OPTICAL RECIPROCITY AND LATERAL DIFFUSION ERROR

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ABSTRACT: In a paper presented at the 1993 annual TAGA meeting, Voglesong reported that measured densities of ink-on-paper samples made with 0/45 geometry did not agree with values obtained using 45/0 geometry. In a 1985 paper, Clarke & Parry, reported that 0/45 and 45/0 geometry reflectance measurements agreed within the 50% confidence level of their measurement system. While Clarke and Parry used a reflectometer configuration similar to that used by Voglesong, they only measured white reflectance standard reference materials.

Ink-on-paper reciprocity failure has been investigated using both the fiber optic coupled configuration used in the Byk-Gardner spectrocolorimeter and an apparatus similar to that of Voglesong, and Clarke & Parry. In this latter configuration small integrating spheres were used in the source and detector channels to insure that effects of polarization, optical element placement, and changes in source-sample-detector geometry were minimized. The transformation from 0/45 to 45/0 geometry was accomplished by physical exchange of the detector and light source at the entrance ports of the spheres - the sample and/or the detector and source optics were not changed, as was the case in the aforementioned investigations.

Further investigations, using the sphere configuration were performed to determine the magnitude of lateral diffusion error in the 0/45 and 45/0 geometries.

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INTRODUCTION

In the simplest terms, the principal of optical reciprocity (OR), as understood by the author states that interchanging the source and detector in a photometric/radiometric measurement apparatus will not affect the measured values. Over the years, investigators have cited circumstances in which they felt that OR had failed. Generally, upon further inquiry, it has turned out that they have failed to account for some aspect of their experimental setup which caused the source-detector interchange to give different measurement results.

About three years ago, Alan Robertson of the NRC, Canada, gave the author a copy of a 1985 paper by Clarke and Parry **(1)** which gives a better definition of the OR principle than had previously been available in the literature. Specifically, Clarke and Parry stated that OR did not hold if the sample was optically active and/or the polarization states of the source and sample channel were not the same. They demonstrated this latter aspect by measuring a number of white standard reference materials under different states of polarization of the source and detector. The results of the 0/45 and 45/0 geometry measurements agreed to within ±0.35% fullscale (fs), the 50% confidence level of their measurements, when the channels were unpolarized or met the polarization states specified in their statement of the OR principle.

W. F. Voglesong presented a paper **(2)** at the 1993 annual meeting of TAGA which brought into question the validity of the OR principle as commonly accepted in density and, by inference, color measurements. Specifically, Voglesong reported that, while the 0/45 and 45/0 measured density values for white standards materials did agree within 0.001 optical density (OD) (i. e. the measurement uncertainty of his system) the measured OD values of ink-on-paper samples disagreed by as much as 1.5%.

Voglesong's paper was of concern to the author for two reasons: 1) if his data was correct, then assumptions that are being made about the interchangeability of color and density measurement data of graphic arts products made with 45/0 and 0/45 instruments are incorrect and 2) if he had overlooked some factor, then a paper, by a highly respected scientist, which might confuse less experienced workers had been entered into the graphic arts technical literature.

COMMENTS ON MEASUREMENT METHODS

In the measurement systems used by both Voglesong and Clarke & Parry, a circular source pattern was projected on to sample surface at normal incidence. The change from 0/45 to 45/0 geometry was accomplished by rotating the sample plane by 45° from a position where the axis of the source optics was normal to the sample surface to a position where the detector optical axis was normal to the surface. With this rotation, the area illuminated changed from a circular pattern to an elliptical pattern with a minor axis equal to the diameter of the circular pattern and a major axis equal to about 1.4 times the circular diameter. Clarke & Parry corrected for this increased illumination area by applying a cosine function to the resulting measurement data obtained from the detector. Voglesong corrected for this increased area by inserting an elliptical mask into the source optical path. This gave an elliptical cross-section beam which, when projected on to the sample surface at 45°, resulted in a circular illuminated area.

This rotation of the sample and subsequent correction for the change in the illuminated area represents a possible source of error. The Clarke & Parry uncertainty of ±0.35% fs is made up of a 0.1% fs photo-optical uncertainty and 0.25% fs uncertainty from error in setting the angular positions of the source, sample, and detector. Voglesong did not use a cosine correction, but rather used a calibration standard in each of the two positions prior to making measurements. While his approach appears to be better than that of Clarke & Parry, there may still be some question as to what effect the rotation of the sample and insertion of the elliptical mask had on the measurement accuracy.

A MEASUREMENT PROGRAM

Clearly, investigating this reported OR failure would best accomplished by measuring ink-on-paper samples similar to those used in the original work. Bill Voglesong kindly made two sets of samples available and also suggested some standard Pantone colors which he found to also exhibited OR failure.

The Voglesong sample set consists of 12 circular color patches approximately 4 cm in diameter. Five of the colors are single ink colors: white, yellow, cyan, magenta, & black. Three of the colors are two ink over print colors: red (yellow over magenta), green (yellow over cyan), & blue (magenta over cyan). The remaining four colors are process screen colors: purple, gray, brown, & pastel (a medium beige). These colors are printed on a coated, non-fluorescent white paper (about 70# basis weight). The back side of the sheet is printed with black strips to provide the standard black backing.

In our first experiment, a measurement head from a Byk-Gardner spectrocolorimeter was used. In the normal configuration, light from the source is transferred to the measurement head via a 0.5 M long fiber optic bundle. The light reflected from the sample is transferred to the detector by a second fiber bundle. This configuration allowed easy interchange of

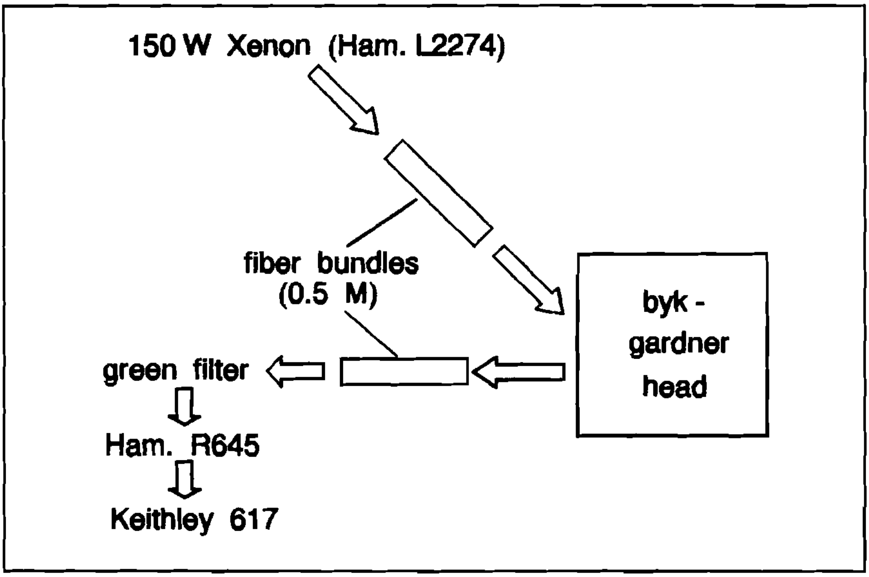

Figure 1 *Configuration used for 45/0 measurement with the Byk-Gardner measurement head. Note: the fiber bundles are part of the head assembly.*

the detector and light source without any change to the measuring head configuration. Figure 1 gives a schematic of the 45/0 configuration.

The lamp used was a Hamamatsu L2274 150 W Xenon arc lamp in an elliptical cold mirror reflector. The green filter, two layers of a Wratten 58 color separation filter, and the Hamamatsu R645 planar vacuum photo diode were packaged together in a shielded box with two 9 volt batteries for diode bias. The white reference signal level from the R645 was adjusted to about 1.9 na. This level, which is well below the 1 μa rating of the tube, takes full advantage of the 5½ digit logging capability of the Keithley 617 electrometer.

The measurement head has a motor driven white reference assembly which can be positioned in front of the sample to give a reference signal before and after sample measurement. This motor assembly also allows the measurement fiber bundle to be shielded from sample reflected light to give a zero (black) reference.

The control of the motor and the logging of the data from the Keithley, via an IEEE-488 bus, were provided by an program running on an Intel 486 based PC. A typical measurement sequence would consist of a white, black, and white measurements followed by 5 pairs of sample and white measurements followed by a black and white measurement. Each sample, white, and black measurement consisted of 18 one second measurements by the Keithley. Only the last 11 measurements were used as data since the earlier measurements often were affect by transients.

TABLE I *Measured reflectance values (%) of the Voglesong samples obtained using the apparatus of figure 1.*

SAMPLE	0-25/45-25	45-25/0-25	Δ
WHITE	82.229±0.031	83.151±0.028	-0.922
BLACK	1.822±0.001	2.425±0.004	-0.603
CYAN	43.845±0.025	44.971±0.017	-1.126
MAGENTA	6.550±0.002	7.509±0.003	-0.959
YELLOW	73.133±0.046	74.100±0.025	-0.967
GRAY	26.611±0.012	27.560±0.005	-0.949
RED	7.834±0.012	8.713±0.016	-0.879
GREEN	38.870±0.010	39.879±0.006	-1.009
BLUE	5.712±0.003	6.455±0.002	-0.743
BROWN	11.075±0.003	11.752±0.006	-0.677
PURPLE	10.291±0.003	11.126±0.003	-0.835
PASTEL	34.328±0.013	34.391±0.012	-1.063
AV. SD	0.013	0.011	

Table I shows that the standard deviation (sd) of the data obtained with this apparatus is less than 0.05% fs. The differences between the 0/45 and 45/0 values is 10 to 100 times the sd of the measured vales. This clearly seemed to confirm the OR failure of ink on paper observed by Voglesong. Note: in the table headings the two values before the slash (/) are the illumination angle relative to the surface normal in degrees and the aperture size in millimeters; the two values after the slash are the viewing angle and aperture size.

TABLE II *Reflectance values for white materials measured by the apparatus of figure 1.*

SAMPLE	0-25/45-25	45-25/0-25	Δ
TiO_2 PAPER	93.150±0.048	96.515±0.045	-3.365
OPAL GLASS GLOSSY	96.386±0.034	97.333±0.007	-0.947
OPAL GLASS MATTE	98.392±0.039	99.859±0.012	-1.467
0.1% TiO_2 IN STYRENE	69.263±0.014	66.933±0.012	2.330
5.0% TiO_2 IN STYRENE	86.835±0.012	87.701±0.016	-0.866

Both Voglesong and Clarke & Parry indicated that there was no failure of OR for white samples. Table II shows that the 45/0 and 0/45 measurements of Russian opal glass made with this apparatus indicate OR failure. This indicates that some problem with the measurement setup. This was confirmed by examining the data taken as part of the lateral diffusion error investigation. In that data, reflectance values were found to increase as the difference between the source and detector areas projected on the sample decreased.

This "pseudo OR failure" is caused by artifacts in the instrument and test procedure configuration. The original intent for setting up the test was to use integrating spheres at the ends of the fiber bundle. However, at the time the test was conducted, it seemed logical that the incoherent fiber bundles would depolarize and randomize the illuminating and reflected light. Obviously, something unexpected happened. Unfortunately, the problem with this data was discovered after the apparatus had been disassembled and some of the parts had been reinstalled in the laboratory instruments from which they had been borrowed. The reassembly of the test instrumentation with spheres at the fiber bundle ends has been put on the agenda for further investigation and possible publication in a later TAGA paper.

The OR failure was discussed with Byk-Gardner personnel and they

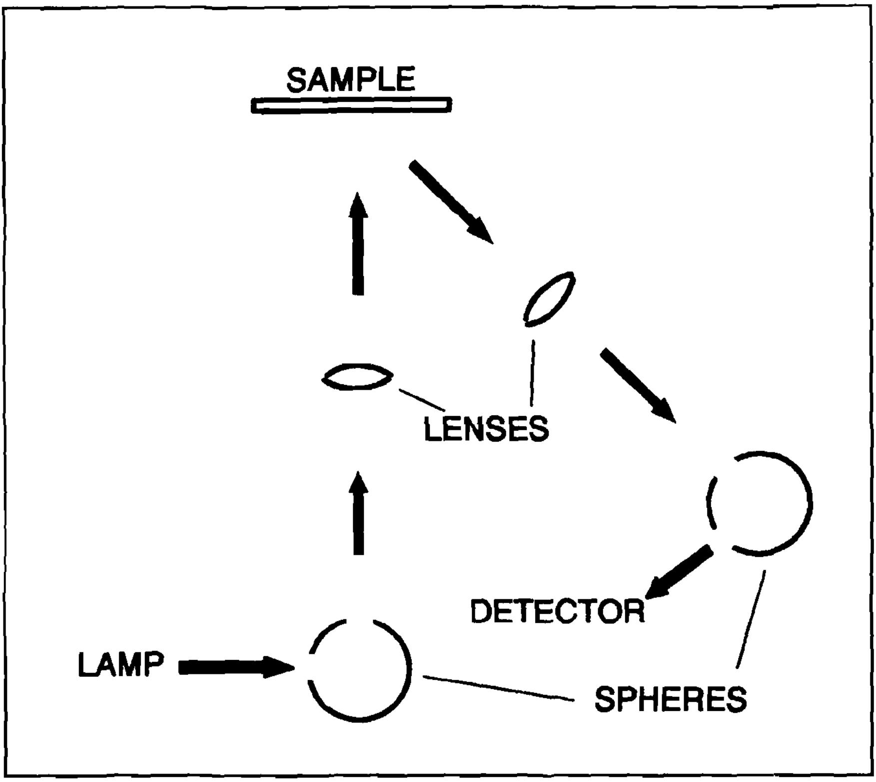

FIGURE 2 *0/45 geometry using spheres as the source and detector.*

suggested light entering the bundle at an angle, relative to the fiber axis, would emerge at the end, 0.5 M away, at an angle relative to the fiber axis. This possibility will be investigated with a new setup later this year.

Figure 2 shows a 0/45 geometry schematic of a second apparatus, somewhat similar to the Voglesong configuration, which was built to further investigate the possibility of OR failure of ink samples.

In this configuration, as with that of figure 1, the geometry is changed from 0/45 to 45/0 by physically interchanging the source and the detector. The sample plate is not rotated as is the case with the Voglesong system. The spheres are made of standard ping-pong balls (approximately 38 mm in diameter). Two 10 mm ports, 90° apart, were drilled into the balls. The interior surfaces of the balls were coated with a slurry of barium sulfate paint. Each sphere was mounted in a metal tube with the axis of one of the ports aligned with the tube axis. The assembly was cemented to an iris to allow the size of the port to be adjusted.

The inclusion of these spheres attenuate the light levels to a considerable extent. Originally, it was hoped that the aperture sizes used by Voglesong, 5 & 9 mm, might be reproduced. However, aperture sizes of 15 & 20 mm were used to increase the detector signal level. Even with these larger apertures, the signal was reduced by more than a factor of 10 (i. e. from 1.9 na to 150 pa) relative to that of the previous setup.

This new apparatus did not incorporate a motor driven white reference such as that used in the Byk head. The procedure of interleaving

TABLE III *0/45 and 45/0 sphere apparatus measurements of the white materials of Table II.*

SAMPLE	0-20/45-15	45-15/0-20	Δ
TiO_2 PAPER	96.55±0.21	96.31±0.08	0.24
OPAL GLASS GLOSSY	96.24±0.14	96.10±0.15	0.14
OPAL GLASS MATTE	97.74±0.21	97.84±0.10	0.10
0.1% TiO_2 IN STYRENE	66.64±0.29	66.28±0.14	0.36
5.0% TiO_2 IN STYRENE	87.59±0.07	87.33±0.04	0.26
AVERAGE SD & Δ	0.18	0.10	0.18

sample measurements between white reference measurements was performed manually. Specifically, the measurement sequence consisted of white reference, black reference, white reference, 3 sample/white reference interchanges followed by a black reference white reference interchange. In the prior procedure used with the Byk head, the sample was not moved during the measurement procedure. With the new apparatus, the sample was replaced on the sample port 3 times. The inexact placement of the sample increased the standard deviation of the measurements.

The differences between the 0/45 & 45/0 white measurements with the sphere apparatus (Table III) are generally less than the measurement uncertainity. The greater difference of 5% TiO_2 values appears to be an anomaly which may be caused by sample non-uniformity. The measurements of the sample with different aperture sizes did not exhibit this disagreement.

TABLE IV *0/45 and 45/0 sphere apparatus measurements of the Voglesong colors.*

SAMPLE	0-25/45-25	45-25/0-25	Δ
WHITE	82.41±011	82.76±0.13	-0.35
BLACK	1.84±0.31	1.93±0.08	-0.09
CYAN	41.35±0.16	41.72±0.07	-0.37
MAGENTA	7.22±0.22	7.47±0.29	-0.26
YELLOW	74.39±0.23	74.46±0.31	-0.07
GRAY	26.24±0.14	26.56±0.19	-0.32
RED	8.57±0.30	8.72±0.17	-0.15
GREEN	37.36±0.20	37.50±0.08	-0.14
BLUE	5.69±0.08	5.78±0.12	-0.09
BROWN	11.47±0.05	11.38±0.08	0.09
PURPLE	10.42±0.07	10.61±0.14	-0.19
PASTEL	34.99±0.14	35.29±0.14	-0.30
AVERAGE SD	0.17	0.15	

Table IV compares the sphere apparatus 0/45 and 45/0 measurements of the twelve Voglesong colored samples. With the exception of the white, cyan, and pastel samples, the differences in the measured values of the colors are less that the total of the standard deviations of the 0/45 and 45/0 values.

Voglesong provided his green OD measurements of the samples. His OD values were converted into reflectance values so that the differences between his 0/45 and 45/0 measurements might be compared with the sphere measurements. Table V shows this comparison. Note that the source and filter used by Voglesong are different than those used in this work; therefore values for some of the samples do not agree.

The Voglesong uncertainty is stated to be 0.001 OD. This is equalient to a 0.23% full scale uncertainity. The Voglesong gray measurement difference definitely exceeds this uncertainity. At first the cyan difference appears to exceed the uncertainity, but if the 0/45 and 45/0 measurements have an uncertainity of 0.23% fs, then the 0.38% fs value just barely falls within the uncertainity.

TABLE V *Comparison of 0/45 and 45/0 differences between Voglesong and sphere measurements.*

	VOGLESONG		**SPHERE**	
SAMPLE	**0-9/45-5**	**Δ**	**0-20/45-15**	**Δ**
WHITE	78.70	0.18	82.41	-0.35
BLACK	1.95	0.11	1.84	-0.09
CYAN	41.88	0.38	41.35	-0.37
MAGENTA	4.32	0.17	7.22	-0.26
YELLOW	70.31	0.16	74.39	-0.07
GRAY	20.14	0.69	26.24	-0.32
RED	5.36	0.15	8.57	-0.15
GREEN	36.39	0.17	37.36	-0.14
BLUE	4.42	0.11	5.69	-0.09
BROWN	7.52	0.12	11.47	0.09
PRUPLE	7.01	0.14	10.42	-0.19
PASTEL	23.39	0.22	34.99	-0.30
AVERAGE **Δ**		0.22		-0.20

The significant factor in Table V is that all of the Voglesong measurement differences are positive and all but one of the sphere measurement differences are negative. The consistent offset of the values would seem to indicate that the measurement apparatuses or the calibration procedures in some way biased the 0/45 and/or 45/0 measurements.

LATERAL DIFFUSION ERROR MEASUREMENTS

Lateral diffusion error (LDE), also know as translucent blurring error and, in the plastics industry, edge loss error, has been described by the author in a paper presented at the 1993 annual TAGA meeting **(3)**. Quite simply, this error occurrs when the detector in an instrument fails to evaluate all of the light reflected by a specimen. This often occurs when a translucent sample is being measured and some part of the reflected light diffuses laterally out of the field of view the detector channel. Voglesong in his 1993 TAGA paper questioned whether the LDE would be the same for 0/45 and 45/0 geometries.

The OR principle would seem to dictate that the value of the LDE

TABLE VI *Comparison of 0/45 and 45/0 lateral diffussion errors*

SAMPLE	0-20/45-10 45-10/0-20	0-20/45-15 45-15/0-20	0-20/45-20 45-20/0-20
TiO_2 PAPER			
	100.00	99.91±0.07	99.67±0.12
	100.00	99.90±0.07	99.52±0.15
OPAL GLASS GLOSSY			
	100.00	99.61±0.05	98.46±0.06
	100.00	99.61±0.05	98.52±0.04
OPAL GLASS MATTE			
	100.00	99.66±0.07	98.72±0.09
	100.00	99.65±0.06	98.75±0.05
0.1% TiO_2 IN STYRENE			
	100.00	95.37±0.13	89.01±0.15
	100.00	95.42±0.07	89.24±0.08
5.0% TiO_2 IN STYRENE			
	100.00	99.78±0.06	99.68±0.10
	100.00	99.89±0.03	99.84±0.07

should remain the same when the source and detector are interchanged. To check this out, OR was examined on a series translucent samples using a 20 mm normal channel aperture and 10, 15, and 20 mm apertures on the 45° channel. Table VI gives the results of this study.

The configurations which have the largest differences between the normal and 45° channel apertures have the least LDE. The measurements for these conditions were set to 100% and the other measurements were normalized to these values. Once again, the TiO_2 in styrene samples showed the greatest variation. This will be addressed in a future study.

CONCLUSIONS

The experience with the measurements made with the Byk-Gardner head suggest that great care must be taken to get good measurements that will confirm the OR principle. Over the course of this study the precision and repeatibility of the measurements has been continuously improved. Generally this has solved most unexplained differences and occassionally brought some other problems to light.

The sign difference between the Voglesong and sphere instruments 0/45 and 45/0 measurements appears be a function of the instrument configurations and not a failure of OR. In the first approximation, LDE appears to be independ of 0/45 and 45/0 geometry.

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