

# Effects of Stochastic Screening on the Color Gamuts of Wide Gamut Printing Systems

*Karl Guylar*  
*Hallmark Cards, Inc.*  
Kansas City, MO

## Abstract

A method is described for mapping triangulated surfaces of printer characterization targets in colorant space to CIELAB color space. Particular attention is paid to the dark, bottom side of the gamut where subgamuts converge with increasing black in the targets. Once in CIELAB color space tetrahedra are formed from surface triangles and a center point. The volumes of the tetrahedra are computed and summed to produce the gamut volume. This method does not employ the use of convex hulls. Therefore it preserves any concavities of the printing gamut and does not overestimate gamut volume.

The methods for visualizing gamuts and computing volumes were used to measure the effects of stochastic (FM) screening versus amplitude modulated (AM) screening in lithographic printing gamuts. Besides the conventional 4-color process printing scheme, wider gamut 5-color and 6-color gamuts were analyzed on two stocks. The 5-color ink set has a ramp of pink before the onset of a magenta ink. The 6-color has a light cyan printed before the strong cyan plus the same magenta channel as the 5-color system. Volume analysis was broken down further to analyze the individual red, green and blue faces as well as the bottom halves of the gamuts. The use of fluorescent pink in the 5- and 6-color process printing systems greatly expands chroma and lightness in the red and orange portions of these gamuts. These colors extend beyond the ISO 12640-3 reference gamut for both coated and uncoated stocks. Adding light cyan in the 6-color ink set, enhances the green face of the gamut at the expense of the blue face. Adding the sixth ink causes little change to the total volume but the gamuts fill different color regions.

Four-color gamuts benefited most from changing from AM to FM screening, about 15%. The much larger 5- and 6-color gamuts benefited significantly less, 7.5% and 4%, respectively. Of the top three faces of the color gamut, the green face gained the most volume from the screening change. Next in ranking came the blue face followed by the red. Overall FM screening did little to expand the gamuts that already had high lightness and chroma values due to the use of fluorescent pink or light cyan. The change in screening type had little effect on the bottom, shadow half of the gamuts.

The 3-dimensional loci of the halftone scales of cyan and magenta bow away from the Neugebauer loci. This latter line extends from white to solid ink coverage as predicted by the Neugebauer model without scattering correction. When the 4-color cyan and magenta halftone scales are compared to their non-scattering Neugebauer loci, the FM data shows the greatest shifts in hue and lightness. This is the source of gamut enhancement of FM screening. The yellow scales bowed only slightly and were

unaffected by screening type. In ink sets extended by a light colorant both the AM and FM halftone scales closely follow the Neugebauer loci over most of the halftone scale. When the strong cyan or magenta were added to their light color counterparts, the FM scale again bows away from non-scattering Neugebauer locus. Hue shift and lightness gains of FM screening are almost totally lost with 6-color gamuts with two light colorants.

## **Background**

Hallmark Cards has a forty year history of lithographic printing with a set of wide gamut 5- or 6-color process inks. These systems are unlike the heptatone and hexatone system of Keuppers<sup>1</sup> and Pantone's Hexachrome<sup>TM2</sup>, which contain inks of intermediate hue angles between the primary process colors of cyan, magenta and yellow (CMY). The Keuppers systems use red, green and blue, while Pantone uses fluorescent orange and green. Other 7- and 9-color systems were investigated by Ostromoukhov.<sup>3</sup> Color separation of these high fidelity ink systems is complex but not intractable. Several schemes have been developed. A simpler approach is to extend the gamut with light inks. The ink sets described in this study use light cyan and a fluorescent pink to extend the printing scales of cyan and magenta respectively. This use of 'light colors' is now common place in the field of wide format ink jet printers. Many such devices now use six to eight colorants to produce photo quality images. If the transition from the light colors to strongest process color is handled in the RIP, these devices operate in a pseudo 4-color world with three opponent chromatic colorants plus black. The advantage is that there are 4-color targets, such as the ANSI IT8.7/3 and ECI2002, can be used to characterize the printer and provide a sampling of the gamut surface of the printing process. Such targets are readily recognized by commercial profiling and gamut visualization software.

The use of fluorescent pink and light cyan greatly expands the red and green regions of the simple 4-color system.<sup>3</sup> Historically Hallmark has printed with conventional amplitude modulated screening (AM). The question arose as to whether stochastic or frequency modulated screening (FM) would produce even cleaner and brighter colors and larger gamuts than the traditional AM system. Could stochastic screening enhance the color gamuts of each of the 4-, 5- or 6-color printing processes?

To address these questions a gamut visualization tool was developed to examine the faces of the AM and FM gamuts. An algorithm was developed to compute gamut volume of gamuts with concave regions. These tools were applied to ANSI IT8.7/3 and ECI2002 data.

## **Gamut Descriptor and Volume Calculator**

Bakke<sup>4</sup> recently evaluated three techniques for constructing gamut boundary descriptors and computing their volumes: the convex hull, an  $\alpha$ -modified convex hull and the segment maximum method. The last two performed well if the correct  $\alpha$  and volume sampling size is chosen. Convex hulls overestimate gamut volume when gamuts have

surface concavities. In this study a triangulated grid approach was used to define the gamut surface. This is very similar to technique used by Willert et al.<sup>5</sup> The volumes however are calculated in a different manner by computing the tetrahedron volumes as described by Saito and Kotera.<sup>6</sup> The volume is computed by the scalar triple product using vectors  $\mathbf{a}$ ,  $\mathbf{b}$  and  $\mathbf{c}$  from the vertices of the gamut face triangles to the center point,  $[50\ 0\ 0]$  in Lab coordinates:

$$V = 1/6 |\mathbf{a} \cdot (\mathbf{b} \times \mathbf{c})| \quad (1)$$

The Lab coordinate form of (1) is found in equation 2 where  $V$  is tetrahedron volume,  $||$  is the determinant and  $L_4 a_4 b_4$  in this study is always the center point,  $[50\ 0\ 0]$ <sup>7</sup>. The result of the determinant can have a sign and thus give a negative volume. Therefore the absolute is taken before summing over all tetrahedron.

$$V = \text{abs}(1/6( \begin{vmatrix} L_1 & a_1 & b_1 & 1 \\ L_2 & a_2 & b_2 & 1 \\ L_3 & a_3 & b_3 & 1 \\ L_4 & a_4 & b_4 & 1 \end{vmatrix} ) ) \quad (2)$$

The characterization target samples the top of the gamut with a 6 x 6 grid pattern for the IT8.7/3 or a 9 x 9 pattern for ECI2002. Although ECI2002 targets were measured, only the points of the IT8.7/3 were used in this analysis. The mesh grid spacing for this latter target is  $[0\ 10\ 20\ 40\ 70\ 100]$  dot percent. In colorant or ink space the gridding is shown in Figure 1a below. Each of the squares or rectangles is replaced by two triangles. Only the red, green and blue faces are mapped to CIELAB color space and plotted in 3-dimensions. The connectivity of triangles is maintained in this mapping. Figure 1b shows the same faces in color space. The bottom half of the gamut uses a different construction.

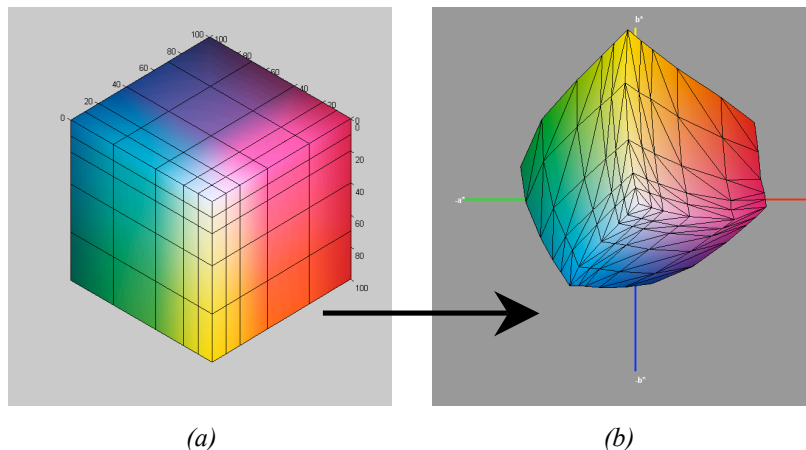
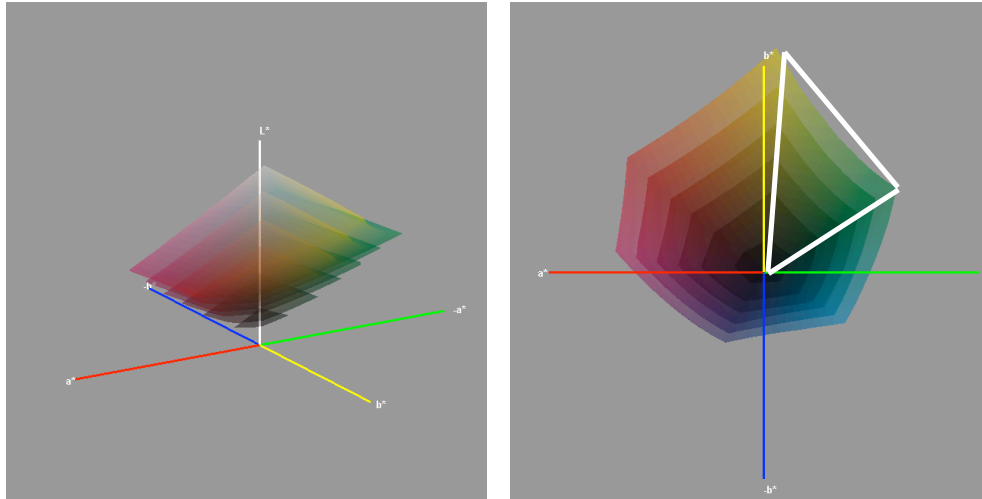


Figure 1. IT8.7/3 grid spacing in %dot (a) in colorant space and (b) in Lab space

The visualization of the bottom half of the gamuts, which uses the black printer, presents a challenge. The mapping of the colorant cube is straight forward if one uses only CMY with 0% black. In reality the target has five additional colorant cubes with combinations

of CMY with 20, 40, 60, 80 and 100% black. If one visualizes all of these cubes simultaneously, as shown in Figure 2, it is clear that the bottom half of the gamut is the union of the six colorant cubes. These appear like matryoshka or nested Russian dolls. The bottom of the gamut must connect the Y-R-M-B-C-G-Y perimeter of each subgamut to the next black level and finally unite with the 4-color black. This nadir is the KCMY point [100, 100, 100, 100].



(a)

(b)

Figure 2 Bottom half of an IT8.7/3 gamut with nested subgamuts with increasing black

The gamut bottom can be broken to six triangular regions such as the region highlighted in Figure 2b. As the percent black increases the number of tonal steps for C, M and Y

	K	C	M	Y
1	0	0	0	100
2	0	10	0	100
3	0	20	0	100
4	0	40	0	100
5	0	70	0	100
6	0	100	0	100
7	20	0	0	100
8	20	10	0	100
9	20	20	0	100
10	20	40	0	100
11	20	70	0	100
12	20	100	0	100
13	40	0	0	100
14	40	20	0	100
15	40	40	0	100
16	40	70	0	100
17	40	100	0	100
18	60	0	0	100
19	60	20	0	100
20	60	40	0	100
21	60	70	0	100
22	60	100	0	100
23	80	0	0	100
24	80	40	0	100
25	80	70	0	100
26	80	100	0	100
27	100	0	0	100
28	100	100	0	100
29	100	100	100	100

Table I. Ink table for yellow to green with varying black on the gamut bottom

decrease. The available points from Figure 2b are collected in Table I. The table shows only two columns are variable, C and K. The exception is in the last row, the lowest gamut point [100 100 100 100]. If this is given false coordinates of C=50 and K=120, one can make a 2-dimensional map in colorant space, Figure 3. Using MATLAB a 2-dimensional DeLaunay triangulation is made for the K and C channels shown in Table I. This function returns a 39 x 3 connectivity matrix using the row indices of the input points. For each row of Table I there is a corresponding set of the Lab coordinates. The Delaunay connectivity matrix is applied to these CIELAB coordinates to construct one sixth of the triangulated bottom surface of the gamut in 3-dimensional space. The MATLAB patch command was used to paint 39 surface triangles in color. Finally the volumes of 39 tetrahedra, which all use the same the center point, are computed using equation (2) and totaled.

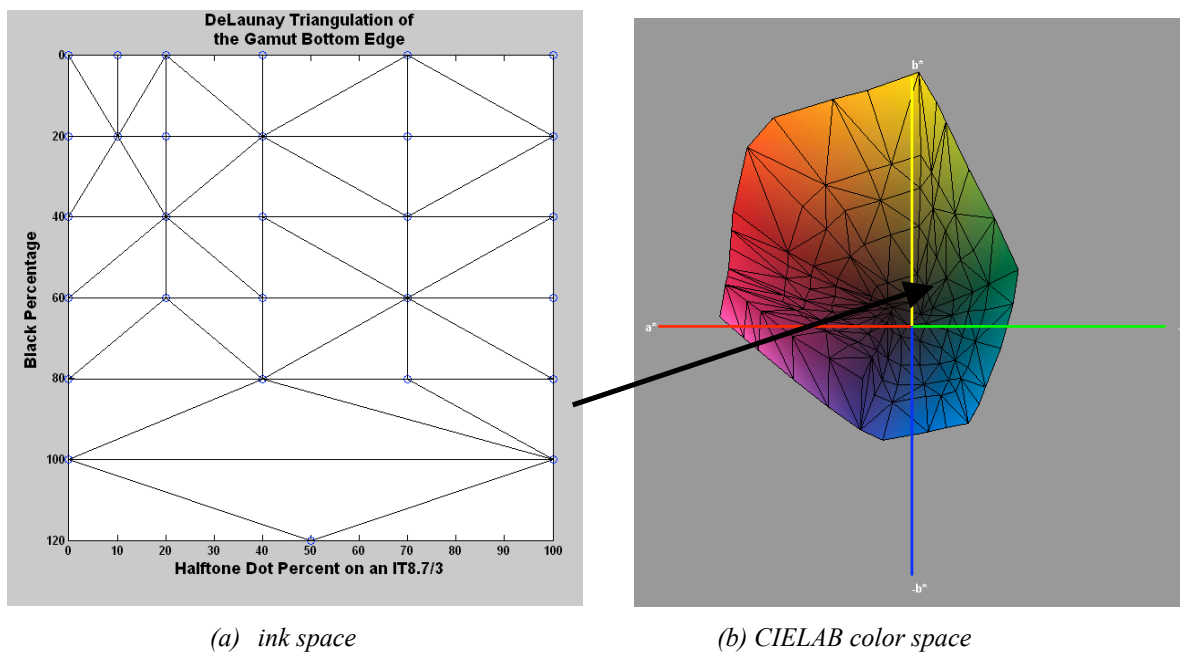


Figure 3. Bottom triangular region of an IT8.7/3 in (a) ink space and (b) in color space

The other five sections of the gamut bottom are derived by holding the black column of Table I constant and permuting the C, M, Y columns in the table. The Delaunay connectivity remains the same. A function was written in MATLAB that takes the full inking table like Table I and returns the corresponding Lab table for plotting and volume calculations. Color data is averaged for duplicate patches in the target.

This gamut boundary descriptor of this treatment is fixed by the number of dot percentages gradations of the target with increasing black. An ECI2002 target has a different mapping, which begins with nine steps in dot percentage and ends in three. With this method color gamuts are compared with the same surface points and surface triangles under different experimental treatments. In contrast convex hulls can use different numbers of points and different target points from the same target. Results from this method do not depend on optimizing any volume sampling factors or  $\alpha$  parameters to separate interior points from surface points.

## Analyzing screening effects

The three process color ink sets used in this study were printed by offset lithography. The AM screening used 175 lines per inch and the FM screening used approximately 25 micron dots. The printing order was KCMYP for 5-color and KCMLYP for 6-color, where P in fluorescent pink and L is light cyan respectively. Measurements were taken with a Gretag-Macbeth Spectrolino for both coated and uncoated stocks. Both stocks contained optical brighteners. All combinations of ink sets, stock and screening type produced twelve gamuts for analysis. During the calculation of gamut volumes intermediate sums were taken for the red, green and blue faces of the upper gamut and the volume of the lower gamut with increasing black. Table II shows the results using a Lab center of [50 0 0]. This point is very close to the center of gravity of a 4-color gamut. The face and gamut half volumes are completely dependent on this choice of the center point for tetrahedra construction, while the total volume is not. Computations with neutral centers with L\*-values of 40 and 60 were tested. These showed the same total volumes but different face volumes as expected.

Table II Gamut and face volumes as a function of ink set, screening and stock

Screening	Colors	Stock	Red Face	Green Face	Blue Face	Gamut Top	Gamut Bottom	TOTAL VOLUME
AM	4-Color	Coated	74,814	72,114	47,278	194,206	202,099	396,305
AM	5-Color	Coated	138,299	71,917	97,235	307,452	231,092	538,544
AM	6-Color	Coated	138,217	86,741	90,587	315,546	232,506	548,052
AM	4-Color	Uncoated	56,068	50,036	33,403	139,507	62,264	201,771
AM	5-Color	Uncoated	128,996	49,009	85,644	263,649	89,802	353,451
AM	6-Color	Uncoated	126,783	66,289	75,416	268,488	85,944	354,432
FM	4-Color	Coated	83,895	93,584	59,923	237,402	212,843	450,245
FM	5-Color	Coated	142,239	95,649	103,434	341,322	237,991	579,313
FM	6-Color	Coated	147,626	98,118	95,152	340,897	229,580	570,477
FM	4-Color	Uncoated	62,974	67,926	41,036	171,936	62,286	234,222
FM	5-Color	Uncoated	127,531	67,249	91,262	286,042	87,616	373,658
FM	6-Color	Uncoated	131,556	75,260	78,293	285,109	82,814	367,923

Table II shows that adding pink in the 5- and 6-color ink sets roughly doubles the volume of the red faces of the gamuts. This occurs irrespective of the screening or stock type. Figure 4 shows that adding pink extends the red and orange colors beyond the ISO 12640-3 reference gamut. Adding light cyan to go from a 5- to a 6-color ink set expands the green face at the expense of the blue face. As a result total gamut volume changes little. AM total volume increases slightly with this change, while FM total volume decreases slightly.

Volumes changes caused by screening changes from AM to FM are shown in Figure 5. FM screening enhances the 4-color gamut volume on the two stocks an average of 15%. The 5-color gamut showed only about half this amount and the 6-color gamuts showed the least change with an average of 4%. Table III shows how the hemispheres and face volumes changed with the switch from AM to FM. The green face always shows the greatest growth in volume. The blue shows the next largest gain in 4-color, but this drops precipitously with the 5- and 6-color ink sets. The red face showed the least changes.

Another important observation is that the bottoms of the gamuts show only slight volume changes. Unlike in the top face, bottom gamut patches have little opportunity for light to enter the paper and exit the printed dot.

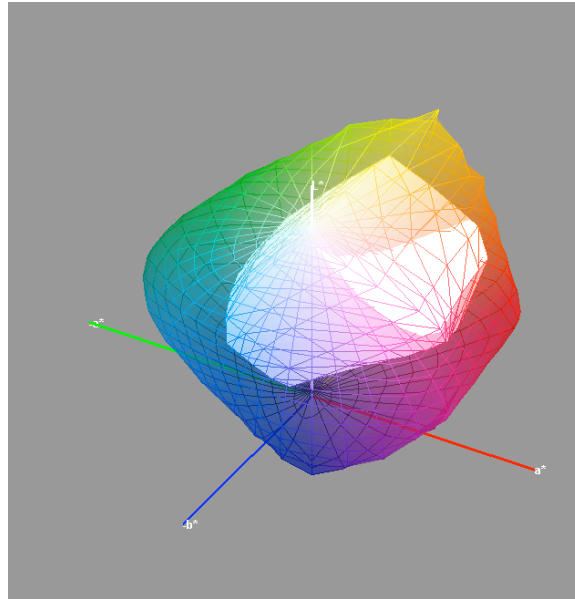


Figure 4 Red and orange regions of FM 6-color inks on coated stock extend beyond the ISO 12640-3 reference gamut

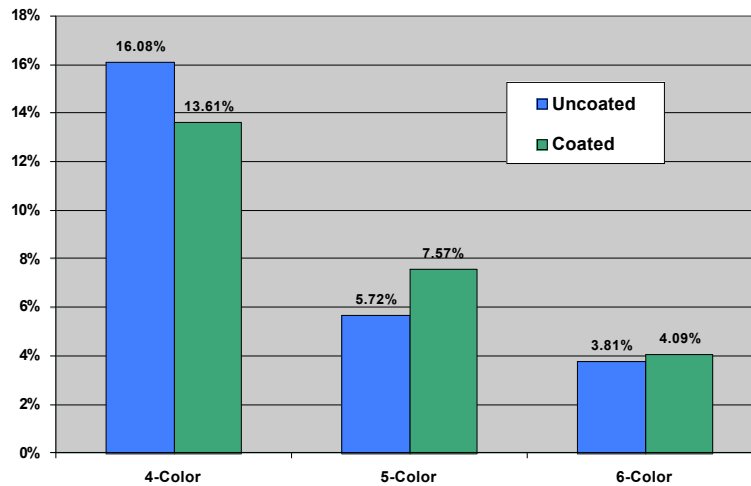


Figure 5 Percent gamut volume increase from changing AM to FM screening

These changes in going to stochastic screening are expected based on the large optical dot gain with much smaller FM dots. When stochastic screening was implemented plate curves were adjusted so that the tone reproduction curves, density versus halftone dot percent, of FM closely followed the historical AM curves. Even though the AM and stochastic density scales were coincident, visual examination showed they were clearly two different colors. All the density channels did not agree. Visually cyan and magenta were cleaner and brighter with stochastic screening. Engeldrum showed the color gamut

limits of halftone scales with and without scattering by paper.<sup>8</sup> Without light scattering the color locus along a halftone scale should be defined by percentage of paper and ink coverage. The locus is a straight line connecting paper color to full tone ink color in tristimulus space, XYZ, or 2-dimensional chromaticity space, xy. Mapping this to Lab space produces a curved locus with this simple Neugebauer model. Engeldrum showed that light scatter due to the Yule-Nielsen effect produces added lightness and hue shifts to the cyan and magenta halftone ramps. The maximum shifts occur near the midpoints of the ramps. The yellow halftone scale is only slightly affected by this scattering. Both hue shifts and lightness shifts were found for cyan and magenta, but none for yellow. Arney et al have shown that the color of a halftone scale can be constructed from three colors: the stock, the solid color and the color of the solid at half thickness plus a scattering coefficient.<sup>9</sup> Arney found curvature in xy chromaticity plots of the halftone scales. He points out that it is the non-linear relationship between path length and transmission that control the halftone ramp colors and cause the color shifts. This increase in lightness from light scattering is the basis for gamut volume enhancements. The smaller dot size of stochastic screening provides a higher probability for light to enter the paper and exit the ink than does AM screening.

Table III AM to FM face and hemisphere percent volume changes

	R Face	G Face	B Face	Top	Bottom	Total
Coated 4-Color	12.1%	29.8%	26.7%	22.2%	5.3%	13.6%
Coated 5-Color	2.8%	33.0%	6.4%	11.0%	3.0%	7.6%
Coated 6-Color	6.8%	13.1%	5.0%	8.0%	-1.3%	4.1%
Uncoated 4-Color	12.3%	35.8%	22.9%	23.2%	0.0%	16.1%
Uncoated 5-Color	-1.1%	37.2%	6.6%	8.5%	-2.4%	5.7%
Uncoated 6-Color	3.8%	13.5%	3.8%	6.2%	-3.6%	3.8%

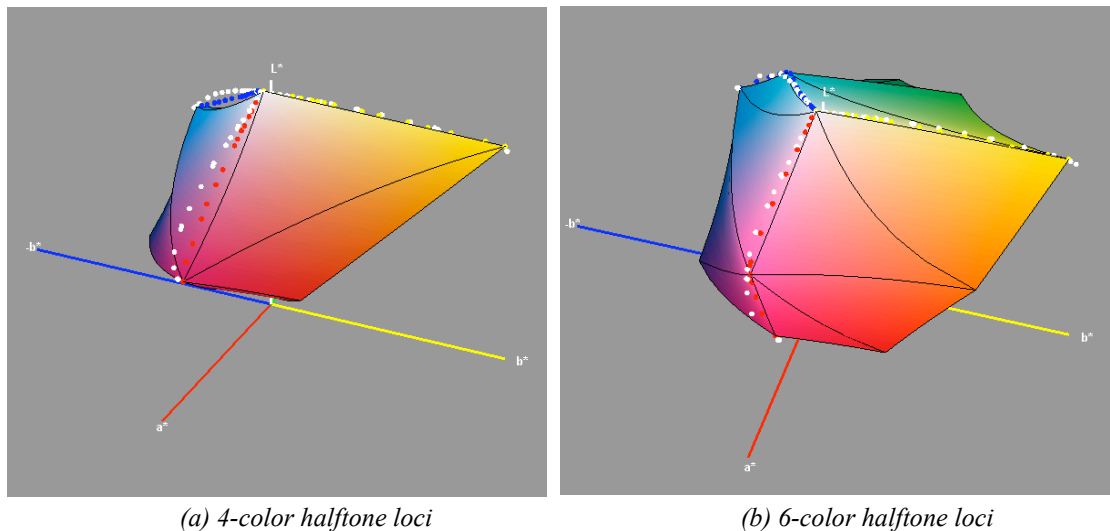


Figure 6 Loci of CMY halftone scales in Lab space compared to their respective simple Neugebauer loci  
Stochastic scales are in white and AM scales are colored

In the 4-color gamut the FM screening shows larger scatter effects than with the AM screening. In Figure 6(a) the 4-color gamut surface was constructed from just eight

points. A convex hull was formed in XYZ space and the edges mapped to Lab space. The edges of the solid are lines derived by the simple Neugebauer model. The closest edge to the viewer connects the white paper to the solid magenta. Onto this are plotted the magenta halftone scales for stochastic screening in white and AM screening in color. The FM locus shows the greater departure from the gamut edge. In the background is a similar plot for the cyan to paper edge. The stochastic cyan halftone has greater lightness than the AM scatterplot in white. On the yellow edge both halftone scales are nearly coincident with the gamut edge and show little if any scattering effects.

Figure 6(b) shows a similar gamut surface constructed for a 6-color ink set. The magenta halftone scale has two edges on the gamut surface. One connects paper to pink and another connects pink to magenta-pink. Both the AM and FM halftone scatterplots closely follow the theoretical locus for the pink portion. There is little differentiation between the two screening algorithms. This indicates little effect from light scattering. In the region from pink to pink-magenta both scatterplots show significant curvature away from the pink to pink-magenta theoretical line. The cyan ramps behave similarly and closely follow the edges predicted by a simple Neugebauer model. In this respect the light inks behave like yellow. When printing with the light ink sets there is little discrimination between the halftone scales. There is very little gamut volume enhancement in going to stochastic screening with these ink sets.

In conclusion the stochastic screening provides the largest gamut volume increase for the smaller 4-color gamuts. The AM to FM enhancement decreases as lighter inks are added to expand to the total gamut volumes. The least change in volume with screening, 4%, occurs with the largest volume 6-color ink set.

## References

1. Kueppers H. US Patent 4,812,899; March 14, 1989.
2. Herbert, R, DiBernardo A. US Patent 5,734,800; March 31, 1998
3. Guyler K. Visualization of Expanded Printing Gamuts Using 3-Dimensional Convex Hull, TAGA Proceedings 2000. p 696
4. Bakke AM, Hardeberg JY, Farup I. Evaluation of Gamut Boundary Descriptors. In: Fourteenth Color Imaging Conference, Scottsdale, AZ; November 2006. p 50
5. Willert A, Flaspohler M, Hubler AC. Calculating a Color Gamut Border Using a Grid Approach. In: Proceedings of the Second European Conference on Color in Graphics, Imaging and Vision, Aachen, Germany; April 2004. p 156
6. Saito R, Kotera H. Extraction of Image Gamut Surface and Calculation of its Volume. In: Eighth Color Imaging Conference, Scottsdale, AZ; November 2000. p330
7. Weisstein, EW. CRC Concise Encyclopedia of Mathematics. New York: Chapman & Hall/CRC; 1999. p 1799
8. Engeldrum PG. The Color Limits of Halftone Printing with and without the Paper Spread Function, J Imaging Sci Technol 1996; 40:239-244
9. Arney JS, Scigaj C, Mehta P. Linear Color Addition in Halftones, J Imaging Sci Technol 2001; 45:466-471

10. Holm J, Tastl I, Johnson, T. Definition & Use of the ISO 12640-3 Reference Color Gamut, In: Fourteenth Color Imaging Conference, Scottsdale, AZ; November 2006. p 62-68

### **Author Biography**

Karl Guyler received his BS in Chemistry from Lebanon Valley College (1969) and his MS in Chemistry from the University of Delaware(1972). Since 1981 he has been a research chemist for the Advancing Technologies division of Hallmark Cards in Kansas City, MO. Areas of activities include printing inks, coatings and colorants used in lithography, rotogravure, flexography, screenprint and inkjet proofing. His research interests include lightfastness of fluorescent materials and color gamut boundary descriptors. He is a member of the ACS, the GAA, TAGA, RadTech and IS&T