MEASUREMENT WITHOUT BOUNDS

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Keywords: color, error, measurement

ABSTRACT: During the past eight years the author has presented seven papers detailing various aspects of lateral diffusion error, (LDE) (a.k.a. edge-loss error, translucency error, and translucent blurring error). LDE is caused by the failure of the instrument to see all of the light reflected by a translucent sample. In general, this error is larger when samples of greater translucency are measured. The original aim of the present work was to derive correction functions for each type of instrument which would transform its measurement data to that of a theoretical instrument which has an infinitely large illumination area and a small view area. This paper discusses the merits of the use of presently available methods of correcting for LDE and details a new instrument configuration which allows LDE corrected data to be derived in a single measurement operation.

BACKGROUND

Instrumental measurements of spectral reflectance, color, and density can be compromised by errors from a number of interactions of instrument components with the light reflected by the sample being measured[1]. Lateral diffusion errors[2,3,4] (LDE) can occur when translucent samples are measured and some of the illuminating light from the instrument diffuses laterally in the sample to locations outside of the area viewed by the instrument detection system. In some of the literature, LDE is referred to as translucent blurring error[5], translucency error[6], edge loss error[7], and stray darkness[8]. Figure 1 gives a schematic illustration of an idealized 45°/0° geometry instrument in which the sample is illuminated by a beam of light incident at 45° from the surface normal and the detection system is viewing

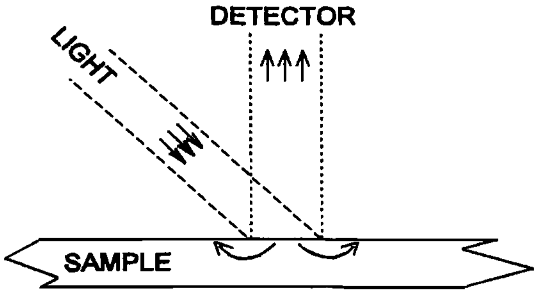

Figure 1 *Idealized 45/0 measuring configuration with the viewed and illuminated areas equal.*

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the illuminated area from above the sample (i.e. 0° from the sample surface normal). In this configuration, the light measuring system cannot detect the light that is diffused laterally beyond the common edge of the illumination and detector view areas. The light that diffuses beyond the area viewed by the detector represents the LDE - thus, the measured value reported by the instrument is the *true value*[9] less the light that has laterally diffused out of the area viewed by the detector.

The value of the LDE is a first order function of lateral penetration of light in the sample. In general, more translucent samples will have greater LDE when measured with a given instrument. Also, the backing of thinner samples can affect the LDE value - the LDE with a black sample backing is usually less than the LDE obtained when the same sample is measured with a white backing. The dimensions of the illuminated and viewed areas on the sample also affect the LDE value. For example, if the instrument uses circular illumination and viewing areas, the light not seen by detector is in an annular ring surrounding the circular area viewed by the detector. If the diameter of the illumination and viewing is doubled, the area of this annular ring roughly doubles and the area viewed by the detector quadruples. This result in the LDE being about one-half the values that it was with the smaller apertures. As the diameter of the illuminated and viewed areas goes to infinity, the LDE goes to zero. If the LDE for a given instrument configuration can be determined, then the true value of the reflectance can be obtained by adding measured value and the LDE together. This combined value represents the value that would be obtained measuring an infinitely large sample with an instrument with infinite illumination and viewing areas. Thus, LDE corrected measurements are *measurements without bounds*.

PREVIOUS LDE CORRECTION METHODS

One method of overcoming the LDE problem is to increase the area viewed by the detector so that it is greater than the illuminated area. Figure 2 illustrates this approach.

How much should the viewing area be increased relative to the illuminated area ? The increase needed depends on the range of the translucencies of the samples

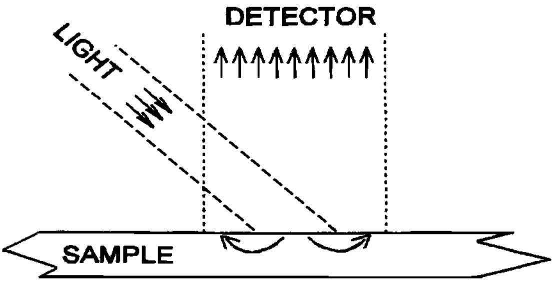

Figure 2 *Idealized 45/0 measuring configuration with the viewed area larger than the illuminated area.*

being measured. For measurements of density of photographic products, ISO standard 5/4[10] requires that the illuminated area be larger by two mm on the side than the viewed area. Helmholtz reciprocity, as defined in a paper by Clarke and Perry[11] allows the source and detector to be interchanged without affecting the measured value as long as certain conditions of optical path polarization and sample inactivity are met. Thus, a carefully designed 45°/0° geometry instrument in which the area viewed by the detector is two mm on the side bigger than the illuminated area should give the same measurement values as a carefully designed 45°/0° geometry instrument in which the area illuminated is two mm on the side larger than the viewed area. A further extension of Helmholtz reciprocity would indicate that 0°/45° geometry instruments with small view-large illumination and large view -small illumination should give similar measurement values to their 45°/0° geometry counterparts.

While the ISO two mm requirement minimizes the LDE when measuring photographic materials, it is not adequate to minimize LDE when measuring some of the color standards (e.g. BCRA red and yellow tiles) often used for calibrating color measuring instruments. Also, note that many of the instruments used for measurement of graphic arts products have illuminating and viewing apertures which differ by less than two mm on the side. Many of these instruments have apertures which are mechanically fixed and cannot be easily changed. Therefore they cannot be easily reconfigured to meet the ISO standard.

In the past the author developed a method for determining and correcting for LDE in measurements made by instruments which do not have interchangeable apertures. The method requires that two measurements of the sample be taken. One measurement is made with the sample positioned at the normal measuring position and a second measurement is made with the sample removed a fixed distance from the normal measuring position. Figure 3 illustrates one possible geometry of this second measurement. With the sample in this position, the detector can view some part of the light that has laterally diffused away from the illuminated portion of the sample. This second measurement can then be used in conjunction with calibration

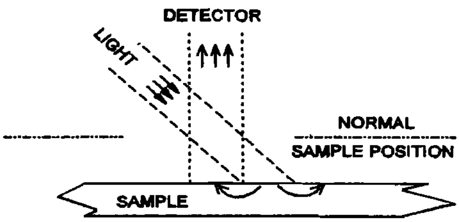

Figure 3 *A way of positioning the sample so that the detector can see some portion of the laterally diffused light.*

data obtained from samples of known translucency to predict the LDE of the measured value.

Most real world 45°/0° and 0°/45° instruments use some sort of annular illumination or viewing. This reduces the sensitivity to any grain or other azimuthal non-uniformities on the sample surface. As a sample is moved away from the port of a 45°/0° instrument which employs annular illumination, the area illuminated increases and the edge of the illuminated area begins to dim. When the sample is at a distance of about one quarter of the normal illumination diameter, there is a noticeable bright spot in the center of the lighted area. As the sample is moved further away, this bright spot decreases in diameter and the diameter of the dimly illuminated area increases. When the sample is at a distance of about one-half the diameter of the illumination aperture, this bright spot disappears. With further movement, a dark spot develops at the center. When the sample is brought to a distance equal to the normal, on-port, illumination diameter, this dark spot is approximately the same diameter as the illumination aperture. These patterns can be readily observed by placing a piece of tablet paper on the instrument port and slowly moving away from the port.

The idealized diagrams in figures 1 through 3 show the illumination and viewing channels as perfectly collimated beams. Generally, instruments use auxiliary optics which in some manner focus the view and illumination channels on the sample when the sample is in the normal measurement position. When the sample is moved away from the measuring position, the illumination and/or viewing are both out of focus. This gives a fuzzy edge both to the illumination and the detector view. For this reason, the use of this off-port correction method requires a measurement of the instrument response as a function of distance from the port using a number of samples of various translucencies. Figure 4 gives a plot of the

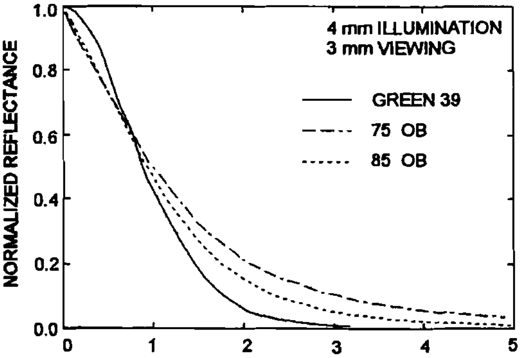

Figure 4 *Comparison of 600 nm wavelength off-port reflectance measurements of two translucent samples and a FTS Green 39 standard.*

responses of a Byk-Gardner Color Machine (BGCM) at a wavelength of 600 nm (10 nm bandwidth) when three samples[12] of different translucencies are moved away from the measuring port. Note that the Green 39 sample, which is very nearly opaque, still shows some response at a distance of two mm. This is due to the out-of-focus optical spread of the light source and the detector system. By way of further explanation, the 75 OB sample (a sample with a 75% over-black/over-white contrast ratio which was measured over a black backing) is more translucent than the 85 OB sample which is in turn more translucent than the Green 39 sample. As can be seen from the graph, at displacements from approximately one mm to three mm, the measured values correlate to the sample translucency.

In a paper presented at the 1996 Society of Plastics Engineers Color and Appearance Division Regional Technical Conference in St. Louis[13], the author described implementation of this method for correcting LDE. In this work, samples of various translucencies were measured with the BGCM equipped with a 4mm diameter illumination aperture and a 3mm diameter viewing aperture (hereafter termed a 4/3 configuration). This data was compared to measurement data taken with the instrument equipped with a 38 mm diameter illumination aperture and a 3 mm diameter viewing aperture (hereafter termed a 38/3 configuration) and the LDE for each sample was calculated. Next, a series of measurements were made using the 4/3 configuration with the samples moved back from the instrument port. Reflectance data from seven white samples of varying translucencies were then used to fit a function to 600 nm wavelength on-port and off-port measurements to the relative or normalized LDE (rLDE) of the seven samples. This function was then used to derive LDE corrected values for 4/3 measurements of 14 colored samples. The LDE corrected values for these samples were then compared to the 38/3 measurements of the samples. This correction procedure reduced the CIE L*a*b* color differences between the 4/3 and 38/3 data by 75% or more.

In a paper presented at Scottsdale in 1998[14], the author applied this method to derive simulated X-rite 938 spectrophotometer measurements from data taken with a Gretag SPM-100 spectrophotometer. All of the simulated X-rite measurement values were closer to the actual X-rite measurements than the measurements made with the Gretag. However, the results were not as good as had been hoped. Much of the problem of improving the results laid in finding a reliable method for normalizing data from calibration samples with different reflectances. Also, positioning difficulties were encountered when off-port measurements were made with the Gretag SPM-100.

A NEW INSTRUMENT CONFIGURATION FOR DETERMINATION AND CORRECTION OF LDE

Both of the presently available methods for correcting for LDE involve measuring the desired sample area and some area adjacent to the desired sample area. If the standard set forth in ISO 5/4 is used as a guide for the design an instrument to measure the 5 mm square elements of a print control strip, the instrument would have to illuminate a five mm square area and view a one mm square area in the center of the illuminated area. Not only would such a measurement configuration have problems getting adequate energy to the detector, but, measurement data from a one mm square area of most halftone samples would vary considerably with minor changes in instrument placement. If the viewed area was increased to 5 mm square to overcome halftone sample problems, then the illuminated area would have to be increased to 9 mm square. With this configuration, areas of different colors adjacent to the desired sample area would be illuminated. In many cases this illumination of adjacent colors would affect the measurement value of the sample area. Clearly, a reflectance measuring system which could illuminate the entire 5 mm square area and take measurements from the entire 5 mm area with little or no LDE uncertainty in the reported measured values would be highly desirable. But can this be done ?

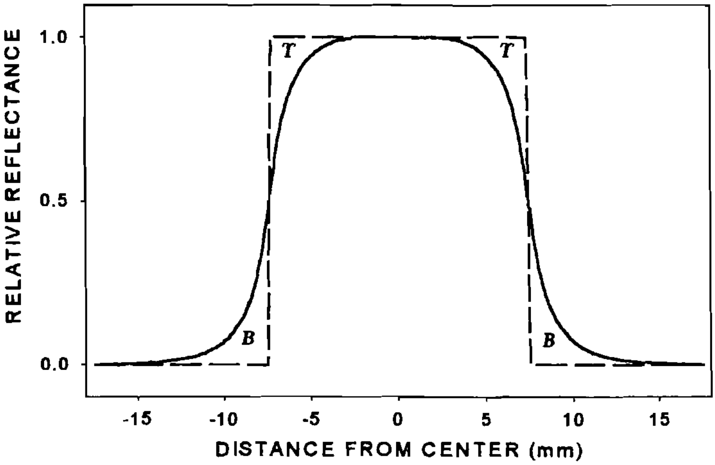

Figure 5 *Narrow slit scan of a lighted area on a 0.1% TiO_2 loaded polystyrene exhibit (solid line) compared to an idealized scan of an opaque exhibit (dashed line).*

Figure 5 is a plot of data derived from a narrow slit scan of an approximately 15 mm wide lighted area on a black backed polystyrene chip loaded with 0.1% rutile

TiO_2. (Note that this data was modified to compensate for measurement differences caused by small non-uniformity in the illuminating source.) The lighted area was measured at 0.1 mm intervals with a 0.75 mm vertical slit focused on to an integrated filter (540 nm center wavelength and eight nm bandwidth) and silicon photodiode. The solid plot line shows the peak normalized results of this scan. The dashed line curve is what the scan would have looked like if the sample had exhibited little or no lateral diffusion. The areas marked ***B*** represent the amount of light that laterally diffused out of the lighted area into the unlighted area of the sample. The areas marked ***T*** represent the amount of light that was lost from the lighted area in the lateral diffusion process. Note that the ***B*** areas are exactly equal in size and, when rotated, in shape to the ***T*** areas. The normal method for getting the true value of the reflectance of the sample would be to make the aperture of the detector system large enough to see all of the light coming from the ***B*** areas.

On the basis of this data, an alternative method for getting the true value would be to make the area viewed by the detector equal to that of the illuminated area and then make a second measurement which would determine a value for the ***T*** areas. The two measurements could then be added together to get the correct reflectance value.

While there is no simple way of measuring the value of the ***T*** areas, it is possible correlate the value of the ***B*** areas, which are equal to the ***T*** areas, to the difference of measurements made at the center and inside edges of the lighted area. To get data for this correlation, a 45°/0° narrow band (540 nm with 8 nm bandwidth) reflectometer using single beam illumination was set up on an optical bench. Eighteen samples of various translucencies were measured using 38 and 8 mm diameter illumination and 8 mm viewing. The differences between the measurements made with the 38 and 8 mm illumination gave a $LDE_{38\text{-}8}$ for each sample. Each of these values was divided by the 38 mm illuminated reflectance to give a normalized or relative LDE value. Next, light viewed from the surface normal of each sample illuminated with 8 mm diameter lighting was focused onto a fiber optic assembly which consisted of a center circular bundle and a ring bundle surrounding the center bundle. The two bundles had approximately equal areas. The center bundle viewed a circular area of the sample approximately 4.6 mm diameter and the ring bundle viewed a ring area on the sample with an 8 mm OD and a 6.5 mm ID (a ferule in the fiber bundle assembly separated the center bundle from the ring bundle; this resulted in the ID of the area viewed by the ring being approximately 1.1 mm greater than the diameter of the center bundle). For reference, the center bundle in the fiber optic assembly is designated C and the ring bundle is designated R. Measurements of the light from each of these bundles for each of the samples were adjusted using the measured values of the relatively opaque Green 39 sample which was used in the earlier published work.

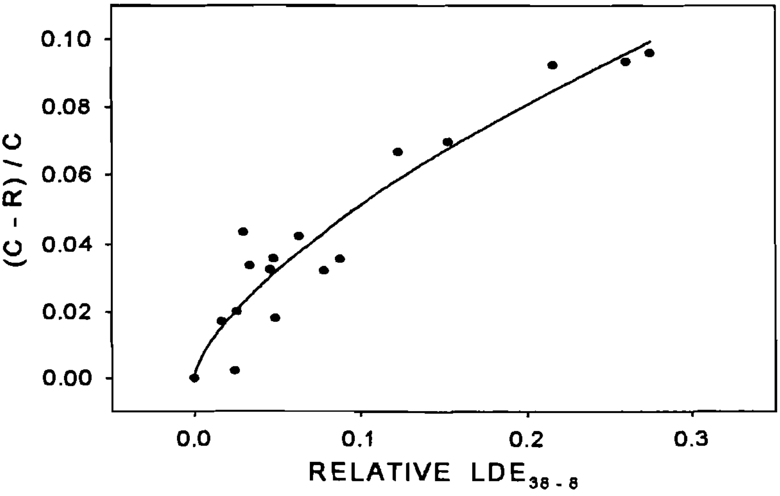

Figure 6 *Measurements of 18 samples with the two channel detector system. Plot is the relative LDE versus the normalized center to ring values of the measurements. The solid line curve is a three parameter fit to the data.*

Figure 6 is a graph of the normalized difference between the center and ring bundle, (C-R)/R, for each of the eighteen samples plotted against the relative LDE_{38-8}. The solid curve on the graph is a three parameter fit to the set of data. The curvature of the fitted curve results from the center bundle viewing some of the reflectance fall off area in samples with greater translucency. Figure 7 (next page) is a slit scan plot of a Lucite® IV2147 sample which is more translucent than the 0.1% rutile TiO_2 loaded styrene sample shown in the figure 5 plot. Note that a 7.5 mm wide center detector channel would view only the flat area of the sample reflectance as plotted in figure 5, whereas, it would view some of the fall off area of the sample reflectance as plotted in figure 7.

DISCUSSION

An instrument designed to minimize LDE while measuring 5 mm square print control elements by meeting the ISO 5/4 requirements (i.e. 5mm illumination and 1 mm viewing) would be measuring only one twenty-fifth of the illuminating energy. An instrument employing the two segment detector used in this experimental work would be measuring one-third of the illuminating energy in each channel. This would give almost a ten to one improvement in signal to noise ratio and would reduce uncertainty caused by halftone sample non-uniformity.

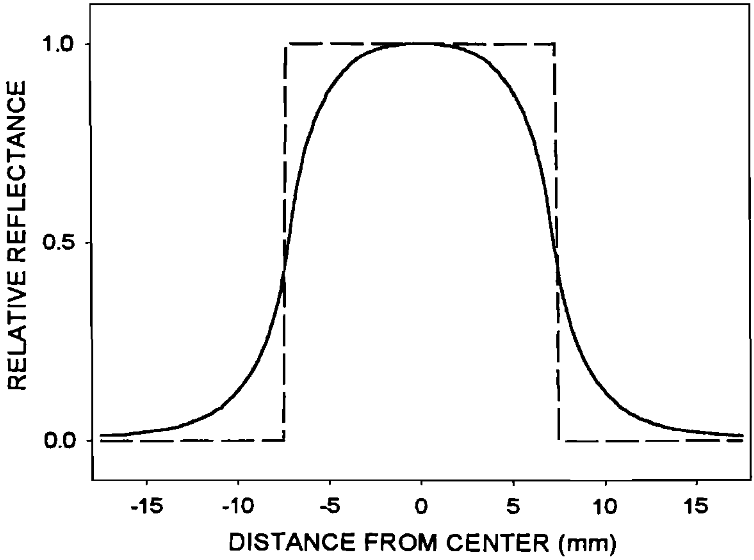

Figure 7 *Narrow slit scan of a lighted area on a Lucite® IV 2147 sample (solid line) compared to an idealized scan of an opaque exhibit (dashed line).*

Application of Helmholtz optical reciprocity indicates that LDE correction could be achieved by serially illuminating the sample in two regions while a single detector viewed the sample. Also, surface normal illumination could be used with a single channel or annular collection/detection system. This design is also adaptable for use with the various diffuse/normal and normal/diffuse and other reflectance and transmission measuring geometries as detailed in ASTM 179.

CONCLUSIONS

The ISO 5/4 approach and its variations and the author's on-sample/off-sample method are both useful for LDE correction over a limited range of sample translucencies. For optimum results, the sample must be uniform beyond the area being measured. This further limits the usefulness of both methods. At present, these two methods are only ones available for correction of the LDE problem. The two segment detector method detailed in this work and its variations provide a means of measuring the true value of reflectance by examining only the light reflected by the sample in a illumination/detector common area of the sample. However, the full proof of this method will require the construction and test of prototype instruments incorporating the design features described in this paper.

ACKNOWLEDGMENTS

The author acknowledges the contributions to this work of the following individuals: the late William Voglesong who specified the original 2 mm standard set forth in ISO 5/4 and who, in numerous person-to-person discussions, gave the author greater insight to the problem of lateral diffusion; Frederick Simon who provided many of the translucent samples used in this work; Paul Tannenbaum, a former colleague at duPont, who has been a sounding board for ideas and experimental methods; Costas Krikelis and Bruce Monroe who encouraged and assisted in the filing of a patent on this new instrument configuration.

PATENT STATUS

A patent application has been filed on the instrument configuration described in this paper and derivative instrument configurations not specifically discussed in this paper.

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