Digital Presses Color Uniformity

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Abstract

This study addressed the color uniformities of digital printing systems. It compared the color uniformities of 28 electrophotographic presses and 9 inkjet presses. The results in this report are coded to protect the identities of the participants.

This study is the third in a series by this research team examining the color uniformity of digital presses. The first study, published in the 2013 TAGA Proceedings, examined the color uniformities of six electrophotographic presses compared to the uniformities of a lithographic press and an inkjet proofing device. The second study (2014 TAGA Proceedings) focused on the color uniformities of large solid areas for seven electrophotographic presses, again compared with an inkjet proofing device.

A 12-page digital test form was designed for this study. The first page included 6 repeats of a 96-color target at different locations on the page. The remaining 11 pages were dominated by large checkerboard patterns providing significant coverage of a single color. Different colors were chosen for each of the pages. All 12 of the test form pages have a cyan, magenta, yellow, and black (CMYK) color bar imaged across the top of the page, as well as a continuous register track around the perimeter of the page.

The analysis for this study included examination of the color bar to evaluate two things:

- The uniformity of the CMYK colors across the page.
- The consistency of the color bar on the 12 pages of the form.

The second phase of the analysis was to measure the color uniformity of the 11 checkerboard pages. These results shed light on the capacity of the digital presses to uniformly image large solid areas of color.

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The third phase of the analysis was to evaluate the color uniformity of the digital presses from the 96-patch color field. This involved reproducing a large number of colors (96) a limited number of times (6) widely spaced across an 11x17-inch page.

The final analysis made in this study was to make subjective comparisons between the register accuracy and the resolution of the digital presses based on photomicrographs taken of sections of the register grid and the Star Targets.

Background

Color uniformity of a printing press is defined as the consistency of color appearance across a printed sheet. This study uses a sheet size of 11x17 inches, which is compatible with most digital presses. A spectrophotometer was used to measure CIELAB values from targeted areas of the printed sheet. Pairs of CIELAB values from areas of the printed sheet that should be the same color were used to calculate ΔE2000 color differences. Color differences of zero indicate an exact color match between the two measured areas. Color differences of one equate to a just noticeable difference for the average human observer.

When color measurements of a given color are made from several locations on a printed sheet, many different combinations of measured pairs can be examined, and, thus, many ΔE2000 color differences result. The average of these color differences is computed as the color uniformity value for that printing press and that color.

This study includes a larger range of electrophotographic and inkjet presses than the previous studies. The market for digital printing has grown rapidly, and there are an increasing number of presses aimed at that market. Significantly, several inkjet presses have been introduced to compete with electrophotography in the digital color printing arena.

There were 37 digital presses included in the study. Nine were inkjet and 28 were electrophotographic. The inkjet presses included 2 proofing presses, 6 high-speed inkjet presses, and 1 wide-format inkjet press. The 28 electrophotographic presses included 6 liquid-toner presses and 22 dry-toner presses. Appendix A contains a list of the presses in the study, as well as the substrates that were used.

Test Form

The test form used for this study was a 12-page design using 11x17-inch pages. The test file was made available in several different formats to accommodate presses that printed on different sizes of paper. In every case, the participants submitted four samples of the 12-page test form for analysis. To avoid the warm-up effect that was identified in the 2013 study, the third version of the printed pages was measured for the analysis.

The test form design evolved from the two test forms used in the earlier studies. Figure 1 shows all 12 pages of the 2016 test form.

Figure 1. *Twelve-page test form (each page 11x17 inches).*

The first page of the 2016 test form, which is depicted at a larger scale in Appendix B, is a modified version of the test form that was used in the 2013 study (shown in Appendix C). The modifications include the addition of a continuous register track around the page to measure the register accuracy of digital presses. In addition, the photographic images were changed from two repeats of the same image in the 2013 form to two different photographs in the 2016 form. The new images include a daylight image that is rich in saturated memory colors and a highlight image that contains a variety of light textures and colors that are difficult to reproduce accurately.

Pages 2–12 of the 2016 test form are based on the large solid-color blocks that were used in the 2014 test form (shown in Appendix D). The large color areas from the 2014 form were broken up into checkerboard patterns for the 2016 form. This was done to make a more reasonable coverage demand on the digital presses and to avoid the occurrence of image streaks, which were observed in the 2014 results. Also, color bars and continuous register tracks were added to pages 2–12 on the 2016 test form to provide continuity in measuring register and solid-color consistency across all the pages of the form.

The 2016 test form used the same 11 colors that were used in the 2014 study. Ten of the colors for the large solids were selected from colors that were found to be least uniform in the 2013 study. These colors, referred to as 90th percentile colors, were in the highest 10% for average ΔE2000 color difference scores for one of the three types of printing in the 2013 study: electrophotography, inkjet, and sheetfed lithography. The 11th color was a 260% coverage patch added to check the uniformity of dark shadow areas. The patch designations, CMYK color values, and processes for which the colors were in the 90th percentile are shown in Table 1.

	Patch	Cyn	Mag	Yel	Blk	Color
Electrophoto	B7	75	63	63	0	
	F2	80	90	20	15	
	H3	0	0	0	75	
	D2	65	45	25	15	
Litho	C4	50	40	40	0	
	G9	0	75	75	0	
	D10	90	80	20	0	
Inkjet	A11	25	0	25	0	
	G6	20	80	90	15	
	C8	0	25	25	0	
	260%	65	58	57	80	

Table 1. *Solid-color patch designations, CMYK color values, and processes for which the colors were in the 90th percentile in 2013.*

Color Field of 96 Patches

The six repeats of the 96-patch color field (Figure 2) remain the same for all versions of the test form. This target was the heart of the 2013 color uniformity analysis, and it has provided continuity between all three phases of this study.

Figure 2. *96-patch color field and its six positions on page 1 of the test form.*

The cyan, magenta, yellow, and black dot values for each of the 96 patches in the color field are shown in Appendix E. The color values were chosen to provide a uniform sampling of the color space with reference to hue, lightness, and saturation.

Analysis

The analysis of the printed samples had several phases, including analysis of:

- The color bars at the top of all 12 test form pages.
- The color uniformity of the single-color checkerboard pages.
- The 96-patch color field targets from page 1 of the test form.
- The register accuracy for each of the presses.
- The resolution of the printed Star Targets.

Color Bar Analysis

The color bar at the top of each page consisted of solid cyan, magenta, yellow, and black patches that repeated 10 times across the width of the page. The first task of the analysis was to evaluate the consistency of color across the page. The optical density of each patch was measured, and the density profiles across the pages were examined for uniformity. Densitometry was used for this analysis because it yields a single color value that is easily compared rather than the more complex tristimulus values that underlie colorimetric measurements. After examining the uniformity of solid ink colors across the color bar, colorimetric measurements will be used exclusively in this report so that color differences can be evaluated in perceptual terms for a human observer, which is not practical with densitometric measurements.

Ideally, regardless of the strength of the optical density, each press should produce a horizontal profile for each of the process colors. The density profiles for the cyan patches across the first page of the test form for each participant are shown in Figure 3. The density profiles for cyan, magenta, yellow, and black are shown in Appendix F.

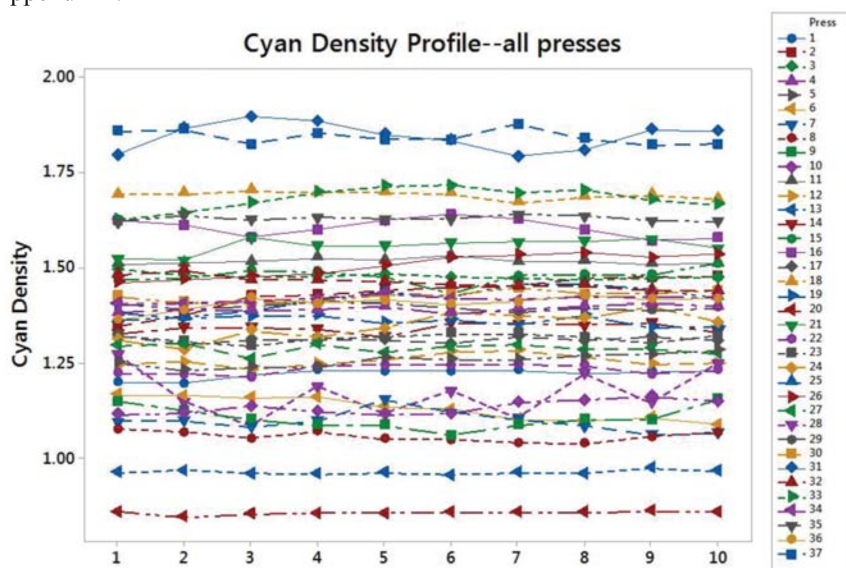


Figure 3. *Page 1 cyan optical density profiles for all test participants.*

The density profiles in Figure 3 show a striking range of solid densities among the 37 digital presses in the study. Cyan densities as low as 0.84 (14% reflectance) and as high as 1.88 (1.4% reflectance) were measured from different digital presses. The density profiles are relatively horizontal with a few exceptions. These observations were also true for the other process colors, as can be seen in Appendix F.

Table 2 shows the mean CMYK densities of the color bars from all the presses, and then separately for electrophotographic presses and inkjet presses. Table 2 also shows, for reference, the last published SWOP specifications (2007) that included solid density aimpoints.

	Cyn	Mag	Yel	Blk
All presses	1.37	1.40	0.98	1.73
Electrophoto.	1.40	1.43	0.99	1.79
Inkjet	1.28	1.30	0.96	1.53
SWOP pre 2007	**1.30**	**1.40**	**1.00**	**1.60**

Table 2. *Mean solid density values.*

Overall, the elctrophotographic presses had higher average densities than the inkjet presses. None of the digital presses were aimed at achieving the pre-2007 SWOP densities, but using them as a reference point, the electrophotographic press densities were high in cyan, close in magenta and yellow, and high in black. The inkjet press densities were close in cyan, low in magenta, close in yellow, and low in black.

As noted above, the color bar profile plots showed large ranges of densities produced by the different digital presses. To determine if this was related to the types of digital presses in the study, the data was separated and density profiles were plotted for electrophotographic presses using dry toners (22), electrophotographic presses using liquid toners (6), high-speed inkjet presses (6), and proofing plus wide-format inkjet presses (3). The cyan density profiles for these four groups are shown in Appendix G. These profiles show that each of the categories of digital presses had a wide range of cyan densities. This was also observed for the magenta, yellow, and black densities.

An anomaly was observed for one of the proofing presses in the study. For two of the ink colors there was a distinct difference in the densities across the color bar. The cyan, magenta, yellow, and black density profiles for this press are shown in Figure 4.

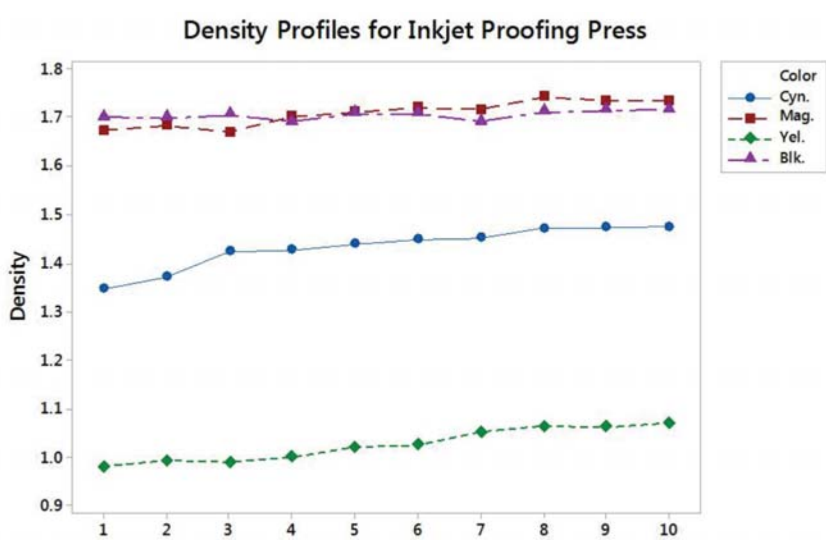


Figure 4. *CMYK density profiles from page 1 of inkjet proofing press.*

The profiles in Figure 4 show a distinct increase in density across the page for the cyan and yellow densities. Also, the magenta density is high compared to most of the other presses in the study.

Colorimetric Analysis of the Color Bar

The consistency of the color bars across the 12 pages of the test form was evaluated using ΔE2000 color differences. The rationale for choosing ΔE2000 as the preferred perceptual measure of color differences was presented as a section in the authors' 2013 TAGA paper, "Color Uniformity of Electrophotographic Presses" (Stanton, et al., 2013).

Each of the 40 patches in the color bar was compared to the patches in the same position on the color bars from the other 11 pages of the test form. Paired comparisons were used to get accurate estimates of the average color differences between the patches at the same location across different pages. There are 66 comparison pairs for each patch on the color bar on 12 pages.

A ΔE2000 color difference of zero would be a perfect color match, and a ΔE2000 value of 1.00 approximates a just-noticeable difference for a standard observer. Figure 5 shows the average ΔE2000 color differences for the 10 cyan color bar spots on all presses. To make the data more visually accessible, 3D bar charts were used. Similar charts for all the process colors are shown in Appendix H. The data for the four process colors was displayed with a fixed Y-axis so the magnitudes of the color differences could be visually compared.

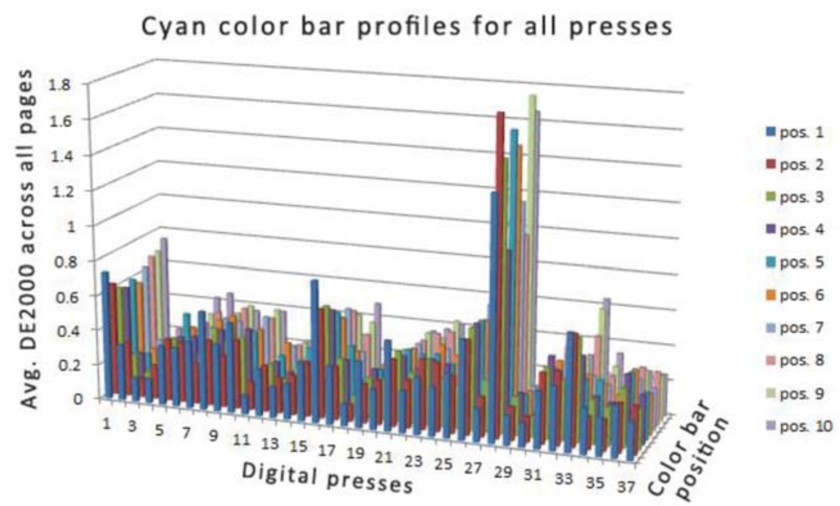


Figure 5. *Average cyan color differences for color bar patches across 12 pages for all 37 presses.*

The profiles in Figure 5 show that most of the presses in the study had low average color differences for the cyan patches in the color bar across the 12 test form pages. One digital press (#27) showed average color differences from page to page that were above the threshold for a just noticeable difference to a standard observer (DE2000 = 1.0). A few of the other digital presses showed high cyan color differences compared to the other presses, but the averages were below the noticeable difference threshold.

Examination of Appendix H shows that the yellow patches were the most consistent, and the black patches were the least. To pursue this observation further, average color differences were calculated for each of the process colors. Figure 6 shows the average color differences for each patch on the color bar across all of the pages of the test form. Thus, each bar in Figure 6 is the result of averaging 660 paired comparisons.

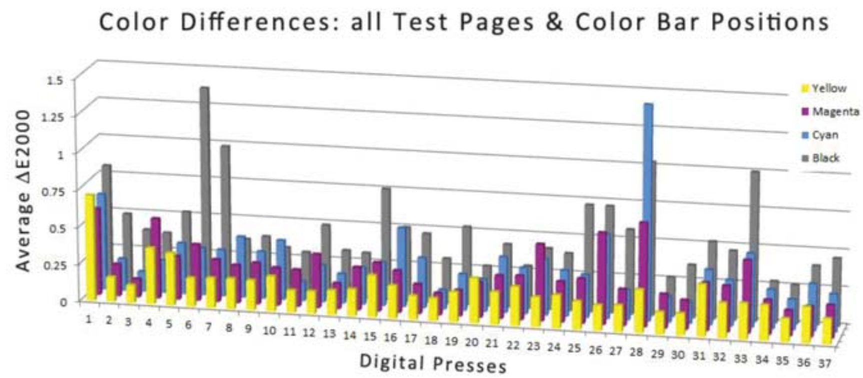


Figure 6. *Color differences for process colors across all test form pages and color bar positions.*

It is clear from Figure 6 that some digital presses had more uniform renditions than others of the CMYK solids. It also appears that the yellow uniformity was the best and the black was the worst.

A one-way ANOVA was performed to determine if the color of the toner/ink was significantly related to the magnitude of color difference. The Welch method was used, which does not assume equal variances. Color differences for the 10 positions for each process color on the color bar and across the 12 pages of the test form resulted in 660 calculated comparison pairs for each color on a given press. Combining the color differences for the 37 presses in the test yielded n-values of 24,420 for each of the colors in the ANOVA. The large sample size provided high precision for the estimated mean CMYK color differences. Table 3 shows some of the data from the ANOVA.

Welch's ANOVA CMYK across color bar & test pages

Sample	Sample Size	Mean	Standard Deviation	Individual 95% CI for Mean
cyn	24420	0.32179	0.34658	(0.31744, 0.32614)
mag	24420	0.29441	0.24892	(0.29129, 0.29753)
yel	24420	0.20995	0.18738	(0.20760, 0.21230)
blk	24420	0.50004	0.46493	(0.49421, 0.50587)

Table 3. *Statistics from ANOVA of CMYK.*

Games-Howell pairwise comparisons were used to test the significance between the means of the ink colors in the ANOVA. Also, the Bonnett test of standard deviations was used to test if the standard deviations significantly differed from each other. Both the mean and standard deviation for each color were found to be significantly different than those of all the other colors. Yellow had the lowest color differences and the least variance. Magenta was the second for both categories, followed by cyan and then black.

In the 2013 and 2014 studies of color uniformity, electrophotographic presses were compared with a single inkjet proofing press. In both studies the inkjet press had significantly better color uniformity than any of the electrophotographic presses. In this study, 28 electrophotographic presses were compared with 9 inkjet presses. To examine whether the inkjet presses in this study had better color uniformity than the electrophotographic presses, the data from Figure 6 was split into two 3D bar graphs: one for electrophotograhic presses and one for inkjet presses. These are shown in Appendix I.

Examination of the graphs in Appendix I confirms that the inkjet presses have among the best results for the color uniformity of the solid CMYK color bar patches on the 12 pages of the test form. To illustrate this observation, the 37 participants were placed in rank order according to their average color differences for each of the process colors as shown in Table 4.

The press identification nomenclature in Table 4 is as follows:

- *prf*—inkjet proofing press
- *hsi*—high-speed inkjet press
- *wfi*—wide-format inkjet press
- *epd*—electrophotographic dry-toner press
- *epl*—electrophotographic liquid-toner press

CMYK Rank Orders: Mean ΔE2000 w/Press Type & Participant Code

Rank	Cyan	Press	Code	Mag.	Press	Code	Yellow	Press	Code	Black	Press	Code	Rank
1	0.13	hsi	18	0.12	prf	3	0.12	prf	3	0.26	epd	35	**1**
2	0.13	epl	11	0.15	hsi	18	0.15	epl	30	0.27	epl	29	**2**
3	0.14	prf	3	0.17	epd	35	0.15	epl	29	0.27	hsi	20	**3**
4	0.15	epl	30	0.17	hsi	13	0.15	epl	11	0.28	epd	34	**4**
5	0.18	epl	29	0.17	hsi	19	0.15	epl	12	0.29	epd	22	**5**
6	0.20	hsi	13	0.20	epl	30	0.15	hsi	18	0.29	epl	11	**6**
7	0.20	epd	35	0.20	wfi	17	0.15	epd	35	0.30	hsi	18	**7**
8	0.20	hsi	27	0.20	epd	36	0.16	wfi	17	0.31	epl	14	**8**
9	0.22	prf	2	0.22	prf	2	0.16	hsi	13	0.32	epd	10	**9**
10	0.22	hsi	20	0.22	epd	37	0.17	prf	2	0.32	hsi	13	**10**
11	0.22	epl	4	0.23	epl	29	0.17	epd	37	0.36	epl	30	**11**
12	0.25	hsi	19	0.23	epd	34	0.17	epd	26	0.36	epd	8	**12**
13	0.25	epl	14	0.24	hsi	20	0.18	hsi	27	0.37	epl	4	**13**
14	0.25	epl	12	0.25	hsi	27	0.18	epl	14	0.39	epd	9	**14**
15	0.26	epd	37	0.25	epl	11	0.19	epd	25	0.39	prf	3	**15**
16	0.26	epd	34	0.25	epd	10	0.19	epd	6	0.39	epd	24	**16**
17	0.29	epd	25	0.26	epd	8	0.20	hsi	7	0.40	epd	36	**17**
18	0.29	epd	15	0.27	epd	24	0.20	epd	23	0.41	epd	23	**18**
19	0.31	epd	32	0.28	epd	9	0.20	epd	9	0.43	epd	21	**19**
20	0.31	epd	24	0.28	epd	16	0.20	hsi	19	0.46	epd	37	**20**
21	0.31	epd	22	0.29	hsi	7	0.20	epd	8	0.47	wfi	17	**21**
22	0.32	epd	36	0.29	epd	21	0.22	epd	21	0.47	epd	32	**22**
23	0.32	hsi	7	0.29	epl	14	0.22	epd	16	0.49	epl	12	**23**
24	0.32	epd	9	0.29	epd	5	0.22	epd	24	0.49	prf	2	**24**
25	0.32	epd	6	0.29	epd	22	0.23	epd	32	0.50	epd	16	**25**
26	0.34	wfi	17	0.30	epd	25	0.23	epd	10	0.52	epd	31	**26**
27	0.35	epd	5	0.31	epd	32	0.23	epd	34	0.52	epd	5	**27**
28	0.37	epd	31	0.32	epd	31	0.24	epd	36	0.53	hsi	19	**28**
29	0.38	epd	21	0.33	epd	15	0.24	epd	33	0.57	hsi	27	**29**
30	0.38	epd	23	0.36	epl	12	0.26	epd	22	0.72	epd	26	**30**
31	0.40	epd	10	0.38	epd	6	0.28	epd	15	0.72	epd	25	**31**
32	0.41	epd	8	0.49	epd	33	0.29	epd	28	0.75	epd	15	**32**
33	0.49	epd	33	0.51	epd	23	0.30	hsi	20	0.81	epd	1	**33**
34	0.53	epd	16	0.54	epl	4	0.35	epd	31	0.98	hsi	7	**34**
35	0.57	epd	26	0.59	epd	1	0.35	epd	5	1.00	epd	33	**35**
36	0.65	epd	1	0.62	epd	26	0.38	epl	4	1.03	epd	28	**36**
37	1.44	epd	28	0.70	epd	28	0.71	epd	1	1.37	epd	6	**37**

Table 4. *Rank order of participants for mean color difference of CMYK.*

The entries in Table 4 representing the inkjet presses are highlighted. They showed better color uniformity than most of the electrophotographic presses for cyan, magenta, and yellow, but not for black. Also, one of the high-speed inkjet presses (#7) scored in the bottom half of the group for three out of the four process colors.

The mean cyan, magenta, yellow, and black ΔE2000 color differences were combined in order to obtain an overall ranking of the uniformities of the presses at reproducing solid patches of the process colors both across and between the test form pages. The combined CMYK ranking is shown in Table 5.

Combined CMYK Rank Order: Mean ΔE2000

Rank	DE2000	Press	Code	Rank	DE2000	Press	Code
1	0.183	hsi	18	20	0.302	epd	10
2	0.191	prf	3	21	0.308	epd	8
3	0.197	epd	35	22	0.312	epl	12
4	0.206	epl	29	23	0.327	epd	21
5	0.206	epl	11	24	0.329	epd	32
6	0.212	epl	30	25	0.374	epd	25
7	0.214	hsi	13	26	0.377	epd	23
8	0.251	epd	34	27	0.378	epl	4
9	0.257	hsi	20	28	0.378	epd	5
10	0.258	epl	14	29	0.384	epd	16
11	0.271	prf	2	30	0.390	epd	31
12	0.275	epd	37	31	0.414	epd	15
13	0.287	hsi	19	32	0.446	hsi	7
14	0.288	epd	22	33	0.518	epd	26
15	0.289	epd	36	34	0.555	epd	33
16	0.291	wfi	17	35	0.566	epd	6
17	0.296	epd	9	36	0.689	epd	1
18	0.298	epd	24	37	0.865	epd	28
19	0.299	hsi	27				

Table 5. *Rank order of participants for mean color difference of CMYK, overall.*

It is noteworthy that 7 of the 9 inkjet presses ranked in the better half of the group. It is also noteworthy that the top-ranked press (the one with the lowest average color difference) was a high-speed inkjet, with an inkjet proofing press finishing second in this phase of the study.

Another observation was that 4 of the 6 liquid-toner electrophotographic presses finished in the top 10 of the group of 37 presses. Of the 22 dry-toner electrophotographic presses in the study, only two finished in the top 10 for overall uniformity of printing CMYK color patches.

Large-Color-Sample Analysis from Test Form Pages 2--12

Seventy-two spectrophotometric measurements were made from each of the large checkerboard color pages to yield CIELAB values. Four measurements were made in each solid square within the checkerboard pattern. All of the checkerboard pages were measured in the same locations. One of the checkerboard pages is shown in Figure 7 with the measurement spots identified. Color difference calculations (ΔE2000) were made between all of the 2,556 unique pairs of measurements on each page.

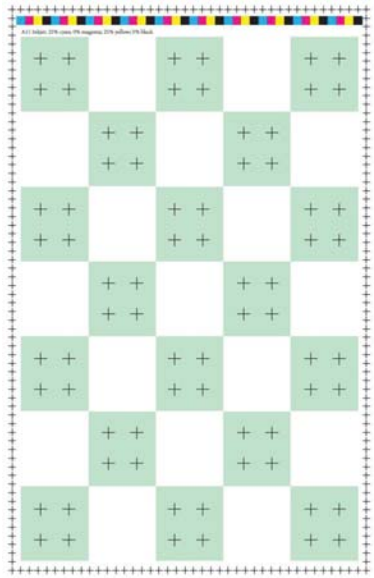


Figure 7. *Test form page with measurement locations identified with plus signs.*

The mean value of the 2,556 color differences for each page was treated as an index of color uniformity for large-area color coverage for a specific press/color combination. The color differences for all 11 checkerboard pages were combined to determine an overall color uniformity score for large solid areas for a given press. This score was based on 28,116 individual color differences calculated for the 11 pages from each press.

A Welch's one-way ANOVA showed clear differences (P-value = 0.000 and F-value = 1629.27) between the mean color differences based on the factor of digital press. Games-Howell pairwise comparisons were used to test the significance between the means of the 37 digital presses. The results of this analysis are shown in Appendix J, which shows the rank order of the of the 37 digital presses, the mean ΔE2000 values across the 11 checkerboard pages for each press, the type of press, the code number for the participants, and its level of significance among the other presses.

Table 6 shows the information for Appendix J without the complex significance field. Unlike the data in Appendix J, the inkjet presses are highlighted in Table 6.

Rank order for large solid color uniformity

Rank	Avg ΔE	Code	Press	Rank	Avg ΔE	Code	Press
1	0.198	3	prf	20	0.892	33	epd
2	0.246	2	prf	21	0.907	8	epd
3	0.259	27	hsi	22	0.915	11	epl
4	0.327	17	wfi	23	0.952	14	epl
5	0.351	20	hsi	24	0.956	30	epl
6	0.505	19	hsi	25	0.975	15	epd
7	0.535	35	epd	26	1.059	12	epl
8	0.541	18	hsi	27	1.099	31	epd
9	0.567	34	epd	28	1.101	9	epd
10	0.607	22	epd	29	1.112	37	epd
11	0.695	7	hsi	30	1.122	36	epd
12	0.711	1	epd	31	1.143	4	epl
13	0.754	23	epd	32	1.167	26	epd
14	0.770	13	hsi	33	1.206	10	epd
15	0.787	32	epd	34	1.314	16	epd
16	0.837	24	epd	35	1.327	6	epd
17	0.839	21	epd	36	1.567	25	epd
18	0.888	5	epd	37	1.661	28	epd
19	0.890	29	epl				

Table 6. *Rank order of participants for mean color difference for checkerboard pages.*

The highlighting in Table 6 shows that the best scores (lowest average color differences) were dominated by inkjet presses. Inkjet presses occupy the first six places in the table, with none of the 9 inkjet participants placing lower than 14th. The inkjet proofing presses finished 1st and 2nd in the ranking, with the 3rd-place high-speed inkjet press having no significant difference from the 2nd-place inkjet proofing press. It is noteworthy that the wide-format inkjet press finished in 4th place for color uniformity of the checkerboard pages. The 6 liquid-toner electrophotographic presses finished in the lower half of the rankings.

These findings were restricted to the 11 colors chosen for the checkerboard pages of the test form. These pages tested the capacity of the digital presses to produce large areas of coverage uniformly as evidenced by low color differences among 72 measurement spots.

Analysis of the 96-Patch Color Field Targets

To test the color uniformity of the presses for a larger number of colors, the 96-patch color fields printed in 6 locations on the first page of the test form were analyzed. In this instance, there was little coverage on the page for any of the colors. The patch size for each color was 0.25x0.25 inches.

All of the patches in the color fields were measured with a spectrophotometer to yield CIELAB values. From these data, ΔE2000 color differences were calculated for the 15 possible pairs of each of the 96 target patches. All the color differences for each press were combined, yielding a total of 1440 color differences. To test if the means of color differences for the digital presses differed significantly from one another, a one-way Welch's ANOVA was run on the data. The ANOVA revealed a high probability that some of the means differed from the others. The P-value was 0.00 and the F-value was 513.23.

The results were analyzed with Games-Howell pairwise comparisons to identify which presses were significantly different from one another. Appendix K shows the rank order of the digital presses, along with the average color difference for the 1440 ΔE2000 calculations, the type of press, the code number of the participant, and the presses from which it significantly differs at a 95% confidence level. Table 7 shows all of this information except the significance data.

Rank Order of ΔE2000 for 96-patch target

Order	ΔE2000	Type	Code	Order	ΔE2000	Type	Code
1	0.241	hsi	27	20	0.780	epd	5
2	0.272	prf	3	21	0.785	epl	14
3	0.301	wfi	17	22	0.800	epd	21
4	0.350	hsi	20	23	0.806	epd	9
5	0.369	prf	2	24	0.811	epd	37
6	0.472	hsi	19	25	0.831	epd	36
7	0.492	epd	35	26	0.842	epd	15
8	0.548	epd	34	27	0.861	epd	10
9	0.578	epd	22	28	0.864	epl	12
10	0.579	hsi	18	29	0.892	epl	4
11	0.580	hsi	7	30	0.918	epl	29
12	0.604	epd	1	31	0.947	epl	30
13	0.625	epl	11	32	1.015	epd	26
14	0.689	epd	32	33	1.043	epd	31
15	0.698	epd	24	34	1.136	epd	25
16	0.701	epd	23	35	1.144	epd	28
17	0.724	epd	8	36	1.146	epd	16
18	0.738	epd	33	37	1.147	epd	6
19	0.761	hsi	13				

Table 7. *Rank order of participants for mean color difference for 96-patch color targets.*

The inkjet presses are highlighted in Table 7. Again, inkjet occupies the top 6 ranks in the color uniformity results, although the order of the top presses shifted between the two tests. It is apparent that the color uniformity of inkjet was better than that of electrophotography as measured in this study. Although there was only a single inkjet press used in the 2013 and 2014 studies of color uniformity, it was noteworthy that inkjet scored better than the electrophotographic presses in both of those studies.

Appendices J and K show that the top five inkjet presses have significantly lower mean color differences than any electrophotographic presses in the study. However, the mean color differences of the high-speed inkjet press (#19) that finished in 6th place in both instances were not significantly different from the 7th-place press, which was a dry-toner electrophotographic press (#35).

Analysis of Register Marks on the Test Form

Photomicrographs were made from the continuous register track on the first page of the test form at the same four locations (top left, top right, bottom left, and bottom right) for all of the digital presses. All of the photographs are shown in Appendix L. The photos are grouped by type of press, with the electrophotographic dry-toner presses first, followed by the electrophotographic liquid-toner presses, the inkjet proofing presses, the high-speed inkjet presses, and the wide-format inkjet press.

It was not practical to make physical measurements of the displacement of the process colors from each other. But the photographs were used to rate the digital presses for:

- Line quality (LQ)
- Register accuracy (Fit)
- Consistency of register between the four targets (Con)
- Absence of background noise (Bgd)

Each category was judged on a one-to-four scale, with one being the worst score and four the best. Table 8 shows the scores for all of the presses. The presses in Table 8 are grouped by type and shown in the same order as was used for Appendix L.

Register Evaluations

Code	Press	LQ	Fit	Con	Bgd	Code	Press	LQ	Fit	Con	Bgd
1	epd	3	4	4	3	35	epd	2	3	3	1
5	epd	4	2	4	4	36	epd	4	4	4	3
6	epd	3	4	4	2	37	epd	4	3	3	3
8	epd	4	4	4	3	4	epl	4	2	2	4
9	epd	3	3	4	3	11	epl	4	2	1	4
10	epd	3	3	3	4	12	epl	3	3	2	4
15	epd	3	4	4	3	14	epl	only black is used for mark			
16	epd	3	4	4	3	29	epl	4	3	3	4
21	epd	4	2	3	3	30	epl	4	4	4	4
22	epd	only black is used for mark				2	prf	3	3	4	3
23	epd	only black is used for mark				3	prf	3	2	3	3
24	epd	3	4	4	3	7	hsi	3	2	1	4
25	epd	2	3	3	1	13	hsi	3	4	4	3
26	epd	only black is used for mark				18	hsi	4	1	2	4
28	epd	only black is used for mark				19	hsi	4	1	1	4
31	epd	3	3	3	2	20	hsi	3	3	4	4
32	epd	4	4	4	3	27	hsi	4	3	4	4
33	epd	3	4	3	3	17	wfi	1	2	3	3
34	epd	4	4	4	3						

Table 8. *Evaluations of register marks for line quality, fit, consistency, and background noise.*

Examination of the photomicrographs in Appendix L showed that the digital presses in the study differed from one another in terms of all four of the judging criteria (line quality, image fit, consistency of the four register marks in different locations on the page, and background noise).

Some of the digital presses from the dry-toner electrophotographic group and the liquid-toner electrophotographic group did not print four-color register marks. Instead, the register marks were imaged with black toner only, in spite of the fact that the marks were designated in the digital file as 100% cyan, magenta, yellow, and black. An example of this can be seen in Figure 8, taken from a page printed by dry-toner electrophotographic press #22.

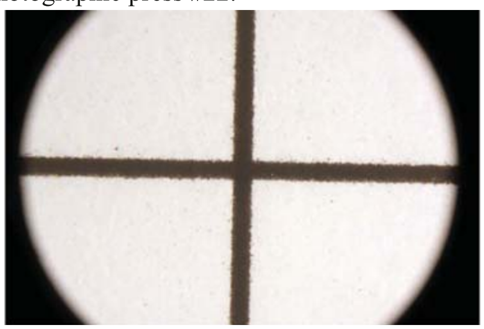


Figure 8. *Register mark printed by #22 with black toner only instead of CMYK.*

The digital press that had the highest score in the study for register was a liquid-toner electrophotographic press (#30). The photos of the register marks from this press are shown in Figure 9.

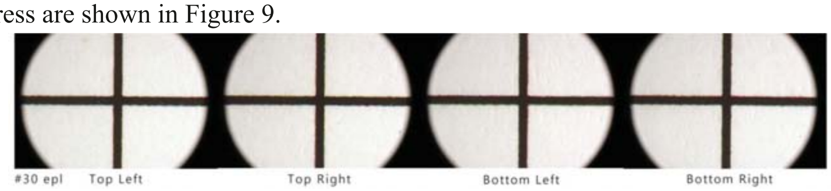


Figure 9. *Register marks from four locations from liquid-toner electrophotographic press #30.*

Taken as a group, the line quality of the liquid-toner electrophotographic presses was better than the dry-toner presses. Some of the inkjet presses also showed good line quality, but other inkjet presses had poor line quality. For example, high-speed inkjet press #20 and wide-format inkjet press #17 had line quality that was judged as poor, as can be seen in Appendix L.

In terms of image fit, the dry-toner electrophotographic presses scored better than the other types of digital presses in the study. To impart a sense of the outer limits of image fit observed in this study, the worst cases of image fit for each of the four categories of digital presses are shown in Figure 10.

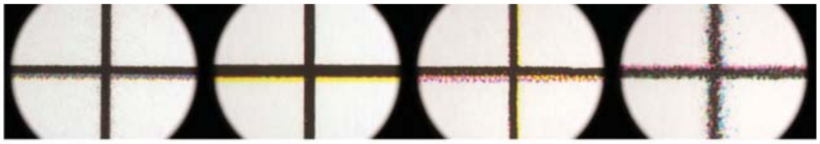


Figure 10. *Worst-case misregister from four categories of digital presses.*

The photomicrographs in Figure 10 show clear examples of digital presses that are out of register for some process colors. However, the degree of misregister would not be considered excessive by traditional printing standards. On the whole, the register of the 37 digital presses in this study was very good.

On the criterion of **consistency** of register at the four corners of the test page, the dry-toner electrophotographic presses scored better than the other categories of digital presses in the study. The choice of printing substrate was left to the participants, enabling them to optimize the results from their presses. Therefore, samples were submitted on a variety of papers with different printing characteristics. The inkjet and liquid toner presses, which applied liquid to the substrate during printing, might have affected the dimensional stability of the paper, leading to lower register consistency.

As with image fit, the magnitude of register inconsistency at different points on the sheet was not excessive. The results in Appendix L for presses #11 (epl), #7 (hsi), and #19 (hsi) show the outer limits for register inconsistency.

The **background noise** scores from Table 8 were based on the amount of toning or stray ink droplets that were deposited on the substrate in nonimage areas. The degree to which this occurred varied widely. It was more prevalent with dry-toner electrophotographic presses than any of the other types of digital presses. All six of the liquid-toner electrophotographic presses were relatively free of background noise, and all scored 4 (the highest rating) in this criterion.

The inkjet presses showed some background noise, particularly the wide-format press (#17), but as a group, the backgrounds were cleaner than those printed by the dry-toner electrophotographic presses. Examination of the photomicrographs for the inkjet proofing presses (#2 and #3) showed a uniform distribution of very tiny droplets across the background of the substrate making it appear as a deliberate efforts to control the tint of the paper.

A pronounced example of high background noise is shown in Figure 11.

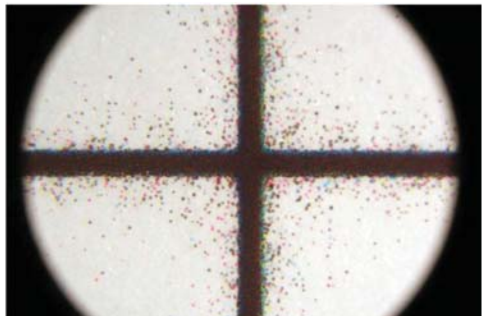


Figure 11. *High background noise from dry-toner electrophotographic press (#35).*

It should be noted that many of the dry-toner electrophotographic presses showed little evidence of the background noise pictured in Figure 11. This malady appears to be a concern primarily for dry-toner presses, but it was well controlled for most of the presses in this study.

Analysis of Star Targets

Star Targets were included on the test form to test the resolving power and directional bias of the printing presses. The Star Target was adopted from the optics industry for use in the printing industry by the Lithographic Technical Foundation in the 1950s. It provides a visually sensitive indicator of image resolution and some printing maladies such as slur or doubling. Figure 12 shows the design of the Star Targets used for this study.

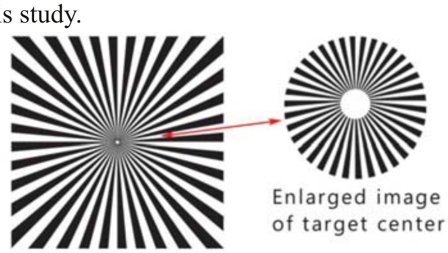


Figure 12. *Star Target design with enlargement of the target center.*

The Star Targets are vector graphics consisting of 36 wedge-shaped elements arranged in a circular configuration and terminating in a small circular center. Printing processes do not have sufficient resolution to image the fine wedge elements at the point where they meet the circumference of the white target center. This causes the target center to be filled in for some distance out from the white center. Printing systems with higher resolutions can reproduce Star Targets will less fill-in in the center area. If the filled-in shape at the center of the Star Target is not circular, it indicates that there is some directional bias in the printing system. For example, an elliptical pattern indicates that slur is taking place during image transfer. In this case, the direction of the slur can be diagnosed as perpendicular to the long axis of the ellipse. Doubling in the printing system will cause a figure-8 pattern to occur at the Star Target center.

Photomicrographs were made of the cyan, magenta, yellow, and black Star Targets on the left side of the first page of the test form. These images for the 37 presses in the study are shown in Appendix M. The presses are grouped by type with the electrophotographic dry-toner presses first, followed by the electrophotographic liquid-toner presses, the inkjet proofing presses, the high-speed inkjet presses, and the wide-format inkjet press.

The printed Star Targets were evaluated visually and graded on a 0-to-5 scale, with 0 being the worst score and 5 the best. The results of this evaluation are shown in Table 9.

Star Target Evaluations

Code	Press	Cyan	Mag	Yel	Blk	Code	Press	Cyan	Mag	Yel	Blk
1	epd	3	4	4	5	35	epd	2	1	1	2
5	epd	5	5	4	5	36	epd	2	2	1	2
6	epd	4	5	5	4	37	epd	2	2	1	2
8	epd	4	4	3	2	4	epl	2	2	2	3
9	epd	4	3	3	4	11	epl	3	3	2	3
10	epd	3	3	3	3	12	epl	3	3	1	3
15	epd	2	2	0	2	14	epl	3	3	2	3
16	epd	2	3	1	3	29	epl	3	3	3	3
21	epd	4	4	3	3	30	epl	5	5	5	5
22	epd	3	4	3	4	2	prf	5	5	4	5
23	epd	3	4	3	4	3	prf	5	5	4	5
24	epd	3	4	4	3	7	hsi	3	3	0	4
25	epd	4	4	3	4	13	hsi	4	4	0	3
26	epd	3	3	3	3	18	hsi	3	3	1	3
28	epd	2	2	2	3	19	hsi	3	3	3	4
31	epd	3	2	1	2	20	hsi	2	2	0	2
32	epd	4	4	2	3	27	hsi	5	5	4	5
33	epd	3	3	3	3	17	wfi	1	0	0	0
34	epd	2	2	1	2						

Table 9. *Evaluations of Star Targets based on resolution and sharpness and grouped by type of press.*

There was a wide range of quality in the printed Star Targets from the digital presses in this study. The press with the highest scores was a liquid-toner electrophotographic press (#30). The results from this press are shown in Figure 13.

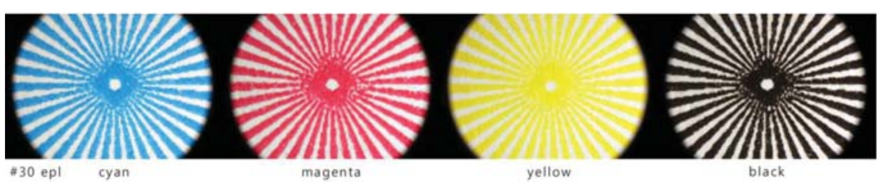


Figure 13. *Star Targets with the highest evaluation—liquid-toner electrophotographic (#30).*

The presses with the highest resolutions in the study were the two inkjet proofing presses (#2 and #3). These presses were not evaluated as highly as press #30 because the yellow Star Targets lacked sharpness.

The average scores for the Star Targets were: cyan 3.16, magenta 3.22, yellow 2.30, and black 3.22. ANOVA analysis showed that the yellow mean was significantly different than the other three colors. This indicates that, as a group, the digital presses printed yellow with lower resolution than the other process colors.

The Star Targets in Figure 13 show the filled-in center areas to be offset rectangular patterns rather than circular ones. This indicates that wedge elements at 90-degree and 0-degree orientations were imaged with slightly less resolution than wedge elements with other angular orientations.

Many of the other digital presses (especially dry-toner electrophotographic presses) had square image centers. This condition means that wedge elements at 90-degree and 0-degree orientations were imaged with slightly more resolution than wedge elements with other angular orientations.

The press with the lowest Star Target evaluations was the wide-format inkjet press (#17). The Star Targets for this press are shown in Figure 14.

Figure 14. *Star Targets with the lowest evaluation—wide-format inkjet (#17).*

The photos in Figure 14 show very low resolution for all the process colors. The yellow target shows a tinting of cyan and magenta dots, while the black target appears to be imaged with four colors. The imaging of the black target as four colors was unique among the presses in this study. However, several digital presses added color tints to some of the cyan, magenta, and yellow targets. Also, some presses produced the Star Targets as halftone images rather than as solid patterns.

It is apparent that the attributes of image resolution and color uniformity are not closely related because the wide-format inkjet press ranked lowest in image resolution, but fourth in color uniformity for large color solids and third for the 96-patch color field uniformity.

Summary of the Study

The purpose of this study was to compare the color uniformity of digital presses. The authors performed two earlier studies (2013 and 2014) on the color uniformity of electrophotographic presses. This study expanded the range and number of digital presses to include high-speed inkjet presses that have entered the market to compete with electrophotography for the short-run color market. Thirty-seven presses were compared in this study, including 22 dry-toner electrophotographic presses, 6 liquid-toner electrophotographic presses, 6 high-speed inkjet presses, 2 inkjet proofing presses, and 1 wide-format inkjet press.

The test form made for this study consisted of twelve 11x17-inch pages. Each page had a color bar across the top consisting of 10 repeats of solid cyan, magenta, yellow, and black patches. These targets were used to measure the density profiles across the page and the color uniformity from page to page across the 12 pages of the test form.

Optical density measurements were used to view the uniformity of cyan, magenta, yellow, and black across the page. Most of the digital presses showed little density difference between the 10 color bar spots for each process color. However, a surprisingly high range of density values was produced by the 37 digital presses. The average cyan density across the color bar ranged from a low density of 0.84 (14% reflectance) to a high density of 1.88 (1.4% reflectance). It was clear that the digital presses in the study were not targeting a standard set of density aims for the four process colors.

The rest of the color difference evaluations utilized colorimetric rather than densitometric measurements. Measured CIELAB values were used to calculate ΔE2000 color differences, which are tied to the perceptual color differences of a standard observer.

Color differences were calculated between all of the comparison pairs available across the 12 pages of the test form for each of the 40 patches of the color bar for each of the 37 presses in the study. These data were subjected to Welch's ANOVA and Games-Howell pairwise comparisons which showed significant differences between the page-to-page uniformity of the digital presses and also significant differences related to the process colors, with yellow having the best uniformity, magenta second, cyan third, and black the worst.

Table 4 shows the digital presses listed in rank order for each of the process colors from the best color uniformity (lowest average ΔE2000) to the worst. Interestingly, the inkjet presses scored disproportionately well for cyan, magenta, and yellow, but not particularly for black.

Next, the color uniformities of the presses were compared for the reproduction of large solid areas of coverage for eleven selected colors. Pages 2–12 of the test form are each dominated by a checkerboard pattern of a single color. The colors were chosen from the 90th percentile colors (those having low color uniformity) from the 2013 study. The 2014 study used the same colors imaged as large solids covering entire 11x17-inch pages (as seen in Appendix D). The current study used checkerboard patterns to avoid image streaks that were found in the 2014 study and to lessen the toner transfer demands on the digital presses.

CIELAB coordinates were measured from the checkerboard pages at 72 spots. Delta-E2000 color differences were calculated for the 2,556 comparison pairs for each checkerboard page. For each press, an overall color uniformity index for large-solid colors was calculated as the mean of the color differences for the 11 checkerboard pages (28,116 individual color differences). A Welch's one-way ANOVA showed clear differences between digital presses for large-solid color uniformity. The Games-Howell pairwise comparison showed how the digital presses significantly differed from on another (Appendix J). Table 6 shows the rank order of the 37 presses and their mean ΔE2000 values. A remarkable aspect of these findings was that the 9 inkjet presses in the study all placed within the top 14 places among the rankings for the group of 37 presses; moreover, inkjet presses held the top 6 ranks.

The study next evaluated the color uniformity of the presses to image 96 different colors from 6 locations on an 11x17-inch page. These patches were small (0.25x0.25 inches). The analysis was similar to that used for the large solids. In this case, the ANOVA again showed significant differences between some of the presses. Appendix K shows the results of the Games-Howell pairwise comparisons indicating which presses significantly differed (0.95 confidence) from which other presses. The rank order of the presses and their mean color difference scores are shown in Table 7. As with large-solid color uniformity, the inkjet presses occupied ranks 1 through 6. The other three inkjet presses in the study finished with ranks of 10th, 11th, and 19th.

The next phase of analysis was to evaluate the register accuracy of the digital presses. Photomicrographs of the continuous register track were taken from four locations (shown in Appendix L). The evaluation of register accuracy was subjective and is only presented as anecdotal observations. Evaluations were made of four attributes based on the photomicrographs: line quality, image fit, consistency of register from the four corners of the page, and background toning, or noise.

The electrophotographic presses were given higher evaluations for image fit and consistency of register than inkjet presses, but scored lower in background toning. An unexpected finding from the register evaluation was that 5 of the 28 electrophotographic presses imaged the register track with only black toner rather than the CMYK color specified in the test form.

The last attribute addressed by this study was an analysis of the printed Star Targets. The Star Target is a sensitive indicator of image resolution and directional biases of the imaging system. Photomicrographs (Appendix M) of the cyan, magenta, yellow, and black Star Targets were evaluated. Again, there were no objective measurements made and the results are presented only as anecdotal observations.

The quality of the imaged Star Targets were rated on a 0-to-5 scale (Table 9) on the basis of the resolution and sharpness of the targets. There was a wide range of qualities of the Star Targets. Overall, the quality of the yellow Star Target was found to be the lowest of the four process colors.

The Star Targets with the lowest scores were from the wide-format inkjet press (#17), and the highest-scoring targets were from a liquid-toner electrophotographic press (#30). The three digital presses that were tied for the second highest scores were the two inkjet proofing presses (#2 and #3) and a high-speed inkjet press (#27).

It was observed from the Star Target images that many of the digital presses produced noncircular (usually square), filled-in center areas indicating printing systems with directional biases. This means that the resolution with which a Star Target wedge is produced is dependent on the angular displacement of the wedge.

It was also observed that some of the digital presses added other primary colors to the Star Target images. This was most common in the yellow Star Targets, but occurred in stars of other colors as well. It was also noted that some of the digital presses produced the Star Targets as a halftone image rather that a solid vector graphic.

References

Anonymous, SWOP 2007 Specifications and Guidelines (11th Edition), Special Supplement to Graphic Arts Monthly, May, 2007, 24 pp.

Stanton A., Bohan M. and Ferrari, L, Color Uniformity of Electrophotographic Presses, TAGA Proceedings 2013, pp. 237–275.

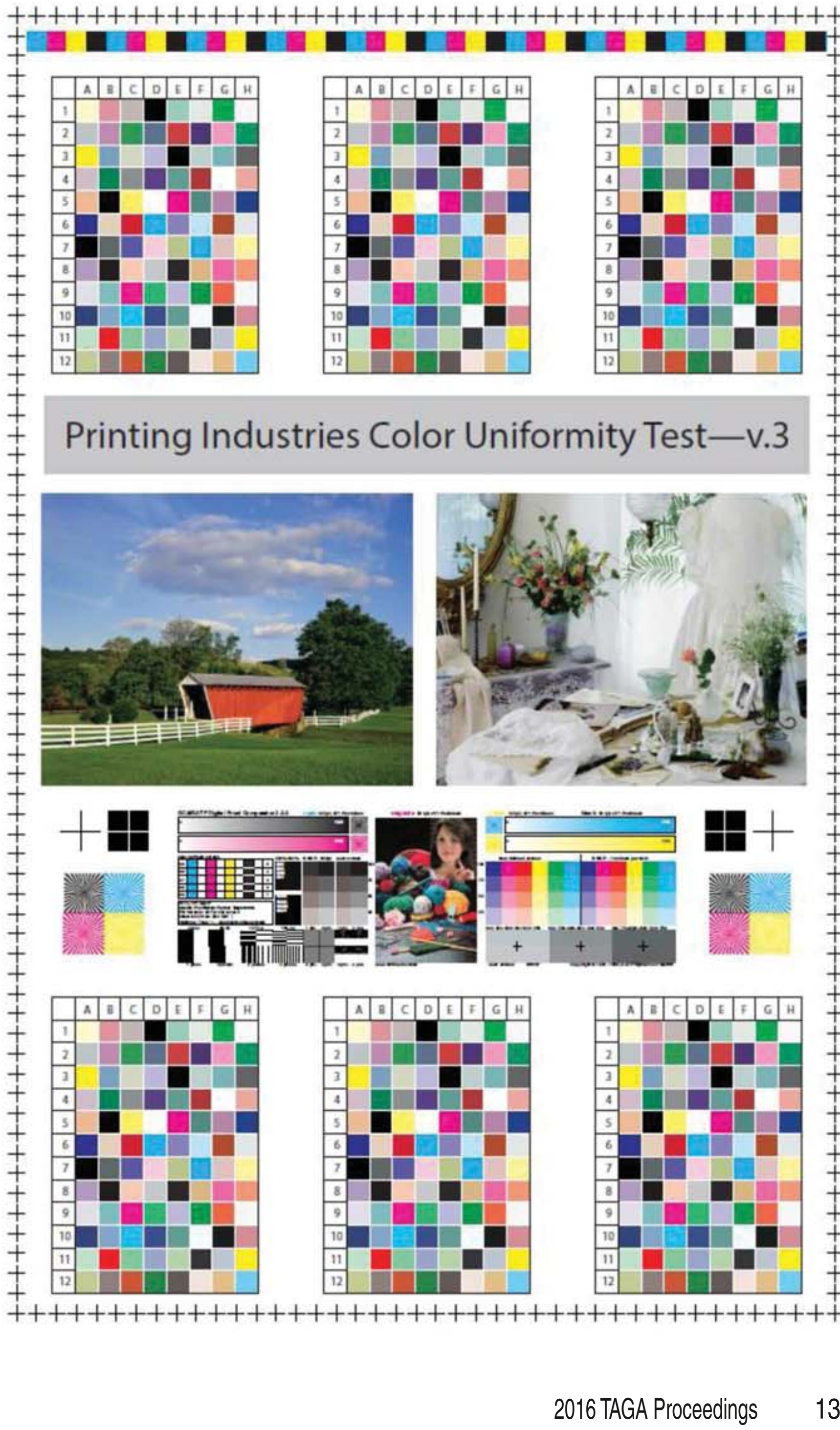
Stanton A., Bohan M. and Ferrari, L, Color Uniformity of Electrophotographic Presses: Uniformity of Large Solids, TAGA Proceedings 2014, 41 pp.

Appendix A. Participants in the Study

Inkjet Presses	Substrate
Epson 7900	GMG Proof Paper Semimatte 250
Canon image PROGRAF iPF6450	GMG Proof Paper Semimatte 250
Fuji Acuity Advance Select 6	100# Gloss Text
Kodak Prosper 6000C	19" 86# Mitsubishi Sword Gloss text
HP T-200 Inkjet web	70# Accent Opaque offset w/color pro
Kodak Prosper 6000C	Verso Sterling Ultra Gloss 60# text (90gsm)
Kodak Prosper 6000C	Artic Paper G-Print 100gsm
Oce Colorstream 3500 Inkjest	60# American Eagle Select
JPress 720 S	Sappi 100# Flo Gloss Cover

Electrophotographic Presses	Substrate
bizhub C71HC Press	Sterling Ultra, digital 80lb dull text, 90 brightness
Konica Minolta BizHub C8000	100# Gloss Text
Kodak NexPress 2100 Plus	100# Gloss Text
Canon C7010 VP	100# Sterling Dull text
Kodak Nexpress 3900	Sterling Premium Digital 80# Gloss
Kodak Nexpress 3300	Sterling Premium Digital 80# Gloss
Ricoh A - C9110	
Ricoh B - C7110	
IPR 10,000	
Canon IPR C800	
Image Press C7011 UPS	
Canon Image Press C10000VP	100# Gloss Text
Konica Minolta C8000	100# Endeavour Gloss Book
Kodak NexPress 2100	100# Endeavour Gloss Book
Ricoh Aficio SP C821 DX	Finsh Fine iD Bright White Ultra Smooth 10lb text
Cannon Image Press 7011 VP	80# Future Gloss Text 11x17
Versant 2100 Press (GRACoL)	Xerox Bold Coated Gloss 120 GSM
Versant 2100 Press (Direct)	Xerox Bold Coated Gloss 120 GSM
Xerox iGen 5 150PPM w/matte dry ink (GRACoL)	Xerox Bold Coated Gloss 120 GSM
Xerox iGen 5 150PPM w/matte dry ink (Direct)	Xerox Bold Coated Gloss 120 GSM
HP 5000	12x8 80# Xpri gloss text
HP 5500	13x19 80# flo gloss text
Indigo 561	80# Sterling gloss text
HP 5600 indigo	100# titan gloss text
Indigo 3500	100# Silk Text
indigo 7800	80# Endurance Digital Gloss Text

Appendix B. Page 1 of 2016 Test Form



Appendix C. 2013 Test Form

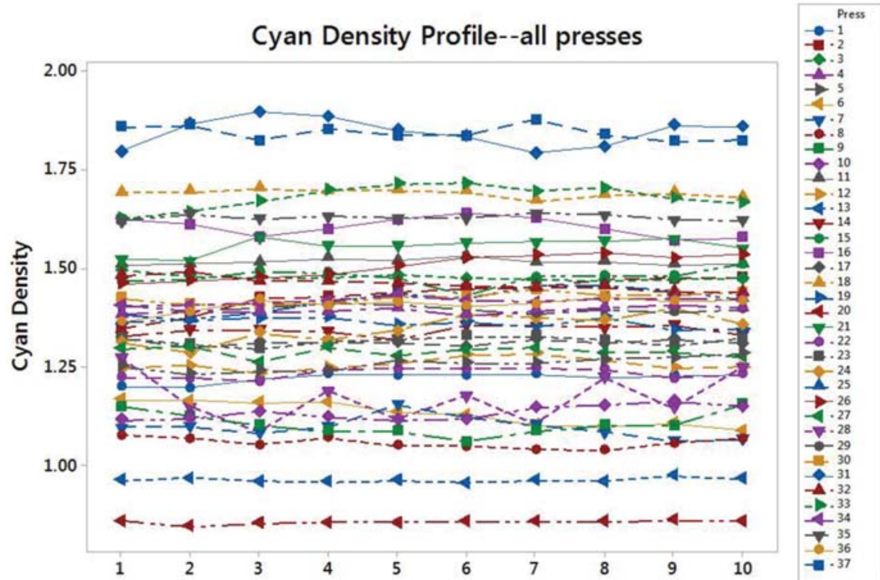
Appendix D. 2014 Twelve-Page Test Form

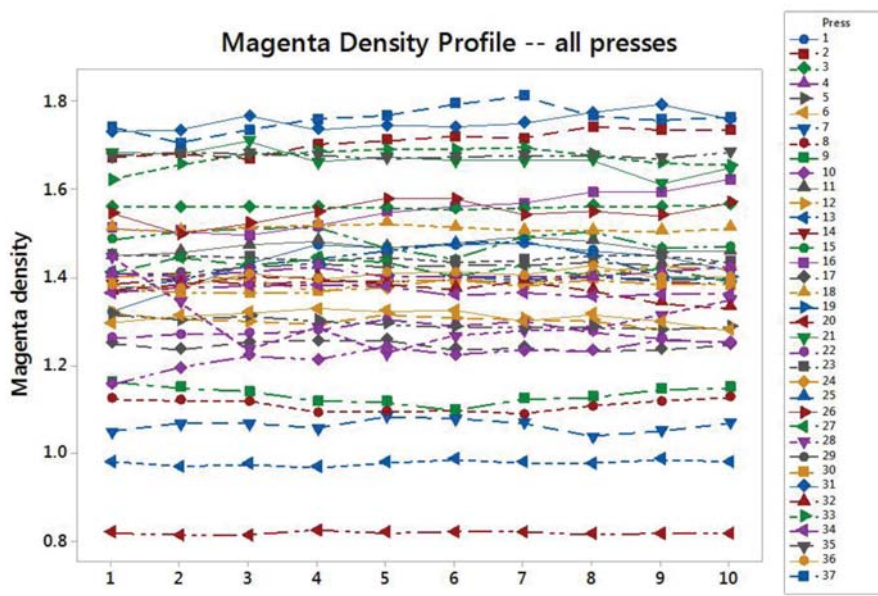
Appendix E. CMYK Values for 96-Patch Color Field

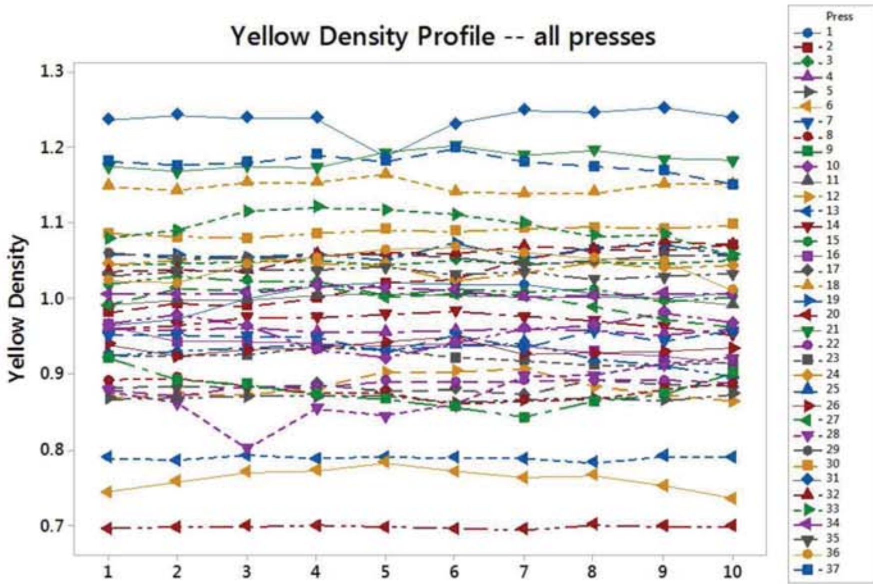
	A		B		C		D		E		F		G		H	
1	0	0	10	50	25	25	100	100	40	5	10	4	100	0	0	3
	25	0	25	0	25	0	100	100	30	0	10	0	100	0	0	0
2	25	17	25	50	80	20	65	45	20	90	80	90	0	50	90	20
	17	0	10	0	90	0	25	15	80	0	20	15	0	0	80	0
3	0	0	50	25	17	10	25	25	74	63	25	10	50	10	0	0
	97	0	10	5	25	0	0	0	63	100	17	0	25	5	0	75
4	17	25	90	20	50	40	80	90	65	25	20	90	0	0	5	40
	10	0	80	15	40	0	20	0	45	0	80	15	0	0	30	0
5	5	30	80	70	0	0	0	0	0	100	65	25	25	50	100	90
	40	0	70	100	75	0	3	0	0	0	45	15	10	5	15	0
6	100	100	10	17	15	100	97	0	50	50	25	0	20	80	10	6
	0	0	25	0	90	0	0	0	0	0	0	0	90	15	6	0
7	90	80	75	63	75	75	0	25	25	10	100	0	10	17	0	0
	80	100	63	0	0	0	0	0	50	5	0	0	25	0	50	0
8	30	40	0	0	0	25	0	0	0	0	10	25	0	75	0	50
	5	0	0	100	25	0	0	25	0	97	50	5	0	0	50	0
9	10	10	50	10	0	97	75	0	0	0	90	15	0	75	0	0
	4	0	25	0	0	0	75	0	0	50	100	0	75	0	0	3
10	90	80	50	25	75	0	90	80	65	45	3	0	65	58	10	50
	20	15	10	0	0	0	20	0	25	0	0	0	57	80	25	5
11	25	0	0	100	50	0	40	30	30	5	100	100	25	17	0	0
	25	0	100	0	50	0	5	0	40	0	100	0	10	0	100	0
12	25	10	50	50	20	80	80	20	75	75	4	10	10	25	50	0
	50	0	50	0	90	0	90	15	75	0	10	0	50	0	0	0

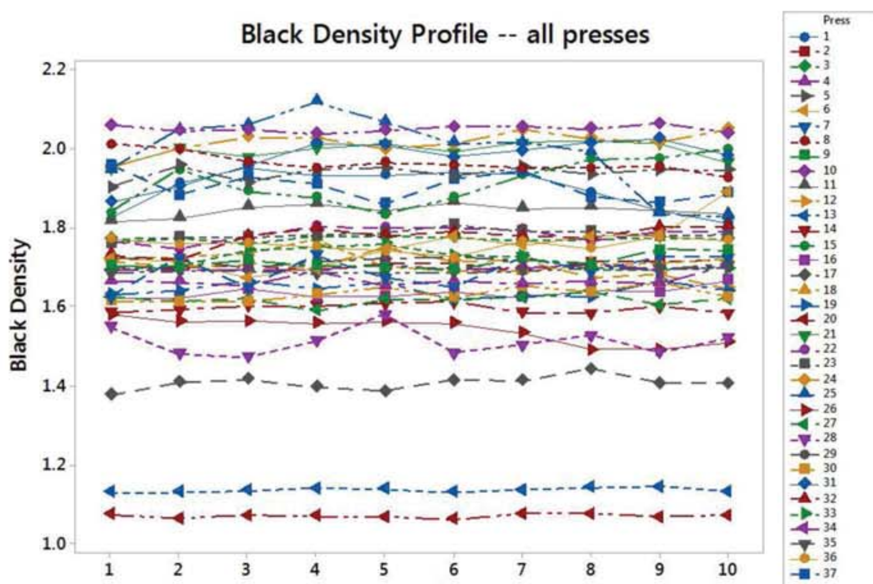
Order of values in each patch: {cyan, magenta}
{yellow, black}

Appendix F. Cyan, Magenta, Yellow, and Black Density Profiles for Page 1 of All Presses

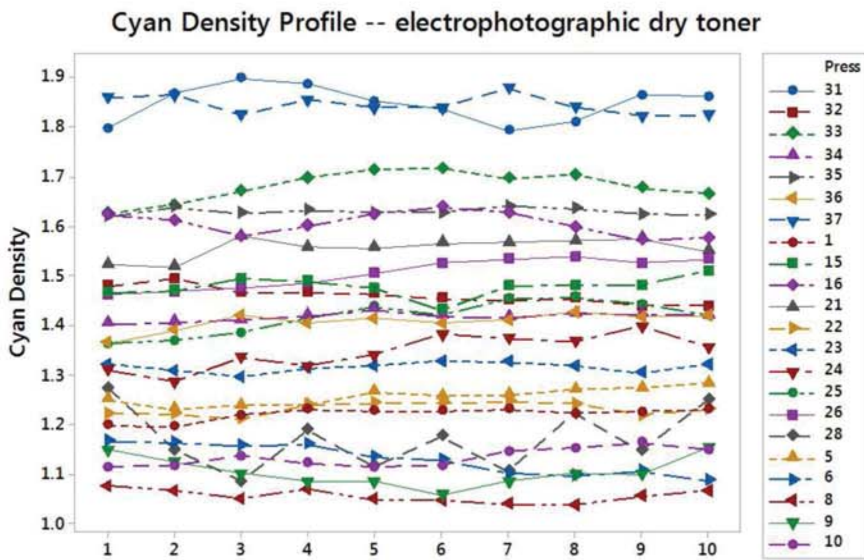


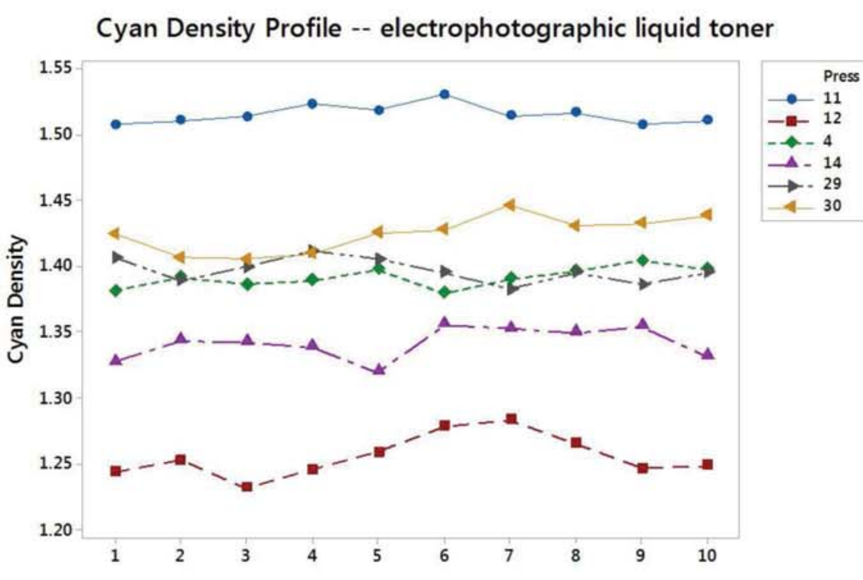


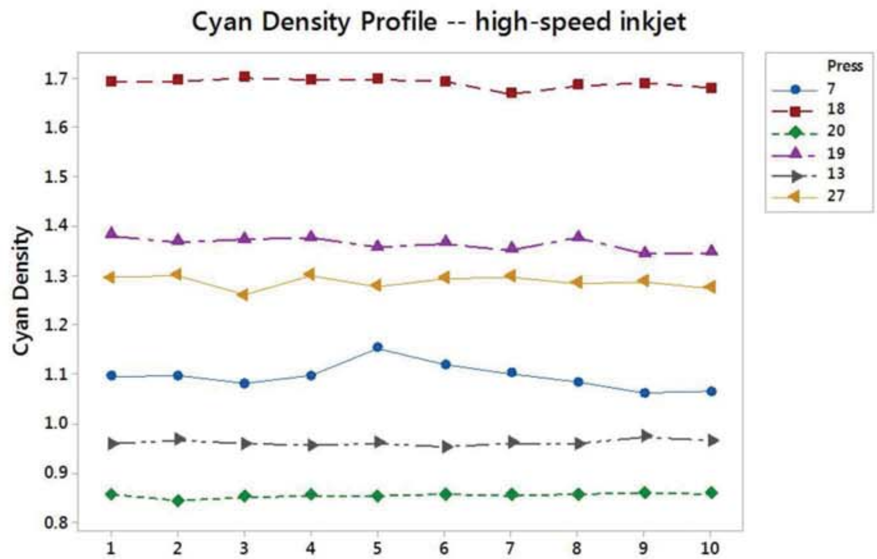

Yellow Density Profile -- all presses
Yellow Density
1.3
1.2
1.1
1.0
0.9
0.8
0.7
1
2
3
4
5
6
7
8
9
10
Press
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37

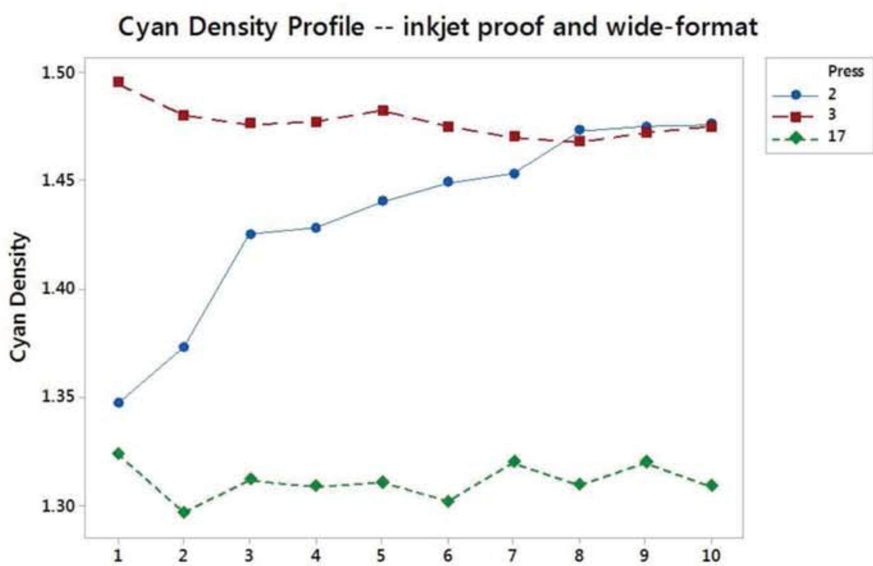

Black Density Profile -- all presses
Black Density
2.2
2.0
1.8
1.6
1.4
1.2
1.0
1
2
3
4
5
6
7
8
9
10
Press
1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37

Appendix G. Cyan Density Profiles for Four Categories of Digital Presses

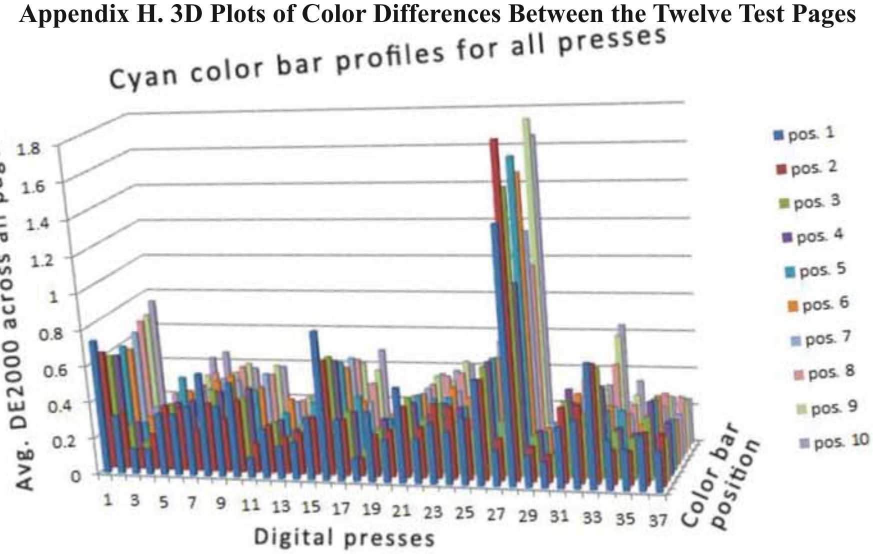


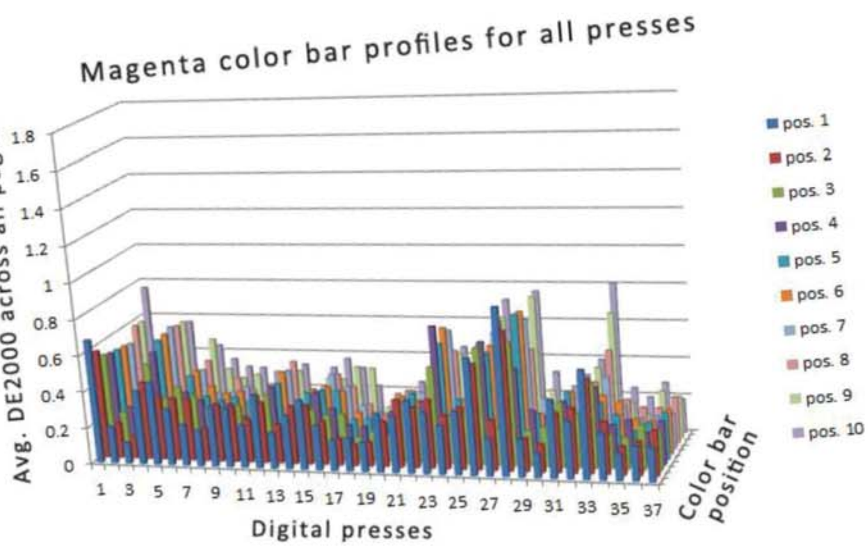


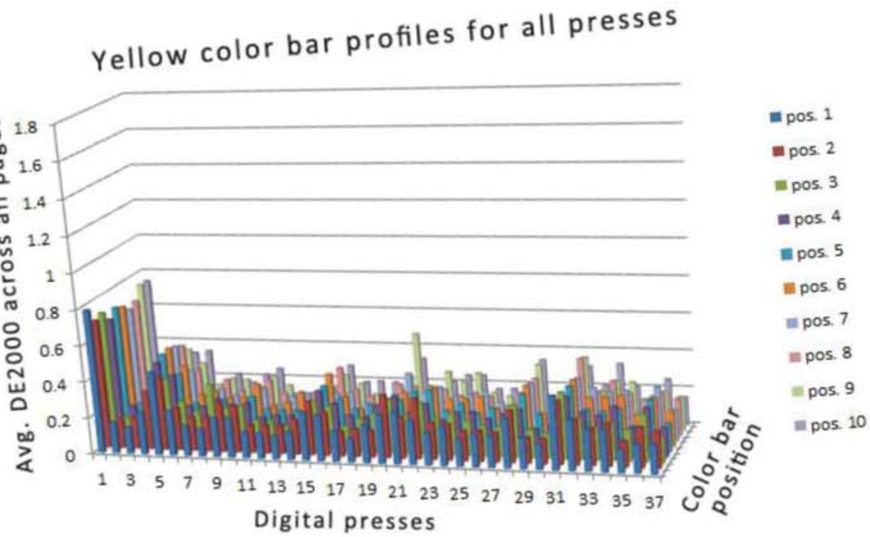

Cyan Density Profile -- high-speed inkjet
Cyan Density
Press
7
18
20
19
13
27
1.7
1.6
1.5
1.4
1.3
1.2
1.1
1.0
0.9
0.8
1
2
3
4
5
6
7
8
9
10

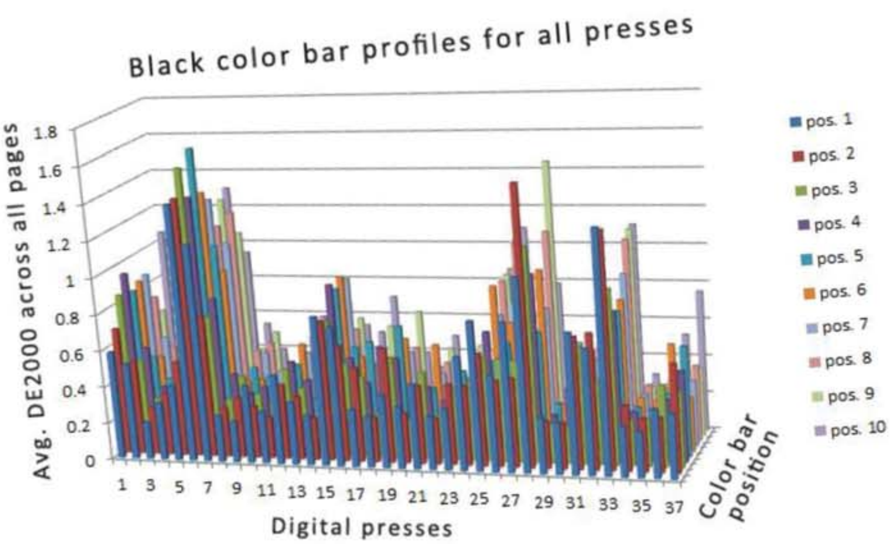

Cyan Density Profile -- inkjet proof and wide-format
Cyan Density
Press
2
3
17
1.50
1.45
1.40
1.35
1.30
1
2
3
4
5
6
7
8
9
10

Appendix H. 3D Plots of Color Differences Between the Twelve Test Pages

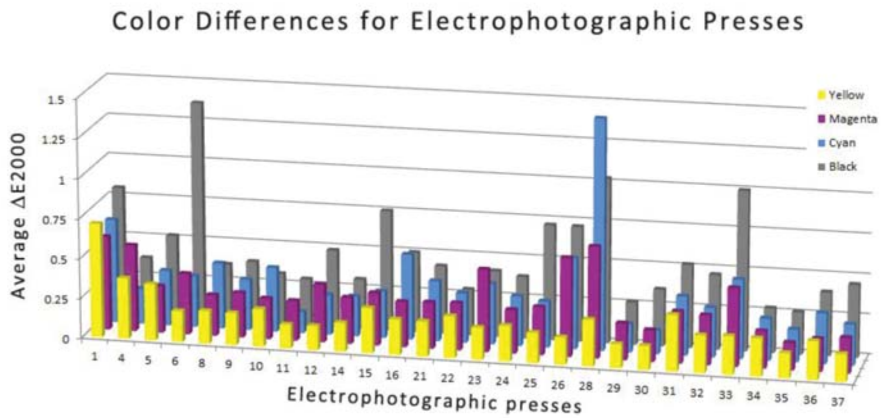


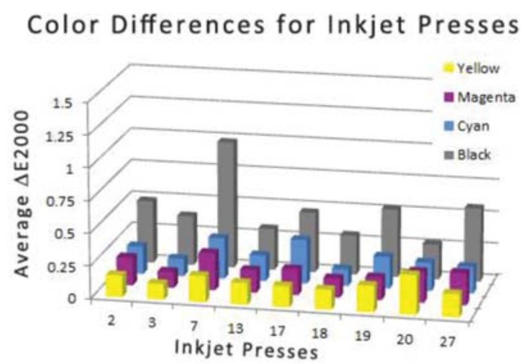



Yellow color bar profiles for all presses
Avg. DE2000 across all pages
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33 35 37
Digital presses
Color bar position
pos. 1
pos. 2
pos. 3
pos. 4
pos. 5
pos. 6
pos. 7
pos. 8
pos. 9
pos. 10


Black color bar profiles for all presses
Avg. DE2000 across all pages
0
0.2
0.4
0.6
0.8
1
1.2
1.4
1.6
1.8
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33 35 37
Digital presses
Color bar position
pos. 1
pos. 2
pos. 3
pos. 4
pos. 5
pos. 6
pos. 7
pos. 8
pos. 9
pos. 10

Appendix I. 3D Plots of Color Differences Between the Twelve Test Pages by Type of Press





Appendix J. Games-Howell Significance Test (α=0.05) for Large-Solid Color Uniformity

Note: Presses that share a letter are not significantly different from one another.

Games-Howell Pairwise Comparisons -- Large Solids

Order	ΔE2000	Type	Code	Significance
1	0.198	prf	3	A
2	0.246	prf	2	B
3	0.259	hsi	27	B
4	0.327	wfi	17	C
5	0.351	hsi	20	C
6	0.505	hsi	19	D
7	0.535	epd	35	D E
8	0.541	hsi	18	E
9	0.567	epd	34	E F
10	0.607	epd	22	F
11	0.695	hsi	7	G
12	0.711	epd	1	G H
13	0.754	epd	23	H I
14	0.770	hsi	13	H I
15	0.787	epd	32	I J
16	0.837	epd	24	J K
17	0.839	epd	21	J K
18	0.888	epd	5	K L
19	0.890	epl	29	K L
20	0.892	epd	33	K L
21	0.907	epd	8	L M
22	0.915	epl	11	L M
23	0.952	epl	14	L M
24	0.956	epl	30	L M
25	0.975	epd	15	M
26	1.059	epl	12	M
27	1.099	epd	31	M
28	1.101	epd	9	M
29	1.112	epd	37	M
30	1.122	epd	36	M
31	1.143	epl	4	M
32	1.167	epd	26	M
33	1.206	epd	10	M N
34	1.314	epd	16	N
35	1.327	epd	6	N
36	1.567	epd	25	O
37	1.661	epd	28	O

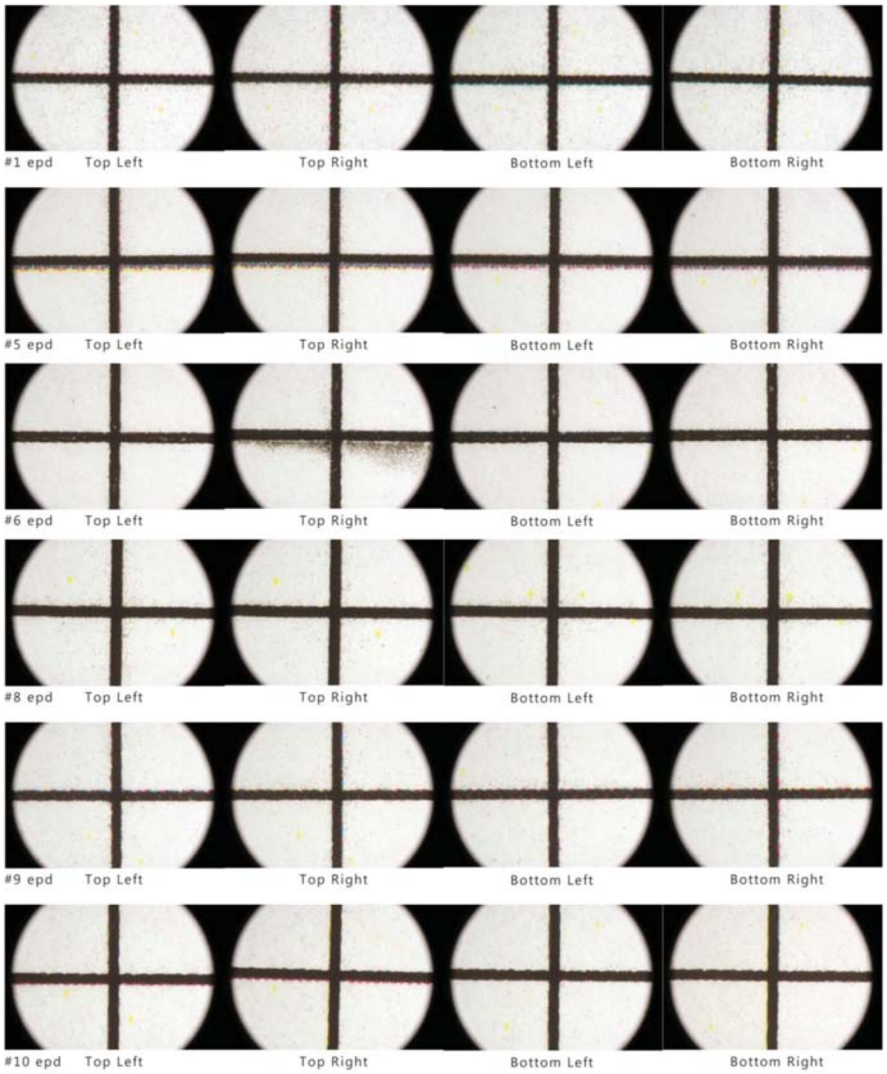
Appendix K Games-Howell Significance Test (α=0.05) for 96-Patch Color Uniformity

Note: Presses that share a letter are not significantly different from one another.

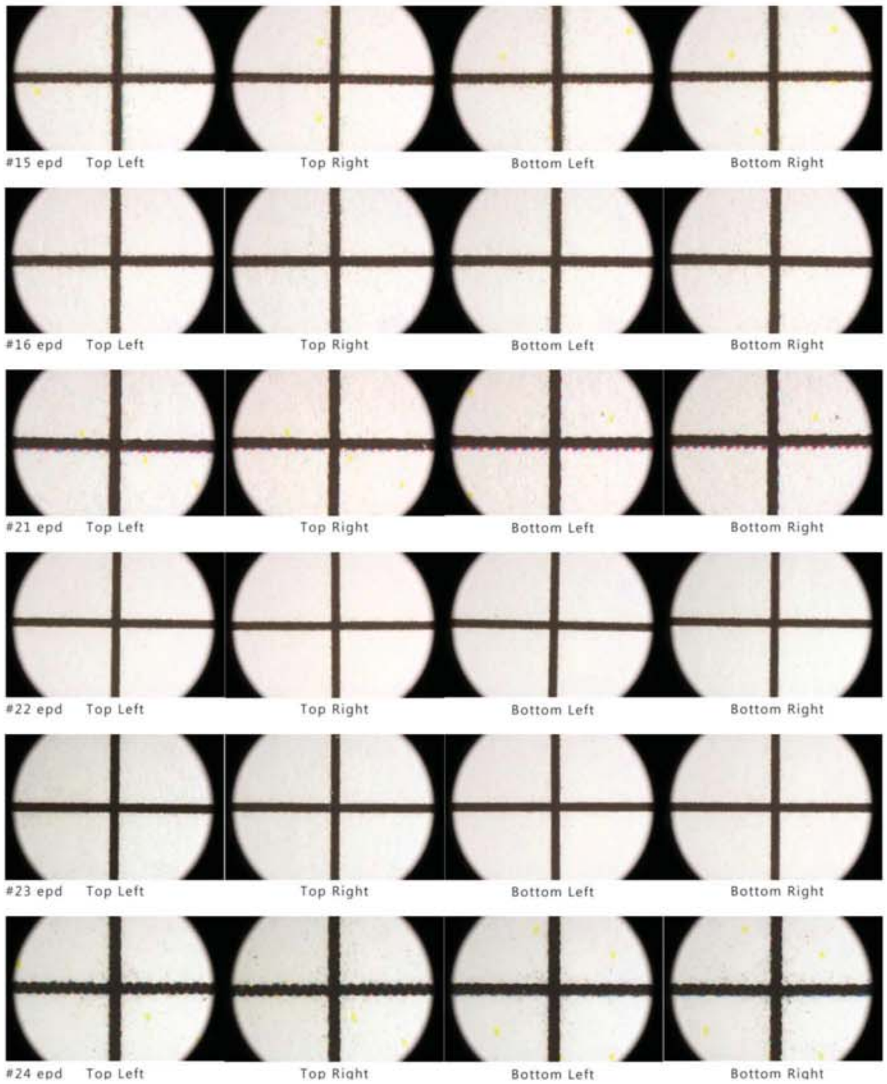
Games-Howell Pairwise Comparisons -- 96-patch target

Order	ΔE2000	Type	Code	Significance
1	0.241	hsi	27	A
2	0.272	prf	3	B
3	0.301	wfi	17	B
4	0.350	hsi	20	C
5	0.369	prf	2	C
6	0.472	hsi	19	D
7	0.492	epd	35	D
8	0.548	epd	34	E
9	0.578	epd	22	E F
10	0.579	hsi	18	E F
11	0.580	hsi	7	E F
12	0.604	epd	1	E F
13	0.625	epl	11	F G
14	0.689	epd	32	G H
15	0.698	epd	24	H
16	0.701	epd	23	H
17	0.724	epd	8	H I
18	0.738	epd	33	H I J
19	0.761	hsi	13	H I J K
20	0.780	epd	5	I J K
21	0.785	epl	14	I J K L
22	0.800	epd	21	J K L M
23	0.806	epd	9	J K L M N
24	0.811	epd	37	J K L M N
25	0.831	epd	36	K L M N
26	0.842	epd	15	K L M N O
27	0.861	epd	10	L M N O P
28	0.864	epl	12	M N O P
29	0.892	epl	4	N O P
30	0.918	epl	29	O P Q
31	0.947	epl	30	P Q R
32	1.015	epd	26	Q R S
33	1.043	epd	31	R S T
34	1.136	epd	25	S T
35	1.144	epd	28	S T
36	1.146	epd	16	S T
37	1.147	epd	6	T

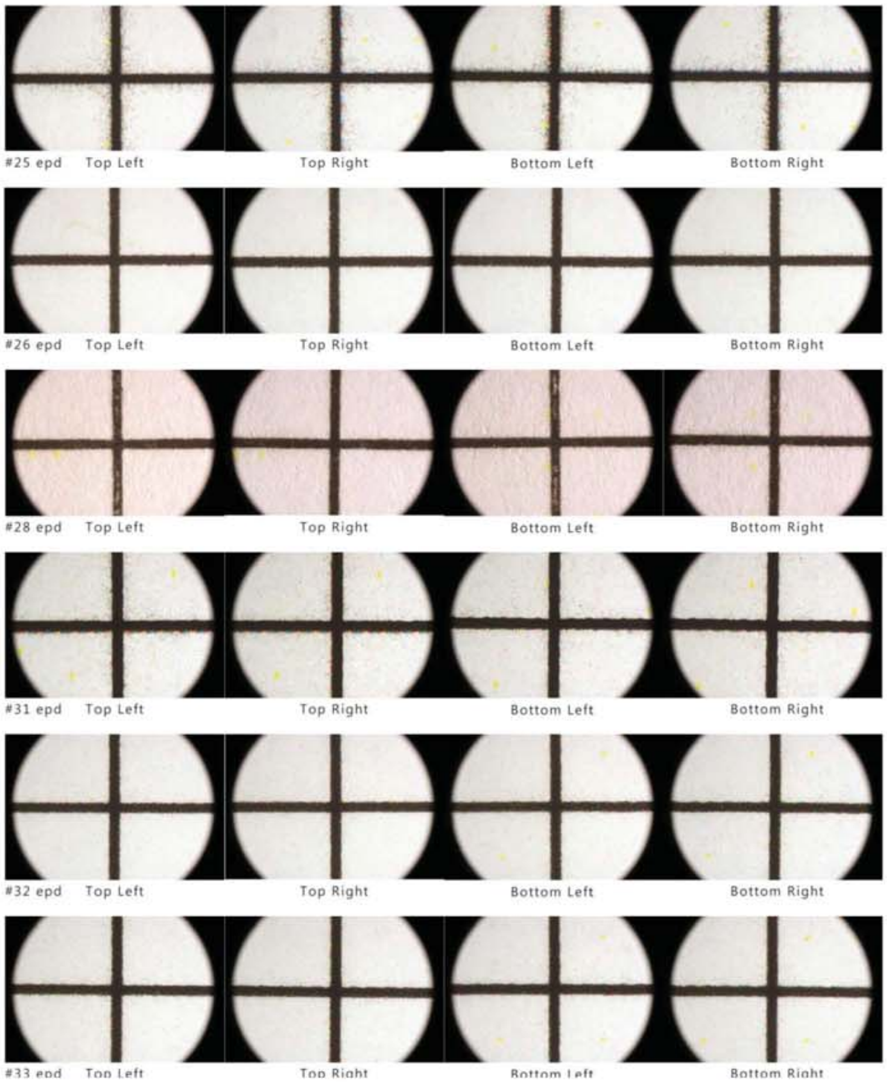
Appendix L. Register Marks from Four Locations on Digital Presses, Grouped by Press Type



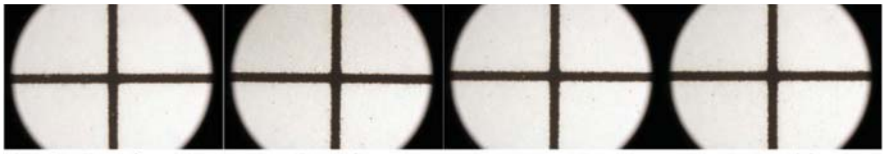
Electrophotographic presses—dry toners (continued)



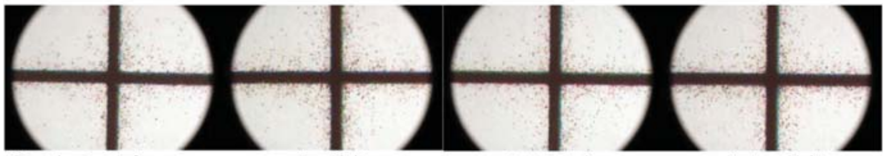
Electrophotographic presses—dry toners (continued)



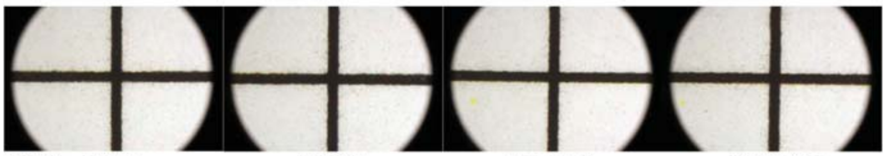
Electrophotographic presses—dry toners (continued)



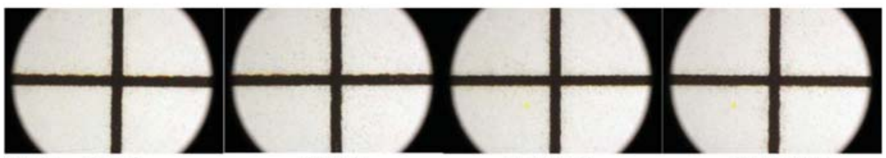
#34 epd Top Left Top Right Bottom Left Bottom Right



#35 epd Top Left Top Right Bottom Left Bottom Right

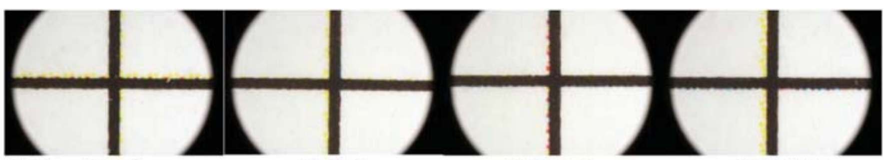


#36 epd Top Left Top Right Bottom Left Bottom Right

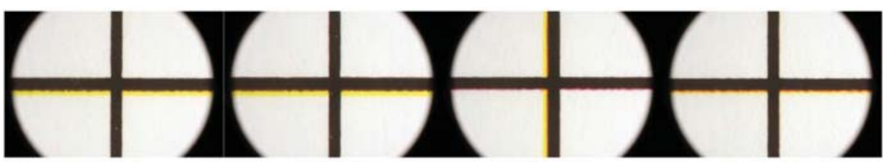


#37 epd Top Left Top Right Bottom Left Bottom Right

Electrophotographic presses—liquid toners

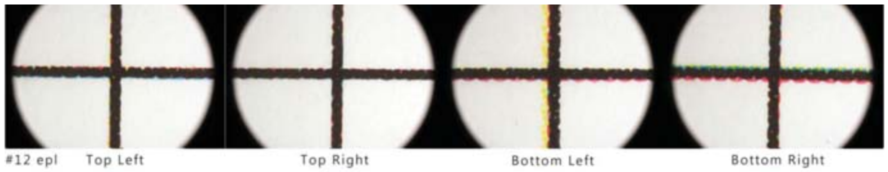


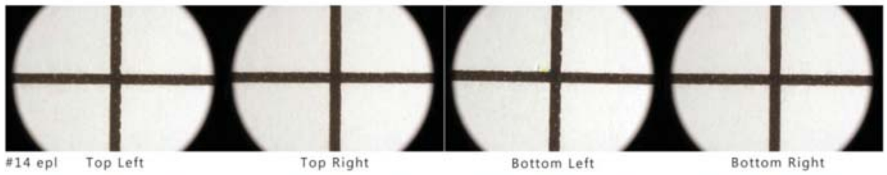
#4 epl Top Left Top Right Bottom Left Bottom Right

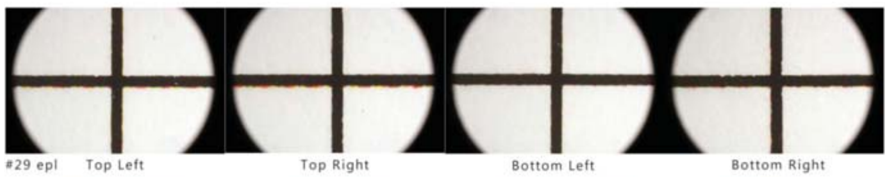


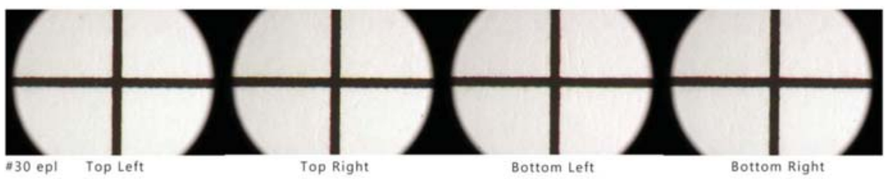
#11 epl Top Left Top Right Bottom Left Bottom Right

Electrophotographic presses—liquid toners (continued)

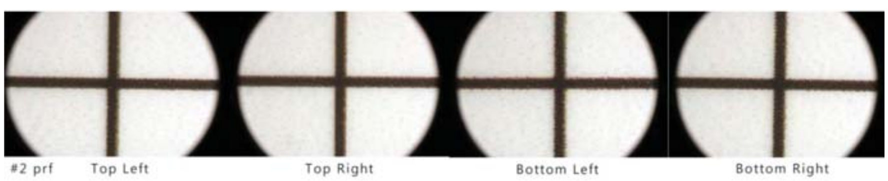


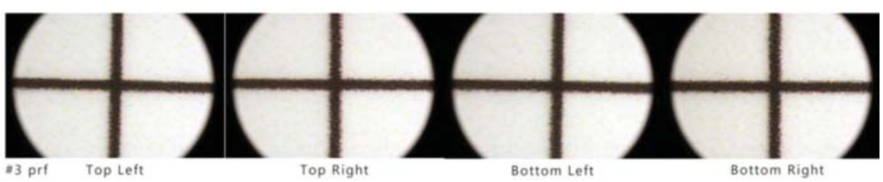




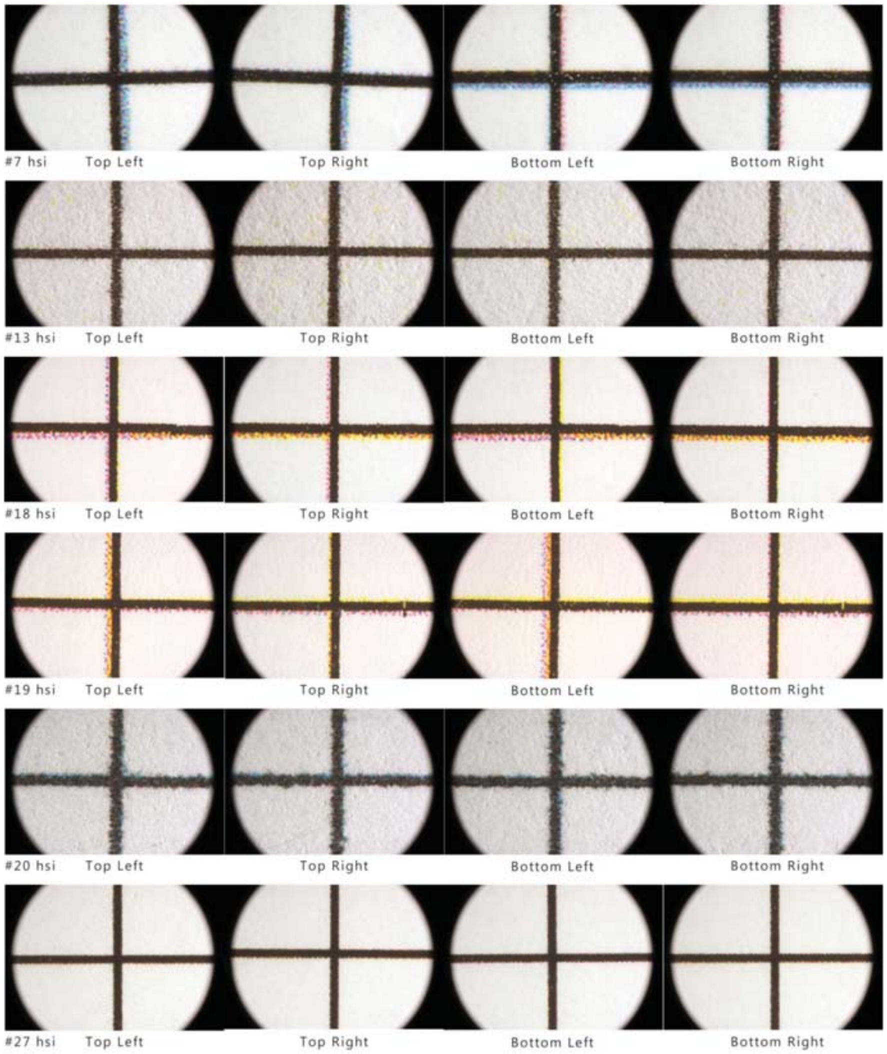


Inkjet proofing presses

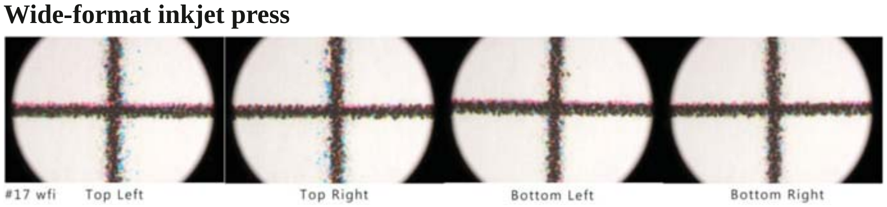




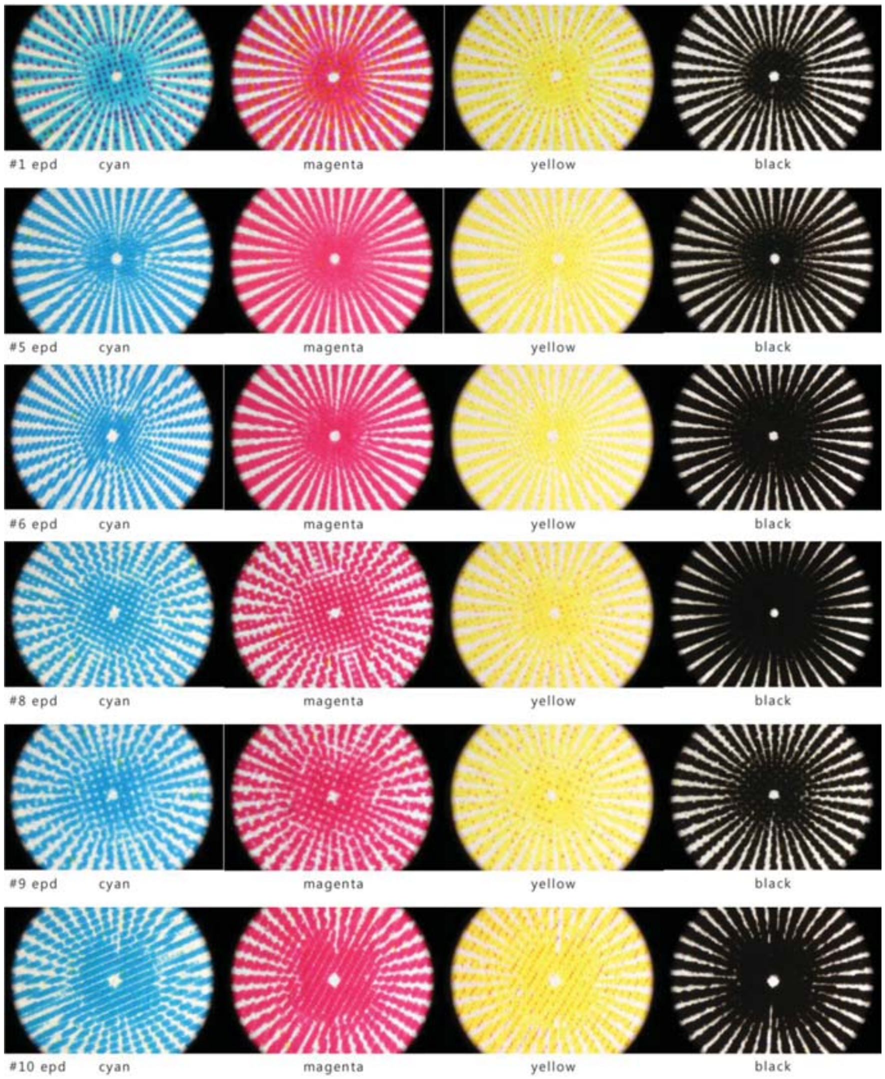
Inkjet high-speed presses



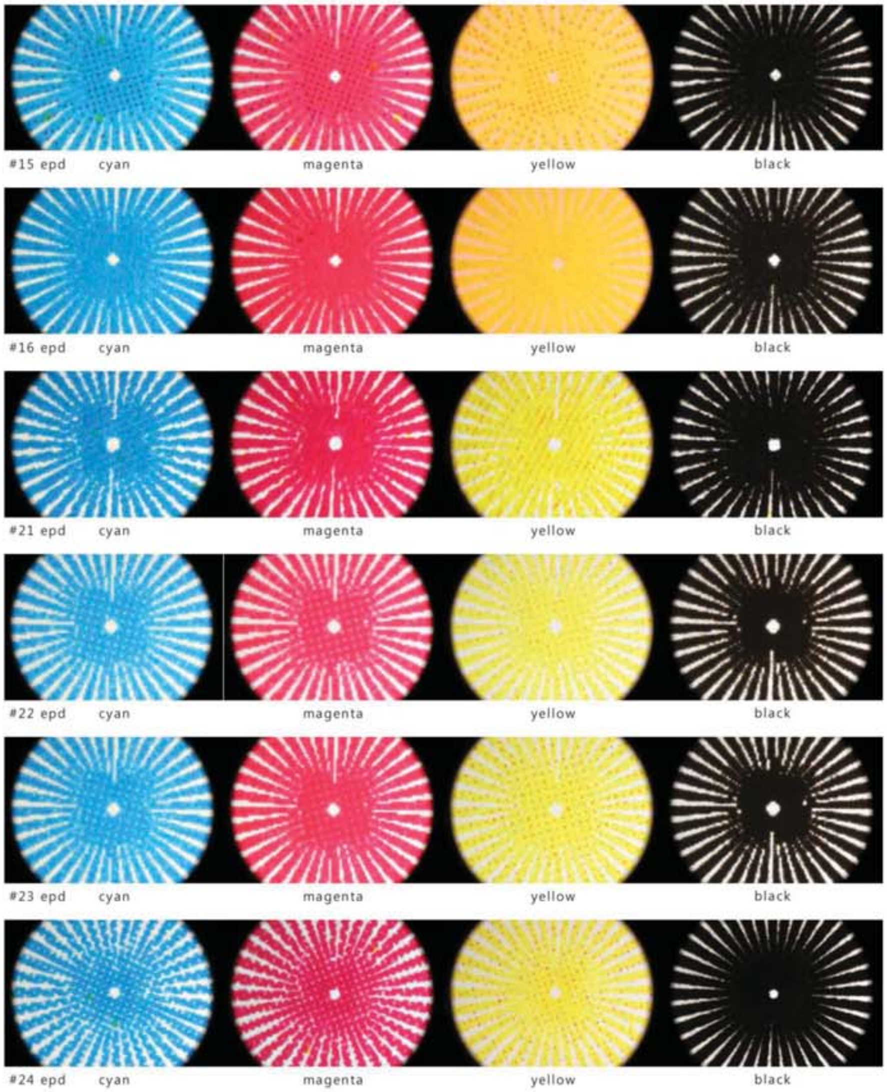
Wide-format inkjet press



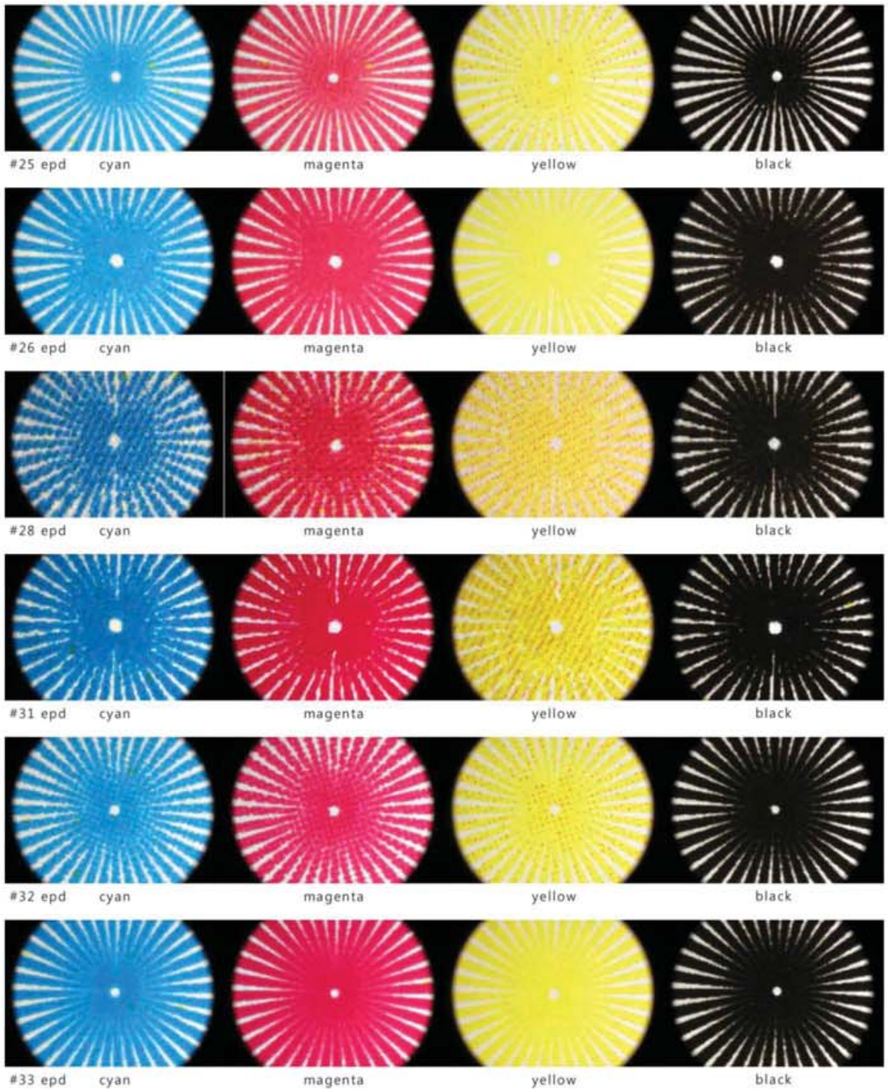
Appendix M.CMYK Star Targets, Grouped by Press Type
Electrophotographic presses—dry toners



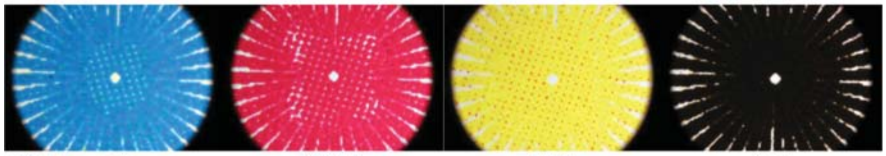
Electrophotographic presses—dry toners (continued)



Electrophotographic presses—dry toners (continued)

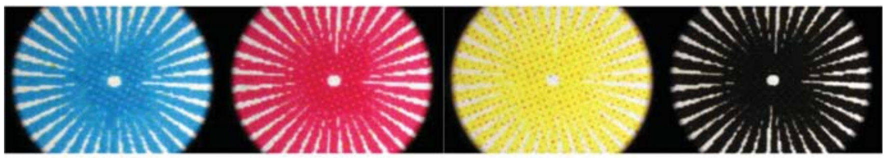


Electrophotographic presses—dry toners (continued)



#34 epd cyan magenta yellow black

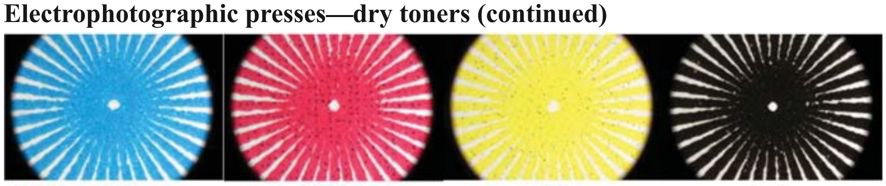
#35 epd cyan magenta yellow black



#36 epd cyan magenta yellow black

#37 epd cyan magenta yellow black

Electrophotographic presses—dry toners (continued)



#4 epl cyan magenta yellow black

#11 epl cyan magenta yellow black

Electrophotographic presses—liquid toners (continued)

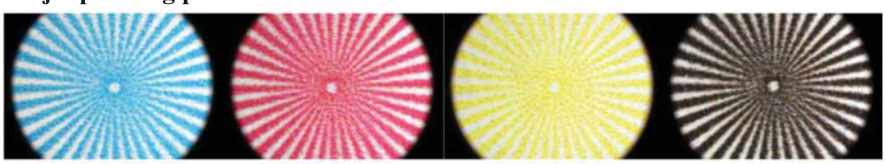
#12 epl cyan magenta yellow black

#14 epl cyan magenta yellow black

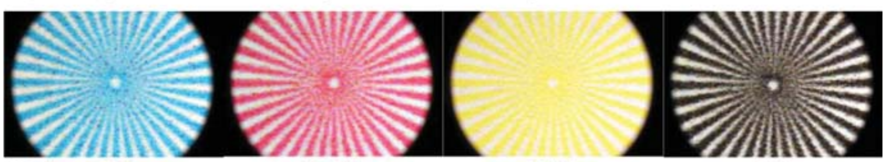
#29 epl cyan magenta yellow black

#30 epl cyan magenta yellow black

Inkjet proofing presses

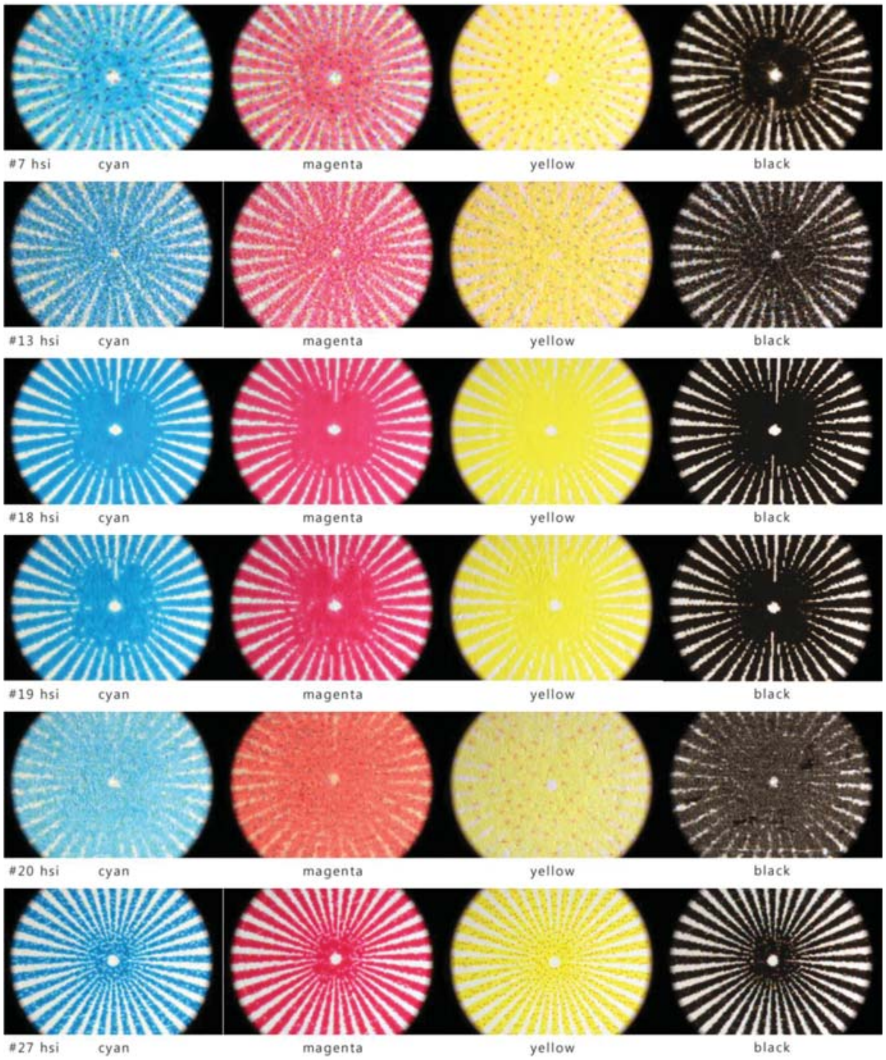


#2 prf cyan magenta yellow black



#3 prf cyan magenta yellow black

Inkjet high-speed presses



Wide-format inkjet press