REFLECTION

DENSITOMETRY

TOBIAS
ASSOCIATES, INC.

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About Light

The human eye perceives only a small fraction of the electromagnetic spectrum, within this small range each part of the spectrum is seen as a different color. Most people can detect color in the range of about 400 to 700 nanometers, that is from violet to deep red. When there is no light, we see Black; when light from all of the spectrum is present in approximately equal quantities, we see White. Color filters allow only part of the spectrum to pass and we see just the color of the filter. For example, a green filter will block blue and red light letting only the green part of the spectrum pass, so when we look through it everything appears in shades of green, in essence a monochromatic image.

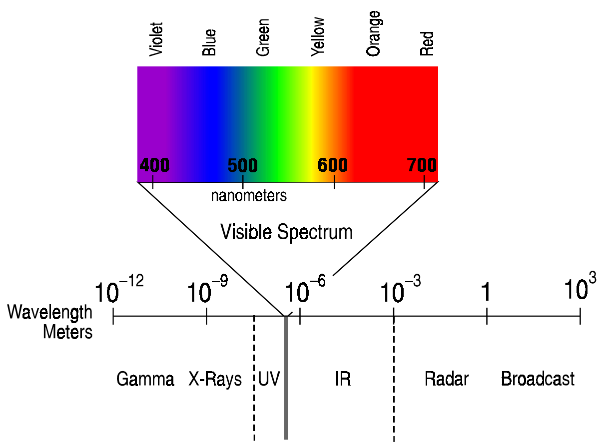

Figure 1: Electromagnetic Spectrum

How We Print

To reproduce the colors of an original image, the subtractive color process is used. Colored inks are printed sequentially on a white substrate, usually paper. These inks are, for the most part, transparent and act as color filters. Thus, white light shining on a green ink patch on white paper is seen as green since the blue and red parts of the spectrum were absorbed as the light passes through the ink. Then it is reflected by the white paper and filtered a second time as it reemerges from the ink surface. The thicker the ink film, the more light the ink absorbs and the darker the ink seems. It appears to have a greater density.

In process color printing, only three inks are used to substantially reproduce most of the colors that we see. This range of colors is called the color gamut and is dependent on the formulation of the inks and the quality of the paper or substrate. These three inks are **Cyan**, **Magenta** and **Yellow**. When cyan ink is printed on white paper, the red part of the spectrum is absorbed and the green and blue portions are reflected from the paper. To the eye, the result appears as cyan. Magenta ink absorbs green light and reflects red and blue, while yellow ink absorbs blue and reflects red and green. In theory, a combination of these three inks absorb all parts of the spectrum and appears as black. In reality, due to the characteristics of the pigments, a three-color mix appears brown. For this reason a fourth ink is used, namely pure black.

Color Separations

To reproduce a color original, an electronic color scanner separates the image into its cyan, magenta and yellow components using red, green and blue filters. A combination of these is then used to create the black component. The output of the scanner consists of a halftone screen for each of the four separations of the original with graduated dot sizes reproducing the tonal range of the original. Printing plates are then made from these screens which, in turn, print the image on paper using the four process inks. To ensure color control and to maintain a consistent printed product, the ink film thickness and the size and color strength of these halftone dots must be monitored.

Now, while the human eye is quite good at comparing the density of adjacent ink patches, it is not very good at judging them when they are separated, across a press sheet for example, and can not assign numerical values to a sample. Perception is a subjective judgment and may change with fatigue or vary from person to person. What is needed is an objective method of evaluating the ink film thickness.

Enter the **Densitometer**! This device measures the ink film thickness and provides an **Optical Density** value. As mentioned previously, as more ink is applied, the darker it looks. The densitometer measures the amount of light being reflected from the sample and, within certain limitations, gives higher density readings with increasing ink film thickness. When the ink film thickness approaches a certain point, however, there is no further increase in density.

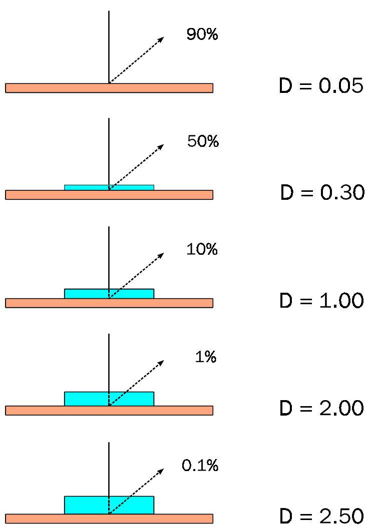

Figure 2: Ink Film Thickness vs. Density

How Does a Densitometer Work?

A reflection densitometer fundamentally measures the amount of light reflected from a surface. There are certain specific conditions to be met which have been defined by the American National Standards Institute (ANSI) and by the International Standards Organization (ISO). These specifications deal with the geometric conditions of measurement and with the spectral responses of the instruments.

A reflection densitometer consists of a light source that has a stable output, optics to focus the light into a defined light spot on the sample, filters to define the spectral response of the unit and a detector to monitor the reflected light. The sample is usually illuminated from above, i.e. at 90° to the sample surface, and viewed at 45° to the surface. This viewing condition may be reversed if required. This viewing condition eliminates gloss reflections and only the diffuse reflections are seen by the detector. It is similar to looking at a glossy photograph –– you tend to look at it at an angle to avoid shiny reflections that obscure the image. The electronics of the densitometer usually consist of a **logarithmic** amplifier and a digital display.

Why a logarithmic response? This is because the densitometer tries to provide numbers that correspond to what we see. The human eye has a logarithmic response, as, incidentally, does the human ear. We tend to see equal differences in density as equal visual effects. For example if a sample has a density of 0.80, it will appear to be about twice as dark as a sample having a density of 0.50. The density scale is logarithmic, a density of 1.00 indicates that 10% of the light has been reflected and a density of 2.00 shows a 1% reflection. In the example above, the sample that is twice as dark has a density difference of 0.30 from the lighter sample. The logarithm of 2 is 0.30.

Over a restricted range, the density readings from a densitometer are approximately proportional to the ink film thickness. So, if you run an ink to a specific density value, you can be reasonably sure that the ink film thickness and, in turn, the product appearance, will be consistent.

Density Readings of Inks

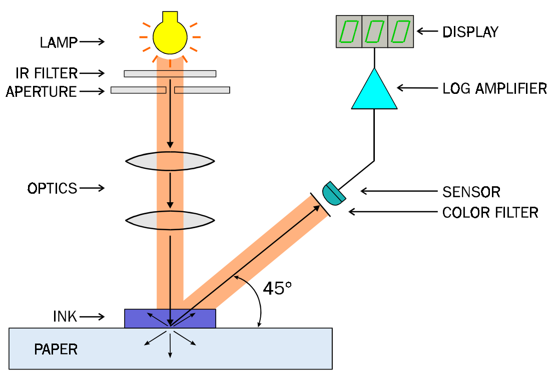

Figure 3: Components of a Reflection

To measure the reflection density of process inks, it is necessary to use a complementary filter in the optical path of the densitometer. This is because the ink absorbs one part of the spectrum while allowing the rest to be reflected almost unchanged by the white paper substrate. For example, cyan ink strongly absorbs the red component of the spectrum while leaving the green and blue components relatively unchanged. Small changes in the ink film thickness have a much greater effect on the red part of the spectrum than on the green and blue. Thus, if the densitometer detector has a red filter, it blocks the green and blue components and only sees the red, the component that is strongly influenced by the ink film thickness. The densitometer then sees the ink as shades of gray for measurement purposes.

The filters used to read process colors are: a red filter for cyan ink, green for magenta ink and blue for yellow ink. The black ink is not spectrally selective and a wide band visual response is used. If you are measuring non-process inks, you should try each filter, the red, the green and the blue, and use the one that gives the highest reading. In this way the reflection densitometer can give accurate and precise optical density readings of the ink patches on your press sheet and provides objective numerical data of your printing

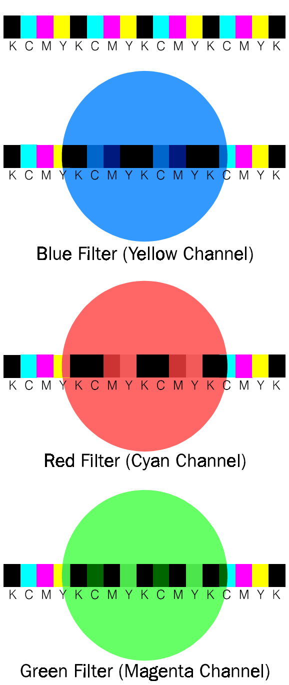

Figure 4: Ink and Color Filters

process.

Spectral Response

The reflection densitometer uses similar color filters to those that produce the separations. So you might think that different densitometers would read the same. However, there are some differences in the filters of various types of densitometers causing discrepancies in readings between units. To overcome this, ANSI specifications have defined several **System** responses for densitometers. Units conforming to these specifications should have a reasonable agreement. Among these spectral responses are Status A and M which are used in photographic applications and **Status T**, which is generally accepted as the Wide Band Graphic Arts response in North America. European responses are different giving a higher reading on yellow ink; this response is called Status E. Other responses exist such a Status I which is a narrowband response. Because these varying system responses exist, it is important that the Status response of the densitometer that you are using be included in any communication between customer and vendor.

Using a Densitometer

Today's densitometers are a sophisticated blend of electronics, optics and software. Many of the functions, such as filter selection and calibration have been automated and digital displays provide easy-to-read results. These numerical measurements permit objective evaluation of press sheets and ensure consistent color control. In addition to the solid ink densities, today's densitometers will also provide numerical data on other test targets that characterize the printing process, such as dot size and ink trapping.

Figure 5: IQ 200 Reflection Densitometer

Print Control Strips

Since the finished printed image generally consists of the overprint of the four halftone screens, it is very difficult to isolate each of the various components affecting the reproduction of the original image.

To overcome this problem, a series of test elements can be printed along with the image, and each element can be designed to highlight a particular aspect of the printing process. While some of these test targets can be evaluated by eye, others require the use of measuring equipment. The usual form of these test elements is a strip across the edge of the press sheet, although in boxboard and label work these elements may be interspersed with the images. These test strips, called **print control strips** or **colorbars**, are available commercially from various vendors, and consist of strips of film containing the various test elements for each of the four colors. In some cases six color versions are available when special colors might be used.

The usual densitometric targets in a colorbar are: Solid Ink Density, Dot Area/Gain of the quarter, half and three-quarter tints, Contrast and the Trapping of ink overprints.

Figure 6: Colorbar Elements

Densitometric Functions

Solid Ink Density

In the halftone process, as mentioned above, the tonal scale of the image is represented with dots of differing sizes. This procedure makes the assumption that the ink film thickness of each dot is the same irrespective of its size or diameter. Also, as the image coverage varies across the press sheet, the amount of ink that is required to print the image changes, requiring different ink fountain key setting across the press sheet. To measure the ink film thickness and to ensure its uniformity across the press sheet, patches of solid ink, i.e. 100% dot, for each color are placed in the colorbar and may be measured with the densitometer.

Absolute density is the measured density of the ink sample including the substrate, while **relative density** is the density of the ink sample minus the density of the substrate or base.

Typical values for solid ink density are:

$$D = \log_{10} R$$

$$R = \frac{1}{10^D} \times 100$$

D = Optical Density
R = % Reflection

STATUS T DENSITIES*

	Coated Stock	Uncoated Stock
Black	1.55 -1.85	1.40 - 1.70
Cyan	1.25 - 1.45	1.15 - 1.30
Magenta	1.20 -1.40	1.10 - 1.30
Yellow	0.90 - 1.00	0.80 - 0.90

* Use these values as guidelines only. Actual optimum values will vary from press to press.

The ink, paper and press characteristics influence the choice of target solid ink densities. Too high a set of densities tends to dirty the appearance, clog the shadows, warm the magentas and yellows, whereas low values give a washed-out look. The densities set should be balanced to give neutral grays over the entire range of gray values. Variation in ink densities from the target, or reference values, should be carefully monitored. To minimize color shift, it is desirable that the ink densities are balanced. It is better to have the 3/c solid ink densities too high or too low in value as a group, rather than having some high and some low. Trap and dot gain should be within acceptable limits. Different combinations of ink and paper will require different standards. Adopt as your standard what works best for you. Once you have set a standard, using a densitometer helps to give you consistent results.

Dot Gain

In addition to solid ink patches, print control strips may also include dot test targets for the quarter, half (midtone) and three quarter tone tints for each of the inks used. These test targets are used to monitor the way the dot is reproduced. As the image progresses through the reproduction process from film to plate, plate to blanket and finally blanket to paper, the size of the dot changes. This is called **Dot Gain** and is expressed as a difference between the original dot on the film and the measured dot on the printed image. For example, if the original had a dot area of 50% on the film and the resulting printed dot area was 68%, the dot gain would be 18%. Generally, the higher the screen ruling, the higher the dot gain.

Because we are comparing the result to an original, it is very important that we do indeed use *original* colorbar film and not a dupe, since the dupe will itself have some degree of distortion. Dot gain on press is a fact of life and as long as it is consistent and the dot gain of each of the inks is approximately the same, its effect can be accounted for when the halftone separations are made.

$$\text{Effective Dot Area} = \frac{1-10^{-D_t}}{1-10^{-D_s}} \times 100$$

D_t = Relative Density of Tint
D_s = Relative Density of Solid

To measure dot gain, the reflection densitometer is used to take a reading of the halftone tint, a solid ink patch adjacent to, or as close as possible to, the tint patch, and a reading of the paper base. Then using the **Murray-Davies** equation the dot area and dot gain values are calculated automatically by the densitometer. Typical midtone dot gain values are:

MIDTONE DOT GAIN using Murray-Davies Equation*

	Sheet Fed	Web Offset
Black	22% ± %5	25% ± %5
Cyan	20% ± %5	22% ± %5
Magenta	20% ± %5	22% ± %5
Yellow	18% ± %5	20% ± %5

* Use these values as guidelines only. Actual optimum values will vary from press to press.

Optical Dot Gain

There are special cases where the internal light scattering properties in the paper will significantly affect the readings of a densitometer. This is especially true when working with photographic material, newsprint, some coated stocks, and any material that exhibits substantial internal light diffusing characteristics. It is safe to say that almost any white base will exhibit this light diffusing characteristic.

Figure 7: The Effect of Light Scattering Properties

Unprinted paper appears white because of the perceived combination of the light reflected from the surface, and the light diffused into and reflected from the substrate. A dot, printed on paper, acts as a mask and affects the reflection of light from the printed sheet primarily in two ways.

First, the dot prevents light from entering the substrate of the paper and thereby prevents the diffusion, or scattering, of that light into areas adjacent to the dot.

Second, the converse of this occurs and light scattered by the white paper adjacent to a dot decreases the effective density of the areas inside the boundary of the dot, in opposition to the effect of the shadow halo in the white areas.

The white paper in the area next to the dots, then, has a lower apparent reflectivity than unprinted paper, resulting in a darker ‘‘halo’’ surrounding the dot. Since a dot area calculation is based upon the reflectivity of the unprinted white paper, the halo causes the dot area to be reported as a higher value than expected.

Optical dot gain is affected by dot size, screen ruling, and paper characteristics. For example, resin-coated photographic papers or a press print on an ‘‘opaque’’ white plastic base because of the great translucency of the base, will exhibit substantial optical dot gain.

$$\textbf{Physical Dot Area} = \frac{1 - 10^{D_t/n}}{1 - 10^{D_s/n}}$$

D_t = Relative Density of Tint
D_s = Relative Density of Solid
n = Empirically-derived Factor

When the actual dot size, or physical dot area, needs to be determined, the **Yule-Nielsen Equation** attempts to compensate for the light scattering effects of the paper. This modifies the Murray-Davies Equation for dot area calculation by introducing the **‘‘n’’ factor**. This factor is chosen to give an approximate correlation between the measured dot and the physical dot size and must be determined for each of the various types of work that you are printing. Its value depends on the combination of paper, ink and screen ruling that is used.

$$\textbf{Trap} = \frac{D_{op} - D_1}{D_2} \times 100$$

D_{op} = Density of 2/c overprint
D_1 = Density of first ink
D_2 = Density of second down ink

Note: All density measurements use the first ink's filter.

Typical values for ‘‘n’’ will range from 1.0 (no correction, or equivalent to Murray-Davies) to as high as 4.0.

Trap

When a job is run, the four process colors are sequentially printed. The order, or rotation, of the inks is usually cyan, magenta, yellow with black printed either first or last. The inks are formulated to have a graded tack according to the rotation on press. This ensures that each ink adheres to the previous ink that was printed rather than lifting it from the paper. To monitor this, colorbars have targets where solids are overprinted -— yellow on magenta giving red, yellow on cyan giving green and magenta on cyan giving blue. These patches, together with patches of the component single colors, are then measured with a densitometer.

A calculation is made, generally using the equation proposed by **Frank Preucil**, to give a percentage **Trap** figure.

This, then, is a measure of how well the inks are adhering to each other. Typical trap values are:

Contrast

$$\textit{Printing Contrast} = \frac{D_s - D_t}{D_s}$$

D_s = *Density of Solid*
D_t = *Density of Tint*

Print contrast is a measure of the ability of the printing process to hold shadow detail. A density measurement is taken of the three-quarter tone patch and of a solid patch. Print contrast is expressed as the percentage ratio of the difference in density between the two patches and the solid ink. A value above 30% is generally considered acceptable.

TRAP VALUES*
for a Cyan, Magenta and Yellow print sequence

	Sheet Fed	Web Offset
Red	70%	65%
Green	80%	75%
Blue	75%	70%

* Use these values as guidelines only. Actual optimum values will vary from press to press.

Hue Error & Grayness

To monitor the quality of your inks and to check for contamination, characteristics called **hue error** and **grayness** may be read from the solid process ink patches. Hue error is a measure of the deviation of the ink from a theoretically perfect process color. The larger the error, the smaller the gamut of colors that can problem, merely a characteristic of the ink. The term ‘‘error’’ is really a misnomer since it does not indicate a problem, merely a characteristic of the ink.

$$\textit{Hue Error} = \frac{D_M - D_L}{D_H - D_L} \times 100$$

D_H = *Highest Density*
D_M = *Middle Density*
D_L = *Lowest Density*

The grayness reading shows how ‘‘dirty’’ the ink is. For these measurements, a three-filter reading of the solid ink patches is taken and, again, the densitometer can calculate the results.

$$\textit{Grayness} = \frac{D_L}{D_H} \times 100$$

D_H = *Highest Density*
D_L = *Lowest Density*

Balance Patches

Gray balance patches are often printed adjacent to a 50% black and are used to visually check color balance. They usually consist of all three halftones: yellow and magenta printed at about 40% dot and cyan at about 50%. They should yield a neutral gray and will serve to typify the color balance of the job for the combination of press, paper and ink being used.

Scanning Densitometers

Scanning Densitometers are generally color reflection densitometers that will take multiple readings automatically across a sheet, store the values and often translate the data into statistical charts for quality control purposes.

There are two types of scanning densitometers: a linear scanner that reads along the length of a colorbar and a two-dimensional or X/Y scanner. A linear, colorbar scanner stores the sequence and position of the elements of commercial control strips in memory. It can then ‘‘find’’ the bar on a scan and automatically read solid ink densities, halftones and traps, providing immediate feedback to the pressman on how the job is running. An X/Y scanner has the ability to not only scan a colorbar but also to scan test targets anywhere on the press sheet, for example those found on the flaps of cartons in boxboard printing.

The speed with which these scanners can read hundreds of measurement targets in a few seconds provides an opportunity for detailed analysis of the print job; in addition they may be included in a low-cost loop system. The scan data can be examined using statistics and allows the power of **Statistical Process Control (SPC)** to be brought into the pressroom.

Statistical Process Control (SPC)

Statistical Process Control is an information feedback system that assures acceptable levels of product quality are maintained throughout a process. It monitors samples taken during the process and indicates appropriate changes as needed. Using statistics in the printing process, a relatively limited number of samples can be measured to characterize the color quality of an entire press run since it is not economically feasible to read the densities of every sheet. While printing customers are now pushing to obtain reports that indicate how their job ran, proper use of Statistical Process Control, or SPC, can actually help the printer produce a better product.

In any process there is always some variability. It will not operate at a fixed setting and hold to a specific result without some imposed "process control". This is evident when measurements are taken on a series of production pieces. The readings tend to fluctuate in a random pattern around the mean value, may show large swings or may have an upward or downward trends. By correcting these abnormalities, variations may be reduced to be within acceptable limits.

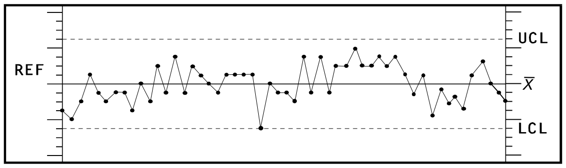

Figure 8: SPC Run Chart

By plotting the readings, at regular time intervals, a control chart can be produced. This graphically shows the process characteristics over a period of time. It is used to monitor the stability of a process and to recognize any abnormal or cyclic patterns. Variations in the process are due to ‘‘***random causes***’’ over which one has no control. Others are attributed to ‘‘***assignable causes***’’ such as a change of paper, ink or press settings or characteristics. With the proper analysis, relative evaluations can be made for various inks, blankets, roller coverings, water fountain solutions, job layouts, press procedures, and press maintenance and design.

Polarization Filters

It is generally agreed that **polarization** filters can give less difference in densitometer measurements between a wet and a dried-back printed sheet. This effect, however, is not always consistent, since ink ‘‘soak-in’’ depends upon the constitution of the ink as well as the porosity of the paper.

When a wet film of ink is applied to paper, the surface of the ink is fairly smooth. The densitometer illuminates the ink surface vertically and views the reflected light at 45° (or the converse geometry). Thus, the density measured approaches the true diffuse density of the body of the ink. As the ink dries, the surface becomes rougher and, under normal conditions, the density is lowered by the increase in surface reflections. The effect of these surface reflections can be substatially reduced by the use of polarizing filters. The underlying problem here is that the eye *does* see a reduction in density due to the surface roughness effect. The polarization filters do not eliminate the actual reduction in diffuse density due to the ink and pigments soaking into the paper. This absorption produces a thinner effective film of ink on the surface and hence a reduction in density. The ‘‘true’’ density changes as the ink film on the surface decreases on drying. This change in ink density upon drying is due to a poorly defined combination of several factors. The elimination of one of these is suspect since the effect is not consistent for different circumstances.

The use of polarization filters in a densitometer is somewhat controversial. Since the effect is not controllable and each situation will produce different results, and due to the distortion of spectral response caused by the filters, there are no published standards for the use of polarization filters.

Spectrophotometers and Colorimeters

Other measurement devices used in the graphic arts industry are Spectrophotometers and Colorimeters. These instruments are designed to measure color and color deviation from a reference sample. There are several ways of defining a color, one of which is the **L*a*b*** color space devised by CIE organization (Commission

Internationale de l'Eclairage). This is calculated from the XYZ **Tristimulus Response**, also defined by the CIE, which matches human vision. ''X'' is the red response, ''Y'' the green and ''Z'' the blue. The L*a*b* color space expresses a color's lightness with the ''L*'' term, its red/green component with the ''a*'' term and its blue/yellow with the ''b*'' term.

The main difference between the two types of units is that a colorimeter has actual filters that match the tristimulus response while a spectrophotometer measures equally across the visible spectrum and mathematically synthesizes the tristimulus response. Since the spectrophotometer measures equally across the spectrum, it is possible to calculate any filter response that may be required, for example a Status T densitometric response.

The spectrophotometer is used for comparing colors or for matching colors. For example, from the L*a*b* reading of each sample, adifference value, called delta e, can be calculated. This combines differences of the three properties of lightness, the red/green component and the blue/yellow to give a single number that expresses a color difference. A delta e of 1.0 is just perceptible to the human eye.

It is important to remember that the L*a*b* readings are calculated using a mathematical combination of the tristimulus response. The ''L*'' reading, representing the samples lightness, is derived from the green Y response, regardless of the color of the sample. A densitometer on the other hand uses the filter that gives the highest reading. The ''a*'' and ''b*'' values are calculated using a combination of the X and Y, and Y and Z responses respectively. This means that there is no correlation between readings from a spectrophotometer and a densitometer. While a spectrophotometer can very accurately measure color, its readings do not have a simple relationship to ink film thickness. A densitometer does not measure color, but gives readings that are proportional to ink film thickness and is the instrument of choice for controlling it. Thus, a spectrophotometer may be used to measure printed color differences, but a densitometer would be used to control the printing process.

Equations Summary

$$D = \log_{10} R$$

$$R = \frac{1}{10^{D}} \times 100$$

D = Optical Density
R = %Reflection

$$\text{Effective Dot Area} = \frac{1 - 10^{-D_t}}{1 - 10^{-D_s}} \times 100$$

D_t = *Relative Density of Tint*
D_s = *Relative Density of Solid*

$$\text{Physical Dot Area} = \frac{1 - 10^{D_t/n}}{1 - 10^{D_s/n}}$$

D_t = *Relative Density of Tint*
D_s = *Relative Density of Solid*
n = *Empirically-derived Factor*

$$\text{Trap} = \frac{D_{op} - D_1}{D_2} \times 100$$

D_{op} = *Density of 2/c overprint*
D_1 = *Density of first ink*
D_2 = *Density of second down ink*

Note: All density measurements use the first ink's filter.

$$\text{Printing Contrast} = \frac{D_s - D_t}{D_s}$$

D_s = *Density of Solid*
D_t = *Density of Tint*

$$\text{Hue Error} = \frac{D_M - D_L}{D_H - D_L} \times 100$$

D_H = *Highest Density*
D_M = *Middle Density*
D_L = *Lowest Density*

$$\text{Grayness} = \frac{D_L}{D_H} \times 100$$

D_H = *High Density*
D_L = *Low Density*