Paper: Meaningful Measurements and Metrics for Reflective Displays

Jack Timmons, Richard G. Failing, and John C. Brewer; Eastman Kodak Company; Rochester, NY/USA

Abstract

Reflective display contrast and bright state seem to be deceptively simple concepts. Many people, however, are unaware of the complexity of these quantities and unknowingly engage in flawed metrology and faulty analyses. As a result, reliably estimating the expected visual differences of reflective displays is impossible without a bona fide side-by-side comparison. In this paper, we briefly review common practices that warrant skepticism, and we report on our efforts to implement measurement procedures and associated metrics that are expected to be more visually predictive.

Introduction

Reflective materials come in many forms, from the relatively simple photographic papers to complex electronic displays. While their physical properties might differ greatly, reflective materials share two fundamentally similar attributes. First, their reflection properties can be described in the same ways. Both photographic papers and electronic displays exhibit specular, haze, and Lambertian reflections.

Second, no matter the display type, in order to characterize the display, one must be able to measure the light reflected from its surface and do so in a controlled and repeatable fashion. International Standards define the methods to make these measurements, however, considering the fact that many reflective materials exhibit a combination of specular, haze, and Lambertian surface characteristics, one must make an assessment of the display material's reflectance properties and then choose a method that is both robust and appropriate.

This paper will describe measurement methods we employ and our attempts to accurately measure reflective displays whose surfaces can be quite complex indeed.

Reflective Display Measurements

Traditional methods for measuring the reflectance of materials include densitometers, spectrophotometers, spot meters, and spectroradiometers. Each of these instruments is designed for capturing specific information, under strict guidance of established standards. Measurements made with these devices yield data that are used to help understand the reflective characteristics of subject materials such as imaging papers (photographic, thermal, inkjet, etc.), fabrics, color paper swatches, paints, and pigments.

Efforts to measure electronic reflective displays have created awareness that there is more to obtaining meaningful reflection measurements than what the "traditional" methods provide. For example, some of these materials change color with viewing angle, so a single geometry measurement may be inadequate.

Consider Figure 1, reproduced from reference [1], which shows four different materials and their reflection properties. Real life examples would include polished white or black glass, which reflects only specular light and has no haze or Lambertian components. Photographic papers and other reflective displays exhibit haze, specular or Lambertian, and, in some cases, a combination of two or more components.

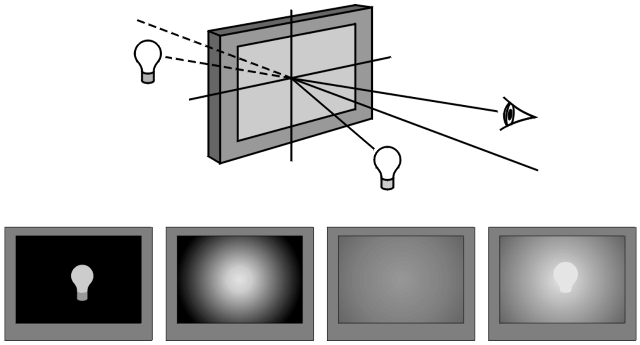

Figure. 1. *Specular, Lambertian, Haze: The Three-Component Reflection Model*

In 1931 the CIE committee defined the standard observer, standard illuminants and sources, and standard geometries for reflection measurements [2]. During this time it was concluded that an object's *color* was largely defined by its diffuse reflection characteristics. The standard geometries, including 45/normal, diffuse/8 specular included, and diffuse/8 specular excluded, were an attempt to create measurement configurations that correlate to visual observations concerning color.

Given that light reflects off display surfaces in many ways, what then is the appropriate way to measure a reflective display? First, let us consider the 45/0 geometry (Fig 2). This geometry is intended to characterize the diffuse component of reflectance. The term 45/0 refers to incident/collection angles.

Figure 3 is a graphical representation of the Bidirectional Reflection Distribution Function (BRDF) [3] that shows that the 45/0 geometry does not include the specular component, and may exclude all, a portion, or none of any haze component present. Note that because 45/0 uses only collimated light, it does correlate well with the diffuse illumination found in the real world.

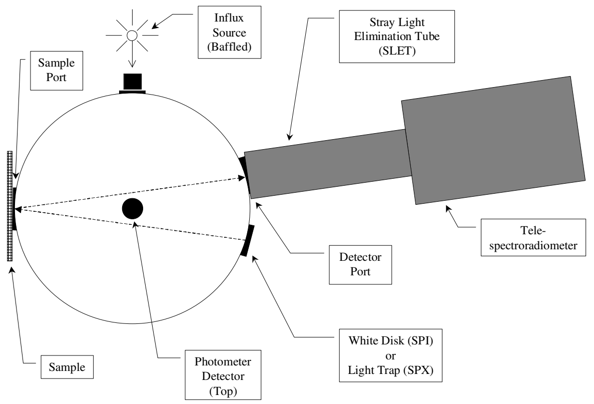

Figure 2. *45/0 measurement geometry*

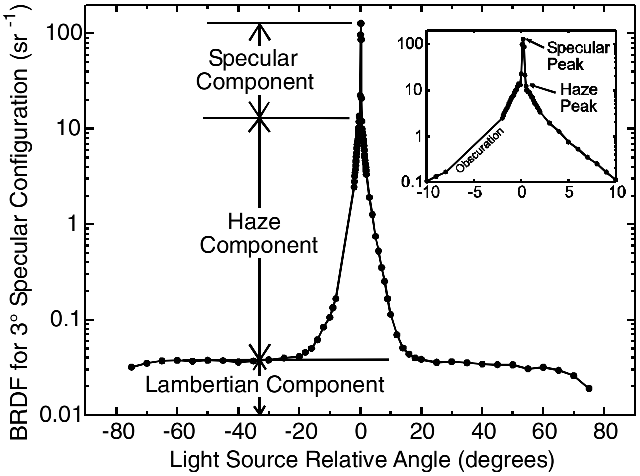

***Figure 3**. Bidirectional Reflection Distribution Function*

In addition, the CIE concluded that people who view reflective materials always position them in a way that excludes specular reflections. With this in mind, the CIE standardized two other geometric configurations utilizing integrating spheres, as shown in Fig. 4. These geometries illuminate samples with diffuse light and collect reflected light from the sample off-axis. A specular port allows for both including the specular component (d8:i) and excluding it (d8:e). The d8:i geometry accounts for all three of the BRDF components. This geometry is considered to be more "real world" in that it includes the reflections that one would normally see from surrounding surfaces. This geometry is not commonly reported because of the lower contrast values it yields.

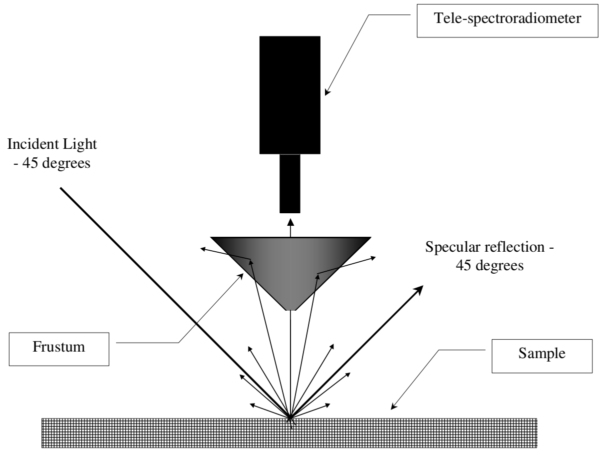

Figure 4. *Diffuse sphere*

Application of 45/0 and d8:i & d/8:e Geometries

In this section we will examine reflection data collected via 45/0, d8:i, and d8:e geometries. The samples of interest are black and white glass, two photographic papers, an electric sign, and an electronic book.

Black state (Yk) and white state (Yw) luminance factors reported for 45/0 and diffuse geometries were determined relative to a calibrated white and black Spectralon [5] disk. Diffuse illumination measurements were corrected for light flux variations. This is accomplished by measuring the illuminance in the sphere at the same time the luminance is measured. Luminance contrast ratios (LCR) were computed from the ratio of Yw to Yk, each adjusted by respective illuminance.

Prior to making measurements, the dark states of materials to be measured were qualitatively assessed for BRDF properties using a point source illuminant as discussed by Kelley et al. [4]. The results are listed in the last row of each data table.

The results for the measurements of reflectance "standards" are shown in Table 1. Black and white pairs with different surface properties were chosen. The glass standards are quite remarkable samples. Depending upon your geometry of interest, a luminance contrast (LCR) of 190,000:1 or 23:1 could be reported. Note that the total reflectance geometry (d8:i) yields about 4% Yk values for the black glass. This reflection value is most likely the result of the Fresnel reflection associated with glass/air interfaces. The 45/0 results show that the Lambertian component of the black glass is exceedingly small (as one would expect). The "Lambertian" white and black disks yield similar results (when appropriately calibrated) for all measurement geometries, making these materials the most "foolproof" to quantify. Unfortunately few, if any, materials of interest have purely Lambertian reflectance properties.

The paper samples measured consist of 2-inch square flat-field "blacks" and "whites" (minimum achievable paper density). Papers 1 and 2 are photographic papers that were printed on a commercial LED writer and appropriately processed. When measured on the Gretag Spectralino, the photographic paper "blacks" have Yk values of about 1%.

As shown in Table 2, the two papers have very different surface reflection characteristics. Based upon d8:i total reflectance measurements, Papers 1 and 2 would appear to be identical in Yk, Yw and of course, LCR values, but their qualitative BRDF's clearly show they have different surface reflection properties, and due to their different haze characteristics, they respond quite differently to specular excluded geometries. Paper 1, which has a strong specular reflection component, is sensitive in both white and black values to specular excluded measurement geometries. The data in Table 2 show that there are many different conclusions one could arrive at regarding the similarity or lack of similarity between photographic paper samples. This medium might not be adequately described by simply reporting one or two reflection values.

Table 3 summarizes the reflectance measurements completed on two consumer devices: (1) an electronic book, and (2) an electronic sign. The black and white states measured were those available from normal operation of the devices.

Table 1: Reflectance measurements of "standards"

Geom	Opal / Glass			Spectralon		
	Yk	Yw	LCR	Yk	Yw	LCR
45/0	5.1E-6	0.956	1.9E+5	0.015	1.0	66
d8:i	0.043	0.992	23	0.018	1.0	57
d8:e	0.003	0.944	292	0.018	1.0	57
	Dark State Appearance: Specular			Dark State Appearance: Lambertian		

Table 2: Reflectance measurements of two papers

Geom	Paper 1			Paper 2		
	Yk	Yw	LCR	Yk	Yw	LCR
45/0	0.010	0.596	60	0.010	0.765	81
d8:i	0.062	0.878	14	0.059	0.797	14
d8:e	0.017	0.782	45	0.044	0.782	18
	Dark State Appearance: Specular			Dark State Appearance: Lambertian		

Table 3: Reflectance measurements of devices containing reflective displays

Geom	Electronic Book			Electronic Sign		
	Yk	Yw	LCR	Yk	Yw	LCR
45/0	0.065	0.38	5.8	0.58	0.19	3.3
d8:i	0.15	0.43	2.9	0.13	0.26	2.0
d8:e	0.09	0.37	4.0	0.08	0.22	2.6
	Dark State Appearance: Dominantly Haze & Lambertian w/Some Specular			Dark State Appearance: Specular, Haze & Lambertian		

Sources of Error

Often reflection measurements are made using some type of spot meter (e.g., spot photometer, telespectroradiometer, or camera), because one is interested in light reflecting off the surface of the material. Unless measurements are made carefully, and proper techniques are applied, errors will occur. For example, stray light (SL) is a common source of error when measuring materials with spot meters. Only light reflecting off the area of interest of a material should enter the influx aperture of the instrument. Unwanted light from surrounding areas will corrupt measurements, and must be eliminated. This can be accomplished by using a frustum (see the 45/0 configuration in Fig. 3), and/or a Stray Light Elimination Tube (SLET) [6]. Unwanted light is reflected away from the instrument because the sides of the frustum are angled at 45° and are painted glossy black. The SLET is simply a tube that fits over the lens of the instrument that blocks unwanted light. In Table 4 one can see that our contrast measurements "improved" by 21% when corrected!

Table 4: Effect of frustum on measurements

	White L	Black L	LCR
Uncorrected	868	52.6	16.5
Corrected	953	46.7	20.4

To simply not hold samples flat or to use improper geometry configurations will cause errors in measurements. On the other hand, carefully arranged sample, illumination, and collection, as well as instrument configuration, would result in good measurements. Robust measurements will be made when close adherence to reflection measurement standards are followed.

Finally, when making d8:i and d8:e measurements, it is important to measure the illuminance at the same time the luminance of each sample is measured. Luminance should be corrected by the illuminance in order to account for the effect each sample has on the amount of light inside the sphere. For instance, a black sample reflects less light than a white sample, and consequently, the amount of light illuminating each sample is different. Not correcting for illuminance has resulted in as great as 10% errors in our measurements, as presented in Table 5.

Table 5: Effect of illuminant correction on newspaper

Illuminant Adjustment	White L	Black L	LCR
Not included	1071	94.5	11.3
Included	970	94.4	10.3

Dr. Edward Kelley at the National Institute of Standards and Technology has published several very good documents regarding display measurement techniques. His literature can be obtained at the NIST website (http://www.fpd.nist.gov/).

Standards

Standards for reflection measurements, called a "white reference" or "reference white," are obtained from a calibration standards laboratory such as NIST, or from secondary standards laboratories. Generally these materials are highly reflective with Lambertian-like surface characteristics. Standards are supplied with a calibration appropriate for the application in which they will be used. For instance, a white reference might be calibrated for spectral reflectance; those values should be used only in computing the spectral reflectance of an unknown sample. To use a calibration from a different geometry can produce errors.

Summary

Metrology of display materials is not as trivial as it would seem and, in most cases, more than one measurement is required to characterize a display's reflection properties.

In order to universally communicate display characteristics such as contrast and bright state, one must first assess the surface reflections. Subsequently, the appropriate measurement geometry is chosen.

Metrology in this field is relatively new, but the groundwork for robust measurements has been laid, and one must be attentive to the potential pitfalls in making measurements of these types of displays.

References

[1,3] Edward Kelley, NIST Conquering Electronic Display Reflection Measurement Irreproducibility, Kent State University Seminar, April 11, 2001.

[2] R.S. Berns, Billmeyer and Saltzman's Principles of Color Technology, 3rd Edition, Wiley-Interscience, New York, pp. 84–87 (2000).

[4] Edward Kelley, NIST, Seminar: Importance of Display Metrology in a Competitive World, 2005.

[5] Labsphere Diffuse Coatings Materials and Materials Catalog, Spectralon Diffuse Reflectance Standard, Part No. SRS-99-020 (White), SRS-02-020 (Black).

[6] P.A. Boynton, E.F. Kelley, NIST Stray Light Elimination Tube Prototype, NIST publication NISTIR 6861.

Author Biographies

Jack Timmons is an alumnus of Gannon College, SUNY Brockport, and the Rochester Institute of Technology. He has worked in the Research Laboratories of Eastman Kodak Company since 1977. During this period, Jack's focus has been in the areas of analytical chemistry, electron, optical, and atomic force microscopy, quantum sensitivity, image and color science, and, most recently, spectroradiometry and photometry..

Richard Failing is a graduate of Monroe Community College with an A.A.S. degree in Engineering Science. He has worked in product development in several areas in Eastman Kodak Company, most recently in an optical measurement laboratory specializing in uv/vis spectroradiometry, photometry, and color science applications.

John C. Brewer has been with Eastman Kodak Company since 1992, and he holds a Ph.D. in Inorganic Photochemistry from the California Institute of Technology. John spent his first eight years with Kodak in product development for Entertainment Imaging, working closely with customers in the animation, special effects, and theatrical film areas. Subsequently, he spent three years with the Consumer Division in color paper products. John is currently in the Display Science & Technology group, engaged in the metrology, modeling, and simulation of new display concepts.