

## How Many $\Delta$ Es Are There in a $\Delta$ D?

John Seymour

### Keywords

CIE, Colorimetry, Density, Densitometry, Standards, Process

### Abstract

Process control in the pressroom is currently set up around the idea of meeting specific tolerances in terms of density, not in terms of colorimetry. ISO 12647-2 is changing this direction. This standard specifies the range of acceptable color of the four process solids in terms of  $\Delta E$ , rather than in the traditional  $\Delta D$  (delta density). As CIELAB makes its way into the pressroom, the question of conversion of tolerances is becoming an issue. The standard does allow for densitometric process control during the press run, but it does not specify equivalent tolerances for density.

This paper analyzes data from three press tests on web offset and sheetfed presses, with two different ink formulations, and with a total of thirty printing stocks to show that *within a press run*, running to a density tolerance will assure a colorimetric tolerance. The results agree quite well with theoretical calculations.

A further analysis of hardcopy proofs from twenty-one proofing system vendors demonstrates that single channel density measurements *cannot* be used to assure a colorimetric match between a proof and a press sheet.

## What Do the Standards Have to Say?

### Color Tolerancing

ISO 12647-2 (2004) is a standard that defines a set of requirements for process control of web offset printing. These requirements are set up to assure that a print run produces (among other things) the intended colors. One section of the standard gives targets and tolerances for control patches in terms of colorimetric units. It also allows for densitometric tolerances, but only under specific conditions.

To understand where densitometry is appropriate and where it is not, we need first to look closely at the places in the process where color matching is used. ISO 12647-2 has identified three separate places where color tolerances are important. First, the control patches on the proof must be close to the color values specified in 12647-2. Second, the control patches on the OK sheet must look like the control patches on the proof. Third, the control patches throughout the press run must look like those on the OK sheet.

The relevant colorimetric specifications are found in ISO 12647-2, Section 4.3.2.4, along with Tables 2 and 3. I have created the table below to summarize the six specifications from this section.

*Table 1 – ISO 12647-2 requirements for the color of solid, single color patches*

Req #	Patches	Sheet	Aux. verb <sup>1</sup>	Aim val	Tolerance
1.1	Process color solids	Proof	Shall	Spec'ed values	5 ΔE
1.2	2 & 3 color overprints	Proof	Should	Spec'ed values	unspecified
1.3	Primary color solids <sup>2</sup>	Digital proof <sup>3</sup>	Should	Spec'ed values	2.5 ΔE
2	Process color solids	OK print	Shall	Proof	5 ΔE
3.1	Process color solids	Production sheet	68% shall	OK print	4 ΔE (CMK), 5 ΔE (Y)
3.2	Process color solids	Production sheet	68% should	OK print	2 ΔE (CMK), 2.5 ΔE (Y)

<sup>1</sup>In standards language, the auxiliary verbs “should” and “shall” have specific definitions. The word “shall” connotes an absolute requirement. Compliance to the standard is contingent upon meeting a specification with the word “shall” in it. The word “should” is used when it is desirable to meet a tighter specification, but it is realized that such adherence may not always be possible.

<sup>2</sup>Since Table 2 refers to CMYK and CMYK only, I assume that “primary color solids” refers to solid control patches of cyan, magenta, yellow and black. I further assume that “process color solids” means the same.

<sup>3</sup> A *digital* proof is called out specifically because a closer tolerance is possible for digital proofs than for traditional analog proofs.

## Color Tolerancing Through Densitometry

To what extent is density part of the standard? Quoting from ISO 12647-2 (section 4.3.2.4, Note 4):

*Density values can be very valuable for process control during a print run, where the instrument, the ink and the print substrate remain the same; see ISO 13656. However, in a general situation, density values do not define a colour to the required degree...*

This paper provides data to support these two statements. The paragraph continues:

*...Therefore, for the purpose of this section of 12647, reflection density values are only recommended for the determination of tone values.*

This sentence seems to be an odd conclusion. Density values are very valuable during the print run, but are not recommended? The rest of the paragraph reads:

*Following ISO 13656, the production press operator first achieves the correct colour of the solids on the press, then reads the densities with the instrument from the OK print. The densities are then used as aim values for process control during the production run.*

This final sentence reads like a recommendation to use density during the press run. We can turn to ISO 13656 for clarification of this paragraph. Section 5.1, excerpt from paragraph 2:

*Many of the parameters specified in clause 5, particularly those based on densitometry, are useful for process control but tell the user little about the appearance of the print. Many of these are appropriate measures for controlling a production run, others for defining the difference between proofs and prints and yet others for defining variation within a print...*

This paragraph, in effect, defines three distinct uses of general reflectance measurement devices. Controlling the print run and measuring the variation in a sheet are both encompassed in requirements 3.1 and 3.2 from Table 1. Measuring the color difference between proof and prints is covered under

requirement 2 of Table 1. There is a hint that densitometric measurements are appropriate for at least some of these, but this paragraph does not specify which. Section 5.1, excerpt from paragraph 3:

*Where colour appearance and matching are paramount requirements, densitometry should not be used unless it is known that the pigments being matched are very similar. Colorimetry is necessary in the general situation.*

In other words, density may be appropriate if the pigments are similar. I would add that the printing substrate must also be very similar. Certainly the pigments and substrate are similar when we compare patches within a single printed sheet, or when we compare amongst patches from throughout a print run. Based on this, it would appear that density may be appropriate to meet requirements 3.1 and 3.2.

If the proof was produced on the same stock and the same pigments as the print, then density measurements may also be appropriate to meet requirement 2. This is, however, seldom the case.

- Sections 5.2 through 5.7 clarify where colorimetry and densitometry are appropriate.
- Section 5.2 states that colorimetry is appropriate for the comparison of proof sheet to press sheet.
- Section 5.4, 5.5, and 5.6 states that the standard print attributes of tone value, apparent trap, and doubling and slur are all derived from densitometric measurements.
- According to 5.7, densitometry is to be used when measuring variation within one press sheet.
- Finally, section 5.8 talks about monitoring the inking during the run. Colorimetry is “preferred” and densitometry is “additional”.

Another interpretation of ISO 12647-2 is available in the “G7” document (IDEAlliance, 2006) This is not a standard, it is merely a guideline. It is, however, based on 12647. The following is a quote from Appendix A, Production Press Control:

*Begin by running the press to specified ink colorimetric values (see Appendix H) or SIDs. Remember that CIELAB values take priority over density values. Once make-ready is complete, RELATIVE densitometry (based on reading a good sheet with your densitometer) remains a valid and efficient basis for run-time press control, and the*

*same density goals can be used to make-ready future runs – at least for that specific paper/ink/densitometer combination.*

Aside from the one confusing statement, there seems to be an agreement that holding density during a print run is an acceptable means for holding CIELAB values. I am not aware of a comprehensive study to back up this conclusion, and the standards lack a conversion factor between changes in density to changes in colorimetry.

This paper provides that information: How many  $\Delta E$ s are there in a  $\Delta D$ ?

## **General conversion problem**

### **Ab Initio Look at the Relationship**

“Ab initio” in this context means “from first principles”. Ab initio results are based on theoretical concerns, but are only as good as the initial assumptions. In contrast, empirical results are based on measurements from an experiment, so they are subject to flaws in experimental procedure and measurement error.

In this paper, I take both approaches. Agreement between the two will strengthen the case that this reflects reality.

### **Beer’s Law**

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. Refer to the Appendix for the “proper” name of this law.

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:

$$S_k(\lambda) = \left( \frac{S_1(\lambda)}{P(\lambda)} \right)^k P(\lambda) \quad (1)$$

Dividing the reflectance of the ink on paper by the reflectance of the paper gives an approximation of the transmittance of the ink. (Technically, this is an approximation to the transmittance of two layers of the ink, since according to the model, light passes through the ink to the paper and then back through 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.

In order to determine the relationship between changes in colorimetric values and densitometric values, I start with a measured spectrum of each of the process inks. Beer's law will then be used to predict the spectra of the inks at various ink film thicknesses. For each predicted spectra, I compute both the CIELAB and the density values. This allows a computation of the rate of change in colorimetric values versus the change in density values.

## **Limitations**

The use of Beer's law for printing ink ignores the effect of surface reflectance and of the translucency of the ink. The model actually does a rather poor job of estimating density, since the amount of surface reflected light and light reflected from within the ink film are a significant portion of the light collected from a solid ink patch.

At least six empirical mathematical models have been proposed to provide a better approximation to this relationship (Blom 1990, Chou 1991, MacPhee 2002). In addition, the Kubelka-Munk equation (Kang 1997, Gustavson 1997), which is derived from physical properties, has proven to be fairly accurate.

While it is acknowledged that there are many models that are more accurate at predicting the spectrum of an ink with respect to ink film thickness, it is my hope that the simpler Beer's law will be suitable for this discussion. After all, I am not looking for a relationship between ink film thickness and spectrum per se, but rather I am looking to generate plausible spectra with arbitrary thickness.

## **Beer's Law Results**

Spectra for paper and for each of the four solid process colors were pulled from the TR 001 data set. Beer's law was used to predict the spectra of the inks for ink film thickness ranging from 10% smaller than nominal to 10% larger. Density and CIELAB values were computed from the resulting spectra. Plots of the relationships between density and CIELAB values are shown in Appendix B.

NOTE: I have used Status T density throughout this paper. Colorimetric values were computed using D50 lighting and the tristimulus functions for the 2° observer. I have no reason to expect that any of the results would be appreciably different using different measurement standards, other than stating that Status E densities of yellow patches are consistently higher than Status T, so 1.0 ΔE of color difference between yellow patches will probably be a somewhat larger ΔD for Status E than reported here.

Regression was employed between the density and each of the three colorimetric values. The slope of this regression line is the rate of change in L\*, a\*, or b\* with respect to density. The square root of the sum of the squares of these three numbers is the rate of change of ΔE with respect to density. That is to say, a change of 1.0 in density will theoretically give a ΔE of this amount. The reciprocal of this number is the density change that corresponds to 1.0 ΔE. If this final number is multiplied by the appropriate colorimetric tolerance (4 ΔE for cyan, magenta, and black, and 5 ΔE for yellow), one arrives at a tolerance for density (see Table 2).

*Table 2 – Results from Beer’s law computation*

Ink	Slope L*	Slope a*	Slope b*	ΔE/ΔD	ΔD/ΔE	Density tolerance
Cyan	-17.5	-6.7	-19.7	27.2	0.037	±0.15D
Magenta	-15.7	19.6	15.9	29.8	0.034	±0.13D
Yellow	-4.6	4.9	62.9	63.2	0.016	±0.08D
Black	-27.0	0.1	-0.9	27.0	0.037	±0.15D

The density tolerances in the chart above are not that far from the solid ink density tolerances suggested in GRACoL 5.0, which states that one may see a variation in solid ink density of ±0.10D.

Lesson one is that there is a theoretical relationship between colorimetric and densitometric measurements of solid patches. Based on this theoretical relationship, the colorimetric tolerance in ISO 12647-2 can be converted to a reasonable density tolerance.

## Empirical Results

### Coated Stocks

#### Sheetfed on Eleven Stocks

To verify the theoretical answer, data was taken from a test run performed in 1999 on a sheetfed press. Solid patches of each of the four process colors were printed at ten different ink film thicknesses. Fifteen different paper stocks were used: eleven coated and four uncoated. The collection of stocks was chosen to cover a range of brightness, fluorescent component, and gloss. Table 3 shows the eleven coated stocks included in the test.

*Table 3 – Coated stocks in the sheetfed experiment*

	Paper name	Grade	Gloss	Fluor. <sup>4</sup>	L*	a*	b*
1	Champion proofing paper white	3	68.8	-0.029	88.87	0.21	4.07
2	Consolidated centura dull cover white (grade 1)	2	42.5	0.116	94.86	-0.70	-1.38
3	Consolidated centura dull text white (grade 1)	2	42.1	0.118	92.73	-0.44	-1.93
4	Consolidated fortune gloss cover white	1	83.8	0.156	94.45	-0.10	2.72
5	Consolidated reflections gloss text white (grade 1)	2	35.5	0.146	95.05	-0.85	-2.64
6	DalEl preeminence dull cover white	1	55.2	-0.001	94.67	-1.20	-1.50
7	DalEl preeminence gloss cover white	1	79.0	0.160	94.06	-0.84	-1.07
8	Fraser halopaque offset cream white	2	45.5	0.060	91.44	0.28	6.42
9	Mohawk 50/10 text fluorescent	1	70.0	0.008	95.75	-0.55	-2.16
10	Sappi opus gloss text white	1	66.3	0.061	92.27	-0.62	-2.20
11	Sappi somerset gloss text white	2	32.9	0.136	92.27	-0.62	-2.20



<sup>4</sup>The fluorescence reported in this column was determined by comparing reflectance with and without a UV filter on the light source. The higher the number, the more the paper fluoresces.

Figure 1 is an example of how the transform between densitometric and colorimetric values depends upon the substrate. This concept is developed further in Appendix C. I have shown only the plots of cyan. Graphs for the three inks are not shown because the cyan graph is illustrative.

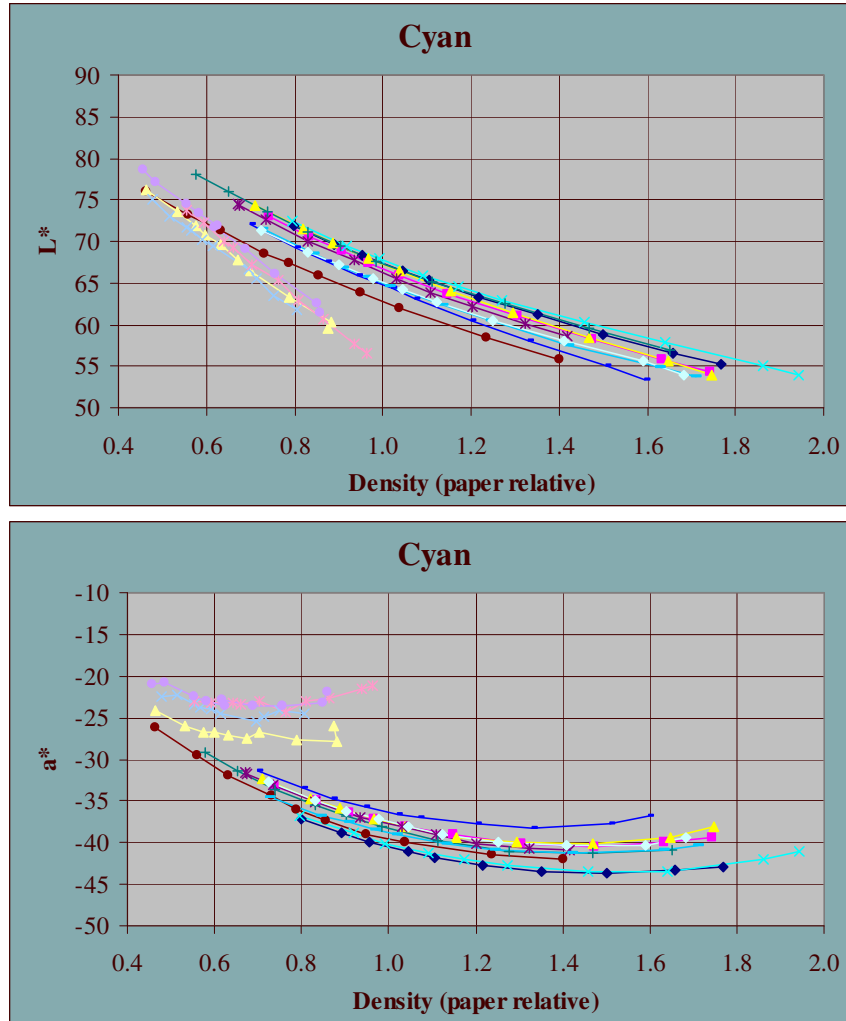
The four uncoated stocks are included in Figure 1 to illustrate that the transform from density to CIELAB values depends upon whether the paper is coated or uncoated. Four lines are distinct from the rest. The lines all have a sharper downward slope, and their maximum densities are all below 1.0. These four lines are from the four uncoated stocks. Lesson two is that uncoated stocks are significantly different from coated stocks.

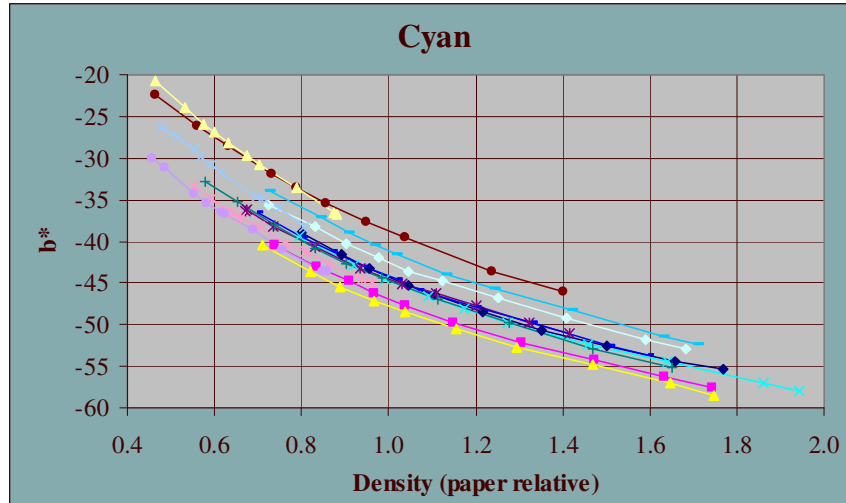
For any particular coated stock, the correspondence between density and L\* value is quite well behaved. The data points relating density and colorimetric values are all smooth curves.

As we go from one stock to the next, however, there is at least a five point spread in L\* values for any particular density.

Lesson three is that direct conversion from density to colorimetry is possible for any particular stock, but that the conversion depends on the stock that is printed on.

Figure 1 –  $L^*$ ,  $a^*$ , and  $b^*$  value of cyan ink versus density on fifteen stocks





### Computing Conversions

Since the Beer's law experiment was done with spectra from coated stock, I look first at data strictly from the 11 coated stocks.

For each of the four process inks on each of the 11 coated stocks, I computed the density and the  $L^*a^*b^*$  values of each of the ten patches. Regression was used to fit a parabola to this data (e.g. the  $a^*$  values versus density of magenta ink, as measured on paper 7). I computed the derivative of these parabolas at the same density as had been used in the Beer's law experiment. For each combination of colorimetric value and paper, I thus had eleven slopes. I computed the average and the standard deviation of these eleven slopes, recorded as  $\bar{x} \pm \sigma$  in Table 4. The results from the Beer's law calculations are shown in this table for comparison.

Table 4 – Experimental results from 11 coated stocks

Source	Ink	Slope L* ( $\bar{x} \pm \sigma$ )	Slope a* ( $\bar{x} \pm \sigma$ )	Slope b* ( $\bar{x} \pm \sigma$ )	$\Delta E/\Delta D$	$\Delta D/\Delta E$	Dens. tol.
11 stocks	C	-17.5 ± 1.0	-4.4 ± 1.7	-16.4 ± 0.9	24.3	0.041	±0.16D
	M	-15.2 ± 0.7	17.1 ± 1.6	20.8 ± 1.5	30.9	0.032	±0.13D
	Y	-3.6 ± 0.6	7.0 ± 0.4	60.7 ± 1.4	61.2	0.016	±0.08D
	K	-26.4 ± 0.7	0.5 ± 0.5	-4.8 ± 1.5	26.9	0.037	±0.15D
Beer's law	C	-17.5	-6.7	-19.7	27.2	0.037	±0.15D
	M	-15.7	19.6	15.9	29.8	0.034	±0.13D
	Y	-4.6	4.9	62.9	63.2	0.016	±0.08D
	K	-27.0	0.1	-0.9	27.0	0.037	±0.15D

The standard deviations of the slopes are fairly small compared to the magnitude of the slopes, being all less than 2.0 out of a range of up to 60. In other words, while the relationship between density and L\*a\*b\* values depends upon the paper, the relationship between the *changes* in the two is fairly independent of paper, at least within the class of coated stocks.

Lesson four is that the conversion between densitometric and colorimetric tolerances for coated stocks is pretty much the same for all stocks.

It is seen that the density tolerances derived from the empirical test and from the previous ab initio test are nearly identical. Lesson five is that, for coated stocks, Beer's law is adequate to predict the conversion between  $\Delta E$  and  $\Delta D$ .

### Web Offset Results

A web offset test was recently run on 16 different stocks, all of which were coated. Table 5 is a list of the 16 stocks in this test. The stocks are almost all different from the stocks of the sheetfed test. The press and press crews were different. The inks used were from a different manufacturer.

*Table 5 – Coated stocks in the web offset experiment*

Paper	Grade	Weight	L*	a*	b*
Admiral Gloss	2	60	91.86	0.09	-3.48
Influence	3	60	92.03	-0.11	-2.68
Orion	3	60	91.42	-0.07	-2.49
Somerset	3	60	92.03	0.19	-2.81
Vision Plus	3	60	91.90	-0.04	-2.28
BowBrite 76	4	45	87.84	-0.69	-1.41
DeltaBrite	4	60	91.11	-0.44	-2.21
Escanaba Enamel Plus Gloss	4	45	90.25	-0.35	-1.33
Mission Web Gloss	4	45	91.37	-1.00	-0.18
New Liberty	4	45	89.82	-0.32	-2.48
Polaris Press	4	45	89.65	-0.47	-1.13
Advocate Offset	5	32	85.47	-0.40	0.77
Consolidated	5	32	85.00	-0.46	0.82
ElectraCote	5	32	85.74	-0.61	0.91
Krukote	5	32	85.81	-0.72	1.40
UPM Cote	5	32	84.77	-0.77	0.07

There are a number of caveats about this data set. While this is the only web offset data that I have with multiple stocks, the press conditions were not quite as tightly controlled as one would like. (The test was run for other purposes.)

A second significant limitation is that each sheet was run at only a single ink key setting I had to rely on natural variation across the sheet to get a sampling of densities. Fortunately, the sheet had solid patches of each of the inks printed in five places scattered around the sheet. Still, the relatively small amount of variation means the calculations are more susceptible to the normal measurement noise.

Another source of variation is that the five patches selected for measurement did not all have the same image printed on the obverse side. Although the measurements were all made with black backing, there is a potential for a small amount of variation to be introduced for the 32 pound stocks.

It is expected, then, that there will be significantly more variation in the results than with the sheetfed experiment, and this was indeed the case. Averaging over 16 stocks has helped, though, and the overall results are very similar to the results of the two previous experiments (see Table 6).

Table 6 – Experimental results from 16 web offset coated stocks

Source	Ink	Slope L* ( $\bar{x} \pm \sigma$ )	Slope a* ( $\bar{x} \pm \sigma$ )	Slope b* ( $\bar{x} \pm \sigma$ )	$\Delta E/\Delta$ D	$\Delta D/\Delta E$	Dens. tol.
16 stocks	C	-18.4 ± 3.4	-2.9 ± 5.1	-15.4 ± 4.8	25.2	0.040	±0.16D
(web offset)	M	-11.1 ± 3.9	13.7 ± 6.4	21.3 ± 8.4	29.3	0.035	±0.14D
	Y	2.7 ± 2.7	-2.3 ± 1.8	72.0 ± 4.9	72.2	0.014	±0.07D
	K	-28.5 ± 0.5	-0.6 ± 0.4	-3.0 ± 1.0	28.7	0.036	±0.14D
Single stock	C	-17.5	-5.0	-18.3	25.8	0.039	±0.15D
(web offset)	M	-11.7	17.2	20.1	28.9	0.035	±0.14D
	Y	0.8	2.6	73.1	73.2	0.014	±0.07D
	K	-25.3	-1.2	-5.1	25.8	0.039	±0.15D
11 stocks	C	-17.5 ± 1.0	-4.4 ± 1.7	-16.4 ± 0.9	24.3	0.041	±0.16D
(sheetfed)	M	-15.2 ± 0.7	17.1 ± 1.6	20.8 ± 1.5	30.9	0.032	±0.13D
	Y	-3.6 ± 0.6	7.0 ± 0.4	60.7 ± 1.4	61.2	0.016	±0.08D
	K	-26.4 ± 0.7	0.5 ± 0.5	-4.8 ± 1.5	26.9	0.037	±0.15D
Beer's law	C	-17.5	-6.7	-19.7	27.2	0.037	±0.15D
	M	-15.7	19.6	15.9	29.8	0.034	±0.13D
	Y	-4.6	4.9	62.9	63.2	0.016	±0.08D
	K	-27.0	0.1	-0.9	27.0	0.037	±0.15D

As stated before, the data that went into the test of 16 web offset stocks did not span a large difference in density. To rectify this, I look at one further set of web

offset data. This data set was collected from only a single stock, but patches were measured at nominal density, at roughly 0.10D high, and at roughly 0.10D low. Unfortunately, the name of the paper stock has been lost, but the L\*a\*b\* values of the stock are {89.79, -0.06, 4.14}. Table 6 also incorporates the results from this web offset test.

The numbers track fairly well with each other. While there are individual differences that are statistically significant, the end result is four sets of densitometric tolerances that differ by no more than 0.01D.

Lesson six is that the conversion between  $\Delta E$  and  $\Delta D$  does not depend greatly on whether the press is web offset or sheetfed, or on the manufacturer of the process inks.

## Uncoated Stocks

### Results

The theoretical and the empirical experiments were run on the data from the four uncoated stocks listed in Table 7, with the results from the experiment in Table 8.

*Table 7 – Uncoated stocks in the sheetfed experiment*

	Paper name	Grade	Gloss	Fluor.	L*	a*	b*
12	Sappi strobe dull cover white	4	5.3	0.032	95.75	-0.55	-2.16
13	Unisource pressmaster offset white	4	8.1	0.022	90.03	-0.19	-0.61
14	Unisource star bright opaque white fluorescent	5	8.4	0.254	91.86	-1.34	-5.37
15	Weyerhaeuser cougar opaque white fluorescent (uncoated freesheet)	5	7.6	0.242	92.97	-1.32	-5.94

Table 8 – Theoretical results from four uncoated stocks

Source	Ink	Slope L* ( $\bar{x} \pm \sigma$ )	Slope a* ( $\bar{x} \pm \sigma$ )	Slope b* ( $\bar{x} \pm \sigma$ )	$\Delta E/\Delta D$	$\Delta D/\Delta E$	Dens. tol.
4 stocks	C	-39.3 ± 3.3	9.6 ± 2.9	-25.8 ± 3.7	47.9	0.021	±0.08D
	M	-27.1 ± 3.3	35.6 ± 2.1	14.4 ± 11.6	47.0	0.021	±0.09D
	Y	-4.6 ± 1.9	4.6 ± 4.4	72.2 ± 5.7	72.5	0.014	±0.07D
	K	-37.3 ± 1.9	1.6 ± 1.3	-2.0 ± 3.7	37.4	0.027	±0.11D
Beer's law	C	-28.2	-9.2	-24.2	38.3	0.026	±0.11D
	M	-28.4	39.4	15.6	51.0	0.020	±0.08D
	Y	-3.2	2.9	75.2	75.3	0.013	±0.07D
	K	-39.2	-0.1	3.3	39.3	0.025	±0.10D

The results between Beer's law and data from the four uncoated stocks concur well, with the exception of the L\* and a\* values of cyan. The ultimate conversion between  $\Delta E$  and  $\Delta D$  is not particularly different between Beer's law and actual computed data.

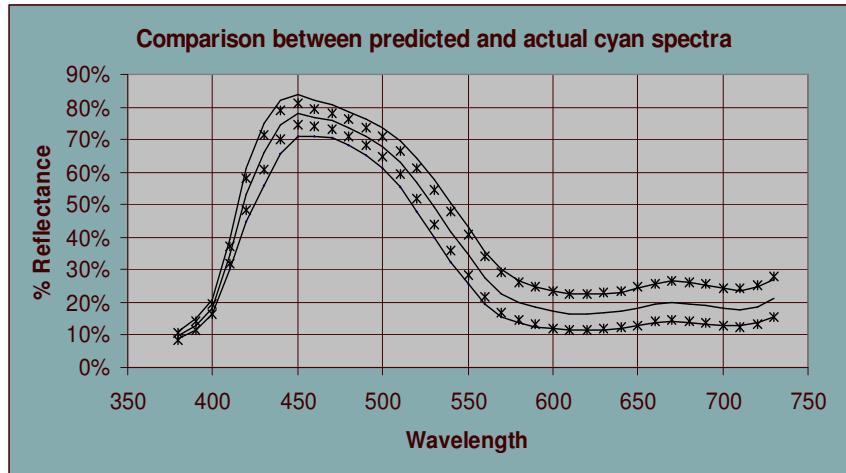
Lesson seven is that Beer's law can also be used to predict the conversion between  $\Delta E$  and  $\Delta D$  for uncoated stocks.

### Why is Cyan Different?

It is curious that those two individual values stand out against otherwise excellent agreement between empirical and theoretical results. The solid lines in Figure 2 show three measured spectra of cyan ink on an uncoated stock. The asterisks show spectra computed from the middle of the three spectra using Beer's law. The thickness parameter  $k$  was adjusted so as to match in the region of 600 to 700 nm where cyan density is measured. It is clear that the Beer's law model underestimates the change in reflectance in the region from 400 to 500 nm.



Figure 2 – The source of the discrepancy for cyan



One possible explanation might be that fluorescent whitening agents in the paper have caused the difficulty. The Beer's law computations in Table 8 and the graph in Figure 2 were based on paper 14. Paper 14 has the single highest fluorescence of all the sheetfed stocks.

To rule out this possibility, Table 9 compares empirical and theoretical results on each of the four uncoated stocks.

Table 9 – Beer’s law on stocks 12, 13, 14, and 15

Source	Ink	Slope L*	Slope a*	Slope b*	$\Delta E/\Delta D$	$\Delta D/\Delta E$	Dens. tol.
Empirical 12	C	-37.0	6.3	-29.6	47.8	0.021	$\pm 0.08D$
Beer’s 12	C	-28.0	-14.4	-30.9	44.2	0.023	$\pm 0.09D$
Empirical 13	C	-38.7	9.8	-28.2	48.9	0.020	$\pm 0.08D$
Beer’s 13	C	-29.5	-13.7	-29.	43.8	0.023	$\pm 0.09D$
Empirical 14	C	-40.2	9.1	-23.2	47.3	0.021	$\pm 0.08D$
Beer’s 14	C	-28.2	-9.2	-24.2	38.3	0.026	$\pm 0.11D$
Empirical 15	C	-41.2	13.2	-22.0	48.5	0.021	$\pm 0.08D$
Beer’s 15	C	-28.1	-10.1	-25.7	39.4	0.025	$\pm 0.10D$

Fluorescence is not the issue, since all four stocks show the same effect. The reason for the failure of Beer’s law to estimate spectra of cyan ink on uncoated stock is unknown.

Danny Rich (Sun Chemical) pointed out that inks will sink into an uncoated stock more so than into a coated stock. This may be the reason why the Beer’s law model is less accurate for uncoated stocks. The Kubelka-Munk model, which takes opacity into account, may work better. This does not explain why there was no apparent problem with the other inks. Yellow and black may have had good results just because the spectra of these inks are less interesting. Magenta is a puzzlement.

## Proof to Press Sheet Comparison

The results from the previous section demonstrate that densitometric tolerances can be an effective proxy for colorimetric tolerances when comparing the ok sheet (from the press run) to the subsequent press sheets. Are densitometric tolerances equally effective for colorimetrically comparing a press sheet to the proof? The conventional wisdom says “no”. The 2006 IPA proofing roundup

(Sharma et. Al, 2006a, 2006b, and 2006c) provides us with a data set to put this to the test.

The data set consists of spectral measurements made on proof sheets printed on twenty-one proofing systems from eleven different vendors. There are also spectral measurements from the press sheets that the vendors were requested to match.

If we *can* use density measurements to compare a proof to a press sheet, then we should see that matching the density of the press sheet and proof sheet will guarantee that the  $\Delta E$  values are very small. All we need to do is compute  $\Delta E$  values between the solid patches on the press sheets and the solid patches on the corresponding proof sheets.

There is however, a small catch. The solid patches on the two sheets do not necessarily match either colorimetrically or densitometrically. Fortunately, we have demonstrated that the Beer's law can be used to estimate the spectrum of a solid ink on a press sheet at a different ink film thickness. I used this to estimate what the spectrum of the solid on the press sheet would be, if the densities matched. From the estimated spectra, CIELAB values were determined.

### Comparison of Absolute Numbers

Table 10 shows the results. Surprisingly, the colorimetric differences between the proof and press sheet paper by itself were up to almost 3  $\Delta E$ . One would expect that this would cause some problems in trying to match the proof.

*Table 10 – Results from test of densitometric matching of proof and press sheets*

Proofing system	Paper $\Delta E$	Cyan $\Delta E$	Magenta $\Delta E$	Yellow $\Delta E$	Black $\Delta E$	Worst $\Delta E$
System 01	1.70	2.85	0.70	2.03	0.40	2.85
System 04	0.44	4.26	2.33	0.76	4.29	4.29
System 07	0.41	4.46	1.77	2.75	0.34	4.46
System 09	0.31	2.79	3.16	2.30	0.36	3.16
System 14	0.19	1.55	1.99	1.65	0.22	1.99
System 15	0.53	0.78	6.05	1.11	0.91	6.05
System 17	0.26	1.38	0.24	3.43	0.79	3.43
System 18	1.49	0.63	4.75	2.42	0.29	4.75

System 19	1.96	0.93	1.65	1.22	0.87	1.96
System 23	0.70	0.31	6.98	1.31	0.29	6.98
System 24	0.16	1.22	4.88	2.68	0.69	4.88
System 31	2.10	0.99	1.98	0.98	0.99	2.10
System 33	2.95	2.03	2.95	4.87	2.30	4.87
System 35	1.05	0.74	5.17	1.94	0.55	5.17
System 36	0.40	2.20	3.00	1.42	1.01	3.00
System 38	0.26	1.47	1.23	0.96	1.47	1.47
System 43	0.75	1.35	2.67	4.65	0.81	4.65
System 44	1.17	1.96	4.94	1.71	1.14	4.94
System 46	0.72	0.57	4.70	2.04	0.35	4.70
System 47	0.54	0.79	6.17	1.41	0.88	6.17
System 48	0.12	0.34	5.93	2.15	0.27	5.93
Average	0.87	1.65	3.53	2.12	0.94	6.98

If our goal is to establish a match between proof and press sheet to within 5  $\Delta E$ , an average measurement error of, for example, 3.5  $\Delta E$  on the magenta is unacceptable.

### Comparison of Paper Relative Measurements

In the previous section, it was pointed out that, in some cases, the proof paper and the press stock had a surprisingly large  $\Delta E$ . Would it improve the results of this experiment to correct for this difference?

In densitometry, there are proponents for the use of paper relative measurements for the purpose of quality control. The paper relative density is computed by simply subtracting the density of the paper from the density of the ink patch. This is mathematically equivalent to converting the densities of paper and patch to reflectances, dividing the patch reflectance by the paper reflectance, and then converting back to density.

It is possible to compute CIELAB measurements that are paper relative by the same technique. That does not mean subtracting the  $L^*a^*b^*$  values of paper. Paper relative CIELAB values are arrived at by dividing the XYZ values by the XYZ values of the paper. Note that the formula for computing  $L^*a^*b^*$  already

normalizes the XYZ values by dividing by  $X_n$ ,  $Y_n$  and  $Z_n$ , which “describe a specified white object color stimulus” (CIE 15.2, section 4.2.2). Paper relative CIELAB is just using the paper as the specified white object color stimulus.

Are the results better?

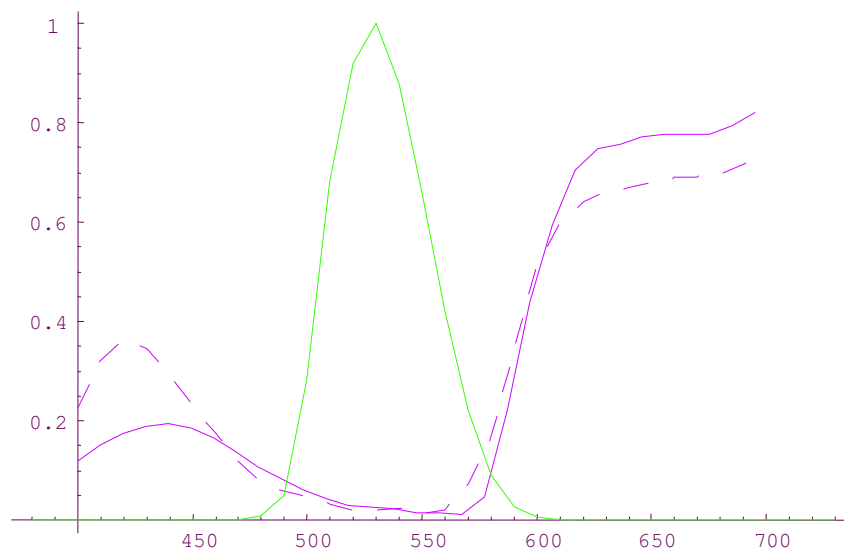
Unfortunately, no. Some numbers improve, some get worse, but on the whole, there is little difference. If a press sheet matches the paper relative density of a proof sheet, the paper relative colorimetric agreement is not any better than using absolute measurements.

Lesson eight is that density measurements are not useful for comparing proof to press sheet.

### Why Doesn't Proof to Press Sheet Comparison Work?

Figure 3 shows a comparison of the spectra of the solid magenta patch printed by proofing system 23 (dotted magenta line) as compared with the estimated spectra of the solid magenta patch on the press sheet (solid magenta line). The solid magenta for system 23 had the largest color error (see Table 10). The magenta densities of these two patches are equal. The green line shows the Status T filter used to measure Status T magenta density.

Figure 3 – Comparison of spectrum of magenta inks



As can be readily seen, the spectra of these two inks are significantly different. One would assume that the different pigments are being used. The difference in pigments is the cause of the metamerism between densitometric and colorimetric measurements (Habekost 2006).

This difference in pigments will also cause problems in matching the proof with the press sheet under different illuminants. It will not be possible to match this proof under both D50 and incandescent lighting.

## **What about Ink Contamination?**

An assumption of this whole study is that the inks should not change through the run. Under normal conditions, this will be the case, but there is one situation where the inks may change through the run. This situation is known as backtrap. Backtrap occurs when the ink from an upstream print unit contaminates a downstream print unit. In severe cases, the ink in the yellow ink fountain (which is often the last ink printed) may take on a greenish cast from backtrapped cyan ink.

The colorimetric tolerances in ISO 12647-2 will flag such a problem. Ink contamination from backtrapping will cause a change in the hue of the ink which will show up in the  $\Delta E$ . This is problematic for traditional density measurement, where only a single number is generally recorded.

Hypothetically, the off-channel data could be used to detect contamination. For example, the blue channel of a densitometer is used to measure the density of yellow ink. A significant change in the green channel indicates that yellow ink contaminated by magenta, and a significant change in the red channel indicates that yellow ink has been contaminated by cyan.

In 1957, Preucil defined the calculation of hue error and greyness in order to deal with the unwanted absorbances of the standard printing inks for color separation. These two numbers are calculated directly from density measurements (CGATS 1993). The two quantities are plotted on a circular graph (Yule 1967, page 160 – 162, and Breede 2006).

A recent TAGA paper (Breede 2006) showed that hue error and greyness are essentially equivalent to CIELAB for measuring three-color gray patches.

In another TAGA paper (Viggiano 1991) Viggiano demonstrated a technique for the conversion of colorimetric data into values that are functionally equivalent to greyness and hue error.

Manfred Breede of Ryerson has reported in a personal communication that ink trap values can be used as an indication of when conditions are such that ink contamination might occur. Trap is computed from densitometric measurements of overprint patches (red, green, and blue). A trap value which is too low suggests that the tackiness of the first down ink may be inadequate to allow transfer of the second down ink. These are precisely the conditions where the ink might be contaminated due to backtrapping.

From this, it is a reasonable hypothesis that densitometrically derived parameters, such as hue error and greyness, could be used to quantify ink contamination.

There was no discernible ink contamination in any of the data sets presented here, so I have no data to gauge the efficacy of using densitometry to gauge ink contamination. This is a topic for future research.

## Conclusions

The one general conclusion for this paper is that densitometry and colorimetry are equivalent in terms of maintaining consistent color on press. I also offer the following eight detailed conclusions

1. There is a theoretical relationship between colorimetric and densitometric measurements of solid patches. Based on this theoretical relationship, the colorimetric tolerance in ISO 12647-2 can be converted to a reasonable density tolerance.
2. Uncoated stocks are significantly different from coated stocks in terms of conversion of color measurement tolerances.
3. Direct conversion from density to colorimetry is possible for any particular stock (and ink set), but that the conversion depends on the stock that is printed on.
4. The conversion between densitometric and colorimetric *tolerances* (not actual values, but changes in values) for coated stocks is pretty much the same for all stocks.

5. For coated stocks, Beer's law is adequate to predict the conversion between  $\Delta E$  and  $\Delta D$ .
6. The conversion between  $\Delta E$  and  $\Delta D$  does not depend greatly on whether the press is web offset or sheetfed, or on the manufacturer of the process inks.
7. Beer's law can also be used to predict the conversion between  $\Delta E$  and  $\Delta D$  for uncoated stocks.
8. Density measurements are not useful for comparing proof to press sheet.

I provide the following conversions from the  $\Delta E$  tolerances in ISO 12647-2 to densitometric tolerances:

	$\Delta E$	$\Delta D$ (Coated)	$\Delta D$ (uncoated)
Cyan	4.0	$\pm 0.16$	$\pm 0.10$
Magenta	4.0	$\pm 0.14$	$\pm 0.09$
Yellow	5.0	$\pm 0.08$	$\pm 0.07$
Black	4.0	$\pm 0.15$	$\pm 0.11$

## Acknowledgements

I would like to thank the members of CGATS for their review and comments. Additional comments were provided by John MacPhee and Manfred Breede. Appendix C was inspired by a diagram from Bill Birkett. I appreciate permission from Steve Bonoff to use the IPA data.



## Appendix A – Who Made Beer’s Law?

Stigler’s law of eponymy states that “No scientific discovery is named after its original discoverer.” (Stigler 1999)

I have stated that Beer’s law says that optical density is proportional to ink film thickness. There is some confusion in the literature about the proper name for this law.

The authoritative early text on color and ink (Yule 1967) refers to the “additivity rule”, that the densities of overlaid inks ideally should be additive. The only mention of Beer, Lambert, or Bouguer is in the index, which contains the phrase “Beer’s law”, and refers the reader to the page that talks of the additivity rule.

Referring to the law of additivity as “Beer’s law” is a misnomer, however.

The first statement that transmission of light through a medium is proportional to the thickness of that medium is due to Pierre Bouguer in 1729, when he investigated the loss of light through the atmosphere (Wikipedia, Answers.com [Bouguer]). Johann Heinrich Lambert was unaware of the work of Bouguer and wrote a treatise in 1760 that made him the father of the science of photometry (*Photometria sive de mensura et gradibus luminis, colorum et umbrae*). This treatise provided a theoretical basis for the relationship between absorption and thickness of a medium (Wikipedia, SEDS, and Watson).

The contribution of August Beer did not come until 1852, when he showed that the optical density of a medium is also proportional to the pigment concentration in the medium.

According to one encyclopedia (Van Nostrand, 1968), the Bouguer law (AKA the Lambert law of absorption) states that optical density is proportional to the thickness of an absorbing substance. Bouguer published this law in 1729. The law was again published in 1760 by Lambert, and the law is often attributed to him (p. 229). The entry for “Beer’s law” extends the law to state that the optical density is also proportional to the concentration of pigment (p. 190).

Wikipedia’s entry under Beer-Lambert law states that the law that optical density is proportional to thickness and to concentration is known by “Beer’s law”, “Lambert-Beer law”, and as “Beer-Lambert-Bouguer law”. This encyclopedia agrees with the dates for Bouguer and Lambert, and adds that Beer’s contribution was in 1852.

A second reference (Menzel, 1960) defines Bouguer's law (note the spelling change) as the statement that optical density is proportional to thickness, and Beer's law is the statement that optical density is proportional to concentration and to thickness (p. 419). These two definitions agree with the Scientific Encyclopedia (Van Nostrand, 1968). However, in another section of this encyclopedia (Menzel, p. 662), this second law is referred to as the Lambert-Beer law.

According to a third reference (Lapedes, 1978), Beer's law states that optical density is proportional to pigment concentration alone (p. 86). The law that optical density is proportional to thickness is referred to as the Bouguer-Lambert-Beer law, the Beer-Lambert-Bouger law, and the Beer-Lambert law (p. 106-7). The entry for Lambert-Beer law (p. 541) directs the reader to Bouger-Lambert-Beer. The definition for the Bouger-Lambert law (also known as Lambert's law) is a differently worded statement of the same law.

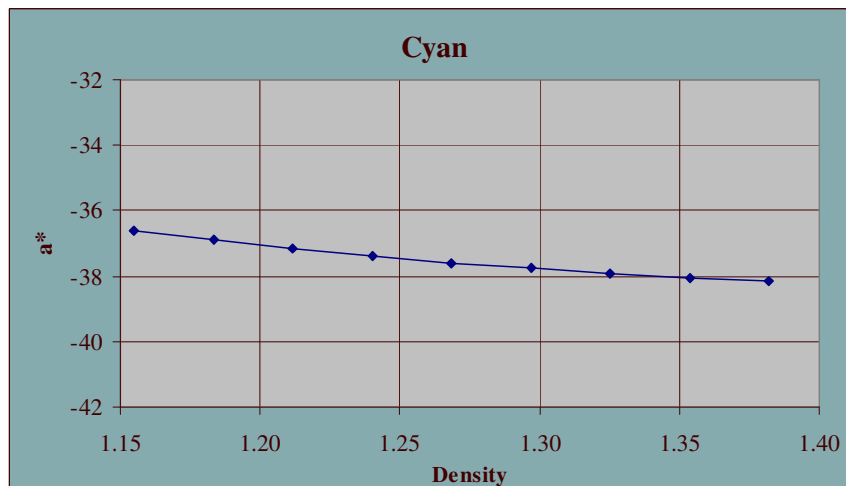
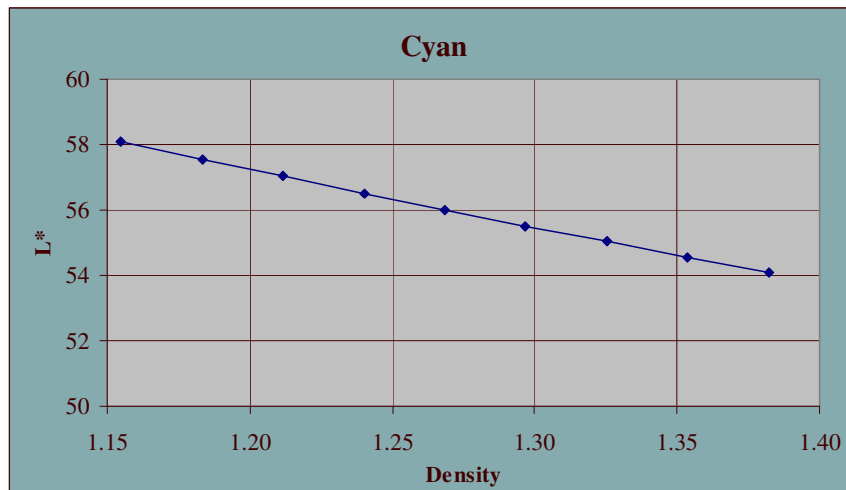
A fourth reference (Gray, 1963) says that Beer's law is the statement that optical density is proportional to concentration (page 6-2), and that Lambert's law of absorption is the statement that optical density is proportional to thickness (page 6-5). Forty pages later (page 6-45), this book gives the same definition for the Lambert-Beer-Bouger law.

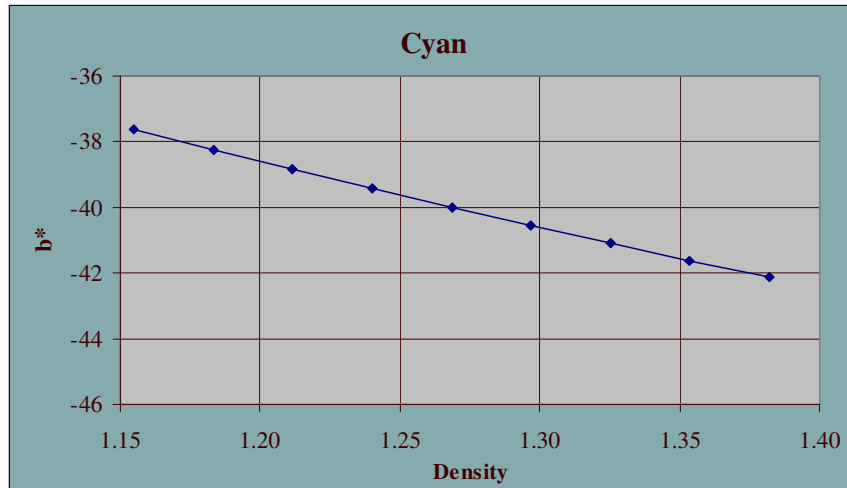
Confused?

Since there seems to be little agreement about who is responsible for which law, I have chosen to refer to the statement that optical densities of filters add as Beer's law. My decision is not based on historical evidence, but on the gedanken I introduced in a paper given at IS&T (Seymour, 1995). In this, I demonstrated the law by using a varying number of mugs filled with beer. My hope is that my further corruption of already corrupt historical fact will help remember the law!

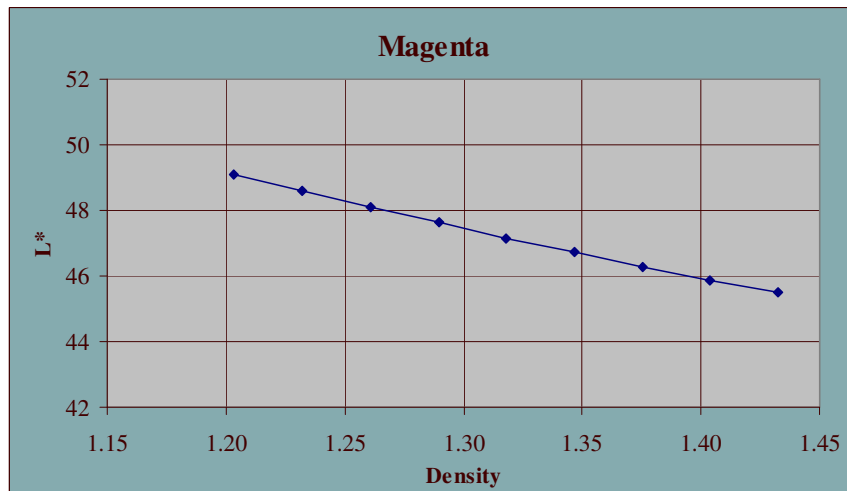
## Appendix B – Graphs from Theoretical Results

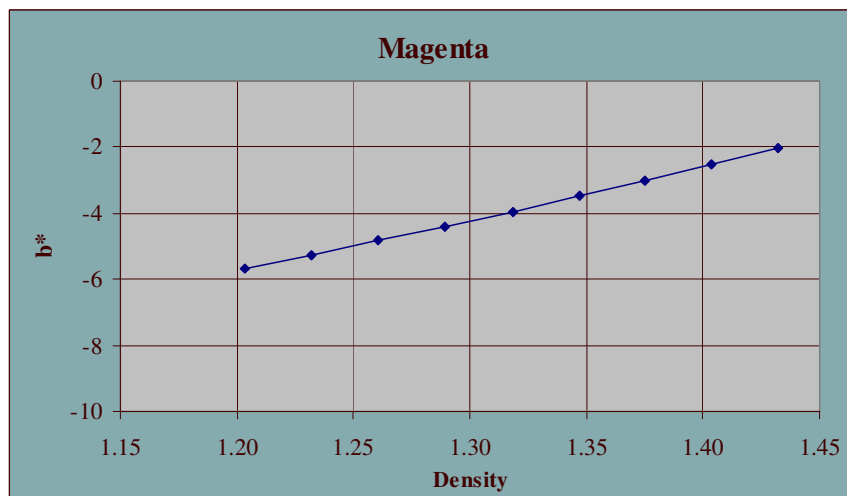
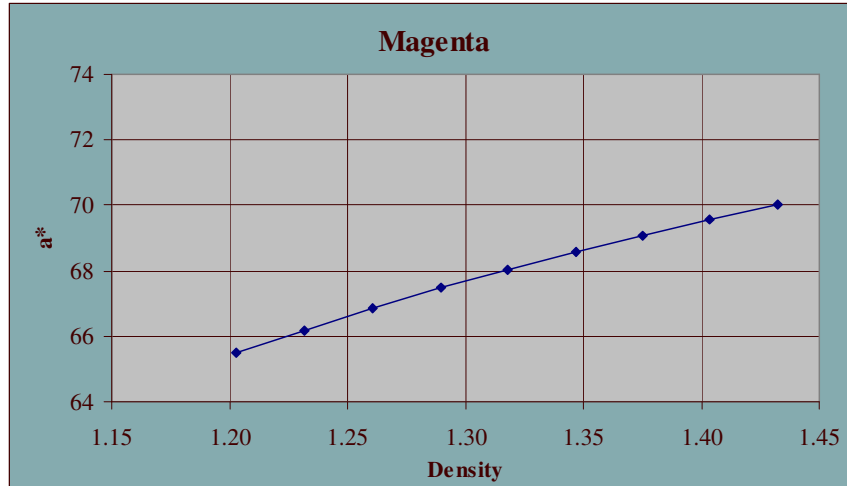
### Cyan



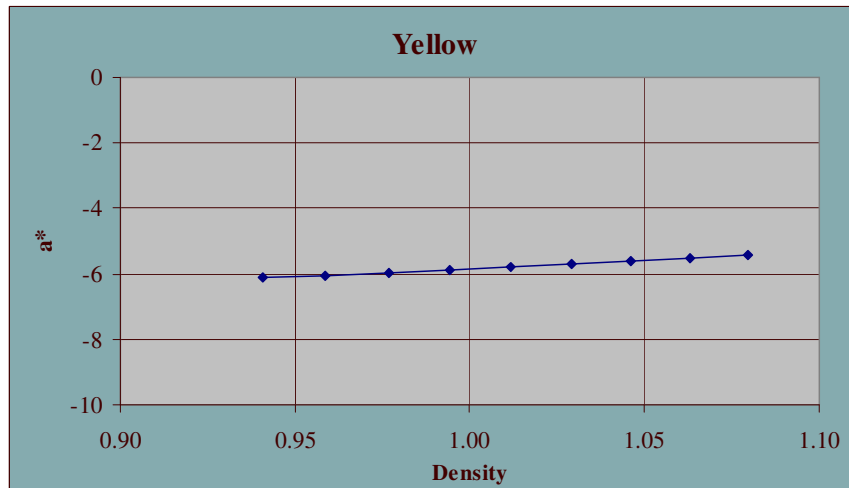
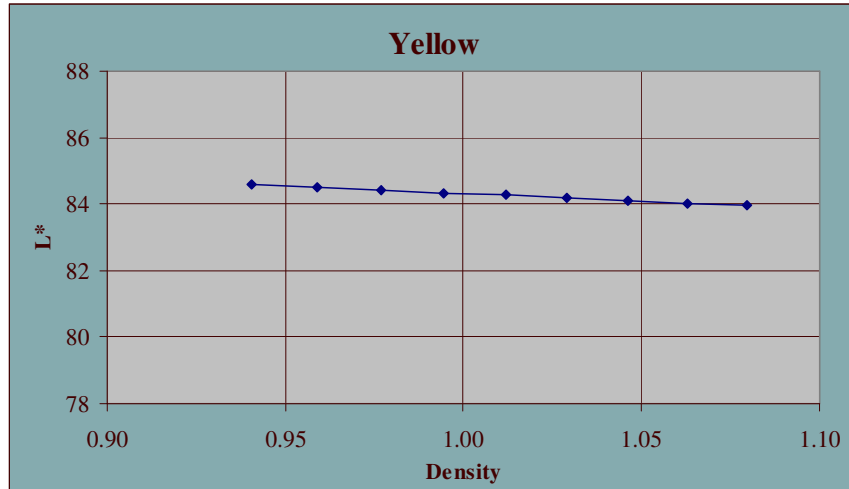


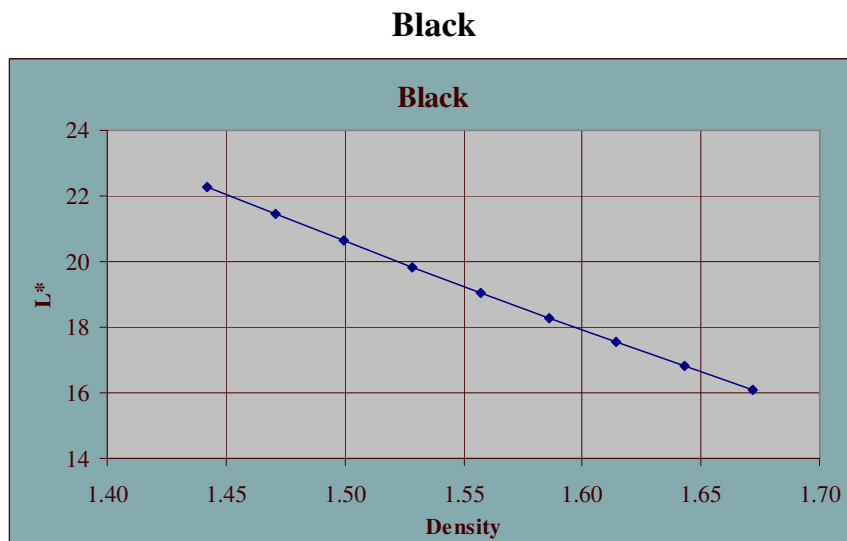
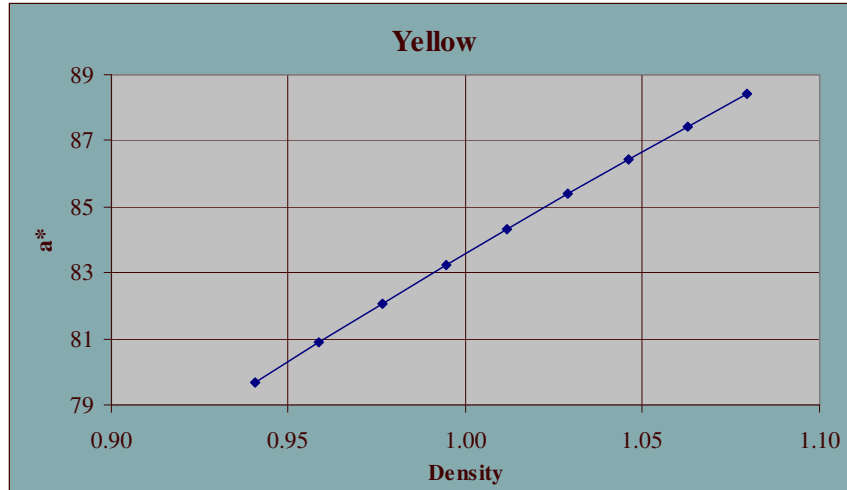
### Magenta

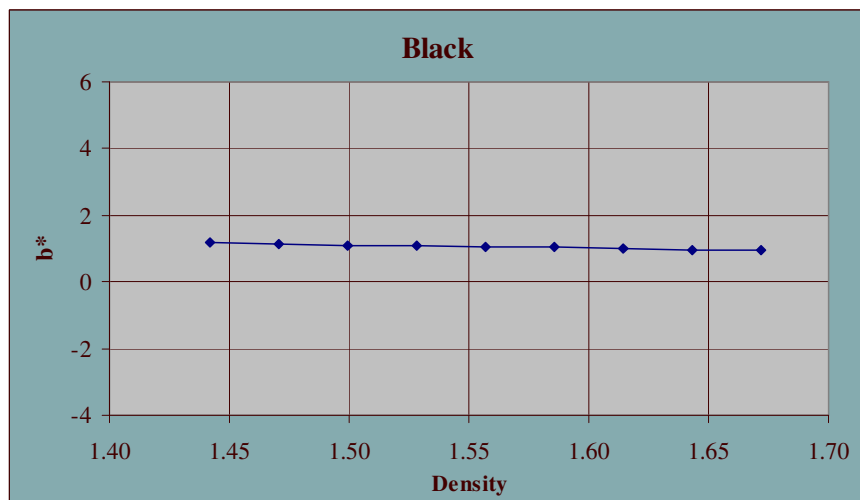
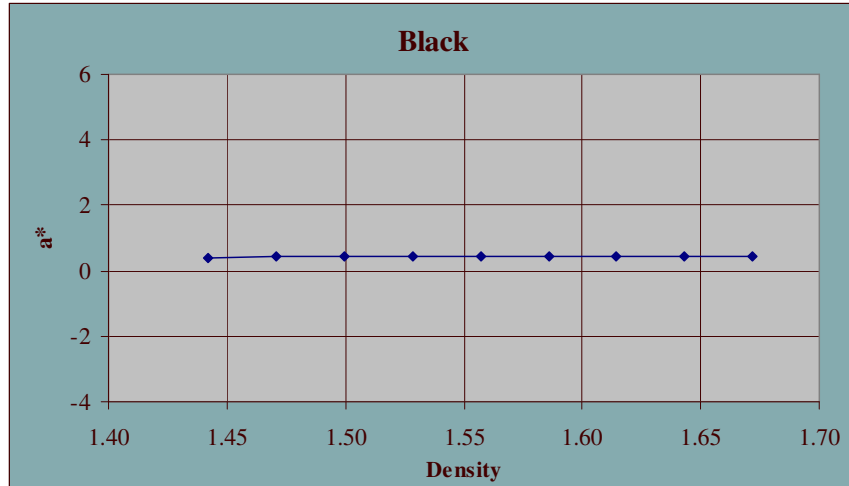




## Yellow





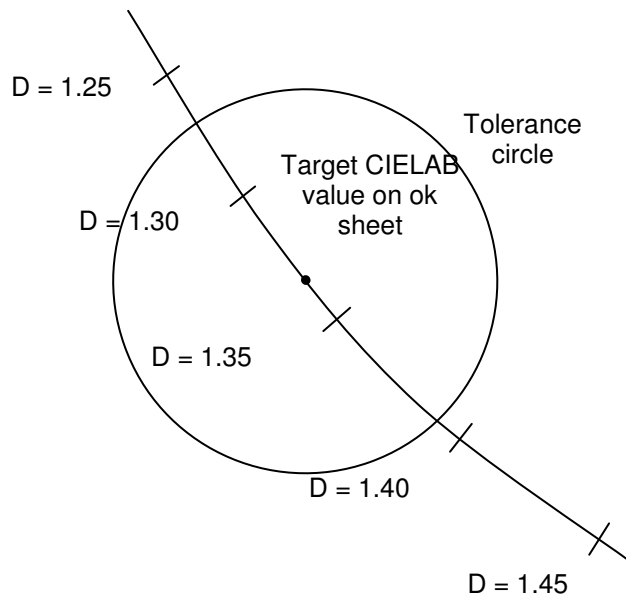




## Appendix C – General conversion problem

In this appendix, I describe diagrammatically the problems with conversion of tolerances.

Figure C.1 – CIELAB trajectory of ideal ink on press sheet



In the hypothetical diagram C.1, we are comparing the ok sheet against subsequent press sheets. We have previously established that the ok sheet has proper CIELAB values when the density is, say, 1.34. As we adjust the ink level, the CIELAB values will follow the trajectory in CIELAB space. Holding the density between 1.27 and 1.39 will ensure that the CIELAB value is within the tolerance circle.

Figure C.2 – CIELAB trajectory of realistic ink on press sheet

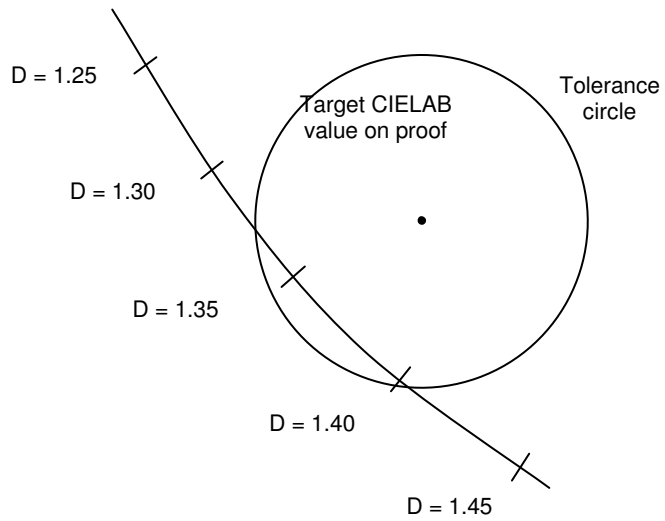
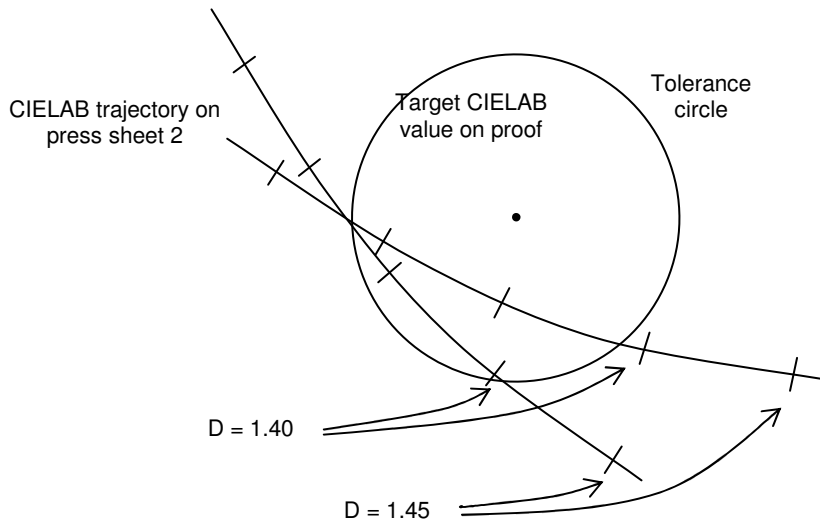


Figure C.2 demonstrates that, when matching a press sheet to the proof, it may not be possible to exactly reach the target CIELAB value. If all is well, it will be possible to get within the tolerance circle. From this drawing, it would appear that a range of density from 1.33 to 1.40 will yield CIELAB values within the tolerance.

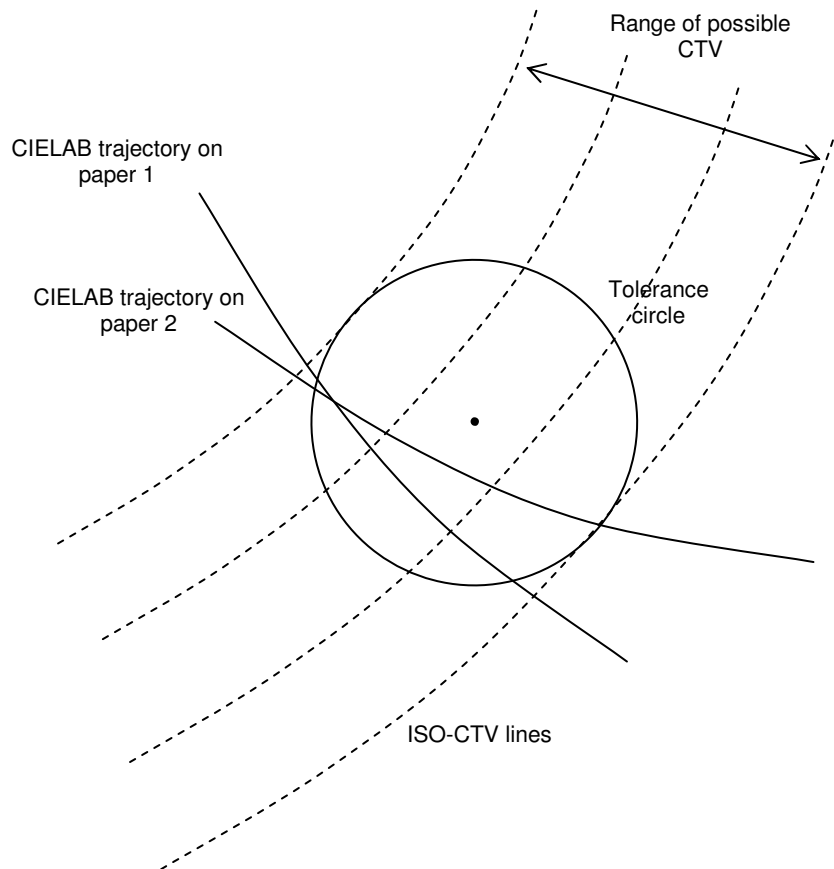
Figure C.3 – CIELAB trajectory of ink on two different stocks



In figure C.3, it is shown that ink on two different stocks may have different ranges of density that yield CIELAB values within the tolerance. The density range for this hypothetical second stock is perhaps from 1.27 to 1.39.

This is an issue! We can't define an acceptable range for density that is independent of the stock.

Figure C.4 – Comparison of CTV to density



Birkett has defined a preferable measure called the “colorimetric tone value”. The “ISO-CTV lines” in the figure C.4 are the lines that have constant CTV. The benefit of CTV is that the relationship between CTV and CIELAB values is independent of what paper you are dealing with. One benefit is that the range does not shift back and forth with stock. A second benefit is that, it is a necessary, but not sufficient, condition that the CTV be in a certain range in order to be within the tolerance circle.

## Selected Bibliography

- Blom, B. E., T. J. Conner  
“Optical density and ink film thickness; a comparison of models,” TAGA Proceedings, 1990
- Breede, Manfred H  
“Testing the Validity of Measuring Gray Balance with the GATF Color Circle, Grayness and Hue Error Values,” TAGA 2006
- CGATS.4-1993  
“Graphic arts reflection densitometry measurements – Terminology, equations, image elements and procedures,” Graphic Technology, 1993
- Chou, Shem, Norman Harbin  
“Relationship between ink mileage and ink transfer,” TAGA Proceedings, 1991
- CIE 15.2  
Colorimetry, 2<sup>nd</sup> Edition
- Gray, Dwight E., editor  
American Institute of Physics Handbook, second edition, (McGraw-Hill), 1963
- Gustavson, Stephan  
Dot Gain in Color Halftones, PhD Thesis, Linköping University, 1997
- Habekost, Martin  
“The effect of colorants in proofing systems in comparison to standard four color process inks,” TAGA Proceedings, 2006
- IDEAlliance  
“Calibrating, Proofing and Printed by the G7<sup>TM</sup> Method,” Version 6, August 2006
- ISO 12647-2:2004(E)  
“Process control for the production of half-tone colour separations, proof and production prints – Part 2: Offset lithographic processes,” Graphic technology, 2004
- ISO 13656:2000(E)  
“Application of reflection densitometry and colorimetry to process control or evaluation of prints and proofs”, Graphic technology, 2000
- Kang, Henry R  
“Color Technology for Electronic Imaging Devices,” SPIE, 1997
- Lapedes, Daniel N, editor  
“McGraw-Hill Dictionary of Mathematics and Physics,” (McGraw-Hill), 1978

- MacPhee, John, and John Lind  
“Insight into the relationship between print density and ink film thickness,”  
TAGA Proceedings, 2002
- Menzel, Donald, editor  
“Fundamental Formulas of Physics,” (Dover Publications), 1960
- Seymour, John  
“The why and the how of video-based on-line densitometry,” IS&T’s  
Fourth Technical Symposium on Prepress, Proofing and Printing, 1995
- Sharma. Abhay, Tom Collins, Ray Cheydleur, Steve Smiley  
2006a “IPA Proofing RoundUP Results,” IPA  
2006b “IPA Proofing RoundUP Webinar,” IPA
- Sharma. Abhay, Tom Collins, Ray Cheydleur, Steve Smiley, Florian Suessel  
2006c Visual and Colorimetric press to proof matching using the new  
GRACoL reference printing condition, TAGA Journal, Vol 3
- Stigler, Stephen M.  
Statistics on the Table, Harvard University Press, 1999
- Van Nostrand’s Scientific Encyclopedia  
Fourth Edition, (D. Van Nostrand Inc.), 1968
- Viggiano, J A Stephen, and Wang, C Jeffrey  
“A Suggested Method for Computing Colorimetric Densities,” 1991,  
TAGA Proceedings, p 196 - 215
- Yule, J.A.C.  
“Principles of Color Reproduction,” (John Wiley and Sons), 1967

## Links

- Beer’s law, Wikipedia entry  
[http://en.wikipedia.org/wiki/Beer%27s\\_law#History](http://en.wikipedia.org/wiki/Beer%27s_law#History)
- Bouguer, Pierre, Answers.com entry  
<http://www.answers.com/topic/pierre-bouguer>
- Students for the Exploration and Development of Space website  
<http://www.seds.org/~spider/spider/Misc/lambert.html>
- W.P. Watson Antiquarian Books website  
<http://www.polybiblio.com/watbooks/2823.html>