Evaluation of a Method for Correcting for Measurement Errors Caused by Adjacent Colors

David L. Spooner*

Keywords: Color, Error, Measurement

Abstract: At the TAGA 2000 and 2001 annual meetings, the author presented papers which illustrated that colored areas adjacent to calibration proof elements being measured can induce color measurement errors. The magnitude of these errors varied with the size of the area being measured and the location of the adjacent colors. It was concluded from a modeling of the physical makeup of the instrument and media that lateral diffusion of light within the substrate (e.g. paper) was most likely the principle cause of the measurement error. At the 1999 annual TAGA meeting, the author presented a paper which described a method of correcting reflectance/color measurement errors caused by lateral diffusion of light within the sample. A further refinement of this method was reported in a paper presented at the 2000 SPE-RETEC Color and Appearance meeting. The present paper reviews the previous work and examines the applicability of the lateral diffusion error correction method for correction of errors caused by adjacent colored areas. To accomplish this test, the single color bandpass optical bench breadboard instrument used for the 1999 measurement study was upgraded to give corrected 35 wavelength spectral reflectance measurements. Exhibits similar to those used in the 2000 and 2001 studies will be measured using this upgraded instrument and the results are reported.

Background

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 (Spooner, 1995). Lateral diffusion errors (Spooner, 1991, 1993, 1994) (LDE) can occur when some of the illuminating light from the instrument diffuses laterally in a translucent sample to locations outside

*rhoMetric Associates, Ltd., www.rhometric.com

of the area viewed by the instrument detection system. In some of the literature, LDE is referred to as translucent blurring error (Hsia, 1976), translucency error (Hunter, 1987), edge loss error (Atkins, 1966), and stray darkness (Spooner, 1999a).

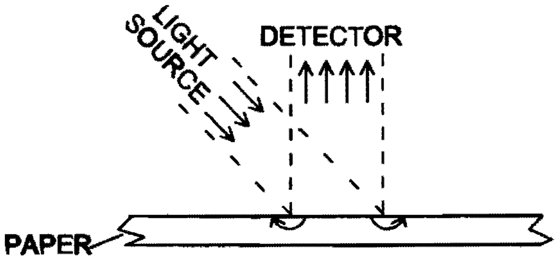

Figure 1

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 views the illuminated area from above the sample (i.e. 0° from the sample surface normal). In illustrated configuration, the light measuring system cannot detect the light that is diffused laterally beyond the edge of the illumination and detector view areas. LDE is a function of the light that diffuses beyond the area viewed by the detector. Thus, the measured value reported by the instrument is the *true value* (ISO, 1993) lessened by the light that has laterally diffused within the sample and exited the sample surface out of the area viewed by the detector. In the illustrated configuration, the value of the LDE is a first order function of the distance that the light laterally penetrates in the sample. In general, more translucent samples will have greater LDE when measured with a given instrument. Also, the color any material in contact with the back surface of thin samples can affect the LDE value - the LDE with a black sample backing is usually less than the LDE when the same sample is measured with a white backing. Secondarily, the LDE is dependent on the size of the measured area.

The common instrument design strategy used to reduce or eliminate LDE is to make the viewed area larger than the illuminated area or vise-versa. Thus, in the figure 1 configuration, increasing the area viewed by the detector would allow the light exiting the surface outside of the illuminated area to be seen by the detector. An alternative method is to make the illuminated area larger than the area viewed by the detector. Helmholtz optical reciprocity, as defined in a paper by Clarke & Parry (1985), indicates that both methods will generally give equivalent measured values if all other parameters of the measuring/illumination system are the equivalent.

The size of the viewing area on the sample can also affect the LDE value. For example, if the instrument uses circular illumination and viewing areas, the light not seen by detector in figure 1 is in an annular ring surrounding the circular area viewed by the detector. If the diameter of the illumination and viewing areas are doubled, the area of this annular ring roughly doubles but the area viewed by the detector quadruples. This results in the LDE being about one-half the values that it was with the smaller apertures.

The ANSI (1989) and ISO (1983) standards, which define the measurement geometries for photographic reflectance density, recognize the lateral diffusion error problem. They both specify that the illuminated area should be 2mm on the side larger than the area viewed. Most, if not all, densitometers used for measurement of photographic and printed materials do not meet these standards (Voglesong, 1997). The author has found that even the 2mm distance specified in these standards is not adequate to eliminate LDE from measurements of some high gloss printing papers and inkjet photo papers.

The method specified in the standards is normally termed "over-illumination" (i.e. the illuminated area is larger than the viewed area). If the viewed area is larger than illuminated area, it is called "over-viewing". Note that both methods are "passive" in that the reduction of LDE as a function of sample translucency is fixed by the instrument apertures. Also, since the illuminated and viewed areas differ, the sample must be relatively uniform throughout the largest area viewed in the over-viewing configuration, or illuminated, in the over-illumination configuration (e.g. an error can be caused by a colored area different from that of the area being measured which intrudes into the area illuminated by the instrument even though the detector does not directly view the intruding color).

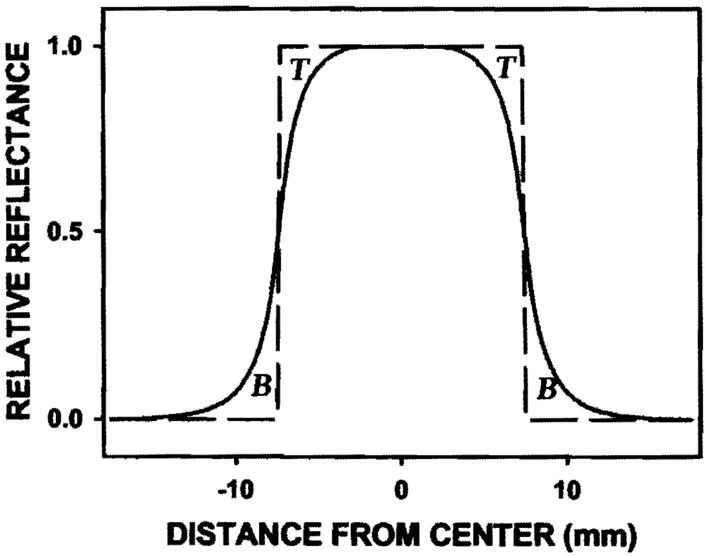

Figure 2

Can the Illuminated and Viewing Areas Be Identical ?

Papers presented at the 1999 TAGA meeting (Spooner, 1999) and the 2000 SPE-RETEC CAD meeting (Spooner, 2000a) discussed the relationship of the spatial distribution of the light reflected from the illuminated area of the sample to the light that diffused out of the illuminated area into the surrounding unilluminated area. Figure 2 (preceding page) 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 a small non-uniformity in the illuminating source.) The lighted area was measured at 0.1 mm intervals with a 0.75 mm vertical slit area focused on a silicon photodiode detector with an integrated filter (540 nm center wavelength and eight nm bandwidth). The solid plot line shows the peak normalized results of this scan. The dashed line curve is an idealized plot of the intensity of the lighted area. 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 by lateral diffusion. Note that the ***B*** areas are exactly equal in size and in shape to the ***T*** areas. The conventional 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 reflectance 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 total 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 edges of the lighted area. To get data for this correlation, a 45°/0° narrow bandpass reflectometer using the filtered photodiode detector was set up on an optical bench. Twenty-nine 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 chrome green pigmented plaque which was used in the earlier published work.

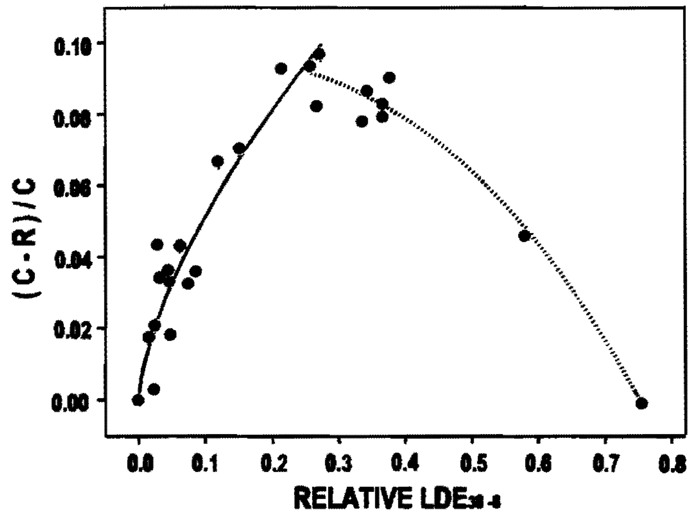

Figure 3

Figure 3 is a plot of the relative $LDE_{38\text{-}8}$ and the normalized difference between the center and ring bundle, (C - R)/ R, for each of the twenty-nine samples. In this plot, the solid curve on the graph is a regression fit to the set of data that ascends as the LDE increases and the dotted curve is a fit to the set of points which descends as the LDE increases.

Why do the data presented in figure 3 start decreasing at high LDE values ? It is caused by a change in the shape of the pattern of the reflected flux distribution across the lighted area. Figure 4 (next page) shows the slit scan of a sample of Lucite® WT2447. In this curve, the top flat area apparent in figure 2 has completely disappeared and the edges have changed from the modified exponential shape of the sides of the curve in figure 2 to a nearly elliptical shape. Clearly, an algorithm which relates the signals from the optical bench reflectometer two channel detector to LDE of samples with low translucency will not give good results when the flux distribution changes so radically. One answer to this problem to add a third detector channel which could detect the change in the distribution of the reflected flux in the illuminated area. To this end, the two channel bundle was replaced by a three channel fiber assembly consisting of a center bundle and two concentric ring bundles

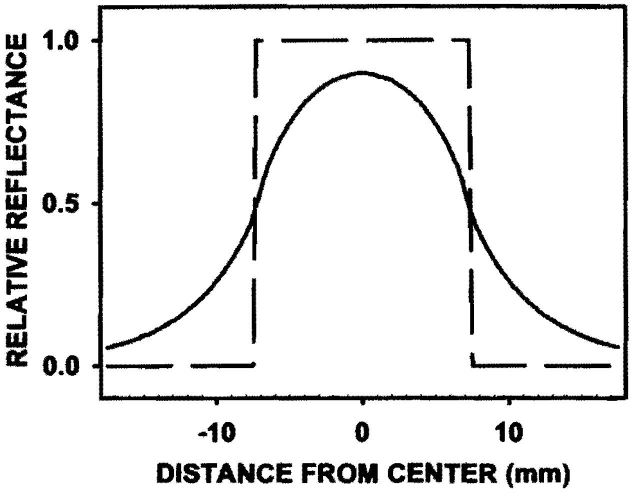

Figure 4

The optics of the viewing system were repositioned so that the image of the outside edge of the 8 mm diameter illuminated area exactly coincided with the outside edge of the outer most fiber ring. The use of this third fiber bundle gives additional data on the spatial distribution of the light reflected from the illuminated area of the sample. This added data can be used to determine which branch of the two curves in figure 3 should be used to derive the normalized LDE for any measured sample.

A SPECTRAL REFLECTOMETER WHICH USES SPATIAL DISTRIBUTION LDE CORRECTION

A spectral reflection measuring instrument which measures a function of the spatial distribution of the reflected light was assembled on an optical table. The measuring head from a Byk-Gardner Color Machine(TM) (BGCM) was used to provide annular 45° illumination. A circular ring of copier paper, 18mm ID and 25mm OD was placed on a 4mm diameter aperture plate which defined the illuminated sample area. This positioned the sample surface approximately 100μm away from aperture plate. (Work reported in the 2000 paper had shown that a colored aperture plate in contact with the sample surface can affect the measured reflectance value.) The measuring head was modified by removing the normally used viewing fiber bundle and replaced it with a lens which focused the illuminated sample area onto the center/two ring fiber assembly which used in the 2000experiments. The lens and fiber bundle were positioned so that the outer edge of the outer ring of the fiber assembly viewed a 4mm diameter circle on the sample surface. A 45° prism and stepping motor assembly allowed the output ends of the bundles to be sequentially viewed by the grating-diode array detection system of a fully functioning BGCM. (In normal operating mode the BGCM measures reflected light in 35 ten nanometer bands from 380nm to 720nm.) The initial calibration of the transmission of the fiber bundle channels was accomplished by measuring a $BaSO_4$ pressed pellet while using a 31mm illumination aperture. Measurements of several paper samples were then made using 31mm and 4mm illumination aperture plates. Appropriate calibration procedures were employed to minimize the effects of light source and detector drift on the measured values. The LDE for each sample was determined by summing the three measurement values at each of 35 wavelength bands for the 4mm illumination. These values were then compared to similar data obtained using 31mm illumination and used to determine the spectral LDE. These LDE values were then normalized using the 31mm illumination reflectance. A normalized spatial distribution value for each wavelength for the sample can be determined by subtracting the inter ring reflection value from that of the center bundle and dividing by the center bundle value.

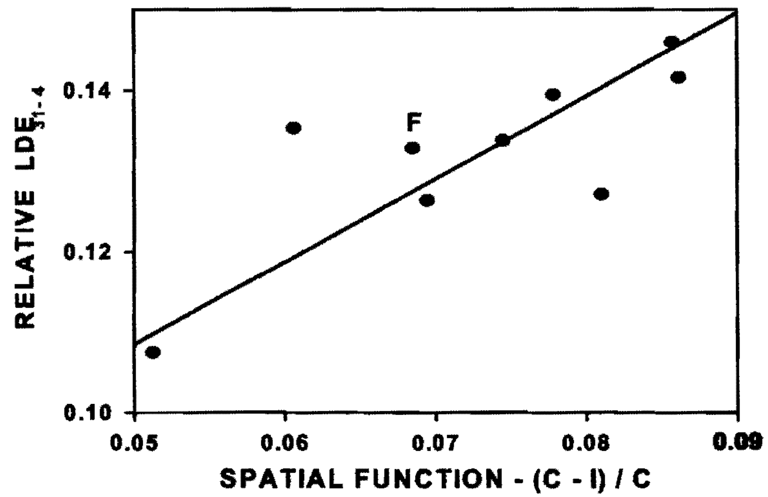

Figure 5

Figure 5 is a point plot of the 550nm normalized (relative) LDE values versus the spatial function values for nine paper samples measured with black backing. The straight line plot is a linear regress line for the points excluding the two outliers (copier paper and Jet-Print Photo(TM) Multi-Project Photo paper). The point marked "F" on the plot is data derived from measurement of Whatman #1 qualitative filter paper. Figure 6 (next page) compares spectral plots the 31mm illumination measured reflectance with the 4mm illumination uncorrected and corrected reflectance curves. Note that the full spectrum corrected data was computed using only the spatial function derived from the 550nm data. Note also, that the correction at the shorter wavelengths is not as good as it is at the longer wavelengths. This may indicate that a spatial function and normalized LDE should be derived for each wavelength and then applied to each wavelength of the 4mm illumination curve.

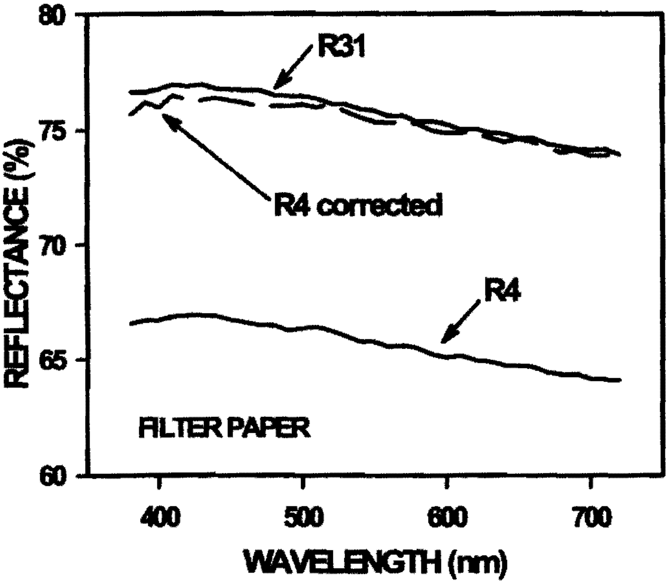

Figure 6

The table below shows the color differences between the 4 and 31mm curves before and after the 550nm spatial function was applied to each of the measurements of the nine paper samples.

SAMPLE	DE-R31-R4	DE-R31-R4 corrected
Copier Paper	4.95	0.72
duPont Digital Waterproof®	5.18	0.20
Whatman #1 filter	4.90	0.23
HP Premium Photo paper	4.77	0.30
HP Premium Plus Photo	5.65	0.50
HP Brochure & Flyer paper	4.10	0.55
Jet-Print Photo(TM) Multi-Project	4.88	0.67
Jet-Print Photo Ultra®	5.22	0.18
Kodak Ultima Picture paper	5.44	0.42

On average, the delta E was reduced by a factor of 12.0; the minimum reduction was 6.9 (Copier paper); the maximum was 29.5 (Jet-Print Photo Ultra®). All of the color differences were reduce from four or more to less than one.

Will this Method Correct for Errors Caused
By Colors Adjacent to the Area Being Measured ?

The outward diffusion of light from the illuminated area in the diagram in figure 1 is a simplification of the actual diffusion process. Actually, some portion of the light that diffuses out of the illuminated area diffuses back into the illuminated area. The result, the outward diffusing light minus the inward diffusing light, is a net outward diffusion of light, as represented in the diagram. In the region where this diffusion and re-diffusion is taking place, any discontinuity introduced into the region will affect the LDE value. For instance, only about 40% of the diffuse light within the sample that impinges on the underside of the unilluminated sample surface is transmitted through the surface; the other 60% is reflected back into the sample (Saunderson, 1942). Some portion of this reflected light will re-diffuse back into the illuminated area of the sample. If the unilluminated surface of the sample is coated with a totally absorbing layer (e.g. black ink) then none of the diffuse light impinging on the underside of the surface will be reflected back into the sample. This will often result in a detectable decrease in the light received by the instrument detector. Thus, adjacent colored areas outside the measured area can increase, and only increase, the lateral diffusion error.

In the work reported in the 2000 and 2001 TAGA papers (Spooner, 2000b, 2001), colored, not black, ink was applied in the areas adjacent to the measured area. This resulted in very noticeable color differences in the spectral reflectance curves. Had black been used, the entire curve would have been uniformly lowered, a result that would not be as readily apparent to the causal observer.

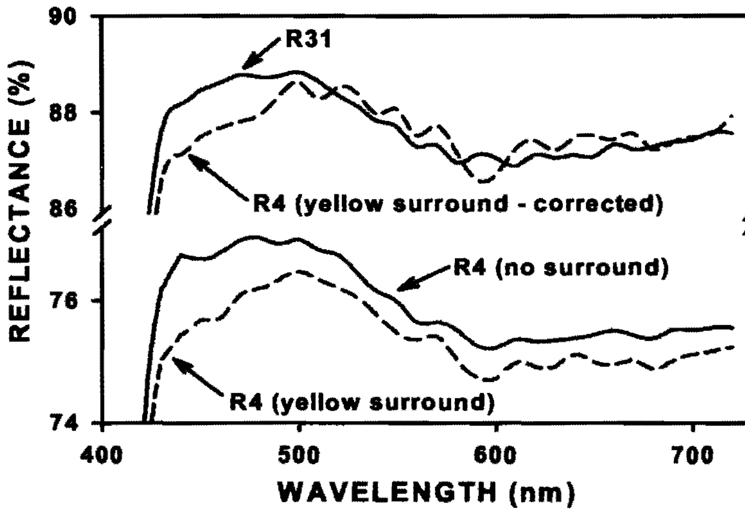

Figure 7

To test the applicability of this new measurement system for reducing the effects of adjacent colors, sets of exhibits were printed on three different paper stocks. Each exhibit set consisted of three samples with circular white areas, 6, 8, and 10mm diameter, surrounded by a 100% yellow area printed with a HP 930C printer. Figure 7 (preceding page) shows plots of measurement data from the duPont Digital Waterproof(TM) target with an 8mm circular white area. The bottom two curves are the reflectance values for 4mm/4mm illumination/viewing of a sample with no yellow surround (solid curve) and the 4mm/4mm measurement of the 8mm diameter white area with a yellow surround (dashed curve). The upper two curves are 31mm/4mm measurement of duPont media with no surrounding color (solid curve) and the 4mm/4mm yellow surround data corrected using the spatial function algorithm (dashed curve). Note that in the region between 430 and 500nm the effects of the yellow surround are still apparent in the corrected curve. However, in the region between 500 and 720nm there is better match between the plane paper and corrected curves. The first two sets of CLab coordinates in the table below show this lightness match and survival of the yellow.

SAMPLES	dL	da	db	dE
31/4 4/4 yellow surround	5.39	-0.18	0.37	5.40
31/4 4/4 yel. surround corr.	0.04	-0.22	0.73	0.77
31/4 4/4	-5.18	-0.04	-0.09	5.18
31/4 4/4 corrected	-0.06	-0.07	0.18	0.20

The last two entries in the table detail the color differences between the31mm/4mm and 4mm/4mm, no surround uncorrected and corrected measurements of the media. Note that the correction process increases the yellow value by roughly 0.3 CLab b (yellow-blue) unit. The first two entries in the table also show about a 0.3 CLab b unit increase resulting from the correction process. Examination of data from samples printed on the three paper with the three different size white areas also showed that the 430 to 500nm yellow absorption was generally not reduced by the correction process. The correction process suffers from noise as can be seen from 4/4 corrected curve in figure 7. Another cause of this problem may result from using 550nm data to derive the correction data for all wavelengths. Also, some difficulty was experienced positioning the samples relative to the instrument port. Further investigation will be needed to pinpoint the cause of this yellow problem.

Ongoing Investigations

The process of measuring sample reflectance with the present optical bench instrument involves using two computers, parts of two BGCM instruments and a stepping motor with computer controlled driver unit. Manually inserted black and white calibration plaques are measure prior to and after measurement of the sample. Once the data is logged, the reduction process involves six or so manually initiated operations with a spread sheet/plotting program. These processes in total can often be subject to equipment malfunctions and operator inattention. An upgrade effort is underway to integrate all of these manual operations into an automated, computer controlled, system. Once this effort is completed, it will be possible to readily observe the effects of changes to the correction algorithm and optical design changes on a near real-time basis (e.g. the signal from outer ring of the fiber bundle is only about 75% that from the inner ring and center bundle; is this from a misalignment of the bundle with the 45° prism or is the illumination aperture plate interfering with the view of the sample).

This LDE correction method appears to be also applicable to correcting measurement of other translucent materials. To this end, a number of plastic samples have been assembled including a full collection of all 26 of the Corian® solid colors. The full determination of the limitation of this correction method will require measurements of hundreds if not thousands of samples of various translucent materials. The measurement speed and reliability of the upgraded instrument will make such an effort practical.

CONCLUSIONS

The application of the LDE spatial distribution correction algorithm has been demonstrated to give useful results when applied to the spectral measurement of white, translucent, printing papers. At present, it applicability to reducing the effects of adjacent colors on measured reflectance has not been demonstrated and will require additional work to fully determine if it is useful for that purpose.

REFERENCES

ANSI
1989 "Photography - Reflectance density - Geometrical conditions", ANSI/ASC PH2.17, American National Standards Institute, 1430 Broadway, New York, NY 10018

Atkins, J.T., and Billmeyer, F.W., Jr.
1966 "Edge-loss errors in reflectance and transmittance measurement of translucent materials", Materials Res. and Std., 6, pp 564-569

Clarke, F. J. J. and Parry, D. J.
1985 "Helmholtz reciprocity: its validity and application to reflectometry", Lighting Res. & Tech., vol. 17, pp 1

Hunter, Richard S., and Harold, Richard W.
1987 "The measurement of appearance" (John Wiley and Sons, New York), 2nd ed, pg 410

Hsia, Jack
1976 "The translucent blurring effect - Method of evaluation and estimation", NBS Technical Note 594-12

ISO
1983 "Photography - Density measurements - Part 4: Geometric conditions for reflectance density", ISO 5/4-1983 (E), International Organization for Standardization

1993 "International Vocabulary of Basic and General Terms in Metrology", pg 169, International Organization for Standardization (ISO),

Saunderson, J. L.
1942 "Calculation of the color of pigmented plastics", J. Opt. Soc. Am., 32, 727

Spooner, David L.
1991 "Translucent blurring errors in small area reflectance spectrophotometer & densitometer measurements", TAGA Proc., pp 130-143

1993 "Lateral diffusion errors caused by layered structure of graphic arts products", TAGA Proc., pp 176-192

1994 "Optical reciprocity and lateral diffusion error", TAGA Proc., pp 117-129

1995 "An anthology of color measurement error mechanisms", SPE Color & Appearance Division RETEC Proc.

1999a "Stray darkness: A new error or a previously known error recast ?", SPIE Proc., 3648, pp 242-248

1999b "Measurement without bounds", TAGA Proc., pp 671-681

2000a "A spectral reflectometer which corrects for edge-loss error", SPE Color & Appearance Division RETEC Proc.

2000b "Surrounding color can affect the measured color of a sample", TAGA Proc, pp 209-217

2001 "Effect of adjacent color on sample measured color", Taga Proc., pp 346-356

Voglesong, William F.
1997 Personal communication from the late William F. Voglesong, former chair, ANSI/IT2.28 subcommittee on photographic density