How Big Is Color?

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Abstract

What is the physical size of the smallest identifiable color?

A person with 20/20 vision can distinguish between two dots that are one arc minute apart. At a distance of one arm's length, a person with normal acuity has a resolution of about 0.007". That is to say, dots that are separated by of 0.007" can just be distinguished as different dots. I would expect that the smallest identifiable color is somewhat larger than this.

For the purposes of the paper, I will assume that the smallest identifiable color is 0.025", or 40 DPI. I offer no data to support this. It is just a reasonable supposition.

On the other hand, standards for measuring color (with a densitometer or with a spectrophotometer) require that the color of a halftone cannot be accurately measured if the aperture of the instrument is smaller than 0.11".

There is an apparent disagreement here. Why is it apparently not possible (according to standards) to measure a printed halftone color at the resolution that the eye can see color? Just how big is color, anyway?

Motivation

The printing industry needs a way to objectively compare a press sheet against a proof. It would be desirable to lay the two sheets on a scanner, line the images up in software, and subtract one image from the other. There are three stumbling blocks, however.

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The first stumbling block is that colorimetrically correct scanners are uncommon. Typical scanners can be, to some extent, calibrated to provide L*a*b* measurements, but the accuracy is limited and the calibration is only good for one set of inks and printing stock. Since proofs and press sheets use different pigment sets and are usually printed on different paper, a different profile must be used to scan the two sheets.

A second stumbling block is that halftone dots lead to moiré problems when scanned. Areas of halftone color show bands when imaged. The position of the bands is critically dependent upon the positioning of the sheet.

The third stumbling block is that, even if we had two accurate L*a*b* images, we would not know how to compare them in a way that correlates well with human perception. Predicting when an observer can detect a difference in color between two large patches of uniform color against neutral backgrounds has been a fairly recent research goal, coming to fruition with the CIEDE2000 of 2001. Determining what amount of color difference is acceptable is a harder question, and being able to decide upon the acceptability of color differences in a complicated image is an area of research. (The CGATS Subcommittee 3 Task Force 1 - Objective Color Matching is working on this project.)

It is technically feasible to build a scanner that will eliminate the first stumbling block. The third stumbling block is a major undertaking. This paper addresses the second of these stumbling blocks, the moiré problem.

The Sigg effect

Franz Sigg published a paper that pointed out a source of variability in measuring the reflectance of halftones (Sigg, 1983). This uncertainty is due to the positioning of the aperture of a densitometer with respect to the positions of the halftone dots. Basically, when a densitometer is repositioned, a different number of dots may be included in the measurement. According to various standards based on the Sigg paper (CGATS.5:2003, ISO 12647-1, ISO 13655:1996 E, ISO/CD 14981, ISO 13656:2000), it would appear that accurate scanning of a 133 LPI halftone image cannot be done with pixels smaller than 0.075” (13.37 DPI) and preferably would use pixels at least 0.114” (8.75 DPI). (I have followed the convention of using “DPI” when referring to the scanned resolution of an image, and using “LPI” when referring to a screen ruling.)

In this paper, I provide data to show that Sigg has overestimated the error, by about a factor of two. I then scan a variety of halftone images at 40 DPI and measure positional error. I look at two-dimensional Fourier transforms of halftones to explain when there will be large errors due to small changes in positioning. This understanding is then used to develop a descreening technique that allows for repeatable measurements of halftones at a higher resolution than allowed by the standards.

Review of the Literature

Figure 1 illustrates how positioning of the aperture can greatly affect the reading of a spectrophotometer. The apertures on the right and left are of the same size and they are positioned over halftone patterns with the same screen ruling and dot area. In one positioning the spectrophotometer sees four halftone dots, whereas in the other, the spectrophotometer sees only one. Because the distance between halftone dots is not small compared to the aperture, the reflectance reading is very dependent upon the positioning.

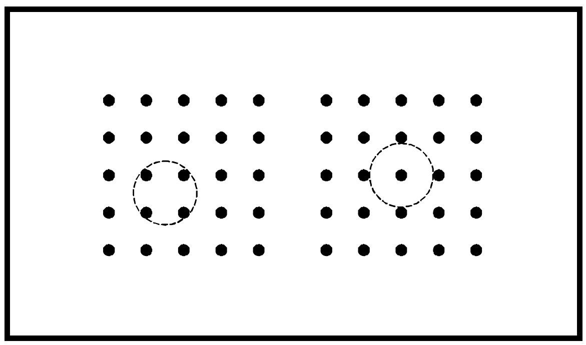

Figure 1: The Sigg Effect

Sigg's paper contained a formula to estimate the maximum uncertainty that can occur due to this effect:

$$\text{Minimum Error (\% Dot Area)} = \frac{3650}{\sqrt{(D \times S)^3}}$$

where:

D is the diameter of the aperture in mm, and
S is the screen ruling in lines per inch.

Figure 2 is a graph of this equation for a screen ruling of 133 LPI. The graph shows that an aperture size of 1.78 mm or larger will assure an error in calculation of apparent dot area of no more than one percentage point. An aperture size of 2.84 mm or larger will bring the error down to one-half of a percentage point or less.

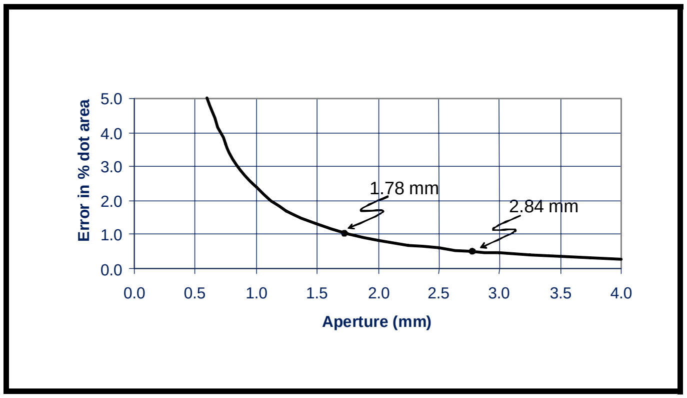

Figure 2: Magnitude of the Sigg effect(133 LPI)

Sigg's paper was strictly theoretical. The work is mathematically sound, and skillful, but there is no experimental evidence provided to corroborate his results. I know of only one paper [7] that has provided experimental evidence, and the author (Crouse) was apparently unaware of Sigg's work, since it is not referenced, and the experimental results are not compared against his formula.

In Crouse's paper, a comparison is made of the variability of measurements made with densitometers with apertures of 1.6 mm, 3.2 mm and 4.0 mm. He concluded that a 4.5 mm aperture would be optimal for the 65 LPI ruling that they measured. According to Sigg's formula, these conditions would yield a maximum error of 0.7 percentage points in dot area measurement. The standards would require a more conservative aperture of 5.9 mm.

Crouse also provided data for the variation of measurement of dot area on screen rulings of 65, 85, 100, 110, 120, 133, and 150 LPI, measured with densitometers with apertures of 1.6 mm and 3.2 mm. Unfortunately, the data he reported cannot be directly compared with Sigg's formula. The data that Crouse reported indicates, however, that the variation is not correlated with screen ruling, as one would expect.

Test of the Sigg effect

A sample was procured of a variety of color patches each measuring slightly more than 4 mm by 4 mm. The patches were printed by a sheetfed press on Consolidated Fortune Gloss White paper. From this test sheet, four black patches were selected: two 25% patches and two 50% patches. The selection of patches was made to try to get near 50% dot area, since according to Sigg, this is where the variability due to positioning is the largest.

These patches were imaged with a video camera at roughly 500 DPI. Sixteen images of the patches were collected and averaged together to reduce any possible effects of measurement noise.

Figure 3 shows a picture of an 80 by 80 pixel area that was used for the measurements of the collected image. A simulation was made of the effect of positioning of apertures on the image. Apertures from 1 by 1 pixel up to 45 by 45 pixels were used, including all combinations of rectangular and square apertures for a total of 2025 different apertures.

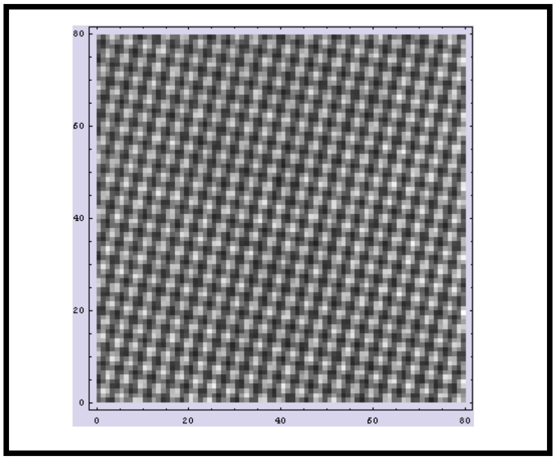

Figure 3: A Halftone Image from the Experiment

For each of these 2025 apertures, the aperture was positioned in every possible position in the image. In each of these positions, the average pixel value was computed. The dot area was computed for each of the aperture positions, and the standard deviation of the dot areas was determined. This is used to assess the variability as the aperture is moved about the patch. To compare the standard deviation that I have computed against the maximum error from Sigg's formula, I have multiplied the standard deviations by three, assuming that 3 sigma is a good approximation to the maximum error.

Figure 4 shows a comparison of the experimental results with the Sigg formula for one of the four patches in my experiment. The results from the other three patches were similar, and show that the error from my experiment is one-third to one-half of the Sigg prediction.

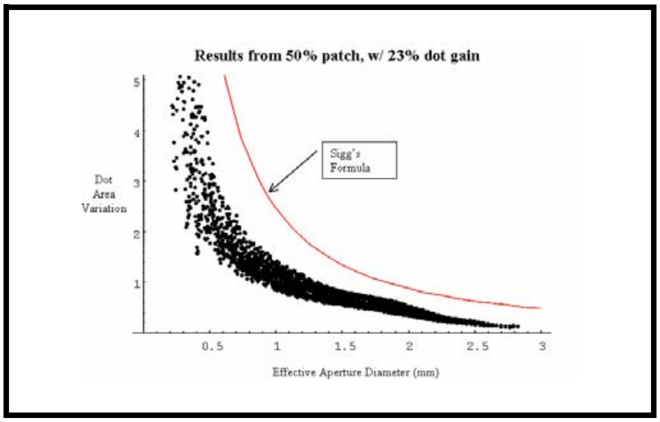

Figure 4: Comparison of Data Against Sigg Formula

Why the discrepancy? The mathematical model that Franz Sigg started with assumed that pixels were either black or white. In real printing, physical and optical dot gain causes a blurring of the pixel values so that the effect of aperture positioning is only roughly half of the theoretical worst case. A crisp dot on paper without optical dot gain would yield results closest to the theoretical maximum of Sigg's paper.

Assuming a leeway of a factor of two due to soft dots, then this means that we can scan at 15 DPI instead of 8.75 DPI. This is significantly less than what is needed to match the human eye, so in the next section we will try to get this to 40 DPI.

Application to spectrophotometry

Sigg's paper addressed the question of error in the computation of apparent dot area. This print attribute is computed from density measurements via the Murray-Davies equation. As such, his recommended formula was based on some reasonable tolerances for the error in measurement of apparent dot area.

The minimum aperture size in the standards is the smallest aperture that guarantees an error in computation of dot area that is less than 1%. The recommended aperture size is the smallest aperture that guarantees an error less than 0.5%.

Sigg's formula has been incorporated into standards for the aperture size of a densitometer (ISO 12647-1 and ISO/CD 14981). The same values have been fed forward (without comment) into standards for aperture size of a spectrophotometer or colorimeter (CGATS.5:2003, ISO 12647-1, ISO 13655:1996 E, ISO 13656:2000). Is the standard reasonable for the measurement of CIELAB?

To a first order approximation, the CIELAB values of halftones of a solid are equally spaced along a line from the CIELAB value of paper to the CIELAB value of the solid. If the distance from paper to the solid is about 100 ΔE, then each percentage point change in dot area corresponds to a colorimetric change of on the order of 1 ΔE.

The recommended and minimum aperture sizes thus represent a positional error of on the order of 0.5 ΔE and 1.0 ΔE, respectively.

Scanning

This section demonstrates that it is possible to produce a 40 DPI image that avoids the deleterious effects of moiré. Moiré is a banding in the image that is the result of frequencies in the image that are higher than the maximum frequency that can be accommodated by the scanning resolution.

The Source of Moiré

In Figure 5, a waveform with a frequency of ten cycles per unit looks like one cycle per unit when it is sampled at nine samples per unit (dotted lines). This is a moiré pattern. As a result of moiré, scanned images of a flat halftone field may have large bands of light and dark.

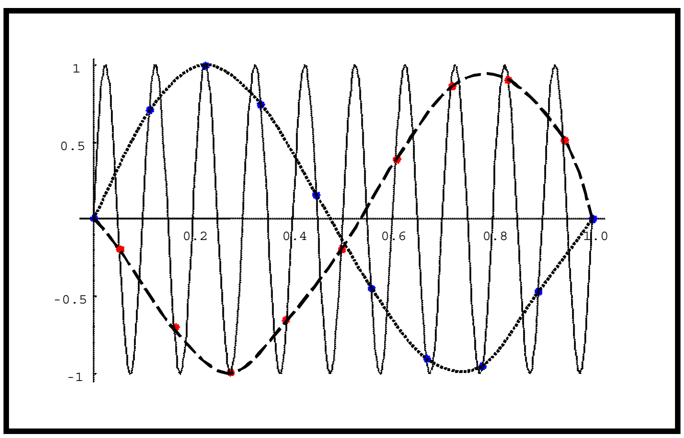

Figure 5: Illustration of Sampling a Sine Wave

Another undesirable aspect of moiré patterns is that a tiny shift in the position of the sampling will cause a big change in the position of the bands, as illustrated by the two dotted lines in Figure 5. Although the position of the scan points in one is shifted by only about 0.05 units, the peak of the banding has been shifted by 0.5 units. This is the phenomena that Sigg had investigated. When moiré is present, the intensity of pixels in an image depends critically on the placement of the printed sheet on the scanner when the scan is performed.

Simple scanning

Measuring moiré

This section demonstrates a technique for quantifying this dependence of scanned pixel values on positioning. One way to do that would be to scan a sheet on a scanner a number of times, say twenty times, repositioning in between scans. The resulting twenty images would be aligned so that corresponding pixels represent the same area of the sheets. The standard deviation of the twenty pixel values would be an indication of the amount of moiré at that pixel. There would be a standard deviation computed for each pixel in the image, so these would be averaged together.

This is a time consuming endeavor, especially when looking at many images at different resolutions. A different approach was taken in this paper. A single scan was taken of each image, but at a high enough resolution to digitally simulate the repositioning.

Setup

Halftone patches were printed on a proofer at a number of screen rulings: 80, 110, 133, 150, and 200 LPI. The patches included 25%, 50%, 75% and solids. These twenty-one patches were scanned at 2400 DPI. Each image was 0.2 inch by 0.2 inch or 480 pixels by 480 pixels.

These images were then decimated down to 40 DPI by averaging 60 by 60 pixels in the original image to arrive at a single pixel in the resulting image. I simulated the repositioning of the scanned sheet by starting the decimation at each of 144 positions (12 by 12). For each pixel in the resulting images, I computed the standard deviation over the 144 positions. The set of standard deviations was then averaged.

Results

The results for the five screen rulings are shown in Figures 6 through 10. Each graph is the variability of pixel intensity caused by small changes in registration. As a reference point, nominal image contrast is about 25. If the moiré pattern has a variability of 2.5, then it has a contrast that is one-tenth of that of a typical image, so it will be readily noticeable.

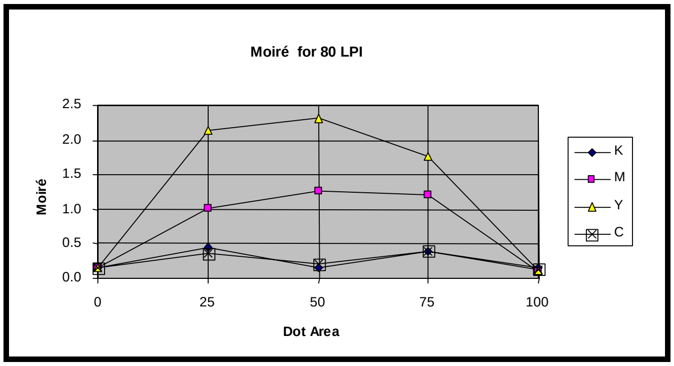

Figure 6: Measured Moiré for 80 LPI Patches

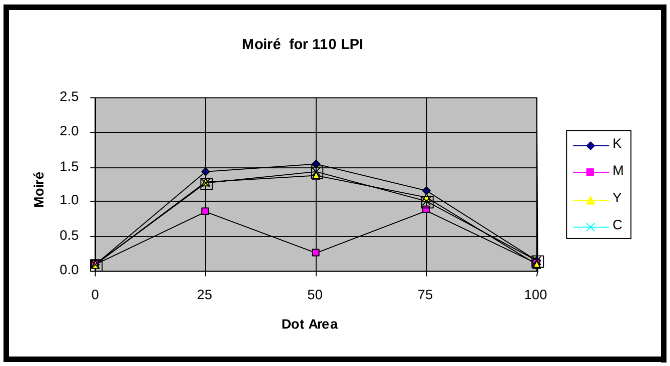

Figure 7: Measured Moiré for 110 LPI Patches

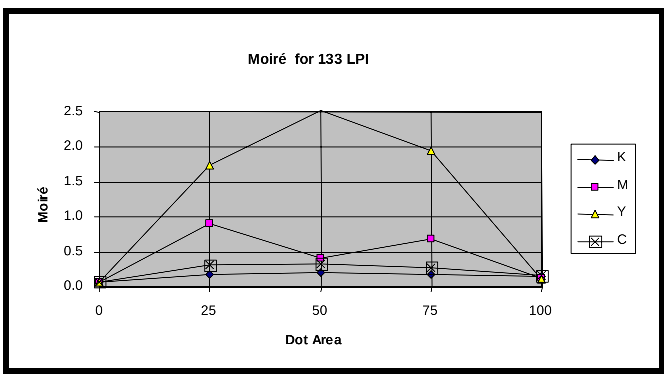

Figure 8: Measured Moiré for 133 LPI Patches

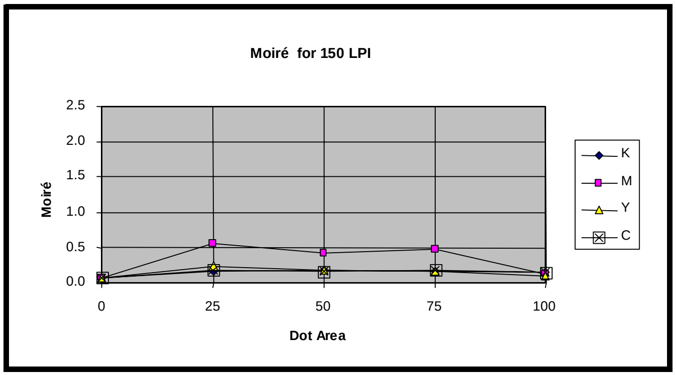

Figure 9: Measured moiré for 150 LPI patches

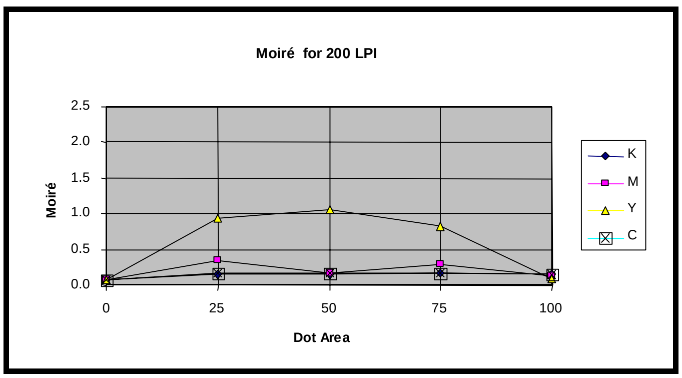

Figure 10: Measured Moiré for 200 LPI Patches

All screen rulings, with the exception of 150 LPI, exhibit moderate moiré for some of the inks, although there is a negligible amount of moiré in the magenta 150 LPI. Yellow ink (with a screen angle of 90°) shows moiré at all screen rulings except 150 LPI.

Moiré seems to be a bit capricious. It seems to favor certain inks (or screen angles). It does not increase or decrease monotonically with screen ruling. Frequency space offers an explanation.

The capriciousness of moiré

Using frequency space plots to understand moiré

Figure 5 demonstrates that moiré is caused by sampling a high frequency at a low resolution. This is analogous to measuring the reflectance of halftone dots with an aperture that is small compared to the screen ruling.

In the preceding section, images were decimated down to 40 DPI image with a 60 by 60 average. Taking the straight average is one of many possible ways to reduce the resolution. It would be possible to merely pick one of the pixels from that set of 60 by 60 pixels. This could, of course, eliminate fine detail and it also misses the opportunity to average out some noise in the image.

It would also be possible to average an area slightly larger, incorporating some of the information from neighboring pixels, but this would blur the image a bit. On the other hand, there is no reason why all 60 by 60 pixels need the same weighting. I will refer to this set of weightings for the averaging of the pixels from the high resolution image as the aperture, since it behaves analogously to the aperture of a spectrophotometer.

The 60 by 60 aperture has its own Fourier transform, which is illustrated in Figure 11. (Note that the aperture illustrated is a square aperture, as one would expect when dealing with pixels in an image. Since a spectrophotometer usually has a round aperture, the Fourier transform of the aperture of a spectrophotometer is circularly symmetric.) This figure is helpful in understanding when moiré will occur. The red box in the center of the image shows all those frequencies that can be faithfully reproduced (that is, reproduced without moiré) in a 40 DPI image. Where this image is brightest, the energy at those frequencies will be reproduced at full intensity. Where this image is black, those frequencies will be eliminated.

Every frequency outside this red box has the potential to cause moiré. This potential may or may not be realized, however, depending upon where the frequency lays with respect to the brighter areas in Figure 11. If the frequency is outside the box and happens to land in a dark area of the aperture's Fourier transform, then there will be no moiré. If the frequency lands in a bright area, then there will be moiré.

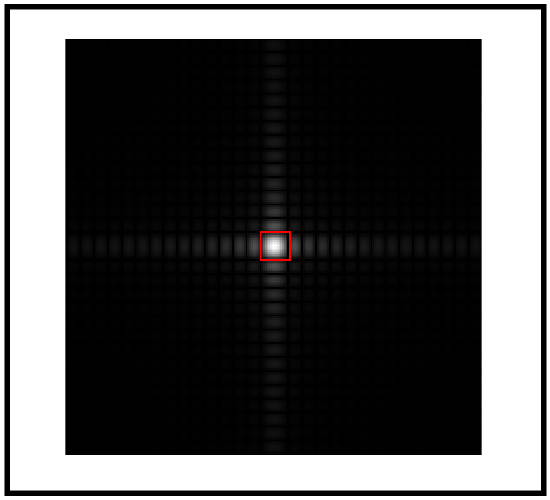

Figure 11: Fourier Transform of Averaging Aperture

In Figure 12, the Fourier transforms of 110 LPI cyan, magenta, yellow and black 50% halftone patterns have been overlaid on the Fourier transform of the aperture. Each of the Fourier transforms of halftone patterns is plotted in its color, except that the black Fourier transform is in white.

It can be seen in Figure 12 that the black, cyan and yellow frequencies overlap a white area of the Fourier transform of the aperture, meaning that they will show moiré. The magenta frequencies are between the humps, so little moiré is present.

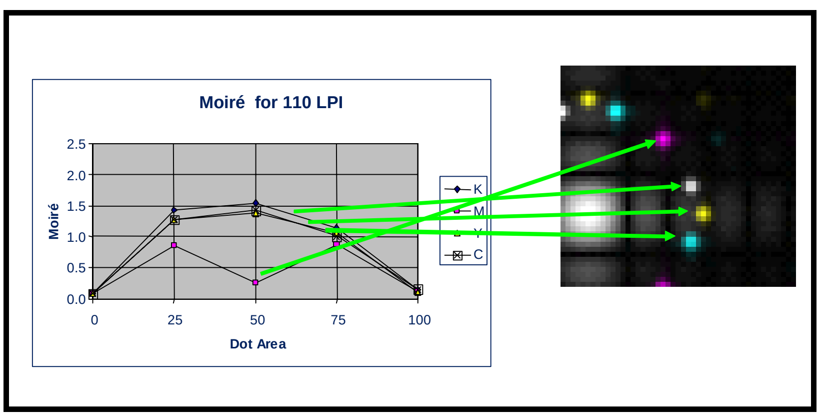

Figure 12: Using Fourier transform to explain when there is moiré

This illustrates that analysis of Fourier transforms can be used to predict moiré.

Intelligent decimation

Suppose we were to arbitrarily decide to scan images at the moderate resolution of 200 DPI, and then apply a digital filter to reduce this image to 40 DPI. Is it possible to eliminate moiré?

A digital filter was designed to decimate an image from 200 DPI down to 40 DPI. This filter was optimized to reduce the frequencies above 40 DPI. The filter is performed by decimating first in the horizontal and then in the vertical direction with the following filter:

{0.017, 0.074, 0.126, 0.182, 0.202, 0.182, 0.126, 0.074, 0.017}

Figure 13 shows the frequency response of this filter as compared against straight averaging. The bumps at 50, 100, and 150 DPI have been almost entirely eliminated. The bump around 175 DPI is, however, not reduced. The bumps seen at higher frequencies are similarly unaffected. This is inevitable. This frequency is too close to that of the scan. To remove moiré effects from images at higher than 175 DPI, the original image needs to be scanned at something greater than 200 DPI.

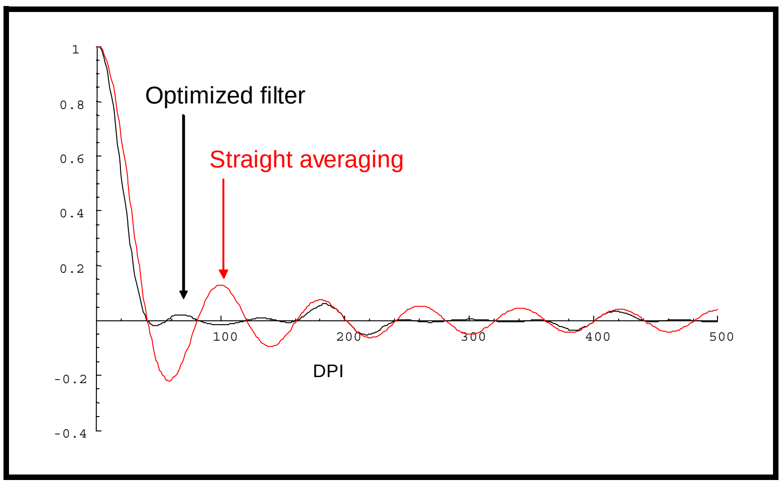

Figure 13: Fourier Transform of an Optimized Filter

Figure 14 illustrates that the moiré pattern of 110 LPI images is eliminated as expected.

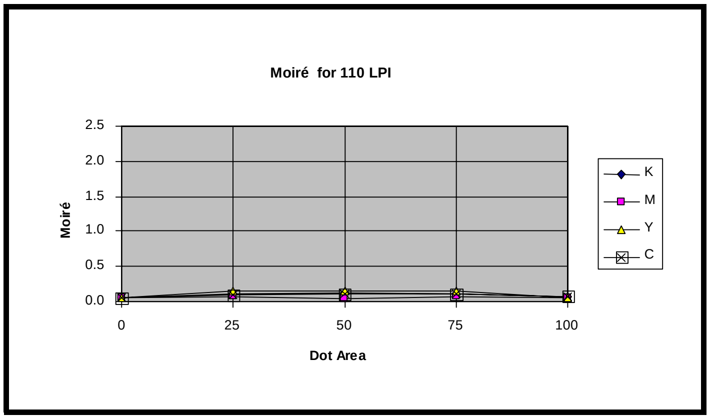

Figure 14: Affect of Optimized Filter on 110 LPI

Yellow halftones at 200 LPI show unexpected moiré patterns, as shown in the moiré graph in Figure 15. One would expect that the 200 LPI frequency of yellow would fall directly between the bumps at 175 DPI and 225 DPI, and hence there would be no moiré. A close analysis of the scanned yellow images explains the confusion. The actual screen ruling for 200 LPI yellow is about 220 LPI. (Yellow is often screened at a slightly higher ruling. This tends to smooth out flesh tones.)

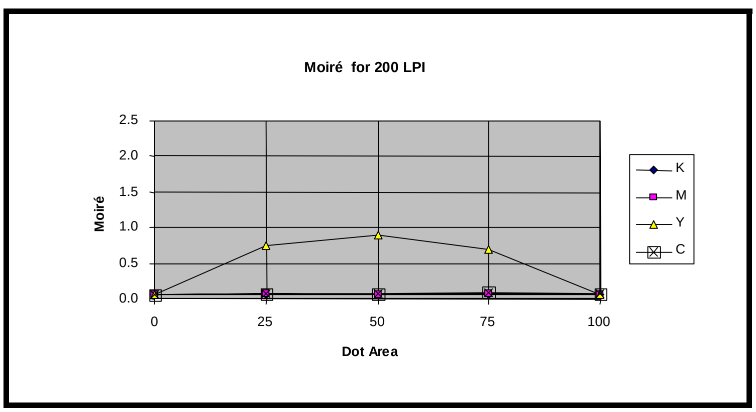

Figure 15: Affect of Optimized Filter on 200 LPI

Since 133 LPI is significantly lower than 175 DPI, one would expect that moiré would not be present at 133 LPI. Figure 16 shows the moiré graph for 133 LPI, clearly indicating that there is moiré in the magenta channel, at least for the 25% and 75% images. Surprisingly, there is no apparent moiré in the 50% image.

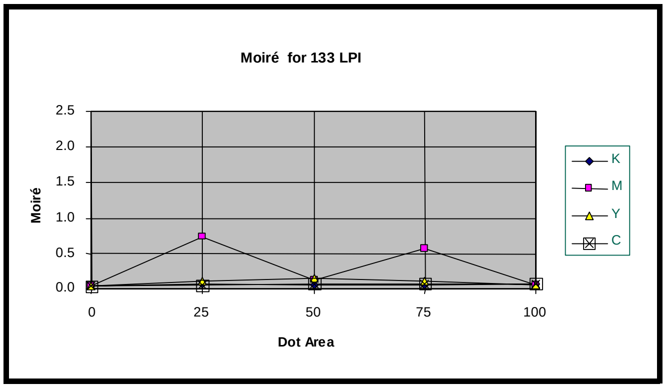

Figure 16: Affect of Optimized Filter on 133 LPI

Fourier transforms can be used to understand the issue with magenta halftones, as shown in Figure 17. The Fourier transforms of all four 133 LPI 50% patches is shown on the left, superimposed on the Fourier transform of the optimized aperture.

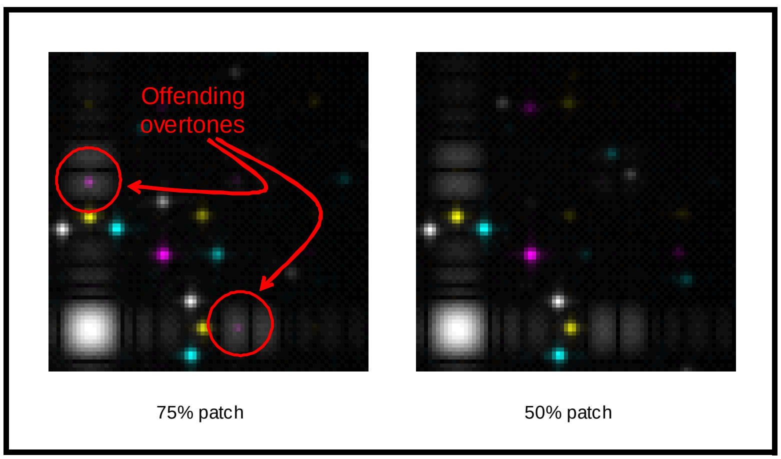

Figure 17: Fourier Transforms of 133 LPI Patches

The fundamental magenta frequency, which is the brighter magenta dot, is in an area of frequency space where the filter suppresses the energy. There are, however, two overtones to the fundamental frequency that lay in areas that are not suppressed. This is the source of the moiré patterns. Note from the image at the right that the overtone frequencies are not seen in the Fourier transforms of the 50% patches, so there is no moiré in those images.

Conclusions

This paper demonstrates that it is possible to use decimation with digital filters to significantly reduce the effects of moiré when decimating from 200 DPI to 40 DPI. It has been seen that Fourier transforms can be used to predict when moiré patterns will occur, and hence are a useful tool in designing a technique to eliminate moiré.

The choice of decimating a 200 DPI image down to 40 DPI was an arbitrary choice made at the start of this experiment. The initial scan should be at something higher than 200 DPI in order to eliminate moiré patterns in all cases; scanning at perhaps 350 DPI would suffice for screen rulings up to 200 LPI. It is also reasonable to expect that moiré free images at greater than 40 DPI could be produced.

So, how big is color? What I have demonstrated is that the color of halftone images can be measured at a resolution of at least 40 DPI.

Literature Cited

Crouse, David B. 1989 “Densitometric aperture size vs. density measurements and dot area calculations,” TAGA Proceedings, pp. 11-26.

Sigg, Franz 1983 “Errors in measuring halftone dot area,” Journal of Applied Photographic Engineering vol. 9, pp. 27-32.

CGATS.5:2003, “Graphic technology–Spectral measurement and colorimetric computation for graphic arts images.”

ISO 12647-1, “Graphic technology–Process control for the production of half-tone colour separations, proof and production prints – Part 1: Parameters and measurement methods.”

ISO 13655:1996 E, “Graphic technology–Spectral measurement and colorimetric computation for graphic art images.”

ISO/CD 14981, “Graphic technology–process control–optical, geometrical and metrological requirements for reflection densitometers for graphic arts use.”

ISO 13656:2000, “Graphic technology–Application of reflection densitometry and colorimetry to process control or evaluation of prints and proofs.”