MEASUREMENT OF THE TRANSFER FUNCTION OF HARDCOPY COLOR REPRODUCTION SYSTEMS: A METRIC FOR COMPARISON

David L. Spooner*

INTRODUCTION

The ultimate test of the quality of color image reproduction is the customer's sign-off on an approval proof. While consistently passing this test is the ultimate goal for any color reproduction system development effort, it does not provide a quantitative basis for evaluating progress in the development of new systems or the improvement of existing systems.

In the past, attempts have been made to make system evaluations using a standard set of reproduced images and a panel of observers. Evaluations using such techniques invariably suffer from the vagaries of human judgement and the variabilities of human eyesight. Also, the choice and placement of the standard images on the proof sheet can, at times, affect relative ratings of proof samples. In essence, this method of evaluation is just an elaborate variation of customer sign-off procedure.

Parametric evaluation methods, in which the properties of the imaging system are expressed by one or more numeric parameters, are potentially much more useful tools for the development and improvement of reproduction systems than are procedures which are based on only observational evaluations. Parametric procedures, when properly designed, can provide indicators of improvement in system performance which would be totally missed with observational evaluations. Also, since the evaluation parameters are generally derived from measured data, changes in evaluation criteria usually do not invalidate previously prepared exhibits.

Accurate mathematical models of color reproduction systems can reduce the need for preparing exhibits for many of the evaluation phases. They also allow comparison of the color gamuts of two or more systems without making exhibits. A paper presented at the Neugebauer Memorial Seminar showed that color reproduction models can aid in the simulation of systems with hypothetical characteristics (1).

* DuPont Printing & Publishing
Wilmington, DE 19880-0352

MODELING

Over the past 60 years, there have been numerous attempts to mathematically model 3 and 4 color process printing and proofing systems. Ideally, such a model, when calibrated with measurements of proof exhibits, should be able to predict the color produced by any given mix of color component (e. g. CMYK) inputs to the printing or proofing process.

Generally, most of these models have not provided the desired degree of accuracy over the entire color gamut. Also, as the requirements for prediction accuracy have become more stringent, models which initially seemed to give adequate color predictions have become marginal performers. The short-comings of these models are evidenced by the large numbers of modeling algorithms that are "supposed" to describe the same or similar reproduction processes. If any of these models gave results that correlated closely enough with process color reproduction, we could reasonably expect that the others would be only historical curiosities (indeed, the 50+ year old Neugebauer equations are still the basis for the many models of process color).

In some of our early efforts, we attempted to bypass some of the problems associated with conventional direct physical analog models by employing neural network models. We made these models by educating a neural network program with 500 or so evenly spaced colors produced by the proofing system being modeled. The resulting neural network was then able to give a color value for any combination of CMY inputs. While these models did prove useful for illustrating simulation (1) and color gamut plotting techniques (2), their accuracy appeared to be no better than that of existing physical analog models.

Warren Rhodes, in a paper reviewing the history of the Neuge-bauer equations (3), gives reference to a comment made by Dr. Neugebauer (4) to the effect that he did not trust his equations -

> "... I had the feeling that these equations may be excellent for some theoretical work, but I didn't trust them enough to apply them for basing color computers on these equations."

Instead, Dr. Neugebauer suggested -

> "... what I do first is disconnect the computer from the recording section and put in arbitrary signals ... yellow, magenta and cyan. These signals will be recorded and processed to the three color separations. Then I put in a different set of signals, and I use - let me say 1000 different sets, each a triplet of signals. I process these corrected color separations in the standard manner which is intended for the final printing process. I print them together and obtain 1000 different color patches. "If, now, I put these 1000 color patches on the reading section of the scanner, then I obtain for every color patch three tri-stimulus signals, three signals, red, green and blue, and I can correlate every triplet of signals, red, green and blue, to my original triplet of signals, yellow, cyan and magenta. In this

way, I obtain an empirical correlation between tristimulus values and yellow, cyan and magenta signals."

This disclosure in Rhodes' paper, which was presented at the Neugebauer Memorial Seminar on Color Reproduction, was coincident with our decision that we needed a better model for relating CMYK input to print color.

Both Rhodes' paper and Dr. Negebauer's comments suggest the use of a 1000 entry lookup table. The French patent (5) that Dr. Neugebauer referenced in his comment at TAGA as an example of this approach describes an analog image processing system and does not refer to a lookup table as we normally think of it today. It does, however, use something like an "analog lookup table" which is based on x-y positioning of a CRT spot on a transparency mask (called a control filter in the patent) with density that is a function of the x-y position. While this device is the analog equivalent of a 2 dimensional lookup table, it is not clear from the patent how a 3 dimensional lookup table was implemented. Also, the lookup table derivation process which consisted of exposing transparencies and then reading them with a system scanner to derive these filters (lookup tables), which Dr. Neugebauer described in his TAGA meeting remarks, is not apparent from the text of the patent.

IMPLEMENTING THE NEUGEBAUER TABLE LOOK-UP MODEL

Our ultimate goal was to derive an improved 4 color model. Using a 1000 entry lookup table, as proposed by Neugebauer, seemed like a reasonable approach for a 3 color model. We decided that it would be good to test a 3 color model before trying to expand the concept to a 4 color model.

A symmetric sample array of 1000 combinations of cyan, magenta, and yellow (CMY) was made using 10 steps each of C, M, & Y. For the purposes of our test, we used steps of 0, 10, 20, 30, 40, 50, 60, 70, 80 & 100 percent screen. The patterns were produced on an electronically driven proofing engine using test pattern software that we had written for our previous modeling work. Magnetic tape recordings of these test patterns were also made and later used to produce screen negative sets for preparation of optical proofs.

The test pattern consisted of two sections of 528 (i. e. a 22x24 grid) samples each. Each of the proof sections contained about 500 unique color combinations with repeats of white and some of the colors. Each sample was approximately a 0.5 inch square. In laying out this test pattern, we made an effort to randomize the color positions (e. g. the nine pure cyan steps were not located in adjacent positions).

The duplicated colors on the proofs gave an indication of the consistency of the proofing process (note: we have now measured more than 200,000 proof samples - the agreement of the repeated samples on a proof set are typically much less than 1 CIELab ΔE). Measurements of the proofs were made using a Gardner Color Machine with a 30mm diameter illumination area and a 6mm viewing area. The 35 wavelength (380 - 720nm) reflectance data for each sample was used to calculate D50 tristimulus values.

This measurement data was used to make a 1000 entry table which related the CMY input values to the CIE tristimulus XYZ color values of each proof sample. While CIELab values correlate more closely to human color perceptions than tristimulus values, tristimulus values have a closer correlation to the input CMY values. Thus, using tristimulus for the table instead of CIELab values reduces the potential error that might be caused by any scheme used to interpolate values.

The prediction model created by this table consisted of a software procedure for finding the 8 CMY values in the table that are closest to the CMY input value and then doing a trilinear interpolation to the get the corresponding tristimulus values. While it would have been possible to use more than 8 points and do a surface fit, straight line interpolation was chosen to simplify the software for our initial work and speed up the computational process.

Once the technique for making CMY proof targets was proven, we expanded the technique to make CMYK proof targets. For this purpose, 7 black levels were chosen: 0, 10, 20, 30, 50, 75, & 100 percent screen. Seven black levels were used to economize on the cost of negative sets - the 10 and 20 percent black negatives were made as part of the negative sets for the two sections of the target. A third set of negatives, with all components made with the black screen angle, were used to provide the 30, 50, 75, & 100 percent black screens. Thus, we only needed to buy three sets of negatives to produce seven proof target sets (14 proofs total). This approach gave a saving of almost 80% on the purchase cost of the negative sets needed for producing the targets. A quadlinear interpolation routine was incorporated into the model software to allow the derivation of tristimulus values from the CMYK input values.

TRADE-OFFS

The economics of producing test target exhibits is very much a function of the proofing system being used to prepare the targets. The accuracy or representativeness of the samples also depends on the proofing process used. The cost of sample measurement is dependent on the number of samples in the target set and the instrumentation used to measure the targets. Also the accuracy of color measurements of samples is dependent on the instrument geometry and sample measuring area as well as the printing substrate.

Efforts to reduce the total cost of preparing proofs might seem to dictate making the area of the color samples as small as possible. Today, print control bars, which are used as an aid for adjusting ink density on press runs, typically have elements as small as 5mm square. These elements are measured using densitometers and spectrophotometers with measurement areas as small as 2 to 3 mm in diameter. While the use of such small target elements may aid in the reduction of the cost of producing both print control bars and process calibration targets, it can compromise the accuracy of the measured data. We have shown in a paper presented at the 1991 annual TAGA meeting (6) that the instruments used to measure these small area targets on on-press and off-press proofs are subject to lateral diffusion (translucent blurring) errors of 1 CIELab ΔE or more. Our work shows that the sample area standard set forth in ISO 5/4, Part 4 (7), which specifies viewing geometry for densitometers, gives a reasonably low lateral diffusion error. This standard states in paragraph 4.3 that -

"The irradiated area of the specimen shall be greater than the sampling aperture, and its boundary shall lie at least 2 mm beyond the boundary of the sampling aperture."

To the best of the author's knowledge, none of commercially available small aperture reflectance densitometers meet this specification. An instrument designed to measure a 5mm target which met this standard would have to view a 1mm spot on the target. Considerations of instrument sensitivity and noise and target variability would make such an instrument impractical for evaluating printed products. Therefore, a practical target should have color elements larger than the 5mm patches used on print control strips (e. g. we normally use elements about 0.5 inch square).

The large number of samples to be measured, 7000 in our previous example, practically makes automatic measurement and data logging a necessity. Therefore, the target should be laid out in a pattern that allows for efficient automatic measurement. Irregular spacing of target elements, which require excessive instrument set up effort, should be avoided. Ideally, the measurement of all target sections should be possible with only one set up of the instrumentation. (Note: programmable instruments for making multiple measurements on press sheets are available from at least 2 manufacturers.)

The per proof cost of images from electronically driven proofing engines is often less than that of a comparable optical proof. Furthermore, these proofs do not require the expense of film intermediates. This allows us to structure the proof target color arrays without consideration of external costs (e. g. with the off-press proofs described in the previous section, we were concerned with the cost of negatives). On the down side, electronic proofing engines exhibit non-linearities or even discontinuities for some input ranges (e. g. there is a minimum dot size that an inkjet printer can produce). With some dye sublimation printers, we found a non-linear threshold effect at low input signals and another non-linear region at high input signals. To help account for this, we added 5 and 90 percent steps to our three color targets and a 5 percent step in the black array. This gave 1728 three color targets and 13,824 four color targets (as noted in the previous section, the corresponding numbers for the optical proof targets were 1000 and 7000).

Electronically driven proofing engines which use thermal transfer mechanisms can suffer from a thermal decay errors. The drive electronics typically compensate for this thermal error by using a model of the thermal transfer process to predict the drive needed to produce the proper print density. This process is not always perfect. We have found that printing alternate white and colored target rows gives more consistent results than having all colored target rows.

The method used for producing targets to derive optical proof transfer functions was detailed in the previous section. This scheme reduces the cost of making the separation negatives. Prior to adopting this procedure, we attempted to layout a single section target (i. e. 500 or so color areas) that would produce all 1000 colors by printing the negatives in different color order (e. g. printing cyan with the yellow negative, etc.). We found that when the yellow negative is printed with cyan or magenta, a moire pattern results, however, interchanging the cyan and magenta negative printing colors had no effect. With proper design, this cyan-magenta interchange could be used to increase the total number of colors without any increase in the separation negative cost.

The preparation of on-press transfer targets has generally been done with patterns similar to those used for off-press proof targets. Considering the cost of making the plates and the press run, using this off-press scheme which was designed to minimize film cost may not be cost effective. Also, when pictorial targets are included on the press sheet with the targets, the unusually high ink demands of some sections of the target may make it impossible to control the inking on the pictorial target. Indeed, if multiple color targets are on one press sheet it is possible to have one target affecting the color of a second target on the sheet. In short, not only is the on-press proofing of transfer color targets more expensive than off-press proofing, but greater care must be exercised in the design of the proof sheet to insure that the targets are representative of the results that are obtained with normal half-tone pictorial prints.

USE OF TABLES FOR COMPARISON OF PRINTING/PROOFING PROCESSES

The lookup tables prepared using our procedures are effectively models of various on-press and off-press printing and proofing systems. Comparison of the seven dimensional table data to determine the differences between two systems is, for the most part, humanly impossible. We have developed several graphic techniques to make comparison possible. It should be noted, however, that even with the use of these aids, the full impact of the differences and similarities of different printing/proofing processes is still difficult to assess.

About 15 years ago, we developed techniques for deriving the color gamut of a palette of pigments. We plotted these gamuts as a series of contours of constant L* value. In 1989, we adopted these techniques to derive the color gamut of process printing. A paper presented at a 1990 SPIE conference (2) details the process for deriving contour plots of the gamut from the transfer function of any printing process.

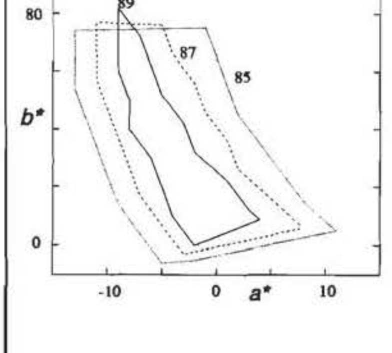

Figure 1 *The upper contours of the color gamut typically overhang the lower contours in the two +b quadrants.*

This contour derivation process involves systematically setting ratios of two colors and then adding black or white to adjust the L* value to that of the targeted lightness level. The yellow used in most printing applications typically has an L* value very close to that of the paper substrate. Therefore, adjusting to contour target L* in the yellow region typically requires the addition of black. As the target L* is decreased, more black must be added. This increasing black content with decreasing target lightness results in a smaller yellow chroma value on the lower contours. This gives the contour plot an overhanging cliff characteristic as shown in Figure 1.

The paper that the proof is printed on has an L* value of 91.86. The solid (100%) yellow printed on this paper has an L* value of 89.03. The point on the upper end of the L* = 89 contour represents the a*b* value of pure yellow. We had to add black to the yellow to adjust its L* value for the L* = 87 and the L* = 85 contours. This reduced its chroma and thus, these lower contours do not extend as far in the +b* direction as L* = 89 contour.

This overhang tends to make plots with multiple contour levels somewhat cluttered. Superposition of two or more multi-contour plots of different color gamuts results in a very confused image. For this reason, we generally use several plots with one contour level each when comparing two or more color process systems. Figure 2 shows an example of such a comparison plot. In this plot, the transfer lookup table data for each system were paper normalized (i. e. dividing the paper XYZs into the measured XYZs and multiplying by 100) prior to deriving the contours in order to minimize variations caused by the differing paper brightness of the two proofs.

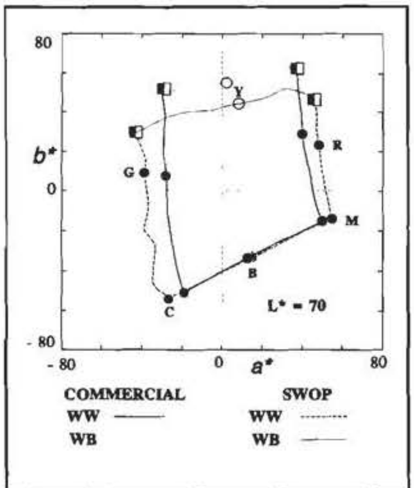

Figure 2 *Comparison of the contours of commercial and SWOP on-press proofs at L*=70. WW - white was added to bring L* value to 70. WB - CMY black was added to bring the L* value down to 70.*

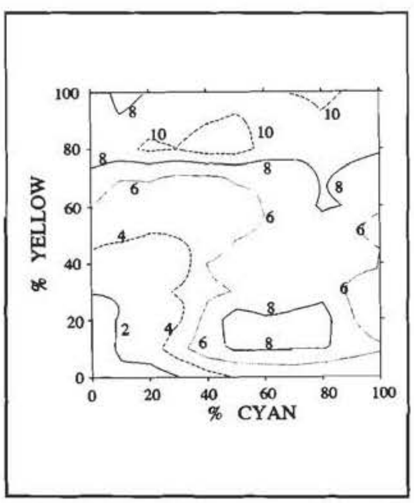

Figure 3 *Color difference between off-press and on-press proofs as a function of yellow and cyan screen density.*

Figure 3 shows another use of the model table data. This plot was made by comparing the paper normalized tristimulus values of on-press and off-press tables and doing a contour plot of the CIELab color differences as a function of cyan and yellow screen percentages. As might be expected, the color difference at 0% cyan and 0%yellow is 0. At 100% cyan and 100% yellow, otherwise known as green, the difference is about 9 E. In a more complicated way, the detail in the region bounded by 20 to 60% cyan and 20 to 60% yellow should give an indication of differences in mid-tone dot gain.

Figure 4 illustrates yet another use of the table data. This is a view of the color gamut solid looking down from above. The 6 radial lines are, from the top of the figure (counter-clockwise), the locus of yellow, green, cyan, blue, magenta, and red. The three inter hexagons represent the locus of 25, 50, and 75% screen density. The lookup table used to generate this plot was derived from a three color on-press target made with commercial ink.

We are not sure what caused the sawtooth edge on the line between the yellow and red perimeter points. However, such a feature could be explained by a non-uniform adjustment of the press ink fountain interacting with the target pattern.

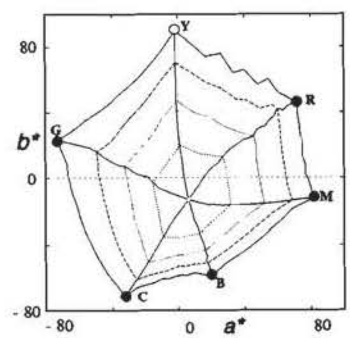

Figure 4 *CLab color gamut of on-press commercial proof projected on to a horizontal plane at L* - 0.*

Figure 5 is what might be termed a pseudo Mercator projection of the color solid. The L* values of the 25, 50, 75, and 100% screen lines (hexagons in figure 4) are plotted as a function of the angle around the paper white point (center of the star). The angular displacement in this plot is referenced to the 100% yellow point. The on-press data was only for CMY inks, therefore, CMY black was used in this plot as well as all of the other plots presented here.

AN ALTERNATIVE TARGET FOR ON-PRESS PROOFS

At this point, we have only attempted to derive CMY transfer functions for on-press systems. To do this, we have printed and measured the 1000 target set that we used for our original work with off-press proofs. The question may be asked, "Do we need to print a target set of 7000 or more colors to get a full CMYK on-press transfer function?". On the basis of our work with more than 15 off-press proofing system combinations, the answer is no.

Even spacing of the CMYK inputs to the target array does not give even spacing of the resulting colors in color space. Forgetting for the moment the need for simple table lookup procedure, let us look at the problem of generating evenly spaced points in the color space. Suppose we decided that we want to space the sampling points n 10 CIELab centers. To determine how many samples are needed, we could make a set of contour plots spaced 10 L* units apart and determine the number of 10 CIELab spaced points that we could layout on each contour plane. A rough estimate of the number points needed could then be obtained by taking the total area of all of the contours and dividing it by 100.

The total area of contours from L* = 30 to 90 for a typical off-press CMY system is about 85,000 square CLab units. This means that we would need approximately 850 points to have samples on a 10 CLab spacing. While this specifies the interior sampling of the color solid, it does not define the edges of the contours. For this purpose we need to total the perimeter of the contours and divide by 10. This total length for the 7 contour planes is about

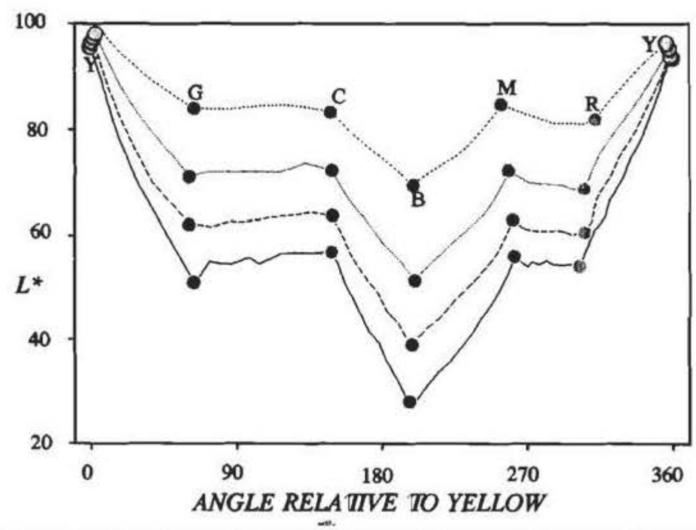

Figure 5 *Pseudo Mercator projection of the color gamut of on-press proof made with commercial ink.*

2200. Thus we add approximately 220 to the 850 interior points and get a total of sampling 1070 points. Interestingly, this is very close to our original 1000 points. The difference is that these points are evenly spaced and probably give us a more accurate model. Unfortunately, deriving the CMY input values for these 1070 points requires the use of the of the data in the table that was derived by measuring the original 1000 point target.

Now let us look at the effect of adding black. To start with, our comparisons of off-press CMY color solids and CMYK color solids show that the inclusion of black adds at most only about 10% to the total CLab color space volume. This addition is on the under side of the color solid where black and CMY black combine to give lower L* values than using CMY black or K black alone. Thus, we are now up to say 1200 points. This allows the maximum CMYK solid to be sampled on a 10 CLab grid spacing. Finally, what do we do about gray component replacement (GCR)?

GCR is usually set by a CEPS system to only one level. Therefore, if we are dealing with only one trade shop, a repeat of the interior points with one GCR level should be enough to define the complete CMYK solid (2100 points total). If we are dealing with several shops, we might want to use 3 GCR levels which requires about 3600 points total. Going further, if we decided to space the sampling points on a 14 CLab grid, we would only need about 1800 points for 3 GCR levels.

Any of these sampling grids would specify irregularly spaced points in CMYK space. Probably the best approach for deriving a lookup table would be to interpolate back to a regularly spaced CMYK grid using some sort of a surface fitting function for the CLab values.

We must note that there is more to the designing a target for getting the on-press transfer function than just picking the points. Ink demand must be taken into account and the individual target colors must be somewhat randomly placed to avoid effects of any poor adjustments in the ink fountain. In addition, sample size should be large enough to avoid lateral diffusion errors in the measured data.

There is some question if a sampling scheme based on an off-press proofing system will provide an adequate proof target for getting an on-press transfer function table. We certainly know that the transfer functions of off-press proofs varies by manufacturer, paper, and simulated ink type. We also know that off-press proofs do not totally simulate on-press proofs.

Fisch (8) points out that the scanner manufacturers do not use the same algorithms for GCR. This might make it impossible to limit the number of GRC levels used in the target.

CONCLUSIONS

The suggestion made be Neugebauer at the 1955 annual TAGA meeting for deriving a table lookup transfer functions of 3 color printing systems using 1000 CMY inputs is very workable. However, the 1943 French patent which Neugebauer said detailed the method does not seem detail the methods for producing a CMY lookup table. His 1955 method can be readily adapted for use in characterizing 4 color off-press proofing systems.

Characterization of 4 color on-press systems presents some problems not present in off-press systems. An alternative scheme, in which samples are evenly spaced in CLab color space, appears to solve some of the on-press problems but may inadvertently introduce other problems.

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