Lateral diffusion error and the overfill requirement, as applied to video densitometry

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Introduction

The standard design for commercially available densitometers today is one where the sample is illuminated over a larger area than the detector sees. Two related developments bring this practice up for re-assessment: web presses with tighter trim (and hence narrower color bars), and the use of video cameras for measuring optical density. Ultimately, the question to ask is whether one can obtain meaningful densitometrics using a video camera to measure 1.5 mm wide color patches, or does lateral diffusion cause problems?

Why are tiny colorbars in use?

The cost of paper has always been a significant fraction of the cost of printing. This year, with high demands for paper, this has been especially so. Needless to say, there is pressure to produce books with less paper. Printers deal with this pressure by reducing run waste. Manufacturers of printing equipment have responded to this pressure by providing presses with slightly smaller diameter plates and rollers so as to produce books that are slightly shorter than the previous generation.

Cutoff systems, which sever the web between pages, have tighter tolerances, so the gap between pages (the "trim area") is shrinking. This is particularly relevant for our purposes, since colorbars are printed in the trim area. With the current generation of short-cutoff presses, the maximum width for a colorbar has been reduced to 1.5 mm.

To make matters worse, with the tight tolerances required, the cutoff occurs very near, if not through, the colorbar, rendering it useless for sampling off-line. There is, therefore, a requirement for an on-line densitometer that can measure the density of 1.5 mm colorbars before they are cut.

How small can colorbars be?

The specifications

Most of the specifications on measuring ink in the graphic arts mention a required relationship between the illumination size and the size of the area where light is collected:

> “9.1.5 Process control area size
> The area shall be larger than the densitometer’s mechanical aperture.” [**1**]

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

"ASTM E 805 specifies an annular ring approximately equal to the depth of penetration of the light into the specimen." [**3**] (Reference also appears in **4**)

There is a consensus that the illumination area should be larger than the detection area, but there is not a firm consensus on how much larger. Surprisingly, the specifications are all mute on what would seem to be an important question: Does the sample need to be as large as the illumination area?

This question is of key importance in web offset printing, where colorbars that are 1.5 mm wide are becoming a common practice. Following the recommendation from [**2**], and assuming the sample must be as large as the illumination, it follows that colorbars must be *at least* 4 mm wide. In practical terms, they must be 5 mm wide.

Reasons for over-illumination

To understand the issue, we must look into lateral diffusion, which is the reason for the over-filling requirement. In figure 1, the illumination (coming from the left at 45°) enters the paper through the ink. Inside the paper, the light scatters. The area in which each individual ray scatters is indicated by an elliptical region[2]. The width of this region is the area that light may escape from the paper and be detected.

The region of detection (as indicated by vertical arrows leaving the paper) is in this case restricted to an area much smaller than the area illuminated. In this way, the detector sees the same amount of light as if the entire surface were illuminated. Since we generally view objects (such as magazines) fully illuminated, this comes closest to simulating normal conditions[3].

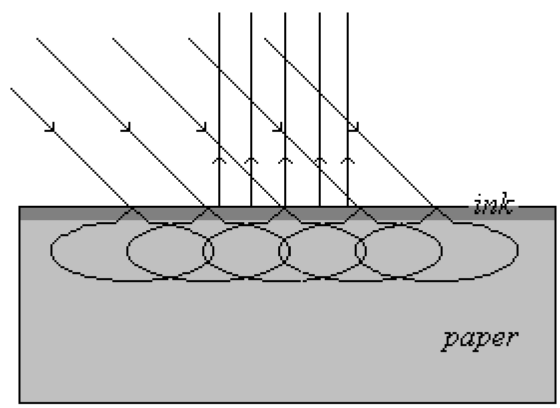

Figure 1 - lateral diffusion and over-filling

Spooner [**4**] considers the case of a reduced area of illumination. A densitometer must resort to this when the color patch is too narrow to allow over-filling. This is illustrated in figure 2, where the illumination that falls outside the detection area has been removed. (The removed illumination and its area of influence are shown in dotted

[2]In the illustration the scatter is shown as an ellipse which has the long axis laterally. I have no reason to assume that this is the shape. On the contrary, Monte Carlo analysis of electron beam penetration into a solid shows a tear-drop shape.

[3] Whether this gives the most direct relationship between ink film thickness and optical density is another question.

lines in the figure.) In this case, there is a reduction in the overall light captured by the detector, so there is an increase in the measured *absolute* density.

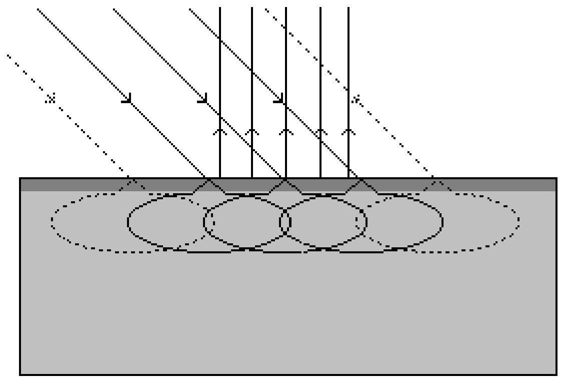

Figure 2 - detection without overfill

If a densitometer were to be truly calibrated for absolute measurements, the density it measures with reduced lighting would increase. Calibration of a densitometer is always performed relative to some standard, however[4]. As Spooner has pointed out, what actually occurs depends on the lateral diffusion of the reflectance standard compared to the lateral diffusion of the sample.

Figure 3 illustrates the lateral diffusion problem encountered when a video camera densitometer must measure 1.5 mm color bars. The difference is that the lighting for the video camera is not apertured to the colorbar size, but illuminates an area that is centimeters by centimeters. Thus, the illumination of the 2 mm surrounding the colorbar is the same intensity as the illumination of the colorbar. The measurement difference comes in that the light that is scattered into the color bar will only pass through the ink once.

Comparing this to figure 1, it can be seen that the detector in figure 3 will measure *more* light, and hence will report a *lower* density. Therefore, if lateral diffusion is a problem on the size scale we are dealing with, it is expected that narrower colorbars will have smaller optical densities than wider colorbars.

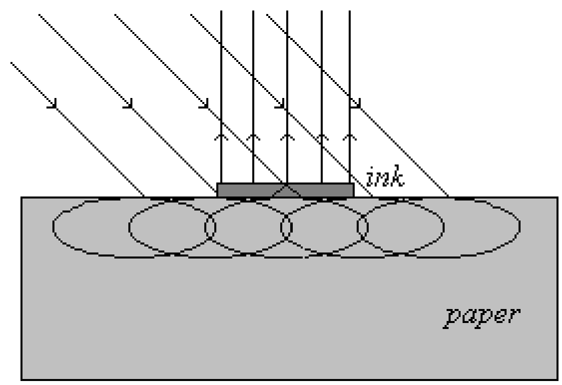

Figure 3 - Lateral diffusion on tiny colorbar

Critical look at requirement

Paper scatter

A paper delivered at TAGA 1995 [5] provides information that provides quantitative information regarding how far light scatters into paper. Engeldrum and Pridham built an apparatus that allowed them to directly measure how much light was scattered at any distance. They surveyed ten different stocks. Their data shows similar results with all the stocks. From their data, light scatters 0.1 mm to 0.2 mm into paper.

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[4] This is true whether the densitometer is in *relative* or *absolute* mode. In the relative mode, the densitometer is measuring density relative to the substrate (generally paper). In the absolute mode, the densitometer is measuring density relative to whichever standard the manufacturer chose. To take this point one step further, to say a standard has 100% reflectance is not *literally* true. The detector is collecting nowhere near 100% of the light emitted from the light source.

This data suggests that it is possible to collect density on a colorbar that is 1.5 mm wide. The entire patch would be illuminated, and only the central 1.1 mm would be sampled.

Use of video camera to measure

We performed an experiment to attempt to verify the conclusions. A form was printed with two sets of colorbars, one set 1.5 mm wide, the other set 3 mm wide. The colorbars were printed roughly a centimeter apart. Colorbar sections were cut from this form, and glued to a smooth black tile that has 0°/45° density of 3.5. The patches were viewed under a video camera and the density was computed of the two black patches. The image processing and software corrections employed to obtain density were described by this author elsewhere [**6**].

Two minor changes were made from the system previously described. First, the software correction for scattered light was disabled. Enabling this correction would beg the question of whether the software was correcting for light scattered within the sample or light scattered in the camera and lens. Second, the magnification of the imaging was increased, yielding a field of view of roughly 5 mm by 6 mm. The purpose of this was to decrease the effect of light scattered within the camera system, since the extent of this effect is basically constant in pixel count. Increasing the magnification has a side benefit of increasing the spatial resolution.

Presumably, patches that are very close to each other, and in line with each other, will have the same ink film thickness. If our measurement system is careful to average pixels that are at least 0.2 mm from the edge of the patch, the densities of neighboring black patches should agree.

The first trial showed the following densities on black patches:

Table 1	Red Channel	Green Channel	Blue Channel
3 mm patch	1.579	1.667	1.629
1.5 mm patch	1.497	1.575	1.535
Difference	0.082	0.092	0.094

Are these differences significant? The precision of the instrument (defined as the ability of the instrument to replicate readings when no changes are made to the sample) was measured at σ=0.009. The differences being roughly seven standard deviation units out[5], the conclusion is that the differences in the measurements are not a statistical anomaly. The fact that the red, green and blue channel differences are consistent further supports the claim.

[5] At first thought, one might say *nine* standard deviation units. The standard deviation of a single measurement was 0.009, but the standard deviation of a *difference* between two measurements is $\sqrt{2} \times 0.009$, assuming that the measurement errors are independent. The average deviation is therefore $\left(\frac{0.082+0.092+0.094}{3}\right) \div \left(\sqrt{2} \times 0.009\right) = 7.02$ standard deviation units out.

What accounts for the difference? Figure 4 shows a three dimensional plot of the reflectance (from 0 to 1, with white paper at 0.766) of the pixels in the 1.5 mm patch. The effect of scattered light (from whatever source) can be seen along the edges. From the plot, it would appear that scattered light is not a problem, so long as the edges are avoided. The edge in this case is about 10 pixels wide, or roughly 0.1 mm. This comes in fair agreement to Engeldrum. From this analysis, one would be tempted to rule out scattered light as the source of the difference between the patches.

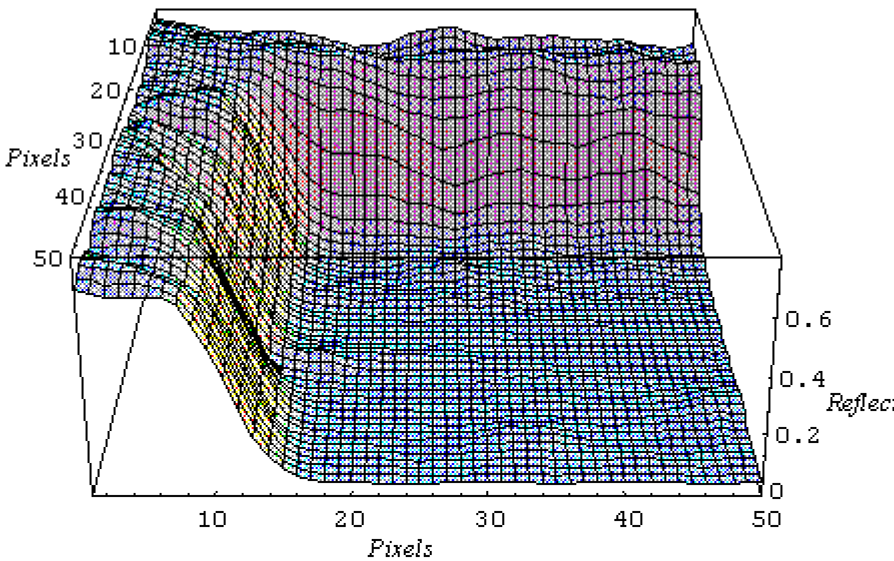

Figure 4 - plot of a patch

One must consider, however, that there are two distinct sources of scattering. Light scatters within the paper, and light scatters in the lens and camera. It could be that the scattering highlighted in figure 4 is just one of the sources of scattering, and that the other scattering source has a point spread function that is too wide to be apparent in the plot.

To eliminate this possibility, a razor blade was used to cut between the patch edges and the white paper. All the white paper was then removed, leaving just a 3 mm wide patch and a 1.5 mm patch. Table 2 shows the results of this test. The difference between this test and the previous test is shown in parentheses.

Table 2	Red Channel	Green Channel	Blue Channel
3 mm patch	1.577 (-0.002)	1.675 (+0.008)	1.682 (-0.053)
1.5 mm patch	1.490 (-0.007)	1.565 (-0.010)	1.568 (-0.033)
Difference	0.087 (-0.005)	0.110 (-0.018)	0.114 (-0.020)

The only significant changes are in the blue channel. It is known that the scatter in the lens/camera is somewhat larger in the blue channel. This suggests that there is a small amount of lens/camera scattering in the table 1 data.

The discrepancy between the 1.5 mm patch and the 3 mm patch has not been found, however. Scattered light in the paper and in the lens/camera has been eliminated, since both phenomena have been significantly reduced in the table 2 data without significant reduction in the discrepancy.

Is the discrepancy due to the size of the piece of paper under the camera, or is there a physical difference between the two patches? To resolve this, the 3 mm patch was further trimmed to approximate the size of the 1.5 mm patch, and the measurement was repeated. Table three compares the original measurement of the 3 mm patch with the same patch after trimming.

Table 3	Red Channel	Green Channel	Blue Channel
3 mm patch	1.577	1.675	1.682
3 mm patch (trimmed)	1.595	1.688	1.682

The fact that there is virtually no change when a 3 mm patch is trimmed to 1.5 mm shows that the discrepancy between the 1.5 mm patch and the 3 mm patch is not a measurement artifact, but is a physical characteristic of the patches.

Is it generally true that 1.5 mm patches have lower density than 3 mm patches? The test of a single pair of patches could easily be a printing artifact or a smudge. The first part of the experiment was repeated for nine more sets of patches. The differences (density of large patch minus density of small patch) are recorded in table 4.

Table 4	Red	Green	Blue
Patch set 1	0.072	0.074	0.061
Patch set 2	0.056	0.053	0.055
Patch set 3	0.016	0.019	0.022
4	0.035	0.036	0.044
5	0.079	0.083	0.094
6	0.044	0.050	0.058
7	0.039	0.053	0.058
8	0.090	0.105	0.113
9	0.067	0.084	0.087
Mean (std dev)	0.055 (0.023)	0.062 (0.027)	0.066 (0.028)

For this particular sheet, the higher density of the wider patch is consistent.

Measurement of patches on Xrite

To determine whether the difference is reality or just an anomaly of the instrument, three of the patch sets from table 4 (#7, #8, and #9) were measured on an XScan scanning densitometer. This densitometer has an aperture size of 1.1 mm by 1.7 mm.

Table 5	Red	Green	Blue
7 - small patch	1.439	1.517	1.501
large patch	1.484	1.563	1.537
difference	**0.045**	**0.046**	**0.036**
8 - small patch	1.545	1.622	1.592
large patch	1.629	1.728	1.679
difference	**0.084**	**0.106**	**0.087**
9 - small patch	1.507	1.584	1.567
large patch	1.619	1.717	1.664
difference	**0.112**	**0.133**	**0.097**

While the numbers are not in perfect agreement with the corresponding numbers from the video camera, the tendency for large patches to have higher densities has continued.

Conclusion

This paper has considered whether accurate densities can be measured on 1.5 mm wide colorbars. The conclusion is that it is possible for an instrument to read a patch this size and obtain reliable numbers. It was also found that an artifact of the printing process (such as a thinner ink film) apparently causes the narrow patches to have a lower density.

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