Building a Bridge from Dense City to Colorimetropolis

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Keywords

CIE, Colorimetry, Densitometry, Standards

This paper reviews the various methods that have been previously proposed to compute density-like parameters from colorimetric measurements. A few new methods are also added. A large data set of spectra is used to compare how well the methods correlate against the various density-derived parameters.

The conclusion is that there are colorimetric equivalents for all the print attributes that are currently computed based on densitometry.

Historical context

Historically, densitometers have been the only tool used in the pressroom for the measurement of the reflectance of ink on paper. As colorimetry has gained universal acceptance, density has become more and more of an island. That island is eroding away.

The standards are moving away from the use of density as a means for measuring color on presses. ISO 2846 (ISO 1997) led the way with colorimetric specification of ink. ISO 13656 (ISO 2000) includes a discussion of both densitometric and colorimetric measurements and outlines where each is appropriate.

ISO 12647-2 (2004) followed with colorimetric specifications for solids, midtones and overprints. This standard talks much less about density, but does allow that it is valid (and common practice) to adjust ink levels based on density. However, the goal is to reach CIELAB values.

Other “semi-standards” are pushing toward colorimetry. The entire TR00x series publishes target colorimetric values for all combinations of inks. The G7 document (IDEAlliance 2006) drastically reduces the role of density in favor of colorimetry. The latest SWOP specification (IDEAlliance 2007) lists solid ink densities, print contrast and TVI targets with the heading “For historical use only”.

Abhay Sharma (currently Chair of Ryerson's School of Graphic Communications Management) has summed up this turn of events with the rather pithy prediction “the days of density may be numbered” (Sharma and Goike, 2003).

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There is, however, some backlash to this change. Some of this backlash comes from misconceptions about density. The first misconception is that a densitometer directly measures ink film thickness and actual dot gain.

The second misconception is that a colorimeter is inherently different than a densitometer when it comes to making indirect measurements of ink film thickness and dot gain.

In an early paper discussing colorimetry (Gray, 1976), it is stated that "Densitometers are the best instruments available for controlling or monitoring the strength variations of colorants of similar or unchanging spectrophotometric curve shape."

These beliefs are reiterated by Hensel (1989): "Solid ink density measurements of strength (ink film thickness) are made using the filter which gives the highest density… Densitometers are used to control the relative ink film thickness, while colorimetry attempts to measure color as seen by the human eye. It is a known fact that the eye is very poor at judging the ink film thickness of a yellow. It follows that colorimetry must also be very poor at judging yellow strength or ink film thickness."

In a survey taken at the 1987 TAGA Color Committee Workshop, Chung (1987) reports that 32% of the attendees felt that the densitometer will continue to be the dominant color measuring instrument in the pressroom. A full 17% of the attendees believed "that colorimeters will never become a dominant color-measurement instrument in the graphic arts industry."

Even Viggiano, who had the vision in 1987 (Viggiano, 1987) to see that a transition from density to colorimetry was needed, states that "Certain physical phenomena in graphic reproduction are inherently narrowband in nature, and are best evaluated using a narrowband instrument."

Twenty years later, there are still strong feelings that densitometry is substantially different from colorimetry.

Uribe (2005) states "it is now widely accepted that the densitometer is the correct instrument for measuring ink film thickness but it is not reliable for color measurements." Also Breede (2006) states "… unlike L*a*b*, optical density bears a close relationship to ink film thickness."

Another reason for this backlash is that press operators are hanging on to something that works! Despite this exodus from Dense City, there is a still a need in the pressroom for measurements that look and feel like the good old density numbers that press operators are accustomed to. Solid ink density, tone value increase, print contrast, and gray balance are useful as diagnostic tools and process control parameters.

I contend that the densitometer only measures reflectance, which is merely indicative of ink film thickness and tone value increase. Both densitometers and colorimeters measure reflected light through a set of filters. The only difference is in the filters, and these differences (in the grand scheme of things) are minimal.

As we travel from the island of Dense City to the mainland Colorimetropolis, a number of researchers have laid footings for a bridge between these cities. These people have proposed a number of ways to compute density-like numbers from colorimetric values. What we lack is a head-to-head comparison between these proposals and against traditional density-derived data. This paper fills that void.

Required Density-Derived Parameters

Press operators routinely use a densitometer to report three diagnostic parameters: solid ink density (SID), tone value increase, and print contrast. There are a number of other parameters that are less frequently used: trap, hue error, and grayness.

Another commonly used densitometric tool is a graph that indicates gray balance. The GATF Color Circle diagram is one example, and the Gray Balance Hexagon from System Brunner is another.

Ideally, we would like to have colorimetric analogs for each of these parameters.

Solid Ink Density

Introduction

It has been established that there is a strong relationship between ink film thickness and density. In fact, there have been four papers that test out formulas that have been proposed (Blom 1990, MacPhee 1991, Chou 1991, MacPhee 2002). This has been the basis of using density as a control system parameter.

One article in the literature (Bassemir 1993) has directly shown that both densitometric and colorimetric values are indicative of ink film thickness.

On the other hand, Serafano (1998) has shown that, at least for gravure printing, neither densitometry nor colorimetry correlates well with ink film thickness when asked to predict across various stocks.

In this section, I demonstrate that colorimetric values can be converted mathematically to a number that bears a close relationship to solid ink density.

Available formulas

Sorting through the literature, I have found six formulas that derive a SID-like parameter from colorimetric values:

Log XYZ - The idea of computing the logarithms of the XYZ values to define a set of colorimetric equivalents to SID is not new (Yule 1950, Pearson 1970). Viggiano (1991) summarizes these suggestions, saying that the colorimetric density for cyan should be measured through the X filter, magenta should be measured through the Y filter, and yellow through the Z filter. G7 (IDEAlliance 2006) describes this as the “logical (if not yet ‘standard’) decision”

Variation on Log XYZ - Balestrini (2007) found the best results when using the Y filter for cyan and magenta, and the Z filter for yellow. The only departure from the first formula is the use of Y for cyan. (It should be noted that Balestrini focused on a measure that best predicted the closest CIELAB match, rather than one that correlated with density measurements.)

Log RGB - Viggiano (1991) suggests a 3X3 matrix transform from XYZ coordinates into an RGB space, and taking densities of these values. The appendix gives this formula. This 1991 paper revised an earlier 3X3 transform that he had proposed (1987).

CTV - Birkett (2005b) defined a parameter known as “colorimetric tone value” (CTV) as a single number means for characterizing the saturation of an ink that is based on colorimetric values.

PRCTV - In this paper, I present a modification of CTV, where the colorimetric calculations are paper relative, rather than absolute. The comparisons are made to paper relative densities.

ΔE - A final candidate for a colorimetric analog to SID is the ΔE between the solid patch and paper. This method is also suggested by Birkett (2005b).

PRΔE – This is the ΔE between the solid patch and the paper, but where the CIELAB values are computed relative to paper, rather than relative to an absolute white as is normally done. The comparisons are made to paper relative densities.

Celio (1990) has proposed the use of the maximum spectral density, that is, the highest density in all spectral channels, as the measure of the strength of the ink. This will not be considered, since this is not strictly a colorimetric parameter.

Description of first SID experiment

I started with spectral measurements of 300 patches of cyan, 300 patches of magenta, and 300 patches of yellow. The patches were printed at a very, very wide range of densities on a total of 21 different stocks. The stocks were chosen to cover a wide range of gloss, brightness and fluorescence. Some were coated; some uncoated.

Status T and E density and colorimetry values were computed from these spectra and each of the proposed parameters were computed from the colorimetric values.

As an example of the relationship between densitometric and colorimetric values, Figure 1 shows a plot of the Status T densities of the solid magenta patches as a function of the “Viggiano densities” of those same patches. Note that even though the range of density (0.4D up to 2.1D) is well beyond any practical range of densities, there is an excellent correspondence between the two.

A cubic curve was fit to the data points, and the RMS of the residual was computed to be 0.008D. From this I conclude that not only is the Viggiano density a useful replacement for Status T density of magenta patches, but there is also simple formula to compute Status T density from Viggiano density.

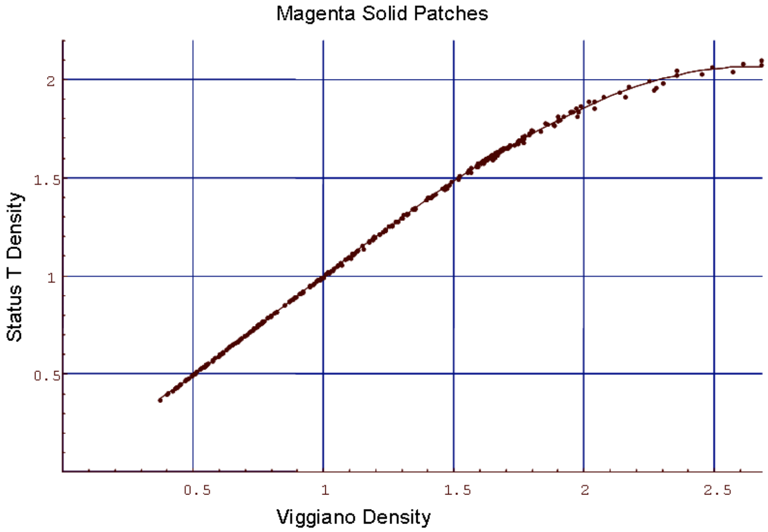

Figure 1

Figure 2 shows a relationship that did not work out as well. Here, the RMS of the residual is 0.061D.

The graph shows that there is clearly a strong relationship between Log (X) and Status T density, but there is more variation. Figure 3 plots the relationship on three different stocks. This shows that, on a particular stock, the relationship between Log X and density of solid cyan patches is quite well behaved. In my opinion, this parameter would be quite useable in the pressroom. On the other hand, it is not possible to reliably determine density based on Log X without calibrating to a particular stock.

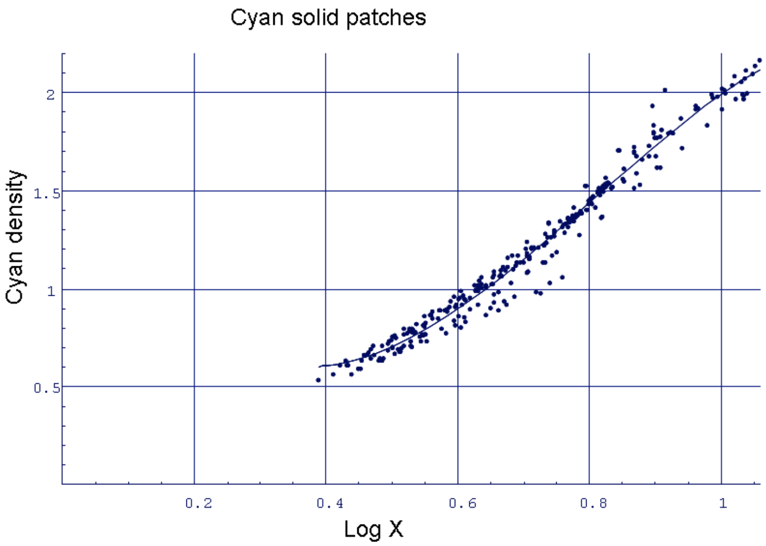

Figure 2

Figure 3

Results

Table 1 shows the RMS of the residuals for all formulas. The RMS is in density units.

	Cyan	Magenta	Y (Stat T)	Y (Stat E)
Log X	0.061	0.144	0.240	0.402
Log Y	0.096	0.071	0.233	0.389
Log Z	0.277	0.109	0.008	0.026
Log RGB	0.025	0.008	0.009	0.029
CTV	0.097	0.105	0.075	0.115
PR CTV	0.069	0.076	0.010	0.026
ΔE	0.064	0.108	0.079	0.120
PR ΔE	0.043	0.058	0.018	0.025

Table 1

I have somewhat arbitrarily set a value of 0.080 or less (highlighted in lighter gray) to be useful in the pressroom on one stock, and 0.030 or less (highlighted in darker gray) for useful for converting to density.

The Log RGB calculation is the most reliable of the formulas, having all four density calculations in the "useful for converting to density" category. Note that the Status E yellow error for the Log RGB transform is not as good as the other three. Viggiano did not provide a separate transform for Status E, so I merely replicated the transform for Status T yellow.

Conclusions from first SID experiment

The Viggiano Log RGB formula, while not quite as simple as Log X, Log Y, and Log Z, correlates much better than these to traditional densities. I recommend that the authors of G7 take this under consideration when they meet for the G8 summit.

When SID and colorimetric alternatives disagree because of a change in stock, it may be a foregone conclusion that the colorimetric alternatives are necessarily "wrong". That is, some may assume that SID is the true indicator of ink film thickness. While this may be true, the difference is indeed small. Further, there have been no systematic studies in the literature that have shown whether colorimetry or density is more accurate when it comes to predicting ink film thickness.

I would hazard to guess that colorimetric and densitometric values correlate much better to each other than to the actual ink film thickness. The relationship between ink film thickness and reflectance depends upon numerous factors that have little to do with ink film thickness: ink holdout, surface roughness of the ink and paper, tint of the paper, fluorescence of the paper, pigmentation and opacity of the ink. No reflectance measurement can ever directly indicate ink film thickness.

Solid Ink Density, Take 2

In the previous section, it was assumed that the goal was to find a parameter derived from colorimetric values that correlated best with SID. This is a reasonable goal, since SID has many miles on it, and we know that it "works". It is reasonable to ask, however, whether it might not be better to find a parameter that "works better", rather than a parameter that works just like the old one.

But what does it mean to say that a parameter "works better"? What is the real goal?

For the purpose of process control, it is important to be able to bring the press to a known state, including a standard ink film thickness, in order that the larger process can be brought under control. SID has given us a link to ink film thickness, and the previous section has shown that colorimetry can give us the same link.

For any given job, however, the ultimate goal is to make the print look good. For that goal, colorimetry is the best tool we currently have. The standards organizations are recognizing this. ISO 12647-2 and G7 require that the solid patches match to specified L*a*b* values to within some tolerance.

As one increases the ink film thickness, the color of a solid patch travels along a trajectory in L*a*b* space. Figure 4 illustrates this in the a*b* plane, but the trajectory is three dimensional. The goal of the pressman (in order to meet ISO 12647-2, for example) is to adjust the ink keys so as to find the ink film thickness along this trajectory that brings the color closest to the target CIELAB value.

In figure 4, maintaining the density between 1.25D and 1.60D will assure that the solid is within the tolerance, with an optimal setting at perhaps 1.41D. Ideally, one would be able to specify a target density of 1.41D as the universal target, and then use this for all jobs.

Unfortunately, SID is not the ideal tool for this purpose. It is well-known that the SID value that yields the best match to colorimetric values depends upon the paper and ink. It is possible to determine a target density for any set of conditions, but this target density should not be used universally.

CIELAB values are not an ideal tool either, since there are three values to compare. Computing the ΔE brings the values down to a convenient single number, but the ΔE does not give an indication as to how to change the ink key setting. Knowing that the color error is 7 ΔE does not tell the press operator which way to adjust.

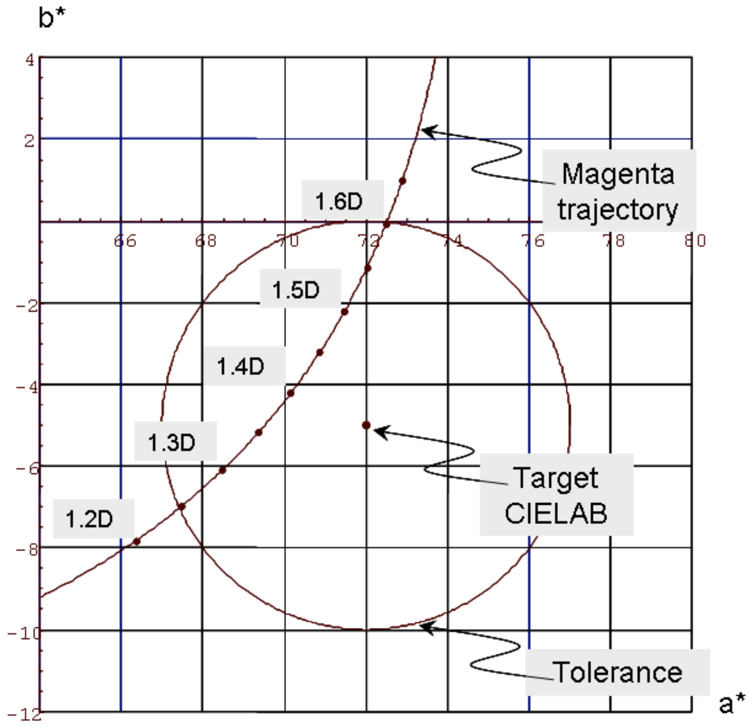

Figure 4

It would be beneficial if there were a single dimensional parameter that could be used such that attaining a target value of this parameter would also attain the closest colorimetric response. To be universally useful, this target value would be the same for all papers and inks. The previous set of SID formulas will be evaluated for this use. If I were to set a fixed target value for each of the parameters, how close would I come to being able to satisfy colorimetric goals?

Description of second SID experiment

Let us say that a press is run in such a way that the ΔE between solid patches and targets for solid patches is kept at the minimum. How much variability would there be in the density of those patches as the press went from one stock to the next? And how big is that variation, compared to the tolerances allowed by ISO 12647-2?

Beer's law can be used to predict the relationship between ΔE and density. Given a representative spectrum of an ink and the spectrum of the paper underneath, one can use Beer's law to predict the spectrum of the ink on paper at various ink film thicknesses. While this relationship is not perfect, there were three papers last year that demonstrated that Beer's law can be used to predict perfectly viable spectra within a small range of thickness variation (Balestrini 2007, Birkett 2007, and Seymour 2007). Beer's law has been awarded the title of "Most Popular Graphic Arts Formula" for 2007, winning out over the always popular Neugebauer equations and the Murray-Davies formula.

Given the Beer's law approximate spectrum, the density and CIELAB values can be computed. The colorimetric values can be compared to the required standard to generate a ΔE as a function of density. Figure 5 shows the results of making this computation on spectra of cyan ink, measured on two different paper stocks. It is seen from this plot that the SID value that produces the closest colorimetric match is about 1.32D on one stock and about 1.39D on the other.

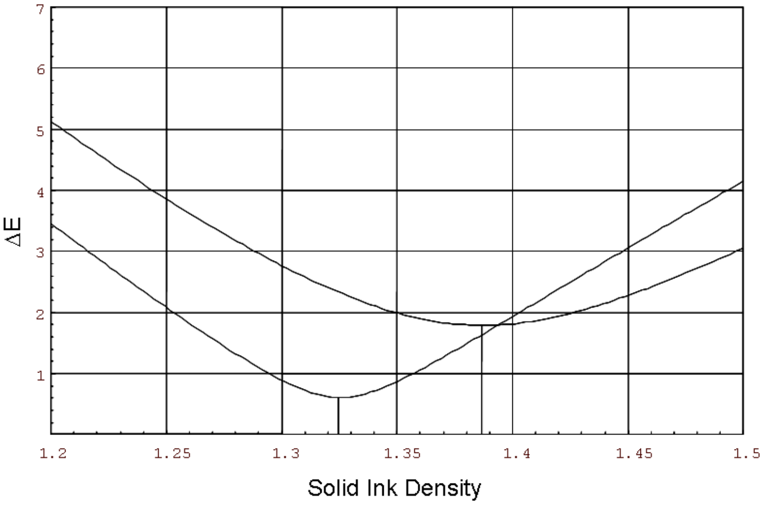

Figure 5

Figure 5 demonstrates that it may not be possible to reach the exact CIELAB value. For one stock, a ΔE of something less than one is possible. On the other stock, a ΔE of 2.0 is the best that can be attained.

Figure 6 is a particularly ugly graph, showing the optimal densities for cyan ink on sixteen widely different stocks. The optimal densities range from roughly 1.31D to 1.40D, with a standard deviation of 0.028D.

At first glance, this would appear to be proof that SID is not a useful parameter to be used for matching CIELAB values. One the other hand, this standard deviation should be compared with the size of the tolerance range. For an ink that is capable of attaining the target CIELAB value, the tolerance range is from 1.19D to 1.52D. For this ink, staying between 1.19D and 1.52D will guarantee that the color is within 5 ΔE of the target CIELAB value. (This tolerance range, 0.32D, agrees with the results from Seymour 2007.)

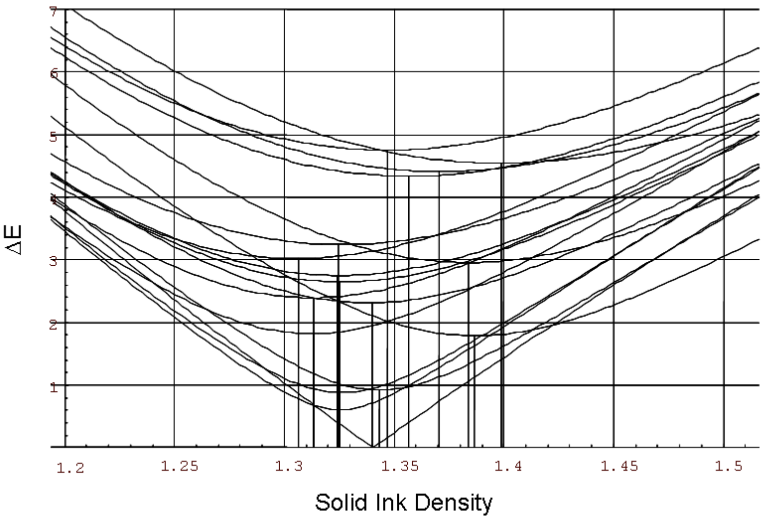

Figure 6

In doing a gauge R&R (repeatability and reproducibility), the ratio of standard deviation of measurement error to the tolerance range (the capability factor) is used to determine whether a measurement device (the gauge) is acceptable for quality control. If the measurement error is less than 10% of the tolerance range, then the gauge is considered acceptable. Measurement error of between 10% and 30% of the tolerance range is considered marginal.

The standard deviation for the cyan SID values above is about 9% of the tolerance range. By standard gauge R&R theory, one could use a Status T densitometer to verify that the CIELAB values of solid cyan patches on press are within tolerance. This result is unexpected. Is this true for other inks?

Results from second SID experiment

Table 2 shows the capability factor for all the formulas.

	Cyan	Magenta	Yellow
Status T density	8.6%	12.5%	43.1%
Log X	32.3%	57.4%	470%
Log Y	37.3%	30.4%	360%
Log Z	142.5%	18.4%	43.8%
Log RGB	10.3%	9.1%	45.5%
CTV	12.2%	31.1%	6.2%

PR CTV	5.3%	9.0%	25.9%
ΔE	21.8%	78.3%	13.1%
PR ΔE	5.7%	30.1%	16.4%
b*	4.5%	7.4%	16.4%

Table 2

From Table 2, there are several formulas that are acceptable for both cyan and magenta. The only formula acceptable for yellow ink is CTV. Unfortunately, there is no single formula of those previously investigated that is acceptable for all three inks. It is desirable to have one common formula for all the inks, rather than having to use a Swiss Army knife of measurement tools.

Figure 7, perhaps, offers some insight into the difficulties. In the region near the target color, the magenta trajectory does not move away from the origin (that is, toward increasing chroma) as one would hope, but rather moves upward (in the direction of increasing b*). Interestingly, the yellow and cyan trajectories are also along the b* direction.

This suggests that b* might be a more useful indicator. The capability factor calculation was repeated using b*, showing that b* is acceptable for cyan and magenta, and marginally acceptable for yellow. (See bottom row of the table.)

Conclusions from second SID experiment

I conclude that setting target b* values as control points would work acceptably well in the pressroom.

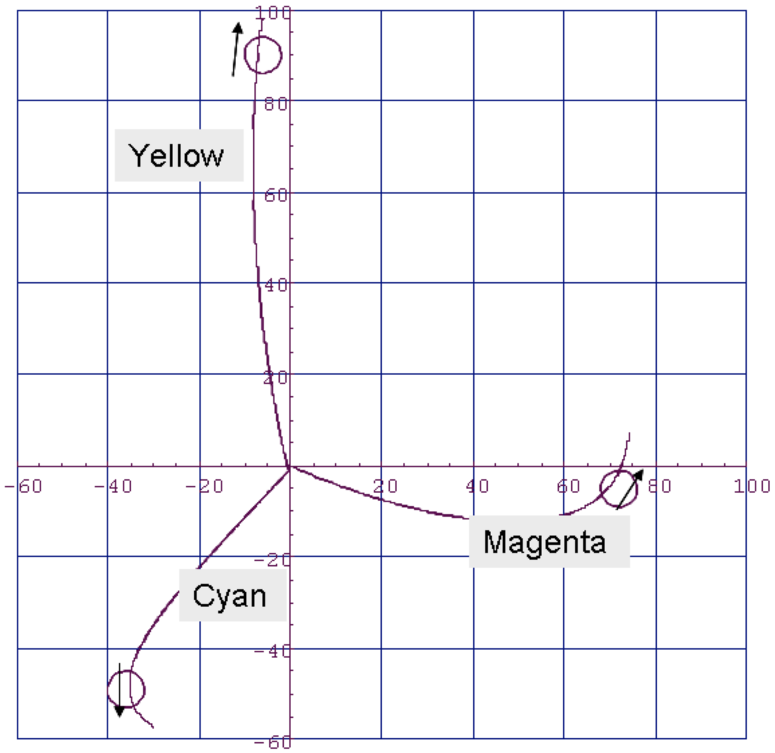

Figure 7

Solid Ink Density, Take 3

In the last section, we started out with a desire. Namely, it would be nice to have a parameter that we could measure on press, such that if we control this parameter to a target value, we would be assured that we would have the closest ΔE to the target CIELAB value. Various proposed parameters were looked at, and b* was the only one shown to be marginally acceptable.

Quoting from Seymour (1995): “When controlling a press, it is of little direct benefit for the pressman to have an instrument which reports a hue error or ΔE. There are no knobs to control L*, a*, or b*.”

Birkett has recognized the need for a method for the press operator to find the closest color match. In his presentation to RIT (2007), he provided a description of a computational technique to do this. The spectrum of a solid patch and of paper is measured during the print run. Birkett has written software to determine the optimal density.

His software uses Beer’s law to estimate the spectrum of the ink on paper at various inking levels. CIELAB values are computed from these estimated spectra. The inking level is adjusted (in software) so as to achieve the smallest ΔE. The density is computed from this winning spectrum, and this is presented to the press operator as the target density.

In addition to reporting a target SID, the software could report best attainable ΔE, and the acceptable SID range. This process could happen throughout the press run.

Conclusions from third SID "experiment"

Birkett's algorithm is an ideal solution. The press operator is given the same tool that has been used in the past, SID. With the addition of a tool to determine which target SID will reach the colorimetric goal, the standards (such as ISO 12647-2) can be met.

TVI

Introduction

In this section, I demonstrate that colorimetric values can be converted into print attributes that correlate very well with the standard densitometric TVI values.

Available formulas

G7 has reduced the role of TVI to just an on-press diagnostic tool, supplanting it with a chart for determining target *visual* densities of CMY gray patches and black patches (the Neutral Print Density Curve). (Visual densities are the densities measured through the status T "visual" filter, which is quite broadband, and usually just used for black ink.) For diagnostics, they recommend using densities as measured in the X, Y, Z channels to compute TVI, using the Murray-Davies formula.

This idea has been around at least since 1951. Yule (1951) used densitometry to develop formulas to explain the reflectance of halftones. He stated that his results would have been essentially the same if the tristimulus functions were to have been used. Birkett (2004) repeated the suggestion. He further suggested taking the average of the three, or taking the geometric mean.

Huntsman (1991) has a slightly different recommendation for computing TVI from colorimetric values. He suggests that the XYZ values (for paper, midtones and solid) should be referenced against paper, rather than absolute white, as is normally done. Huntsman recommends that the normalization values (X_n, Y_n, and Z_n) should be the XYZ values of the substrate. TVI is then computed from whichever value (X, Y, or Z) has the largest contrast. Although this sounds like a reasonable approach, it is mathematically equivalent to using absolute XYZ values.

Viggiano (1991) did not suggest using his Log RGB formula to compute TVI from colorimetric values. But, since this formula worked out so well as a colorimetric replacement for SID, it seems reasonable to see if this works out well for TVI.

Birkett (2005a) describes a method for characterizing dot gain curves based on XYZ data. Regression is performed of a cubic function to the X, Y, and Z values measured from a ramp. This method is a useful way to compute a profile from a limited number of data points. However, it does not work for a single patch; it requires measurements from a number of patches. Also, it does not give one single tone value number. There are twelve numbers.

On the other hand, in a separate paper that year, Birkett (2005b) does offer CTV, which was described before. The measure is not in reflectance or density units, so it is not clear how to plug this number into the Murray-Davies equation. It will be left in its raw form. This puts CTV at the disadvantage of having a built-in nonlinearity. A second disadvantage is that the CTV formula does not consider the solid.

Description of first TVI experiment

In this first experiment, I reuse the data from the previous SID experiments. As said before, this encompasses 300 patches of each type on 21 different stocks. These test runs also included 25%, 50% and 75% patches.

Results from first TVI experiment

Table 3 shows the RMS of the residuals for all formulas. The RMS is in percentage points of tone value. The RMS of cyan ink using Log X is 1.18, which is to say, a tone value of 65% is 65% ± 1.18%.

	Cyan	Magenta	Y (Stat T)	Y (Stat E)
Log X	1.18	2.04	3.88	3.97
Log Y	2.31	0.70	5.95	6.23
Log Z	6.49	2.65	0.28	0.40
Log RGB	0.56	0.13	0.27	0.41
CTV	6.59	9.14	7.13	6.58

Table 3

Conclusions from TVI experiment

TVI can be computed quite reasonably for cyan, magenta, and yellow using the X, Y, and Z values, respectively. The use of Viggiano's formula can greatly improve the agreement with tone values computed using density.

Birkett's CTV does not correlate well with TVI computed from density, but it was not expected to.

Print Contrast

Introduction

Excessive tone value increase on press can cause the holes between dots to plug up so that contrast is lost in shadow regions. Print contrast is the traditionally accepted measure of plugging. It is computed as the ratio of the density of the solid patch minus the near solid patch to the density of the solid. For the purposes of this paper, I will assume that print contrast is computed from a 75% patch.

The 75% tone value is also a measure of plugging. In the interest of laziness, do I need to treat print contrast as a special topic, or is it covered under TVI? Is print contrast really any different than tone value?

Stanton (1999) stated "Within a given printing system, the correlation between print contrast and dot gain is very strong… If the dot gain is known at a given density level, then the print contrast can be predicted with reasonable accuracy." If this is true, we do not need to consider print contrast separately from the 75% tone value.

Figure 8 shows the relationship between print contrast and 75% tone value for a set of 300 cyan patches on 21 different stocks. While there is quite clearly a strong relationship between them (correlation coefficient of -0.750), one does not accurately predict the other. This correlation coefficient means that only 34% of the variability can be explained by the relationship between the two.

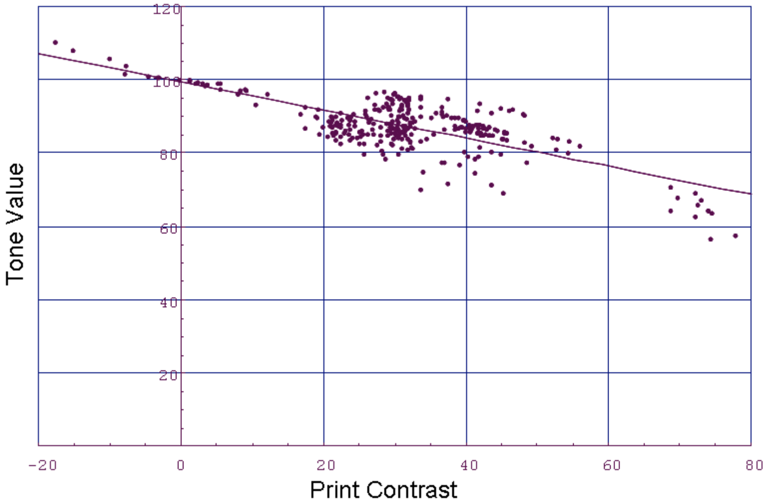

Figure 8

A comment on the chart is in order. There are a number of patches with tone value greater than 100%. These patches are also those patches with negative print contrast. This happens when the 75% patches are actually darker than the solid patches. This is not a fluke. At high inking levels, a solid patch can become mottled due to uneven lay down of the ink. Having holes in the halftone pattern allows a smoother lay down of the ink so that a 75% patch may actually be darker than a solid.

My conclusion from figure 8 is that print contrast is largely a different animal than 75% TVI. One does not predict the other very well. Note that this does not imply that print contrast is the proper tool to be using; it is just a somewhat different tool.

Available formulas

Only two formulas were compared against densitometric print contrast. The first, the Viggiano formula, is rather obvious from the previous experiments. I used the Viggiano transform to calculate RGB reflectance values from XYZ values. The appropriate reflectance values were converted to densities and used to compute print contrast.

The second colorimetric version of print contrast that I developed is the ΔE between solid and 75% patch. CGATS.4 says that print contrast “indicates the printing system's capability to hold image detail in the shadow tones.” It would seem to me that the most meaningful way that we could measure this would be to measure a colorimetric difference. This is the most accurate means that we have today for determining how distinguishable two colors are.

I have some caveats to add. The first caveat is that the world is still searching for the best formula for a color difference, so any recommendation that I make today will likely be usurped in the future. On the other hand, any of the ΔE values is a better predictor of color difference than tone value differences or print contrast.

A second caveat is that ΔE is intended for small differences in color. Ideally, it would be a predictor of when two colors are indistinguishable. It has been extended to determining acceptability tolerances of, for example, 4 or 5 ΔE. I am taking this a step further to ΔE values of perhaps 30.

The third caveat is that I felt the need to define negative ΔE values. If the 75% patch is printing considerably darker than a solid, a straight ΔE would make this look like good printing conditions. I took the convention that the value is given a negative sign whenever the 75% patch is richer than the solid. In this way, the relationship between ΔE and PC still works for extreme conditions.

Description of the experiment

I used data from 300 each of the cyan, magenta and yellow 75% patches, along with solids, to compute the various print contrast attributes.

I used ΔE_{76}, strictly because the other formulas for color difference are too cumbersome to program. While ΔE_{2000} would be more accurate, there is no reason that these results would be substantially different other than in scaling.

Results

Table 4 shows how the two candidate colorimetric formulas stack up against print contrast. The results in this table are the RMS value of the error in print contrast percentage.

	Cyan	Magenta	Y (Stat T)	Y (Stat E)
Viggiano	2.02	1.74	1.25	3.85
ΔE	4.06	3.03	2.09	1.59

Table 4

Once again, the Viggiano formula has performed quite well, although not nearly as well when it comes to Status E. The reason for this, as said before, is that Viggiano did not define a transform for Status E. I have simply repeated his Status T transform. Small changes in the coefficients of the transform can bring this down to a suitable number.

Figure 9 shows a plot of one of these relationships.

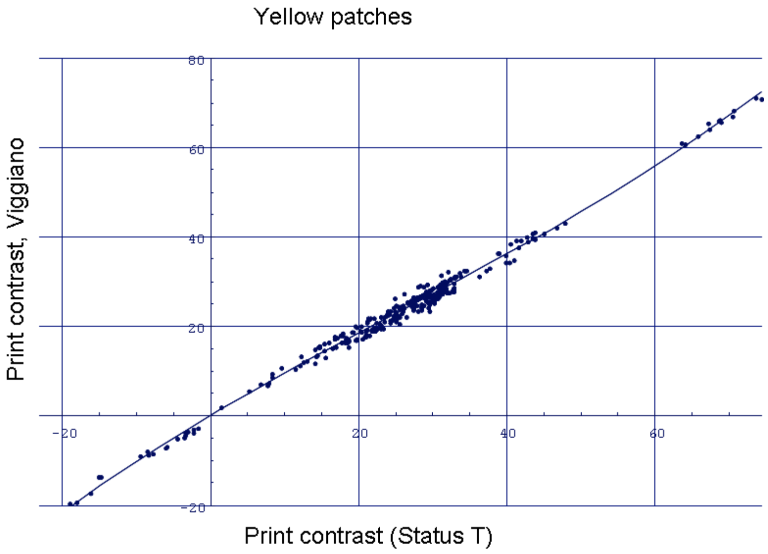

Figure 9

Conclusions from print contrast experiment

I have found that there is a statistically significant correlation between print contrast and 75% tone value. They are however, distinct quantities. One cannot be used to accurately predict the other.

Print contrast can be computed from colorimetric values using Viggiano’s transform. These results compare quite favorably with print contrast computed from densitometric values.

The color difference between solid and 75% patches also correlates very well with print contrast. Since this number is based on visual appearance, this number may ultimately prove more meaningful that print contrast.

Trap

The wonderful thing about standards is that there are so many to choose from. So it is with formulas for trap. Formulas have been introduced by Preucil, Childers, Brunner, Hamilton, and Ritz.

Stanton (2001) reviewed studies by Chen and by Jorgensen that point to limitations of densitometric measurement of actual trap, particularly when applied across different printing conditions. The formulas are nonetheless recommended as a process control parameter.

Stanton has performed a rather rigorous comparison between four of the proposed formulas for trap and colorimetric (ΔE_{94}) measurements. His conclusion was that the Ritz formula predicted color differences best at equilibrium conditions, and the Preucil formula was a better predictor when there was a wider variance. Given that the measurements are more important when variation is a little larger, the Preucil formula is favored.

Stanton had performed special press runs to induce a wide range of trap conditions. My own data sets are not as extensive. In particular, my data would be more useful for trap if I had measurements taken with one ink up and another down. Unfortunately, in my data, the ink levels generally all track with one another.

As such, I will defer to Stanton’s conclusions that the Preucil trap equation was effective at predicting the colorimetric change in trap patches.

Gray Balance

Introduction

A color hexagon had been described at least as early as 1953 (Evans). This was later adapted to printing by Preucil (1960). The plot is a trilinear plot of CMY densities. Figure 10 illustrates how the position in the Evans hexagon can be computed for a patch with CMY densities of (1.1, 1.5, 0.8). As can be seen, the calculation is quite easy, being just a weighted sum of the three vectors.

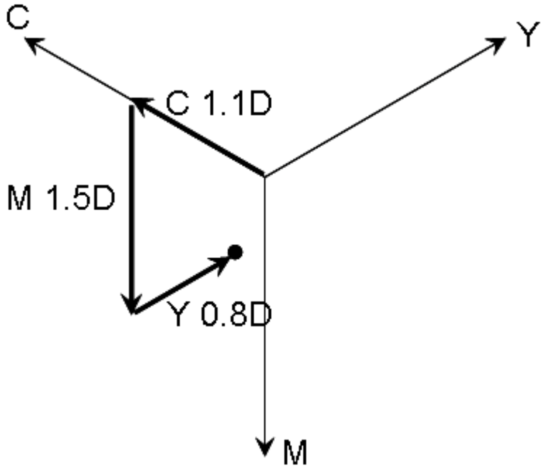

Figure 10

In 1957, Preucil defined a different hexagon based on his definitions of hue error and grayness. These two numbers are again calculated directly from density measurements. The two quantities are plotted on a circular graph which has become known as the GATF Color Circle diagram (Preucil 1957 and 1960, Yule 1967, CGATS 1993, and Breede 2006). The plotting of these points is considerably more involved.

An alternate diagram was offered by Brunner (1987, 1989), and Muirhead (1988), based on differences in tone value. This is referred to as the Gray Balance Hexagon or Color Balance Hexagon.

Many other densitometric means for plotting colors of printing inks have been developed. These include the subtractive triangle (Preucil, 1960), the Enco Spectralinear diagram (Hensel 1984), and the CHG space developed by Chou (1988).

These diagrams look a great deal like a slice from the a*b* plane, so it is natural to ask whether one might be exchanged for the other.

Previous investigations of gray balance formulas

The literature is apparently divided on whether the densitometric and colorimetric versions are equivalent.

Viggiano has worked on using colorimetric values to produce numbers that look like the GATF Color Circle diagram (1987 and 1991). He states that computing the logarithms of the XYZ values do not yield satisfactory results when computing hue error and grayness, but that his Log RGB formula (1991) produces acceptable results.

According to Würgler (2004), each 2% step on this hexagon is roughly equal to 3 ΔE.

Breede (2004 and 2006) has compared the GATF Color Circle diagram to CIELAB for three-color gray patches. He showed that hue error and grayness are essentially equivalent to CIELAB for measuring three-color gray patches.

Hsieh (2005) showed that the CIELAB chroma of neutral gray tint patches (7%) is not well correlated to the standard densitometric suite of print attributes. On the other hand, Hsieh found that the chroma of 80% neutral gray patches did correlate very well with 1) 80% TVI of magenta and yellow, 2) with SID of magenta and cyan, 3) with print contrast of yellow and magenta, and 4) with the cyan / magenta trap.

Fisch (1988) used densitometry (hue/grayness) and CIELAB (hue angle/chroma) as two ways to assess seven different inks. He found that the densitometric assessment was incapable of providing a meaningful distinction between the measurements, whereas that CIELAB hue angle and chroma agreed with visual assessment.

In another paper by Fisch (1990), the density was measured from a set of patches from the Munsell Color Notation Atlas. He computed densitometric hue error and grayness to plot these on the GATF Color Circle diagram. The graphs clearly demonstrate that these densitometric parameters are not useful when applied to the Munsell patches. Since the Munsell patches incorporate different pigments than what is found in printing inks, metamerism will be an issue. Density is not an appropriate tool for measuring Munsell patches.

Description of the gray balance experiment

The data for this experiment consisted of measurements of 2,688 CMY patches near 25% gray, near 50% gray, and near 75% gray. The measurements of the a*b* values of the patches are shown in Figure 11.

Since the Preucil subtractive triangle (Preucil, 1960), the Enco Spectralinear diagram (Hensel 1984), and the CHG space developed by Chou (1988) have not found much acceptance, they will not be considered here.

The Brunner Gray Balance Hexagon is much used today, however, the implementation is proprietary, and so it will not be compared here.

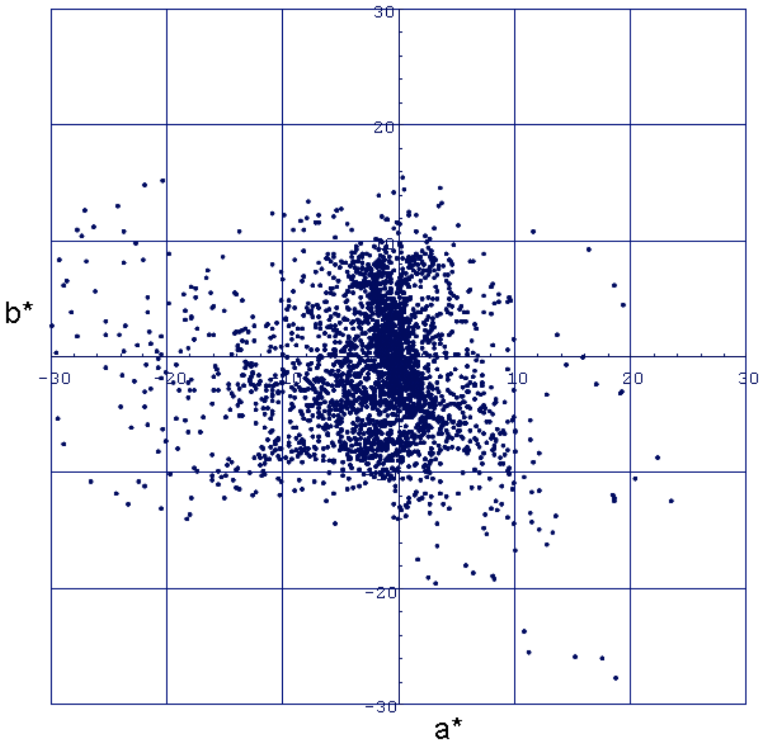

Figure 11

In all previous experiments, I have converted colorimetric values into a well-established densitometric print attribute. In this case, I would argue that a*b* values are the one print attribute that is the most firmly established.

I will compare, therefore, the following density-derived formulas to a*b* values:

1. the GATF Color Circle Diagram,
2. the Evans hexagon, and
3. a*b* values estimated from CMY density using the inverse of the Viggiano formula.

Results from gray balance experiment

We would not like to fault one of these formulas for providing a color space that is squashed a bit in one dimension, for example, and rotated a bit. In particular, the GATF color circle diagram has green to the top, rather than yellow, as in a*b*. In order to compare, I first found the best affine transform to convert the space to a*b*. I have then reported the errors when all the points are transformed through this affine transform.

	Ave ΔE	95th %
GATF Color Circle	1.77	4.88
Evans hexagon	2.04	4.54
Viggiano	1.68	4.37

Table 5

These errors are not small enough to convince someone to throw out their spectrophotometer in favor of a densitometer. Although the errors are larger than one would like, all three of these densitometric color spaces do have the look and feel of a*b*. The Viggiano transform has smaller errors, but there is no clear distinction between the methods.

The 2,688 patches represented in Table 5 were printed on 21 different stocks. Is it possible to calibrate the transform for a particular stock? The experiment from Table 5 was repeated with 200 patches from a single stock. The results are shown in Table 6. Here the GATF Color Circle is the clear winner, and the results are marginally acceptable for control purposes.

	Ave ΔE	95th %
GATF Color Circle	0.68	1.60
Evans hexagon	1.42	2.76
Viggiano	1.08	2.61

Table 6

Conclusion for gray balance experiment

This experiment showed that density values of three-color gray patches can be converted to something that is similar to a*b* values. For a single stock, positions on the GATF Color Circle correlated very well with a*b* values.

The results for gray balance are not as encouraging as for the other print attributes. The poorer results, in my opinion, are due to the extra variables involved. In addition to changes due to paper, CMY patches can vary in dot area and ink film thickness. Because of this, it is possible for two patches to have the same L*a*b* values, but considerably different spectra. Thus the densities will be different.

Tolerance Windows

One final consideration is tolerance ranges. We are accustomed to setting tolerances on print attributes. Can those tolerances be translated to colorimetric values?

Various authors have considered the conversion between tolerance ranges for density and those for colorimetry (Tangvichachan 1993, Nurmi 2002, MacPhee 2004, and Seymour 2007). For the purposes of this paper, I will consider this matter settled. Tolerances can be translated.

Conclusions

In this paper I have tested a variety of formulas for converting colorimetric data into values that look and feel like established densitometric print attributes.

Solid ink density The Viggiano (1991) transform provides colorimetric density values that translate very well to densitometric densities. This formula, however, is not useful in trying to drive a solid to a given L*a*b* value. One way for dealing with this is to shoot for a target b* value. Birkett (2007) has provided a more elegant method for driving a solid to an L*a*b* target.

Tone value increase The Viggiano (1991) transform will allow tone values to be computed from colorimetric values.

Print contrast It is shown that print contrast is a print attribute separate from tone value increase. Once again, the Viggiano (1991) transform provides a means for computing print contrast from colorimetric values.

Trap I have referenced a paper from Stanton (2001) that shows a strong correlation between colorimetric change and Preucil trap values.

Gray balance It has been shown that three different densitometric conversions to a color space are similar to a*b*, but that the accuracy is at best marginally useful for control purposes.

Tolerances Conversion between densitometric and colorimetric tolerances has been covered in four previous papers.

The overall conclusion is that it is possible to derive colorimetric versions of all the popular print attributes. With colorimetric measurements and the proper software, it is possible to have all the functionality we currently have with density. Since density cannot be used to verify appearance, I can foresee a pressroom where density is no longer used.

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Appendix A – Formula used

With Viggiano’s formula (1991), the XYZ values are transformed into a set of RGB values according to the following.

$$\begin{bmatrix} R \\ G \\ B \end{bmatrix} = \begin{bmatrix} 1.4391 & -0.2202 & -0.2027 \\ -0.7310 & 1.6386 & 0.0801 \\ -0.0064 & 0.0171 & 1.1995 \end{bmatrix} \begin{bmatrix} X \\ Y \\ Z \end{bmatrix} \qquad (1)$$

The RGB values are then treated just as reflectances, for example, to compute densities.

Birkett (2005b) defines colorimetric tone value according to

$$L_x = 116 f(x) - 16 \tag{2}$$

$$L_y = 116 f(y) - 16 \tag{3}$$

$$L_z = 116 f(z) - 16 \tag{4}$$

$$CTV = \sqrt{\frac{(L_{xp} - L_x)^2 + (L_{yp} - L_y)^2 + (L_{zp} - L_z)^2}{3}} \tag{5}$$

Where *f* is defined as in CIE 15.2,

$$f(q) = \begin{cases} \sqrt[3]{q}, & q > 0.008856 \\ \dfrac{903.3q + 16}{116}, & q \leq 0.008856 \end{cases} \tag{6}$$

I define the paper relative colorimetric tone values as follows

$$L_{rel,x} = 116 f\left(\frac{x}{x_p}\right) - 16 \tag{7}$$

$$L_{rel,y} = 116 f\left(\frac{y}{y_p}\right) - 16 \tag{8}$$

$$L_{rel,z} = 116 f\left(\frac{z}{z_p}\right) - 16 \tag{9}$$

$$CTV_{rel} = \sqrt{\frac{(L_{rel,xp} - L_{rel,x})^2 + (L_{rel,yp} - L_{rel,y})^2 + (L_{rel,zp} - L_{rel,z})^2}{3}} \tag{10}$$

Since $L_{rel,qp} = 100$ (they are the L values for paper, normalized against paper),

$$CTV_{rel} = \sqrt{\frac{(1 - L_{rel,x})^2 + (1 - L_{rel,y})^2 + (1 - L_{rel,z})^2}{3}} \tag{11}$$

Beer's law is a law of photometry that has been used to approximate the effect of increasing the thickness of ink on paper. The law states that the paper-relative density of ink on paper is proportional to the ink film thickness.

Specifically, given the spectrum of a solid patch at nominal ink film thickness, $S_1(\lambda)$, and the spectrum of paper, $P(\lambda)$, the following is the estimate of the spectrum $S_k(\lambda)$ of a solid patch with an ink film thickness *k* times that of the nominal density patch:

$$S_k(\lambda) = \left(\frac{S_1(\lambda)}{P(\lambda)} \right)^k P(\lambda)$$

Dividing the reflectance of the ink on paper by the reflectance of the paper gives an approximation of the transmittance of the ink. Raising this quantity to the power *k* approximates the effect of a change in ink film. Finally, multiplying by the paper reflectance converts back to absolute reflectance.