The Goniophotometry of Printing Ink

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Abstract: In the initial prototyping of a video-based densitometer, it was found that the calculated density of an ink patch varied slightly with the position of the patch within the field of view. Numerous potential explanations were investigated and dismissed including: the effects of scattered light, incomplete correction for uneven illumination and electronic distortions in the camera or frame grabber. The theory was proposed that the effect may be due to changes in the sample's reflectance with the angles of illumination and of detection. This paper a) describes the eucentric goniophotometer which was built to test this theory, b) gives results from an experiment where the goniophotometer was used to simulate video measurement of density, and c) provides a theory to explain the goniophotometric aspects of ink on paper.

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Specifications for Densitometry Geometry

The International Commission on Illumination provides a definition for 45º/0º geometry which includes the acceptable range of angles (CIE 15.2, ASTM E 1164). The effective axis of the illumination must be within 2º of 45º, and have a spread which positions all the light within ±8º of this axis. The central angle of the viewing must be within ±10º of 0º, and the spread must again be less than 8º. Figure 1 illustrates one interpretation of this specification.

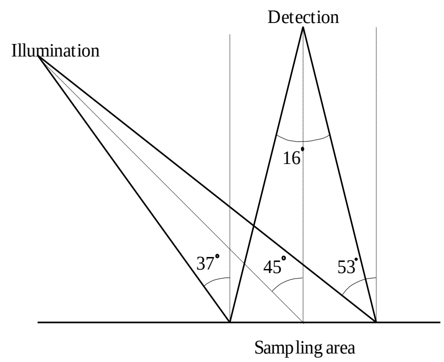

Figure 1 - the range for 45/0

What design constraints does this put on a video densitometer? A video densitometer differs from a standard densitometer in that the sampling area is much larger than a typical densitometer aperture, and in that multiple measurements are made simultaneously from a single image. The size of the field of view combined with the CIE specification forces minimum distances (for any specific field of view) for the illumination and the detector.

Let us say, for example, that the desired field of view of the video camera were to be 2 inches. This size would require an illumination height of at least 3.5 inches, and a distance from the center of image of at least 3.6 inches. The detection must be at least 3.6 inches from the sample area.

Allowing for some safety margin, we will investigate a system which uses a 6 inch height for bulbs and camera. It would appear from this analysis this height would be well within the acceptable limits, and that the geometry of the system would not pose a limit on its accuracy.

Designing to This Spec, First Pass

A video densitometer was built with a pair of bulbs 6 inches above the sample area, and at 45º. The bulbs were mounted opposite one another. A 6 inch working distance was used for the camera, which was mounted perpendicular to the sample. Corrections were made for scattered light within the camera, and for nonlinearity, as well as corrections for black level and for uneven illumination (Seymour).

A small patch of solid black ink on coated stock (density 1.92) was glued to a polished black glass plate (density 3.5). The purpose of the plate was to hold the patch flat and to minimize the effects of scattered light. The patch was successively positioned so as to appear at nine different positions in the field of view, and the reflectance of the patch was calculated at each position. The nine positions were near each of the four corners of the field of view, at the center of each edge, and at the center of the field of view.

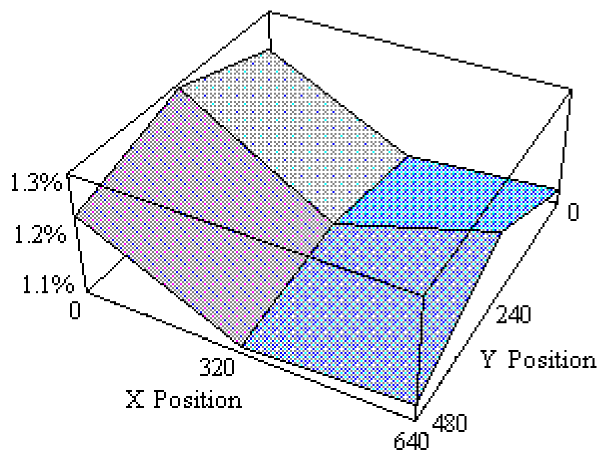

Figure 2 - Variation in reflectance around the field of view

Figure 2 shows the results of this test. The graph is oriented so that the bulbs would be to the left and to the right of the plot.

There is a consistent saddle-shaped pattern in the measured reflectances of this patch. When the patch is moved right or left away from the center column, the reflectance increases. When the patch is moved up or down from the center row, the reflectance decreases.

The density at the center point is correctly measured as 1.92. The highest reflectance is at the left edge, with a density of 1.89. The lowest reflectance is at the bottom of the image, with a density of 1.96. The total range of density (for this patch) is 0.07D.

A Theory and Experimental Verification

A theory was suggested that the variation of the reflectance around the field of view was due to the angular changes in illumination and detection that result from different positions in the field of view. To test this hypothesis, a goniophotometer was built to simulate the illumination and detection angles at various positions in the field of view. This instrument not only allows precise control over the angles of illumination and detection, but it does not use any of the same equipment as the video densitometer. If the goniophotometer were to generate the same variation as the video camera, it could be concluded that the “goniophotometric effect” were the likely explanation.

The goniophotometer has two arms which are mounted to a metal plate (see figure 3). They are free to pivot to any angle. A protractor (not shown) mounted to the sideplate is used to measure the angle of the arms. On one arm is mounted the illumination, and on the other is mounted the detector. Both the illumination and the detector point downward, toward the axis of the pivot.

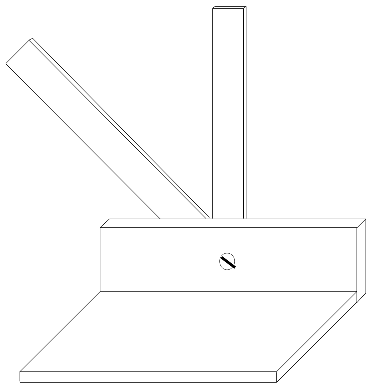

Figure 3 - Arms, baseplate and sideplate of the goniophotometer

The arms pivot about a point above the base plate. In this way, if the sample is mounted at the height of the pivot point, the illumination and detection will point to the same spot regardless of the angle of the arms. This type of motion is known as *eucentric*, so the instrument is a eucentric goniophotometer.

The eucentric goniophotometer so far described is capable of simulating the imaging geometry along a horizontal line through the center of the image. To simulate other positions in the image, a third degree of rotational freedom is required. This degree of freedom is provided by the stage shown in figure 4. Tilting the stage is equivalent to shifting from the center horizontal line in the image to another horizontal line in the image.

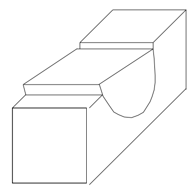

Figure 4 - the stage

The height of the stage is such that it brings the sample up to the eucentric point of the arms. Note that the stage is itself eucentric, so that the goniophotometer is fully eucentric in its three angular degrees of freedom. We need not concern ourselves with the sample point moving as we change the angles.

Illumination is provided by a 35 watt halogen light bulb. In this experiment, the bulb was run at 12.4 volts. The bulb has a parabolic reflector. Scattered light from the bulb is reduced by shining the light through a short section of black PVC pipe. At the end of the PVC pipe is mounted a hot mirror. This is a piece of glass with coatings so that infrared light is reflected, and visible light is passed. This mirror reduces heating of the sample area, and also reduces the unwanted IR illumination which the detector is sensitive to. An aperture is mounted at the end of the pipe to limit the scattered light.

A silicon photodiode is used as the detector. The detector is mounted at the top end of a six inch tube, one inch in diameter. An aperture of 0.06 inch is fitted to the bottom to restrict detection to a small angle of light from the sample. A second 0.06 inch aperture is placed 1.5 inch above the first aperture to reduce scattered light. A second IR cut filter was mounted below the lower aperture.

An amplifier was added to the detector assembly. The amplifier is necessary, since the amount of light delivered to the detector is quite small. The output of the amplifier is digitized with a digital voltmeter.

The goniophotometer arms were positioned to angles corresponding to each of eleven positions across the center row of the image. At each position, the black patch and a white reference (white paper from the same sheet) were measured. Data was collected with the stage flat, and with the stage tilted to 7º to simulate the top and bottom rows of the image.

x (in.)	α (°)	β (°)	0° White	Black	7° White	Black
1	9.5	49.4	31.819	0.370	31.428	0.360
0.8	7.6	48.6	32.548	0.385	32.221	0.370
0.6	5.7	47.7	33.174	0.398	32.924	0.386
0.4	3.8	46.8	34.115	0.418	33.703	0.404
0.2	1.9	45.9	34.666	0.437	34.289	0.418
0	0.0	45.0	35.494	0.460	35.172	0.442
-0.2	-1.9	44.0	36.330	0.491	35.896	0.471
-0.4	-3.8	43.0	36.970	0.530	36.327	0.503
-0.6	-5.7	42.0	37.763	0.590	37.040	0.541
-0.8	-7.6	40.9	38.640	0.657	37.740	0.598
-1.0	-9.5	49.8	39.625	0.745	38.565	0.669

Table 1- the goniophotometer results

Table 1 shows the raw data from the experiment. The first column is the x position within the image, where "0" is taken to mean the center of the image, and the light is positioned far to the negative side. The second and third columns of the table record the angles for the detection and the illumination, respectively. The fourth and fifth columns of the table (labelled "0º White" and "Black") are the raw values read from the meter (in millivolts) with the stage in the 0º position. This simulates the readings taken through the center of the image. The final two columns list the same values

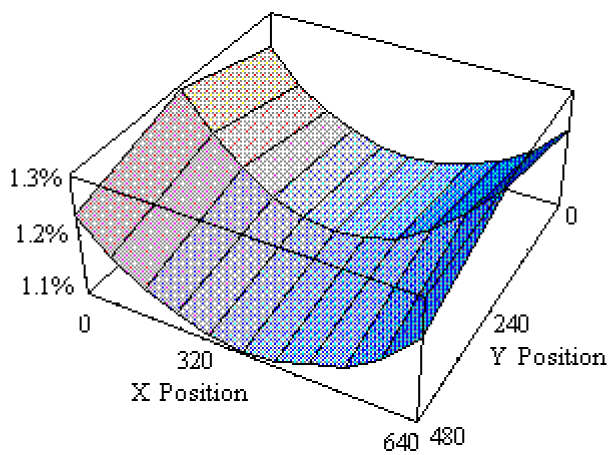

Figure 5 - The goniophotometric effect

collected with the stage set to 7º, which simulates the angles for the top and bottom rows of the image.

Since the goniophotometer only has a single illumination source, data from opposing sides was combined to simulate two bulbs. Figure 5 shows the result of this calculation. The data agrees with the camera data (see figure 2) both qualitatively and quantitatively.

The conclusion is that the small variation in reflectance across the field of view which has been noted in a video densitometer is due to the goniophotometric effect. What is the cause of the goniophotometric effect?

Reflectance 101

The traditional theory of reflectance states that surfaces are classified as being either specular or matte.

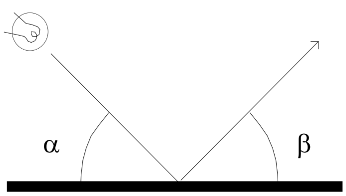

Figure 6 - specular reflection (when $\alpha = \beta$)

Specular (also called glossy, or mirror-like) reflection is illustrated in figure 6. Gloss occurs when the illumination and detection are arranged such that the angle of incidence (angle α) is equal to the angle of reflection (angle β). For a purely glossy surface, all the incident light is reflected in this manner. For a purely glossy surface, the detector will see no light in any other direction.

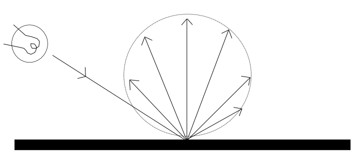

Figure 7 - matte reflection

Matte (also called diffuse, or flat) reflection is illustrated in figure 7. The figure is referred to as an *indicatrix*. With diffuse reflection, light is scattered in all directions. The intensity of the light at any angle is proportional to the cosine of the angle of reflection. Since the surface is foreshortened with the angle of detection (thereby increasing the surface area corresponding to a collection angle), a purely matte surface appears equally bright from any direction.

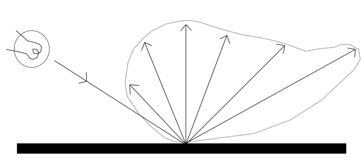

Figure 8 - general reflection

Specular and matte describe the extremes for surfaces. Almost all surfaces lie between these extremes. Figure 8 shows the indacatrix of a more typical surface. There is a general preference for light to reflect in a specular manner, but there is still a fair amount of reflection at all angles. (See Billmeyer and

Saltzman, or Hunter.)

This theory may be used to explain the goniophotometric effect. If paper and the ink printed on it have the same gloss characteristics, then the reflectance (ink reflectance relative to paper reflectance) will be the same for any geometry. If, on the other hand, we assume that paper and ink have slightly different indicatrices, then the relative reflectance may depend on geometry.

Revisiting the CIE Specification

We are left at this point with an apparent contradiction. On the one hand, the video densitometer seems to be in designed in accordance with the proper specifications in terms of geometry. On the other hand, this instrument seems to have a significant variation in readings due to geometry.

To attempt to reconcile this contradiction, we can reconsider the meaning of the specification. The specification for a “point sensor” densitometer was applied directly to the “multiple point sensor” densitometer. The video densitometer is actually a collection of several hundred thousand densitometers – one densitometer for each of the pixels in the image. Each of the pixels individually is a densitometer which must meet the geometric specification.

Does each pixel meet the specification? Figure 9 shows the geometry for a pixel on the left-hand edge of the image, center row, with a single bulb. From the diagram, it is seen that the central beam angle of the detection (9.5º) is just within the specification. The central beam angle for the illumination (39.8º), however, is not within the allowance of 45º ± 2º.

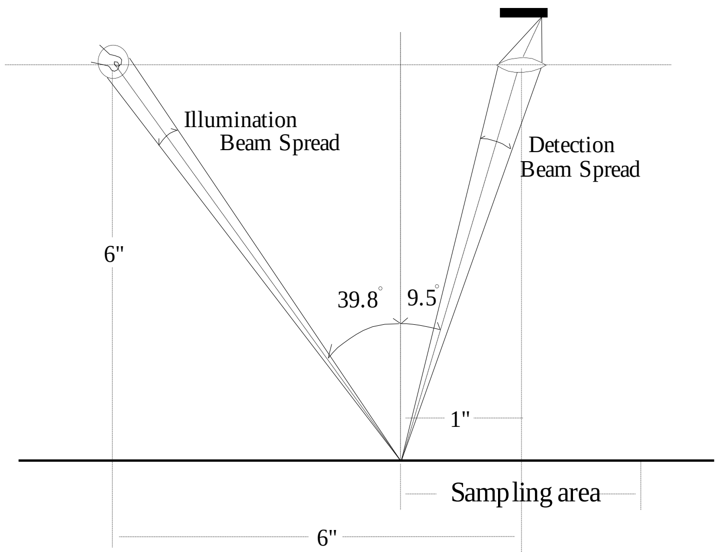

Figure 9 - Revisiting the geometry spec for an edge pixel

The illumination beam spread is calculated as the angle the filament (or the spark gap, if strobe lights are used) makes at the distance it is from the pixel. An estimate of 0.1" is made for the spark width. This gives an illumination beam spread of 0.7º.

The detection beam spread is computed as the angle the aperture of the camera makes at its working distance. The aperture size (for the imaging conditions of the experiment) was on the order of 0.2". This gives a detection beam spread of 1.9º. The beam spreads are well within the specification.

Figure 9 does not tell the entire story, however. In the experiment, there was a second bulb, to the right of the video camera. This second bulb is at an angle of 49.4º from the same left edge pixel.

How does this second bulb effect the measurements? For the pixel illustrated in figure 9, the reflectance with just the bulb on the left would be higher than the reflectance at the center pixel. The difference is due to the fact that the geometry is closer to the specular angle. By similar reasoning, the reflectance with just the bulb on the right would be lower than that at the center. Therefore, with both bulbs, the reflectance errors will tend to balance, so that the overall effect is not as severe.

This raises the question, how is the central beam angle and beam spread determined for a two bulb system?

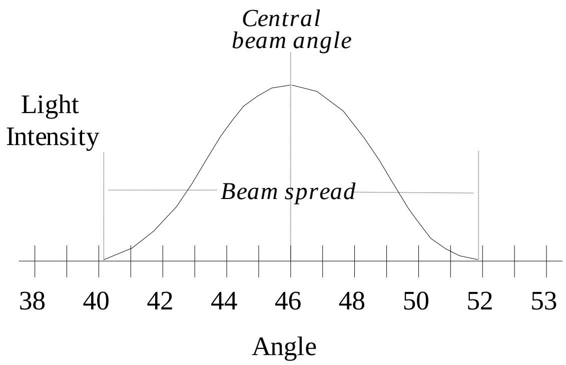

Figure 10 - typical angular distribution

One possible way to answer this question is to treat the two bulbs as if they were a single bulb with an unusual distribution of light. In a system with a single bulb at 45º, not all the light will be coming in at exactly 45º. There will be some amount of light which hits the sample at slightly under 45º, and some amount at slightly above 45º. Figure 10 shows what the angular distribution for a single bulb might be. In this example, the central angle of the beam (46º) is within the specification of 45º ± 2º, and the beam spread (±6º) is within the specification of 8º. This illumination would be considered acceptable.

Figure 11 shows the angular distribution of the illumination at the center of the far left edge in our experiment. There is a peak centered at 39.8º from the left-hand bulb, and a peak at 49.4º for the right-hand bulb. It will be noted that the widths of the peaks are nearly the same, since the angular width of the strobe arc is inversely proportional to the distance. The heights of the peaks show greater disparity, since the intensity of the illumination is inversely proportional to the *square* of the distance.

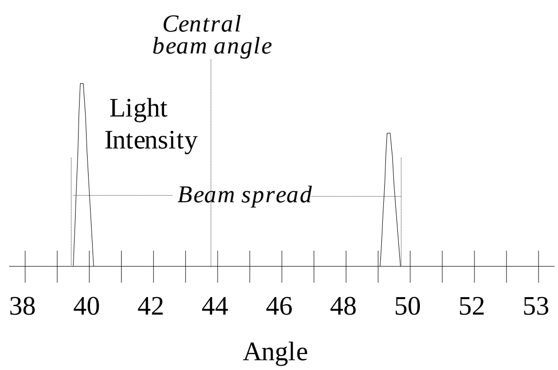

Figure 11- angular distribution for two bulb system, at far left edge of FOV

The central beam of the illumination (the “average beam angle”) is shifted to the left due to the additional light intensity from the left-hand bulb. The central beam angle is 43.8º, calculated as an average of 39.8º and 49.4º, weighted by the reciprocals of the squares of the distances. This is within specification. The beam spread (from 39.45º to 49.7º) is also within specification. The illumination geometry is thus within specification, as was the viewing geometry.

We are back to the same contradiction. An instrument exhibits significant variation in reflectance as the geometry is varied within the limits for geometrical variation. I conclude that the intent of the specification is not to define design parameters which will *guarantee* accuracy or inter-instrument agreement.

It must be noted that any specification is a simplification of the complicated real world, and is arrived at as a consensus of experts in the field. As a rule, standards are broader than someone concerned with accuracy might desire. The CIE specification itself states

> *Measurements of some types of specimens (for example retro-reflective materials) may require smaller tolerances.* (section 1.4, p. 16)

I would also suggest that the video densitometer is presenting novel information. Bringing together densitometric data from a quarter of a million densitometers is inconceivable with conventional instruments! It may well be that the disagreement historically seen between instruments is (at least partly) due to geometric variation, in addition to being due to widely acknowledged differences in spectral sensitivities and nonlinearities. Between two densitometers, it is easy to calibrate this deviation out and forget it. In a video densitometer, the variation is a bit more obvious. (For further discussion on goniophotometry and errors measuring reflectance, see Spooner).

Models for Goniophotometric Variation

A cursory search of literature in the graphic arts turns up little which addresses this question. There are a fair amount of papers which discuss the question of which geometry is most applicable for the graphic arts, however only one paper was found which looks at modelling goniophotometric error.

In a paper by Gardner et al, the question is asked whether colorimetric data of newsprint collected from a small portion of the hemisphere can be used to predict colorimetric data collected with a full hemisphere. Their results are promising. The indicatices which they collect are quite well behaved and predictable. One limitation of their work (from our point of view) is that they have only dealt with colored newsprint. They have reported no data from coated stocks nor paper with ink.

The literature in the field of general colorimetry has more information about the goniophotometric effect. Most texts on colorimetry cover the topic of specular versus matte reflection, and Billmeyer discusses the source of goniophotometric variation qualitatively.

Consider an idealized version of reflection from ink on paper. Figure 12 shows a highly magnified view of some paths which light might take. A small portion of light reflects specularly from the surface of the ink. This represents roughly 6% of the incident light. [I have assumed an index of refraction of 1.6 and used Fresnel's laws of reflection. The number 1.6 is the measured index of a sample of a modified phenolic resin, which is one of the major constituents of ink.]

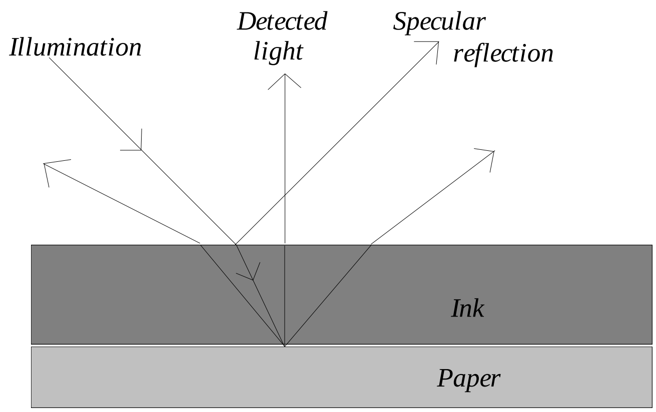

Figure 12- Idealized reflection from ink

The remaining 94% of the light enters the ink, reflects diffusely from the paper and re-exits. Due to absorbption in the ink, the light intensity is attenuated to perhaps 1% of the original intensity.

Next, consider a somewhat less idealized version of the same story. Figure 13 shows several paths of specular reflection from a rough ink surface. It is seen in the figure that specular light will be reflected into the detector wherever the surface tilts toward the illumination at 22.5º. Thus, some percentage of the specular reflection will be measured by the detector. Considering that the total nonspecular light is on the order of 1%, a small amount of specular contamination can cause a large relative change.

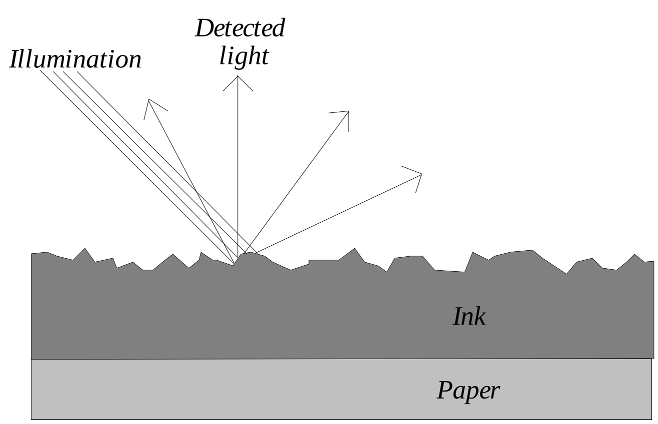

Figure 13 - Scatter of specular reflection

The amount of specular reflection measured by the detector ultimately depends on the percentage of the surface which is angled toward the illumination at this critical angle. If we look at the left-hand edge point of the image, the surface tilt required to introduce specular reflections into the detector is only 15.2º, as compared with 22.5º in the center. The higher reflectance at the edge is due to the fact that there is a greater percentage of surface tilted at 15.2º toward the illumination than there is surface tilted at 22.5º toward the illumination. If we knew the distribution of surface angles for a sample, it would be possible to determine the indicatrix.

Much work has been done in the optics community to relate physical measures of roughness with goniophotometric data (see two texts, Beckman and Spizzichino, and Bennett and Mattsson). In "Total Integrated Scattering", the standard deviation of the surface height and the wavelength of light used to estimate the ratio of specularly reflected light to diffusely reflected light. "Angle Resolved Scattering" and "Bidirectional Reflectance Distribution Function" seeks to determine the indicatrix from statistical information about the surface (specifically, from the autocorrelation of the profile).

In a very informative paper, Robert Sève manages to cover all aspects of the subject of gloss. He broadly categorizes all the previous models as "physical optics". Relevant to this paper, he presents goniophotometric data for surfaces with differing amounts of roughness. He comes to the conclusion that the physical optics models are best applied to surfaces with "optical quality roughness". Fung concurs with this conclusion. The models work well at predicting the scattering from, say, a well polished mirror. These models are not applicable to ink on paper.

The second category of model which Sève describes is "geometric optics". The geometric optics model traces back possibly to Bouger (1760's), but was apparently not well developed until W. W. Barkas in 1939. The assumption is made that the surface can be modeled as a collection of facets. These facets are either specular, reflecting light only at the specular angle, or they are diffuse, reflecting light in all directions.

From this simple model, we would expect that the indicatrix could be modeled as a weighted sum of a diffuse model (proportional to the cosine of the angle between detector and surface normal) and a specular model (which strongly peaks when detection is opposite illumination). The strength of the specular term off the specular axis is generally approximated as being some power of the cosine of the angle away from the specular axis.

This model has been used extensively. The paper by Gardner et al used this model to approximate the indicatrices of newsprint. B. K. P. Horn used this model in the field of image analysis to derive information about an object's shape from reflectance seen across the object. J. C. Russ recommends this model for shading computer rendered pictures. (Curiously, none of these papers list any references for the formula, but all three models boil down the the same concept.)

Application of the Model to Ink on Paper

Data was collected with the goniophotometer previously described. Four samples were chosen, a sample of coated stock without ink, and three samples of coated stock with black ink of various densities. Since uncoated stock has been treated previously, there were no samples of uncoated stock. Inks other than black were not considered, to reduce potential confusion about spectral response.

In these experiments, the detector was fixed at +45º, and the illumination was swept from -70º to 20º in 5º increments. Although illumination at 45º would have been prefered, it was more convenient to leave the detector fixed. The assumption of optical reciprocity is made. It would have been useful to sample beyond 20º, but the arms unfortunately collide when they are within 12º of each other.

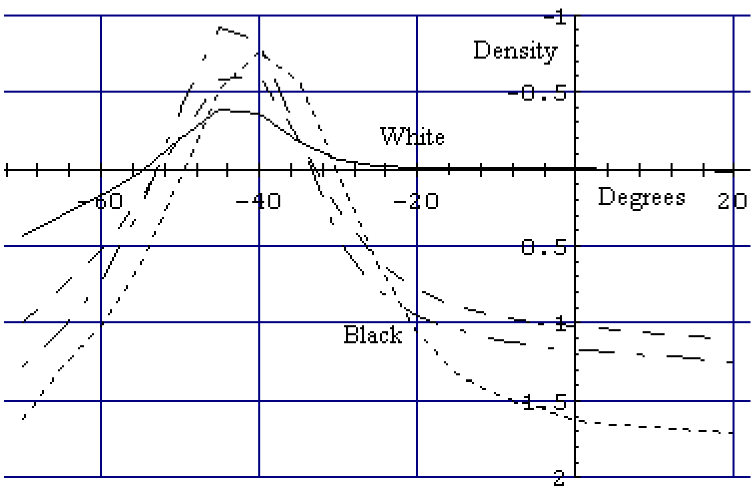

Figure 14 - goniophotometric curves for four samples

Figure 14 shows the results of the experiment. Note that the data has all been normalized to the 0º/45º reflectance of the white sample. The Y axis is logarithmic, that is to say, reported in density. As is readily seen, the specular density approaches -1 for these samples. This is a measure of the highlights reflected from the paper.

One interesting phenomena is that the three samples of ink-coated stock all have higher specular reflection than the white paper. At the specular angle, black ink is whiter than white. This may initially seem counter-intuitive, but it makes sense when it is realized that a layer of ink will tend to smooth out the roughness of paper.

Another item which is not as readily explained is the fact that the reflectances of the samples 1) all peak to the right of 45º, and 2) all peak in different places. At first thought, this seems to indicate an instrument problem. After all, the light intensity *must* be greatest at the specular angle. Suspecting this in earlier data, the placement of the protractor was carefully verified. To avoid possible angular error due to contouring of the samples, the paper was glued to cover slips (as used on microscope slides).

The explanation lies in the fact that the plot shows the combined effect of specular and diffuse reflections. The specular reflections will indeed peak at the specular angle, however, the diffuse reflections are constantly increasing up to 0º. The diffuse light slightly skews the sum, so that the peak is closer to zero.

The white sample and the sample with the highest density were selected to assess how well they fit the model introduced in the last section. Figures 15 and 16, respectively, show the model fits. (Note that in these plots, the Y axis is in reflectance, rather than density.)

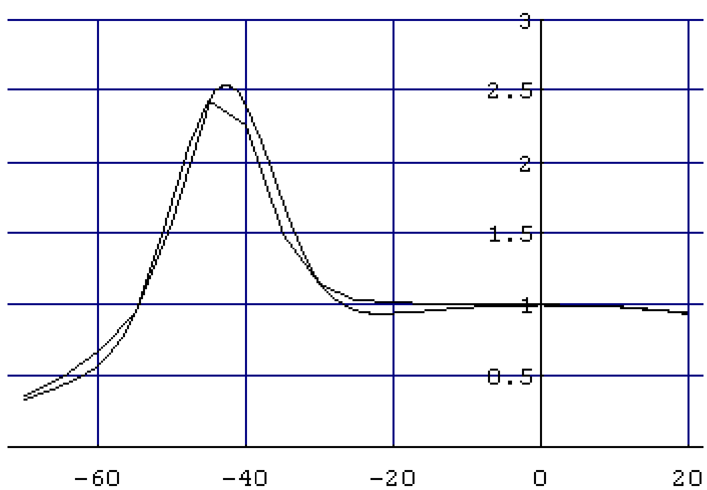

Figure 16 - model fit to the white patch

The equation of the model for the white patch is

$$1.0\cos\theta + 1.8\left(\cos(\theta - 43)\right)^{70}.$$

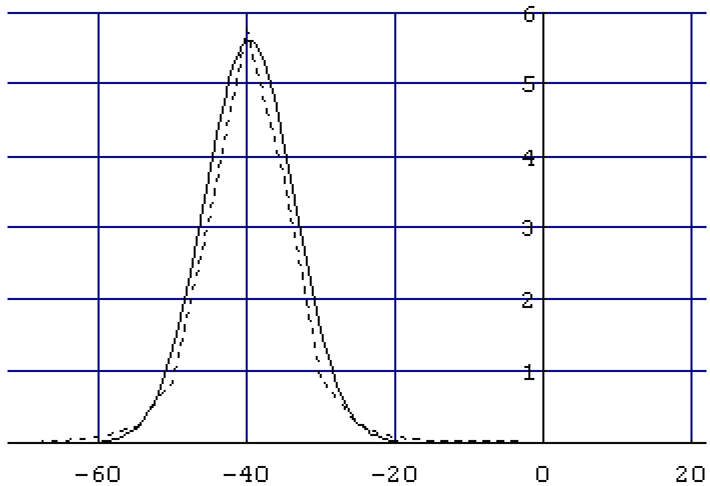

Figure 17 - model fit to a black patch

The equation of the model for the black patch is

$$0.01\cos(\theta) + 5.6(\cos(\theta - 40))^{90}.$$

Thus we see that the data is fairly represented by the model. It is evident that there are some trends to the errors, suggesting that the model can be improved upon. One suggestion for further improvement lay in the choice of specular functions. The particular choice made (cosine) has the property that it will reach zero at a point perpendicular to the specular axis. Beyond that point, it increases (if the power of the cosine is even), or goes negative (if the power of the cosine is odd)! This obviously does not describe the physical situation.

Harvey has suggested a means for warping the specular function such that this anomalous behavior is avoided. Application of this is beyond the scope of this paper.

Conclusions

This paper provides the background for making engineering decisions about minimizing and correcting goniophotometric error in a video densitometer.

Small, but persistent errors in a video densitometer have been described. An experiment was recounted which demonstrated that the errors are goniophotometrically induced. Angular specifications for densitometers were investigated. It is pointed out that adherance to the specification does not necessarily imply accuracy. A brief review has been made of literature concerning reflective scattering. From this, a qualitative description is made and an empirical model is reviewed. This model was tested for applicability to ink on paper, and found to be in fair agreement.

Acknowledgement

The author would like to acknowledge the work of Frank Vroman, whose “Yankee ingenuity” brought the goniophotometer from an incomplete concept to a physical reality in an unbelievably short period of time.

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