Standards Considerations
for
Video Densitometry

Preliminary version

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1. Abstract

The past decade has seen dramatic technological advances in video cameras with charge-coupled devices, both in quality and in price. Concomitant with this are the widespread availability of frame capture boards, and the advancement of general purpose computing power to the point where computationally-intensive image processing is becoming mainstream.

There is also burgeoning market pressure for color measurement devices as a means to provide consistent color, as prepress shops become more reliant on electronic prepress, and as printers and their customers become more quality conscious.

These two observations brought together make it natural to use a color video camera (with frame grabber and computer) to measure color. Building a video densitometer or colorimeter which can be made to report accurate measurements is, however a substantial undertaking.

In this paper, the issues involved in getting accurate density from a video based system are discussed. The general categories discussed are calibration issues, dealing with scattered light, system geometry, and getting adequate precision.

2. Introduction

There has been considerable debate in the literature as to whether a CCD camera is suitable for use as the sensor in a densitometer. Many authors have argued that the CCD camera is not an accurate device for density measurement:

> "These detectors [CCDs] are, however, not efficient enough to meet the measuring requirements of high-quality prints, in which the black printer may have a density scale of up to 2.5 D-units." [14]
>
> "If the density rises a lot above 1.0D-units, the non-standard illumination geometry of the measurement by the matrix camera and the instable flatness of the paper web seriously disturb the accuracy of the measurement." [15]
>
> "When compared with discrete photo detectors, the CCD sensors suffer from rather low signal dynamics, poor noise figures and even low speed due to the serial readout mechanism." [27]
>
> "As [Miles Southworth] points out, the thousands of sensors in each camera each has its own gain and color sensitivity. Sometimes each has a signal-to-noise level that makes it difficult to measure low levels of light accurately." [1]
>
> "One error which has not received much attention which can severely degrade performance is veiling glare." [31]

In contrast, several authors argue that CCDs can be used for measuring density:

> "In comparison with traditional densitometry the technique with CCD-camera and image analysis described in this paper has shown that the two techniques have given results in full correspondence. This means that the CCD-camera technique can be used as a traditional densitometer." [16]
>
> "Acceptable levels of performance may then be achieved by careful hardware selection and sufficient image processing." [18]
>
> "…there are many pitfalls due to the deviation of real cameras from idealized camera behavior… careful modeling and active control can compensate for imperfections of real systems." [19]
>
> "…a complete understanding of video camera technology can be utilized to compute densities that are accurate enough for the pressroom." [21]

This paper documents the issues which must be dealt with in order to accurately measure density with a CCD-based camera. It is the contention of this author that with an understanding of the source of the degradations, it is possible to engineer a video densitometer which provides adequate accuracy.

3. Calibration issues

3.1 Black calibration

Ideally, one would want a reading of zero to correspond to “no light”. This is generally not the case, however, due to numerous causes (dark current, DC restoration and an analog offset in the frame grabber). This necessitates the measuring of the “photometric zero” (PMZ) level, that is, the level read when no light is present.

Since electronic circuits drift (particularly with temperature), it is periodically necessary to calibrate the PMZ level. Ideally, this calibration is performed automatically. If a system has sufficient ambient light protection and is capable of disabling the illumination while capturing a black reference, this is possible. If this is not possible, then it may be possible to derive the value by looking at a black sample of known density.... but this is not recommended.

The PMZ level is assumed to be an offset which is added to subsequent readings, so it must be subtracted from levels which are read in order to compensate.

The PMZ level is most critical when high density readings are taken. An error of one gray value (one part in 256) at a zero density is roughly a 0.0017D error, whereas at a density of 2.0, the same gray value error can yield a density error of 0.2D.

3.2 White calibration

3.2.1 White reference

The illumination drifts as well as the electronics, so it is necessary to periodically sample a white calibration standard to correct for bulb instability and changes in system gain. Possible substances for standards include: pressed barium sulfate powder, Russian opal glass, vitreous tiles, and halon.

The white level calibration is used to scale the reflectance, thus accounting for any dimming of the illumination over time. The formula for reflectance (with the white and black calibrations figured in) is:

$$r = \frac{s - z}{w - z}, \qquad (1)$$

where

r is the reflectance,

s is the sampled value,

z is the PMZ value,

and w is the calibration white value.

The white value calibration is not nearly as critical as the PMZ calibration. A white calibration error of one gray value (for example) will yield a 0.0017D error, regardless of the density being measured. Because of this, it is not necessary to calibrate the white level as frequently as the PMZ.

3.2.2 Spatial variability of white reference

If a uniform white surface is viewed with a video camera, the intensity that the camera sees will most likely vary quite a bit. There are a number of reasons that a uniform white surface will not read uniformly across the field of view:

1. The level of illumination may not be uniform across the field of view.
2. The corner pixels of the camera do not “see” the aperture straight-on so that the solid angle subtended by the aperture is smaller as one moves away from the center. This so-called “vignetting” causes the intensity of a uniformly illuminated field of view to drop off away from the center.
3. There is a variability from pixel to pixel in the sensitivity of the CCD to light.

These three effects are difficult to separate out. Fortunately, this is not necessary, since they all have a multiplicative effect. The effect can be corrected for by taking a white reference of a suitably flat sample, and using this image as the white reference for each pixel in Equation 1.

3.3 Spectral response and color transforms

An off-the-shelf video camera (along with the chosen illumination and spectral response of the lens) probably does not have the same spectral response as a Status T densitometer. The spectral response of one particular commercially available camera was measured. (See Figures 1, 2 and 3).

The camera’s spectral response was used to compute the “camera density” of a typical set of inks. These densities were compared with densities computed using the Status T spectral responses. The error in the camera densities was roughly 0.10D low for cyan, 0.15D high for yellow, and very little error for magenta.

From a strictly *theoretical* standpoint, it is not possible to translate an arbitrary reflectance spectrum from camera densities into Status T densities. The two spectral responses

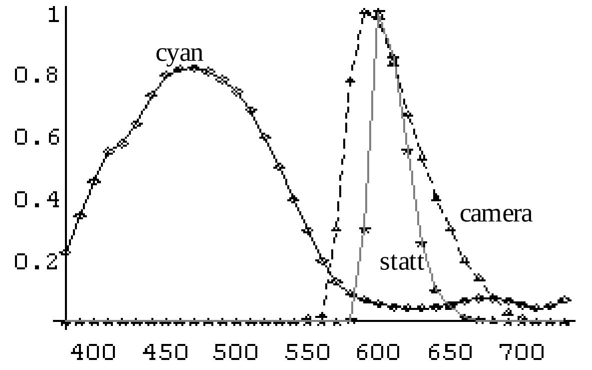


Figure 1 - Comparison of Status T red, video camera red and cyan spectra

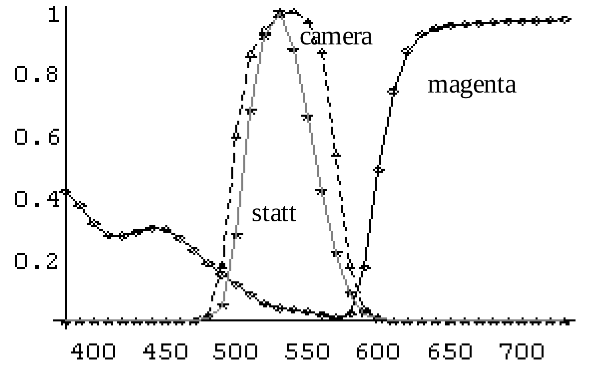


Figure 2 - Comparison of Status T green, video green and magenta ink

emphasize the spectral regions differently, so the relationship between the densities depends upon the characteristics of the inks.

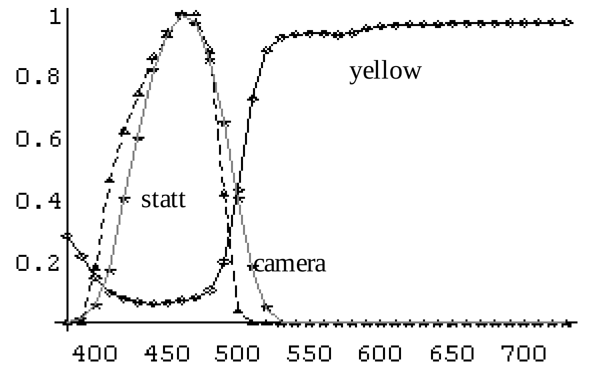


Figure 3 - Comparison of Status T blue, video blue and yellow ink spectra

From a practical standpoint, this is not that critical of an issue. First, the spectra of inks (as well as most solid objects) tends to be rather smooth. Because of this, the error of a general color transforms from camera to Status T is not very large.

Second, the spectrum of a particular ink does not take on just any spectra in a willy-nilly fashion. As halftone coverage and ink film thickness change, the ink spectra only covers a small subset of all possible spectra. This further restriction of possible spectra makes it possible to calibrate a color transform for a particular ink set with fair accuracy.

For further information, see [21], [24] and [32].

3.4 Nonlinearity

Video cameras were designed to produce good pictures, not accurate measurements. While the CCDs themselves are fairly linear (to within 0.1%), the amplifiers in the camera may depart from linearity by 1% or more. Furthermore, video cameras often employ gamma correction circuitry to compensate for the nonlinearity of video monitors. Fortunately, this can generally be disabled. Another frequent source of nonlinearity is the flash A/D converter in the frame grabber which is used to digitize the video level.

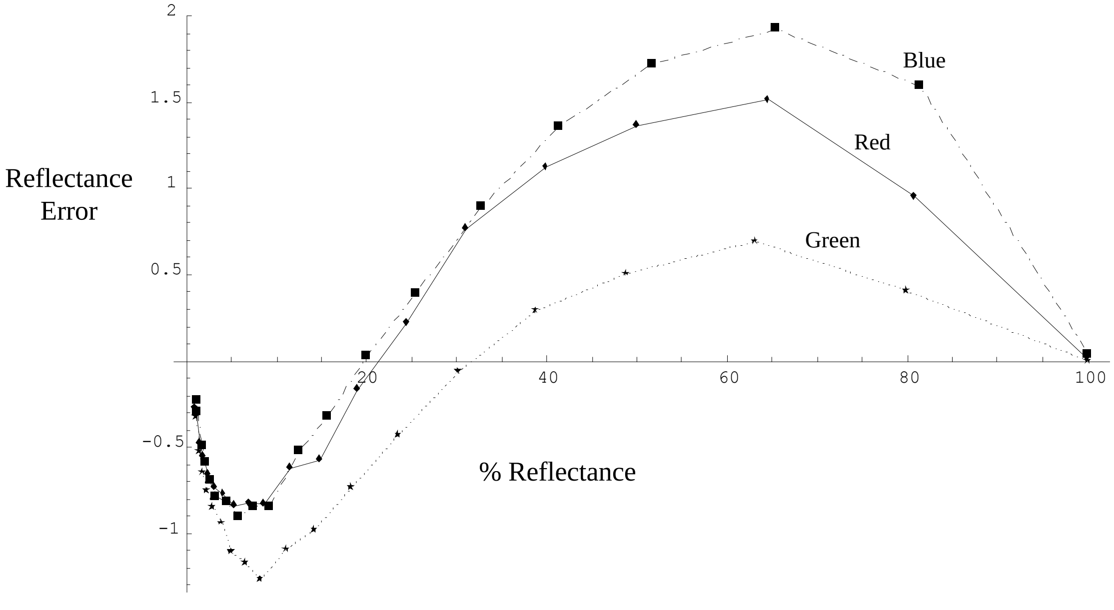


Figure 4 - The nonlinearity of an uncompensated video system

Figure 4 shows the nonlinearity for one combination of commercially available camera and frame grabber. Equation 1 was used to compute reflectance, and from this was subtracted the reflectance as measured against a reliable measurement device. The three curves represent the nonlinearity of the red, green and blue channels.

To help understand the shape of Figure 4, first consider Figure 5. The “Theoretical output” curve represents the ideal relationship between “light in” to “gray value out”. The “Actual” curve shows the exaggerated actual output of the camera. At low levels, the actual response is delayed due to the biasing of the amplifier. Once this is overcome, the “Actual” curve runs roughly parallel to the “Theoretical output” curve.

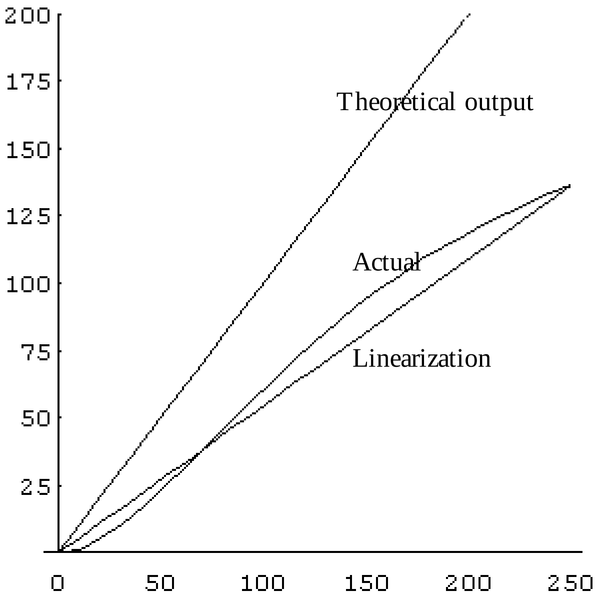


Figure 5 - relationship between light in and video levels out

At high input levels, saturation comes into play. Saturation is introduced as the CCD pixels reach their maximum capacity, as the amplifier tops out, and (abruptly) as the digitizer reaches the upper limit.

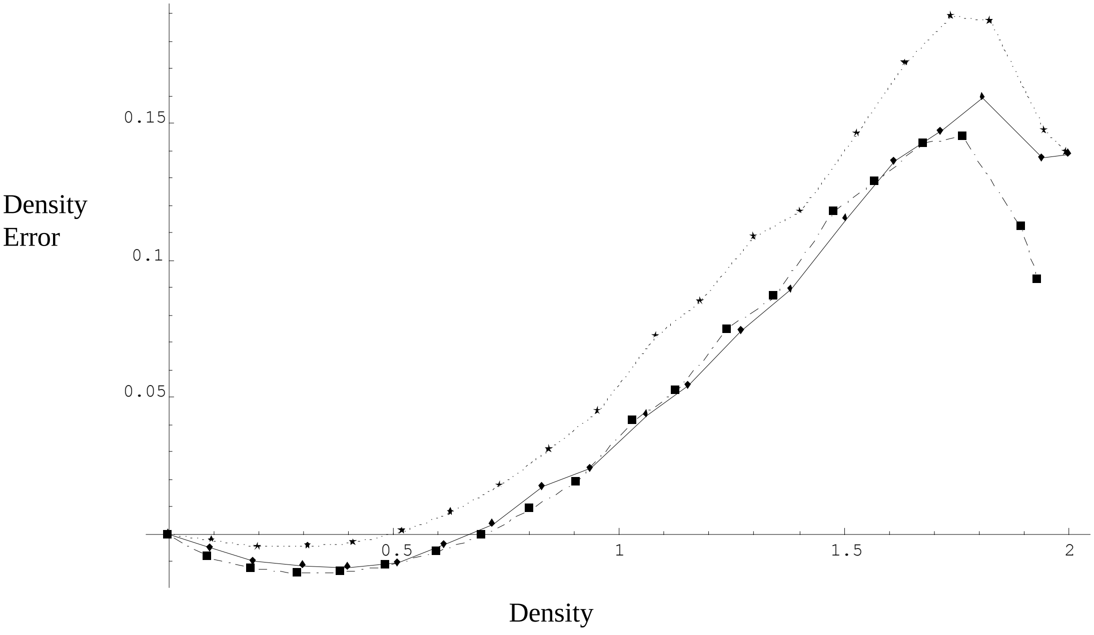


Figure 6 - Density error

In applying Equation 1, the calibrated white level (about 130 in the plot) is used as a tie point so that the error here is zero. Similarly, the PMZ point has zero error because of calibration. The result of calibration is the curve labeled “Linearization”. Figure 4 represents the difference between “Actual” and “Linearization”.

The effect of this error on density is illustrated in Figure 6. Note that the density error on the left side of the plot (between 0.0D and 0.7D) corresponds to reflectance on the right side of Figure 4, with reflectance from 20% to 100%. The effect of nonlinearity here is minimal. Far and away the larger effect of nonlinearity occurs at the lower levels.

Correction for nonlinearity is very easy once the nonlinearity is known. It can be done via look-up table, interpolation from a look-up table, fuzzy logic, or a neural network, for example. One caveat is that the exact shape of the curve will vary with temperature as well as from one camera to the next.

4. Dealing with scattered light

4.1 Lens flare

In a perfect lens, all the light which enters the lens from a point on the sample will be focused to a point on the CCD. In a real imaging system, however, a small amount of light is scattered within the lens. This means that we do not get as sharp an image as we would with perfect optics. The image we collect is the true image convolved with the point spread function of the optics.

Some steps can be taken to minimize scattered light. These include black coatings on all internal surfaces of the lens, apertures which are extremely thin (especially if the aperture is very small), and antireflective coating on all glass surfaces. These make the lens more expensive, but there is a limit to how much these measures can correct. One must weigh cost against benefit.

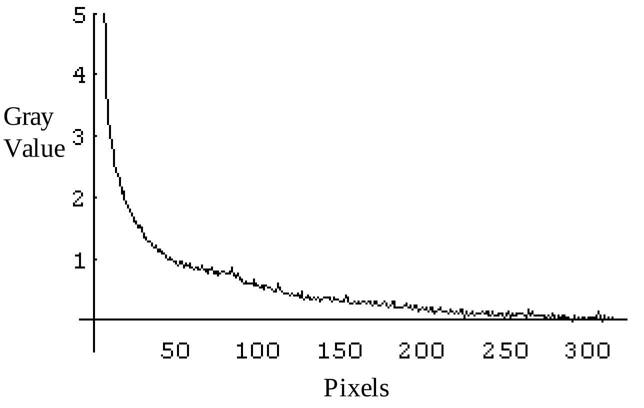
4.2 Internal reflections from cover plates

Another source of blur similar to lens flare is the aluminum shield which most CCDs have over the non-imaging areas. This area reflects on the order of one-half the incident light. Light is reflected from the CCD and can be re-reflected to the CCD by a glass coverplate which protects the fragile CCD against scratches. Since the twice-reflected light may not be imaged at the original pixel, this is a source of blur.

The most direct means for reducing this problem is to attack the problem at its source. On the order of half the light which hits the CCD will hit on the aluminized area, and half of that will be reflected. Merely giving this aluminum a black coating will reduce the problem of reflected light from a small problem to an insignificant problem. CCDs are available with such a black coating (called “black mask CCDs”). An anti-reflective coating on the CCD coverplate will also reduce the reflection significantly.

4.3 The effect of scattered light

Figure 7 - Image taken from an edge



In Figure 7, we see a profile of an image of an edge. The image was white on one half (gray values of about 240), and black on the other (gray values of 0). The edge is at position 0 of the graph. We can see that up to 50 pixels from the white edge, the gray level is increased by more than a full gray level. This is only 0.4% error in reflectance, but the error is exacerbated at high densities. If this 0.4% scattered light is added to an area with density of 2.0D, the system would report a density of only 1.85D.

In one test, a small black patch was surrounded with a black background. The measured density was 1.9D. Placing white paper around this patch reduced the measured density to 1.4D.

One solution to this problem would be to require that color patches be surrounded by 200 pixels of black. In this way, the scattered light at the color bar would be minimized. This is not a realistic request!

One particularly difficult aspect of this problem is that the amount of change in gray level due to scatter depends on the brightness of the surrounding area. If the bleed up to the color patch is white paper, there will be maximum scatter. If the bleed is completely black, there will be virtually no scatter.

A commonly implemented "solution" to this problem is to simply "calibrate the problem away". A set of patches is measured with both the video densitometer and a reliable standard densitometer. Some sort of mapping is then created to translate video densitometer numbers to standard densitometer numbers. This could be done with neural networks, or with interpolation from a look-up table. To the extent that the patches to be measured will differ in what they are surrounded by, these approaches will ultimately fail to yield accurate density.

The proper correction for scattered light can be found by deconvolving the point spread function from the corrupted image. (For further information, see [5], [8], [11], [12], [21], [25], and [26])

4.4 Lateral diffusion errors

Diffusion of light laterally into the substrate can cause errors in the measurement of density, particularly in measuring the density of extremely small patches of ink (see [28]). The errors created this way are referred to as *lateral diffusion errors*.

Grossly speaking, when we measure density, we are measuring the amount of light which travels through the ink, reflects from the paper, and travels back through the ink. At the edges of a color patch, some of the light may only make a single pass through the ink. For instance, light may pass through the ink and scatter in the paper. Some of this light may exit from the paper in an area not covered by ink. Thus, densities of ink on a broadly scattering substrate will be smaller within a certain distance of the edge of the color patch. On a substrate which does not scatter light as broadly, this "edge brightening" will not extend as far.

The standard way of dealing with this potential source of error is the *overfill requirement*. The sample area is illuminated beyond the area which is sampled. In this way, the light scattering out of the sampling area is compensated for by light scattering into the sampling area. Several standards mention this:

> "9.1.5 Process control area size
> The area shall be larger than the densitometer's mechanical aperture." [2]

> “[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.” [10]
>
> “ASTM E 805 specifies an annular ring approximately equal to the depth of penetration of the light into the specimen.” [3] and [28]

By the optical reciprocity principle, it is possible to meet the same ends by sampling a larger area than what is illuminated.

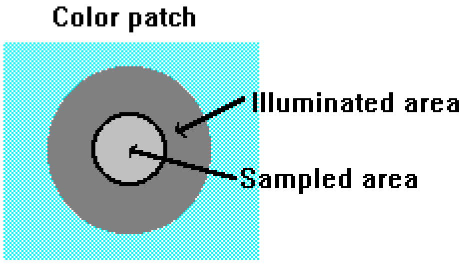


Figure 8 - Overfill by overillumination

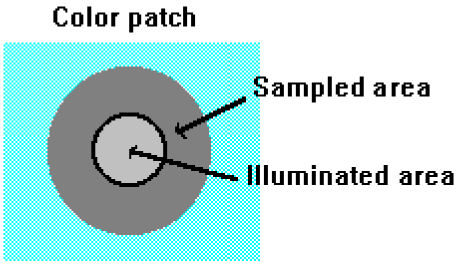


Figure 9 - Overfill by oversampling

For a video densitometer, the overfill requirement will almost certainly be met[1], since measurements are made at most all pixels, and the entire field of view is illuminated. The problem comes that video densitometers encourage the measurement of smaller and smaller color areas. Lateral diffusion errors can make it difficult to relate measurements of small patches to the measurement of larger patches.

This presents us with somewhat of a problem. Short cutoff presses allow for colorbars which are no wider than 1/16 inch (about 1.5 mm). Currently, two off-line scanning densitometer systems (from Tobias and from Xrite) claim to measure 1/16" color bars.

The extent of lateral diffusion error was measured for one particular stock and ink [23]. The edge effects were seen within 0.1 mm of the edge of the patch. For a video densitometer, this is reason to discard pixels within this region. This ability to select the area which gets included in the measurement makes a video densitometer potentially more accurate than a standard densitometer on very small patches.

There are some caveats to the use of discarding edge pixels to allow measuring density on smaller patches, however. The first is that tiny patches may actually have a thinner coating of ink than larger patches. [23] The second caveat is that the technique only works if the extent of lateral diffusion is known. This will vary between coated and uncoated stock, and will vary in coated stocks depending on the amount of opacifiers (such as titanium dioxide) added to the coating. One problem in determining the lateral diffusion is that it’s appearance is very similar to any of the blurring phenomena already in the system.

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[1] Provided the patches are big enough....

5. System geometry

5.1 Annular vs. planar geometry

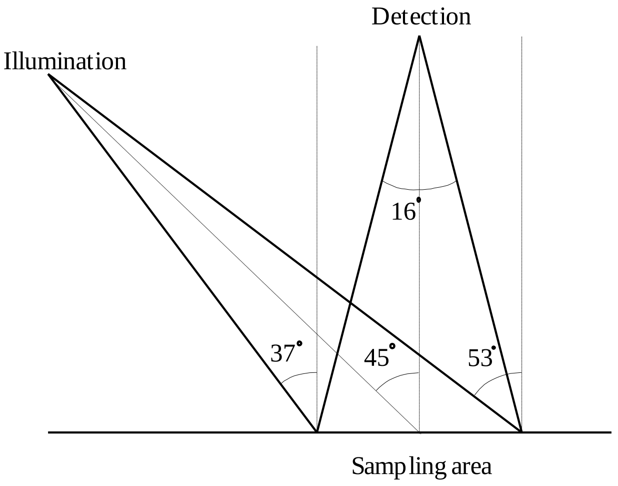
Most 45°/0° densitometers use an *annular geometry* for illumination. This means that the light travels to the sample point along the surface of a 90° cone. This is practical for a small sample point, but is rather impractical for a video densitometer with a moderate size field of view.

The most common practical solution (for a video densitometer) is the *planar geometry*, where the illumination is provided by two lights at 45° which are coplanar with the center of the field of view, the camera and with each other. It is possible for an additional set of two lights to be added, rotated about the camera axis from the first two by 90°. It is doubtful whether the slight improvement in accuracy is worth the added cost.

5.2 How close to 45°/0° do you need to get?

The International Commission on Illumination provides a definition for 45º/0º geometry which includes the acceptable range of angles ([7], [4]). 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 10 illustrates one interpretation of this specification.

Figure 10 - The range for 45°/0°



5.3 Purpose of the spec

The purpose of the specification is to avoid differences between different densitometers because of the specular component. At first glance, it would not seem that the specular component should be an issue. Wasn't 45º/0º selected to minimize this effect?

The answer lies in the “microstructure” of the paper. Looking closely at a copy of print will reveal that the surface is not perfectly smooth, but it has tiny bumps. The bumpiness means that some of the color patch will be oriented toward the illumination. Figure 11 illustrates the geometry of a hypothetical system at the center of the field of view. In the drawing, it is shown that a “microstructure inclination” of 22.5° will produce a specular reflection.

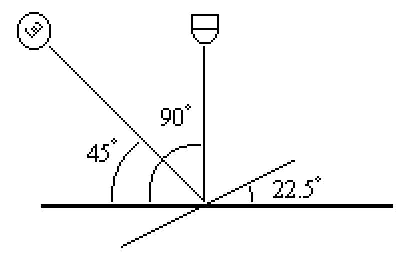


Figure 11 - Inclination required for specular reflection, at center of FOV

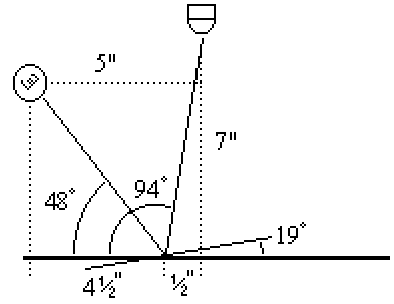


Figure 12 - Inclination required for specular reflection, at edge of FOV

Figure 11 illustrates that there is some specular reflection measured even in a 45º/0º densitometer. The reason that this is a particular problem in a video system is indicated in Figure 12. This figure roughly corresponds to a hypothetical geometry where the distance from the web to the camera is 7 inches, the illumination is 5 inches to the left (and right) of the camera, and the field of view is 1” X 1”. In this figure, a tilt of 19º is shown to be required to catch specular reflections. The probability that there is a 19º inclination in the bumps is certainly larger than the probability that there is a 22.5º inclination. This accounts for a difference in measured density between the two, that is to say, why a patch in the center of the field of view is darker than a patch at the left edge.

Some actual camera data (from a geometry similar to that of Figure 12) is shown in the 3D plot in Figure 13. This plot shows the *reflectance* change across a two inch field of view, with working distance and illumination distance similar to that mentioned above.

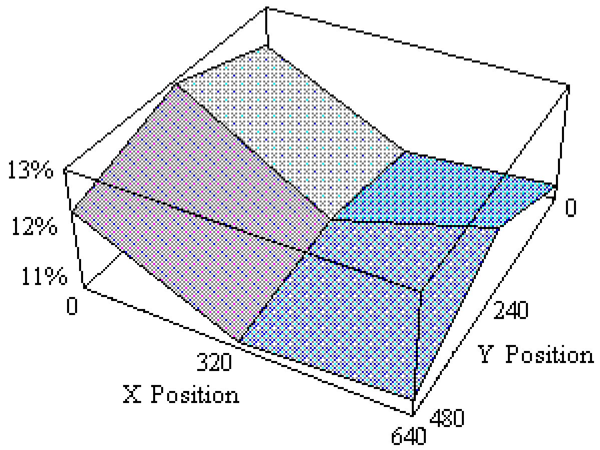


Figure 13 - Variation in reflectance due to the goniophotometric effect

A goniophotometer was built to verify that the change in reflectance seen in the camera was due to the change in angles. The goniophotometer was set up to simulate the angles (camera and illumination), and reflectances were calculated. The plot from the goniophotometer concurred with the camera plot, indicating that the angles were significant. [22]

5.4 Interpretation of angular standard for video measurements

It is tempting to replace "Sampling area" with "Field of view" in Figure 10 and use this interpretation to specify the geometry[2]. This is not the correct interpretation, however. Since each pixel in the image represents, in effect, one point-measurement densitometer, the standard must be applied at each pixel in the image.

When the pixel on the far left side of the image is considered, the light is seen to reach it with a central angle of 37°. This should be within the range of 43° to 47°, so this is out of specification.

The light leaving this spot and being detected is within specification, since light leaves at 8°, which is less than the maximum of 10°.

Figure 14 - Proper interpretation of geometry for video densitometer

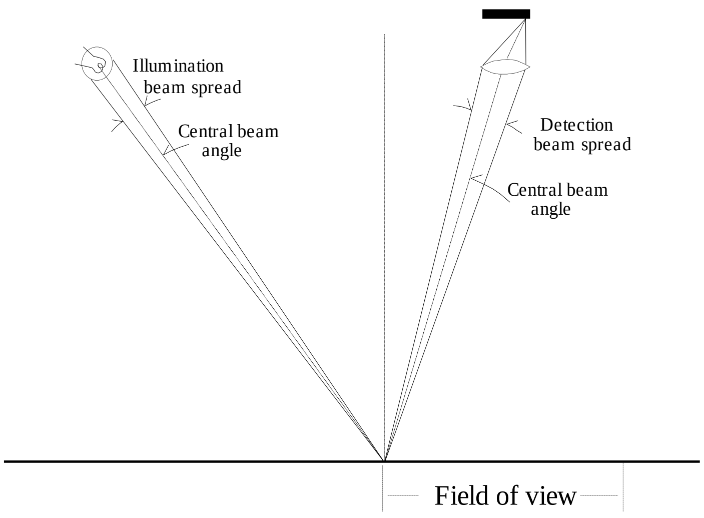


Figure 14 illustrates the proper interpretation of the standard to video densitometry. The illustration shows the geometry for a point at the edge of the field of view. Note that the big difference between Figures 10 and 14 is that in the former, the angles have their vertices at the detector and the illumination. In the latter, the vertices are both at the pixel.

Figure 15 - Central beam angles for dual light system

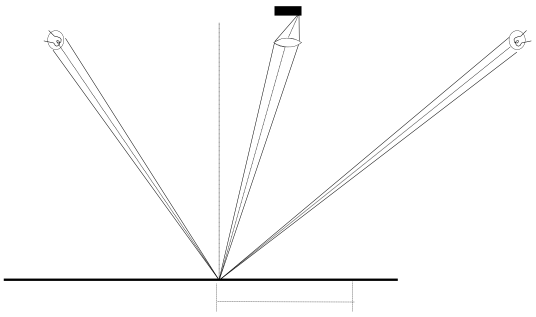


Figure 14 assumes that there is a single point of illumination. What if there are two light sources? Figure 15 shows such a system. The pixel on the left-hand side of the field of view receives light at a rather steep angle from the left-hand bulb, and a shallow angle from the right-hand bulb.

What is the central beam angle in such a case? Are there two central beam angles? Or just one, somewhere between them?

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[2] For simplicity in discussion, it is assumed at this point that there is a single source of illumination for the entire field of view.

Figure 16 - Angular distribution of light for two bulb system

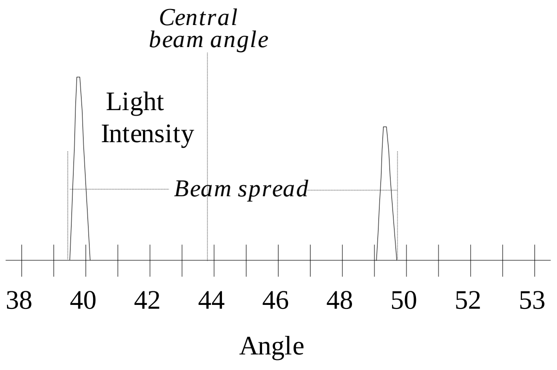


Figure 16 shows a plot of light intensity vs. angle of incidence of the light. This plot is based on the configuration in Figure 15. The left-hand peak in Figure 16 relates to the light from the left-hand bulb. Note that the intensity of this bulb is somewhat larger than that of the right-hand bulb, since the left-hand bulb is closer to the pixel in question.

If Figure 16 is the distribution of incident light, then the central beam angle must be the point at which this curve would balance. That is, the central beam angle is somewhere between the central beam angles of the individual lights. In this case, the central beam angle is just under 44⌖, so the geometry at that pixel are within specification.

5.5 Caveat - following standards does not assure accuracy

In a video densitometer, there are perhaps a quarter of a million densitometers, each with a slightly different geometry. The readings from one of these densitometers to the next will vary, even when the very same sample is moved around in the field of view. The standards expressed here for geometry are not sufficient to guarantee accurate measurements (see [22]).

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 [22] and [29]).

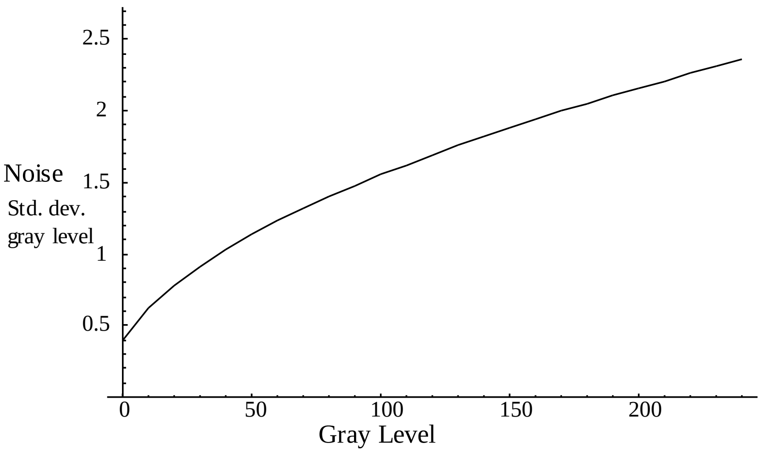
The extent that the readings from around the field of view disagree (the *goniophotometric* error) is, of course, dependent on the extent of the variation in geometry. This is minimized by making the field of view as tiny as possible, by placing the illumination as far from the sample as possible, and by making the working distance as large as possible. These are generally at odds with other design goals, so a balance must be met.

The amount of goniophotometric error is also very dependent on the characteristics of the sample. Very glossy or very matte samples will exhibit relatively small amounts of goniophotometric error. Somewhere in between the glossy and the matte, where most real-world samples lie, is where larger goniophotometric errors exist.

6. Getting adequate precision

Due to the discrete nature of light, there is a variation in the intensity that the detector will see even with the most stable of light sources, called *quantum noise*. With quantum noise, the standard deviation of the number of photons is equal to the square root of the number of photons. Paradoxically, this means that the brighter the light, the larger the noise[3].

Figure 17 - Relationship between pixel noise level and gray level in a clean video system



Let us say that a given CCD is limited to 300,000 electrons. We wish to avoid the saturation effects as we get close to this limit, so the illumination might be set so that a maximum of 100,000 photons are collected per sample time. This establishes a quantum limit signal to noise ratio of about 300:1. The plot in Figure 17 shows the standard deviation of intensity of noise over a range of intensity. At gray value of 0, there is a small amount of dark current noise. As the amount of light increases, it can be seen that the standard deviation increases as well, due to the increase in quantum noise.

Figure 18 - Same relationship, but in density

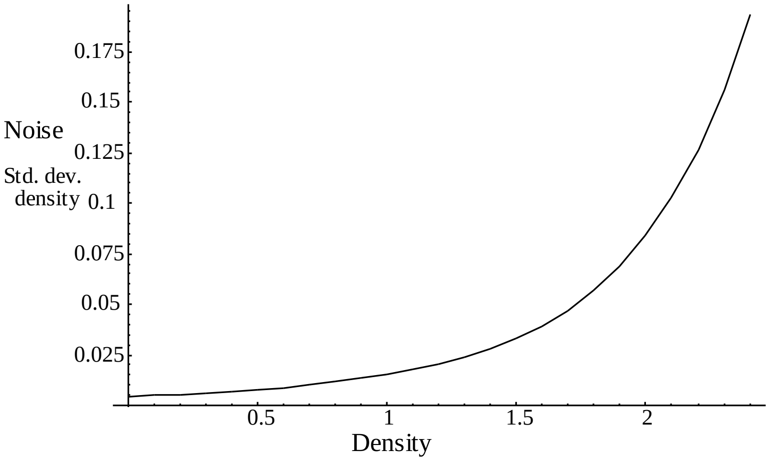


Figure 18 looks at the effect that the noise level has on density measurements. From this graph, it is seen that the effect of quantum and dark current noise is rather benign at densities below 1.0D, but the effect sharply increases above 1.0D.

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[3] Intuition leads us to expect that darker areas will be noisier. They will be noisier in the *relative* sense; the signal to noise ratio is poorest in the darkest areas. The *absolute* noise level is highest, however, in the brightest part of the image, or when the illumination is highest.

Figure 18 underscores the importance of averaging multiple pixels in order to attain precise measurements. Assuming the 300,000 electron limit, and assuming there were no other sources of noise, roughly 200 pixels would need to be averaged in order to achieve a precision of 0.01D at a density of 2.0D. This averaging can be done either spatially (by incorporating mulitple pixels from the same patch), or temporally (by averaging several patches).

Addition data on noise in imaging is available in [18]. A more theoretical treatment is available in [6].

6.1 Getting more than 8 bits out of an 8 bit A/D

Most commercially available digitizers offer only eight bits of precision. This is not nearly enough for accurate density measurements at 2.0D. To achieve precision of ±0.01D at 2.0D, roughly 12 bits of precision are required.

A naive approach would be to increase the bit depth of the digitizer (at great expense) to 10 or 12 bits. This is, however, unwarranted. The precision available in an individual pixel is inherently limited by the total number of photons that the pixel can capture. For a typical CCD, this number is 300,000, yielding a signal to noise ratio which is no better than 550:1, e.g., nine bits provided there is no other noise in the system.

Thus, since each individual pixel is too noisy, a large number of pixels must be averaged together to obtain precise measurements. It is imperative to image at a spatial resolution small enough so that each color patch has many pixels, and to average all the pixels in a patch to reduce the noise level.

I assert that averaging can increase the effective bit depth of the digitizer. This assertion has a firm mathematical and physical basis which is beyond the scope of this paper.

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