

# Print Simulator (the 1<sup>st</sup> report)

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## Abstract

Recently, the method for simulating printed images on a monitor has come into our notice in order to preview them. This report shows the revolutionary method for simulating printed pieces on a monitor based on the spectral data. The new method, which we call "Print Simulator", has the characteristics written below:

1. By calculating the coefficients  $\alpha$ ,  $\beta$ ,  $\gamma$  and  $\eta$ ,  $\xi$  which represent the characteristics of a printer, it is possible to reduce the number of color patches and thus increase accuracy the method achieves. Especially, the coefficient  $\beta$  is essential to representing the optical dotgain with high precision.
2. By presuming the coefficients mentioned above, it is possible to display the same color as an imaginary color printer with a theoretical marking engine and a controller can output.
3. The interpolation method used here is very unique, different from the method utilizing the look-up table based on colorimetry. It interpolates the spectral data in the color gamut from those only on the edges of the color gamut.
4. Such interpolation is carried out on the basis of the measured spectral data. Finally, the interpolated spectral data is transformed into the tristimulus values.
5. The method includes a function to be adapted for fluctuation of the printed images when instability of a printer can not be ignored.

Furthermore, this report details the good results we have got on applying the method to the color patches up to the secondary solid colors and their gradations.

## Introduction

As more printing systems are getting open to other systems and more work comes to be accomplished by utilizing the internet, a soft proofer, especially to simulate printed results on a monitor, becomes more necessary for previewing the results because of its easiness. The methods to simulate printed images to preview the results on a monitor have been developed for a long time and are divided into four categories as shown below:

1. To use the 1-D and 3-D or 4-D look-up tables.(for example, ICC profile etc.)
2. To utilize a set of higher polynomials.

3. To use the Neugebauer's equation or its derivatives. (The method is often used in Graphic Arts.)
4. To assume that it can be modeled by the specular reflection on the surface of paper and the random body reflection in the paper.

These methods are assumed to be well adapted for simulating printed images deductively and thus have to be verified directly, or indirectly by an utterly different phenomena. Especially in the case of visual assessment, the human psychological process of color recognition has much influence on the results, and these results can be no more objective. Even the results obtained by the colorimetric measurements are under much influence of the methods to interpolate between the data and the images used for such measurement, and it is almost impossible to come to a reasonable conclusion.

Moreover, more color patches are necessary for increasing more accuracy on the methods mentioned above. As you will see in the conclusion, Printing Simulator attains more accuracy than any other methods by using 729 color patches.

Therefore, I came to the beginning and have studied for the accurate reflection model for each combination of amounts of 4 toners (cyan, magenta, yellow and black) and paper, based on the measured spectral data.

Up to the present, I have succeeded in making the following facts clear:

1. I have established the algorithm to interpolate spectral values by using a set of the linear equations, based on the spectral data.
2. The data necessary for the algorithm are composed of the M sets of spectral reflectance data on 32 edges. I recommend that the number M should be 11 in the paper. The 11 sets of spectral data represent a gradation of color on each edge. The 32 edges show the edges of the color gamut that a printer with CMYK toners can reproduce.
3. I confirm accuracy of the algorithm up to the secondary gradations.
4. I have succeeded in simulating printed results of the secondary gradations mentioned above on a monitor with high accuracy.

In this paper, I will explain the algorithm to interpolate the spectral values by the 11 sets of spectral data on the 32

edges and shows the good results I have attained by applying the algorithm to the practical cases up to the secondary gradations.

### Coefficients to be Calculated

The 32 edges have the characteristics as follows:

1. Each edge is represented by 11 color patches which show a gradation color.
2. The only one of cyan, magenta, yellow and black values has a value ranging from 0% to 100%. For example, the 11 values are 0%,10%,20%,...,100%. The notation  $i$  shows values at intervals of 10% as mentioned above.
3. The other color components have all the same value of either 0% or 100% on the color patches belonging to the edge.

The coefficients  $\alpha$ ,  $\beta$ ,  $\gamma$  and  $\eta$ ,  $\xi$  of the 352 color patches (32 edges x 11 patches) are calculated from the spectral data based on the 11 gradation color patches belonging to each edge as follows:

$$S_i(\lambda) = \alpha_i \cdot S_{\text{paper}}(\lambda) + \beta_i \cdot S_{50\%}(\lambda) + \gamma_i \cdot S_{100\%}(\lambda) \quad (1)$$

$$S_i(\lambda) = \xi_i \cdot S_{\text{paper}}(\lambda) + \eta_i \cdot S_{100\%}(\lambda) \quad (2)$$

$\lambda$ : wavelength (380nm - 730nm)

$S_i(\lambda)$ : spectral reflectance data of the 11 gradation color patches on each edge

$S_{\text{paper}}(\lambda)$ : spectral reflectance data of paper (0%)

$S_{50\%}(\lambda)$ : spectral reflectance data of the color patch of which color value  $i$  is 50% on the corresponding edge

$S_{100\%}(\lambda)$ : spectral reflectance data of the color patch of which color value  $i$  is 100% on the corresponding edge

$\alpha$ ,  $\beta$ ,  $\gamma$ ,  $\eta$ ,  $\xi$ : coefficients to be calculated by the least square method

Each coefficient shows intensity of the following phenomenon.

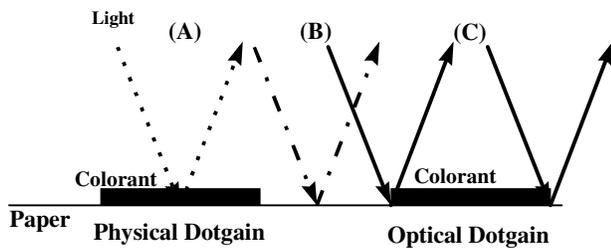


Figure 1. Physical meaning of each coefficient

$\alpha$ : light reflected only on paper (A)

$\beta$ : light which goes through the colorant and goes back through the air, and vice versa

$\gamma$ : light reflected only on the colorant (C)

$\xi$ : real area percentage of paper (no colorant on paper)

$\eta$ : real area percentage of the colorant adhered to paper

In case of the black gradation edge, the least square method can not be applied to this edge because of linearity in spectral reflectances and accordingly only the coefficients  $\eta$ ,  $\xi$  is used. These coefficients are calculated simultaneously as follows:

$$\xi_i \cdot S_{\text{paper}} + \eta_i \cdot S_{100\%} = S_i \quad (3)$$

$$\xi_i + \eta_i = 1 \quad (4)$$

$S_{\text{paper}}$ : average of spectral reflectance ranging from 380nm to 730nm (paper)

$S_{100\%}$ : average of spectral reflectance ranging from 380nm to 730nm (black solid on paper)

In case of the edges with a black solid color except the black gradation, the coefficients  $\alpha$ ,  $\beta$ ,  $\gamma$  and  $\eta$ ,  $\xi$  are not calculated and instead, the following values are adopted as spectral reflectances.

1. a constant value which is equal to  $S_{100\%}$  of black solid color on paper
2. the measured values themselves

### Interpolation of Imaginary Primary Colors

Each set of color patches on the 32 edges mentioned above, represents a gradation of color including color from the primary to the quaternary, with only one color component being changed and the other three being fixed.

Therefore, these colors shall be named "the imaginary primary colors" here.

The number  $j$  represents the area percentage of the color component of the color patch of which spectral reflectance is to be interpolated.

### Imaginary Primary Colors Except Black Gradation Color and Colors Including The Black Solid Color

- The values necessary for interpolation
  - (a)  $\alpha_i, \beta_i, \gamma_i$  of the 11 gradation color patches on each edge
  - (b)  $\eta_i, \xi_i$  of the 11 gradation color patches on each edge
  - (c)  $S_{\text{paper}}(\lambda), S_{50\%}(\lambda), S_{100\%}(\lambda)$ : spectral reflectances of 0%, 50%, 100% color patches
  - (d)  $i(\%)$ : a value of the color component of the 11 gradation color patches on each edge
  - (e)  $l, k$ : nearest neighbored values corresponding to  $j\%$  ( $k \leq j \leq l$ )

Arbitrary spectral reflectance of the imaginary primary colors mentioned above is interpolated linearly as follows:

$$P = (l - j)/(l - k), \quad 1 - p = (j - k)/(l - k) \quad (5)$$

$$\alpha_j = p \cdot \alpha_k + (1 - p) \cdot \alpha_l, \quad \beta_j = p \cdot \beta_k + (1 - p) \cdot \beta_l, \quad \gamma_j = p \cdot \gamma_k + (1 - p) \cdot \gamma_l \quad (6)$$

$$\xi_j = p \cdot \xi_k + (1 - p) \cdot \xi_l, \quad \eta_j = p \cdot \eta_k + (1 - p) \cdot \eta_l \quad (7)$$

$$S_j(\lambda) = \alpha_j \cdot S_{\text{paper}}(\lambda) + \beta_j \cdot S_{50\%}(\lambda) + \gamma_j \cdot S_{100\%}(\lambda) \quad (8)$$

$$S_j(\lambda) = \xi_j \cdot S_{\text{paper}}(\lambda) + \eta_j \cdot S_{100\%}(\lambda) \quad (9)$$

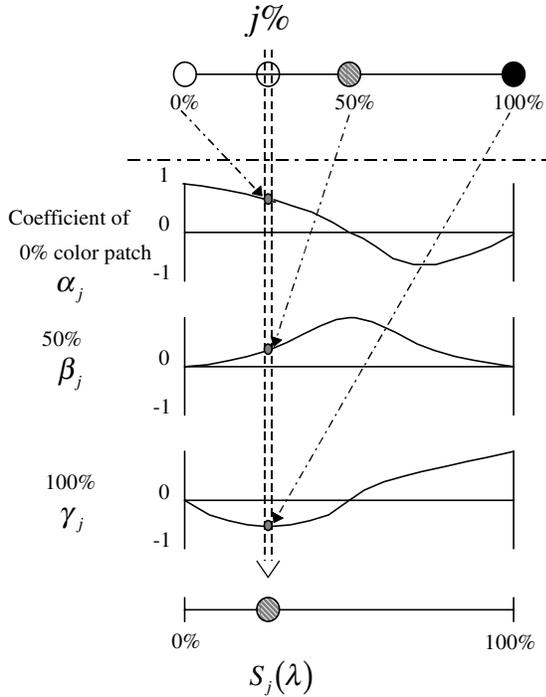


Figure 2. Interpolation of imaginary primary colors

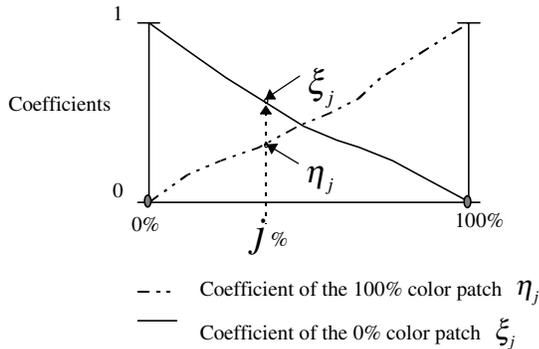


Figure 3. Real area percentage of the colorant(black) and paper

**Black Gradation Color**

- The values necessary for interpolation
- (a)  $\eta_i, \xi_i$  of the 11 gradation color patches on each edge
- (b)  $S_{paper}(\lambda), S_{100\%}(\lambda)$ : spectral reflectances of 0%, 100% color patches
- (c)  $i(\%)$ : a value of the color component of the 11 gradation color patches on each edge
- (d)  $l, k$ : nearest neighbored values corresponding to  $j\%$  ( $k \leq j \leq l$ )

Arbitrary spectral reflectance of the black gradation color is interpolated linearly by using the equations (5), (7) and (9).

**Colors Including the Black Solid Color**

- The values necessary for interpolation

- (a)  $S_i(\lambda)$ : spectral reflectances of the 11 gradation patches on each edge
- (b)  $i(\%)$ : a value of the color component of the 11 gradation color patches on each edge
- (c)  $l, k$ : nearest neighbored values corresponding to  $i\%$  ( $k \leq j \leq l$ )

Arbitrary spectral reflectance of the black gradation color is interpolated linearly by using the Eqs. (10) and (11).

$$p = (l-j)/(l-k), 1-p = (j-k)/(l-k) \tag{10}$$

$$S_j(\lambda) = p \cdot S_{paper}(\lambda) + (1-p) \cdot S_{100\%}(\lambda) \tag{11}$$

**Interpolation of Imaginary Secondary Colors**

Interpolation of the imaginary secondary colors is used by the method to interpolate the imaginary primary colors.

1. The imaginary secondary colors are reproduced by two colorants which are called "Colorant A" and "Colorant B" here. The other two colorants are fixed and have the value of either 0% or 100%.
2. The point(x,y) in the 2-dimensional space is used to locate the spectral reflectance  $S_{x,y}(\lambda)$  of the color patch. The value of Colorant A is x% and the value of Colorant B is y%. [ $0 \leq x \leq 100, 0 \leq y \leq 100$ ]
3. Four sides of the quadrangle including the point (x,y) is determined. The data necessary for interpolation are written as follows and can be calculated by the method to interpolate the imaginary primary colors mentioned before.

- (a) Colorant A side  
It is represented by the point( $i,0$ ),  $0 \leq i \leq 100$ .
  1. spectral reflectance  $S_{x,0}(\lambda)$  at the point(x,0)
  2. coefficients  $\eta_{x,0}, \xi_{x,0}$  at the point(x,0)
- (b) Colorant A, B100% side  
It is represented by the point( $i,100$ ),  $0 \leq i \leq 100$ . This side faces the "Colorant A" side.
  1. spectral reflectance  $S_{x,100}(\lambda)$  at the point(x,100)
  2. coefficients  $\eta_{x,100}, \xi_{x,100}$  at the point(x,100)
- (c) Colorant B side  
It is represented by the point( $0,j$ ),  $0 \leq j \leq 100$ .
  1. spectral reflectance  $S_{0,j}(\lambda)$  at the point(0,j)
  2. coefficients  $\eta_{0,y}, \xi_{0,y}$  at the point (0,y)
- (d) Colorant A100%, B side  
It is represented by the point( $100,j$ ),  $0 \leq j \leq 100$ . This side faces the "Colorant B" side.
  1. spectral reflectance  $S_{100,j}(\lambda)$  at the point(100,y)
  2. coefficients  $\eta_{100,y}, \xi_{100,y}$  at the point(100,y)

4. If any of these four sides include a black solid color, the coefficients  $\eta, \xi$  facing such sides are used instead.
5. The sides mentioned above are arranged into a quadrangle as shown in Figure 4.

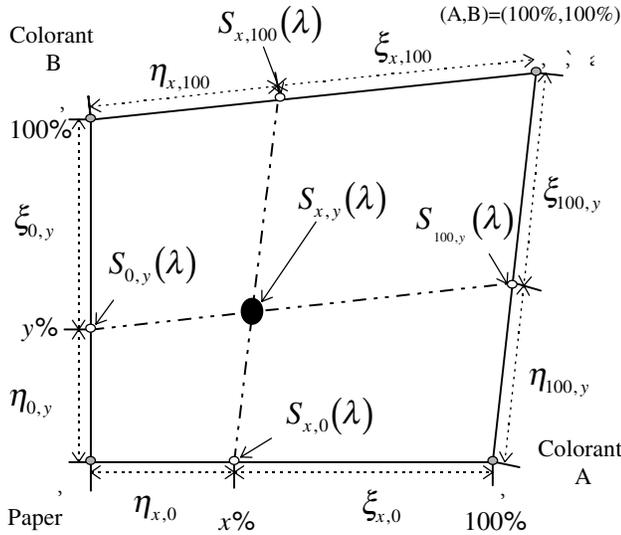


Figure 4. Composition of quadrangle for interpolation

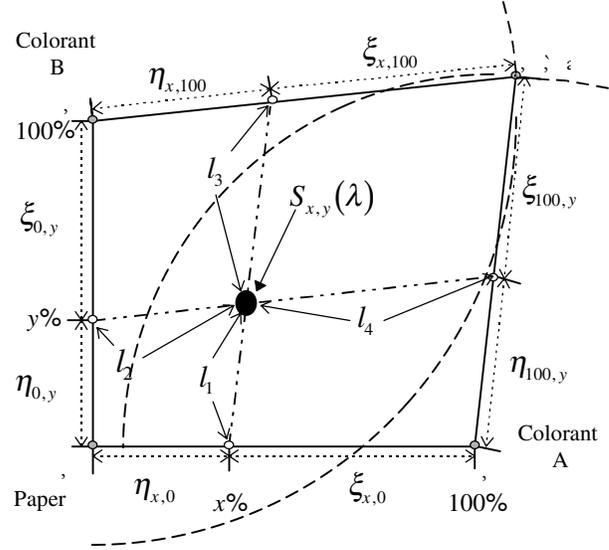


Figure 5. Interpolation of imaginary secondary colors

- (a)The point P is placed at (0,0). The Colorant A side is set horizontally from point P and the Colorant B side is done perpendicularly from P.
- (b)Length of the Colorant A side is set to100( $\eta_{x,0}+\xi_{x,0}$ ). The point(x,0) divides the side by the ratio  $\eta_{x,0}:\xi_{x,0}$  internally. Length of the Colorant B side and location of the point(0,y) is set in the same way.
- (c)Length of the Colorant A, B100% side and the Colorant A100%, B side and location of the points (x,100) and (100,y) are set in the same way as (b). These two sides are arranged as shown in Figure 5.

- 1)Draw a circle with its center being the point A and its radius being the length of Colorant A100%, B
- 2)Draw a circle with its center being the point B and its radius being the length of Colorant A, B100%
- 3)Choose the point nearer to the point(100,100) between the two points of intersection. This point shall be a common terminated point of the Colorant A, B100% side and the Colorant A100%, B side, as shown in Figure 5.

- 6. A line is drawn between the points(x,0) and(x,100), and the other line is drawn between the points(0,y) and (100,y).The intersecting point of the lines described above is the point(x,y).
- 7. Length between the points are defined as follows:  
(Please refer to Figure 5.)
  - (a)length from the point(x,y) to (x,0) ...  $l_1$
  - (b)length from the point(x,y) to (0,y) ...  $l_2$
  - (c)length from the point(x,y) to (x,100) ...  $l_3$
  - (d)length from the point(x,y) to (100,y) ...  $l_4$

- 8. The weight coefficients  $w_i(i=1,2,3,4)$  are determined by the equations below:

$$W_1=1+l_2+l_3+l_4, W_2=1/l_1+1/l_2+1/l_3+1/l_4 \quad (12)$$

$$w_1=1_3/W_1, w_2=1_4/W_1, w_3=1_l/W_1, w_4=1_2/W_1 \quad (13)$$

$$w_1=1/(1_1 \cdot W_2), w_2=1/(1_2 \cdot W_2), w_3=1/(1_3 \cdot W_2), w_4=1/(1_4 \cdot W_2) \quad (14)$$

- 9. The spectral reflectance to be interpolated is calculated by using the weight coefficients mentioned above and the equation below:

$$S_{x,y}(\lambda)=w_1 \cdot S_{x,0}(\lambda)+w_2 \cdot S_{0,y}(\lambda)+w_3 \cdot S_{x,100}(\lambda)+w_4 \cdot S_{100,y}(\lambda) \quad (15)$$

**Nonlinear Correction by Measured Data**

If this algorithm is applied to a printer of inferior quality, for example, a printer with instability in adherence of the colorants, the calculated results might be somewhat different from the measured because such instability causes nonlinear behavior of the printer.

The method for considering such nonlinear phenomenon is shown here.

- 1. Nonlinear correction is done by slightly altering the equations(12), (14) and (15).
- 2. The spectral reflectances and their color values to be coincided with, are defined below:

- (a)color values ...  $(a_m,b_m)$ ,  $(m=1,2,\dots,L)$
- (b)spectral reflectances ...  $S_m(\lambda)$ ,  $(m=1,2,\dots,L)$

### Imaginary Primary Colors

The method to interpolate the imaginary primary colors is not altered simply because the number of spectral reflectances used to calculate, that is to say,  $M$  increases.

Please refer to "interpolation of imaginary primary colors".

### Imaginary Secondary Colors

(1) Length between the points are defined as follows:

- length from the point  $(x, y)$  to  $(a_m, b_m)$ ,  $(m=1, 2, \dots, L)$   
 $\dots l_m, (m=1, 2, \dots, L)$

$$l_m = \sqrt{(x-a_m)^2 + (y-b_m)^2}, (m=1, 2, \dots, L) \quad (16)$$

(2) The weight coefficients  $w_i (i=1, 2, 3, 4, 5, \dots, L+4)$  are determined by the equations below:

$$W_m = 1/l_1 + 1/l_2 + 1/l_3 + 1/l_4 + 1/l_5 + \dots + 1/l_{L+4} \quad (17)$$

$$w_1 = 1/(l_1 \cdot W_m), w_2 = 1/(l_2 \cdot W_m), w_3 = 1/(l_3 \cdot W_m), \\ w_4 = 1/(l_4 \cdot W_m), w_5 = 1/(l_5 \cdot W_m), \dots, w_{L+4} = 1/(l_{L+4} \cdot W_m) \quad (18)$$

(3) The spectral reflectance to be interpolated is calculated by using the weight coefficients mentioned above and the equation below:

$$S_{x,y}(\lambda) = w_1 \cdot S_{x,0}(\lambda) + w_2 \cdot S_{0,y}(\lambda) + w_3 \cdot S_{x,100}(\lambda) + w_4 \cdot S_{100,y}(\lambda) + \\ w_5 \cdot S_1(\lambda) + \dots + w_{L+4} \cdot S_L(\lambda) \quad (19)$$

### Transformation from Spectral Reflectances to RGB values

The presumed spectral reflectances by the method written above is transformed into the RGB values to display the images corresponding to them on a monitor.

The algorithm of such transformation is described below:

- (1) A CRT display to be used is calibrated on a D50 basis.
- (2) The Y value (CIEXYZ1931) of the color patch on the display is measured when the RGB value of it is (255, 255, 255).
- (3) The presumed spectral reflectances is transformed into the CIEXYZ(1931) values according to the specifications of CIE 15.2 - Colorimetry.
- (4) All the CIEXYZ(1931) values calculated above is linearly altered so that the Y value of paper should be equal to the Y value measured in item (2).
- (5) The CIEXYZ(1931) values is transformed into the RGB values according to a 21 inch Reference Calibrator, a BARCO.

$$\begin{pmatrix} R \\ G \\ B \end{pmatrix} = T \cdot \begin{pmatrix} X \\ Y \\ Z \end{pmatrix} \quad (20)$$

$$T = \begin{pmatrix} 255/L_{Rmax} & 0 & 0 \\ 0 & 255/L_{Gmax} & 0 \\ 0 & 0 & 255/L_{Bmax} \end{pmatrix} \cdot \begin{pmatrix} x_R/y_R & x_G/y_G & x_B/y_B \\ 1 & 1 & 1 \\ (1-x_R-y_R)/y_R & (1-x_G-y_G)/y_G & (1-x_B-y_B)/y_B \end{pmatrix}^{-1} \quad (21)$$

- (a)  $R, G, B$ : digital values output to a CRT display
- (b)  $X, Y, Z$ : CIEXYZ(1931) values corresponding to the presumed spectral reflectances
- (c) The characteristics of the CRT display to be used
  - 1)  $R: (x_R, y_R), L_{Rmax} \dots (x_R, y_R)$ : chromaticity of output when  $R=255$ ,  $L_{Rmax}$ : luminance of output when  $R=255$ . (unit:  $cd/m^2$ )
  - 2)  $G: (x_G, y_G), L_{Gmax} \dots (x_G, y_G)$ : chromaticity of output when  $G=255$ ,  $L_{Gmax}$ : luminance of output when  $G=255$ . (unit:  $cd/m^2$ )
  - 3)  $B: (x_B, y_B), L_{Bmax} \dots (x_B, y_B)$ : chromaticity of output when  $B=255$ ,  $L_{Bmax}$ : luminance of output when  $B=255$ . (unit:  $cd/m^2$ )
- (6) The RGB values are corrected according to the  $\gamma$  characteristic of the CRT display.
- (7) The  $\gamma$ -corrected RGB values are output to the CRT display and the outputs are measured on a CIEXYZ (1931) basis. Comparison is done based on  $\Delta E_{94}$ .

### Comparison Between the Interpolated, the Displayed and the Measured Values

Table 1 shows a difference between the interpolated, the displayed, and the measured values by using the interpolation method expressed by the equation(13). Table 2 shows the difference among them by using the interpolation method expressed by the equation(14). All the results are shown based on  $\Delta E_{94}$ .

XX/Y.YY in the following tables represents X.XX as the average of color differences and Y.YY as the maximum value of color differences.

The printer used here is a Print Partner GL-8300 made by Fujitsu Ltd.

**Table 1. Comparison of the presumed and the measured by using the equation(13)**

	Average ( $\Delta E_{94}$ )	Max ( $\Delta E_{94}$ )	Location (Max)
CK	1.21/3.09	3.19/6.81	(30,50)
MC	1.16/1.69	3.42/3.76	(50,90)
MK	0.90/1.65	3.20/5.16	(30,60)
YC	1.28/1.81	3.39/3.39	(20,40)
YK	1.44/2.72	5.66/5.88	(30,40)
YM	1.05/1.45	3.17/3.20	(30,60)
Total	1.17/2.07	5.66/6.81	(Y30,K60)

**Table 2. Comparison of the presumed and the measured by using the equation(14)**

	Average ( $\Delta E_{94}$ )	Max ( $\Delta E_{94}$ )	Location (Max)
CK	1.16/2.60	3.22/4.09	(70,20)
MC	1.16/2.52	3.72/5.07	(50,70)
MK	0.92/1.99	3.25/4.04	(30,60)
YC	1.18/2.27	3.05/3.88	(20,40)
YK	1.44/2.55	5.68/6.33	(30,40)
YM	1.07/2.02	3.16/3.52	(30,50)
Total	1.16/2.32	5.68/6.33	(Y30,K40)

C: cyan, M: magenta, Y: yellow, K: black

Up to the secondary gradation colors, Print Simulator can give us the colors to be presumed with a high degree of accuracy.

### Conclusion

I have succeeded in interpolating the spectral reflectances by using a set of linear equations, based on spectral data.

(1)The data necessary for the algorithm are composed of the M set of spectral reflectance data on the 32 edges. It is recommended that the number M should be 11 in this paper. The 11 set of spectral data represent a gradation of color on each edge. The color subspace surrounded by these 32 edges is the color gamut that a printer with CMYK toners can reproduce.

(2)Accuracy of the algorithm up to the secondary gradations is confirmed. As the average of  $\Delta E_{94}$  is 4 and the maximum is 12 on the ordinary method by using the look-up table (729 patches), Print Simulator achieves much better accuracy.

(3)It is confirmed that the printed results of the secondary gradation colors can be simulated on a monitor with high accuracy. Such accuracy makes Print Simulator a good soft-proofer of printed images and a good predictor of under color removal on printers.

### Further Studies

The following studies are now scheduled.

- (1) Print Simulator will be applied to printers with more than four colorants.
- (2) More realistic reproduction of objects including specular reflections will be done by extending the algorithm.

### References

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### Biography

Mr. Usui is a geophysicist graduated from Tohoku University in Japan. Since then, he has been engaged in exploration by image analysis (Remote Sensing, Acoustic Sensing and so on). At the present, he is engaged in color management and developing the new soft proofing system at Fujitsu Laboratories LTD. He is also an expert of the IEC/TC100/PT61966 Part 7 (colour printer).