the reflectance spectrum. When red filter is used in measuring the density of cyan, then it blocks the color portion of the spectrum and allows light to pass through the absorption region of the spectrum of cyan ink. This explains why cyan looks black when seen through a red filter, because only absorption region is seen. So, for measurement of density only the absorption region of the spectrum of the color and tonal gradation are of interest. This requires a bandpass filter. A plotting of graphs of tonal gradation and K/S allows us to look for the absorption region of the spectrum. Because of the very thin ink film, medium light scattering is very small, when compared to absorption. This results in having higher absorption value compared to very small scattering value in K/S. Due to this, the K/S ratio can be considered as absorption filter. This is very similar to an optical red filter. As each medium has some scattering optical red filter, it also has scattering, but its absorption is very high compared to its scattering. As K/S is calculated from reflectance data, each color has its own K/S curve. This results in generating a unique filter for that color, which can work as an absorption filter for that color only. So, selecting absorption region for any color is important to generate its own bandpass filter. A graph plot of K/S can help, because just by looking at reflectance data of color is not possible to determine its absorption region. As K/S of any color can be plotted, similarly selection of filter range for any color is possible. In the case of ISO filters, numbers in color region are zero because ISO filters are pre-defined. In ISO filter when color region is nullified by multiplying by zero it eliminates color region of spectrum from that color for calculations. As any ink is not ideal, it has some reflection in absorption region. This can result in small errors, so upper limit and lower limit of bandpass filter have to be selected to include absorption region. This provides guidelines for selecting limits for bandpass filters.

5.2 Guidelines for selecting bandpass filters

a) Range of filter should be between 400 nm to 700 nm.

b) If instrument provides data beyond 400 nm and 700 nm, then it is necessary to ignore that region.

c) Based on hue of color look for color portion in the spectrum.

d) If shade is dark, then it is easy to find absorption region in reflectance data.

e) If shade is pastel, then plot K/S and see change in the graph peaks.

f) Always select continuous portion of absorption region.

g) Always provide upper limit and lower limit along with density number and spectral data.

h) K/S graph can be plotted against reflectance graph with proper scaling and it can be used for pastel shades. An example for PMS 677 is shown.

5.3 Scaling factor (C)

Filter bandwidth can be determined by scaling K/S curve on reflectance data curve in the same graph. By plotting both curves on the same scale, it can help in determining absorption region of the color in the reflectance spectrum. This can lead to determine bandwidth of the filter.

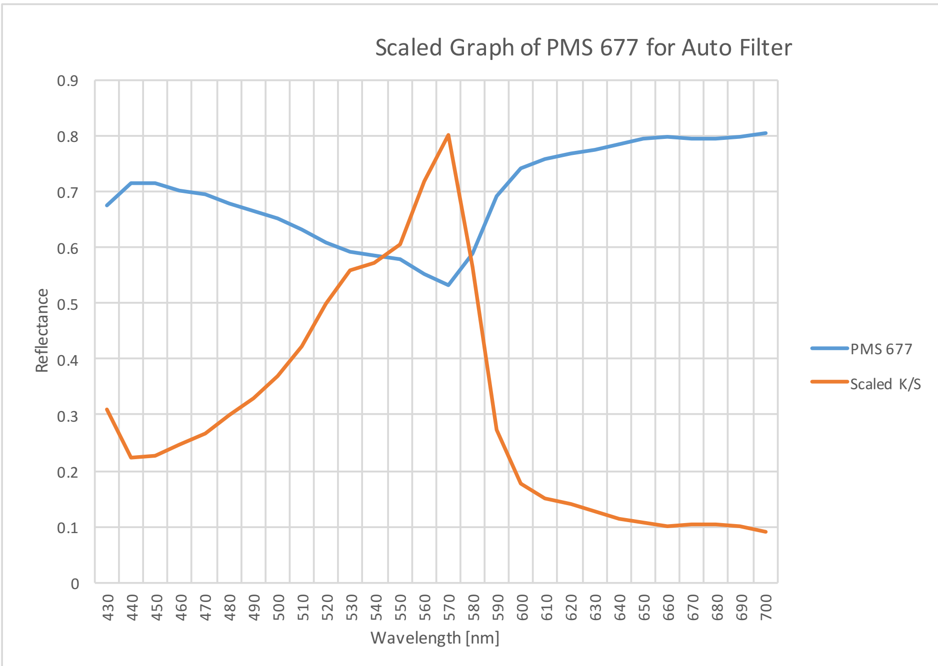


Figure 30: Scaled K/S of PMS 677.

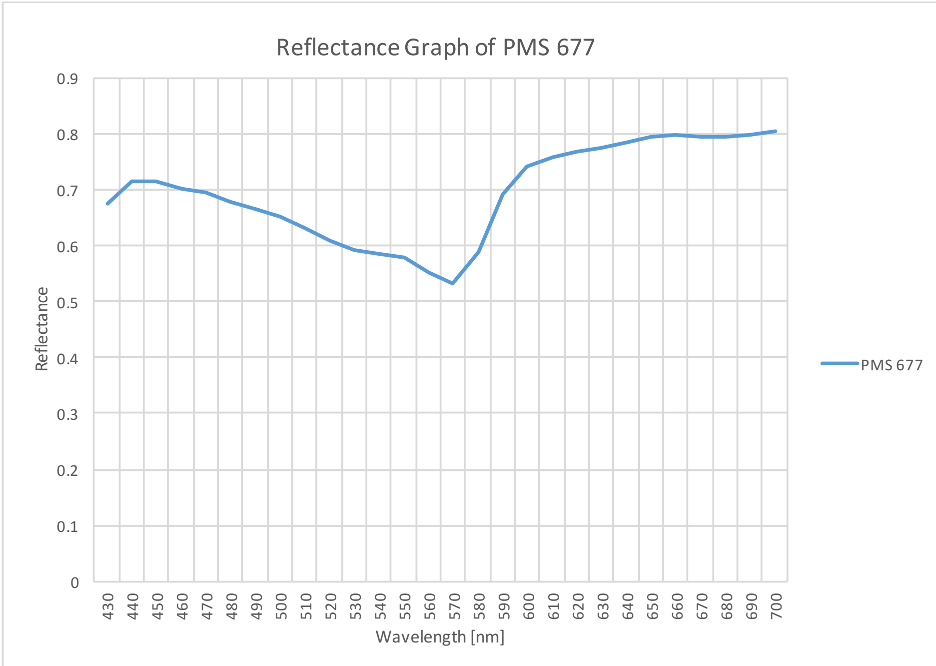


Figure 31: Reflectance graph of PMS 677.

A scaling factor for PMS 677 was calculated as 0.25 Based on this filter range, for PMS 677 can be selected from 540 nm to 580 nm this gives density of 0.25 which looks very low although shade is 100% solid, but shade is close to white so density is very low.

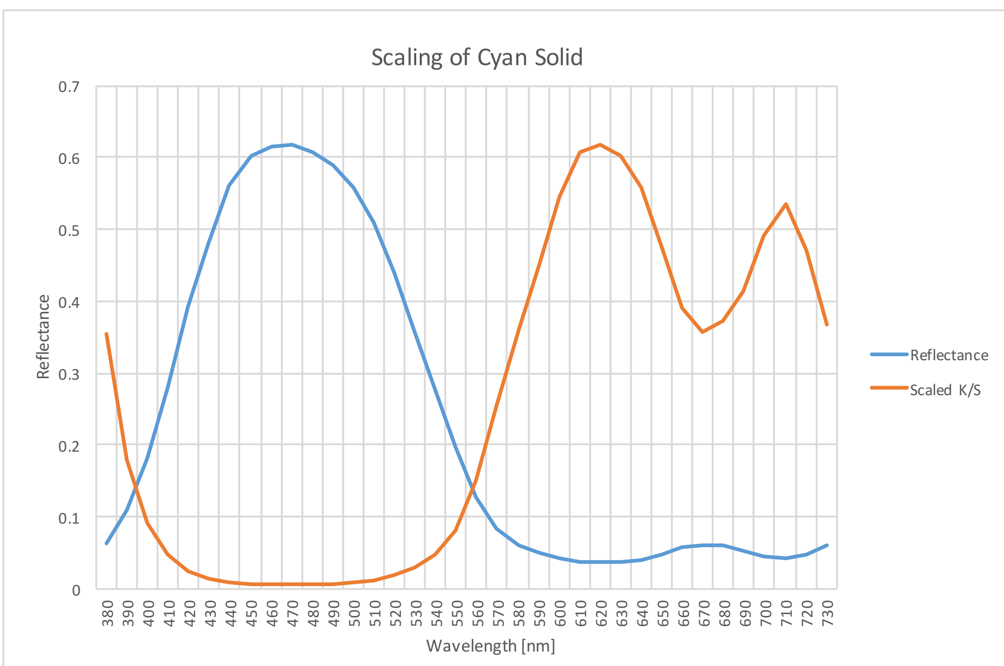


Figure 32: Scaling of K/S of cyan solid.

Figure 32 shows scaling of cyan solid by multiplying K/S by scaling factor. While calculating the scaling factor (C), the highest value in K/S spectrum is divided by highest value in reflectance spectrum. Then K/S is divided by scaling factor (C). Scaling factor for cyan was 20.03. In case of paper reflectance data from 380 nm to 420 nm shows a sharp rise. This causes noise in calculation of density so we ignore 380 to 420 nm region while selecting filter bandwidth. Scaling method gives bandwidth of filter for cyan from 560 to 700 nm.

$$\mathrm{C} = \left[\frac{(\frac{K}{S})_{max}}{R_{max}}\right] \tag{15}$$

Filter bandwidth selected for CMY by scaling auto-filter method provides absorption filter bandwidth. Shendye-Fleming auto-filter method provides filter bandwidth, which is slightly different than ISO status E. To match to ISO status E, manual selection of filter bandwidth is recommended. Change in filter bandwidth or Status does not affect dot area calculations in Murray-Davies equation. For example, the density of Yellow by status E is 1.30, but by status T it is 1.00 and by Shendye-Fleming it could be 1.29. Different filter sets/status show different density for the same color, but they do not affect dot area measurement. By using an auto filter for magenta, it gives 530 to 580 nm range for band pass filter for magenta which gave density of 1.40; which is higher than ISO status E density of 1.34. Figure 33 shows comparison of ISO status E vs auto-filter density.

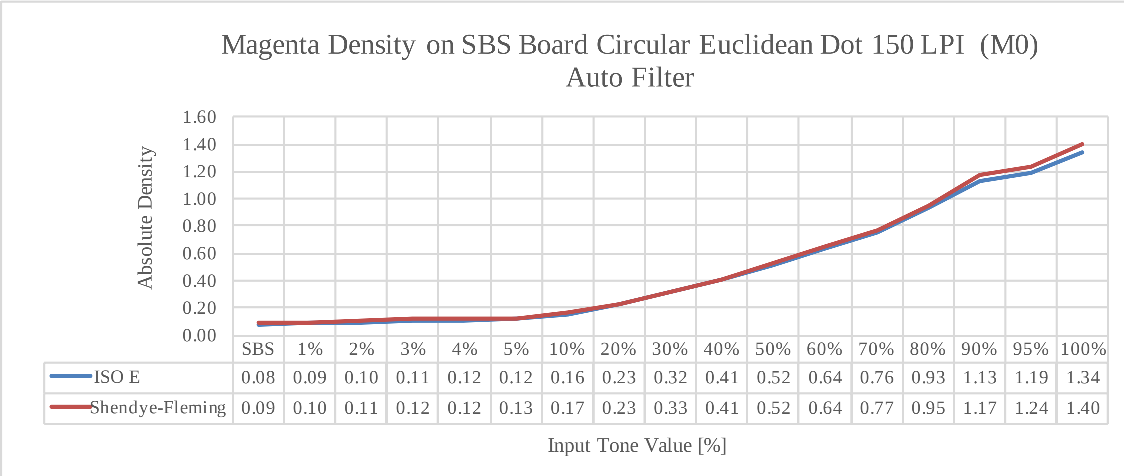


Figure 33: Magenta density by auto-filter.

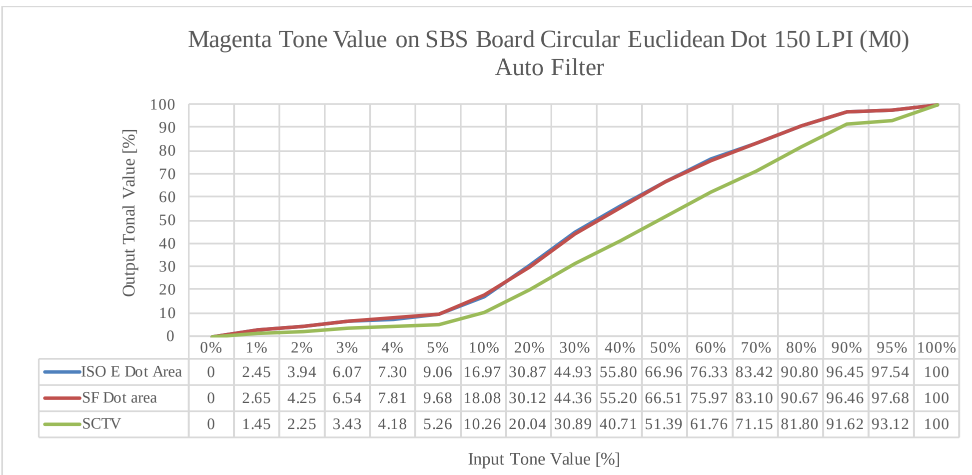


Figure 34: Magenta dot area comparison of ISO vs auto-filter.

Figure 34 shows that magenta dot area calculated by using auto filter method and ISO status E density. No significant difference is observed. Magenta solid density shown in Figure 33 shows difference of 0.06 in solid but this difference does not affect dot area calculation between ISO 5 and Shendye-Fleming method of dot area estimation. This is because slight difference in density of paper by ISO and Shendye-Fleming method. Auto filter method shows acceptable results for magenta ink.

Table 7 shows comparison of density calculation by applying different filters.

Table 7: Density comparison by applying auto-filter

Color	ISO Density E	Manual Filter and Density	Auto Filter and Density
Cyan	1.39	1.33	1.30
Magenta	1.34	1.33	1.40
Yellow	1.30	1.31	1.31

The limitation of ISO filters is that they have fixed bandwidth for each named color and do not account for any change in named color (i.e. different inks, different substrates, different print devices, etc.) For example, there are 2 different yellow pigments available, PY 12 and PY 13. PY 12 is available in 4 different shades and transparencies. ISO 2846 only defines CIE LAB values for CMYK on a defined paper, but when the same pigment is printed on different substrates, it gives different colors and this change in color is a change in nature of reflection spectrum, but is not accounted for in selection of filter for densitometry. In the ISO method, a fixed filter is selected for process color inks, irrespective of its effect of substrate on its spectrum. The Shendye-Fleming method accounts for change in filter bandwidth, as it accounts for change in spectra caused by change in substrate. This allows the Shendye-Fleming method to be used for any color on any substrate. In the Shendye-Fleming method, the user is allowed to override selection of filter bandwidth to match to ISO status E or any other desired results.

Table 8: Shendye-Fleming filter bandwidth by manual selection

Color	**Manual Limits[nm]**	**Auto Filter Limits[nm]**
Cyan	580 to 700	560 to 700
Magenta	480 to 630	490 to 580
Yellow	430 to 470	430 to 480
Black	430 to 700	NA
Orange	420 to 540	420 to 550

Green	600 to 700	590 to 700
Violet	490 to 650	490 to 650

Table 8 shows that filter bandwidth comparison of manual selection and auto-filter. In auto-filter method absorption to scattering graph is scaled to the same scale of reflectance graph. A region where both graph cross each other and reflectance graph has lower values than absorption to scattering ratio graph that region is considered as bandwidth of auto-filter.

5.4 Apparent dot area calculations

The Murray-Davies equation was used for calculating density for solid, tint and paper. For calculating density of paper, use the same filter range as selected for solid and tint. When density is measured to calculate dot area, then the same filter range for solid, tint and paper must be used. The cyan, magenta, yellow and black density are compared to ISO status E and dot area was calculated from Murray-Davies equation by using input density calculated by ISO E and Shendye-Fleming method. The SCTV method does not provide density, it only calculates dot area for colorimetric values. Comparison graphs for Circular Euclidean dot at 150 LPI on SBS board are plotted for analysis to evaluate difference.

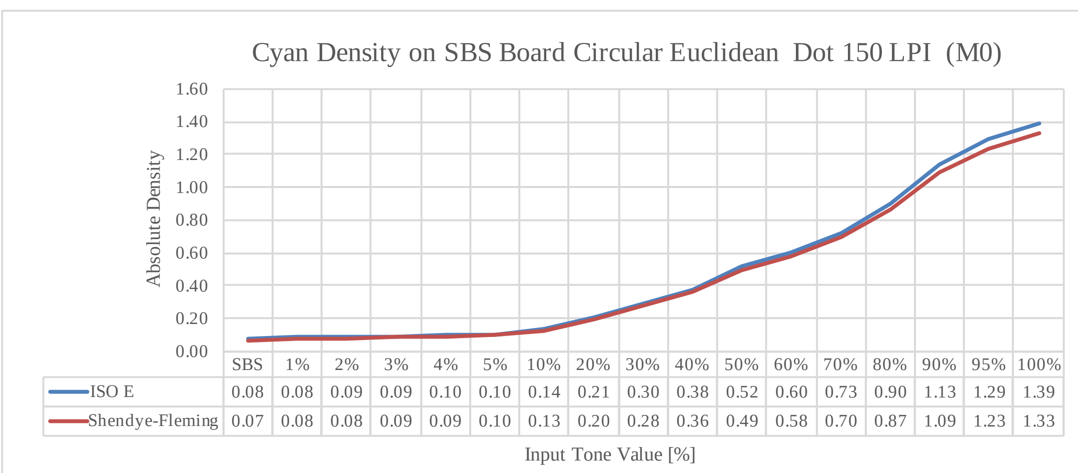


Figure 35: Density comparison of cyan tonal value gradation.

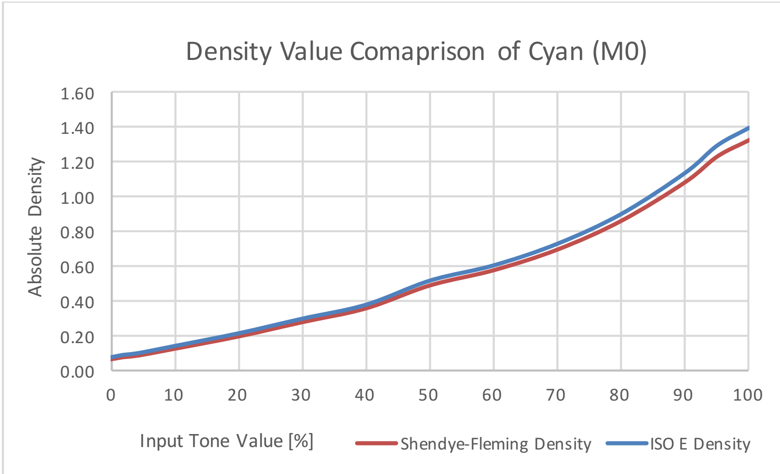
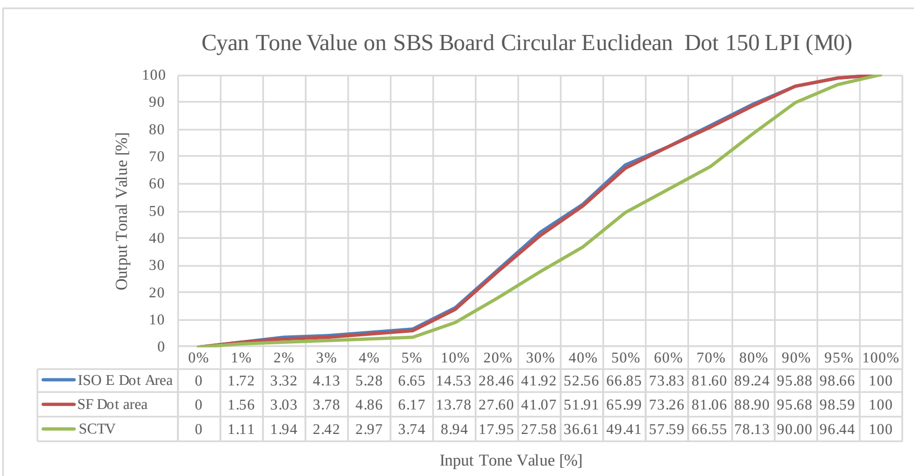


Figure 36: Density comparison of cyan tonal value in Euclidean space.



	0%	1%	2%	3%	4%	5%	10%	20%	30%	40%	50%	60%	70%	80%	90%	95%	100%
ISO E Dot Area	0	1.72	3.32	4.13	5.28	6.65	14.53	28.46	41.92	52.56	66.85	73.83	81.60	89.24	95.88	98.66	100
SF Dot area	0	1.56	3.03	3.78	4.86	6.17	13.78	27.60	41.07	51.91	65.99	73.26	81.06	88.90	95.68	98.59	100
SCTV	0	1.11	1.94	2.42	2.97	3.74	8.94	17.95	27.58	36.61	49.41	57.59	66.55	78.13	90.00	96.44	100

Figure 37: Dot area comparison of cyan tonal gradation.

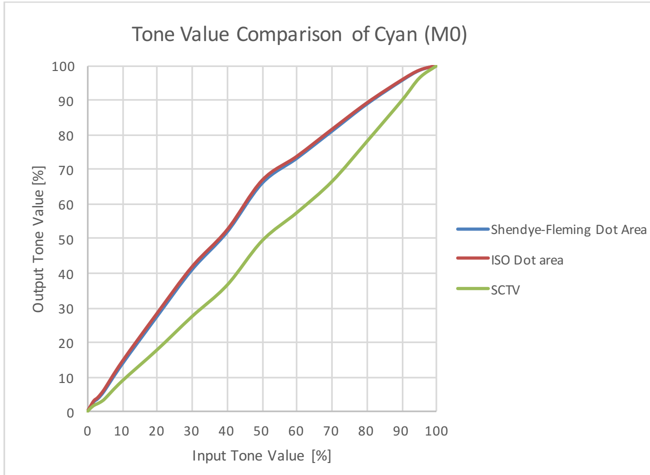
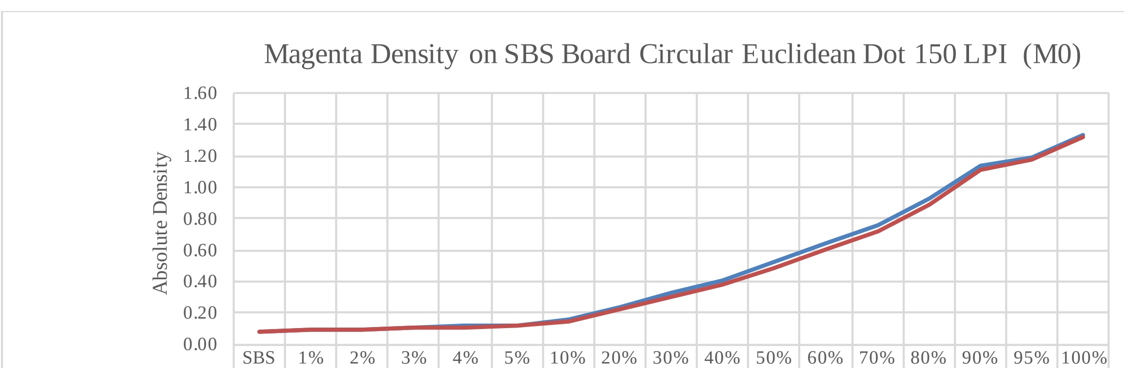


Figure 38: Dot area comparison of cyan tonal value in Euclidean space.

Figure 35 shows that density of cyan calculated by Shendye-Fleming method is less than 0.06 different compared to ISO E method. This was observed in all dot shapes and screen rulings. When dot area is compared Figure 37, shows that dot area calculated by Shendye-Fleming and ISO status E method is just 0.85% off, which can be considered as no significant difference, but SCTV shows very high difference of 17.44% less at 50% tonal value. As significant difference is not found in paper density calculated by both the methods, difference at 50% tonal value of dot area is acceptable considering process variation.



	SBS	1%	2%	3%	4%	5%	10%	20%	30%	40%	50%	60%	70%	80%	90%	95%	100%
ISO E	0.08	0.09	0.10	0.11	0.12	0.12	0.16	0.23	0.32	0.41	0.52	0.64	0.76	0.93	1.13	1.19	1.34
Shendye-Fleming	0.08	0.09	0.10	0.10	0.11	0.11	0.15	0.22	0.30	0.39	0.49	0.61	0.72	0.90	1.11	1.17	1.33

Figure 39: Density comparison of magenta tonal gradation.

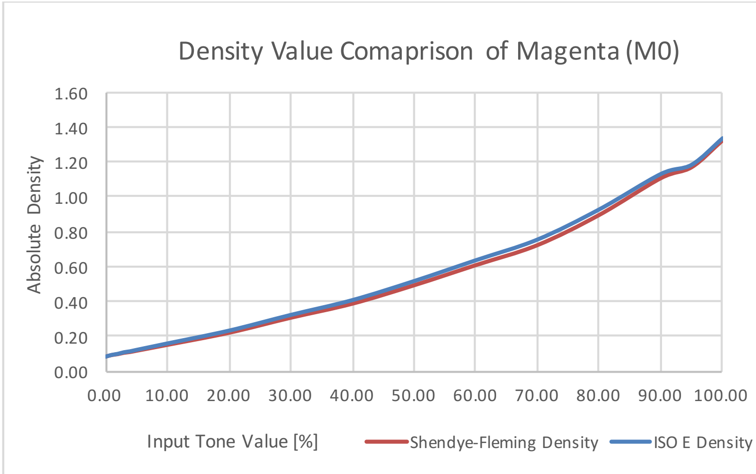
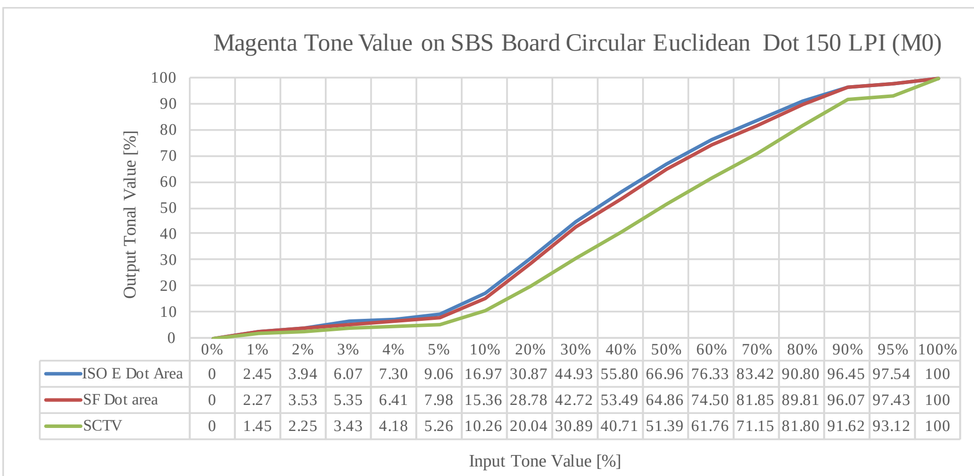


Figure 40: Density comparison of magenta tonal value in Euclidean space.



	0%	1%	2%	3%	4%	5%	10%	20%	30%	40%	50%	60%	70%	80%	90%	95%	100%
ISO E Dot Area	0	2.45	3.94	6.07	7.30	9.06	16.97	30.87	44.93	55.80	66.96	76.33	83.42	90.80	96.45	97.54	100
SF Dot area	0	2.27	3.53	5.35	6.41	7.98	15.36	28.78	42.72	53.49	64.86	74.50	81.85	89.81	96.07	97.43	100
SCTV	0	1.45	2.25	3.43	4.18	5.26	10.26	20.04	30.89	40.71	51.39	61.76	71.15	81.80	91.62	93.12	100

Figure 41: Dot area comparison of magenta tonal gradation.

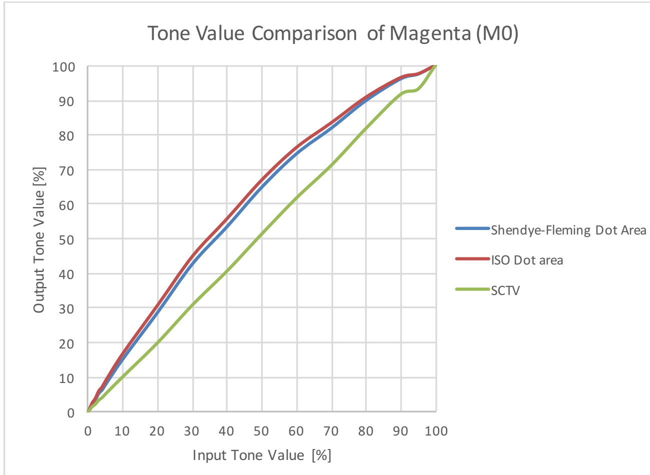
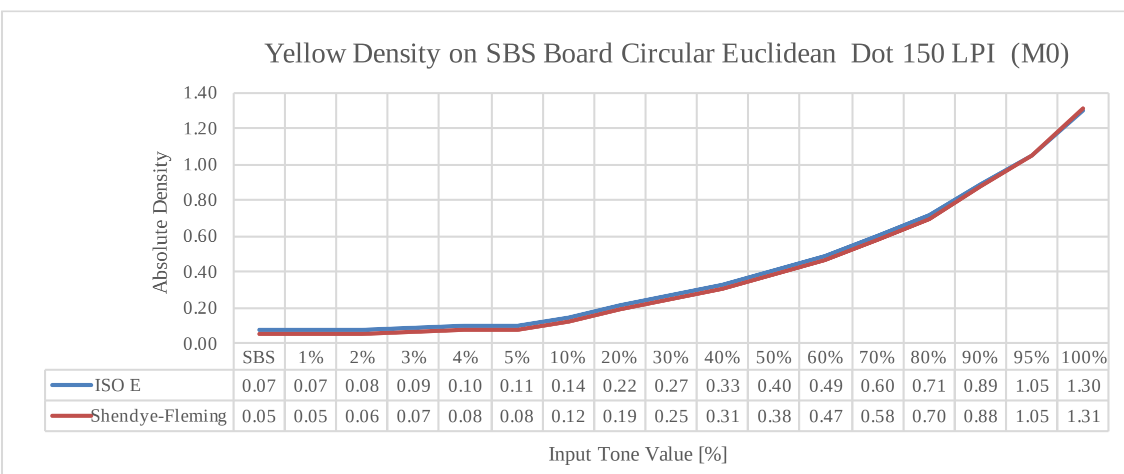


Figure 42: Magenta tone value comparison in Euclidean space.

Figure 39: Density comparison of magenta tonal gradation shows that the density of magenta calculated by Shendye-Fleming method is the same compared to ISO E method. This was observed in all dot shapes and screen rulings. When dot area is compared Figure 41shows that dot area calculated by Shendye-Fleming and ISO status E method is just 2.31% different, which is very close to each other, but SCTV shows very high difference of 15.57% less at 50% tonal value. As significant difference is not found in paper density calculated by both the methods, the difference at 50% tone value of dot area is acceptable considering process variation.



	SBS	1%	2%	3%	4%	5%	10%	20%	30%	40%	50%	60%	70%	80%	90%	95%	100%
ISO E	0.07	0.07	0.08	0.09	0.10	0.11	0.14	0.22	0.27	0.33	0.40	0.49	0.60	0.71	0.89	1.05	1.30
Shendye-Fleming	0.05	0.05	0.06	0.07	0.08	0.08	0.12	0.19	0.25	0.31	0.38	0.47	0.58	0.70	0.88	1.05	1.31

Figure 43: Density comparison of yellow tonal gradation.

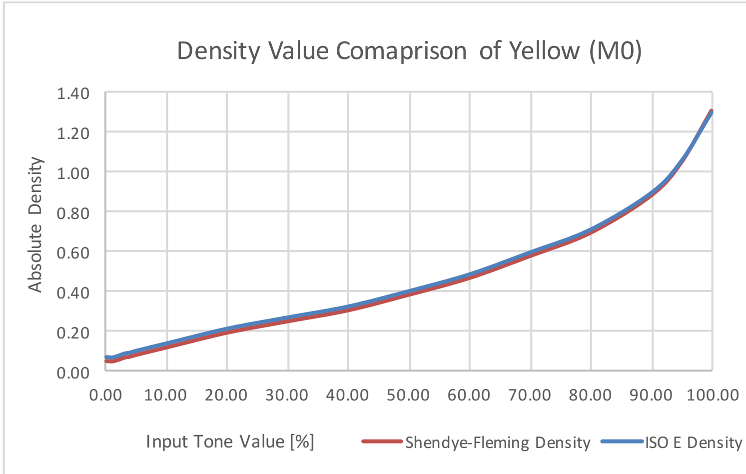
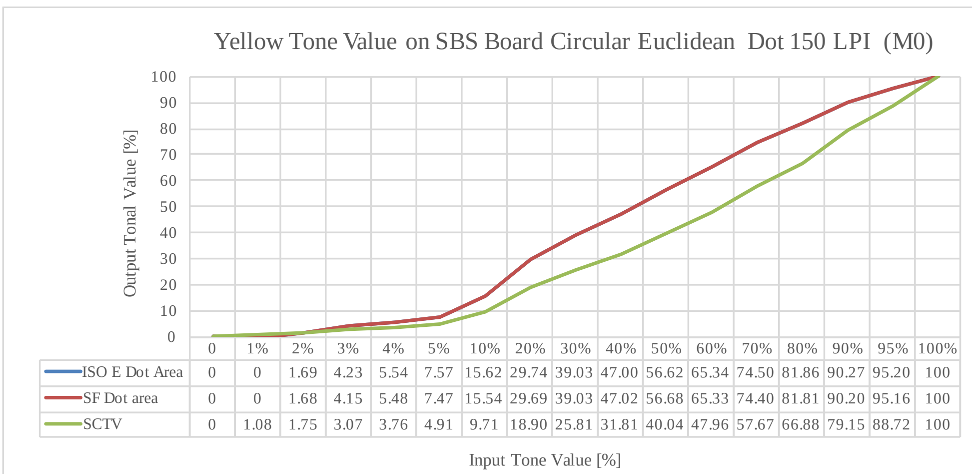


Figure 44: Yellow density comparison in Euclidean space.



	0	1%	2%	3%	4%	5%	10%	20%	30%	40%	50%	60%	70%	80%	90%	95%	100%
ISO E Dot Area	0	0	1.69	4.23	5.54	7.57	15.62	29.74	39.03	47.00	56.62	65.34	74.50	81.86	90.27	95.20	100
SF Dot area	0	0	1.68	4.15	5.48	7.47	15.54	29.69	39.03	47.02	56.68	65.33	74.40	81.81	90.20	95.16	100
SCTV	0	1.08	1.75	3.07	3.76	4.91	9.71	18.90	25.81	31.81	40.04	47.96	57.67	66.88	79.15	88.72	100

Figure 45: Dot area comparison of yellow tonal gradation.

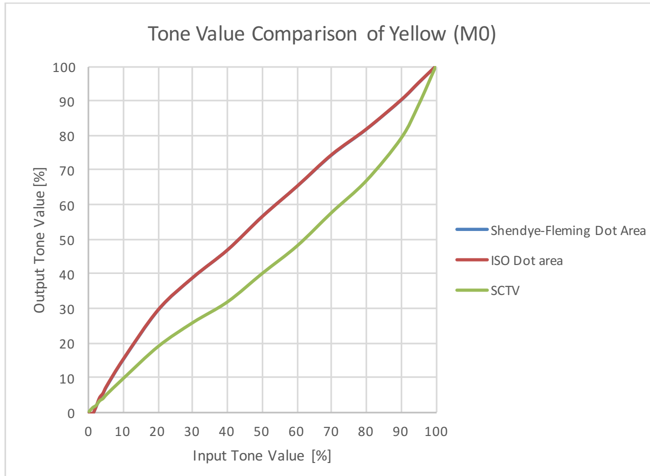


Figure 46: Dot area comparison of yellow tone value in Euclidean space.

Figure 43: Density comparison of yellow tonal gradation shows that density of yellow calculated by Shendye-Fleming method is the same when compared to ISO E method. This was observed in all dot shapes and screen rulings. Figure 45: Dot area comparison of yellow tonal gradation shows that dot areas calculated by Shendye-Fleming and ISO status E method are very close to each other, but SCTV shows 16.6% dot loss at 50% tone value. Here 1% dot is printed on substrate but the densitometer doesn't recognize the 1% dot as it can't differentiate between density of substrate and 1% dot.

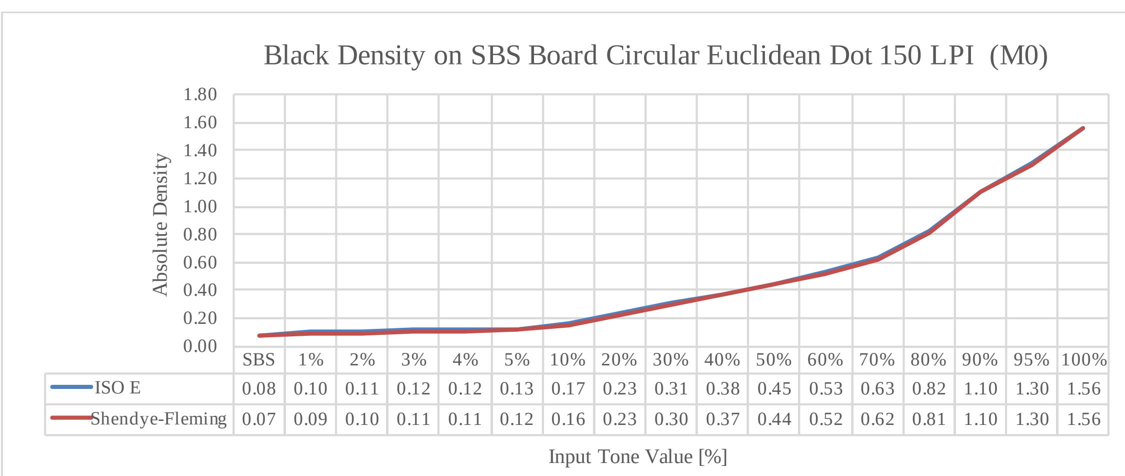


Figure 47: Density comparison of black tonal gradation.

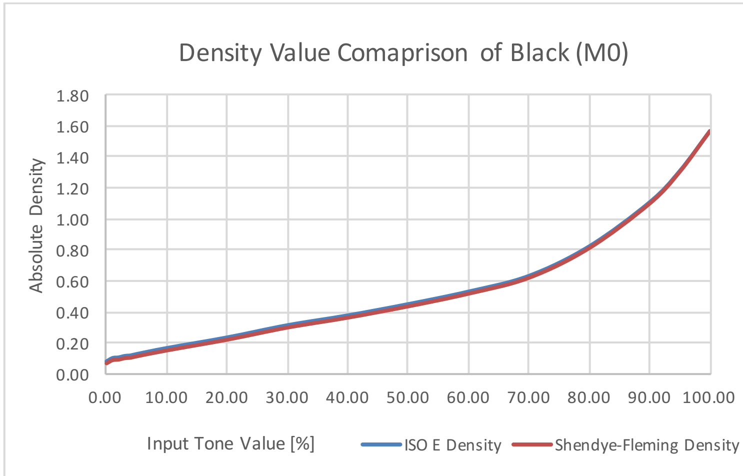
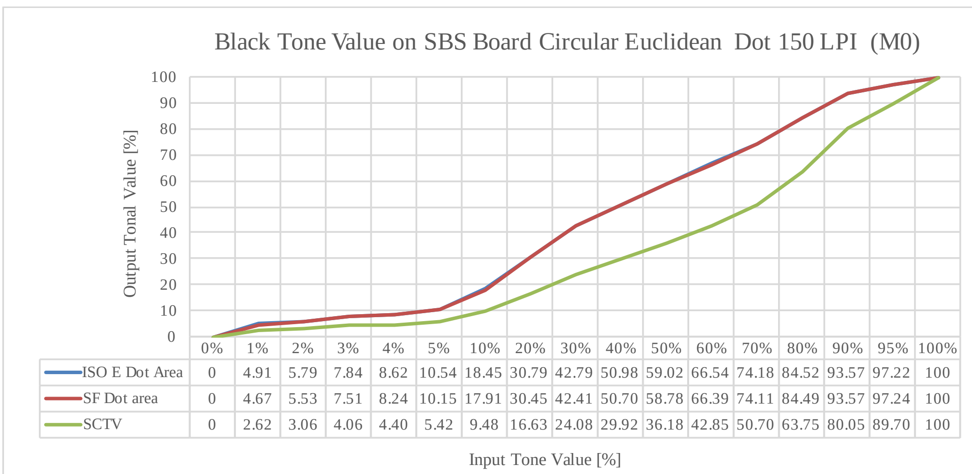


Figure 48: Density comparison of black tonal value in Euclidean space.



	0%	1%	2%	3%	4%	5%	10%	20%	30%	40%	50%	60%	70%	80%	90%	95%	100%
ISO E Dot Area	0	4.91	5.79	7.84	8.62	10.54	18.45	30.79	42.79	50.98	59.02	66.54	74.18	84.52	93.57	97.22	100
SF Dot area	0	4.67	5.53	7.51	8.24	10.15	17.91	30.45	42.41	50.70	58.78	66.39	74.11	84.49	93.57	97.24	100
SCTV	0	2.62	3.06	4.06	4.40	5.42	9.48	16.63	24.08	29.92	36.18	42.85	50.70	63.75	80.05	89.70	100

Figure 49: Dot area comparison of black tonal gradation.

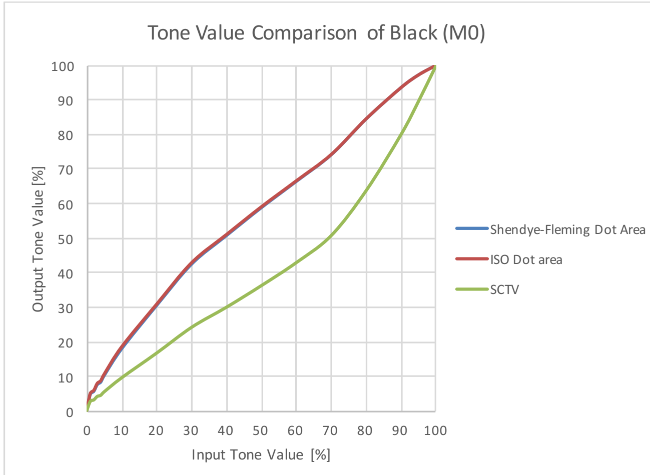


Figure 50: Dot area comparison of black tonal value in Euclidean space.

Figure **47** shows that the density of black calculated by the Shendye-Fleming method is the same compared to ISO E method. This was observed in all dot shapes and screen ruling. Figure 48 shows black density comparison between Shendye-Fleming and ISO visual filter and overlap of graphs shows it looks identical, so these values are given in Figure **47**. When dot area is compared Figure 49 shows that dot area calculated by Shendye-Fleming and ISO status E method are very close to one other, but SCTV shows difference 22.8% at 50% tonal value. As significant difference is not found in paper density calculated by both the methods, the difference at 50% total value of dot is acceptable, considering process variation. For 1% dot ISO and Shendye-Fleming shows significant gain but SCTV shows dot loss.

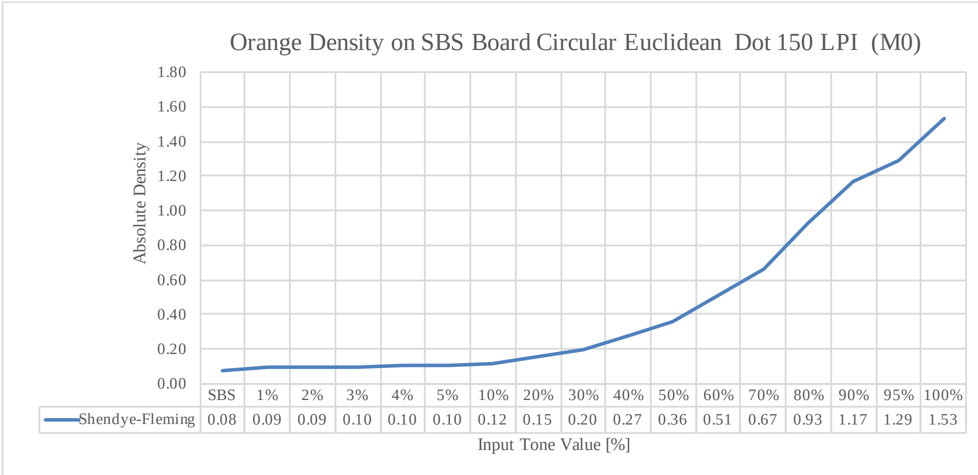


Figure 51: Density of orange tonal gradation.

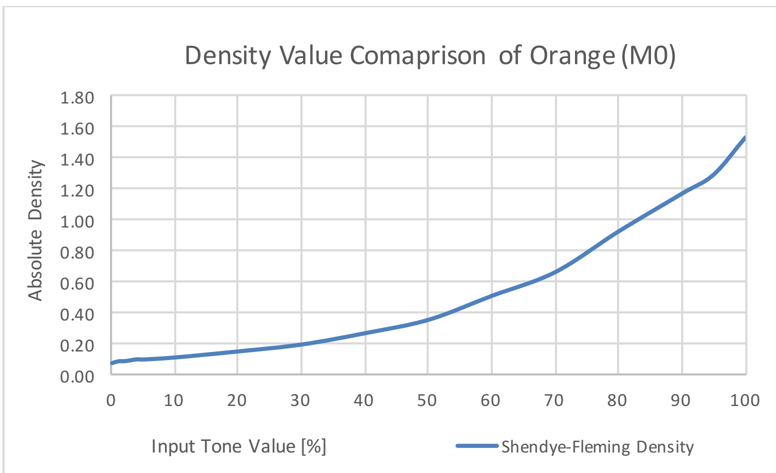


Figure 52: Density of Orange tone value in Euclidean space.

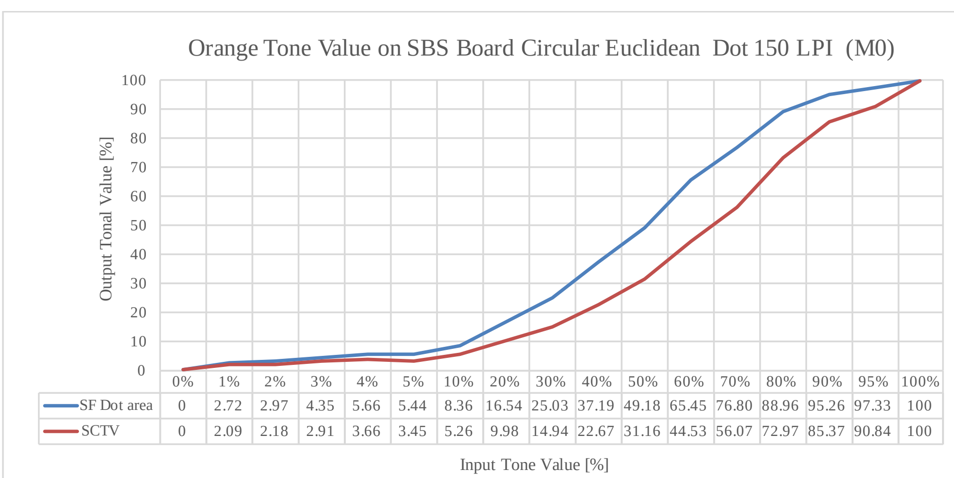


Figure 53: Dot area comparison of orange tonal gradation.

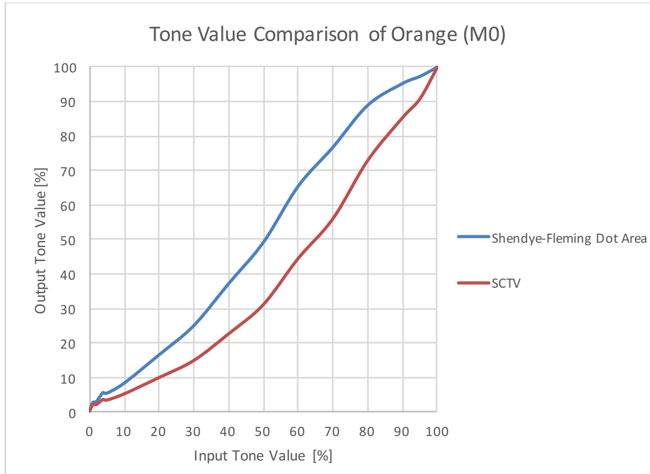


Figure 54: Dot area comparison of orange tonal value in Euclidean space.

Figure 51: Density of orange tonal gradation calculated by the Shendye-Fleming (SFD) method. There is no filter available in ISO set for any other color than CMYK so here comparison is not possible. Figure 52 shows density of orange tonal gradation in Euclidean space. When dot area is compared, Figure 53: Dot area comparison of orange tonal gradation shows that dot area calculated by Shendye-Fleming and SCTV show 18.0% difference at 50% tonal value. A significant difference is found, between SCTV and SFD method.

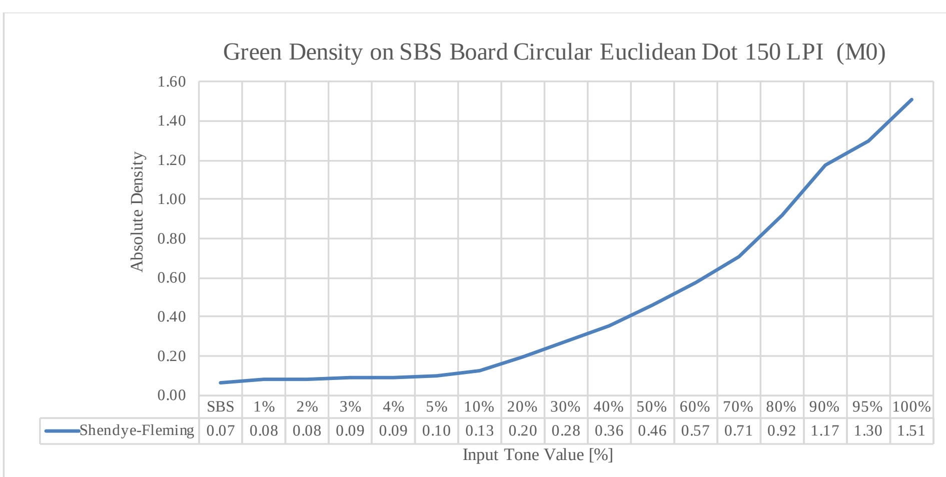


Figure 55: Density of tonal gradation of green.

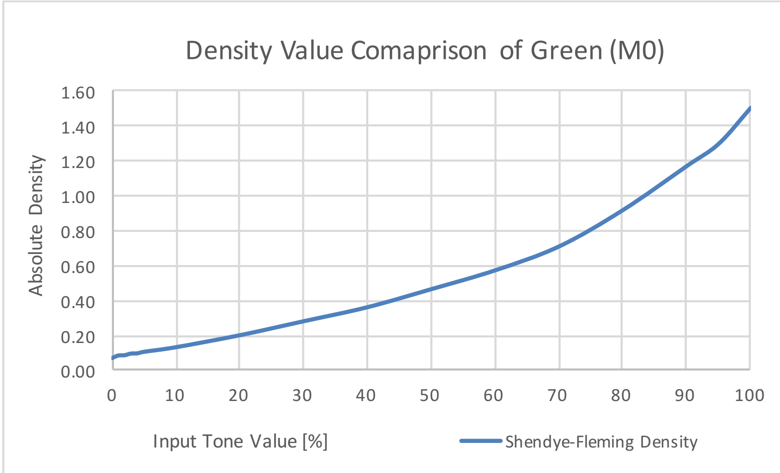
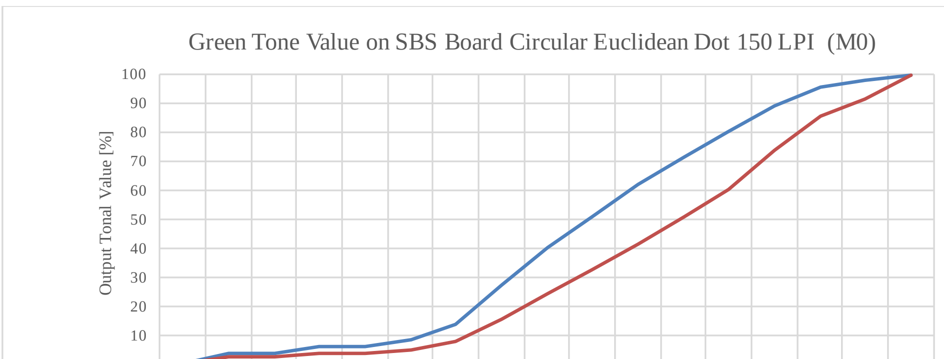


Figure 56: Density of green tonal gradation in Euclidean space.



	0%	1%	2%	3%	4%	5%	10%	20%	30%	40%	50%	60%	70%	80%	90%	95%	100%
SF Dot area	0	3.51	3.96	6.08	6.38	8.29	13.95	27.12	40.07	50.89	62.13	71.33	80.12	89.17	95.62	97.71	100
SCTV	0	2.37	2.51	3.53	3.70	4.74	7.72	15.49	24.43	32.34	41.59	50.85	60.15	74.09	85.79	91.25	100

Figure 57: Dot area comparison of green.

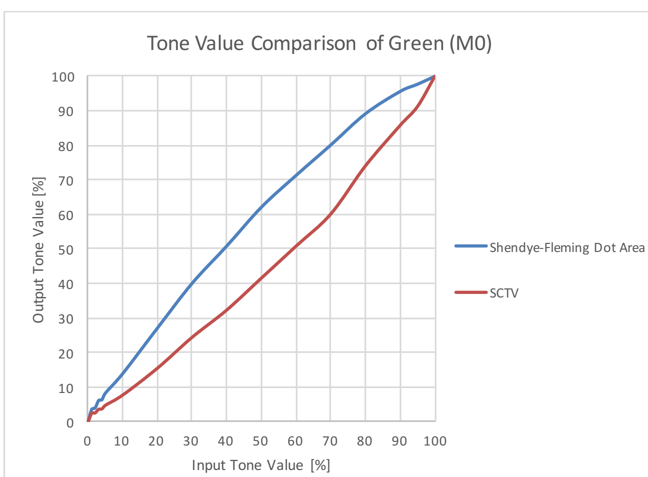


Figure 58: Dot area comparison of green in Euclidean space.

Figure 55 shows density of green tonal gradation calculated by Shendye-Fleming method. There is no filter available in ISO set for any other color than CMYK so comparison is not possible here. Figure 56 shows density of green tonal gradation in Euclidean space. The density curve is very smooth. When dot area is compared in Figure 57: Dot area comparison of green, the dot areas calculated by Shendye-Fleming and SCTV are very different. SCTV shows huge dot loss compared to Shendye-Fleming dot area. Green was printed on the magenta plate and with RIP curves. Magenta 50% dot was cut back to 48% and after printing 50% magenta dot is 67.0% by ISO method and 64.9% by Shendye-Fleming method. Here for green, 50% dot Shendye-Fleming shows 62.1%. As magenta and green are printed by the same plate and in the same unit, without demounting plate, a difference of 2.7% is acceptable, which is shown by Shendye-Fleming method. For the SCTV shows magenta dot as 51.4%, but green dot only 41.6%. This difference of 9.8% is very large while printing in same printing unit and same plate. Here, SCTV does show much difference in highlight area below 5% when compared to Shendye-Fleming results.

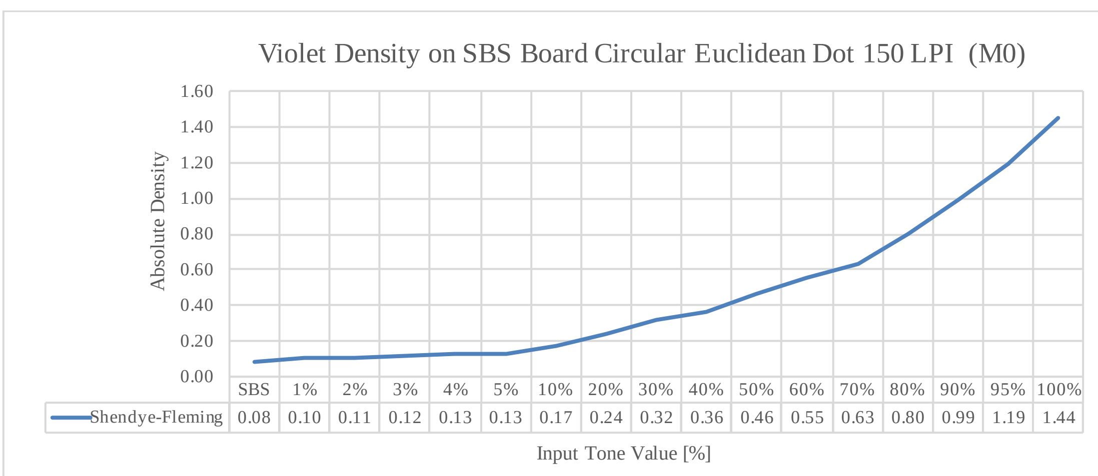


Figure 59: Density of violet tonal gradation.

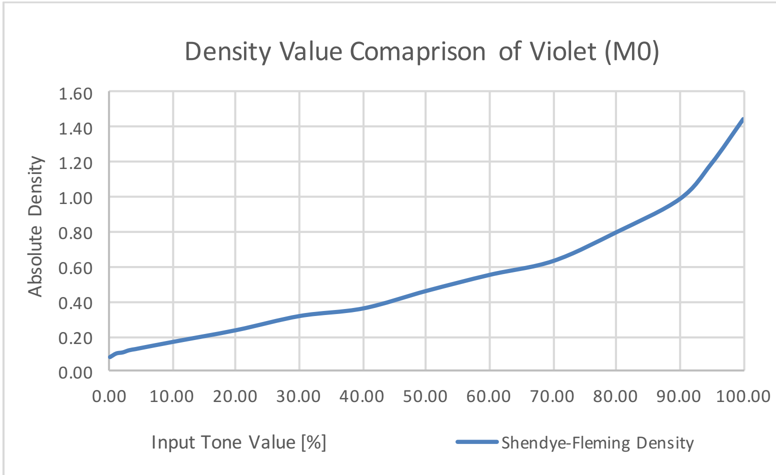
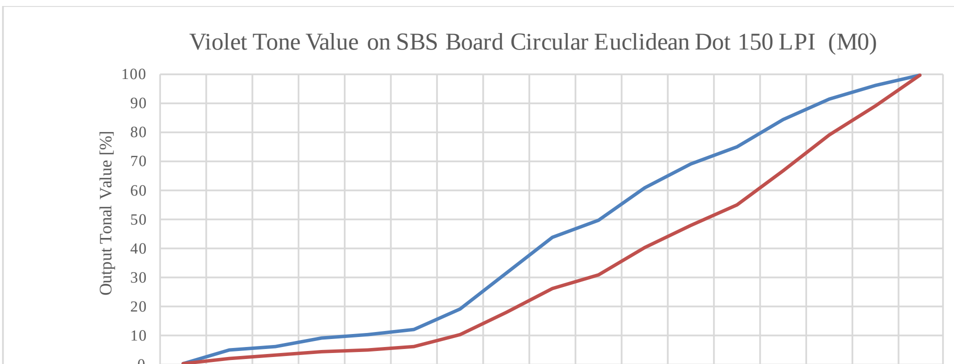


Figure 60: Density of violet tonal gradation in Euclidean space.



	0%	1%	2%	3%	4%	5%	10%	20%	30%	40%	50%	60%	70%	80%	90%	95%	100%
SF Dot area	0	4.88	6.24	8.98	10.42	11.97	19.08	31.36	43.78	49.55	60.92	69.25	75.12	84.44	91.57	96.41	100
SCTV	0	2.21	2.91	4.29	5.10	5.92	10.01	17.66	26.07	30.71	40.27	48.15	54.74	66.85	78.84	89.36	100

Figure 61: Dot area comparison of violet tonal gradation.

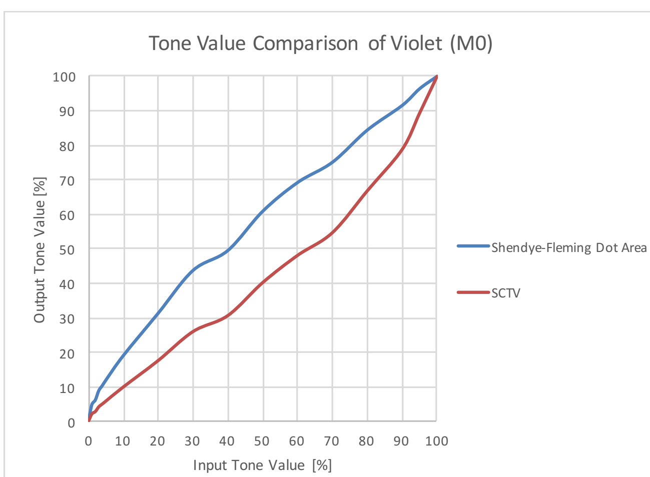


Figure 62: Dot area comparison of violet tonal gradation in Euclidean space.

Figure 59: Density of violet tonal gradation calculated by Shendye-Fleming method. There is no filter available in ISO set for any other color than CMYK, so here comparison is not possible. Figure **60** shows density of violet tonal gradation. The curve is very smooth. When dot area is compared (Figure 61), it shows that dot areas calculated by Shendye-Fleming and SCTV show high difference at 50% tonal value. SCTV is less by 20.7% than Shendye-Fleming. A significant difference is found even in highlight area.

For SCTV method 17.4% difference for cyan, 15.6% difference for magenta and 16.6% difference for yellow and 22.8 for black at 50% tonal value when compared with ISO show considerable differences with dot area calculated by Murray-Davies equation with ISO status E, density values. For process colors, Shendye-Fleming method shows better agreement with ISO method. For yellow color 1% dot, SCTV has shown acceptable value but ISO and Shendye-Fleming have failed to show positive values.

Table 9: Dot from RIP to print at input 50% tone value shows comparison of 50% dot by different methods for CMYKOGV.

Table 9: Dot from RIP to print at input 50% tone value

Color	I-D LUT	ISO E MD	Shendye-Fleming	SCTV
Cyan	49	66.9	66.0	49.4
Magenta	48	67.0	64.9	51.4
Yellow	51	56.6	56.6	40.0
Black	42	59.0	58.8	36.2
Orange	49	NA	49.2	31.1
Green	48	NA	62.1	41.6
Violet	51	NA	60.9	40.3

5.5 Measurement conditions effect

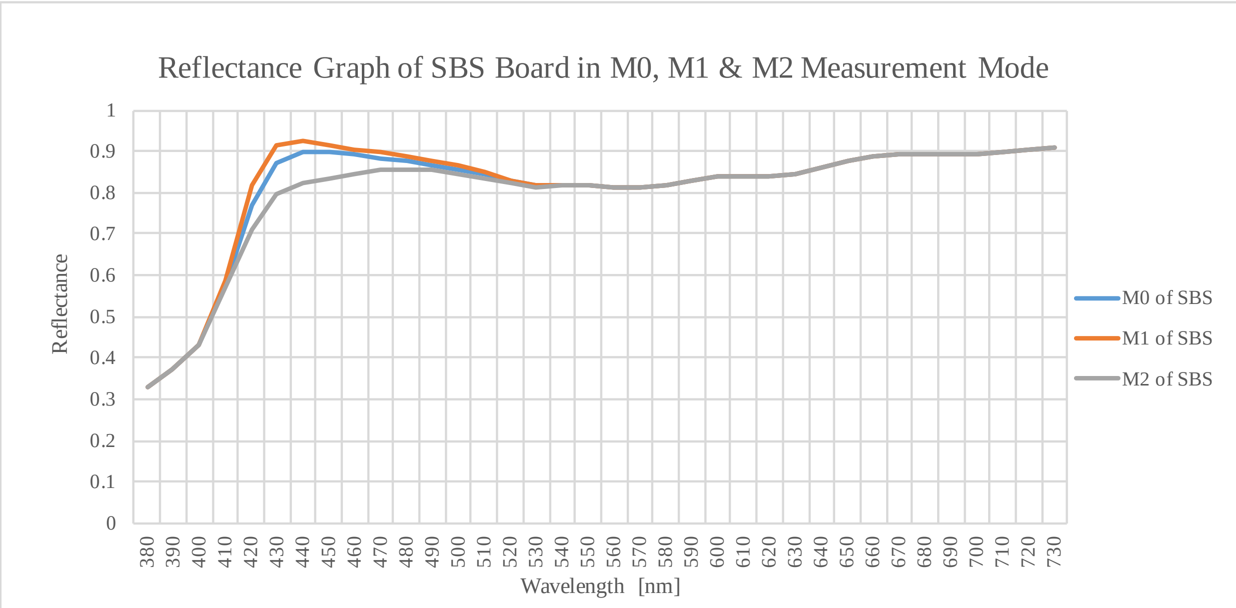


Figure 63: Reflectance graph of SBS board by M0, M1 and M2.

ISO 13655 defines measurement conditions M0, M1 and M2 for measurement of color. It is necessary to see its effect on measurement density. To determine the color measurement effect, the density of solid and density of paper must be checked. If measurement mode is causing a huge impact on difference in the density of paper, then it can cause difference in the measurement of tonal gradation. Figure 63: Reflectance graph of SBS board by M0, M1 and M2 shows that there is some impact of measurement condition in the blue region. To see this impact difference in the density of solid and paper, all three measurement modes must be compared.

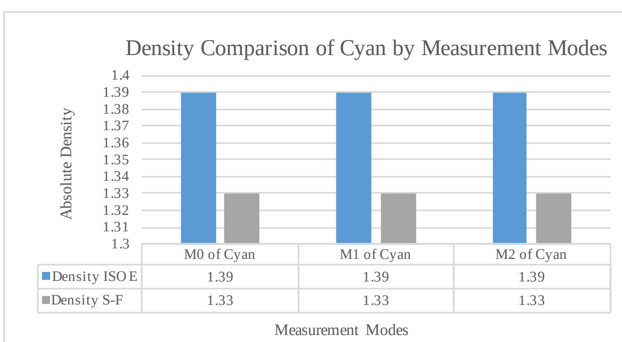


Figure 64: Density comparison of cyan solid by M0, M1 and M2.

Figure 64: Density comparison of cyan solid by M0, M1 and M2. shows that there is no difference caused by measurement condition on cyan solid ink density.

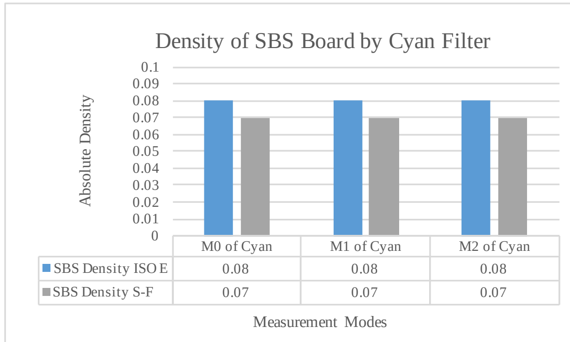


Figure 65: Density comparison of SBS board by filter for cyan in M0, M1 and M2.

Figure 65: Density comparison of SBS board by filter for cyan shows no difference, so measurement mode has no impact on density measurement and dot area measurement for this SBS board.

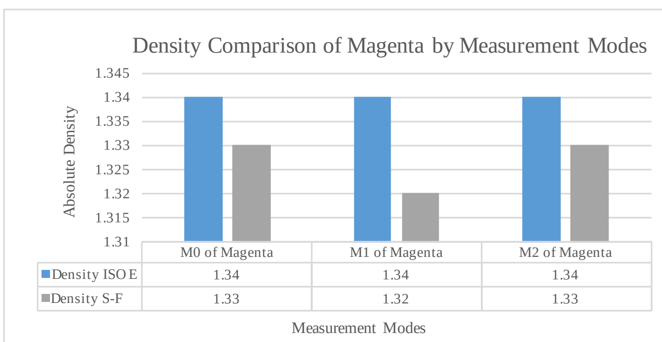


Figure 66: Density comparison for magenta in M0, M1 and M2.

Figure 66: Density comparison for magenta shows that there is no difference in magenta solid density when calculated by ISO E, a small difference of 0.01 is shown in M1 measurements by Shendye-Fleming, which has a negligible effect on tonal gradation.

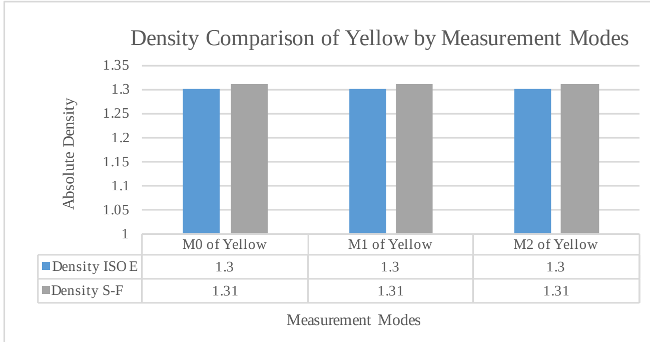


Figure 67: Density comparison for yellow in M0, M1 and M2.

Figure 67: Density comparison for yellow in M0, M1 and M2shows the effect of measurement mode on yellow density.

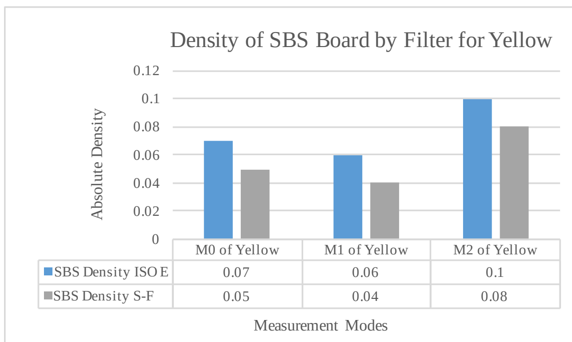
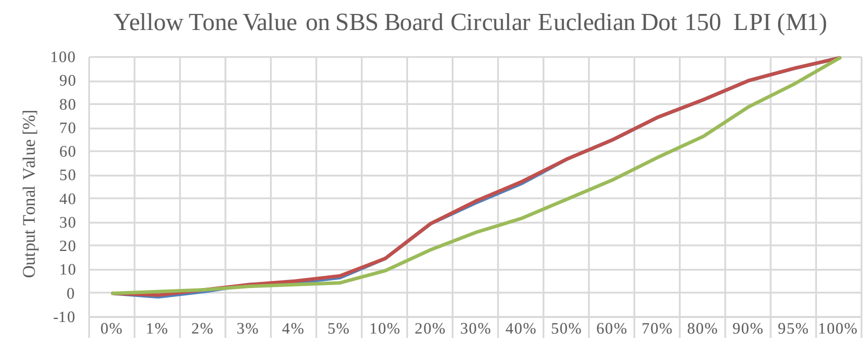


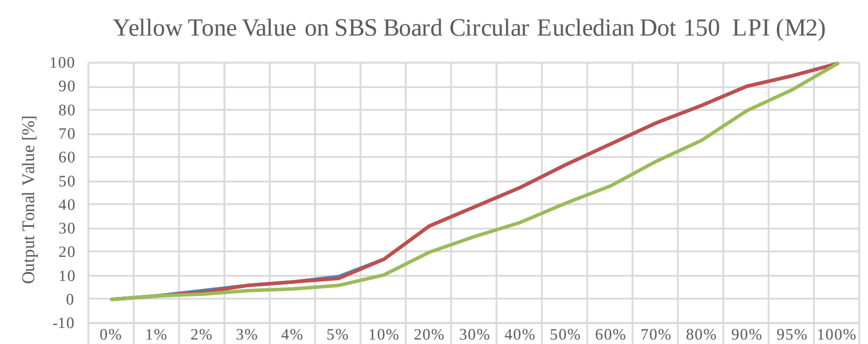
Figure 68: Density comparison of SBS board by filter for yellow in M0, M1 and M2.

Figure 68: Density comparison of SBS board by filter for yellow in M0, M1 and M2shows it is necessary to check measurement condition effects on tonal gradation of yellow.



	0%	1%	2%	3%	4%	5%	10%	20%	30%	40%	50%	60%	70%	80%	90%	95%	100%
ISO E Dot Area	0	-1.41	0.83	3.42	4.67	6.71	14.90	29.18	38.75	46.84	56.57	65.26	74.35	81.84	90.11	95.18	100
SF Dot area	0	0	1.44	3.83	5.09	7.00	15.08	29.30	38.83	46.91	56.63	65.27	74.29	81.77	90.03	95.12	100
SCTV	0	1.07	1.50	2.76	3.43	4.56	9.38	18.60	25.59	31.64	39.90	47.80	57.43	66.71	78.81	88.60	100

Figure 69: Dot area comparison of yellow tonal gradation by M1.



	0%	1%	2%	3%	4%	5%	10%	20%	30%	40%	50%	60%	70%	80%	90%	95%	100%
ISO E Dot Area	0	1.63	3.42	5.86	7.24	9.29	17.01	30.74	39.48	47.20	56.64	65.38	74.69	81.87	90.39	94.84	100
SF Dot area	0	1.49	3.28	5.68	7.11	9.14	16.89	30.64	39.42	47.15	56.66	65.36	74.60	81.84	90.36	94.78	100
SCTV	0	1.57	2.46	3.83	4.59	5.78	10.51	19.63	26.31	32.19	40.36	48.33	58.20	67.26	79.61	88.33	100

Figure 70:Dot are comparison of yellow tonal value by M2.

In Figure 45: Dot area comparison of yellow tonal gradation is plotted under M0 measurement conditions. Figure 69: Dot area comparison of yellow tonal gradation by M1. Figure 70:Dot are comparison of yellow tonal value by M2. Measurement condition does not impact at 50% tone value. However, a significant difference is found from 1% to 5 % dots. This shows measurement mode has impact on highlight of yellow color as yellow inks uses blue filter and measurement mode has impact in the blue region of the spectrum.

Table 10: Yellow dot area comparison by M0, M1 and M2 measurement mode

Input Tone Value	Dot area by ISO Status E Density			Dot area by Shendye-Fleming Density			SCTV		
	M0	M1	M2	M0	M1	M2	M0	M1	M2
1%	0	-1.4	1.6	0.0	0.0	1.5	1.1	1.1	1.5
2%	1.7	0.8	3.4	1.7	1.4	3.3	1.8	1.5	3.3
3%	4.2	3.4	5.9	4.2	3.8	5.7	3.1	2.8	5.9
4%	5.5	4.7	7.2	5.5	5.1	7.1	3.8	3.4	7.1
5%	7.6	6.7	9.3	7.5	7.0	9.1	4.9	5.1	9.1

Table 10: Yellow dot area comparison by M0, M1 and M2 measurement mode shows that measurement condition has effect on the measurement of density of paper and it can affect measurement of dot area of highlights of an image. In this case, to avoid effect of fluorescence, M2 measurement mode is recommended. The Shendye-Fleming method provides reliable results in M0, M1 and M2 measurement modes. A negative dot area is observed if density of paper is higher than density of tone value, which is possible because of variation of paper formation.

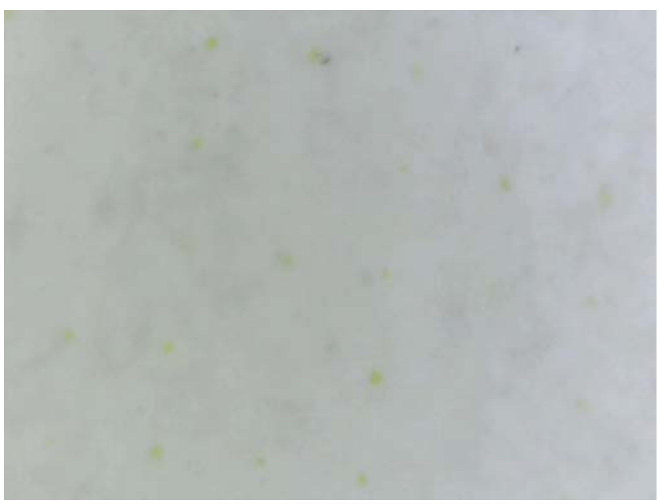


Figure 71: Printed 1% yellow Circular Euclidean.

Due to the interference of fluorescence density of paper could be higher in the blue region. Such interference can be avoided by switching to M2 measurement condition. Figure 71 shows 1%

Circular Euclidean dot was printed on SBS board, but still the M1 measurements shows it negative. This should not be of concern, because only a mall variation of paper density can give a negative value of the 1 % dot.

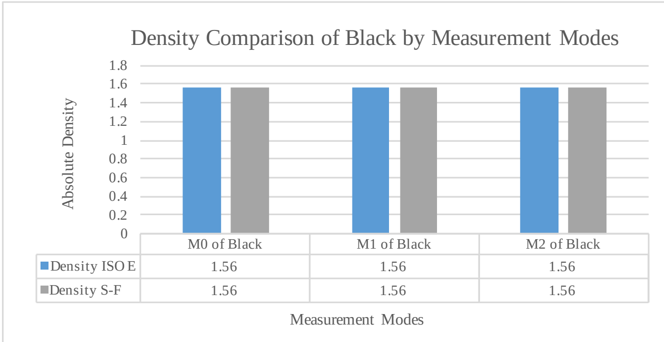


Figure 72: Density comparison for black in M0, M1 and M2.

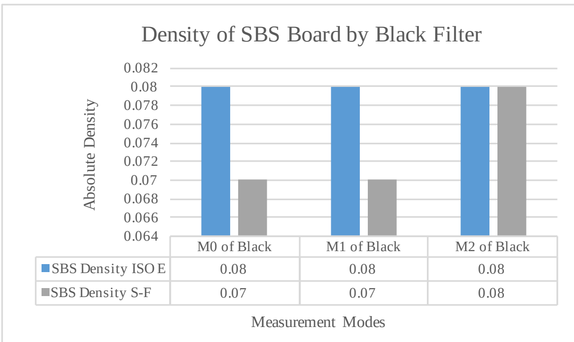


Figure 73: Density comparison of SBS board by filter for black in M0, M1 and M2.

Black has no impact on density of SBS board and black solids, so no effect on tonal gradation of black is observed.

Table 11: 50% tone value image of Circular Euclidean dot at 150 LPI on SBS

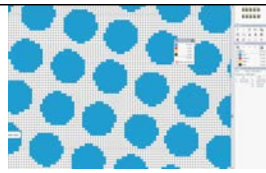
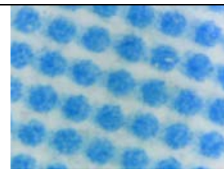
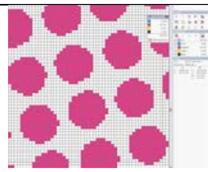
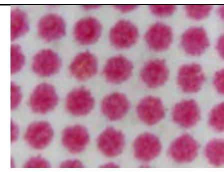
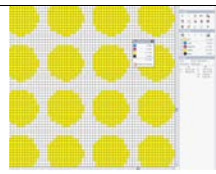
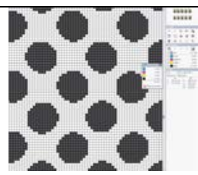
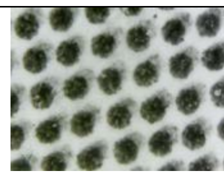
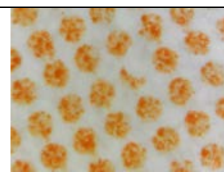
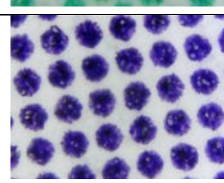
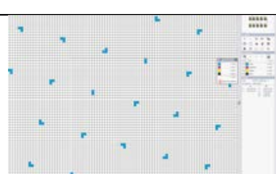
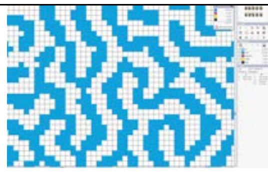
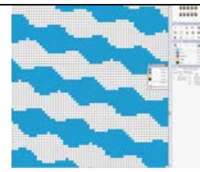
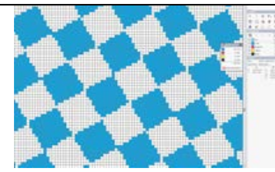
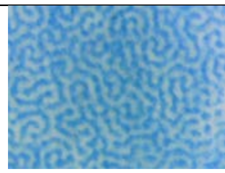
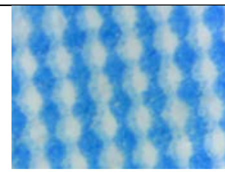
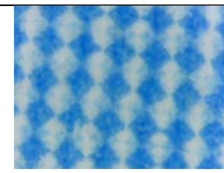
	RIP image	Printed Image	ISO	S-F	SCTV
Cyan Reduced to 49%			66.9%	67.0%	49.4%
Magenta Reduced to 48%			67.0%	64.9%	51.4%
Yellow Increased to 51%			56.6%	56.7%	40.0%
Black Reduced to 42%			59.0%	58.8%	36.2%
Orange Reduced to 49%	NA		NA	49.2%	31.2%
Green Reduced to 48%	NA		NA	62.1%	41.6%
Violet Increased to 51%	NA		NA	60.9%	40.3%

Table 12: 1% tone value image of cyan Circular Euclidian dot shape

	RIP image	Printed Image	Dot area ISO	Dot area S-F	SCTV
Cyan			1.7%	1.6%	1.1%

5.6 Effect of dot shape

Table 13: Dot shapes of cyan dot at 50% tone value

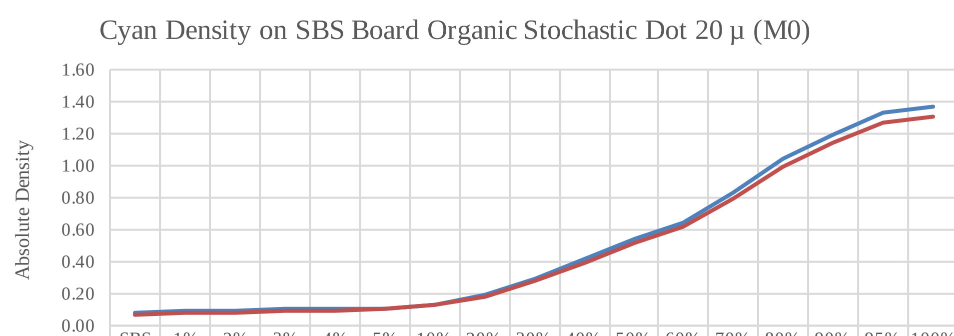
Dot Shapes	Organic Stochastic	Elliptical	Square
RIP			
Printed			

Circular Euclidean, elliptical, and square dot shapes were compared at 150 LPI on SBS and coated recycled board in M0, M1 and M2 measurement modes (Table 13: Dot shapes of cyan dot at 50% tone value) to evaluate implementation of Shendye-Fleming method for different dot shapes. Results found that Shendye-Fleming method is not restricted to any particular dot shape and any measurement conditions.

5.7 Effect of screen ruling

A tonal step for CMYKOGV were printed by Fogra Round dot at 100, 133, 150, 175 and 225 LPI on SBS and coated recycled board. Dot area was calculated with M0, M1 and M2 measurement and Shendye-Fleming method was compared to ISO status E for CMYK.

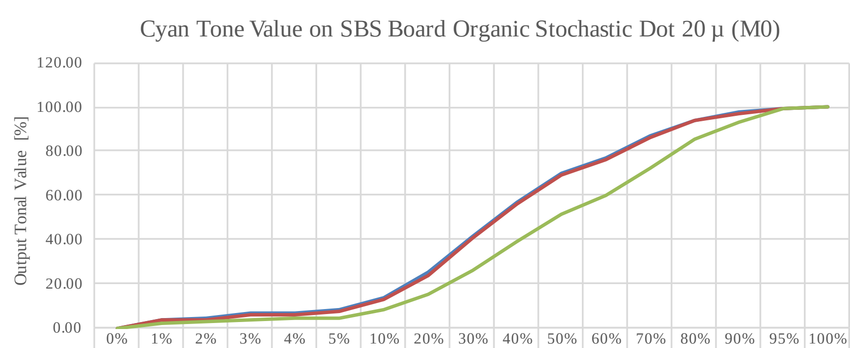
5.8 Effect of screening technique



	SBS	1%	2%	3%	4%	5%	10%	20%	30%	40%	50%	60%	70%	80%	90%	95%	100%
ISO E	0.08	0.09	0.09	0.10	0.10	0.11	0.14	0.19	0.29	0.42	0.55	0.65	0.83	1.04	1.20	1.33	1.37
Shendye-Fleming	0.07	0.08	0.09	0.09	0.10	0.10	0.13	0.18	0.28	0.40	0.53	0.62	0.79	1.00	1.15	1.27	1.31

Input Tone Value [%]

Figure 74: Cyan density comparison Esko organic stochastic screening.



	0%	1%	2%	3%	4%	5%	10%	20%	30%	40%	50%	60%	70%	80%	90%	95%	100%
ISO E Dot Area	0	3.42	4.16	6.24	6.63	8.07	13.57	24.78	41.28	57.11	69.73	77.18	86.65	94.03	97.41	99.54	100
SF Dot area	0	3.14	3.83	5.78	6.16	7.54	12.86	23.93	40.37	56.26	68.91	76.50	86.10	93.69	97.24	99.52	100
SCTV	0	2.08	2.47	3.70	3.88	4.59	7.79	14.71	26.00	38.93	51.22	59.74	72.63	85.54	93.02	98.94	100

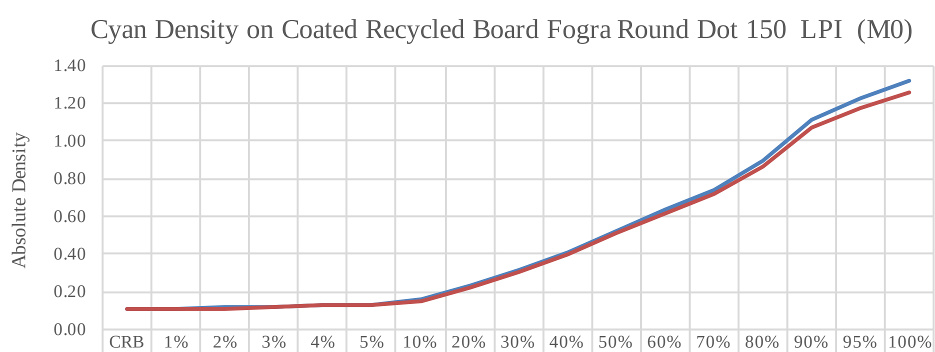
Input Tone Value [%]

Figure 75: Cyan tonal value comparison of Esko organic stochastic.

To evaluate Shendye-Fleming method for different screening techniques tonal gradations of CMYKOGV were printed with AM, FM and hybrid screening techniques and dot areas were calculated by Shendye-Fleming method to compare with ISO method for CMYK. Esko Organic Stochastic 25 micron, and Esko Samba Flex 9H screening was used. Figure **74**3 and Figure 734 show that results of density and dot area calculated by Shendye-Fleming method always match to ISO. Differences of 0.06 between solid density has been observed everywhere, but it is not significant when dot area is calculated. Hybrid screening is a mixture of FM and AM and Shendye-Fleming method works for it. It was observed that Shendye-Fleming method shows similar results to ISO method for FM, AM and hybrid screening techniques. SCTV shows significant differences.

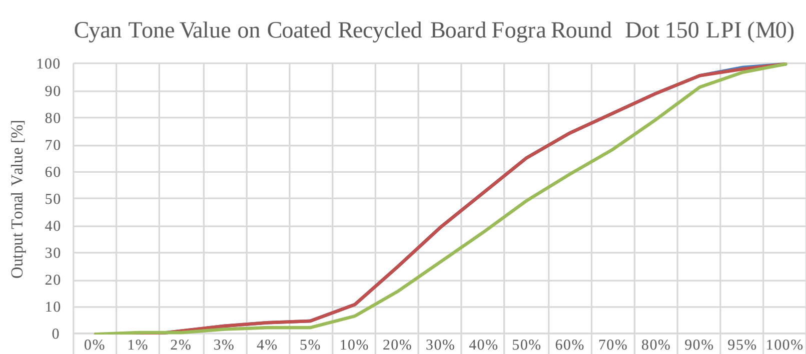
5.9 Effect of substrate

To evaluate if Shendye-Fleming method can work on different substrates, two different substrates were used in the experiments, SBS and CRB board with grammage of 300 gsm. Complete test pattern of different screen ruling, screen technique and dot shapes were printed on both the substrate and measurements were taken.



	CRB	1%	2%	3%	4%	5%	10%	20%	30%	40%	50%	60%	70%	80%	90%	95%	100%
ISO E	0.11	0.11	0.11	0.12	0.13	0.13	0.16	0.23	0.31	0.41	0.52	0.63	0.74	0.90	1.11	1.22	1.32
Shendye-Fleming	0.11	0.10	0.11	0.12	0.12	0.13	0.15	0.22	0.30	0.40	0.51	0.61	0.72	0.87	1.07	1.18	1.26

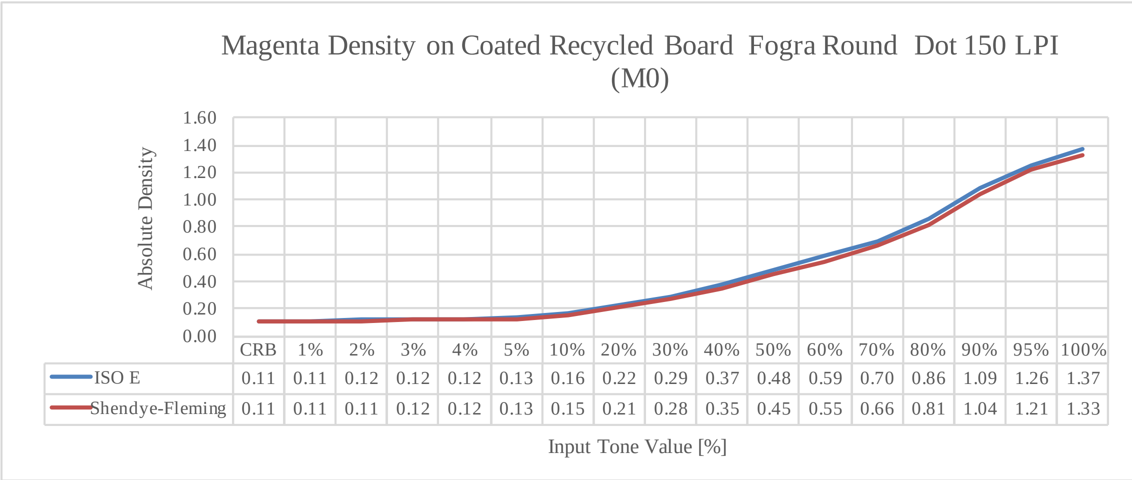
Figure 76: Cyan density comparison for CRB board.



	0%	1%	2%	3%	4%	5%	10%	20%	30%	40%	50%	60%	70%	80%	90%	95%	100%
ISO E Dot Area	0	0	0.94	3.00	4.31	4.97	11.15	25.13	39.55	52.63	65.29	74.47	81.77	89.14	95.91	98.44	100
SF Dot area	0	0	0.94	2.98	4.29	4.93	11.01	25.00	39.37	52.40	65.00	74.18	81.48	88.89	95.78	98.40	100
SCTV	0	0.50	0.42	1.64	2.62	2.66	6.40	15.82	26.67	37.68	49.31	59.20	68.19	79.09	91.29	97.10	100

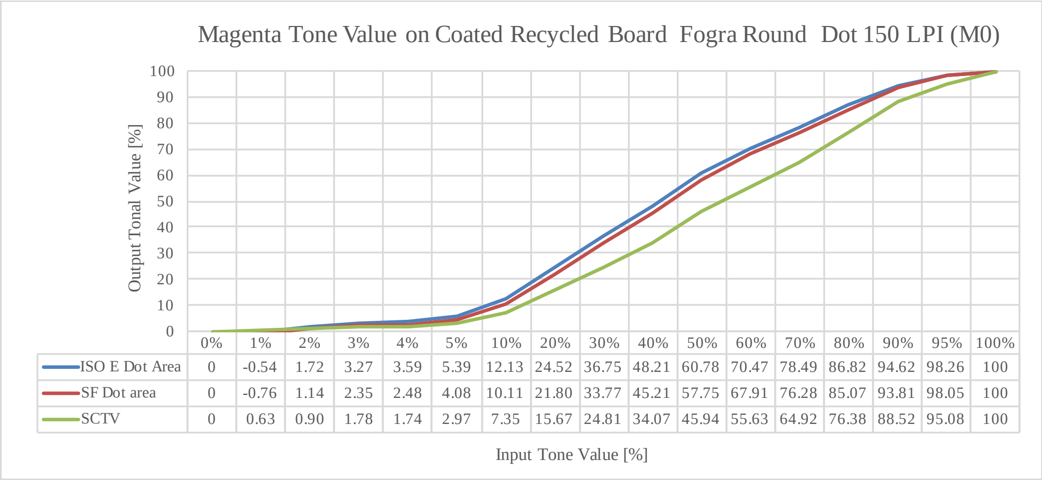
Figure 77: Dot area comparison for CRB board.

Figure 76 and Figure 77 show Shendye-Fleming method has same results when compared with ISO for coated recycled board. The same results were obtained for all remaining colors and it was confirmed that Shendye-Fleming method gives the same results for SBS and coated recycled boards. This provides information that similarly like ISO, Shendye-Fleming method can be used for any white substrate. As substrate has effect on color, a small change in filter bandwidth will still provide correct results. In Figure 39 and Figure 41, magenta density and dot area are plotted on SBS board with filter bandwidth from 480 nm to 630 nm. But if the same bandwidth is used on coated recycled board, and solid ink density calculated by both, the methods don't match. When filter bandwidth is corrected from 490 nm to 600 nm, then the results match.



	CRB	1%	2%	3%	4%	5%	10%	20%	30%	40%	50%	60%	70%	80%	90%	95%	100%
ISO E	0.11	0.11	0.12	0.12	0.12	0.13	0.16	0.22	0.29	0.37	0.48	0.59	0.70	0.86	1.09	1.26	1.37
Shendye-Fleming	0.11	0.11	0.11	0.12	0.12	0.13	0.15	0.21	0.28	0.35	0.45	0.55	0.66	0.81	1.04	1.21	1.33

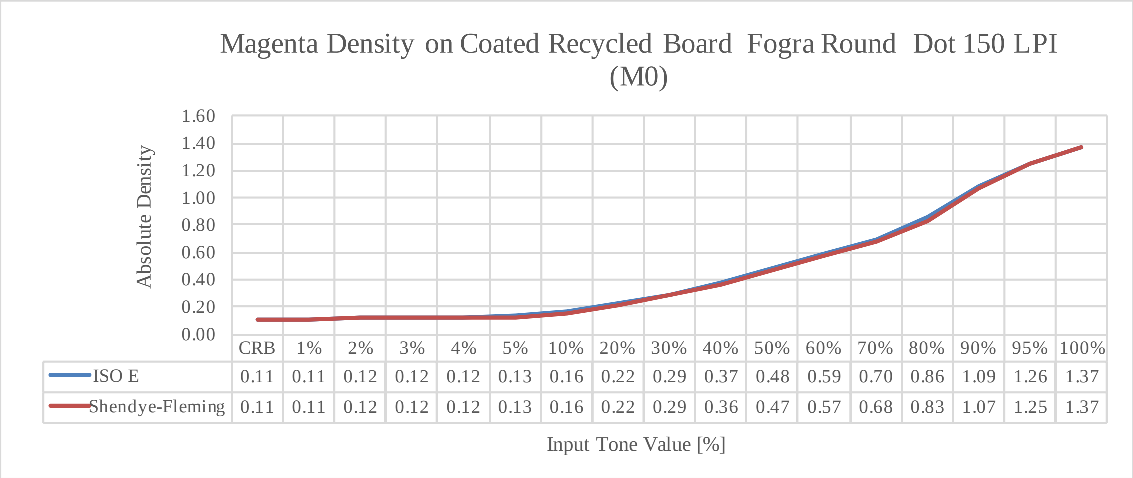
Figure 78: Magenta density on CRB with filter bandwidth 480 to 630 nm.



	0%	1%	2%	3%	4%	5%	10%	20%	30%	40%	50%	60%	70%	80%	90%	95%	100%
ISO E Dot Area	0	-0.54	1.72	3.27	3.59	5.39	12.13	24.52	36.75	48.21	60.78	70.47	78.49	86.82	94.62	98.26	100
SF Dot area	0	-0.76	1.14	2.35	2.48	4.08	10.11	21.80	33.77	45.21	57.75	67.91	76.28	85.07	93.81	98.05	100
SCTV	0	0.63	0.90	1.78	1.74	2.97	7.35	15.67	24.81	34.07	45.94	55.63	64.92	76.38	88.52	95.08	100

Figure 79: Magenta dot area filter bandwidth 480 to 630 nm.

The reason behind the substrate effect is that an ink printed on two different substrates gives two different colors, this results in change in appearance of color. In ISO method, one filter is used for all the substrates, despite that each substrate can cause changes in color appearance, then for ISO, it is not accounted for.



	CRB	1%	2%	3%	4%	5%	10%	20%	30%	40%	50%	60%	70%	80%	90%	95%	100%
ISO E	0.11	0.11	0.12	0.12	0.12	0.13	0.16	0.22	0.29	0.37	0.48	0.59	0.70	0.86	1.09	1.26	1.37
Shendye-Fleming	0.11	0.11	0.12	0.12	0.12	0.13	0.16	0.22	0.29	0.36	0.47	0.57	0.68	0.83	1.07	1.25	1.37

Figure 80: Magenta density on CRB from 490 to 600 nm.

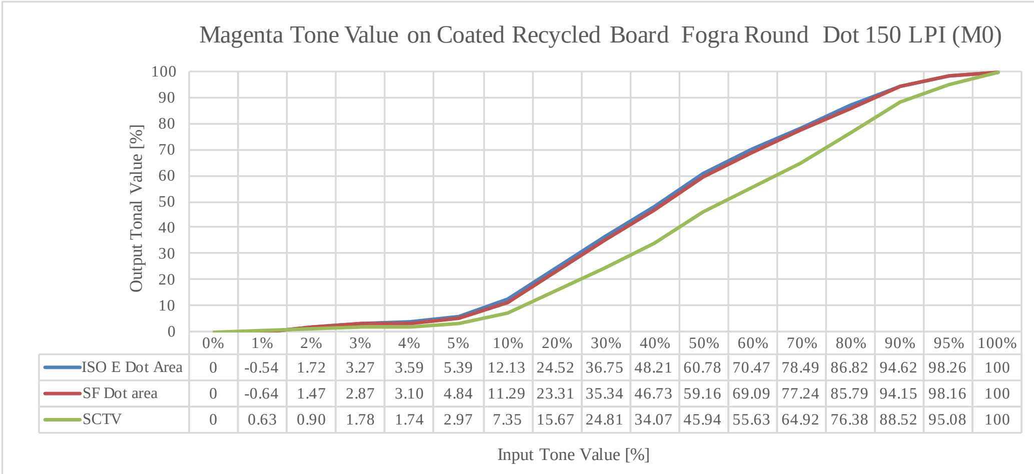


Figure 81: Magenta dot area on CRB by filter bandwidth 490 to 600 nm.

Results from Figure 80 and Figure 81 show that Shendye-Fleming density also considers change in substrate.

5.10 Spot colors

Twelve different spot colors were printed using an offset litho proofing system on SBS board. Filter bandwidth was selected for each color by plotting K/S of tonal gradation. Filter range for each spot color is reported with each color. Graph for density by Shendye-Fleming method was plotted along with its graph for dot area by Shendye-Fleming method and SCTV. Measurements were taken by M0, M1 and M2 measurement conditions. Table 14 shows bandpass filter range selected for calculating density and dot area of spot colors.

Table 14: Filter range and 50% tone value of spot colors (M1)

Color	Auto Filter range [nm]	“C” Factor	Density Solid	S-F DA	SCTV
7704 CRS Orange	420 to 560	40.6	1.74	67.3	46.0
7726 CRS Violet	490 to 640	94.5	1.82	69.6	47.7
7722 CRS Green	580 to 700	71.1	1.74	65.7	48.6
11001 Golden Yellow	430 to 500	12.5	1.27	61.8	44.9
2353 Fire Orange	430 to 550	22.0	1.50	66.5	46.5
13309 Communist Red	430 to 560	27.5	1.48	61.6	46.4

18125 Brilliant Red	430 to 580	26.3	1.55	64.4	45.9
18500 Rhodamine Red	490 to 580	48.9	1.71	65.6	52.1
13694 Offset Purple	490 to 590	37.6	1.56	65.2	50.2
637 Reflex Blue	540 to 650	65.4	1.62	65.2	47.2
758 Brilliant Green	570 to 700	39.8	1.33	64.5	46.1
641 Bronze Blue	550 to 700	82.8	1.63	65.3	48.0

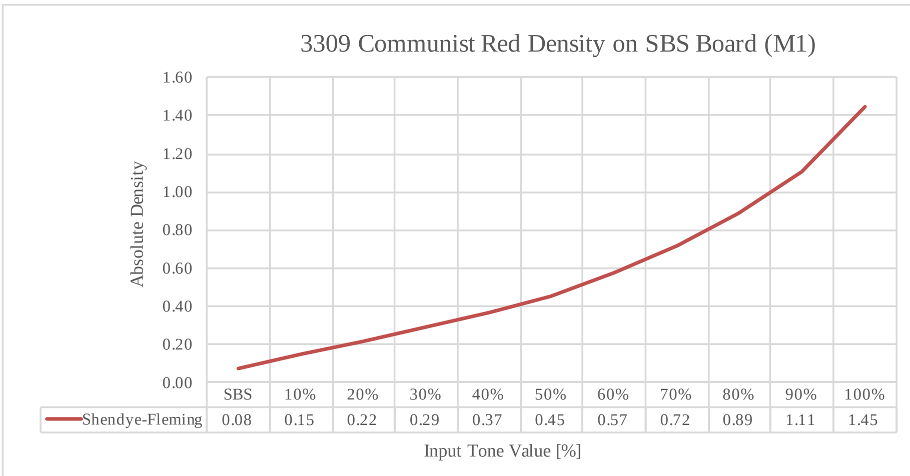


Figure 82: Density plot of Communist red.

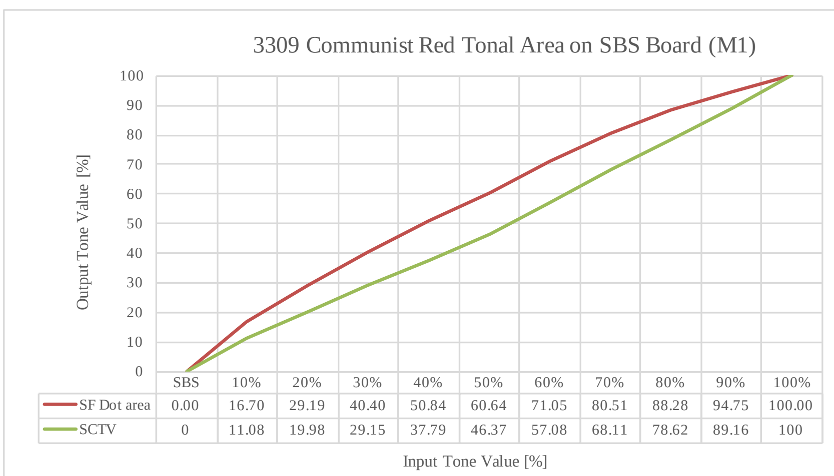


Figure 83: Dot area of Communist Red.

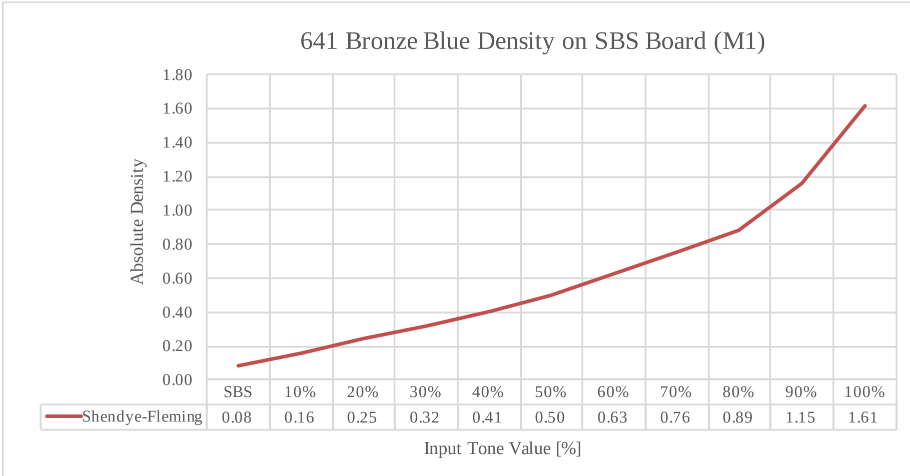


Figure 84: Density plot of Bronze Blue.

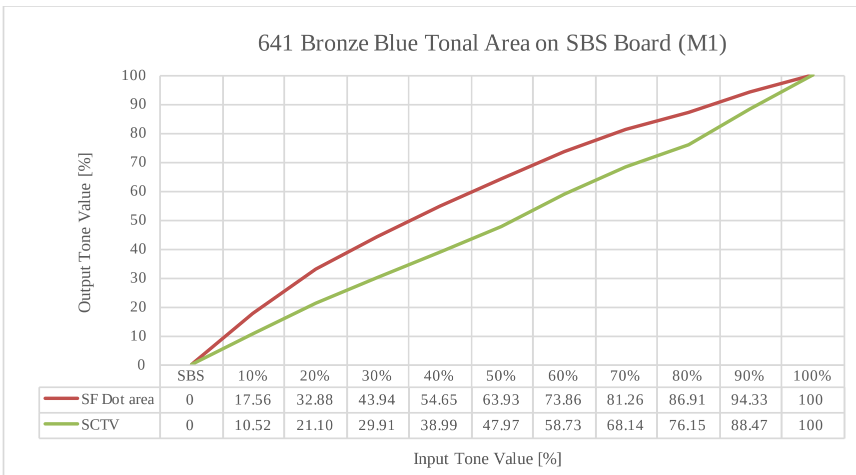
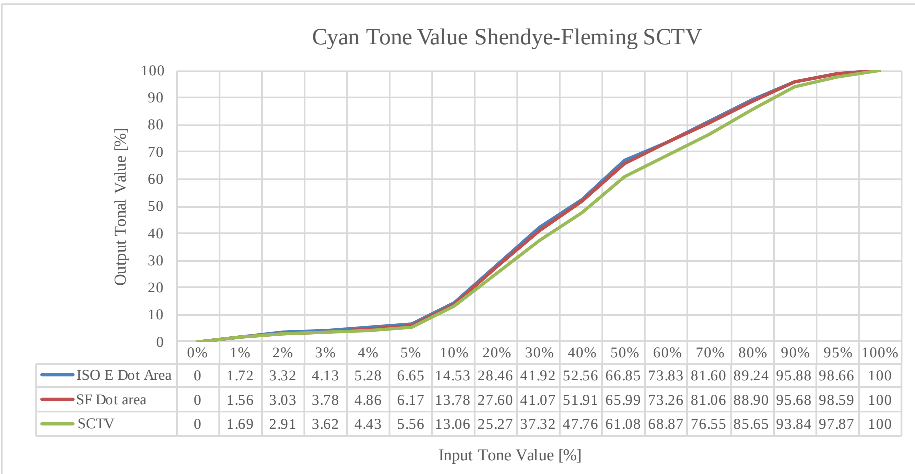


Figure 85: Dot area plot of Bronze Blue.

Figure 82 and Figure 84 show density plot of red and blue spot colors. Figure 83 and Figure 85 show dot area plot for red and blue spot color. It was observed that all 50% tone values calculated by Shendye-Fleming method do not match with SCTV. As all spot colors are printed on the same substrate and on the same proofing system, they show the same tonal gradation curve. This provides information that bandwidth of filter can be set by hue of color. All reds have very similar or close filter range, all greens have similar or closer filter range, all yellows have similar filter ranges.

5.11 Shendye-Fleming modified SCTV

Equation 7 in section 2.13 shows proposed correction to ISO 20654 equation value components. A new function “g” provides calculating factors for value components used in ISO 20654 dot area equation. Dot area is recalculated with this equation and compared with ISO status E and Shendye-Fleming with Murray-Davies equation. When Shendye-Fleming corrections (Equation 7) are applied to SCTV, then it is observed that SCTV has signifying improvement in visual numerical results, which are now acceptable. Results are plotted for M0 measurements of circular Euclidean dot at 150 LPI on SBS substrate.



	0%	1%	2%	3%	4%	5%	10%	20%	30%	40%	50%	60%	70%	80%	90%	95%	100%
ISO E Dot Area	0	1.72	3.32	4.13	5.28	6.65	14.53	28.46	41.92	52.56	66.85	73.83	81.60	89.24	95.88	98.66	100
SF Dot area	0	1.56	3.03	3.78	4.86	6.17	13.78	27.60	41.07	51.91	65.99	73.26	81.06	88.90	95.68	98.59	100
SCTV	0	1.69	2.91	3.62	4.43	5.56	13.06	25.27	37.32	47.76	61.08	68.87	76.55	85.65	93.84	97.87	100

Figure 86: Shendye-Fleming SCTV of cyan.

Figure 86 shows tonal value comparison of Murray-Davies with ISO density, Shendye-Fleming density and corrected Shendye-Fleming corrected SCTV equation. When Figure 86 is compared to Figure 38 then results of Shendye-Fleming SCTV shows significant results. Although Shendye—Fleming equation results are closer to ISO and difference between ISO and SCTV is still more than 5% at 50% input tonal value.

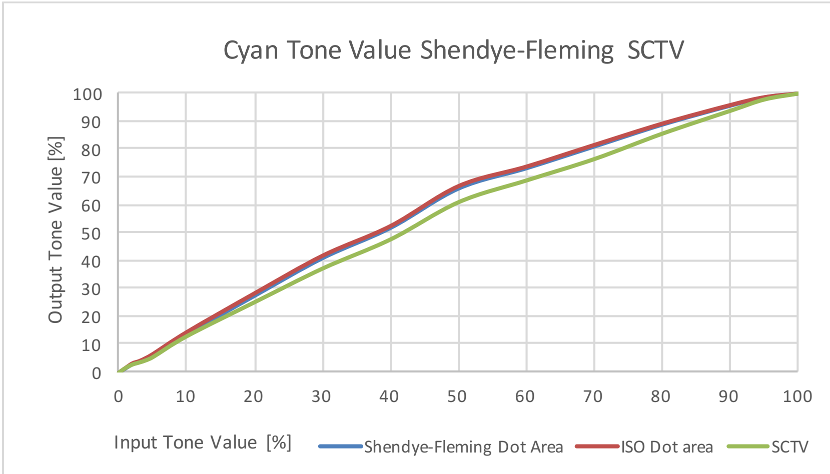
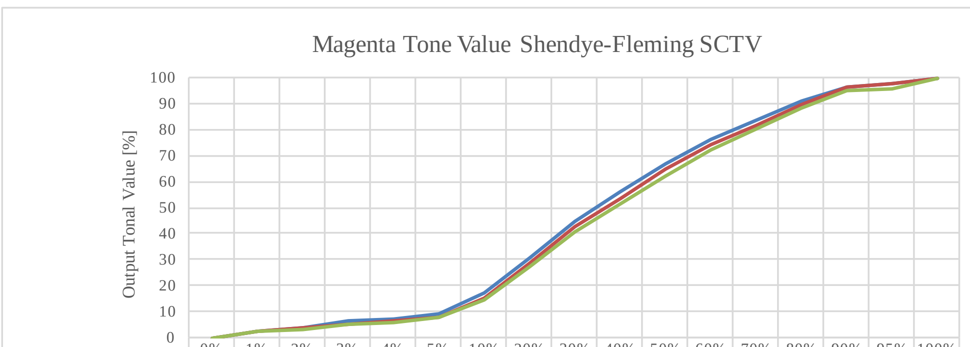


Figure 87: Shendye-Fleming SCTV of cyan in Euclidean space.

Figure 87 shows results of Figure 86 in Euclidean space. It shows midtone has higher difference than highlight and shadows. Difference between curves increases from highlight to midtone and reduces from midtone to highlight. Generally, 50% input tone value shows highest difference.



	0%	1%	2%	3%	4%	5%	10%	20%	30%	40%	50%	60%	70%	80%	90%	95%	100%
ISO E Dot Area	0	2.45	3.94	6.07	7.30	9.06	16.97	30.87	44.93	55.80	66.96	76.33	83.42	90.80	96.45	97.54	100
SF Dot area	0	2.27	3.53	5.35	6.41	7.98	15.36	28.78	42.72	53.49	64.86	74.50	81.85	89.81	96.07	97.43	100
SCTV	0	2.11	3.26	4.94	6.02	7.55	14.49	27.35	40.49	51.46	62.34	71.96	79.91	88.05	94.78	95.72	100

Input Tone Value [%]

Figure 88: Shendye-Fleming SCTV of magenta

Figure 88 shows magenta has 4.4% at 50% input tone value. This shows that correction applied to SCTV is shows it is closer but difference is not negligible. Difference is smaller in highlight and shadow tonal area. Overall Shendye-Fleming SCTV shows values lesser than Murray-Davies ISO and Shendye-Fleming density dot area.

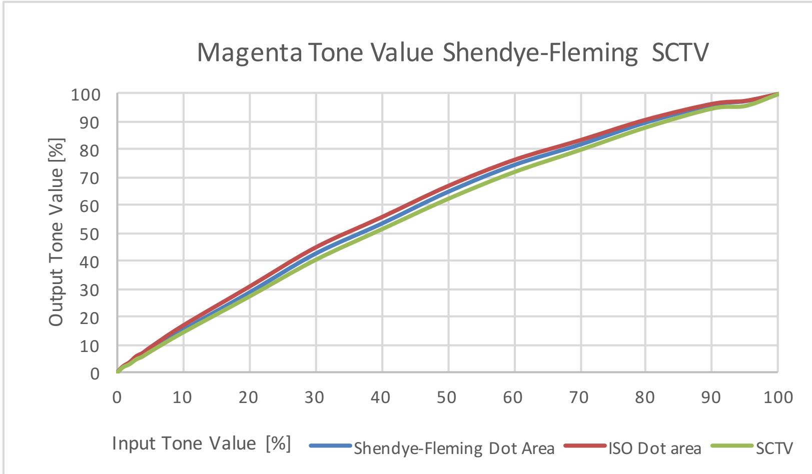
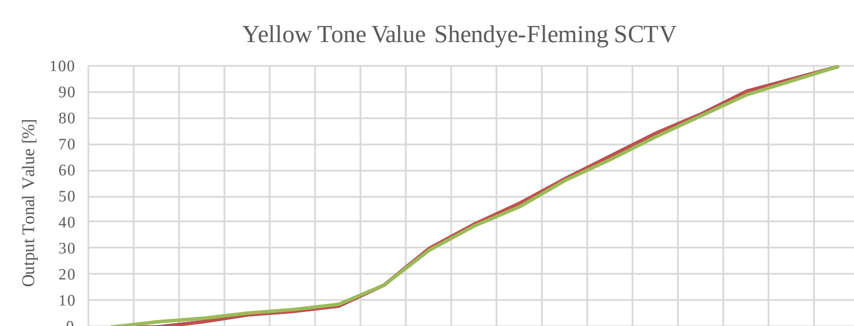


Figure 89: Shendye-Fleming SCTV of Magenta in Euclidean space.

Figure 89 shows data from Figure 88 in Euclidean space. Although curves now look closer, there are considerable midtone differences.



	0	1%	2%	3%	4%	5%	10%	20%	30%	40%	50%	60%	70%	80%	90%	95%	100%
ISO E Dot Area	0	0	1.69	4.23	5.54	7.57	15.62	29.74	39.03	47.00	56.62	65.34	74.50	81.86	90.27	95.20	100
SF Dot area	0	0	1.68	4.15	5.48	7.47	15.54	29.69	39.03	47.02	56.68	65.33	74.40	81.81	90.20	95.16	100
SCTV	0	1.79	2.92	5.12	6.28	8.15	15.79	29.39	38.80	46.32	55.89	64.11	73.16	80.63	88.95	94.66	100

Figure 90: Shendye- Fleming SCTV of yellow.

Figure 90 shows a close match between ISO and Shendye-Fleming modified SCTV results for yellow. Differences between ISO and Shendye-Fleming SCTV are negligible for yellow. So it can be seen that matching of Shendye-Fleming SCTV results with Murray-Davies equation depends upon color and the way ISO filter values are selected and behavior of tonal steps of color in color space. Shendye-Fleming modified SCTV shows positive results, but Murray-Davies can show negative dot area if density of paper is higher than tone value.

5.12 Shendye-Fleming OBA index

The Shendye-Fleming OBA index was calculated for various substrates, which were compared as follows. Optical brighteners are also known as fluorescent whitening agents, so Shendye-Fleming OBA index can also be called as Shendye-Fleming Fluorescent index and can be denoted as “S-F FI” or “S-F OBAI”. In Table 15, M1 measurements are used along with D50/2 illuminant/observer combination to calculate CIE whiteness and Fleming-Aksoy whiteness. CIE tint value is given in bracket along with CIE whiteness (CIE WI).

Table 15: Shendye-Fleming OBA index of different substrates

Substrate	CIELAB (M1)	CIELAB (M2)	CIE WI (Tint)	$W_{F\text{-}A}$	S-F FI
Calibration tile	92.08, 1.09, -0.55	92.08, 1.09, -0.55	82.77(-1.84)	82.77	0
Tissue Paper	95.12, -0.32, 3.09	95.11, -0.31, 3.19	75.17(-0.97)	74.57	0.15
Corrugated White	86.08, 0.95, 0.70	85.99,0.23, 3.44	65.21(-2.37)	63.95	1.85
Coated Recycled	91.13, 0.06, -0.01	91.04, -0.63, 1.73	82.21(0.34)	81.89	1.89
Coated Paper	92.20, 0.63, -5.47	92.05, -0.05, -1.43	104.34(1.74)	91.85	3.19
SBS Board	92.33, 2.79, -6.89	92.08, 1.09, -0.55	110.87(-1.63)	88.52	4.99
Copier Paper	93.31, 3.08, -10.08	93, 0.46, -1.28	126.17(-0.38)	94.16	7.14

Table 15 shows that white calibration tile of spectrophotometer has OBA index 0 as no OBA’s are used while manufacturing calibration material for spectrophotometer. Tissue paper has no OBA, and its OBA index is 0.15, which is close to ~0. CIE LAB values are calculated by D50/2 with M1 and M2 measurement condition in Table 15, and it shows that the more the difference between M1 and M2 measurement in CIE b value, the more is the OBA index number. The more of the OBA used, the more the difference in Shendye-Fleming OBA index. This difference is caused by cutting UV radiation in measurements by UV cut of filter used in M2 measurements. As paper has higher amount of OBA, it gets bluer cast and Fleming-Aksoy whiteness formula shows paper is no whiter and reduces its whiteness value. This observation can be related to OBA index to determine at what OBA index Fleming-Aksoy shows higher whiteness. This way, OBA index can be used for determining correct amount of OBA in paper manufacturing and it can become a good quality control index for OBA dosage monitoring.

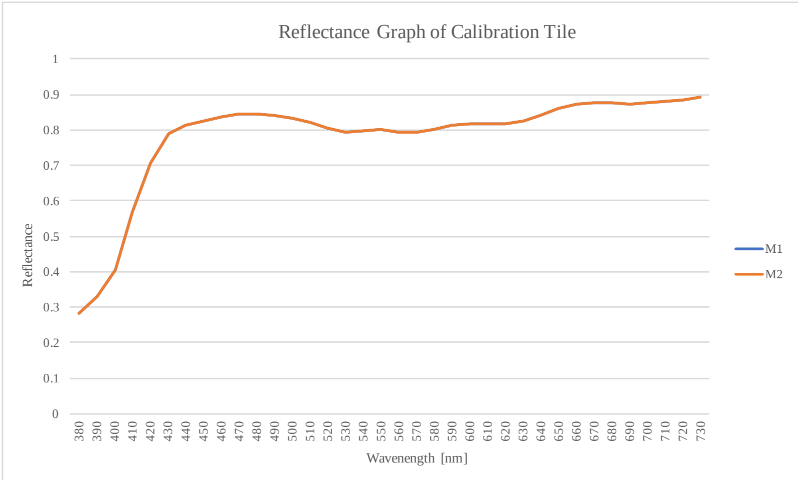


Figure 91: Reflectance graph of calibration by M1 and M2 measurements.

The reflectance graph of calibration tile of spectrophotometer in Figure 91 shows that there is no difference in M1 and M2 measurements for the calibration tile. No OBA's are added in calibration, as it is requirement for calibration standard and as a result of that, the OBA index is 0.

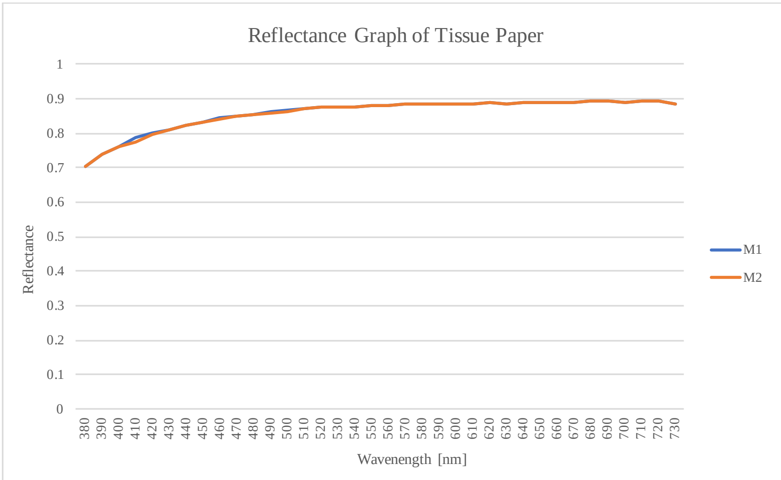


Figure 92: Reflectance graph of tissue paper by M1 and M2 measurements.

Tissue paper has very short shelf life and color or high whiteness or brightness is not a requirement. As it is not printed, no OBA's are added in tissue paper. Tissue paper is bleached to appear white.

This can cause a very small difference in M1 and M2 measurements, which results in OBA index of 0.15 (see Figure 92). OBA index of tissue paper is very small and close to zero.

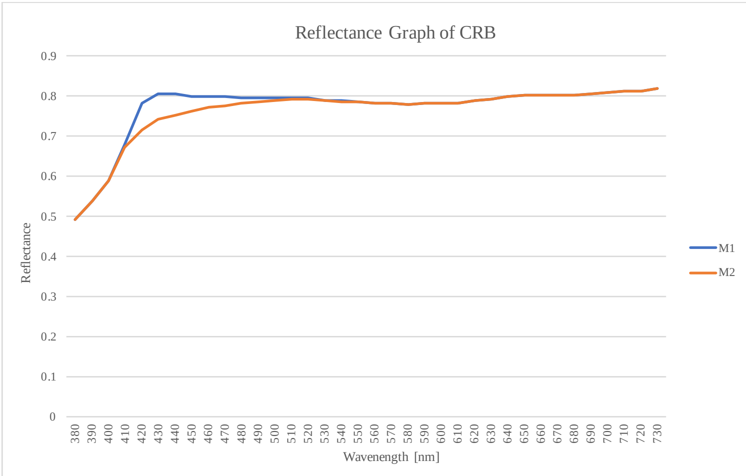


Figure 93: Reflectance graph of CRB by M1 and M2 measurements.

A recycled board requires white coating to provide printable surface. In paper coatings, small amounts of OBA's are added to provide blue cast as this coating can't provide high lightness and whiteness due to recycled nature of paperboard. Figure 93 shows small amount of OBA's are added to coated recycled board.

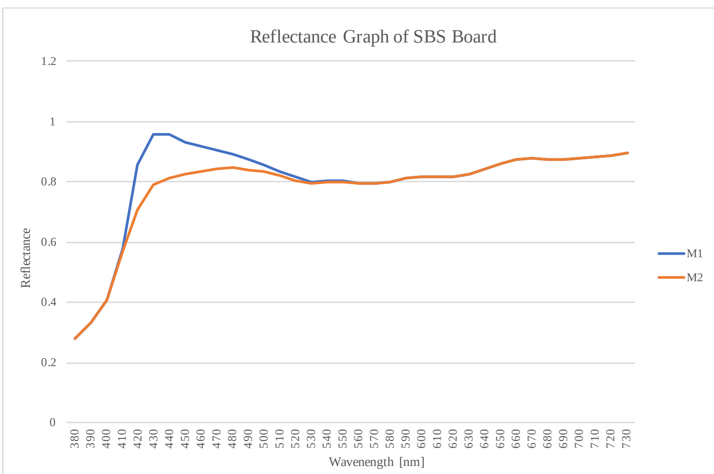


Figure 94: Reflectance graph of SBS board by M1 and M2 measurement.

SBS board has CIE b* value of -6.89 by M1 measurement, which shows it has a good amount of OBA's added for a blue cast. A difference between CIE b* value of M1 and M2 of SBS is 6.34 which shows higher OBA index value of 4.99.

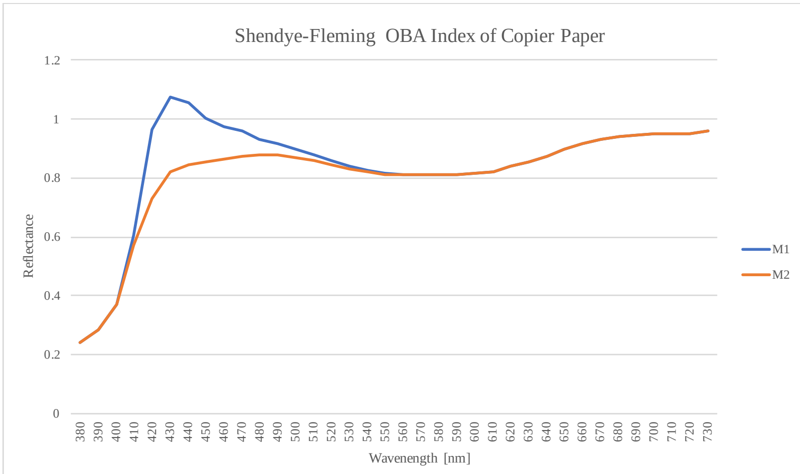


Figure 95: Reflectance graph of copier paper by M1 and M2 measurements.

Copy paper uses a lot of OBA to give blue cast to the paper. More emission in the blue region also gives higher brightness as brightness of paper is measured at 457 nm. The difference between M1 and M2 measurements of CIE b* value for copy paper is 8.8, which is very high. Shendye-Fleming OBA index for copy paper is 7.14. This shows that different amount of OBA can create different blue cast to paper and it can be measured and compared by using Shendye-Fleming OBA index.

CHAPTER 6

CONCLUSIONS AND FUTURE WORK

6.1 Conclusions on Shendye-Fleming universal density equation

The Shendye-Fleming universal density equation was derived to overcome limitations of ISO 5 density calculations. It was tested for different substrates, dot shapes, screen rulings, and halftoning techniques. It provides better results over SCTV method for calculating dot area for spot color and expanded gamut colors. Physical dot area is not considered in this research. Following are the summary findings:

- The Shendye-Fleming universal density equation is tested for reflection mode of color measurement only in thin ink films.
- The Shendye-Fleming universal density equation generates a filter for each measurement, and this makes Shendye-Fleming method distinguished from the ISO 5 method.
- The Shendye-Fleming universal density equation results for calculating densities of cyan, magenta, yellow and black that are close to ISO E status values.
- The Shendye-Fleming universal density equation can be extended to expanded gamut color and spot colors.
- The range for bandpass filter for Shendye-Fleming universal density equation must be between 430 nm to 700 nm.
- The limits for bandpass filter selection have impact on calculations, so these limits must be mentioned with density value.
- The substrate has impact on the width of bandpass filter, so substrate information must be provided with target density.

- The bandwidth of the filter used in Shendye-Fleming method is very close to the bandwidth of the filters mentioned in ISO status E.
- ISO status E filters have negative numbers, but Shendye-Fleming filter never generates negative data in filter set.
- Negative data in filter set of absorption filter is against the laws of physics. Because negative number shows filter is absorbing more photons than are incident.
- An automatic scaling factor method can be used for chromatic and pastel colors also. When a pastel shade is very close to white, its absorption region is smaller than its high chromatic shade.
- Auto-scaling method for selection of filter bandwidth provides scientific and mathematical method to select bandwidth for bandpass absorption filter generation.
- Auto scaling method does not work for black and white. For black, the range is 430 nm to 700 nm.
- SCTV never provides negative numbers on dot area for highlight.
- Measurement modes M0, M1 and M2 can have effect on color based amount of OBA's used in substrate. This difference may be observed more in highlight of yellow and pastel shades.
- The Shendye-Fleming universal density method can be used with M0, M1 and M2 measurements in 0/45 geometry spectrophotometer.
- Density calculated by Shendye-Fleming universal density equation can be used in Murray-Davies equation.
- Paper density must be calculated with the same filter bandwidth used for the measurement of density of solid colors.

- K/S plot of solid and tonal value can be used for determining absorption region of the spectrum of the color.
- No use of Saunderson's correction is recommended for reflectance data.
- Dot area calculated by Murray-Davies with density calculated by ISO status E and Shendye-Fleming provide close results for cyan, magenta, yellow and black.
- While calculating dot area, negative numbers can be found in Shendye-Fleming and ISO method when density of tone value is less than density of paper. This occurs only at very low tint values.
- Dot area calculated by SCTV method doesn't provide a close match with ISO status T and Shendye-Fleming method. SCTV works like Yule-Neilson equation.
- SCTV method does not provide density for process control, which is a vital one-dimensional scale used to determine ink transfer to the substrate.
- SCTV results doesn't provide a smooth curve even in Euclidean space. For the same data ISO Murray-Davies equation shows smooth tonal gradation curves.
- Shendye-Fleming correction to SCTV provides closer results to Murray-Davies equation than ISO 20654 equation.
- Cube root function in ISO 20654 causes discontinuities in second derivative offunction and it can be observed when it is compared to ISO 5 density in Murray-Davies equation.
- Difference between Shendye-Fleming SCTV and Murray-Davies equation depends upon color. Because ISO status E so doesn't consider effect of substrate on color, but Shendye-Fleming SCTV considers it as it considers whole spectrum.
- Shendye-Fleming method can't be used for fluorescent colors as its reflectance is more than substrate one. Conventional color reflects a maximum of 90% of an incident light of

the spectrum; but a fluorescent color can reflect up to 300%. This limitation must be considered in measurements.

6.2 Future work on Shendye-Fleming universal density equation

All of the areas of halftone printing were not evaluated. Some more areas are to be evaluated for implementation of the Shendye-Fleming universal density equation, and they are as follows:

- The Shendye-Fleming universal density equation should be tested for metallic inks, conventional inks printed on metallized foil and aluminum foil with measurements taken by d/8 geometry.
- Metallic inks may require calculation of Saunderson's correction.
- For transparent samples try generation for filter by Lambert-Beer law.

6.3 Conclusion Shendye-Fleming OBA index

Shendye-Fleming OBA Index was successfully implemented for evaluation of effect on OBA on blue tint of paper.

- The Shendye-Fleming OBA index can be calculated for any white paper with M1 and M2 measurement mode by 0/45 or 45/0 geometry spectrophotometer.
- The Shendye-Fleming OBA index calculates difference between M1 and M2 measurements from 410 nm to 550 nm.
- CIE whiteness has no relationship with Shendye-Fleming OBA index.
- Difference between CIE b* value between M1 and M2 measurements can be correlated with OBA index. Higher the difference higher the OBA index.
- The Shendye-Fleming OBA index and The Fleming-Aksoy whiteness formula can be used together for evaluating whiteness of paper.

- The Shendye-Fleming OBA index is compatible with ISO 3664 viewing condition as it uses D50 illuminant and M1 measurement conditions.
- The higher the amount of OBA index number, the higher the amount of OBA added in paper.

6.4 Future work on Shendye-Fleming OBA index

This research provides a basis for further research on the Shendye-Fleming OBA index. Further research will benefit the paper industry to standardize procedure for OBA index as a standard method.

- Obtain reflectance data of M1 and M2 from d/8 geometry spectrophotometer with mode specular included to calculate OBA index.
- Calculate Fleming-Aksoy whiteness and Shendye-Fleming OBA tint index with 0/45 geometry instrument and d/8 geometry instrument to determine optimum OBA levels to get higher amount of whiteness and savings on dosage of OBA added in paper.
- Conduct psychophysical test for OBA index under ISO 3664 viewing conditions.

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Appendix A

Images of 50 % tone value

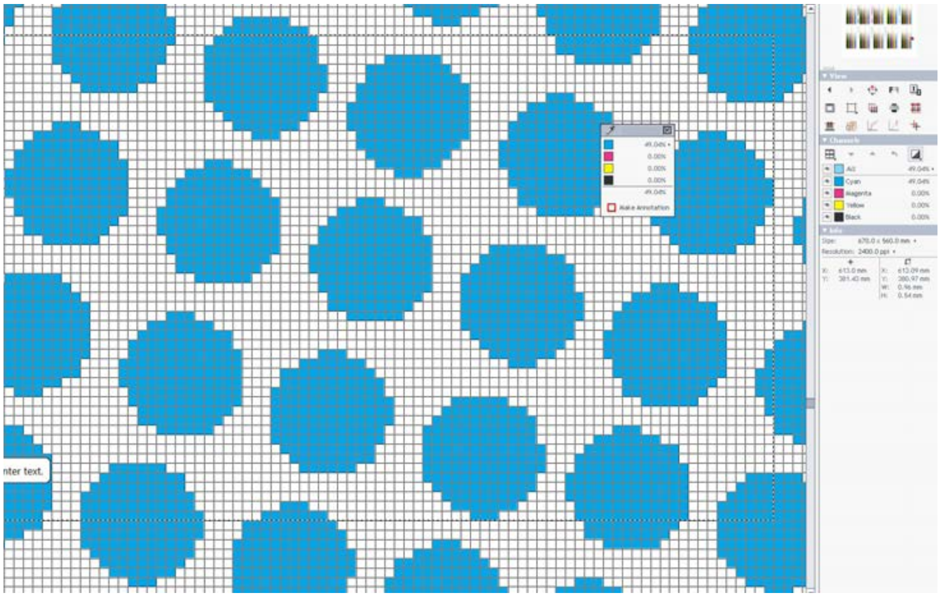


Figure A1: Cyan circular Euclidean RIP image.

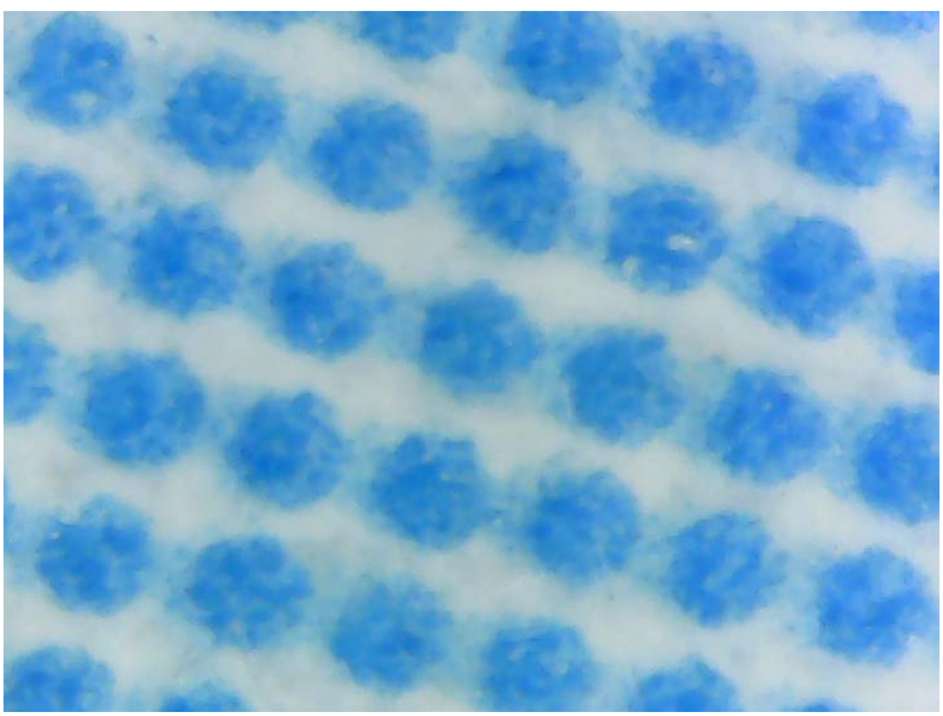


Figure A2: Cyan Circular Euclidean printed image.

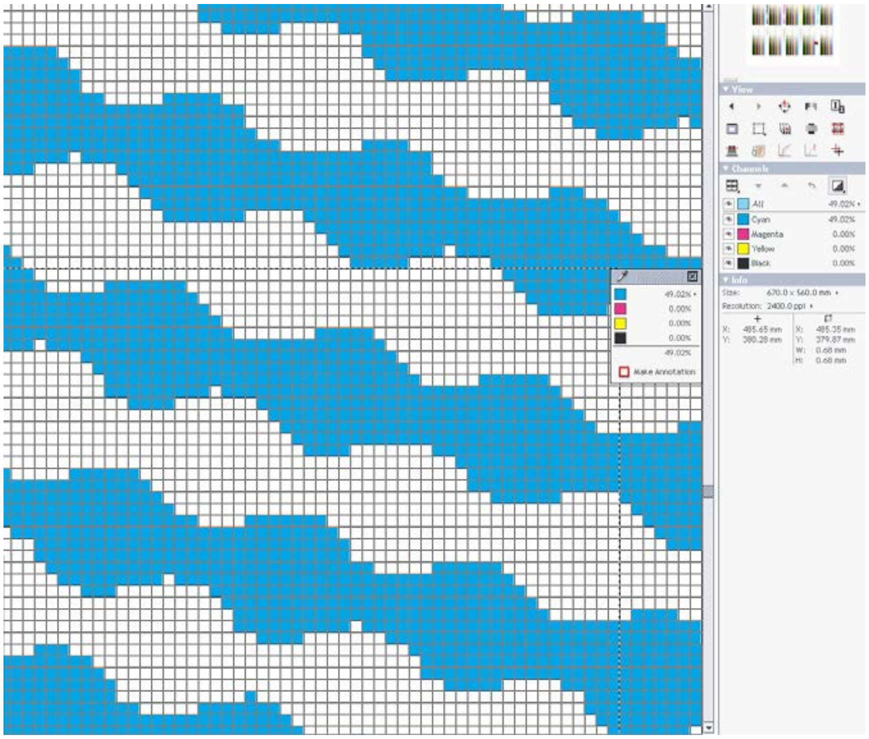


Figure A3: Cyan Elliptical dot.

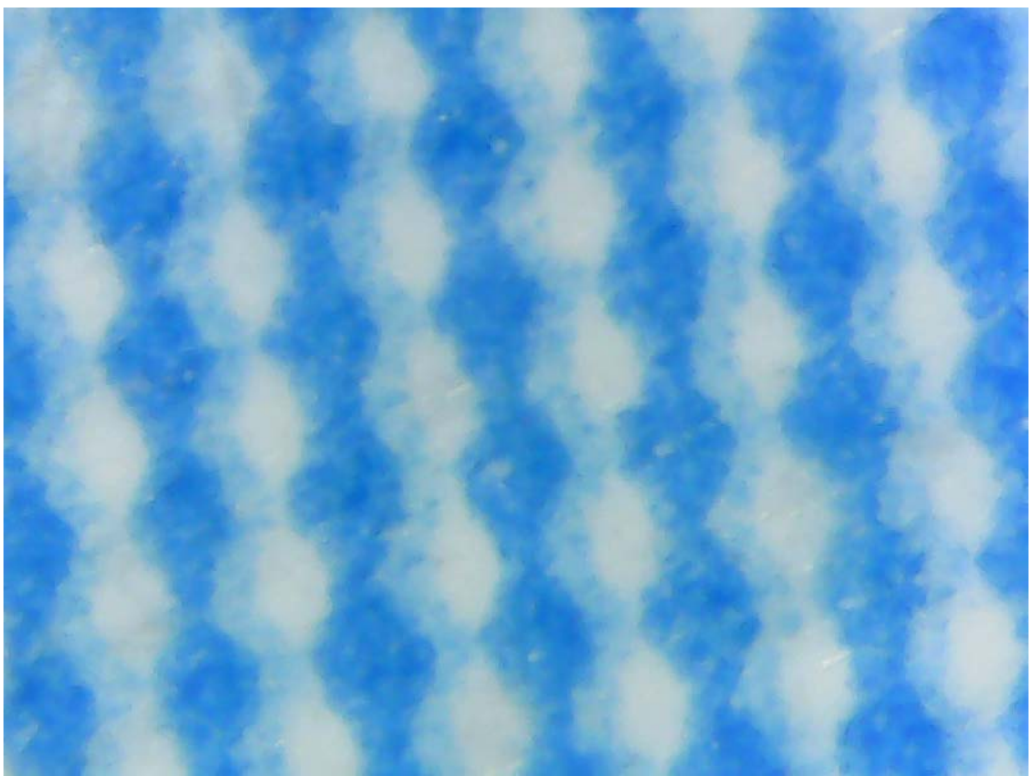


Figure A4: Cyan elliptical dot printed image.

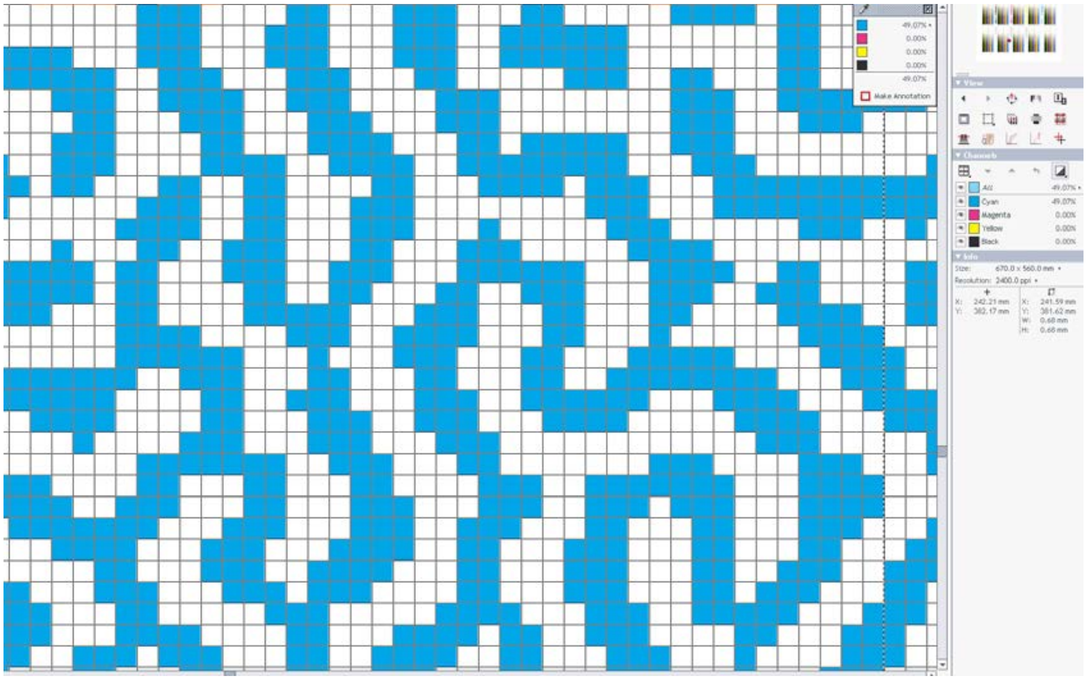


Figure A5: Cyan Organic Stochastic.

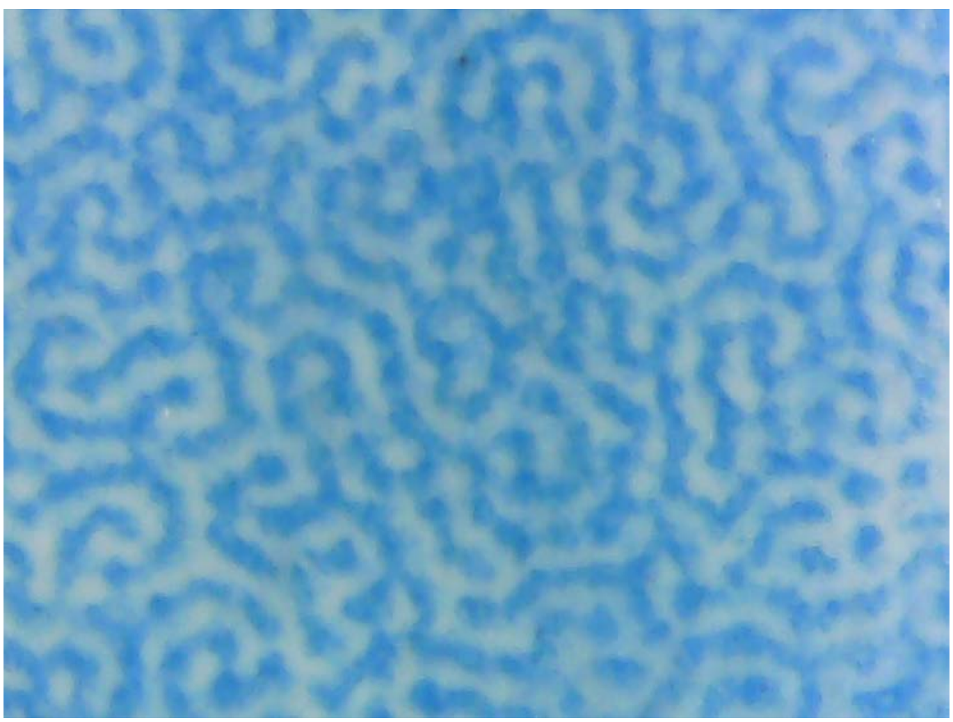


Figure A6: Organic stochastic dot printed image.

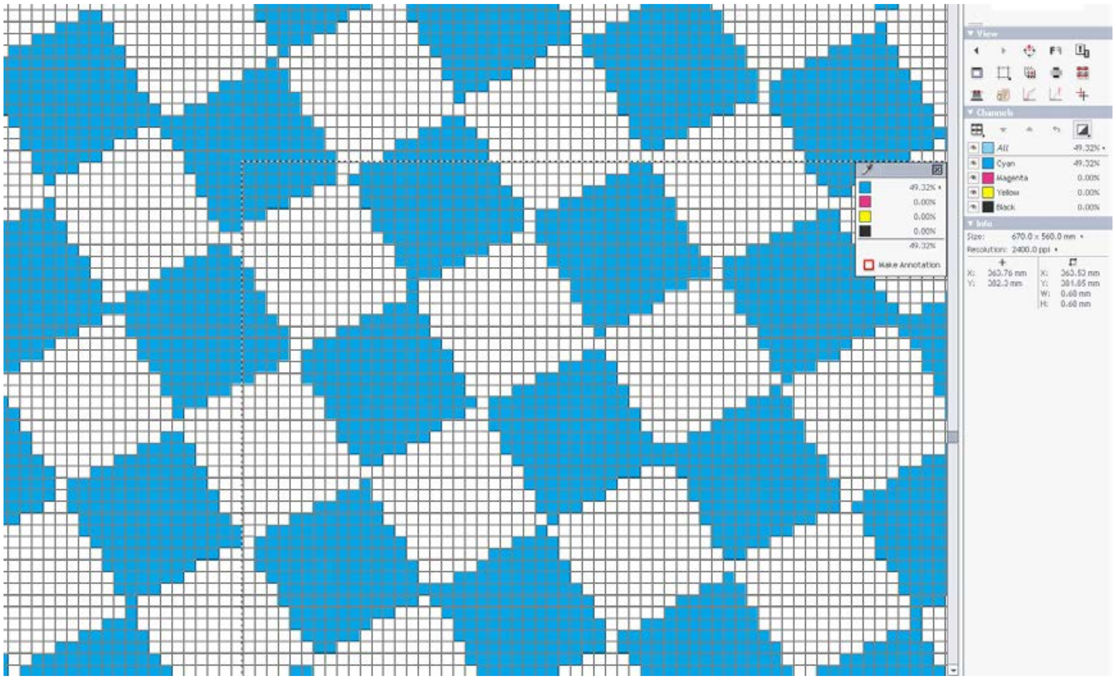


Figure A7: Cyan Square dot.

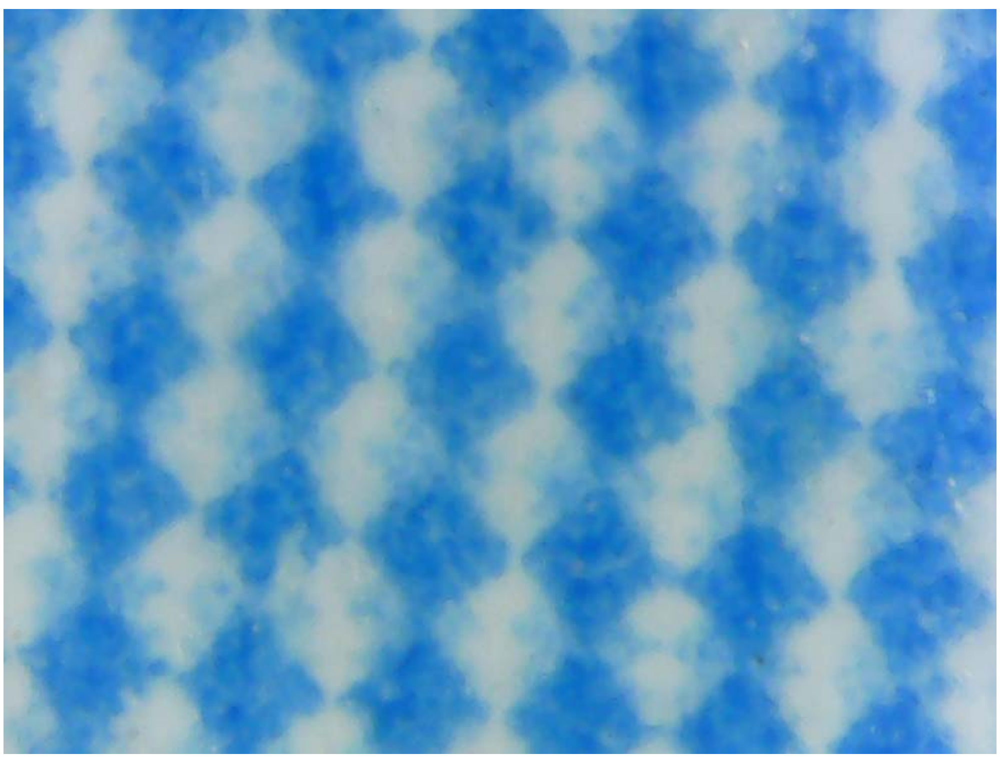


Figure A8: Cyan square dot printed image.

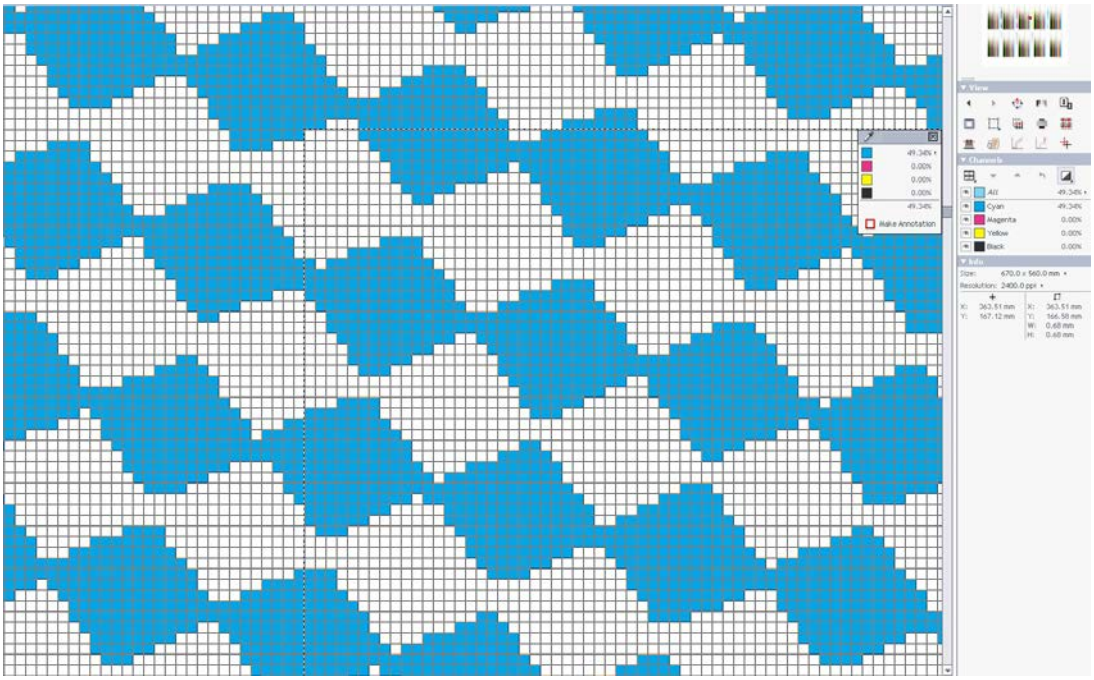


Figure A9: Cyan Round Fogra Dot.

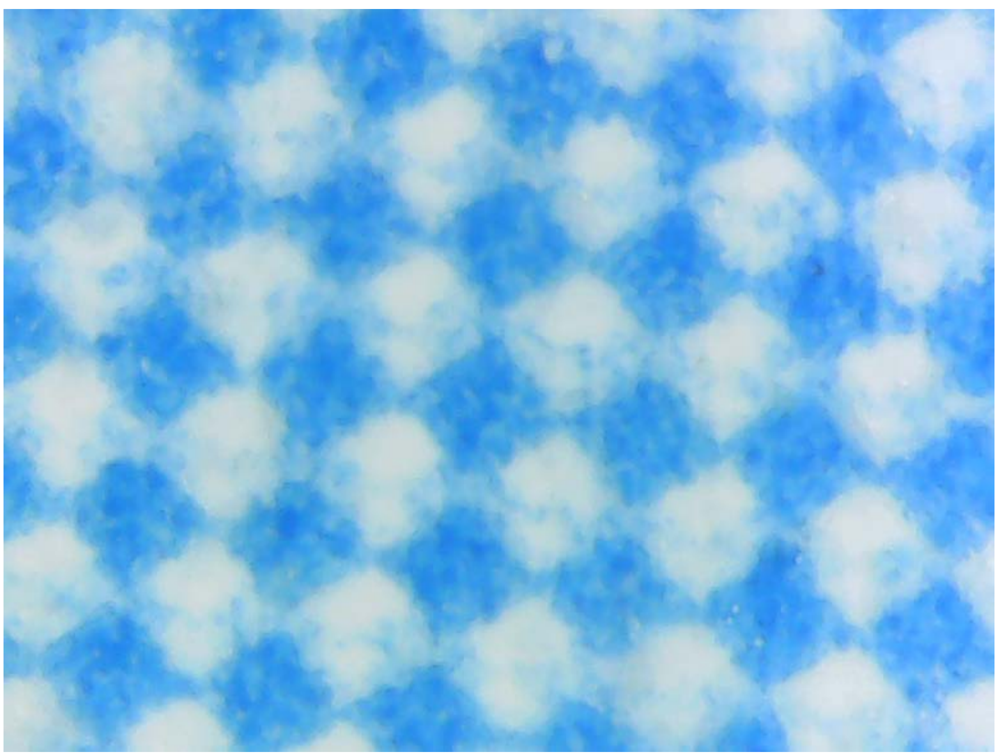


Figure A10: Cyan Fogra Round dot printed image.

Appendix B

Density and tone value of spot colors

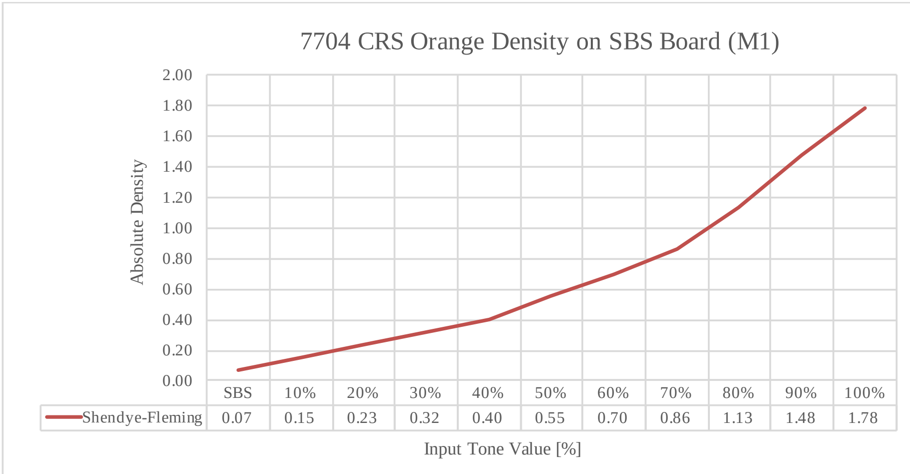


Figure B1: CRS Orange Density.

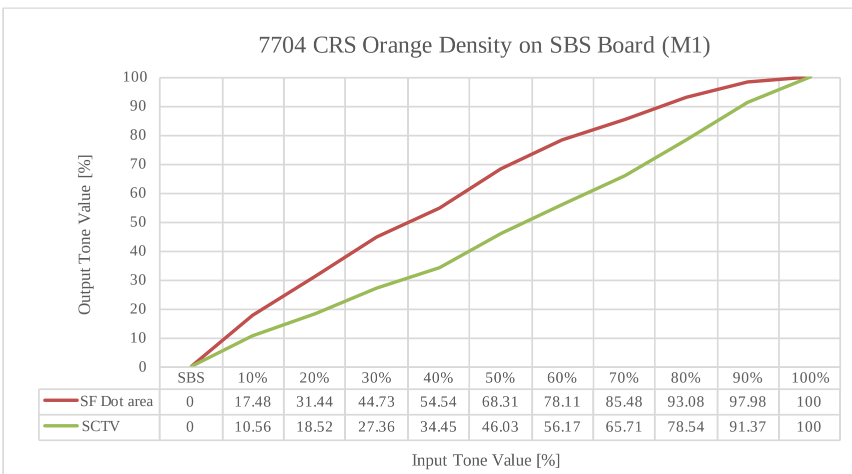
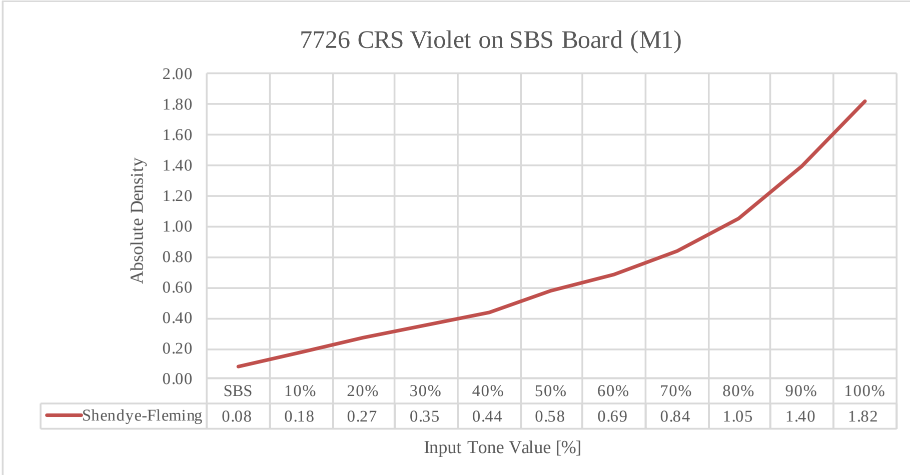
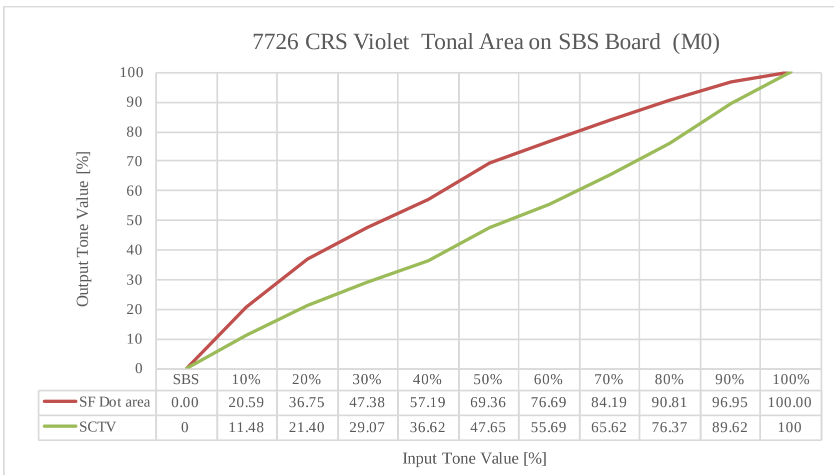


Figure B2: CRS Orange Tone values.



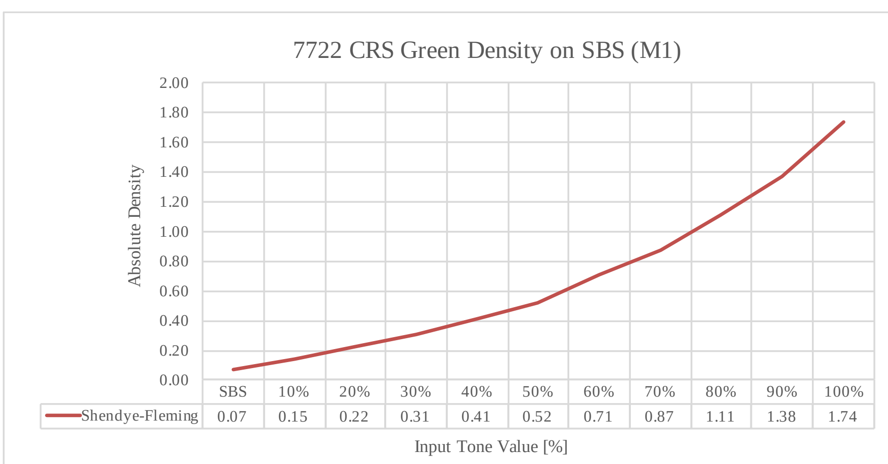
	SBS	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Shendye-Fleming	0.08	0.18	0.27	0.35	0.44	0.58	0.69	0.84	1.05	1.40	1.82

Figure B3: CRS Violet density values.



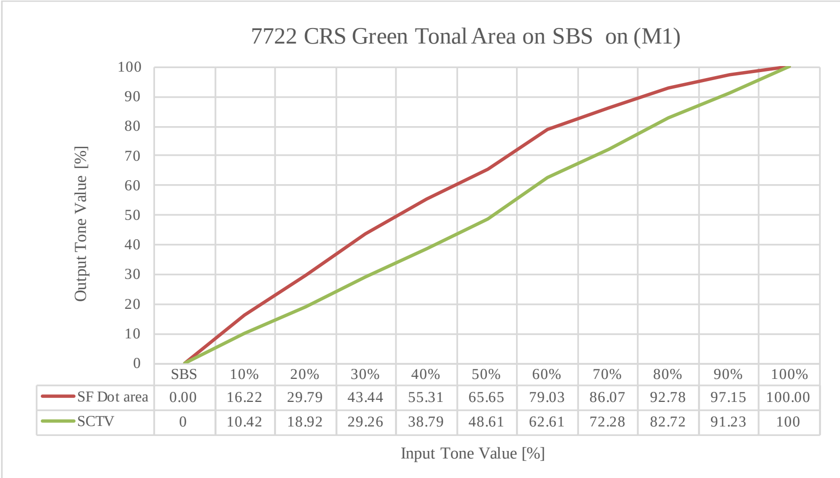
	SBS	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
SF Dot area	0.00	20.59	36.75	47.38	57.19	69.36	76.69	84.19	90.81	96.95	100.00
SCTV	0	11.48	21.40	29.07	36.62	47.65	55.69	65.62	76.37	89.62	100

Figure B4: CRS Violet Tone values.



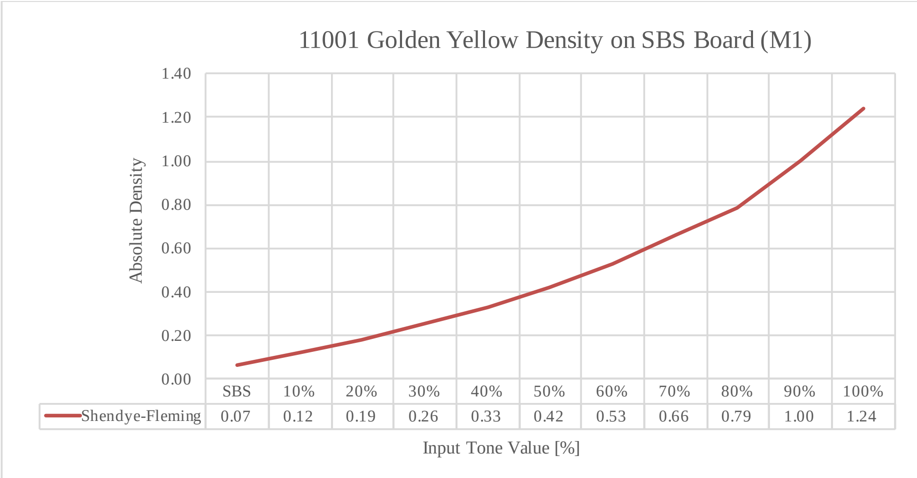
	SBS	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Shendye-Fleming	0.07	0.15	0.22	0.31	0.41	0.52	0.71	0.87	1.11	1.38	1.74

Figure B5: CRS Green density values.



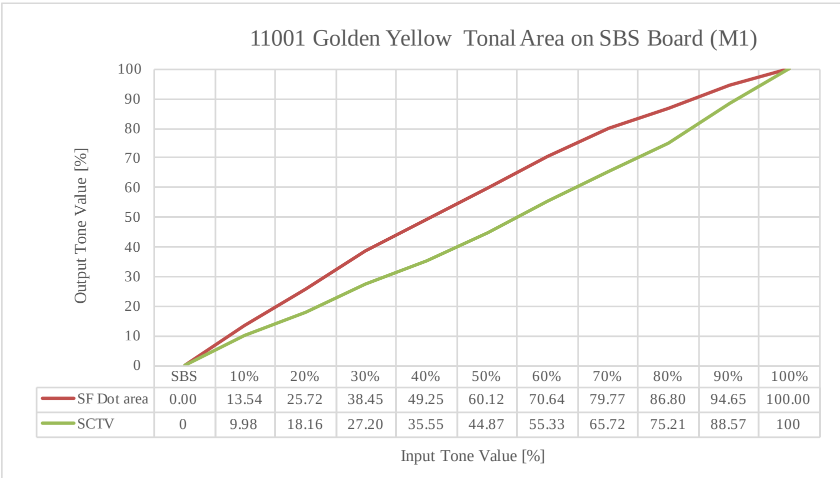
	SBS	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
SF Dot area	0.00	16.22	29.79	43.44	55.31	65.65	79.03	86.07	92.78	97.15	100.00
SCTV	0	10.42	18.92	29.26	38.79	48.61	62.61	72.28	82.72	91.23	100

Figure B6: CRS Green Tone values.



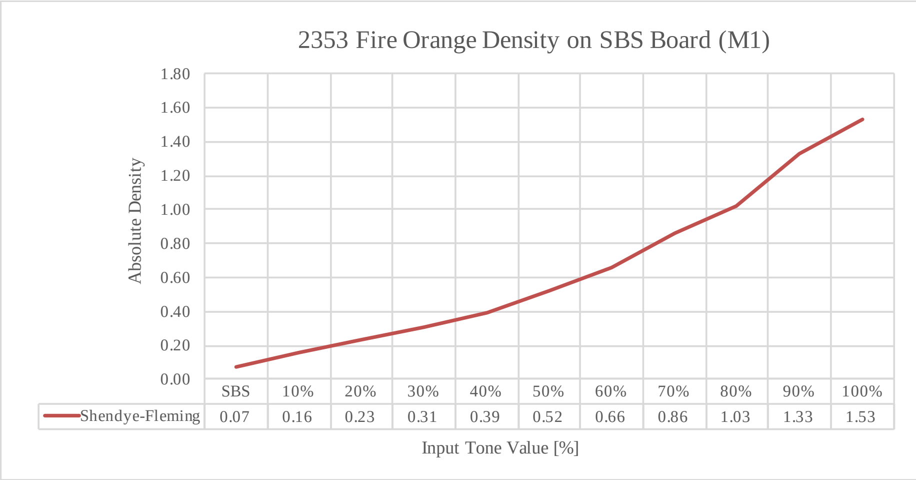
	SBS	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Shendye-Fleming	0.07	0.12	0.19	0.26	0.33	0.42	0.53	0.66	0.79	1.00	1.24

Figure B7: 11001 Golden Yellow density values.



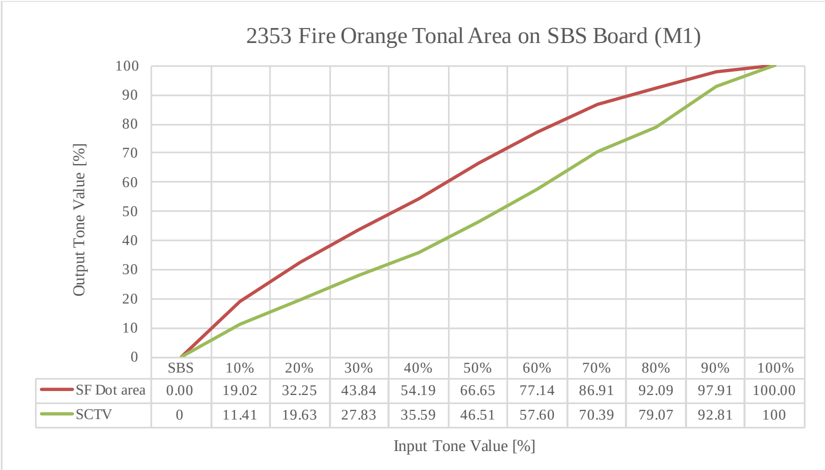
	SBS	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
SF Dot area	0.00	13.54	25.72	38.45	49.25	60.12	70.64	79.77	86.80	94.65	100.00
SCTV	0	9.98	18.16	27.20	35.55	44.87	55.33	65.72	75.21	88.57	100

Figure B8: 11001 Golden Yellow Tone values.



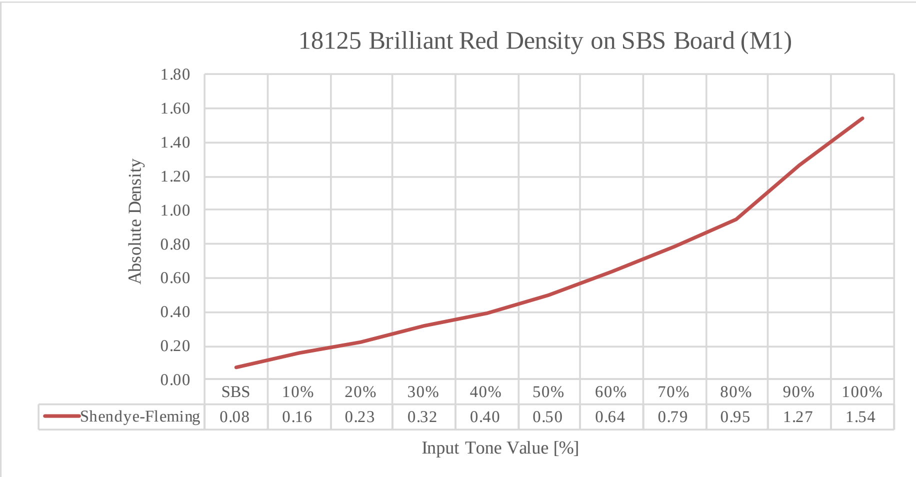
	SBS	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Shendye-Fleming	0.07	0.16	0.23	0.31	0.39	0.52	0.66	0.86	1.03	1.33	1.53

Figure B9: Fire Orange density values.



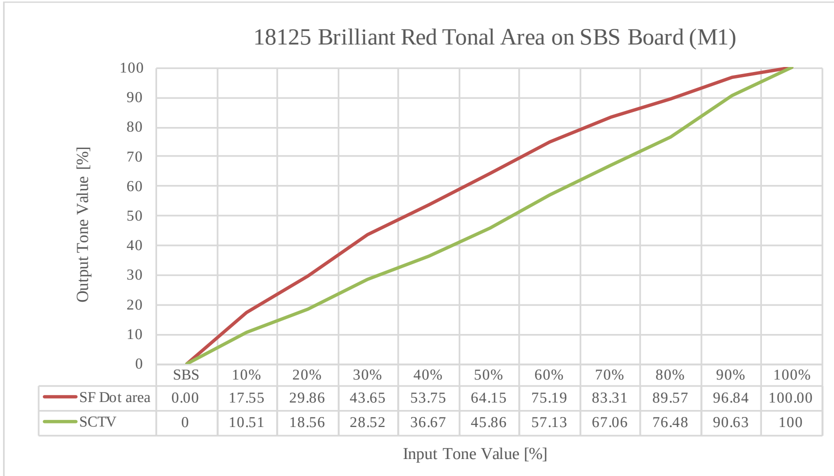
	SBS	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
SF Dot area	0.00	19.02	32.25	43.84	54.19	66.65	77.14	86.91	92.09	97.91	100.00
SCTV	0	11.41	19.63	27.83	35.59	46.51	57.60	70.39	79.07	92.81	100

Figure B10: Fire Orange Tone values.



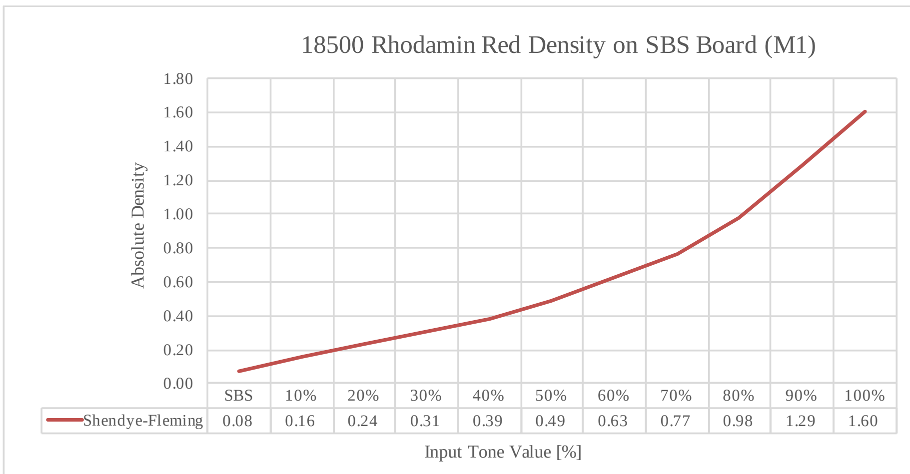
	SBS	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Shendye-Fleming	0.08	0.16	0.23	0.32	0.40	0.50	0.64	0.79	0.95	1.27	1.54

Figure B11: 18125 Brilliant Red density values.



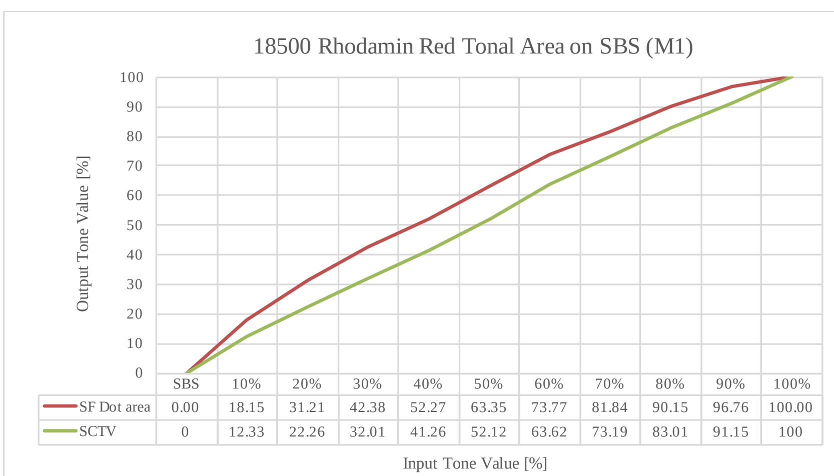
	SBS	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
SF Dot area	0.00	17.55	29.86	43.65	53.75	64.15	75.19	83.31	89.57	96.84	100.00
SCTV	0	10.51	18.56	28.52	36.67	45.86	57.13	67.06	76.48	90.63	100

Figure B12: 18125 Brilliant Red Tonal values.



	SBS	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
Shendye-Fleming	0.08	0.16	0.24	0.31	0.39	0.49	0.63	0.77	0.98	1.29	1.60

Figure B13: 18500 Rhodamine Red density values.



	SBS	10%	20%	30%	40%	50%	60%	70%	80%	90%	100%
SF Dot area	0.00	18.15	31.21	42.38	52.27	63.35	73.77	81.84	90.15	96.76	100.00
SCTV	0	12.33	22.26	32.01	41.26	52.12	63.62	73.19	83.01	91.15	100

Figure B14: 18500 Rhodamine Red Tone values.

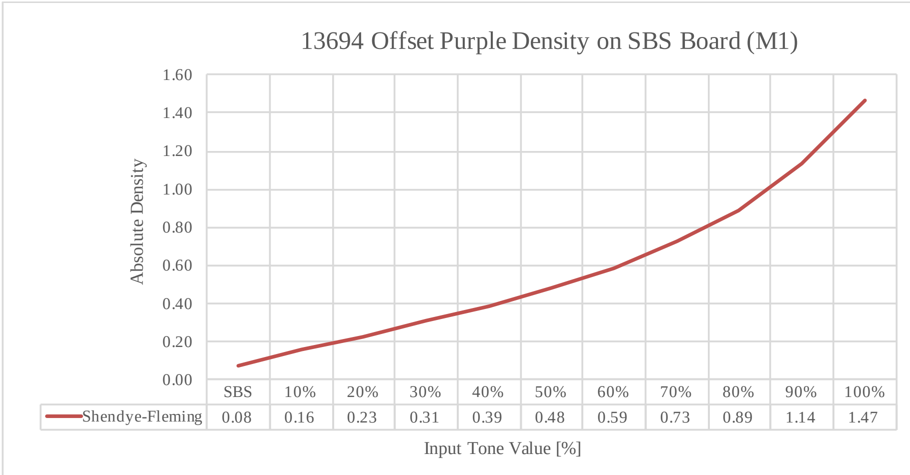


Figure B15: 13694 Offset Purple density values.

Appendix C

Density and tone value graph by auto filters

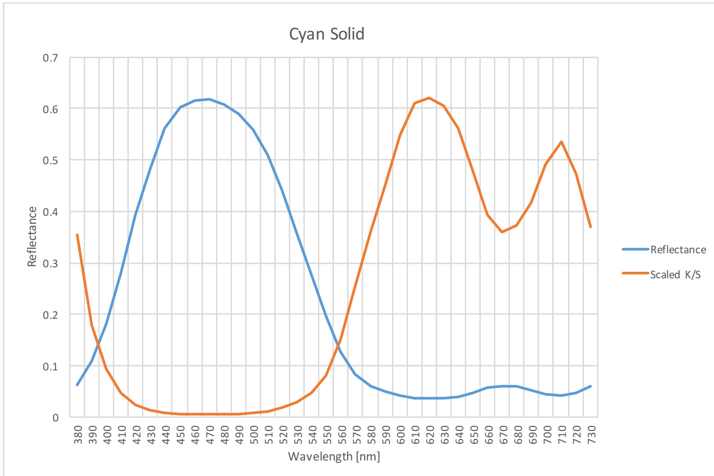
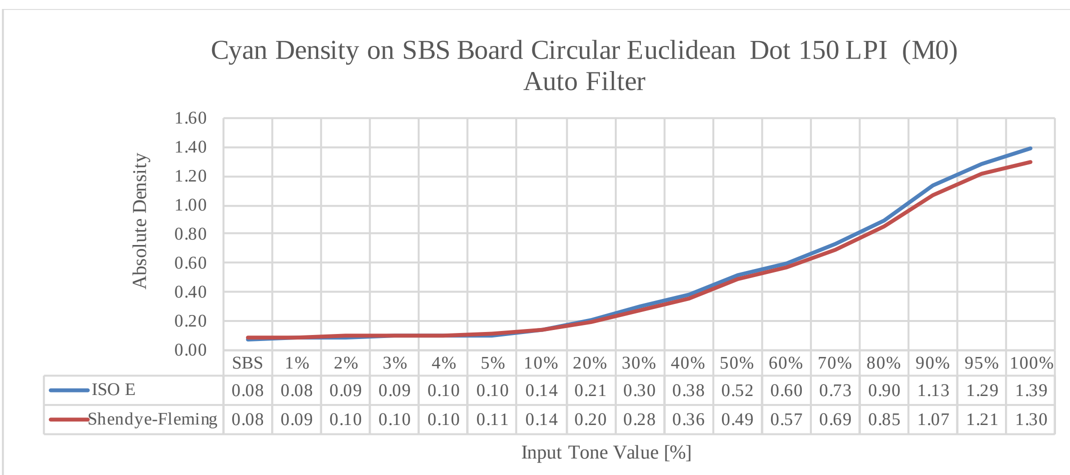
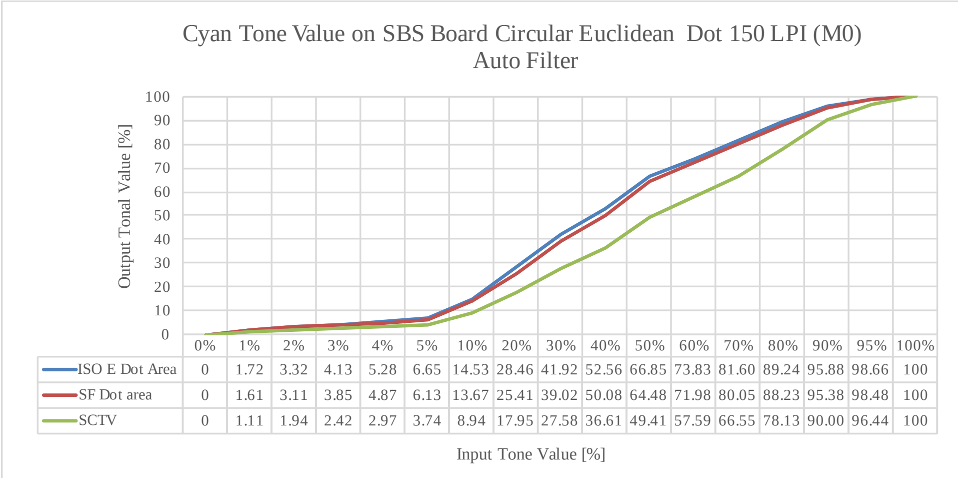


Figure C1: Auto bandwidth method for cyan.



	SBS	1%	2%	3%	4%	5%	10%	20%	30%	40%	50%	60%	70%	80%	90%	95%	100%
ISO E	0.08	0.08	0.09	0.09	0.10	0.10	0.14	0.21	0.30	0.38	0.52	0.60	0.73	0.90	1.13	1.29	1.39
Shendye-Fleming	0.08	0.09	0.10	0.10	0.10	0.11	0.14	0.20	0.28	0.36	0.49	0.57	0.69	0.85	1.07	1.21	1.30

Figure C2: Cyan density values using auto bandwidth method.



	0%	1%	2%	3%	4%	5%	10%	20%	30%	40%	50%	60%	70%	80%	90%	95%	100%
ISO E Dot Area	0	1.72	3.32	4.13	5.28	6.65	14.53	28.46	41.92	52.56	66.85	73.83	81.60	89.24	95.88	98.66	100
SF Dot area	0	1.61	3.11	3.85	4.87	6.13	13.67	25.41	39.02	50.08	64.48	71.98	80.05	88.23	95.38	98.48	100
SCTV	0	1.11	1.94	2.42	2.97	3.74	8.94	17.95	27.58	36.61	49.41	57.59	66.55	78.13	90.00	96.44	100

Figure C3: Auto filter for cyan tonal values of circular Euclidean dot.

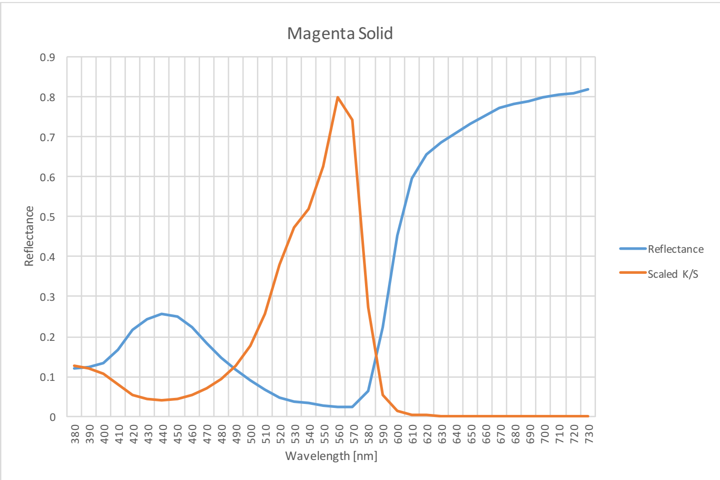
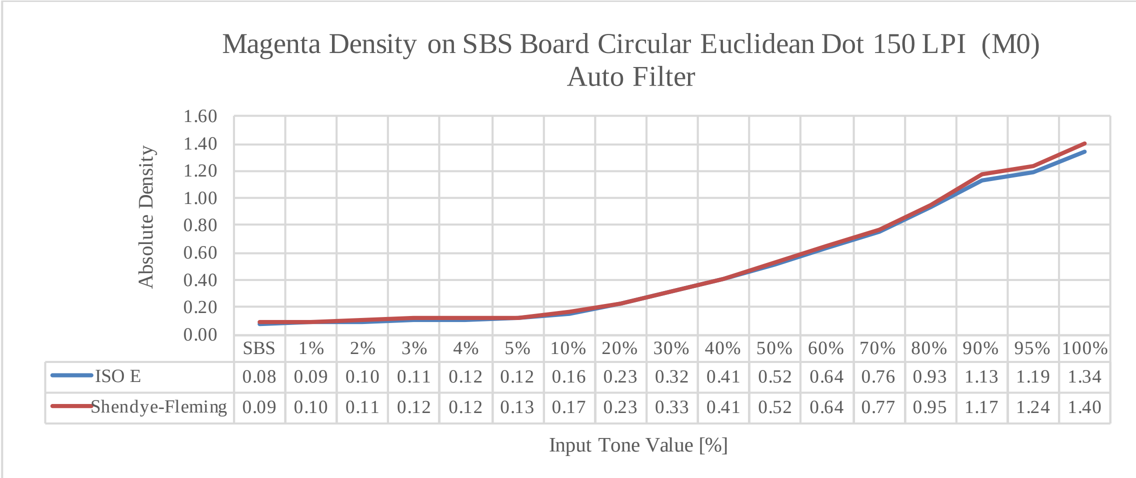
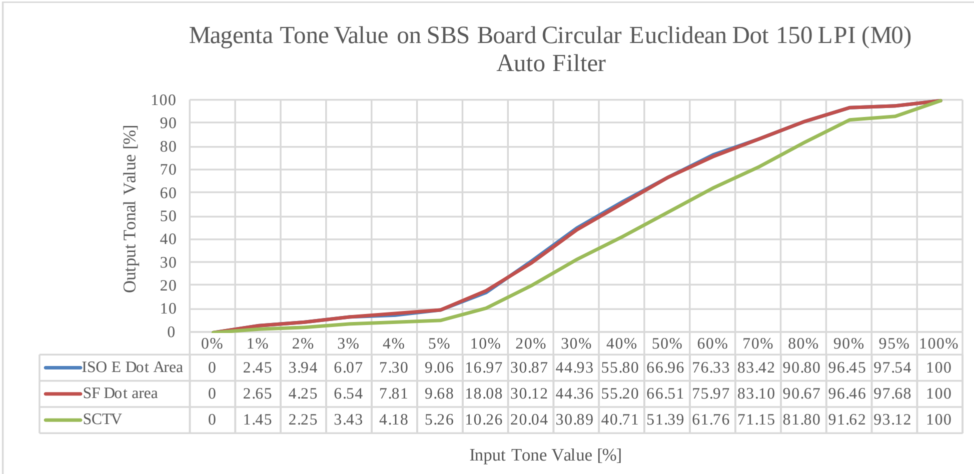


Figure C4: Auto filter calculation for magenta circular Euclidean dot.



	SBS	1%	2%	3%	4%	5%	10%	20%	30%	40%	50%	60%	70%	80%	90%	95%	100%
ISO E	0.08	0.09	0.10	0.11	0.12	0.12	0.16	0.23	0.32	0.41	0.52	0.64	0.76	0.93	1.13	1.19	1.34
Shendye-Fleming	0.09	0.10	0.11	0.12	0.12	0.13	0.17	0.23	0.33	0.41	0.52	0.64	0.77	0.95	1.17	1.24	1.40

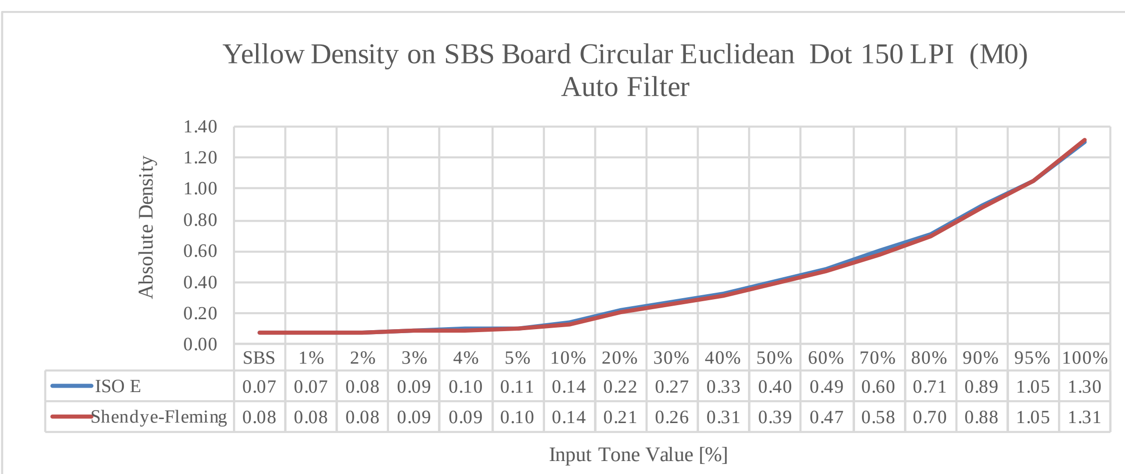
Figure C5: Magenta density values using auto bandwidth method.



	0%	1%	2%	3%	4%	5%	10%	20%	30%	40%	50%	60%	70%	80%	90%	95%	100%
ISO E Dot Area	0	2.45	3.94	6.07	7.30	9.06	16.97	30.87	44.93	55.80	66.96	76.33	83.42	90.80	96.45	97.54	100
SF Dot area	0	2.65	4.25	6.54	7.81	9.68	18.08	30.12	44.36	55.20	66.51	75.97	83.10	90.67	96.46	97.68	100
SCTV	0	1.45	2.25	3.43	4.18	5.26	10.26	20.04	30.89	40.71	51.39	61.76	71.15	81.80	91.62	93.12	100

Figure C6: Auto filter for magenta tonal values circular Euclidean d.ot

Figure C7: Auto filter calculation for yellow circular Euclidean dot.



	SBS	1%	2%	3%	4%	5%	10%	20%	30%	40%	50%	60%	70%	80%	90%	95%	100%
ISO E	0.07	0.07	0.08	0.09	0.10	0.11	0.14	0.22	0.27	0.33	0.40	0.49	0.60	0.71	0.89	1.05	1.30
Shendye-Fleming	0.08	0.08	0.08	0.09	0.09	0.10	0.14	0.21	0.26	0.31	0.39	0.47	0.58	0.70	0.88	1.05	1.31

Figure C8: Yellow density values using auto bandwidth method.

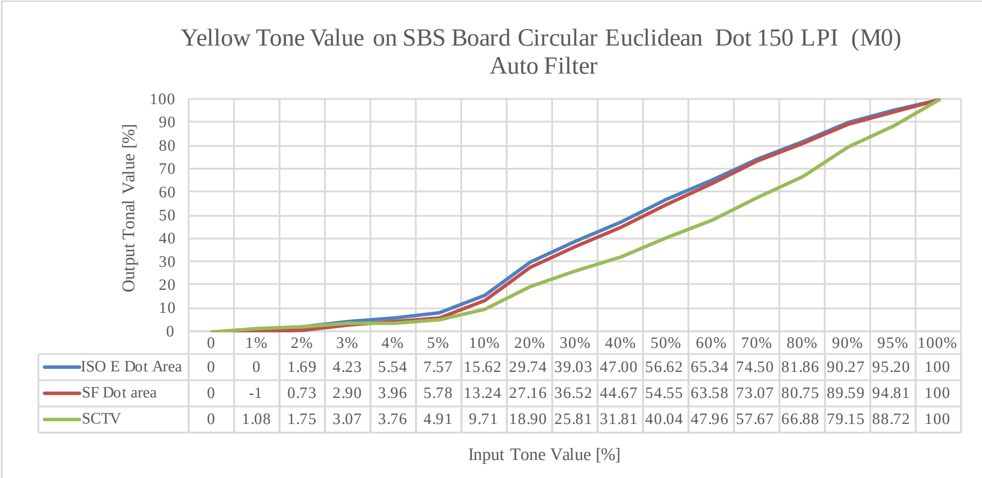


Figure C9: Auto filter for yellow tonal values circular Euclidean dot.

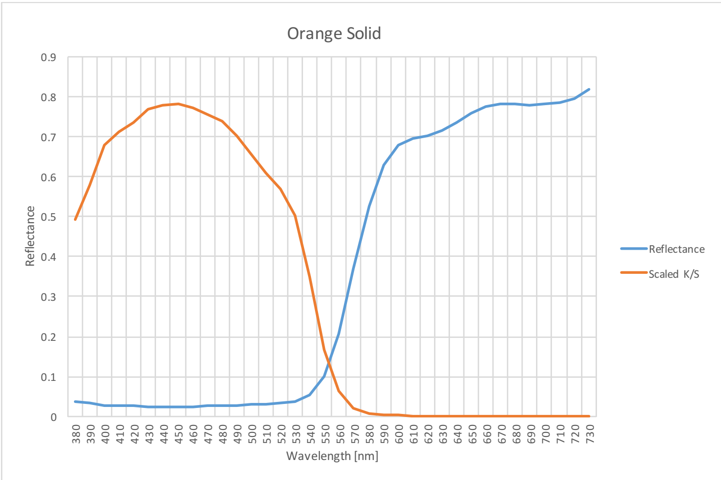


Figure C10: Auto filter calculation for orange circular Euclidean dot.

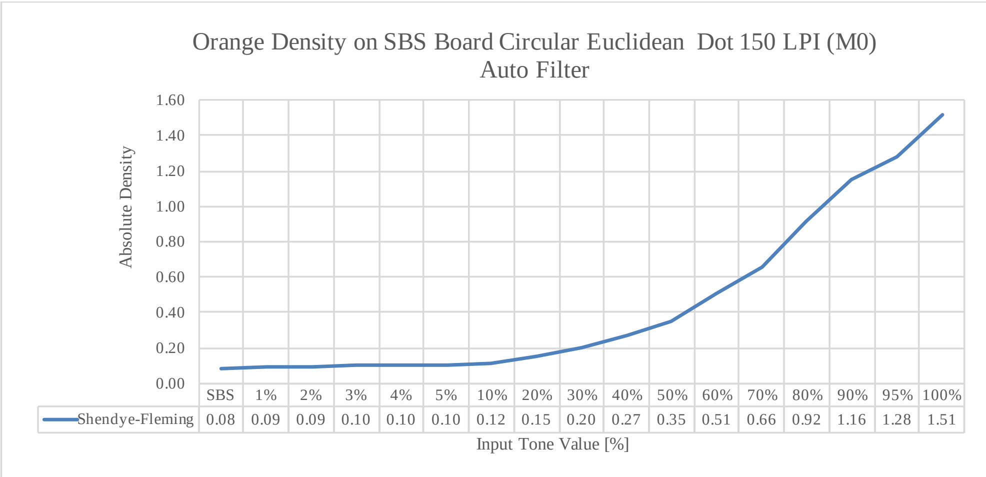


Figure 11: Orange density values using auto bandwidth method.

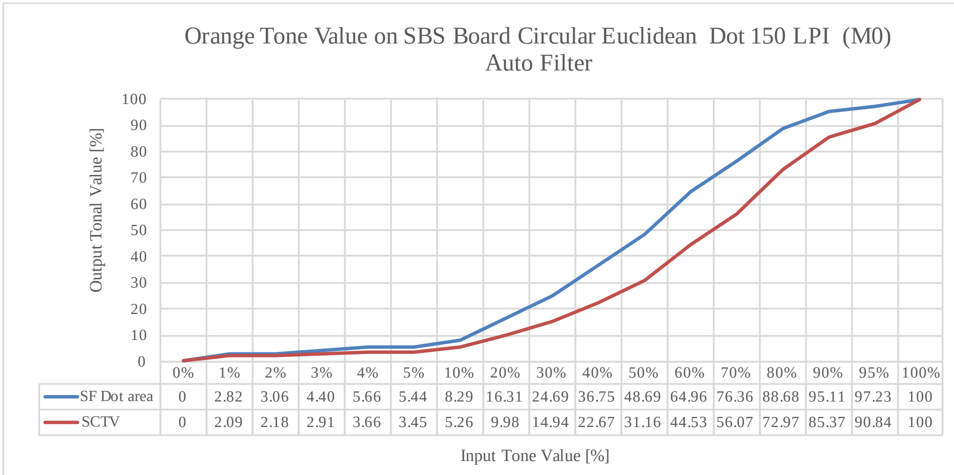


Figure 12: Auto filter for orange tonal values circular Euclidean dot.

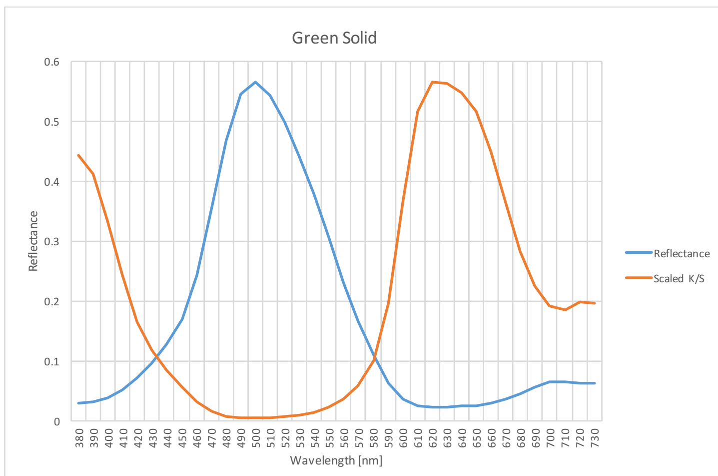


Figure C13: Auto filter calculation for green circular Euclidean dot.

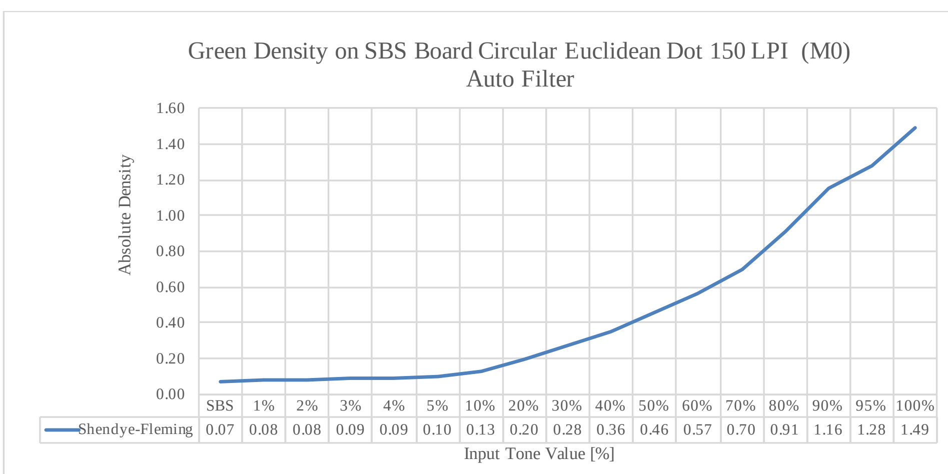


Figure C14: Green density values using auto bandwidth method.

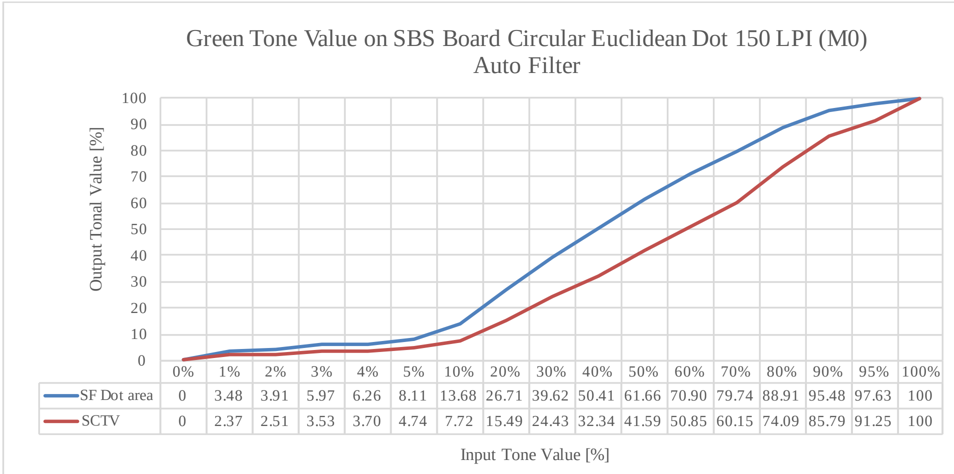


Figure C15: Auto filter for green tonal values for circular Euclidean dot.

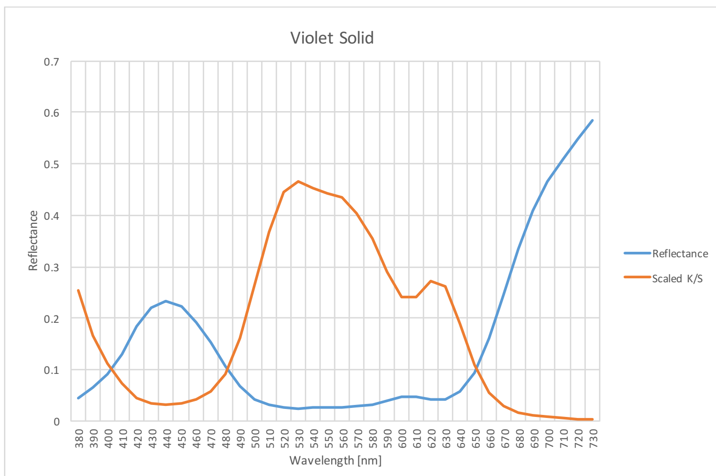


Figure C16: Auto filter calculation for violet circular Euclidean dot.

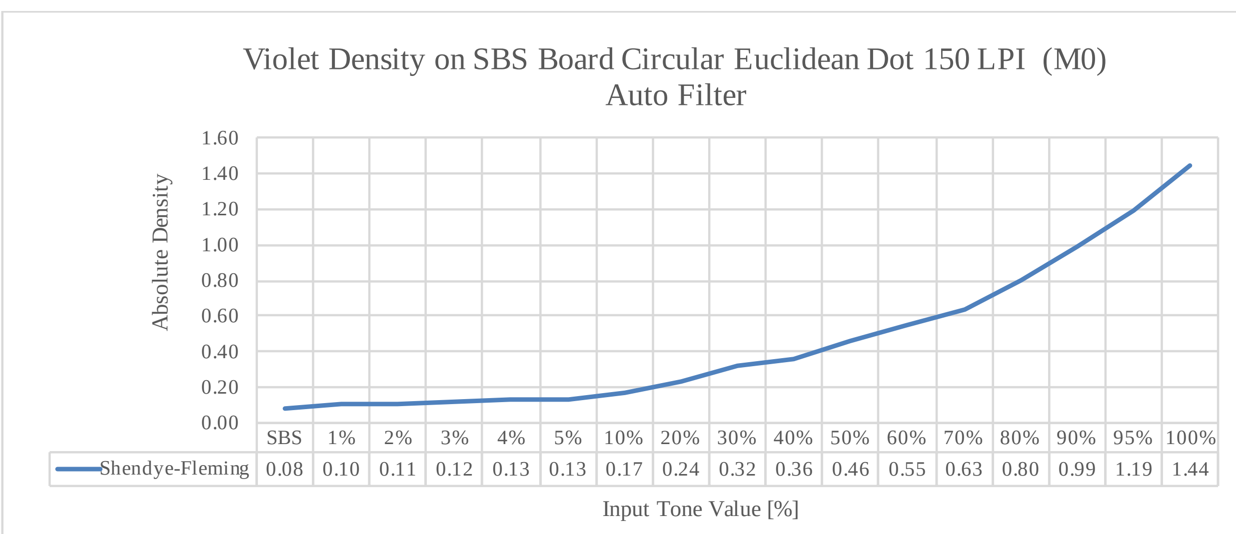
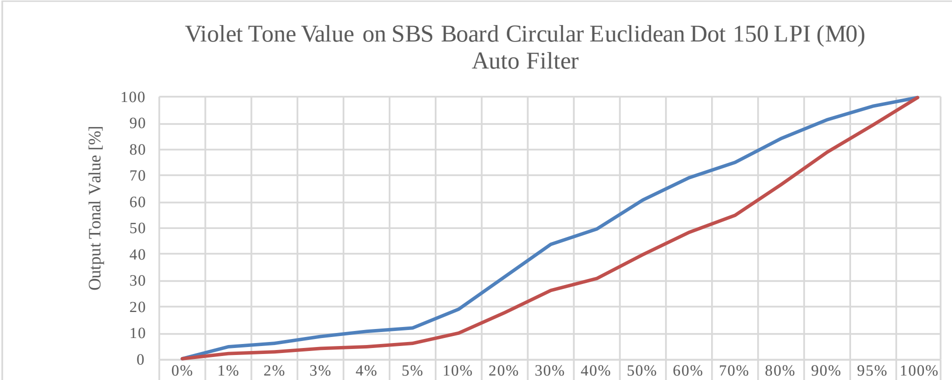


Figure C17 Violet density values using auto bandwidth method.



	0%	1%	2%	3%	4%	5%	10%	20%	30%	40%	50%	60%	70%	80%	90%	95%	100%
SF Dot area	0	4.88	6.24	8.98	10.42	11.97	19.08	31.36	43.78	49.55	60.92	69.25	75.12	84.44	91.57	96.41	100
SCTV	0	2.21	2.91	4.29	5.10	5.92	10.01	17.66	26.07	30.71	40.27	48.15	54.74	66.85	78.84	89.36	100

Input Tone Value [%]

Figure C18: Auto filter for violet tonal values for circular Euclidean dot.

Appendix D

ISO filter data

Table D1: ISO 5-3 status E filter data.

Wavelength nm	ISO visual	Status E Blue	Status E Green	Status E Red
340	0	0	0	0
350	0	0	0	0
360	0	-0.0003	0	0
370	0.0001	-0.0028	0	0
380	0.0002	0.0388	0	0
390	0.0004	0.5362	0	0
400	0.0009	2.4215	0	0
410	0.0019	5.837	0	0
420	0.0078	11.1997	0	0
430	0.0265	15.7929	0	0
440	0.061	18.7024	0	0
450	0.1165	17.4636	0	0
460	0.2091	14.3432	-0.0013	0
470	0.3618	8.8859	-0.0095	0
480	0.6195	3.5169	0.1724	0
490	1.0386	1.1061	0.964	0
500	1.7923	0.1589	5.4663	0
510	3.0873	-0.0013	12.8802	0
520	4.7537	0.0008	17.5928	0
530	6.3209	0.0004	18.9941	0
540	7.5982	0.0001	16.7862	0.0001
550	8.569	0	12.5972	0.0004
560	9.2196	0	8.0105	0.0027
570	9.4564	0	4.2078	-0.0419
580	9.2194	0	1.7152	-0.3728
590	8.5471	0	0.4815	11.4921
600	7.5447	0	0.1252	30.713
610	6.3584	0	0.0163	27.2826
620	5.0773	0	0.0009	17.3613
630	3.7164	0	0.0001	8.0369
640	2.5589	0	0	3.1981
650	1.6395	0	0	1.5211
660	0.9723	0	0	0.4947
670	0.5336	0	0	0.1529
680	0.2898	0	0	0.0911
690	0.1466	0	0	0.0479
700	0.0748	0	0	0.016
710	0.0395	0	0	0.0031
720	0.0204	0	0	0.0005
730	0.0103	0	0	0.0001
740	0.0051	0	0	0
750	0.0025	0	0	0
760	0.0015	0	0	0
770	0.0004	0	0	0
Sum	100	100	100	100

Appendix E

Reflectance data

Table E1: Cyan tonal gradation data of circular Euclidean 150 LPI on SBS.

	SBS	1%	2%	3%	4%	5%	10%	20%	30%	40%	50%	60%	70%	80%	90%	95%	100%
380	0.33083	0.290859	0.290311	0.285406	0.296459	0.285709	0.260119	0.246227	0.228872	0.201471	0.174653	0.146564	0.136256	0.107428	0.0848303	0.0694556	0.0618196
390	0.374241	0.340265	0.338633	0.331696	0.342821	0.336501	0.309537	0.296394	0.278669	0.254571	0.226111	0.200253	0.187526	0.160047	0.133354	0.120788	0.110221
400	0.434112	0.413405	0.410456	0.406736	0.415012	0.412091	0.380559	0.365448	0.346889	0.330742	0.297431	0.273452	0.260776	0.233515	0.204273	0.191148	0.180829
410	0.576343	0.577209	0.570824	0.571112	0.571571	0.573644	0.53571	0.510068	0.482168	0.466912	0.422696	0.395353	0.375005	0.344526	0.307622	0.291465	0.278953
420	0.771437	0.789015	0.780198	0.780523	0.777665	0.779519	0.740127	0.70287	0.663491	0.631716	0.580868	0.544636	0.515078	0.472197	0.428395	0.405209	0.392335
430	0.87098	0.891979	0.884402	0.880005	0.881179	0.878937	0.842016	0.805582	0.767075	0.725236	0.677897	0.639564	0.611352	0.562328	0.519224	0.494578	0.481861
440	0.900561	0.918296	0.911485	0.906861	0.909384	0.906379	0.87417	0.844029	0.811932	0.772445	0.73257	0.698669	0.674799	0.63095	0.592353	0.57128	0.559699
450	0.899767	0.912998	0.906198	0.902941	0.904636	0.902904	0.875124	0.849649	0.82191	0.788006	0.753472	0.724156	0.703256	0.665277	0.63126	0.612292	0.602015
460	0.890756	0.89834	0.892204	0.889444	0.890386	0.889538	0.864712	0.841845	0.816773	0.787233	0.75546	0.728371	0.70912	0.674925	0.642597	0.624488	0.614299
470	0.884742	0.887845	0.882494	0.879771	0.880884	0.879974	0.856852	0.83549	0.811839	0.784219	0.753822	0.727597	0.709431	0.676466	0.645163	0.627755	0.617309
480	0.876751	0.876501	0.871411	0.868892	0.870026	0.86893	0.84681	0.825795	0.802309	0.775574	0.745281	0.719358	0.700815	0.668297	0.636765	0.618641	0.60793
490	0.866588	0.863521	0.858624	0.856173	0.856933	0.856045	0.834263	0.812748	0.788674	0.761633	0.730833	0.704602	0.685408	0.652131	0.619492	0.600466	0.588891
500	0.855435	0.849854	0.844877	0.842405	0.84308	0.84167	0.819825	0.796682	0.771346	0.74273	0.709872	0.68225	0.661836	0.626358	0.591738	0.571142	0.558967
510	0.842517	0.835541	0.83005	0.827633	0.828173	0.826075	0.802764	0.776117	0.747255	0.715294	0.678097	0.647428	0.624468	0.58467	0.546665	0.523975	0.510287
520	0.826871	0.818016	0.812279	0.809422	0.809699	0.806564	0.780531	0.747513	0.712721	0.674548	0.631142	0.595558	0.568254	0.522626	0.479538	0.453808	0.438718
530	0.815425	0.805573	0.799527	0.795746	0.795528	0.791337	0.761115	0.718726	0.675254	0.629757	0.576669	0.535411	0.501743	0.449693	0.400816	0.372432	0.356099
540	0.816697	0.806717	0.799578	0.795898	0.793976	0.789005	0.753215	0.698864	0.643614	0.58993	0.524587	0.477686	0.436081	0.377787	0.32342	0.292825	0.27593
550	0.818493	0.808436	0.79988	0.796019	0.792231	0.78638	0.744323	0.676452	0.608291	0.545487	0.467419	0.415558	0.366224	0.303202	0.24525	0.21367	0.196929
560	0.812124	0.801143	0.791416	0.786845	0.781601	0.77426	0.72631	0.645819	0.565948	0.49522	0.406095	0.351215	0.29636	0.231434	0.172861	0.14269	0.126921
570	0.812937	0.801437	0.790488	0.785332	0.778857	0.770169	0.717103	0.62586	0.536518	0.460038	0.361539	0.305637	0.247267	0.18236	0.124719	0.0970298	0.0827762
580	0.819889	0.807476	0.795926	0.790436	0.782785	0.773324	0.716523	0.617594	0.520963	0.440973	0.335606	0.279644	0.219319	0.155563	0.0993245	0.0737153	0.0608824
590	0.831127	0.818026	0.805972	0.799988	0.791516	0.781555	0.721806	0.61669	0.514433	0.431756	0.321436	0.265422	0.203795	0.141039	0.0859611	0.0617375	0.0498499
600	0.837244	0.823545	0.810908	0.804516	0.795537	0.78496	0.722821	0.612932	0.50662	0.422383	0.308652	0.25311	0.19086	0.129396	0.0757041	0.0530046	0.0419018
610	0.837201	0.823473	0.810545	0.803925	0.794716	0.7836	0.720115	0.607966	0.499687	0.414773	0.299571	0.244436	0.182385	0.122083	0.0697745	0.0481186	0.037872
620	0.836873	0.822935	0.810095	0.803453	0.794058	0.782774	0.719039	0.606093	0.497459	0.412201	0.297063	0.241959	0.180205	0.120468	0.0685993	0.047368	0.0373681
630	0.844769	0.830601	0.817455	0.810947	0.801412	0.789713	0.725231	0.611104	0.501241	0.414545	0.300222	0.243708	0.181781	0.121559	0.0695544	0.0482782	0.0381809
640	0.861297	0.847454	0.834244	0.827696	0.817583	0.805771	0.740235	0.623837	0.511985	0.423337	0.309212	0.250198	0.187786	0.126054	0.0734061	0.0514452	0.0409588
650	0.878287	0.864685	0.852009	0.845146	0.835028	0.822982	0.757702	0.640504	0.527882	0.438004	0.323992	0.262979	0.200058	0.136316	0.0820129	0.0585554	0.0474555
660	0.889346	0.876386	0.864048	0.857679	0.84765	0.835745	0.771727	0.655442	0.543808	0.453362	0.340363	0.278884	0.21524	0.149738	0.0936489	0.0686683	0.0565562
670	0.894582	0.882162	0.869942	0.86339	0.853486	0.841601	0.778248	0.662536	0.551209	0.460841	0.347639	0.286583	0.222576	0.156502	0.0996063	0.0737859	0.0612466
680	0.893603	0.880901	0.868613	0.861704	0.852062	0.839846	0.775798	0.659356	0.54786	0.457181	0.343742	0.282911	0.219068	0.153352	0.0969813	0.0716514	0.0592996
690	0.892422	0.879493	0.86722	0.860001	0.850388	0.837271	0.77211	0.653542	0.540152	0.448453	0.335002	0.273779	0.209784	0.145036	0.0896413	0.0654788	0.0537
700	0.895739	0.882848	0.870405	0.862566	0.852537	0.838593	0.770859	0.648142	0.531654	0.437624	0.324316	0.260803	0.197479	0.133618	0.0798232	0.0574365	0.0461649
710	0.899441	0.886601	0.87422	0.865761	0.855185	0.840237	0.771017	0.644424	0.526058	0.430601	0.318581	0.252665	0.189871	0.127189	0.0748883	0.0532453	0.04271
720	0.904829	0.892126	0.880415	0.871657	0.861168	0.846556	0.777647	0.652014	0.533974	0.437707	0.327876	0.259916	0.197933	0.133704	0.0810869	0.0587481	0.0479205
730	0.911642	0.900284	0.888861	0.880531	0.870902	0.856275	0.789615	0.667046	0.552186	0.455844	0.348968	0.279345	0.21791	0.150817	0.0965409	0.0717012	0.0597636

Table E2: Magenta tonal gradation data of circular Euclidean 150 LPI on SBS.

nm	SBS	1%	2%	3%	4%	5%	10%	20%	30%	40%	50%	60%	70%	80%	90%	95%	100%
380	0.33083	0.294403	0.283465	0.283222	0.275456	0.277118	0.278585	0.251869	0.236815	0.218222	0.206372	0.187474	0.166244	0.150424	0.134077	0.136588	0.119098
390	0.374241	0.338731	0.333447	0.329934	0.323927	0.32238	0.321199	0.291703	0.268799	0.248416	0.228217	0.206412	0.182089	0.160174	0.1423	0.140659	0.125077
400	0.434112	0.405538	0.405374	0.399299	0.396738	0.394135	0.385651	0.35098	0.318988	0.294465	0.26297	0.234672	0.207514	0.179261	0.155185	0.151805	0.134345
410	0.576343	0.563299	0.566227	0.558051	0.558518	0.553723	0.531724	0.487405	0.435755	0.39769	0.347867	0.306677	0.270438	0.229347	0.196849	0.192289	0.168469
420	0.771437	0.776826	0.775728	0.76821	0.763739	0.756983	0.72211	0.658354	0.584783	0.524816	0.458834	0.401476	0.351677	0.298968	0.254038	0.247719	0.215751
430	0.87098	0.883833	0.877459	0.871742	0.86224	0.853858	0.816356	0.739391	0.659884	0.585904	0.516662	0.451514	0.394517	0.338616	0.287824	0.282085	0.244514
440	0.900561	0.912874	0.904675	0.898645	0.888329	0.87992	0.842034	0.762538	0.682348	0.605744	0.535879	0.469549	0.410636	0.354097	0.302056	0.296596	0.257588
450	0.899767	0.908935	0.901226	0.893712	0.88513	0.876208	0.837529	0.757746	0.677093	0.600915	0.529891	0.463452	0.404645	0.346914	0.294857	0.289334	0.250483
460	0.890756	0.893474	0.886312	0.877194	0.869367	0.859873	0.819131	0.737423	0.653739	0.576952	0.504104	0.436297	0.378123	0.31893	0.266556	0.260717	0.22245
470	0.884742	0.880274	0.872823	0.862077	0.854233	0.844219	0.800104	0.713839	0.6257	0.546194	0.470012	0.400262	0.341644	0.280683	0.228219	0.221129	0.184871
480	0.876751	0.866958	0.858796	0.846297	0.838691	0.828173	0.77999	0.688928	0.595433	0.514239	0.434634	0.362874	0.303546	0.241971	0.189645	0.182001	0.14802
490	0.866588	0.854977	0.846105	0.83258	0.824775	0.813057	0.762021	0.666713	0.568902	0.486163	0.403875	0.33062	0.27111	0.209331	0.157635	0.149512	0.118127
500	0.855435	0.842287	0.832788	0.818265	0.809958	0.797739	0.743548	0.644149	0.542144	0.458185	0.373586	0.299271	0.240402	0.178743	0.128358	0.119941	0.091547
510	0.842517	0.827803	0.817551	0.801932	0.792836	0.779993	0.722542	0.618783	0.513007	0.427769	0.341441	0.266715	0.208915	0.1482	0.099668	0.09098	0.066432
520	0.826871	0.809083	0.797414	0.781463	0.771798	0.758494	0.698598	0.591696	0.48342	0.398076	0.311277	0.237399	0.180901	0.122121	0.076203	0.067513	0.046832
530	0.815425	0.794861	0.782887	0.766589	0.756981	0.743265	0.682334	0.574268	0.465295	0.380863	0.294316	0.221623	0.166461	0.109176	0.065387	0.056661	0.038127
540	0.816697	0.795057	0.783468	0.76654	0.756863	0.742845	0.680237	0.570793	0.460283	0.375615	0.28837	0.215783	0.161025	0.104151	0.061255	0.052725	0.035054
550	0.818493	0.797278	0.785245	0.767387	0.757484	0.743056	0.677305	0.564615	0.450983	0.365834	0.277284	0.204424	0.150684	0.094701	0.05336	0.045028	0.02945
560	0.812124	0.791183	0.778005	0.759215	0.748837	0.73369	0.665027	0.549165	0.432569	0.347948	0.258939	0.187196	0.135603	0.081909	0.043857	0.035839	0.023342
570	0.812937	0.792451	0.778775	0.759366	0.748945	0.733235	0.663153	0.545948	0.428303	0.343953	0.255018	0.184046	0.133405	0.080708	0.04422	0.036298	0.025008
580	0.819889	0.801391	0.789771	0.773002	0.76392	0.750437	0.689243	0.583513	0.476713	0.395354	0.31126	0.241569	0.188	0.132414	0.090413	0.082526	0.062906
590	0.831127	0.814981	0.807812	0.797593	0.791915	0.783416	0.744033	0.670647	0.595314	0.53021	0.465712	0.407862	0.357071	0.304958	0.26027	0.255111	0.222509
600	0.837244	0.822068	0.817769	0.813151	0.810676	0.806078	0.786124	0.746098	0.704249	0.664669	0.62677	0.589941	0.553981	0.517122	0.483945	0.481976	0.4512
610	0.837201	0.822418	0.8198	0.817325	0.815981	0.813405	0.802162	0.779	0.754663	0.730902	0.70935	0.686663	0.662835	0.638645	0.617175	0.616466	0.594459
620	0.836873	0.822627	0.820138	0.818199	0.817208	0.815422	0.807189	0.790263	0.772445	0.755077	0.740036	0.72359	0.705203	0.686418	0.670824	0.670502	0.653881
630	0.844769	0.830757	0.828254	0.8269	0.8262	0.824158	0.817072	0.802134	0.786769	0.771727	0.75873	0.744412	0.728156	0.711561	0.698048	0.698013	0.683511
640	0.861297	0.848001	0.845565	0.844211	0.843803	0.841755	0.83508	0.82067	0.806038	0.7916	0.779259	0.765442	0.750048	0.734519	0.721349	0.721295	0.707536
650	0.878287	0.866558	0.864292	0.862435	0.862293	0.860357	0.853854	0.840179	0.825977	0.811931	0.799811	0.786476	0.771597	0.756742	0.743884	0.743859	0.73021
660	0.889346	0.878219	0.875941	0.874148	0.873984	0.872441	0.866504	0.853706	0.840673	0.827188	0.816232	0.80386	0.790195	0.776518	0.764348	0.764459	0.751541
670	0.894582	0.884205	0.881919	0.880328	0.879921	0.878391	0.873472	0.861545	0.850158	0.838033	0.828158	0.817265	0.80489	0.792547	0.781824	0.782144	0.77029
680	0.893603	0.882813	0.880617	0.878823	0.878588	0.877307	0.872559	0.862065	0.852082	0.841004	0.832844	0.823158	0.811854	0.801286	0.791427	0.792163	0.781302
690	0.892422	0.881056	0.87871	0.877052	0.876982	0.875803	0.871393	0.861683	0.852317	0.84234	0.835229	0.826175	0.815879	0.806073	0.797258	0.797837	0.788117
700	0.895739	0.885382	0.883103	0.881627	0.881494	0.880235	0.876073	0.866574	0.857744	0.848255	0.841605	0.832691	0.822864	0.813226	0.805286	0.806086	0.796724
710	0.899441	0.889856	0.887401	0.885648	0.885907	0.884704	0.880432	0.871209	0.862439	0.853351	0.846454	0.838456	0.828214	0.819467	0.811455	0.812343	0.803192
720	0.904829	0.893731	0.891518	0.890038	0.88988	0.888667	0.884566	0.875195	0.866129	0.856713	0.849709	0.841728	0.831438	0.822661	0.814379	0.814864	0.805832
730	0.911642	0.907547	0.904966	0.904019	0.903842	0.902158	0.897801	0.888889	0.879546	0.870136	0.863289	0.854612	0.844003	0.83551	0.827268	0.828029	0.818554

Table E3: Yellow tonal gradation data of circular Euclidean 150 LPI on SBS.

	SBS	1%	2%	3%	4%	5%	10%	20%	30%	40%	50%	60%	70%	80%	90%	95%	100%
380	0.33083	0.30147	0.285476	0.288651	0.287309	0.279843	0.262605	0.240048	0.211411	0.195689	0.175709	0.157398	0.124278	0.10634	0.0819	0.068443	0.046719
390	0.374241	0.34773	0.3356	0.33298	0.330164	0.323596	0.304578	0.270883	0.23926	0.219931	0.192721	0.166717	0.132478	0.108204	0.077682	0.061556	0.039122
400	0.434112	0.418669	0.406379	0.400091	0.397992	0.387936	0.364545	0.31716	0.281745	0.254703	0.221102	0.185711	0.144271	0.11473	0.077446	0.056229	0.033825
410	0.576343	0.57428	0.564002	0.550198	0.545712	0.533261	0.495729	0.423138	0.376863	0.33532	0.285615	0.233748	0.177966	0.139025	0.08857	0.060939	0.032527
420	0.771437	0.779915	0.76598	0.745693	0.736869	0.721118	0.662668	0.558322	0.491681	0.43216	0.361409	0.292597	0.221674	0.168478	0.104529	0.069593	0.034572
430	0.87098	0.882194	0.863111	0.841364	0.82973	0.811893	0.742639	0.621412	0.542366	0.474915	0.393544	0.318713	0.24219	0.181172	0.112457	0.073636	0.036913
440	0.900561	0.908051	0.889082	0.866503	0.854325	0.836936	0.764915	0.640184	0.558563	0.488944	0.404982	0.330058	0.252458	0.189844	0.119336	0.078799	0.040707
450	0.899767	0.903083	0.88503	0.863764	0.851814	0.83511	0.765209	0.644158	0.564457	0.49607	0.414021	0.340966	0.264619	0.201872	0.131371	0.090307	0.050135
460	0.890756	0.889316	0.872885	0.852657	0.841531	0.825642	0.759701	0.644456	0.568132	0.502676	0.42346	0.353809	0.279186	0.217705	0.148014	0.105572	0.063585
470	0.884742	0.879304	0.864093	0.844283	0.834415	0.818571	0.755023	0.644286	0.569817	0.50677	0.429734	0.362129	0.289766	0.228702	0.160338	0.116934	0.074131
480	0.876751	0.868949	0.855014	0.836911	0.827826	0.813259	0.753974	0.650132	0.57938	0.519609	0.446528	0.383086	0.313943	0.253994	0.187707	0.142684	0.098695
490	0.866588	0.857975	0.846889	0.832298	0.825116	0.812883	0.763615	0.675683	0.613086	0.561826	0.497066	0.443328	0.381822	0.325843	0.265758	0.219399	0.173515
500	0.855435	0.846498	0.839633	0.829624	0.824852	0.816671	0.782677	0.719983	0.672064	0.635737	0.58633	0.54875	0.501591	0.457072	0.410699	0.367115	0.324795
510	0.842517	0.833826	0.830057	0.824169	0.821384	0.817057	0.797447	0.75969	0.727436	0.707246	0.675306	0.653904	0.623512	0.59428	0.565604	0.531368	0.500545
520	0.826871	0.816937	0.814558	0.810599	0.809101	0.80618	0.793517	0.769284	0.745485	0.734016	0.712033	0.699442	0.678158	0.658892	0.641106	0.614572	0.593995
530	0.815425	0.804627	0.802602	0.79888	0.797872	0.79495	0.784365	0.76348	0.74234	0.733126	0.713891	0.703212	0.684391	0.668253	0.653182	0.629674	0.612169
540	0.816697	0.805766	0.80403	0.800531	0.799542	0.796821	0.786988	0.767095	0.747379	0.739132	0.721451	0.710468	0.692731	0.677699	0.663335	0.641892	0.625172
550	0.818493	0.807694	0.806048	0.802692	0.801791	0.799175	0.790004	0.770976	0.752419	0.744855	0.728105	0.717494	0.700666	0.686809	0.672612	0.652715	0.63656
560	0.812124	0.800915	0.799145	0.79593	0.795104	0.792363	0.78342	0.764828	0.746654	0.739664	0.723144	0.712991	0.696592	0.683154	0.669328	0.649794	0.634015
570	0.812937	0.801463	0.799714	0.796821	0.796076	0.793461	0.785006	0.767544	0.749884	0.743633	0.728058	0.718696	0.703239	0.690516	0.677307	0.658787	0.644015
580	0.819889	0.807934	0.806555	0.803703	0.803286	0.800976	0.793925	0.779043	0.763257	0.758504	0.745	0.737245	0.723747	0.712943	0.70171	0.685487	0.673229
590	0.831127	0.818599	0.817503	0.815016	0.814605	0.812728	0.807171	0.795062	0.780743	0.77761	0.766124	0.76014	0.748671	0.739886	0.730871	0.716999	0.707579
600	0.837244	0.824223	0.823269	0.820986	0.82063	0.818858	0.814172	0.803385	0.789862	0.787538	0.77709	0.772085	0.761614	0.754272	0.746281	0.73365	0.725927
610	0.837201	0.824344	0.82321	0.821084	0.820696	0.81916	0.814398	0.803447	0.789915	0.787731	0.776985	0.772426	0.76189	0.754459	0.746338	0.733834	0.726375
620	0.836873	0.824235	0.823032	0.820571	0.820366	0.818601	0.813647	0.802314	0.788556	0.786008	0.775086	0.770032	0.759302	0.751475	0.743045	0.72992	0.721961
630	0.844769	0.831612	0.830582	0.828201	0.828064	0.826467	0.821424	0.810697	0.79733	0.79516	0.784489	0.779979	0.769567	0.761992	0.753808	0.741363	0.733614
640	0.861297	0.848327	0.847508	0.845294	0.84502	0.843862	0.839569	0.830132	0.818006	0.816442	0.806918	0.803329	0.79456	0.787815	0.780926	0.769752	0.763605
650	0.878287	0.865944	0.865108	0.863112	0.862766	0.861888	0.858382	0.850667	0.839369	0.838793	0.830527	0.827921	0.820339	0.81483	0.809695	0.799955	0.79551
660	0.889346	0.877913	0.877236	0.875453	0.874981	0.874303	0.871341	0.864635	0.854278	0.854337	0.846867	0.845113	0.838393	0.834062	0.829988	0.82145	0.818752
670	0.894582	0.883546	0.882892	0.881115	0.880873	0.880108	0.877533	0.871516	0.861495	0.861902	0.854775	0.853719	0.847191	0.84353	0.840208	0.832445	0.830612
680	0.893603	0.882285	0.881446	0.879963	0.879592	0.879128	0.876305	0.870826	0.860958	0.861714	0.854697	0.853919	0.847376	0.844071	0.840415	0.83351	0.831907
690	0.892422	0.880824	0.880234	0.878587	0.878214	0.877879	0.875167	0.86981	0.860112	0.861074	0.853761	0.853381	0.84698	0.843624	0.839974	0.833015	0.831761
700	0.895739	0.884516	0.884063	0.882159	0.882173	0.881672	0.879143	0.874091	0.864671	0.865453	0.858537	0.858295	0.852406	0.849231	0.846434	0.838708	0.838192
710	0.899441	0.888465	0.887726	0.886412	0.886298	0.885841	0.883184	0.878679	0.869444	0.87027	0.863663	0.864032	0.858373	0.855126	0.852958	0.845447	0.844811
720	0.904829	0.894083	0.893398	0.89205	0.892025	0.891764	0.888942	0.884243	0.875469	0.87621	0.869544	0.86972	0.864071	0.860863	0.85895	0.851586	0.850987
730	0.911642	0.90227	0.901279	0.900436	0.900127	0.900038	0.897322	0.892778	0.883791	0.884543	0.877902	0.878241	0.87251	0.869251	0.867874	0.859983	0.859866

Table E4: Black tonal gradation data of circular Euclidean 150 LPI on SBS.

nm	SBS	1%	2%	3%	4%	5%	10%	20%	30%	40%	50%	60%	70%	80%	90%	95%	100%
380	0.33083	0.4013	0.4083	0.399	0.4011	0.3875	0.3541	0.3102	0.2679	0.2308	0.2038	0.173	0.1368	0.0858	0.0432	0.0286	0.016
390	0.374241	0.4432	0.449	0.4417	0.438	0.4275	0.3899	0.347	0.295	0.2558	0.2241	0.1905	0.1476	0.094	0.0487	0.0321	0.0171
400	0.434112	0.4889	0.496	0.4878	0.4802	0.4705	0.4274	0.3815	0.3226	0.2802	0.2447	0.2071	0.1607	0.1018	0.0524	0.0323	0.017
410	0.576343	0.5908	0.594	0.5822	0.5746	0.5622	0.513	0.4509	0.3805	0.3283	0.283	0.2381	0.1841	0.1155	0.0583	0.035	0.0182
420	0.771437	0.7327	0.7289	0.7134	0.7086	0.6911	0.6337	0.5397	0.4549	0.3913	0.3326	0.275	0.2119	0.1332	0.0656	0.0388	0.0203
430	0.87098	0.8103	0.8025	0.7857	0.7824	0.7627	0.6999	0.5864	0.4939	0.4233	0.3577	0.293	0.2268	0.1426	0.0693	0.0411	0.0213
440	0.900561	0.8356	0.8272	0.8095	0.8063	0.786	0.7219	0.6026	0.5066	0.434	0.3661	0.2996	0.2323	0.1458	0.0714	0.0423	0.0211
450	0.899767	0.8391	0.8304	0.813	0.8086	0.7889	0.7234	0.6071	0.5089	0.4365	0.3678	0.3017	0.2343	0.1472	0.0723	0.043	0.022
460	0.890756	0.836	0.8277	0.8104	0.805	0.7865	0.72	0.6075	0.5081	0.4361	0.3676	0.3026	0.2353	0.1481	0.0734	0.0439	0.0227
470	0.884742	0.8335	0.8255	0.8078	0.8021	0.7841	0.7175	0.6071	0.5074	0.4353	0.3673	0.3026	0.2358	0.1488	0.0744	0.0445	0.0232
480	0.876751	0.8283	0.8204	0.8029	0.7967	0.7797	0.7128	0.605	0.505	0.4339	0.3662	0.3023	0.2361	0.1491	0.075	0.0454	0.0238
490	0.866588	0.822	0.8141	0.797	0.7902	0.7738	0.7075	0.6019	0.5022	0.4322	0.3652	0.3015	0.2361	0.1498	0.0756	0.046	0.0244
500	0.855435	0.8138	0.8062	0.7894	0.7825	0.7665	0.7008	0.5972	0.4985	0.4294	0.363	0.3002	0.2356	0.1498	0.076	0.0464	0.0247
510	0.842517	0.8037	0.7963	0.7798	0.7731	0.7572	0.6929	0.5913	0.4937	0.4258	0.3601	0.2984	0.2346	0.1496	0.0764	0.0469	0.0251
520	0.826871	0.7911	0.7838	0.7678	0.7617	0.746	0.6828	0.5836	0.4878	0.4212	0.3567	0.2956	0.233	0.1492	0.0765	0.0472	0.0254
530	0.815425	0.7813	0.7741	0.7583	0.7524	0.737	0.6747	0.5771	0.4826	0.4171	0.3533	0.293	0.2313	0.1484	0.0764	0.0473	0.0256
540	0.816697	0.7804	0.7736	0.7576	0.7513	0.7363	0.6735	0.5764	0.4817	0.4163	0.3525	0.2926	0.2312	0.1485	0.0766	0.0476	0.0258
550	0.818493	0.7796	0.7727	0.7567	0.7503	0.7354	0.6725	0.5756	0.4808	0.4157	0.3521	0.2923	0.2313	0.1489	0.0769	0.0479	0.0262
560	0.812124	0.7723	0.7656	0.7498	0.7437	0.7288	0.6666	0.5707	0.4769	0.4126	0.3496	0.2903	0.23	0.1483	0.0769	0.0482	0.0264
570	0.812937	0.7732	0.7666	0.7508	0.7447	0.7297	0.6675	0.5715	0.4776	0.4133	0.3502	0.291	0.2308	0.1491	0.0776	0.0488	0.0269
580	0.819889	0.7799	0.773	0.7569	0.7507	0.7357	0.6729	0.5759	0.4807	0.4161	0.3523	0.2928	0.2322	0.1503	0.0784	0.0495	0.0274
590	0.831127	0.7907	0.7836	0.7671	0.7608	0.7454	0.6818	0.583	0.4861	0.4207	0.3561	0.2959	0.2349	0.1522	0.0797	0.0505	0.028
600	0.837244	0.7963	0.7892	0.7724	0.766	0.7507	0.6866	0.5866	0.4891	0.4233	0.3582	0.2977	0.2367	0.1538	0.0809	0.0514	0.0287
610	0.837201	0.797	0.7898	0.7728	0.7666	0.7511	0.6872	0.5872	0.4897	0.4242	0.3591	0.2987	0.2378	0.1549	0.0819	0.0522	0.0295
620	0.836873	0.7969	0.7898	0.7729	0.7667	0.7512	0.6875	0.5873	0.4902	0.4247	0.3598	0.2995	0.2389	0.1561	0.083	0.0533	0.0303
630	0.844769	0.8047	0.7973	0.7803	0.7741	0.7581	0.694	0.5927	0.4945	0.4286	0.363	0.3021	0.2415	0.1581	0.0845	0.0545	0.0312
640	0.861297	0.821	0.8131	0.7954	0.789	0.7728	0.707	0.6034	0.503	0.4357	0.3689	0.3072	0.2458	0.1612	0.0866	0.0562	0.0325
650	0.878287	0.8376	0.8293	0.8113	0.8043	0.788	0.7207	0.6145	0.5117	0.4432	0.3752	0.3125	0.2501	0.1644	0.0886	0.0577	0.0338
660	0.889346	0.8492	0.8407	0.822	0.8147	0.7981	0.7302	0.6221	0.5176	0.4486	0.3796	0.3164	0.2536	0.1671	0.0906	0.0594	0.0349
670	0.894582	0.8542	0.8459	0.8268	0.8194	0.8028	0.7346	0.6256	0.5207	0.4514	0.3823	0.3188	0.2561	0.1692	0.0923	0.0607	0.0361
680	0.893603	0.853	0.8448	0.826	0.8187	0.8018	0.7342	0.6253	0.5207	0.4518	0.383	0.3197	0.2575	0.1709	0.0938	0.0621	0.0373
690	0.892422	0.8519	0.8433	0.8244	0.8178	0.801	0.7336	0.6248	0.521	0.4523	0.3837	0.3208	0.2589	0.1727	0.0955	0.0635	0.0385
700	0.895739	0.8554	0.8473	0.8285	0.8216	0.8045	0.7369	0.628	0.524	0.4552	0.3866	0.3234	0.2614	0.175	0.097	0.0651	0.0398
710	0.899441	0.8588	0.8505	0.8318	0.8245	0.8073	0.74	0.6303	0.5259	0.4573	0.3886	0.3254	0.2633	0.1767	0.0987	0.0667	0.041
720	0.904829	0.8643	0.8557	0.8368	0.8298	0.8124	0.745	0.6346	0.5296	0.4612	0.3921	0.3285	0.2664	0.1793	0.1009	0.0685	0.0424
730	0.911642	0.8726	0.8644	0.8453	0.8376	0.8208	0.7522	0.641	0.5347	0.4654	0.3964	0.3321	0.2697	0.182	0.1028	0.0698	0.0438

Table E5: Orange reflectance data of circular Euclidean 150 LPI on SBS.

nm	SBS	1%	2%	3%	4%	5%	10%	20%	30%	40%	50%	60%	70%	80%	90%	95%	100%
380	0.33083	0.277803	0.280142	0.276132	0.282809	0.283578	0.27648	0.258564	0.246906	0.226888	0.195152	0.163863	0.138098	0.093914	0.068558	0.058219	0.039302
390	0.374241	0.327272	0.327432	0.321483	0.324483	0.326567	0.3199	0.300599	0.282573	0.256216	0.221132	0.177447	0.145578	0.093301	0.06553	0.054019	0.033749
400	0.434112	0.398276	0.400404	0.390053	0.388377	0.392075	0.386284	0.360584	0.332932	0.296102	0.254347	0.195944	0.153363	0.094167	0.061857	0.049088	0.029095
410	0.576343	0.559217	0.558978	0.544149	0.534673	0.541781	0.534865	0.492579	0.449236	0.388389	0.330303	0.242652	0.181445	0.105441	0.064333	0.049299	0.027815
420	0.771437	0.762098	0.760175	0.744882	0.733075	0.736617	0.718882	0.654967	0.591947	0.503305	0.417449	0.296619	0.21293	0.117931	0.066397	0.049587	0.026955
430	0.87098	0.856973	0.855719	0.841319	0.830825	0.831938	0.802594	0.726715	0.653713	0.550692	0.448536	0.313441	0.218832	0.117475	0.064295	0.04745	0.025897
440	0.900561	0.882965	0.88168	0.867782	0.856619	0.857159	0.82392	0.743633	0.667238	0.558942	0.451876	0.312182	0.214995	0.113336	0.061851	0.045641	0.025508
450	0.899767	0.883139	0.881876	0.867352	0.854439	0.855841	0.822884	0.741561	0.663425	0.554216	0.447017	0.306953	0.210056	0.110562	0.06042	0.044777	0.025452
460	0.890756	0.871226	0.869306	0.85486	0.840775	0.842658	0.810996	0.730774	0.652456	0.544418	0.43921	0.300595	0.205632	0.108166	0.059574	0.044306	0.025788
470	0.884742	0.858999	0.856908	0.842898	0.828534	0.830737	0.799504	0.720681	0.643033	0.536532	0.4331	0.296747	0.202584	0.10722	0.059319	0.044343	0.02627
480	0.876751	0.847049	0.844987	0.831062	0.81689	0.819348	0.788585	0.711112	0.634926	0.530253	0.429053	0.294559	0.201887	0.107505	0.060237	0.04541	0.026803
490	0.866588	0.83758	0.835477	0.822083	0.807909	0.810567	0.78061	0.705577	0.631201	0.528414	0.429289	0.296239	0.204786	0.110414	0.062838	0.047464	0.028208
500	0.855435	0.827	0.824822	0.812139	0.798779	0.801084	0.772559	0.700987	0.629275	0.529376	0.432674	0.301942	0.211729	0.116225	0.067422	0.051055	0.030051
510	0.842517	0.813919	0.811699	0.799841	0.787515	0.789406	0.762193	0.694311	0.626069	0.529838	0.436293	0.308414	0.219499	0.123122	0.072695	0.0555	0.032219
520	0.826871	0.795567	0.79332	0.782544	0.771392	0.772864	0.746682	0.682875	0.618066	0.525672	0.43553	0.311357	0.224788	0.128043	0.076973	0.059256	0.034369
530	0.815425	0.782148	0.779817	0.769655	0.759869	0.760822	0.736162	0.676263	0.614621	0.52623	0.439535	0.319103	0.235131	0.13682	0.084838	0.066104	0.038529
540	0.816697	0.784748	0.782347	0.77291	0.764262	0.76485	0.742999	0.688785	0.631856	0.548704	0.466964	0.350715	0.269336	0.166017	0.109963	0.088164	0.053412
550	0.818493	0.790107	0.788218	0.780278	0.773396	0.774324	0.756621	0.712685	0.665955	0.594804	0.522778	0.417893	0.343663	0.235994	0.174897	0.148476	0.10027
560	0.812124	0.786693	0.785672	0.780339	0.775489	0.777262	0.764928	0.73511	0.703509	0.651505	0.596874	0.515123	0.456492	0.355844	0.29614	0.26707	0.208169
570	0.812937	0.789947	0.789608	0.786313	0.782937	0.785726	0.777923	0.760812	0.74296	0.710072	0.674562	0.620383	0.580691	0.50125	0.453123	0.426632	0.37036
580	0.819889	0.798324	0.79854	0.79634	0.793821	0.797375	0.792425	0.782766	0.773606	0.753761	0.732146	0.69991	0.675393	0.620695	0.587708	0.567234	0.525036
590	0.831127	0.809181	0.809607	0.808362	0.806175	0.809759	0.806293	0.800193	0.795289	0.782067	0.767586	0.748029	0.732012	0.69471	0.672722	0.657478	0.629293
600	0.837244	0.814017	0.814584	0.813476	0.81133	0.814963	0.811969	0.80753	0.804351	0.793815	0.782362	0.768195	0.7557	0.727058	0.710298	0.697934	0.677715
610	0.837201	0.813661	0.814095	0.81335	0.811074	0.815214	0.811726	0.807965	0.805579	0.796084	0.785659	0.773566	0.762567	0.73672	0.722319	0.710984	0.694357
620	0.836873	0.813513	0.813926	0.813069	0.810916	0.814973	0.811865	0.808162	0.806065	0.796967	0.787294	0.776184	0.765778	0.741256	0.728057	0.717016	0.701723
630	0.844769	0.822183	0.822632	0.82183	0.81953	0.823543	0.820684	0.817026	0.81481	0.805827	0.796646	0.785771	0.775738	0.752092	0.739621	0.72894	0.713593
640	0.861297	0.840635	0.840965	0.840373	0.837641	0.84183	0.839009	0.835235	0.832948	0.823908	0.815078	0.80416	0.794304	0.771493	0.759363	0.748729	0.733728
650	0.878287	0.860861	0.861193	0.860408	0.857884	0.862004	0.858826	0.855024	0.852587	0.843646	0.834815	0.824471	0.814637	0.79288	0.781107	0.771059	0.756982
660	0.889346	0.873484	0.873859	0.873184	0.871036	0.874596	0.871007	0.867592	0.865169	0.856567	0.847729	0.837826	0.82824	0.807512	0.796273	0.786835	0.773899
670	0.894582	0.879728	0.880401	0.879846	0.878114	0.88121	0.877602	0.873703	0.871367	0.862931	0.854374	0.844394	0.835025	0.814798	0.803659	0.794302	0.782103
680	0.893603	0.878023	0.87877	0.878375	0.876821	0.879648	0.875883	0.872228	0.869604	0.861146	0.852533	0.842491	0.832748	0.8125	0.80096	0.791813	0.779687
690	0.892422	0.875995	0.876682	0.876227	0.875214	0.877505	0.873674	0.8699	0.86714	0.85881	0.849819	0.839748	0.830275	0.809365	0.798065	0.788512	0.776569
700	0.895739	0.881333	0.88186	0.881402	0.880358	0.882573	0.878696	0.874715	0.871828	0.863572	0.854385	0.84404	0.835059	0.813255	0.801944	0.792361	0.780128
710	0.899441	0.88672	0.886836	0.886829	0.885903	0.888059	0.883719	0.879844	0.877129	0.868634	0.859361	0.849456	0.840585	0.818579	0.807203	0.797828	0.785651
720	0.904829	0.891198	0.891413	0.891503	0.890418	0.892627	0.888162	0.884178	0.881755	0.87291	0.864511	0.854594	0.846241	0.825408	0.814756	0.805735	0.794235
730	0.911642	0.908241	0.908933	0.908814	0.90781	0.909824	0.905464	0.901445	0.898533	0.890266	0.881924	0.872954	0.864973	0.845413	0.835581	0.826723	0.816681

Table E6: Green tonal gradation data of circular Euclidean 150 LPI on SBS.

nm	SBS	1%	2%	3%	4%	5%	10%	20%	30%	40%	50%	60%	70%	80%	90%	95%	100%
380	0.33083	0.284054	0.290366	0.281364	0.284599	0.281398	0.272052	0.238887	0.206329	0.178051	0.161955	0.128661	0.104917	0.076467	0.049322	0.040242	0.029787
390	0.374241	0.329174	0.336829	0.321491	0.329717	0.326466	0.313299	0.277115	0.242105	0.212032	0.186582	0.150204	0.122651	0.088891	0.058611	0.046221	0.031961
400	0.434112	0.397065	0.404318	0.385198	0.397108	0.39098	0.3762	0.33376	0.293681	0.25579	0.223464	0.180919	0.147157	0.105423	0.068886	0.05582	0.038999
410	0.576343	0.552141	0.554864	0.535341	0.547176	0.538928	0.517898	0.459213	0.40263	0.350206	0.298557	0.245445	0.196049	0.138201	0.091595	0.074361	0.051726
420	0.771437	0.759336	0.757081	0.744243	0.745713	0.733852	0.703561	0.624249	0.543088	0.471573	0.396043	0.327387	0.262809	0.184154	0.124966	0.102921	0.07279
430	0.87098	0.862563	0.859829	0.85134	0.8457	0.832017	0.798446	0.711827	0.617687	0.540861	0.456896	0.380835	0.312892	0.223246	0.158346	0.132351	0.097001
440	0.900561	0.891595	0.888581	0.882071	0.874743	0.86242	0.829233	0.745748	0.651817	0.576844	0.495001	0.419357	0.352674	0.260131	0.193721	0.16577	0.126634
450	0.899767	0.892154	0.889583	0.883178	0.877647	0.866323	0.836925	0.762284	0.676426	0.607274	0.531331	0.460321	0.397935	0.306637	0.240687	0.212133	0.169025
460	0.890756	0.880114	0.878441	0.873114	0.869439	0.860099	0.837071	0.775678	0.70341	0.645515	0.580818	0.518469	0.464216	0.379317	0.317864	0.289194	0.243871
470	0.884742	0.868337	0.86789	0.864146	0.862084	0.854666	0.838899	0.792675	0.737517	0.693675	0.643694	0.593467	0.550639	0.477446	0.424662	0.398065	0.354323
480	0.876751	0.85679	0.85717	0.854136	0.853617	0.847803	0.838172	0.80504	0.765338	0.733797	0.697444	0.659402	0.627034	0.569964	0.527869	0.504968	0.466299
490	0.866588	0.847066	0.848064	0.845524	0.845833	0.841539	0.835331	0.810288	0.78032	0.757101	0.729832	0.700072	0.674823	0.630424	0.596295	0.577473	0.54399
500	0.855435	0.83594	0.837449	0.834795	0.835973	0.831853	0.826918	0.804439	0.77784	0.757531	0.733624	0.706709	0.68397	0.643987	0.613108	0.595675	0.564718
510	0.842517	0.822413	0.823775	0.821001	0.822247	0.818116	0.813181	0.790017	0.762604	0.741582	0.71745	0.689279	0.665642	0.624629	0.592918	0.575034	0.543311
520	0.826871	0.803279	0.804866	0.801888	0.802894	0.79873	0.792846	0.767271	0.737152	0.713947	0.687578	0.656215	0.630653	0.585567	0.55126	0.531883	0.498555
530	0.815425	0.788645	0.789962	0.786375	0.78738	0.783049	0.775168	0.745849	0.711059	0.683895	0.653017	0.617668	0.588085	0.536965	0.498423	0.477163	0.441324
540	0.816697	0.788755	0.789843	0.784959	0.785914	0.78096	0.770103	0.734439	0.69276	0.659011	0.621171	0.580278	0.544212	0.484386	0.440297	0.417019	0.377469
550	0.818493	0.791539	0.792232	0.785828	0.786579	0.780748	0.765618	0.722132	0.671487	0.630018	0.583531	0.535822	0.492472	0.423639	0.373527	0.348479	0.306174
560	0.812124	0.785975	0.786153	0.778559	0.778539	0.772125	0.752116	0.700045	0.640155	0.590702	0.536156	0.481559	0.431893	0.355995	0.301202	0.275289	0.232551
570	0.812937	0.787226	0.786738	0.777421	0.777036	0.769387	0.744177	0.681858	0.611963	0.554232	0.490792	0.429757	0.373622	0.292381	0.234193	0.207963	0.1668
580	0.819889	0.79389	0.792569	0.781149	0.779952	0.770624	0.739517	0.665471	0.584434	0.517525	0.444857	0.377645	0.31531	0.231348	0.171434	0.146394	0.109232
590	0.831127	0.803136	0.800827	0.786911	0.784723	0.773231	0.735526	0.647522	0.555053	0.478398	0.396813	0.324487	0.256963	0.17415	0.115007	0.09268	0.062835
600	0.837244	0.806299	0.803007	0.786852	0.784285	0.770448	0.726622	0.626562	0.525548	0.441901	0.353948	0.279511	0.20962	0.13153	0.076275	0.057585	0.035514
610	0.837201	0.804818	0.801055	0.783411	0.780713	0.765149	0.718562	0.611674	0.506695	0.419848	0.329315	0.254761	0.184427	0.111284	0.0595	0.043152	0.025738
620	0.836873	0.804135	0.800145	0.781661	0.779087	0.762644	0.715038	0.605367	0.499005	0.410937	0.319661	0.245679	0.175193	0.10469	0.05468	0.039504	0.023613
630	0.844769	0.812409	0.808061	0.788792	0.786476	0.769076	0.720562	0.608283	0.500798	0.411227	0.318869	0.244605	0.173494	0.103573	0.054151	0.039295	0.023768
640	0.861297	0.830224	0.825692	0.805361	0.803177	0.784864	0.734495	0.618636	0.508536	0.416693	0.322126	0.246794	0.174633	0.104408	0.054971	0.039859	0.02436
650	0.878287	0.849975	0.845285	0.824367	0.821711	0.803113	0.750847	0.631867	0.518943	0.424876	0.328155	0.251575	0.178229	0.10705	0.057044	0.041634	0.025799
660	0.889346	0.863113	0.858375	0.837648	0.834746	0.816305	0.763725	0.644882	0.531151	0.436412	0.339443	0.261835	0.187692	0.114416	0.062995	0.046835	0.029303
670	0.894582	0.870446	0.866134	0.846165	0.843169	0.825851	0.774314	0.659099	0.546446	0.453395	0.357158	0.278822	0.204477	0.127918	0.07408	0.056238	0.035713
680	0.893603	0.86994	0.865684	0.847416	0.844373	0.828169	0.779175	0.669225	0.559906	0.469649	0.376	0.297836	0.223913	0.144272	0.088686	0.068835	0.045093
690	0.892422	0.868738	0.864499	0.84766	0.844635	0.829216	0.782683	0.678187	0.572379	0.484846	0.393516	0.316086	0.242998	0.160922	0.103841	0.082698	0.055303
700	0.895739	0.874505	0.870358	0.853793	0.850778	0.836035	0.790904	0.688656	0.585084	0.499087	0.408684	0.331398	0.258247	0.174455	0.116333	0.09385	0.06422
710	0.899441	0.879833	0.876296	0.859358	0.856235	0.841679	0.796206	0.693344	0.589332	0.502957	0.412472	0.335223	0.26178	0.177545	0.119362	0.096688	0.066297
720	0.904829	0.88417	0.880205	0.863019	0.859846	0.844565	0.797652	0.692712	0.586241	0.498375	0.406788	0.328736	0.255466	0.171652	0.113364	0.09124	0.061938
730	0.911642	0.901699	0.897755	0.879798	0.876236	0.86127	0.812947	0.705886	0.596236	0.505987	0.412963	0.333399	0.259128	0.17342	0.114091	0.092194	0.062416

Table E7: Violet tonal gradation data of circular Euclidean 150 LPI on SBS.

nm	SBS	1%	2%	3%	4%	5%	10%	20%	30%	40%	50%	60%	70%	80%	90%	95%	100%
380	0.33083	0.304915	0.30317	0.291992	0.286324	0.288221	0.273499	0.249603	0.216129	0.207138	0.173162	0.154149	0.13843	0.110606	0.082439	0.06187	0.044438
390	0.374241	0.352633	0.353166	0.337477	0.334196	0.330013	0.322039	0.296692	0.256799	0.248547	0.211772	0.188191	0.172656	0.138238	0.107351	0.085038	0.064791
400	0.434112	0.426492	0.426644	0.407229	0.406022	0.396798	0.392833	0.361019	0.315865	0.307637	0.263369	0.234469	0.217519	0.175646	0.141911	0.117013	0.090875
410	0.576343	0.589351	0.585975	0.562819	0.562694	0.547833	0.53982	0.494423	0.436928	0.419051	0.361999	0.321478	0.298859	0.241975	0.197331	0.165323	0.129902
420	0.771437	0.790641	0.784216	0.766276	0.761229	0.750358	0.723434	0.658635	0.591865	0.55584	0.486496	0.436915	0.398704	0.329037	0.270672	0.227137	0.183112
430	0.87098	0.884905	0.877063	0.867573	0.856836	0.851712	0.810292	0.737812	0.671372	0.6249	0.552122	0.500559	0.45414	0.381561	0.316836	0.267227	0.220673
440	0.900561	0.909322	0.900986	0.892872	0.882051	0.878086	0.832725	0.758443	0.692004	0.644027	0.570641	0.519421	0.470881	0.397733	0.331867	0.280937	0.233253
450	0.899767	0.902356	0.894372	0.884632	0.874398	0.868931	0.825143	0.750375	0.682454	0.634858	0.561323	0.50932	0.460908	0.386679	0.320598	0.270047	0.221698
460	0.890756	0.886396	0.878144	0.866881	0.856675	0.850131	0.806142	0.729869	0.658759	0.611429	0.535899	0.481998	0.433111	0.357737	0.291089	0.240717	0.192678
470	0.884742	0.873929	0.865047	0.852266	0.841637	0.833767	0.787958	0.706959	0.630491	0.582462	0.502762	0.44579	0.395953	0.318302	0.250289	0.200673	0.153717
480	0.876751	0.85947	0.849863	0.834938	0.823406	0.814051	0.764859	0.677847	0.594234	0.544579	0.459913	0.398989	0.348012	0.267968	0.200032	0.151967	0.108004
490	0.866588	0.842361	0.832214	0.814744	0.802425	0.791487	0.738356	0.645062	0.553532	0.503573	0.414024	0.349194	0.297725	0.217115	0.151496	0.106312	0.066937
500	0.855435	0.825216	0.814156	0.794741	0.782503	0.770306	0.714018	0.616685	0.519423	0.469995	0.377911	0.31084	0.260383	0.181161	0.119108	0.077498	0.042937
510	0.842517	0.808289	0.796864	0.776213	0.763887	0.75123	0.693413	0.59378	0.493657	0.445552	0.352934	0.285097	0.236441	0.159783	0.101294	0.062297	0.031731
520	0.826871	0.788522	0.777471	0.755974	0.74358	0.731237	0.672298	0.572458	0.471232	0.424884	0.333354	0.265816	0.218816	0.145326	0.090287	0.053605	0.026338
530	0.815425	0.775167	0.764177	0.74207	0.729942	0.717806	0.6588	0.559209	0.457495	0.413212	0.322457	0.25558	0.21007	0.13861	0.085749	0.050355	0.025316
540	0.816697	0.776791	0.765486	0.742163	0.730742	0.717543	0.659193	0.559371	0.456591	0.412734	0.32152	0.254586	0.209471	0.138179	0.085607	0.050497	0.025975
550	0.818493	0.778645	0.767502	0.743249	0.732154	0.718564	0.660649	0.560461	0.45721	0.413541	0.321977	0.254899	0.210013	0.138482	0.085993	0.050926	0.026525
560	0.812124	0.77122	0.760265	0.736262	0.724984	0.711797	0.654072	0.554564	0.452171	0.408849	0.318336	0.25175	0.207604	0.137008	0.085216	0.05067	0.027072
570	0.812937	0.771548	0.760455	0.736891	0.725466	0.712519	0.654677	0.555425	0.453801	0.409995	0.319712	0.253376	0.209167	0.138895	0.086897	0.052191	0.029027
580	0.819889	0.778632	0.76743	0.744689	0.733054	0.720112	0.6627	0.563907	0.464011	0.418776	0.328501	0.262616	0.217491	0.146324	0.092674	0.056866	0.032714
590	0.831127	0.790306	0.779514	0.757683	0.746203	0.733779	0.677458	0.579566	0.482229	0.435394	0.345612	0.280375	0.233817	0.16077	0.104403	0.066578	0.039445
600	0.837244	0.797219	0.786632	0.765836	0.754101	0.742594	0.687484	0.59128	0.49645	0.449111	0.360538	0.296307	0.249009	0.174614	0.116216	0.076808	0.046793
610	0.837201	0.796877	0.786243	0.765759	0.753922	0.742655	0.686985	0.591167	0.496435	0.448852	0.360319	0.296391	0.249136	0.174731	0.116273	0.07684	0.046664
620	0.836873	0.795701	0.784785	0.763166	0.751539	0.739509	0.682628	0.584934	0.488195	0.440531	0.350991	0.286455	0.239493	0.165865	0.108575	0.070348	0.041813
630	0.844769	0.802762	0.79151	0.769965	0.758143	0.745784	0.688474	0.58955	0.492248	0.443843	0.353625	0.288771	0.241261	0.167528	0.110088	0.071659	0.043476
640	0.861297	0.820594	0.809528	0.788964	0.777082	0.765141	0.709051	0.611909	0.516955	0.467443	0.377886	0.313864	0.265362	0.189919	0.129871	0.088924	0.057779
650	0.878287	0.840319	0.829917	0.811623	0.800379	0.789759	0.737591	0.646557	0.558511	0.509138	0.423716	0.363056	0.313942	0.237647	0.174871	0.130154	0.093831
660	0.889346	0.855483	0.846667	0.831583	0.821298	0.812832	0.767218	0.686939	0.610361	0.563474	0.486853	0.432556	0.385023	0.311746	0.248641	0.201536	0.160044
670	0.894582	0.86392	0.856592	0.844816	0.835979	0.829965	0.791467	0.723243	0.659489	0.617048	0.551443	0.505174	0.461329	0.394876	0.335244	0.288704	0.245443
680	0.893603	0.865554	0.859439	0.850613	0.843146	0.839078	0.806874	0.750026	0.698437	0.66154	0.60682	0.568543	0.529505	0.471947	0.418309	0.374339	0.332894
690	0.892422	0.866087	0.861252	0.854354	0.847992	0.845243	0.818237	0.770424	0.728479	0.695449	0.650347	0.617989	0.583587	0.534491	0.48661	0.446075	0.408143
700	0.895739	0.870374	0.866291	0.860665	0.855093	0.853094	0.829476	0.787474	0.751331	0.721755	0.682864	0.654679	0.623665	0.58043	0.536929	0.499103	0.465025
710	0.899441	0.874621	0.870419	0.866004	0.860881	0.859303	0.837922	0.800326	0.768366	0.741199	0.706503	0.68157	0.653047	0.614461	0.574191	0.538785	0.5081
720	0.904829	0.880707	0.876807	0.873266	0.868374	0.867217	0.848174	0.813712	0.785893	0.761104	0.72977	0.70721	0.681174	0.646295	0.608615	0.575819	0.548602
730	0.911642	0.888257	0.885063	0.880973	0.87689	0.875797	0.858889	0.827108	0.802118	0.778886	0.750685	0.729922	0.706052	0.673919	0.639913	0.608317	0.584423