Color Uniformity of Digital Press

Dr. Anthony Stanton*, Dr. Mark Bohan**, and Lindsay Ferrari**

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Abstract

This study examined the color uniformity of six electrophotographic press systems across a single printed form in comparison to the color uniformity of a sheetfed lithographic press and the color uniformity of an inkjet color proofing device. The hypothesis of the study was that the electrophotographic presses would have color uniformity equal to that of a lithographic press. The study supported this hypothesis for one of the electrophotographic presses in the study with four of the other presses being close. One electrophotographic press in the study had significantly worse color uniformity than all the others. The inkjet proofing device had superior color uniformity compared to any of the other presses in the study, including the lithographic press.

It was found that the colors with the lowest uniformity for the electrophotographic presses were lighter than the least uniform colors for lithography. The colors of lowest uniformity for both electrophotography and lithography were similarly low in saturation. The colors of lowest uniformity for the inkjet proofer were notably lighter and more saturated than the least uniform colors for either lithography or electrophotography.

Analysis of the unprinted paper patch showed that the electrophotographic presses typically distributed tiny toner particles on these areas. Furthermore, some of the electrophotographic presses imaged small yellow dots on the unprinted substrate as well.

Examination of the star targets showed the resolution of lithographic printing to be substantially better than any of the electrophotographic presses. One electrophotographic press printed the black star target with three colors rather than only solid black. Some of the electrophotographic presses produced the solid star target images as screened images. The resolutions of the electrophotographic presses were commonly higher than the resolution of the inkjet proofing device that was used as a reference.

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* Carnegie Mellon University
**Printing Industries of America

Introduction

The impetus for this study was from a presentation made at the Printing Industries of America 2012 Color Management Conference in Scottsdale, AZ. The presenter observed that an electrophotographic press that he was evaluating showed high color variation from one side of the form to the other. During the question and answer session following the presentation, a member of the audience concurred that they also had observed this phenomenon.

This observation was surprising since electrophotographic presses have no means for operators to vary the concentrations of toners across the press form. The authors hypothesized that the situations described at the conference were anomalies due to presses that were improperly maintained. To test this, an experiment was conducted to measure the color uniformity of a variety of electrophotographic printing systems. In this study the color uniformities of the electrophotographic systems were compared with the uniformity of a sheetfed lithographic press system and the uniformity of an inkjet color proofing device.

For this report, a simplified nomenclature will be used. It is understood that color uniformity is a result of the interactions of all of the components of a printing system including the printing press, the paper, the toner, and other factors. When the authors refer to an electrophotographic press in this study, it is meant to include the entire electrophotographic printing system of which the press is a part.

The presses included in the study are shown in Table 1.

Electrophotographic Presses	Lithographic & Inkjet Presses
Xerox iGen4 KODAK NEXPRESS SE3000 HP Indigo 5000 Konica Minolta bizhub PRESS C6000 Konica Minolta bizhub PRESS C8000 Ricoh 901s	Komori LS-29 Sheetfed Lithographic Press Epson 9880 Inkjet Proofer

Table 1. *Presses included in the study.*

The results in this study are coded with respect to the electrophotographic presses. They are labeled as E1 through E6 throughout the study. The labels were randomly assigned to the presses, but they are used consistently, so that E3, for example, always refers to the same electrophotographic press. The results for the lithographic and inkjet presses are clearly identified since they were the presses against which the electrophotographic presses were compared.

The test form

A test form (Figure 1) was made for this study to fit an 11 x 17 inch sheet size. The vertical orientation was used because that is the direction of travel through an electrophotographic press.

Figure 1. *Color Uniformity Test Form*

The most critical element of the Color Uniformity Test Form is the 96-patch color field that is repeated six times on the form. This is the element that was measured to calculate the uniformity of a given printing system.

In addition, the test form contains a row of solid CMYK color patches at the top to enable the adjustment of ink keys on lithographic presses. It also contains a title block that has been made to be color sensitive by incorporating a 25% black tint as the background surrounded by a 3-color border of 25% cyan, 17% magenta, and 17% yellow. The border should approximate a neutral gray in the SWOP or GRACoL printing conditions in which case it will blend seamlessly with the 25% black background tint.

The test form also contains two repeats of a photographic test image to visually judge color uniformity on the two sides of the sheet. This photograph has been used by Graphic Arts Technical Foundation and later by Printing Industries of America in their color testing suite of photographs. This image has proven to be visually sensitive to small variations in printing conditions.

The test form also contains negative and positive four-color register marks to assist with registering the image on presses. The printed marks provide clear documentation of the register accuracy of a given press system. The test form also contains star targets in the four process colors. The star target is an extremely sensitive indicator of the resolving power of a printing system.

Finally, the test form contains a GCA/GATF Digital Proof Comparator, a native PostScript file that queries raster image processor and records salient information about the printing conditions.

In this study, the analysis is restricted to evaluations of the six 96-patch color fields and evaluations of the printed star targets. The 96-patch color field is shown in Figure 2.

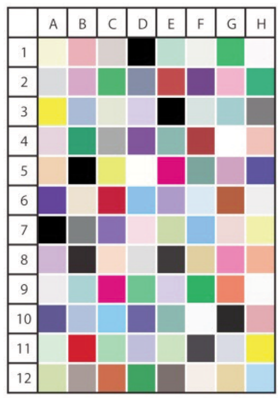

Figure 2. *96-patch color field*

Appendix A contains the cyan, magenta, yellow, and black values for the patches in the color field. In general, the patches provide a representative sample of the CMYK color space from highlights to shadows in one-, two-, three-, and four-color color combinations.

Experimental procedure

Thirty consecutive prints were collected from each of the electrophotographic presses. Only three were used for this study. Initial analysis showed a distinct warm-up effect for electrophotographic presses with prints from the start of the run not being representative of the prints from later in the series. This phenomenon was noted for possible later investigation, but, for this study, only electrophotographic prints from later in the runs were used.

Fifty consecutive prints were taken from the lithographic press run. The prints were taken after the press reached stable operating conditions. The form was image two-up on 19x25 inch paper. The sheets were cut in half and it was arbitrarily decided to use the test form from the left side of the press sheet as the basis for comparison with the electrophotographic prints.

The Epson inkjet proofs were taken from two 25x38 inch press sheets, yielding 8 copies of the Uniformity Test Form. The lithographic prints and the inkjet proofs were included to form a benchmark against which to judge to uniformity of the electrophotographic printing systems.

For each printing system, three consecutive sheets were measured with an X-Rite i1 spectrophotometer. The CIE LAB values from the 96 patches from all six targets on the test form were measured. These values were used to compute ΔE_{2000} and ΔE_{ab} color differences for each of the 96 patches from the color fields between all of the target combinations of the six targets (15 combinations in all: 1-2, 1-3, 1-4, 1-5, 1-6, 2-3, 2-4, 2-5, 2-6, 3-4, 3-5, 3-6, 4-5, 4-6, 5-6). This resulted in 1440 calculated color differences for each sheet coming from 15 paired comparisons of 96 color patches.

The average values from the three sheets were calculated for each of the 1440 color differences. These values were used as the basis for evaluating the color uniformities of the presses in this study.

The ΔE_{2000} values, rather than the ΔE_{ab} values, were used throughout this analysis to indicate the magnitudes of perceptual color differences. As discussed in the following section, Color Difference Measurements, the ΔE_{2000} color differences have been found to be more accurate indicators of perceived color difference than ΔE_{ab}. However, ΔE_{ab} is still a commonly used color difference measure in the graphic media industry. In this study, ΔE_{ab} values were computed to provide references for comparing the older and newer color difference calculations.

In this analysis, some observations were made from the calculated color differences. Then, for each printing condition, the average color difference based on the 1,440 individual color differences measured between the 15 target pairs on the test form was calculated. These average values were used as the color uniformity index of the different printing systems.

Photomicrographs at 50x magnification were made of the cyan, magenta, and black star targets to assess the relative resolutions of the different printing systems. Several observations were then made from these photomicrographs.

Color Difference Measurements

The measurement of color differences is an area of active research and development in the graphic arts. Since 1976, Delta-E (ΔE_{ab}) has been used as a measurement of color differences that relates to the perceived differences of a standard observer. The ΔE_{ab} value is the vector distance between two points plotted in the CIE LAB color space. However, it has been found that ΔE_{ab} does not accurately model color differences in all parts of the color space because it treats differences of lightness, hue, and chroma equally, while the human observer does not respond to changes in these three parameters equally. These inaccuracies can be equated to the fact that the CIE LAB color space is not truly perceptually uniform.

Work is taking place along two avenues to obtain more accurate color difference calculations. One approach is to transform the CIE LAB color space to make it more perceptually uniform. Roesler, Chairman of the Industrial Tolerances Working Group of the German Society of Color Science and Application, reports that the DIN 99 standard for calculating color differences relies on non-linear modifications of the coordinates of the CIE LAB color space. The resulting color space is more perceptually uniform, making it possible to use vector distances to calculate color differences.

The second approach, which has taken place in a number of stages since the mid-1980s, has been to introduce correction factors into the ΔEab equation to improve the correlation between calculated and perceived color differences. The first of these, ΔE_{cmc}, was defined by Clark, McDonald, and Rigg (1984) from work initiated by the UK Colour Matching Committee of the Society of Dyers and Colourists in 1984. This equation includes weighting factors for lightness and chroma that are typically set at 2:1 or 1:1 for graphic arts applications. Although this equation was developed for textiles, it has been found to yield improved color difference values for some printing applications (Habekost, 2008).

In 1995, the CIE adopted the ΔE_{94} color difference equation from work done on a study of automotive paints by Berns, Alman, Reniff, Snyder, and Balonen-Rosen (1991). This equation includes weighting factors for lightness, chroma, and hue designed to improve acceptability tolerances for industrial applications. Acceptability tolerances for graphic arts are not well established, although Johnson and Green (2006) have addressed the subject and published some initial recommendations. The ΔE_{94} color difference equation has been found in several studies to yield improved color difference values compared to the ΔE_{ab} for graphic arts applications.

Another color difference formula, that introduced a hue-chroma interaction term, emerged in 2001 from the work of Luo, Cui, and Rigg (2001). This equation was accepted by the CIE and was released as ΔE_{2000}. Johnson and Green (2006) found this equation, as well as ΔE_{94}, yielded improved color difference values compared to ΔE_{ab} for graphic arts applications.

Relevant color difference research has been done by Habekost and Rohlf (2008) and by Habekost (2008). Both studies found that ΔE_{cmc} and ΔE_{2000} were better measures of perceived color differences than ΔE_{ab}; however, the studies had conflicting results as to which of the two was better. Habekost and Rohlf found that ΔE_{2000} corresponded slightly better to perceived differences than did ΔE_{cmc}.

Habekost, in the second study, found that ΔE_{cmc} was a slightly better measure than ΔE_{2000}. In both studies each of the equations was evaluated with the weighting factors set at unity.

The authors recognize that the science on measuring perceived color differences is unsettled, but there is sufficient evidence that ΔE_{2000} is a more accurate measure than ΔE_{76}. Therefore, ΔE_{2000}, with weighting factors at unity, was used for this analysis.

Results and discussion

Color Uniformity

The color uniformity index that was used in this study was based on the color differences measured between six 96-patch color fields from different areas of the test form. Fifteen target combinations represented all the possible pair comparisons between the six color fields. The ΔE_{2000} color differences were calculated for each of the 96 patches in the color field and for each of the 15 target pairs, yielding 1440 color differences for each sheet. Three sheets from each printing condition were analyzed in this way. The 3 sets of 1440 color differences were averaged forming a composite set of color differences for each printing condition. The mean value of this set of composite color difference measurements was the color uniformity index for that particular press.

Appendix B contains summary statistics including distribution histograms of ΔE_{2000} averages for each printing system. Figure 3 shows a bar graph of the average ΔE_{2000} values for each of the printing systems in this study.

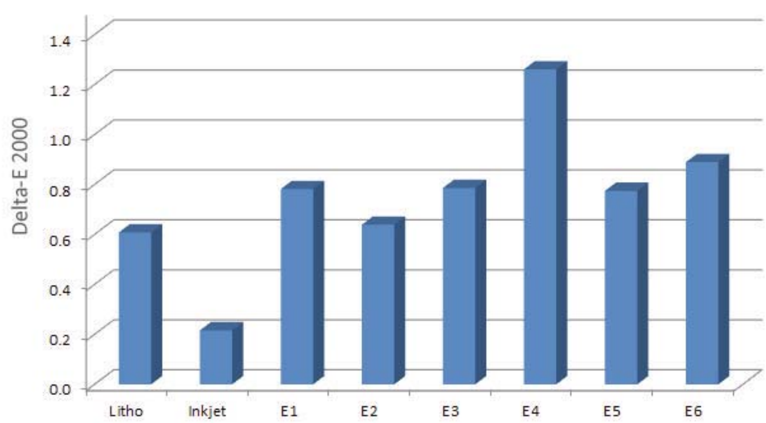

Figure 3. *Bar graph of* ΔE_{2000} *values for all printing systems*

Figure 3 shows that the inkjet proofer had by far the best color uniformity of the presses tested. As a proofing device, the inkjet printer is expected to exhibit superior color fidelity and consistency. These data verify that this is justified in terms of color uniformity.

The second best color uniformity was found with the lithographic press, but it was virtually the same as the best of the electrophotographic systems (E2). The electrophotographic presses overall had varied results for color uniformity with one press, E4, having substantially worse color uniformity than any of the other presses in the study. It should be noted that a value of 1.0 is theoretically equal to a Just Noticeable Difference (JND) on the ΔE_{2000} scale. The E4 press was the only press where the average color difference on the sheet would be noticeable by the standard observer.

Table 2 shows the data depicted in Figure 3 plus other data of interest. The top row of Table 2 shows the mean ΔE_{2000} color differences, the color uniformity index used in this study. The mean color difference for the inkjet proofer was 0.22 ΔE_{2000} units, and the mean color difference for the E4 electrophotographic press was 1.26 ΔE_{2000} units. The statistical significance of differences found between presses is discussed below in the *Analysis of Variance* section.

	Litho	Inkjet	E-1	E-2	E-3	E-4	E-5	E-6
ΔE2000	0.61	0.22	0.78	0.64	0.79	1.26	0.77	0.89
Maximum	3.42	0.87	4.20	2.91	3.81	5.87	3.38	3.50
90%	1.17	0.39	1.51	1.23	1.51	2.54	1.52	1.68
Variance	0.18	0.01	0.17	0.11	0.22	0.81	0.21	0.23
Var/Litho	1.00	0.05	0.97	0.61	1.25	4.50	1.17	1.30
ΔE76	0.94	0.34	1.23	0.99	1.15	1.77	1.16	1.30

Table 2. *Average ΔE_{2000} values, maximum values, 90th percentile values and ΔE_{ab} values for all printing systems*

Table 2 shows the maximum color differences for each printing press. The inkjet proofing device was the only printing system where the maximum color difference between any of the 96 colors, and between any two of the six targets on the test form, was less than a JND. This level of color uniformity was seen as exemplary.

The 90th percentile values for each press are shown in Table 2. These represent the color difference values within which 90% of the samples fell. The samples above the 90th percentile were the colors that showed the lowest color uniformity for a given press. These colors are examined further in the section *90th Percentile Colors*.

The variances of the ΔE_{2000} color differences for each press are also shown in Table 2 along with the ratio of the variance of each press system divided by the variance of the color differences for the lithographic press. This indicates whether a press exhibited lower or higher variance than did lithography. The inkjet proofer had the lowest variance of ΔE_{2000} values with only 5% of the lithography variance. Two of the electrophotographic presses had lower variance than lithography. E1 was nearly equal to lithography, but E2 had only 61% of the variance of lithography. The other four electrophotographic presses had higher variances than did lithography with the E4 press being noteworthy with 450% of the variance of lithography.

Table 2 shows the average color differences calculated via the ΔE_{ab} equation which is still used widely in the industry. The ΔE_{ab} values are higher than the ΔE_{2000} values because the older equation overestimates perceived color differences by not differentiating between changes in lightness, hue, and chroma.

Analysis of Variance

To determine whether the differences in color uniformity were significant, a one-factor ANOVA was run testing the factor of printing press against the sets of ΔE_{2000} values. The ANOVA table and the results of Tukey analysis are shown in Figure 4.

One-way ANOVA: ΔE_{2000} versus Press

Source	DF	SS	MS	F	P
Press	7	865.255	123.608	507.54	0.000
Error	11512	2803.675	0.244		
Total	11519	3668.930			

S = 0.4935   R-Sq = 23.58%   R-Sq(adj) = 23.54%

Grouping Information Using Tukey Method

Press	N	Mean	Grouping
E-4	1440	1.2613	A
E-6	1440	0.8898	B
E-3	1440	0.7864	C
E-1	1440	0.7821	C
E-5	1440	0.7747	C
E-2	1440	0.6393	D
Litho	1440	0.6084	D
Inkjet	1440	0.2163	E

Means that do not share a letter are significantly different.

Figure 4. *One-factor ANOVA presses vs. ΔE_{2000} values plus Tukey analysis*

The ANOVA found significant differences between the mean ΔE_{2000} values based on the presses being used. Figure 4 lists the presses in order of mean ΔE_{2000} from worst to best color uniformity. The E4 electrophotographic press had significantly worse color uniformity (i.e., higher mean color difference values) than any other press tested. The E6 electrophotographic press had better color uniformity than E4, but significantly worse than all of the other presses in the study. The E3, E1, and E5 presses did not differ from each other in color uniformity; they were significantly better than E4 and E6, but worse than E2, the electrophotographic press with the best color uniformity. The E2 press color uniformity was not different from the lithographic reference printing. The inkjet proofer was significantly better in term of color uniformity than any other press in the study.

The confidence intervals around the mean values in this study were small because of the large sample sizes. Therefore, significant differences in mean color difference values were found that might not equate to significant differences in the visual impressions of color uniformity when viewing complex color images produced by those printing presses. For the best of the electrophotographic presses, the hypothesis is supported that the color uniformity of that press is equal to that of the lithographic reference. The researchers feel that the presses E3, E1, and E5 also have color uniformity that is close enough to the lithographic reference to be commercially acceptable for color uniformity. E6, although a more marginal case, still has an average color difference that is below the JND threshold. The E4 electrophotographic press with over twice the mean ΔE_{2000} value of lithography might be perceived as producing lower quality color printing based on its lack of color uniformity. This would be particularly true for prints with large areas of solid colors rather that complex color images.

The ANOVA technique assumes normal distributions with equal variances. In this study, these conditions are not met. As seen in Appendix B, the distributions are all positively skewed because there is a limiting factor of zero on the left tail of the distributions.

Roberts and Russo (p. 69) report that ANOVA is quite robust with reference to violations of normality if the sample sizes are large, if all the cell sizes are equal, and if skewness of cell distributions are all in the same direction. In this study the sample sizes are all equal with 1440 values and the distributions and all share the same type of skewness. Furthermore, the p-values are less than 0.01 giving further confidence that the ANOVA results are correct.

The data in this study contained several outliers that resulted from individual color patches that had higher average ΔE_{2000} values for at least some of the 15 paired comparisons on the printed sheets. This can clearly be seen in the individual value plots shown in Figure 5.

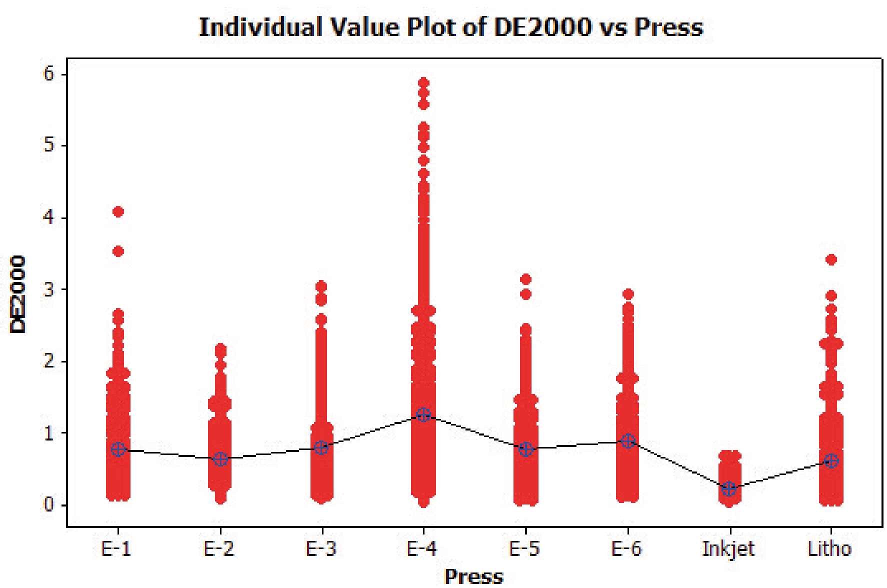

Figure 5. *Individual value plots ΔE_{2000} vs presses.*

There are various statistical techniques, like the Kruskal-Wallis Test, to transform data to reduce the influence on outliers. These approaches were rejected since the researchers believe that in this study the outliers are the most important data points. The outlier color patches have a profound effect on the visual sensation of color uniformity.

To confirm the validity of the ANOVA findings, the data was also tested with the non-parametric Mood median test that used medians rather than means for comparing treatments. This approach greatly diminishes the influence of outliers. Figure 6 shows the results of this test.

Mood Median Test: DE2000 versus Press

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Mood median test for DE2000
Chi-Square = 2129.10    DF = 7    P = 0.000

                                   Individual 95.0% CIs
Press    N<=    N>  Median  Q3-Q1  --+---------+---------+---------+----
E-1      564   876   0.707  0.526                      *)
E-2      773   667   0.569  0.409                (*)
E-3      625   815   0.685  0.621                    (*-)
E-4      365  1075   1.039  1.057                                 (--*)
E-5      628   812   0.677  0.612                    (*)
E-6      481   959   0.799  0.629                         (*)
Inkjet  1434     6   0.196  0.120  *
Litho    890   550   0.490  0.453             (*)
                                   --+---------+---------+---------+----
                                   0.25      0.50      0.75      1.00
Overall median = 0.609
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Figure 6. *Mood median test for* ΔE_{2000} *versus press.*

The results of the Mood median test showed the medians of the presses to be ordered the same as the means were ordered in the ANOVA test. This supports the findings of the ANOVA test. The researchers feel that the means are better indicators of color uniformity than the medians because the means do not reduce the influence of the outliers on the findings.

Regression Analysis

It was hypothesized that a relationship might exist between the total dot area coverage of color patches and the levels of color differences exhibited by those patches. Regression analysis was used to test that relationship for each of the presses in the study, as well as for all the electrophotographic presses as a group. A sample scatterplot for total dot area verses ΔE_{2000} color differences for the E2 press (the electrophotographic press with the best color uniformity) is shown in Figure 7.

The scatterplot in Figure 7 was typical of the group. The hypothesis was rejected. No significant relationships were found between total dot area coverage and any printing of the presses in the study. Typically, the r-squared values were less than 1%.

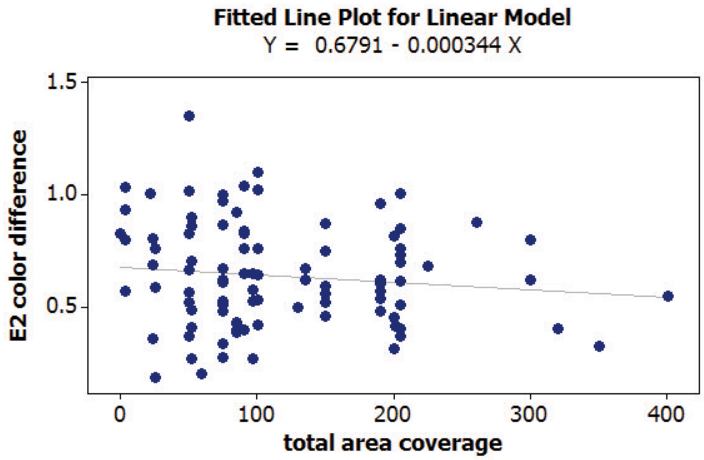

Figure 7. Scatterplot of total area coverage vs. E2 color differences

It was also hypothesized that there were relationships between the color differences found with two different printing presses for each of the 96 color patches. Regression analysis was performed for each press combination finding strong linear relationships in every instance. For some press combinations a slightly better fit could be obtained with quadratic models. The R-squared values for all of the press combinations are shown in Table 3.

R^2 values	Litho	Inkjet	E1	E2	E3	E4	E5
Inkjet	98.68	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx
E1	94.78	95.70	xxxxx	xxxxx	xxxxx	xxxxx	xxxxx
E2	93.48	91.80	99.09	xxxxx	xxxxx	xxxxx	xxxxx
E3	89.82	93.98	98.65	97.82	xxxxx	xxxxx	xxxxx
E4	93.07	96.72	97.33	96.64	96.71	xxxxx	xxxxx
E5	87.54	95.57	97.24	96.33	97.66	97.23	xxxxx
E6	88.60	96.46	97.51	96.75	98.28	96.60	99.12

Table 3. *R-squared values for all press combinations.*

The hypothesis was supported; the color differences for the 96 individual patches were highly correlated between printing presses. For most press pairs, over 90% of the color differences from one press are predictable from the ΔE_{2000} values of the other press.

Figure 8 shows the regression analysis including the scatterplot of the ΔE_{2000} values for the E2 electrophotographic press and the lithographic press with the best fitting line superimposed. Appendix C shows the regression analysis for the lithographic press and all of the other presses in the study. Appendix D shows the regression analysis for the E2 electrophotographic (chosen because it had the best color uniformity of any of the electrophotographic presses) and all of the other presses in the study.

The shape of the scatterplot in Figure 8 was typical for the comparison of

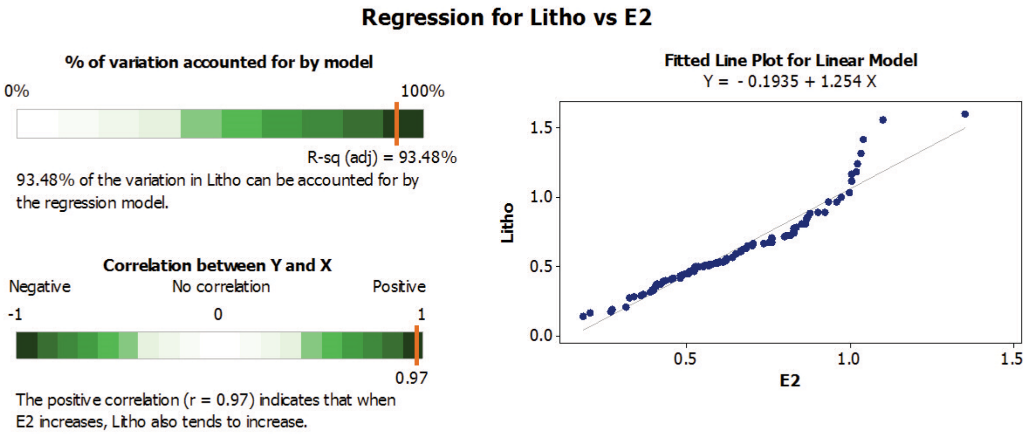

Figure 8. *Regression analysis for lithographic press and E2 electrophotographic press.*

electrophotographic presses with the lithographic press. The color differences of electrophotography track well with lithography except for the patches where lithography exhibits high levels of color difference. This can be confirmed by examining the other scatterplots in Appendix C. Interestingly, it is not true when comparing the inkjet proofing device with the lithographic press where there is a strong linear relationship without the area of divergence seen with electrophotography. The inkjet proofing device has been calibrated to mimic the output of lithographic presses which it appears to do well.

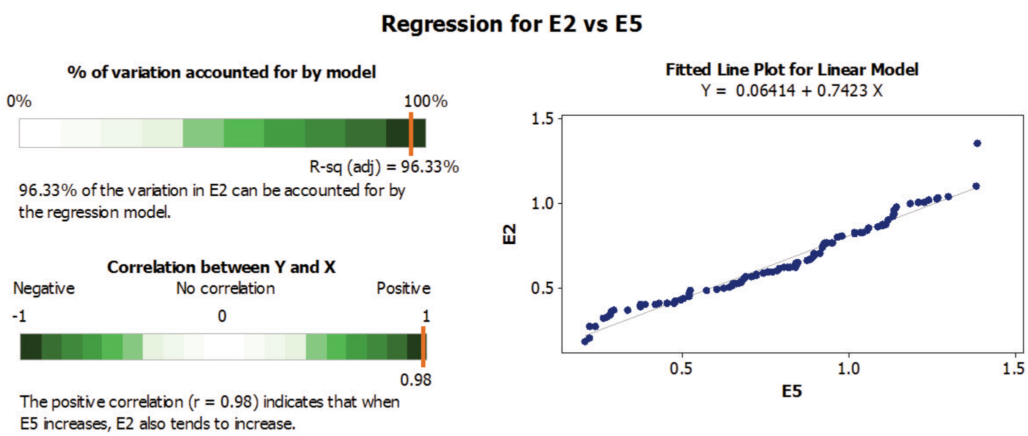

Figure 9. *Regression analysis for electrophotographic presses E2 and E5.*

For contrast, Figure 9 shows the regression analysis for two electrophotographic presses, E2 and E5, which had similar color uniformity scores.

The linear fit between the two electrophotographic presses was better than the fit found for lithography with any of the electrophotographic presses. This finding indicates that, within the context of this study, the individual colors that are least uniform on a lithographic press have better uniformity with electrophotographic presses. A closer examination of the specific colors that had the lowest uniformity scores for each press follows in the section 90th percentile colors.

90^{th} Percentile Colors

For each press the average color difference between the 15 different paired comparisons was calculated for each of the 96 color patches. The patches whose average color differences fell outside of the 90^{th} percentile were identified. These colors were the most difficult to match for each printing system.

Modified color fields were made to highlight these difficult patches and to facilitate the comparison of most difficult colors between printing systems. The modified color fields highlighting the 90^{th} percentile colors are shown for all printing systems in Appendix E. The 90^{th} percentile color fields for the lithographic press, the inkjet proofer, and the E2 electrophotographic press are shown in Figure 10.

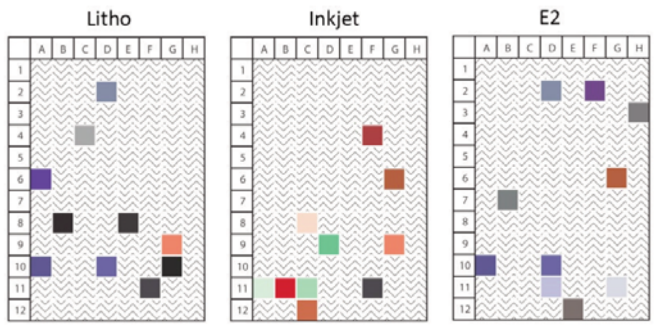

Figure 10. *90^{th} percentile color fields for lithographic, inkjet, and E2 presses.*

Examination of the 90^{th} percentile colors found that the difficult colors for the lithographic press, with a couple of exceptions, were dark colors with low saturation. This observation was expected because these patches are tertiary colors with heavy coverage. Also, being near neutral, they are colors to which the human observer is highly sensitive to small color differences.

Taken as a group, 90^{th} percentile colors for the electrophotographic presses were lighter than the lithographic 90^{th} percentile colors, but were similarly low in saturation. The electrophotographic presses were similar to each other with some idiosyncrasies. The E1 press had trouble with green patches while the E2 press had more difficulty with blue patches, as seen in Appendix E.

The H3 patch (0C, 0M, 0Y, 75K) was in the 90^{th} percentile group for all 6 electrophotographic presses, but it was not in the 90^{th} percentile group for the lithographic press or the inkjet proofer. Similarly, the B7 patch (75C, 63M, 63Y, 0K) was in the 90^{th} percentile group for 5 of the 6 electrophotographic presses, but not for the lithographic or inkjet presses. The F11 patch (100C, 100M, 100Y, 0K) was the only patch in the 90^{th} percentile group for lithographic, inkjet, and 3 of 6 electrophotographic presses.

The 90^{th} percentile colors for the inkjet proofer were dramatically different than those for the lithographic or electrophotographic presses. Six of the 10 patches in the 90^{th} percentile for inkjet were not common with any of the other presses in the study. The problematic colors for the inkjet proofer were noticeably lighter and more saturated than those for the lithographic press or the electrophotographic presses.

90th p	litho	inkjet	E1	E2	E3	E4	E5	E6
Avg. L	28.53	54.62	41.87	47.21	52.39	36.28	45.80	41.81
Avg. Ch	21.32	43.94	23.78	22.09	11.34	14.14	14.62	10.35

Table 4. *Average Lightness and Chroma values for 90^{th} percentile patches.*

To test the validity of these observations, the lightness (LAB L) and the chroma (Ch) of the patches from the 90^{th} percentile groups were calculated and are shown in Appendix F. The 96-patch color field in the upper left of the test form was chosen for making the lightness and chroma measurements. The average LAB L and Ch values from the 10 patches in each of the 90th percentile groups are shown in Table 4.

The average values from Table 4 confirm the observations that the lithographic press showed high color differences for dark colors with low chroma. The electrophotographic presses were similar to each other overall with lighter colors causing more difficulty than for lithography. The chromas of the electrophotographic 90^{th} percentile patches were as low as, or lower than, those for lithography.

The lightnesses and chromas of the difficult color patches for the inkjet proofer were distinctly different from all the other presses in the study. The patches in the 90^{th} percentile for the inkjet proofer were lighter with much higher chromas than the other presses.

Zero Coverage Patches

The color field contains a paper patch with zero CMYK coverage. It was initially conceived that this patch would provide a measurement error value since there would be only slight color difference based on paper uniformity. Therefore, any color differences found between these unprinted patches could be primarily attributed to the measuring instrument. Table 5 shows the average and maximum color differences found from the 15 different target comparisons used for this study. Appendix G shows all of the color differences measured between the zero coverage patches from each of the presses.

	Litho	Inkjet	E1	E2	E3	E4	E5	E6
Avg ΔE	0.134	0.152	0.196	0.206	0.18	0.169	0.238	0.242
Max ΔE	0.238	0.303	0.365	0.376	0.32	0.322	0.364	0.452

Table 5. *Average color differences for paper patch.*

The values in Table 5 show clear differences between printing presses with respect to the color uniformity of unprinted paper patches. It was clear that these color differences could not be ascribed solely to measurement error. It was suspected that the different presses were toning the unprinted paper in some way.

To investigate this suspicion, photomicrographs were taken of the unprinted paper patches. Appendix H shows these images for each of the presses in the study. Figure 11 shows the images from the lithographic press, the inkjet proofer, and the E1 electrophotographic press.

Figure 11. *Unprinted paper patches for lithography, inkjet, and E1 electrophotography.*

The lithographic press had the smallest average color difference for the unprinted patches. It was clear from the photomicrographs that the lithographic samples had the least amount of toning on the unprinted substrate compared to any of the other presses in the study. The inkjet proofer deposited a few tiny droplets on the unprinted paper.

The toning found with the electrophotographic presses was more substantial overall, but uneven from one press to another. Appendix H shows that the E4 electrophotographic press had very few toner particles imaging in areas of zero coverage, while E6 has a substantial amount of toner imaging in the zero coverage patch.

Figure 11 includes the photomicrograph for the E1 press because it was representative of several of the presses in this study. In addition to tiny randomly-distributed toner particles on the unprinted paper, there are larger uniformly-spaced yellow dots. These dots appear to be deliberate and are security features. The tiny randomly-distributed toner particles are probably unfortunate by-products of the electrophotographic printing systems.

Star Targets Observations

The star target is an extremely sensitive diagnostic test target. The size of the filled-in section in the center of the target is an indication of the resolving power of the press system. Furthermore, asymmetrical aspects of the filled-in center indicate directional biases (slur) in the printing. Doubling on a press is seen as offset filled-in centers (a figure 8 pattern).

Appendix I shows 50X photomicrographs of the black, cyan, and magenta star targets from each of the presses in the study. The yellow star targets were not photographed since they did not have sufficient contrast to be easily analyzed and because they were unlikely to provide any insights that were different from the other three colors.

Examination of the targets overall, showed that the lithographic press had superior resolution compared to any of the digital printing devices including the inkjet proofer. In most instances, the electrophotographic presses had higher resolution than the inkjet proofer, however, there were pronounced differences between the different electrophotographic presses and between the different colors that were examined.

For the black star targets the E3 and E6 presses had the highest resolution of the electrophotographic presses, closely followed by the E1 and E4 presses. These were all superior to the inkjet proofer for resolution. E2 had better defined star wedge elements than the inkjet proofer, but slightly lower resolution than inkjet. The E5 black star target showed a serious anomaly. Although the star target was defined as 100% black ink, the E5 press printed it with at least three colors of toner. The toners did not register perfectly showing a rainbowing and doubling pattern in the star target. Figure 12 shows the black star targets from the lithographic press, the E6 electrophotographic press (the best of the electrophotographic presses in this instance), and the E5 electrophotographic press.

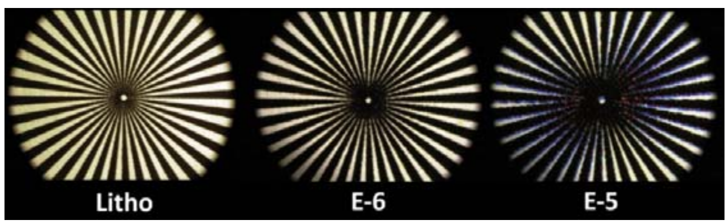

Figure 12. *Three black star targets*

The cyan star targets in Appendix I were similar to the black targets with respect to resolution. In this instance the E5 star target is composed of a single toner and looks similar to the other electrophotographic presses albeit with the second lowest resolution of the group. The cyan star target showed that the electrophotographic presses typically printed the target as a screen rather than a solid. The E3 electrophotographic press was a noteworthy exception to this phenomenon. Figure 13 shows the cyan star targets from the lithographic press, the E3 and the E4 electrophotographic presses.

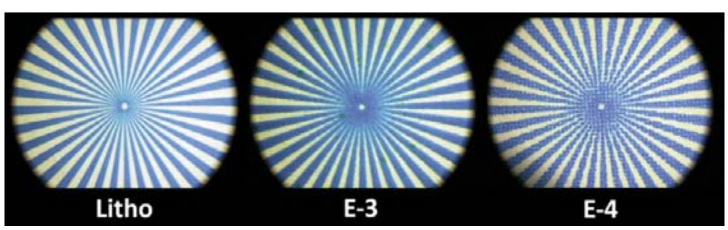

Figure 13. *Three cyan star targets*

The cyan stars in Figure 13 show the superior resolution and precise star wedge imaging of lithographic printing. The resolutions of the two electrophotographic presses are similar, but the E3 press printed the star wedges as solid elements while the E4 press imaged the star target as a screened image. Most of the electrophotographic presses used screened images for the star targets. Furthermore, in the E3 image some randomly distributed dots of yellow toner can be seen.

The magenta star targets showed similar results to the cyan star targets but the screening effect was only apparent on the E4 press for magenta while it was clearly seen on the E1, E3, and E4 presses for cyan.

In summary, the following observations were made from the star targets:

- The lithographic press showed far higher resolution and more precisely defined image elements than any of the electrophotographic presses or the inkjet proofing device.

- The electrophotographic presses overall had higher resolution than the inkjet proofing device.

- The E2 electrophotographic press had substantially lower resolution than the others (lower even than the inkjet proofing device).

- The E5 electrophotographic press imaged the 100% black star target with color toners in addition to black toner. The lack of perfect register caused rainbowing and overall lower resolution for the black star target.

- Some of the electrophotographic presses imaged the 100% cyan and magenta star targets as screened images rather than as solids.

Conclusions

This study examined the color uniformity of six electrophotographic press systems across an 11x17-in. printed test form. The electrophotographic presses were compared to the color uniformity of a sheetfed lithographic press and the color uniformity of an inkjet color-proofing device.

Color uniformity was based on the mean value of measured color differences from three printed sheets. A specially designed 96-patch color field was imaged at six different locations on the test form. Color differences were calculated between all of the 15 possible target pairings for each of the 96 colors in the color field. These 1440 color difference values were averaged across the three samples from each press. The mean of the averaged values was designated as the color uniformity index.

The hypothesis of the study was that the electrophotographic presses would have color uniformity equal to that of a lithographic press. ANOVA analysis supported this hypothesis for one (E2) of the electrophotographic presses. Three of the other presses (E1, E3, and E5) were equal to each other in color uniformity. They were close to, but significantly different from, the color uniformity of lithography. The E6 press was in a group by itself with slightly worse color uniformity than the E1, E3, and E5 presses. The E4 electrophotographic press had significantly worse color uniformity than all the others.

The inkjet proofing device was in a group by itself with significantly better color uniformity than any of the other presses.

Regression analysis reveled strong linear relationships for all of the presses with respect to the specific patches in the color field and the color differences found with those patches. A difference was noted between the lithographic press and all of the electrophotographic presses. The colors that resulted in high ΔE_{2000} values for lithography did not have high color differences with electrophotography.

The colors for each press that were above the 90th percentile in the distribution were compared. These were the colors that had the lowest uniformity for each press. The colors with the lowest uniformity for the electrophotographic presses were lighter than the least uniform colors for lithography. These colors for both electrophotography and lithography were similarly low in saturation with the E1 and E2 least uniform colors having slightly higher saturation than lithography and E3, E4, E5, and E6 having substantially lower saturation than the lithographic colors. The colors of lowest uniformity for the inkjet proofer were notably lighter and more saturated than the least uniform colors for either lithography or electrophotography.

Analysis of the unprinted paper patch showed that the electrophotographic presses typically distributed tiny toner particles on these areas.

Examination of the star targets showed that lithographic printing had substantially higher resolution than any of the other presses. The resolutions of the electrophotographic presses were commonly higher than the resolution of the inkjet proofing device. Some points of interest were noted. For example, the E5 electrophotographic press printed the black star target with three colors rather the solid black that was specified. Also, some of the electrophotographic presses produced the solid star target images as screened images.

To summarize the authors' conclusions regarding the main premise of this study, overall electrophotography had lower color uniformity than the lithographic reference print, but only slightly lower, and probably not a noticeable difference to the human observers. There were distinct differences in color uniformity between the electrophotographic presses in the study. One of the six electrophotographic presses had color uniformity equal to lithography. Four of the other presses had lower color uniformity than lithography, but their average color difference scores were less than one just noticeable difference for a standard observer. One of the electrophotographic presses had unacceptably low color uniformity. This press was deemed unacceptable because the average color difference on the sheet was noticeable to a standard observer.

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Appendix A

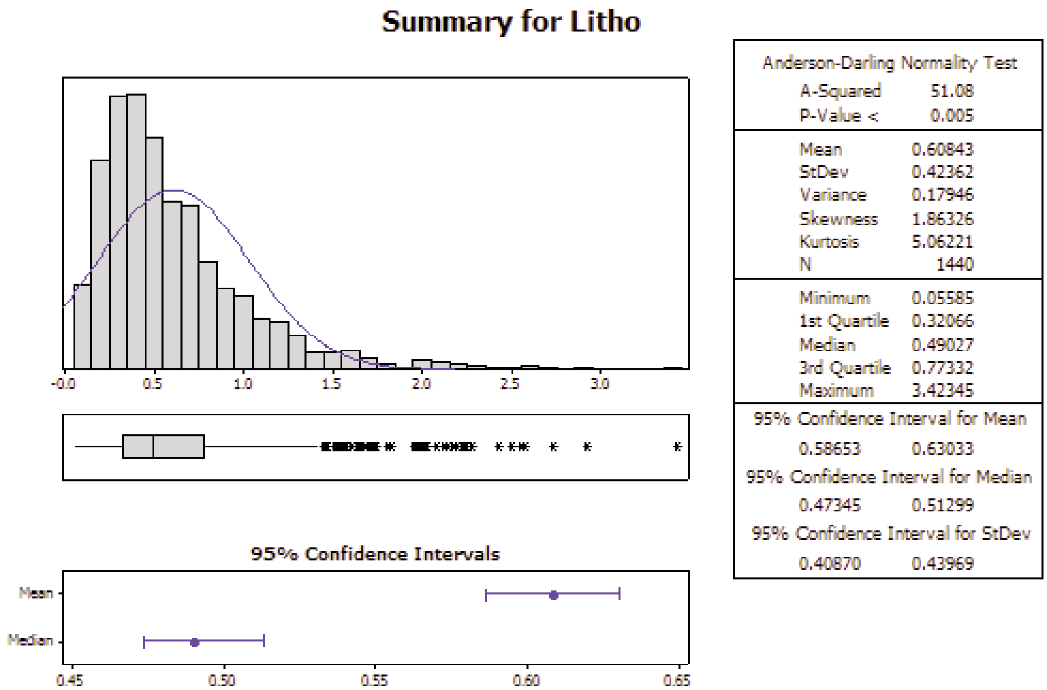
CMYK values for 96-patch color field

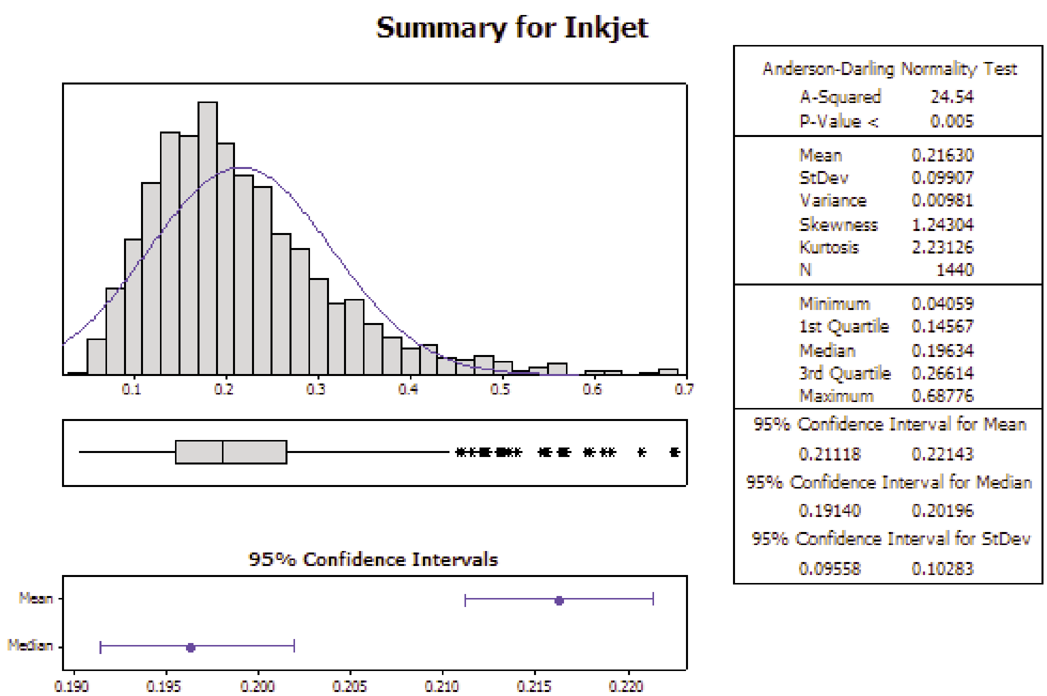
	A		B		C		D		E		F		G		H	
1	0	0	10	50	25	25	100	100	40	5	10	4	100	0	0	3
	25	0	25	0	25	0	100	100	30	0	10	0	100	0	0	0
2	25	17	25	50	80	20	65	45	20	90	80	90	0	50	90	20
	17	0	10	0	90	0	25	15	80	0	20	15	0	0	80	0
3	0	0	50	25	17	10	25	25	74	63	25	10	50	10	0	0
	97	0	10	5	25	0	0	0	63	100	17	0	25	5	0	75
4	17	25	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 B

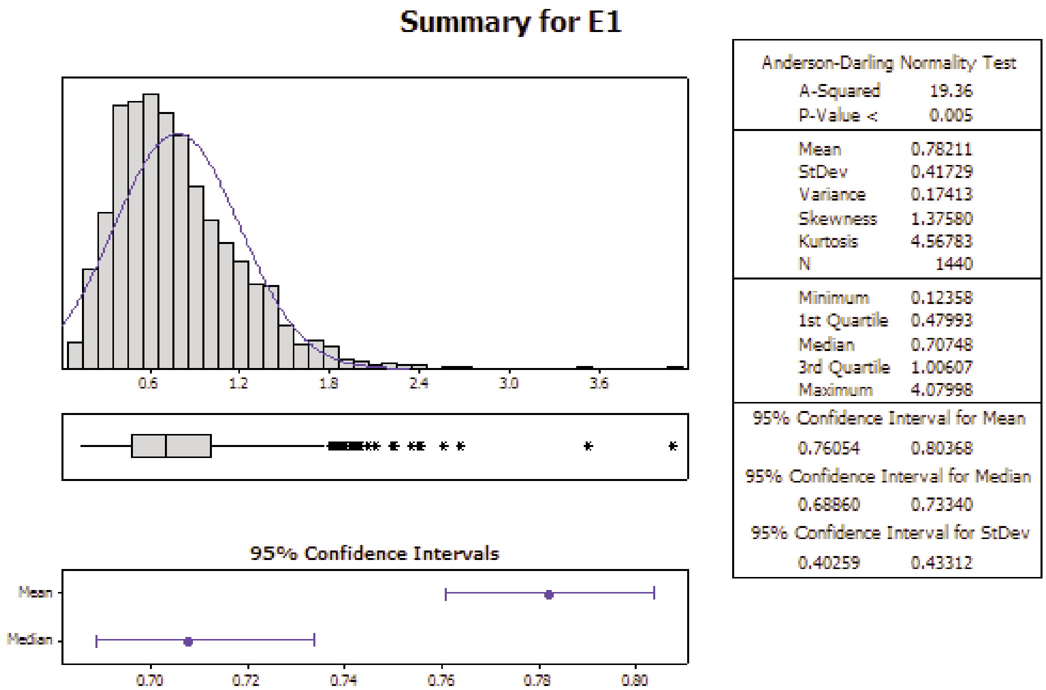
Statistics for ΔE2000 values for each press

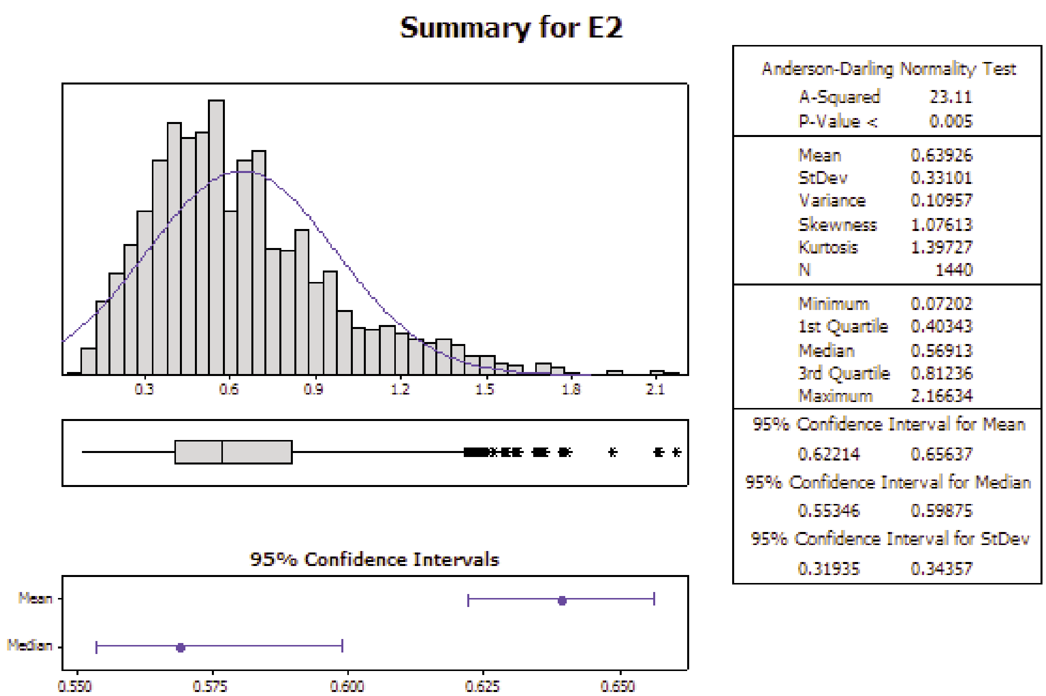




Appendix B (continued)

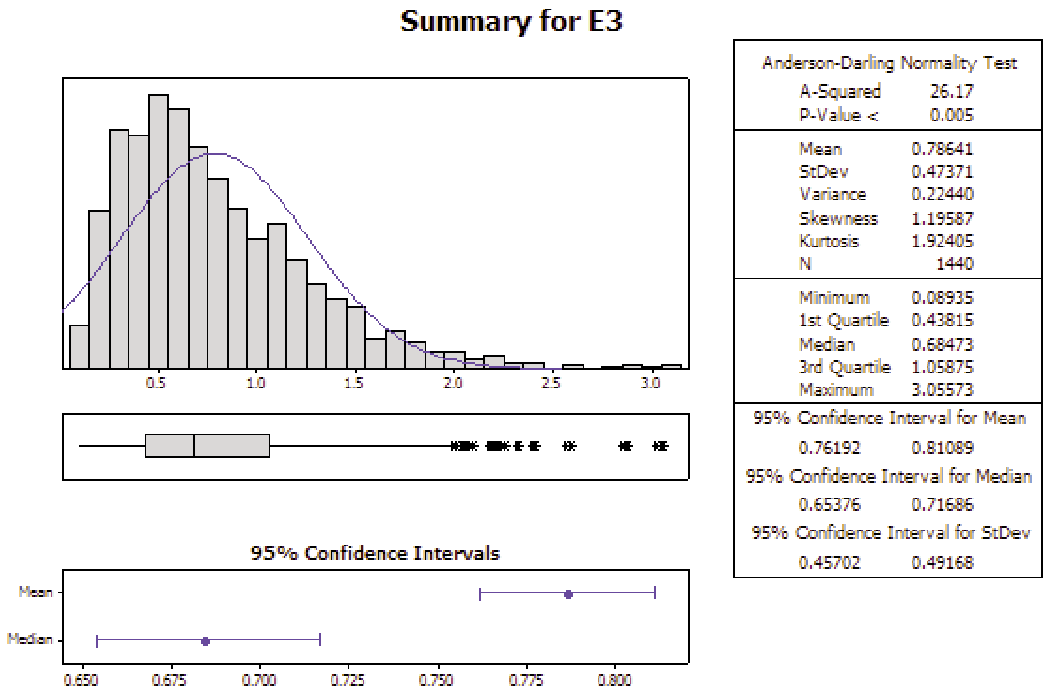
Statistics for ΔE_{2000} values for each press

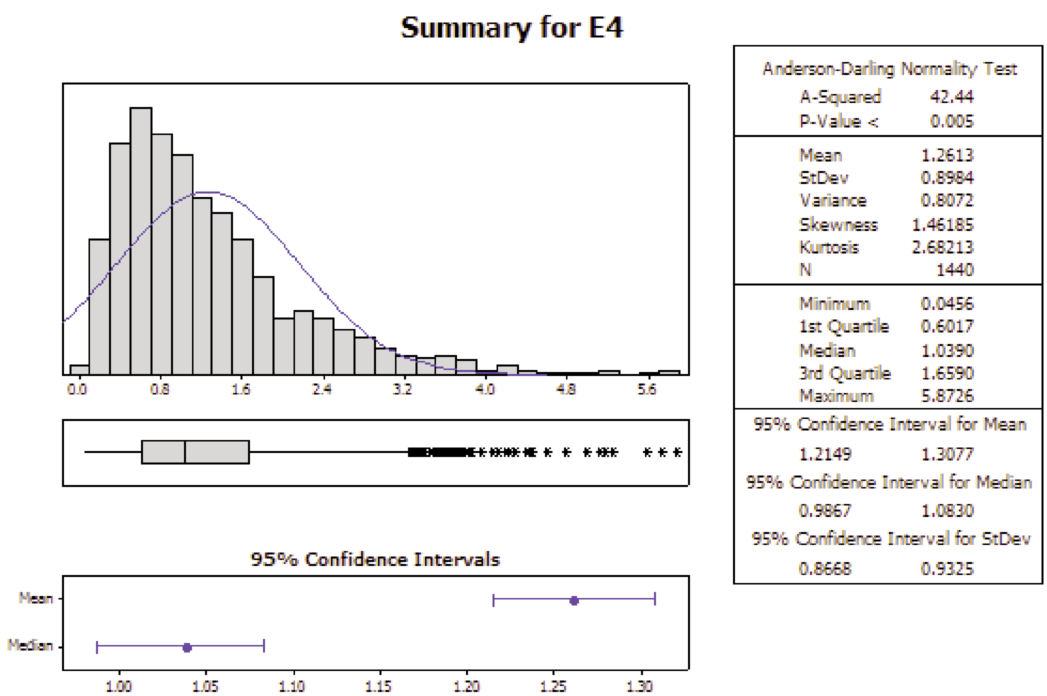




Appendix B (continued)

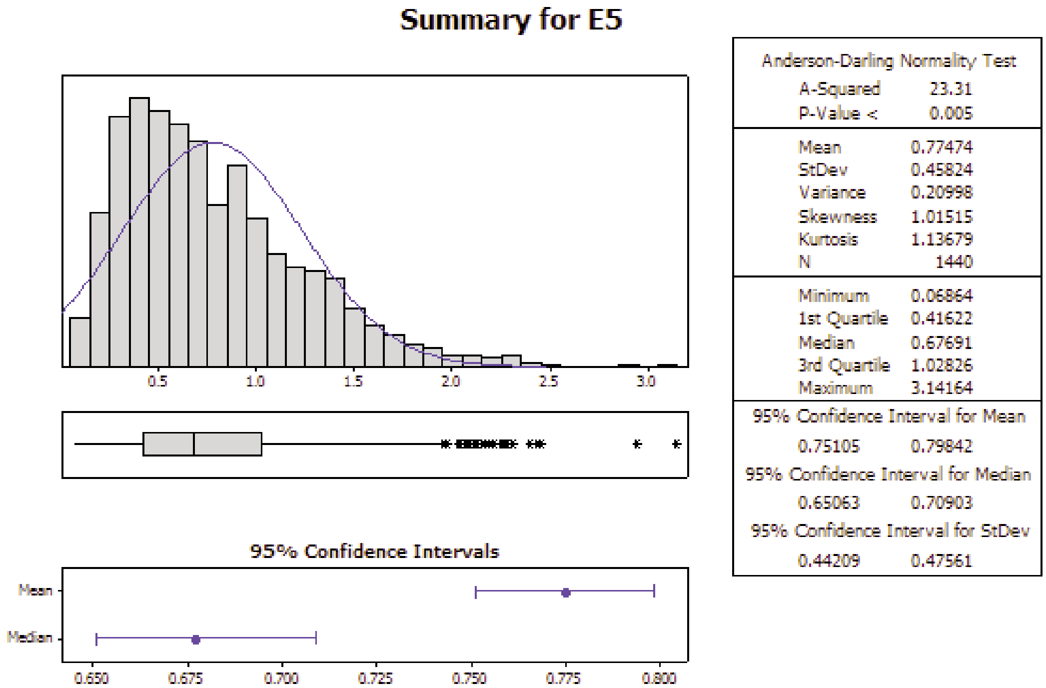
Statistics for ΔE2000 values for each press

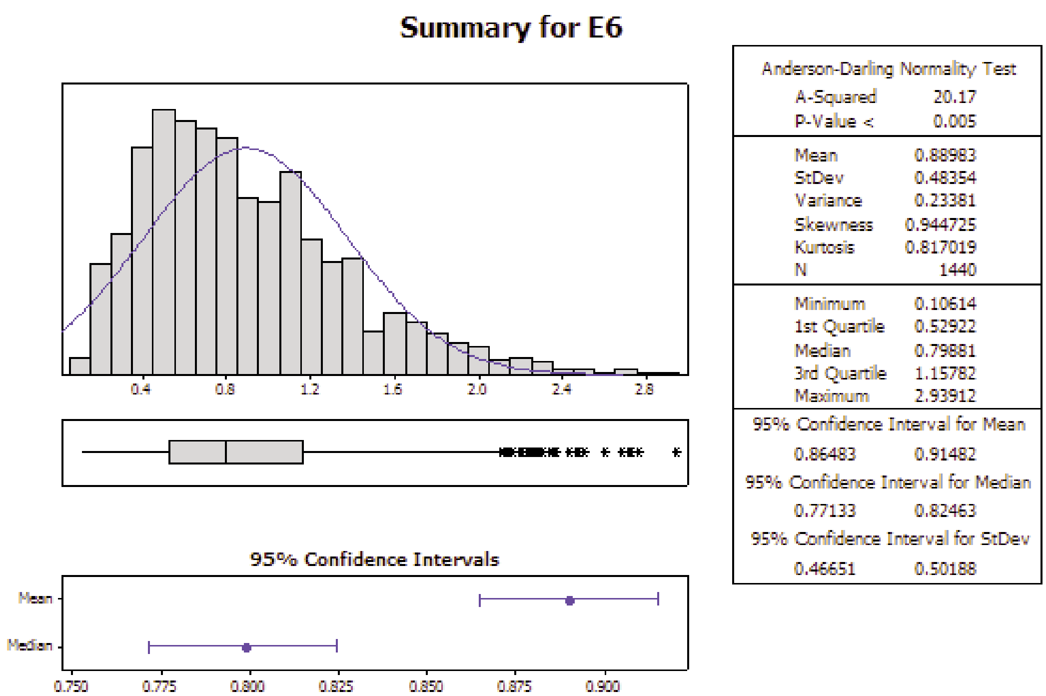




Appendix B (continued)

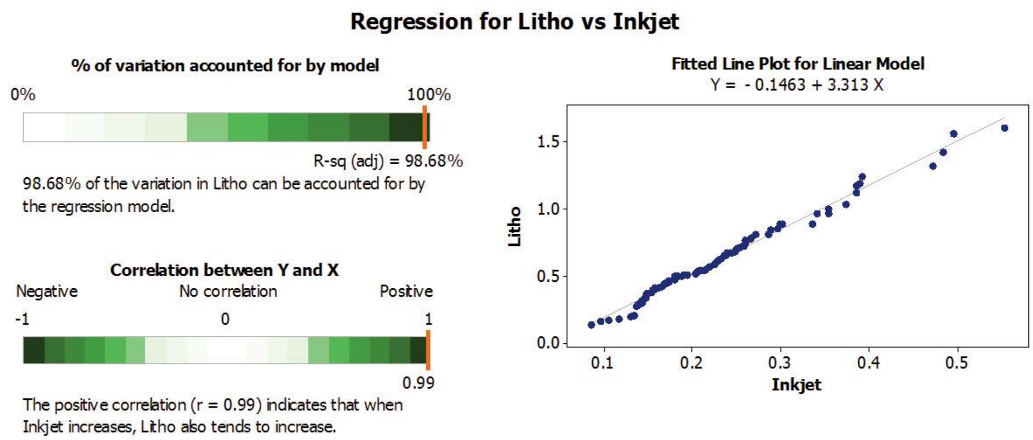
Statistics for ΔE2000 values for each press

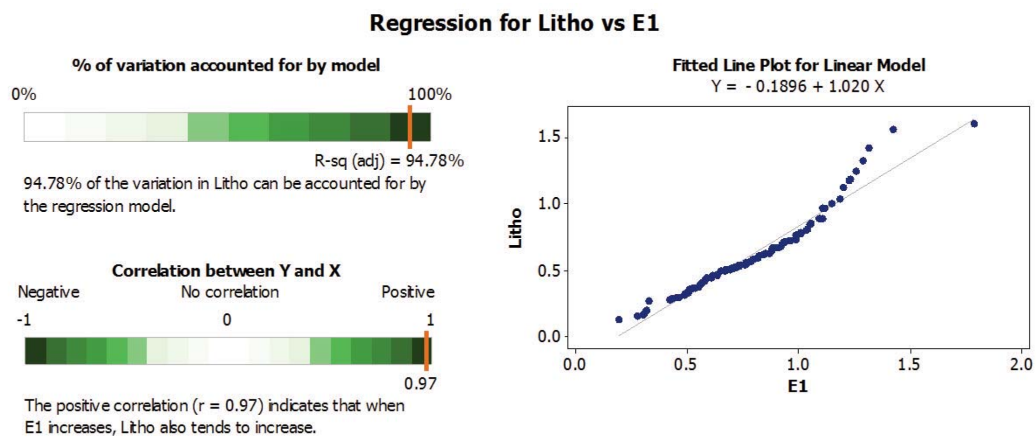


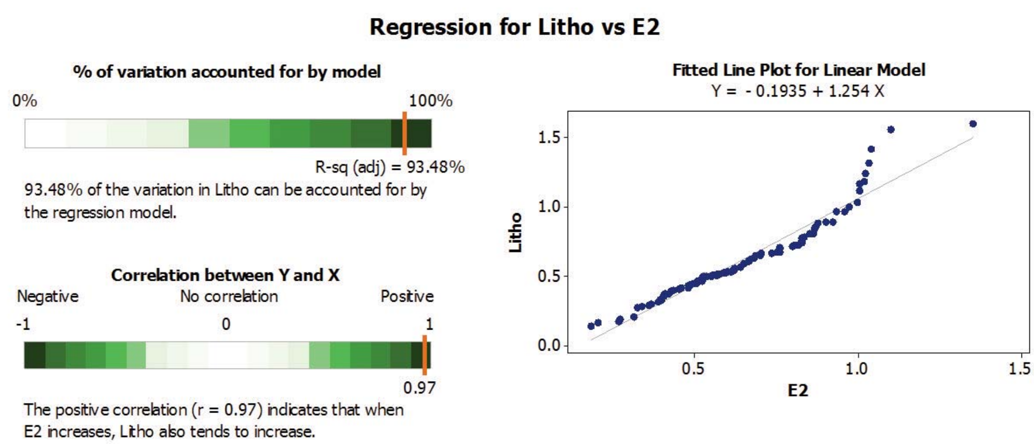


Appendix C

Linear regressions each press with lithography



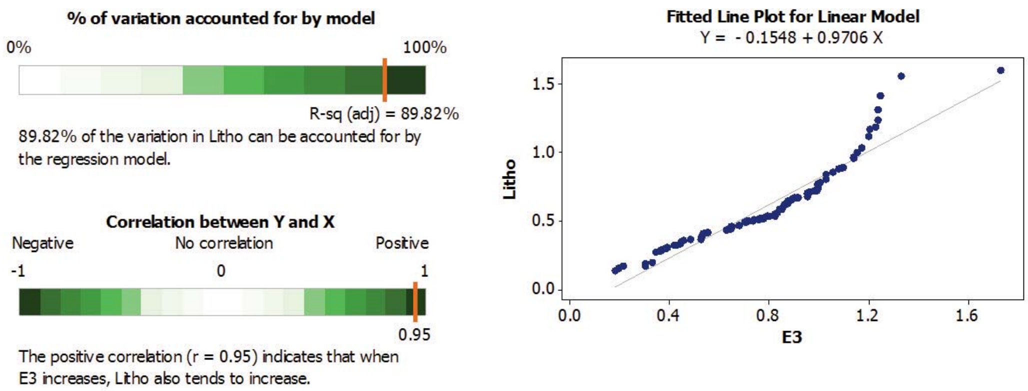




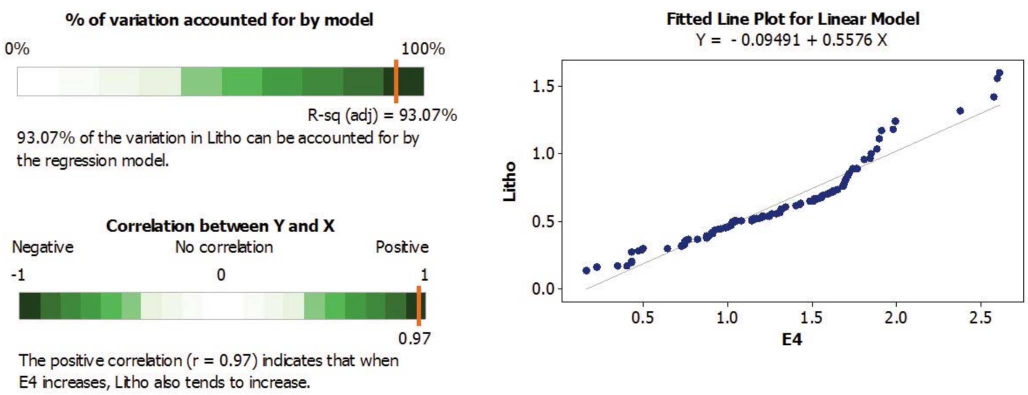
Appendix C (continued)

Linear regressions each press with lithography

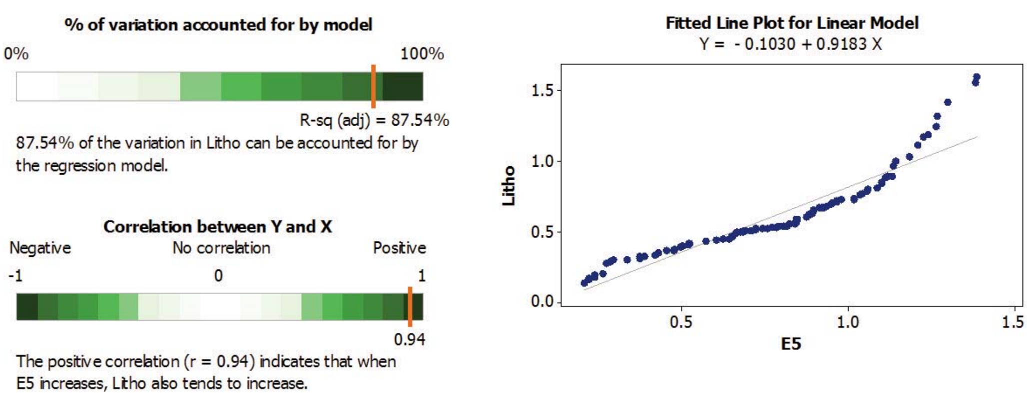
Regression for Litho vs E3



Regression for Litho vs E4

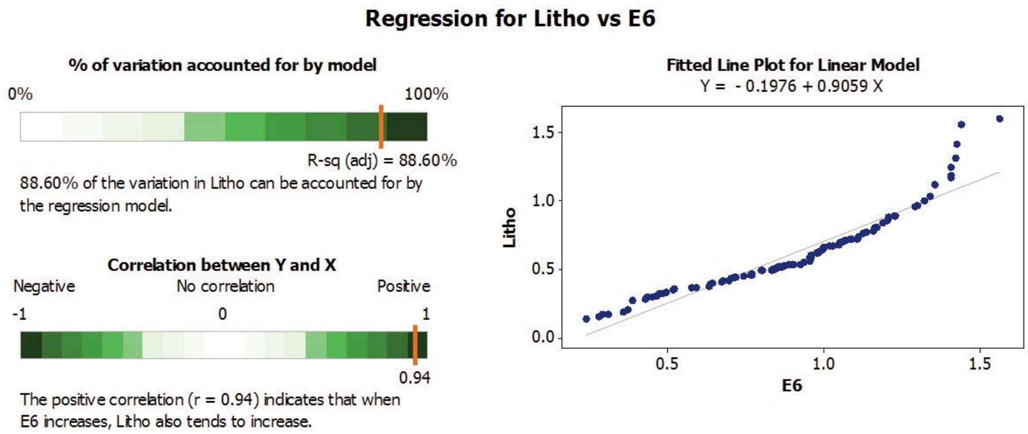


Regression for Litho vs E5



Appendix C (continued)

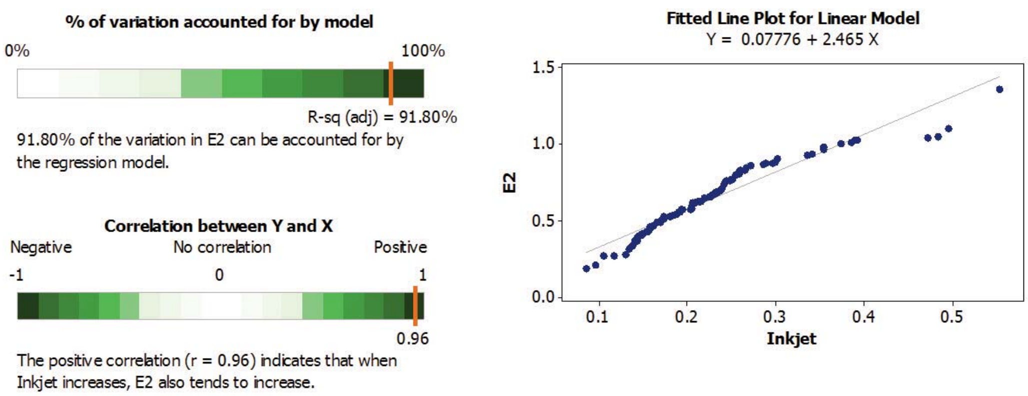
Linear regressions each press with lithography



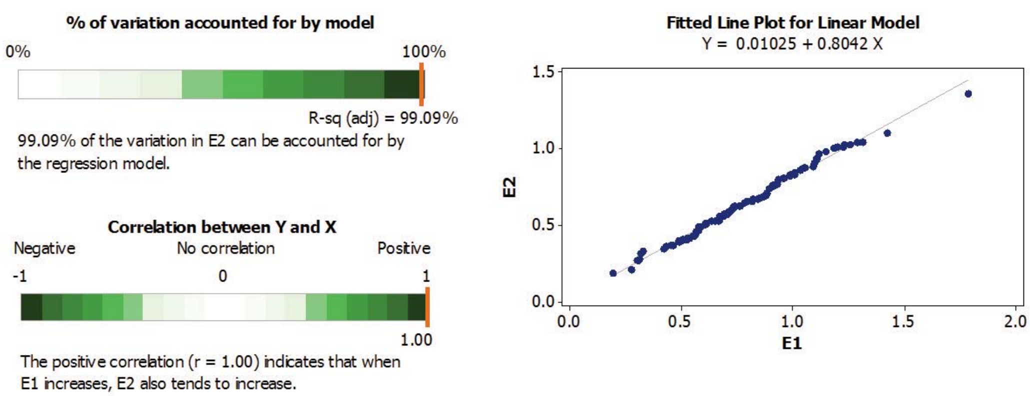
Appendix D

Linear regressions each press with electrophotographic press E2

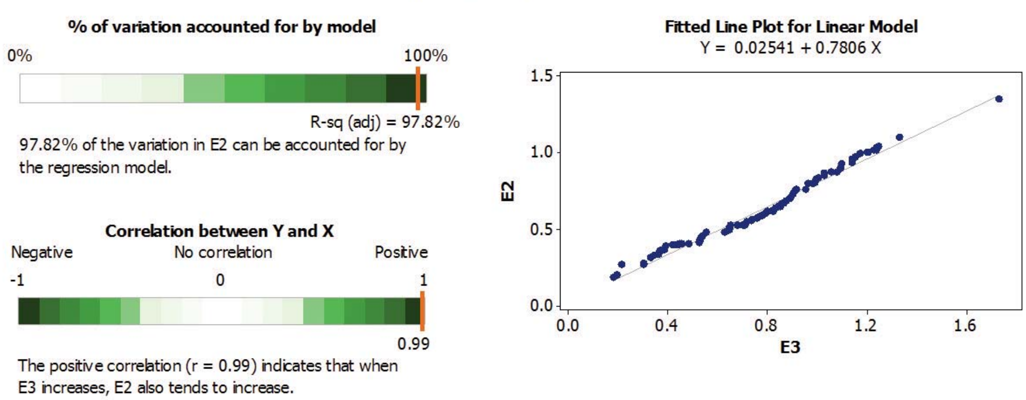
Regression for E2 vs Inkjet



Regression for E2 vs E1



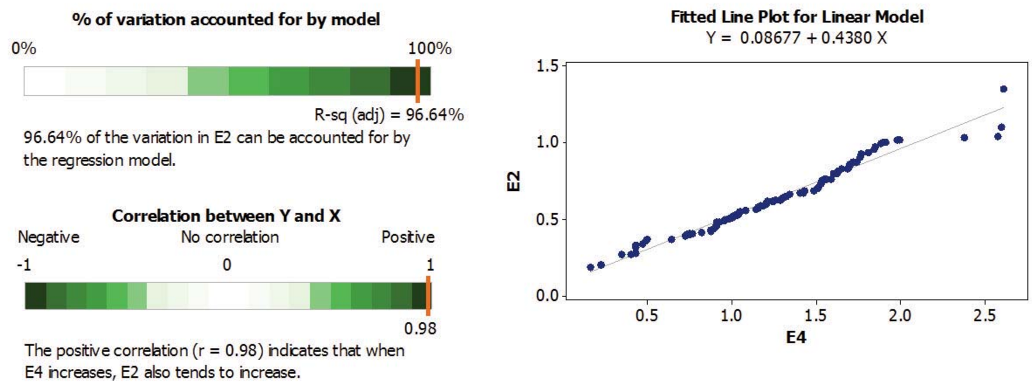
Regression for E2 vs E3



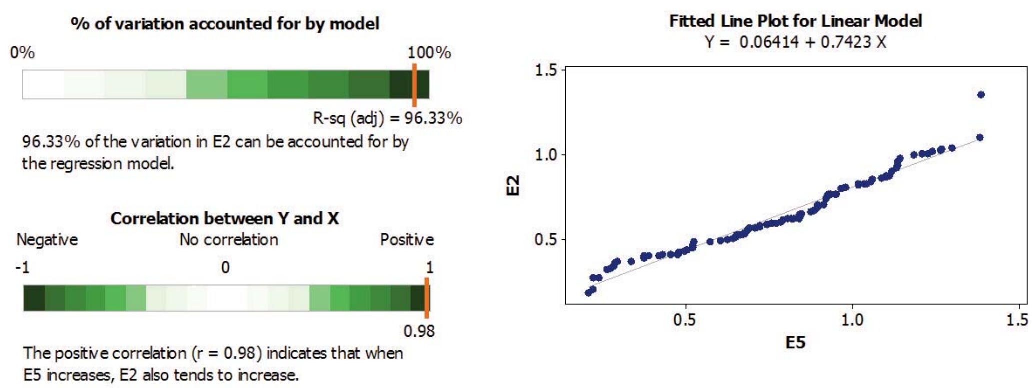
Appendix D (continued)

Linear regressions each press with electrophotographic press E2

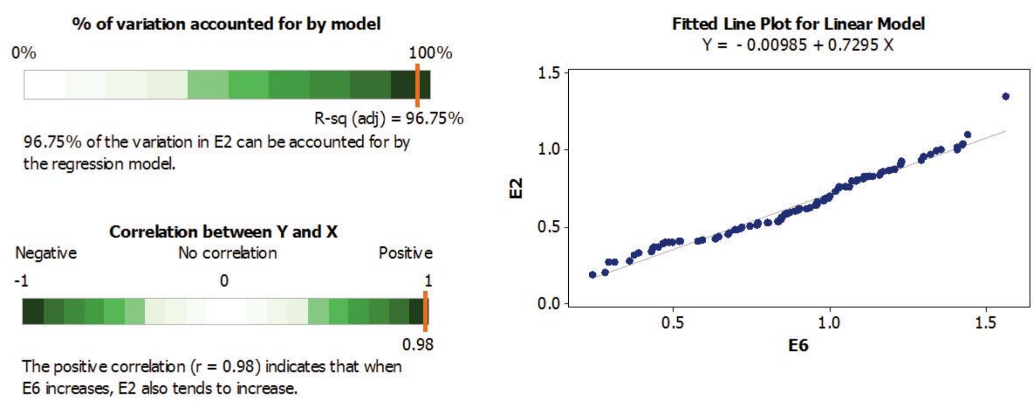
Regression for E2 vs E4



Regression for E2 vs E5

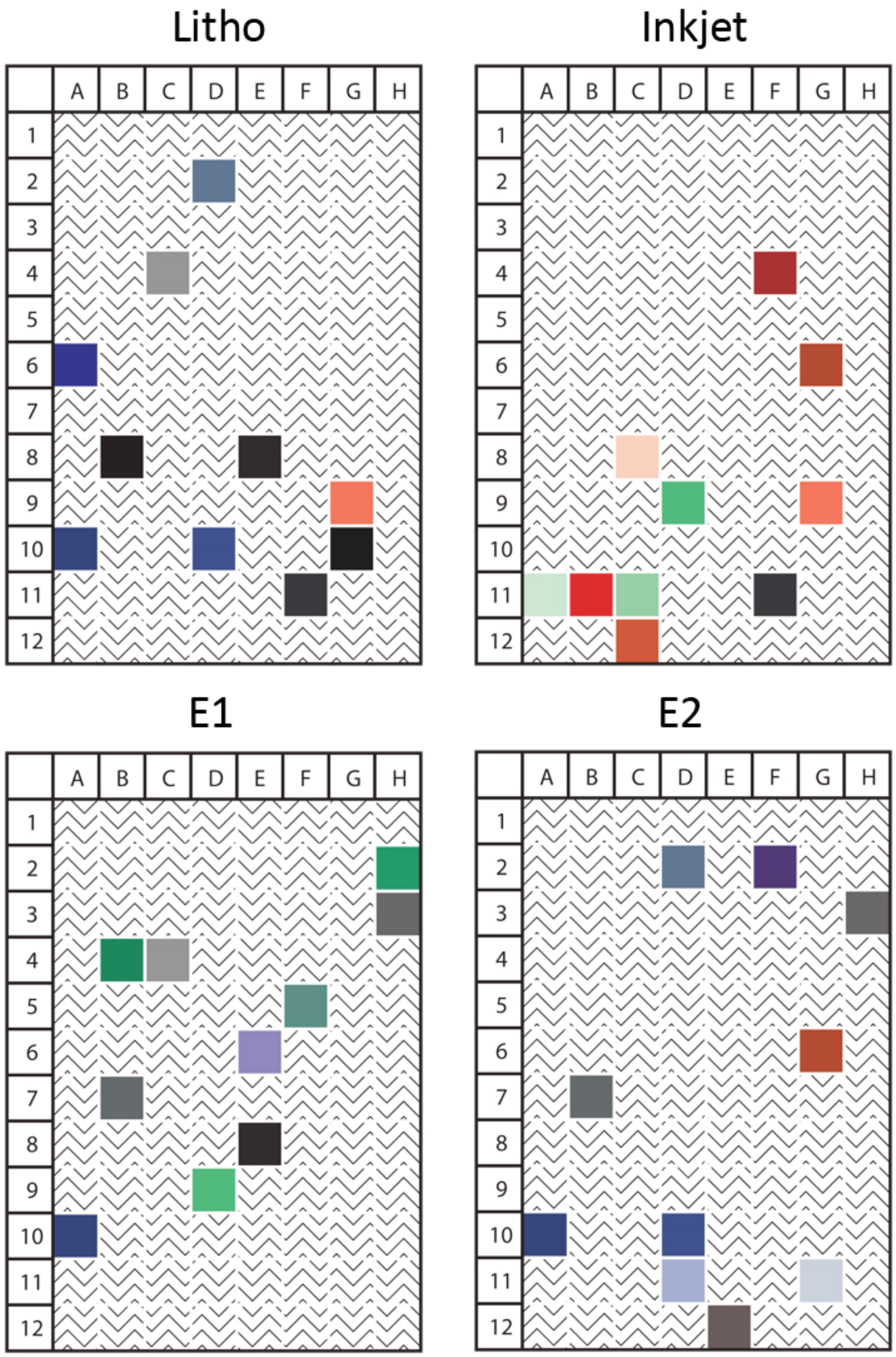


Regression for E2 vs E6



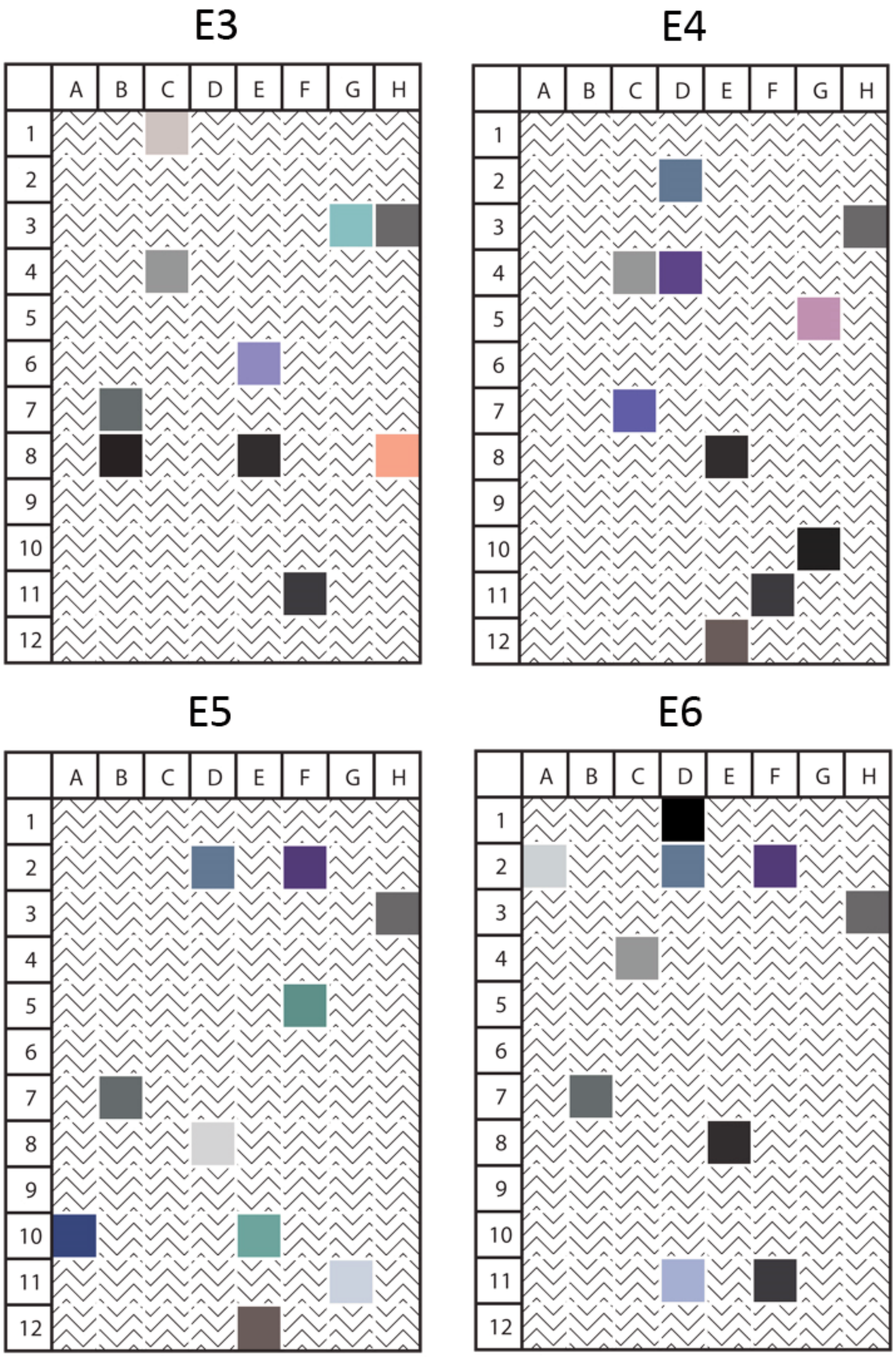
Appendix E

90th percentile patches for each printing condition



Appendix E (continued)

90th percentile patches for each printing condition



Appendix F

Lightnesses and Chromas of 90th percentile patches

Litho	LAB L	Ch	Inkjet	LAB L	Ch
A6	20.18	52.11	A11	83.63	13.65
A10	25.10	31.50	B11	47.64	86.31
B8	10.70	1.36	C8	81.64	19.99
C4	55.23	2.76	C11	72.12	30.83
D2	43.87	13.53	C12	47.64	60.55
D10	28.99	34.68	D9	60.46	52.38
E8	12.28	1.26	F4	39.88	53.22
F11	19.64	6.74	F11	15.37	0.97
G9	53.91	66.14	G6	42.16	52.42
G10	15.43	3.10	G9	55.62	69.07
Avg.	28.53	21.32	Avg.	54.62	43.94
E1	LAB L	Ch	E2	LAB L	Ch
A10	25.01	32.47	A10	32.07	32.13
B4	41.92	44.94	B7	42.46	5.50
B7	37.11	1.10	D2	49.51	17.33
C4	57.14	3.31	D10	35.46	35.85
D9	55.26	50.43	D11	69.35	21.09
E6	50.09	34.84	E12	40.50	8.91
E8	18.70	1.01	F2	32.85	32.78
F5	50.07	18.09	G6	48.27	54.21
H2	46.90	48.79	G11	80.01	10.64
H3	36.47	2.79	H3	41.63	2.45
Avg.	41.87	23.78	Avg.	47.21	22.09

Appendix F (continued)

Lightnesses and Chromas of 90th percentile patches

E3	LAB L	Ch	E4	LAB L	Ch
B7	36.17	1.99	C4	55.29	3.43
B8	12.52	0.88	C7	39.07	38.41
C1	72.37	6.56	D2	44.24	17.31
C4	55.03	1.01	D4	31.98	35.38
F11	21.03	0.23	E8	19.90	1.18
G3	64.13	17.26	E12	35.22	7.95
G4	95.51	5.07	F11	20.80	10.45
G5	56.38	28.49	G5	59.88	23.70
H3	44.00	2.21	G10	16.87	1.44
H8	66.79	49.75	H3	39.60	2.10
Avg.	52.39	11.34	Avg.	36.28	14.14

E5	LAB L	Ch	E6	LAB L	Ch
A10	25.93	25.94	A2	78.19	7.84
B7	35.73	5.15	B7	40.87	5.29
D2	43.82	16.41	C4	59.14	6.60
D8	79.91	5.40	D1	14.71	2.92
E10	56.33	25.46	D2	47.40	20.50
E12	30.21	4.99	D11	67.36	23.45
F2	24.99	29.37	E8	20.23	0.87
F5	48.91	21.76	F2	28.48	30.08
G11	78.37	10.58	F11	24.17	4.56
H3	33.82	1.10	H3	37.53	1.37
Avg.	45.80	14.62	Avg.	41.81	10.35

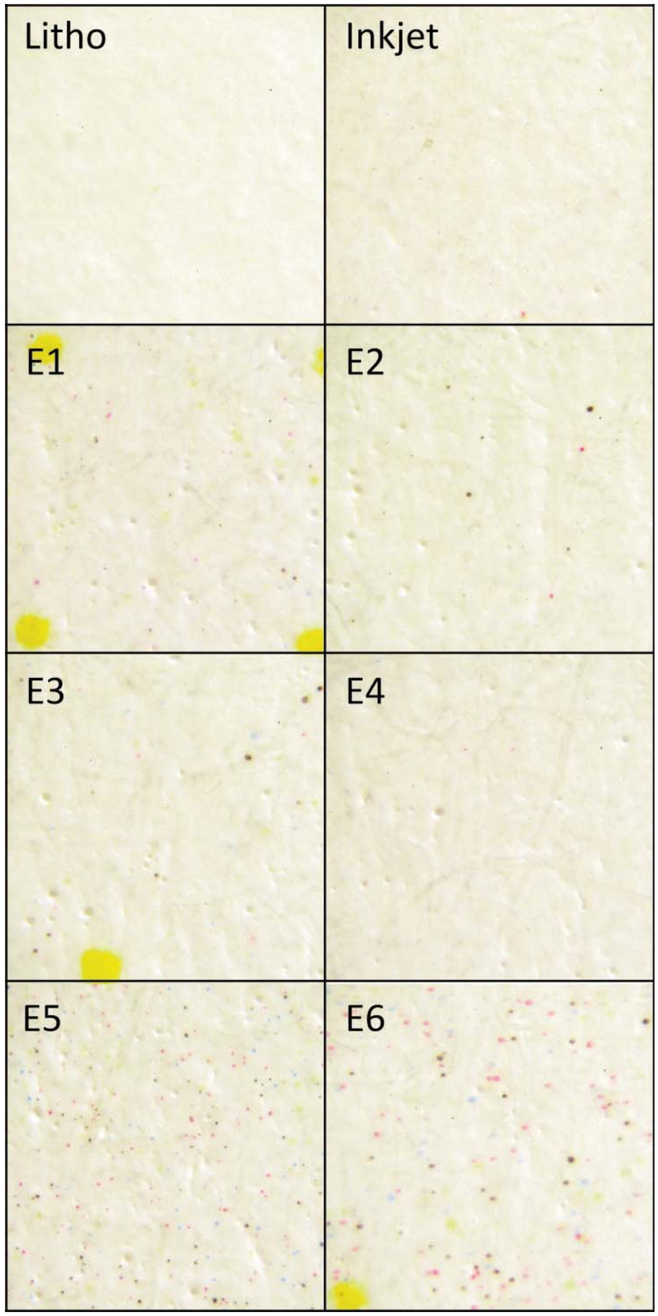
Appendix G

Color differences for zero coverage patches

	litho	inkjet	E1	E2	E3	E4	E5	E6
1	0.204	0.201	0.168	0.158	0.138	0.073	0.195	0.223
2	0.149	0.076	0.165	0.188	0.170	0.109	0.142	0.156
3	0.238	0.137	0.214	0.185	0.234	0.160	0.261	0.373
4	0.138	0.084	0.124	0.117	0.236	0.067	0.318	0.196
5	0.141	0.124	0.196	0.223	0.124	0.292	0.294	0.160
6	0.094	0.098	0.134	0.363	0.119	0.240	0.209	0.280
7	0.088	0.122	0.240	0.072	0.215	0.099	0.104	0.180
8	0.122	0.159	0.144	0.113	0.106	0.046	0.201	0.161
9	0.135	0.303	0.188	0.344	0.166	0.318	0.289	0.294
10	0.181	0.196	0.308	0.103	0.217	0.093	0.216	0.235
11	0.101	0.153	0.143	0.094	0.108	0.072	0.252	0.143
12	0.094	0.098	0.134	0.363	0.119	0.240	0.209	0.280
13	0.126	0.116	0.243	0.096	0.229	0.114	0.218	0.225
14	0.151	0.231	0.365	0.376	0.320	0.322	0.364	0.452
15	0.056	0.182	0.178	0.291	0.205	0.283	0.300	0.268
Average	0.134	0.152	0.196	0.206	0.180	0.169	0.238	0.242
Maximum	0.238	0.303	0.365	0.376	0.320	0.322	0.364	0.452

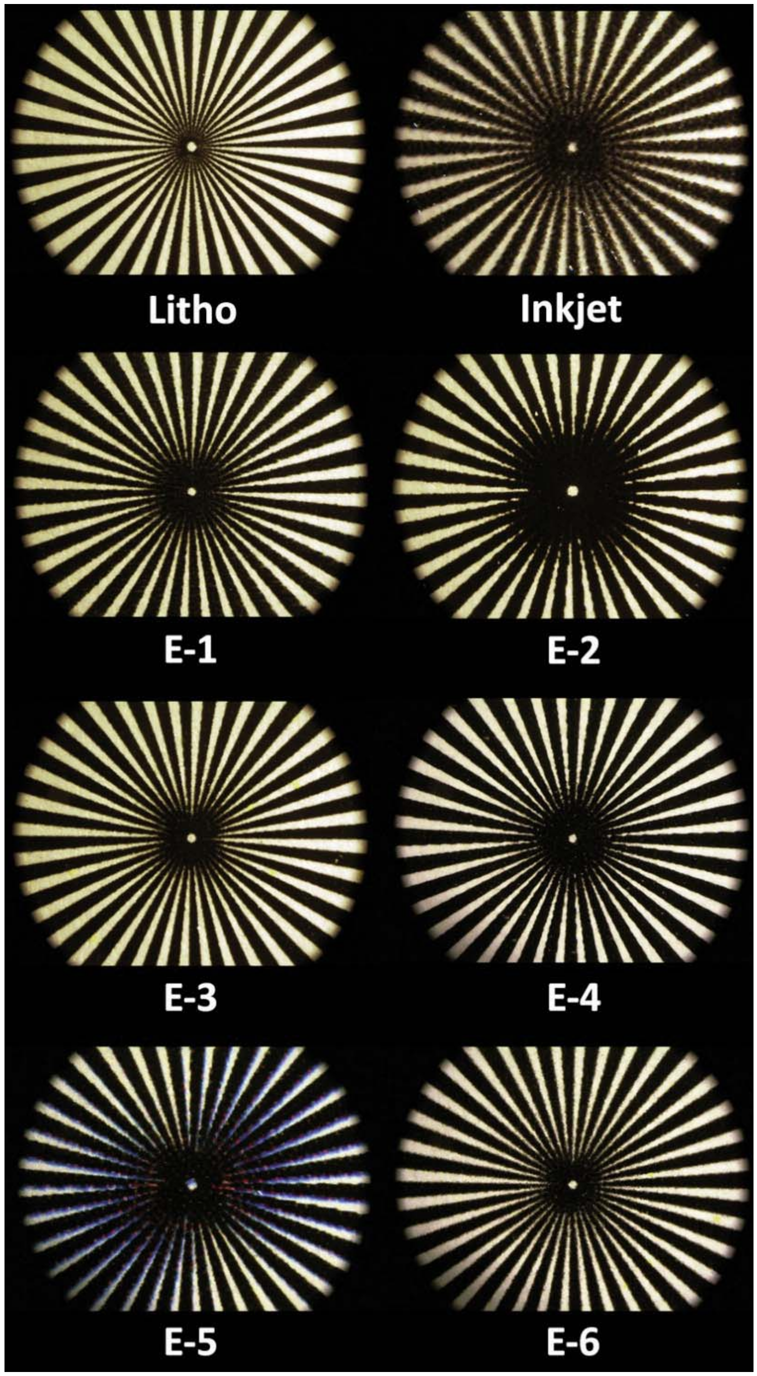
Appendix H

Photomicrographs of zero coverage patches



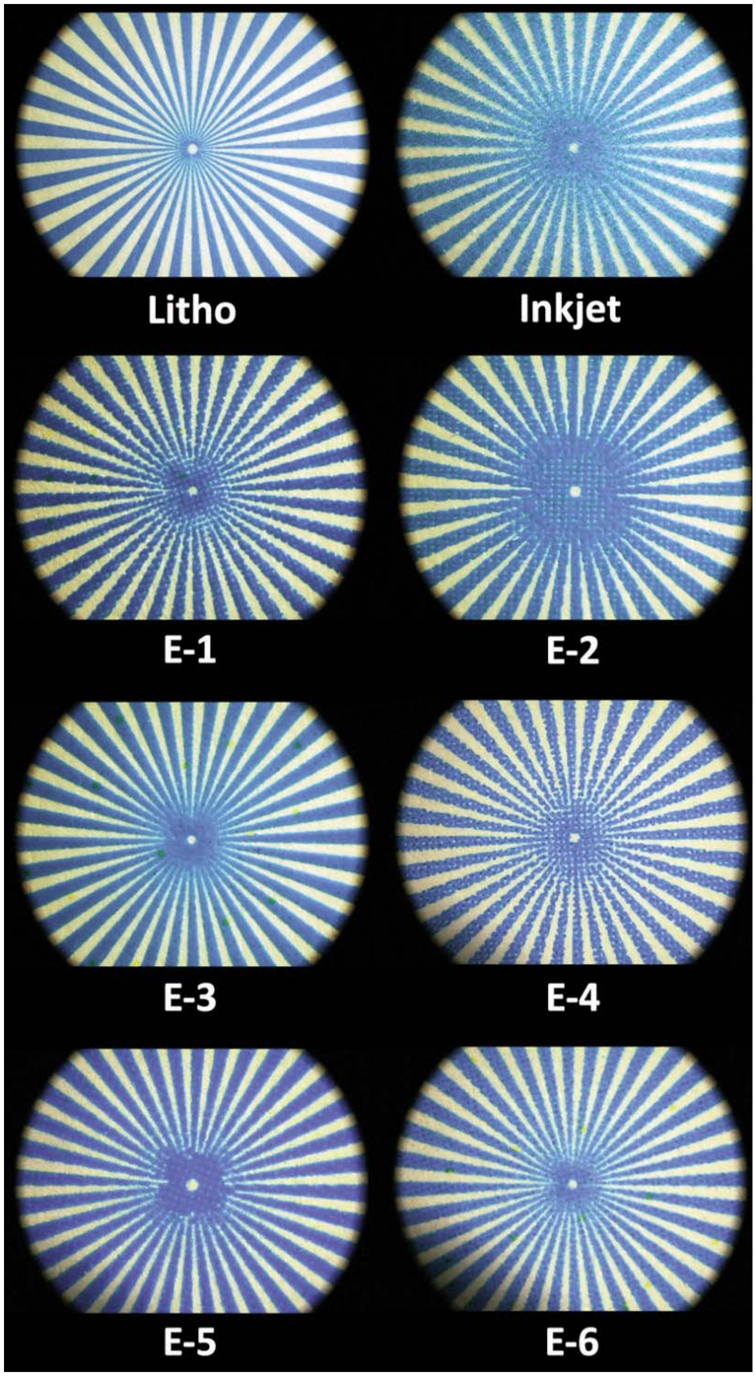
Appendix I

50X photomicrographs of black star targets



Appendix I (continued)

50X photomicrographs of cyan star targets



Appendix I (continued)

50X photomicrographs of magenta star targets