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11.3: Sensitivity of Display Reflection Measurements to Apparatus Geometry

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Abstract[1]

Reflection measurements made upon electronic displays can suffer from non-reproducibility owing to their possible strong dependence upon apparatus geometry. The geometrical dependence arises from non-Lambertian diffusion properties. We show the inadequacies of several conventional reflection measurement methods and offer some guidance on how these methods might be improved or replaced.

1. Introduction

The simple measurements employed to determine the reflection properties of electronic displays generally fall into two categories: diffuse measurements or specular measurements. In reflection, the term "diffuse" refers to light being scattered out of the specular direction; "diffuse" is *not* synonymous with "Lambertian." A surface that exhibits a Lambertian reflectance property is only one type of diffusing surface, and all diffusing surfaces are *not* Lambertian. Misconceptions associated with reflection—and in particular the term "diffuse"—have generated a great deal of confusion in the display industry (author included). Space does not permit a full discussion of these details. When the front surface of a display is neither quasi-Lambertian nor specular (like a mirror), the reflection measurement result can be sensitive to the geometrical arrangement of the apparatus. The intermediate state between Lambertian and specular has been referred to as haze [1]. Having a specific name for this intermediate state has become necessary in order to communicate display reflection characteristics. What seems like such a simple measurement can be ruined by a lack of robustness of the result to small changes in the apparatus set up because of the haze component of reflection whenever it is present and non-trivial. We will investigate the geometrical sensitivity of eight different reflection measurement configurations. These kinds of methods are being considered by various display-evaluation standards-making bodies.

2. Apparatus Configurations

In Fig. 1 we show the eight apparatus configurations that are employed in the testing. When reflection measurements are made using such apparatus a luminance L measurement of the display is made under a source illuminant configuration. Several kinds of results might be extracted: (1) the luminance L by itself as in making a contrast measurement under illumination; (2) the specular reflectance $\zeta = L/L_s$ (note that CIE uses ρ_r [1]), where the luminance L_s of the source is considered an important apparatus characterization quantity (as in specular types of measurements)—such a measurement is essentially the same as a luminance measurement from the standpoint of this sensitivity analysis; (3) the luminance factor $\beta = \pi L/E$, where the illuminance from the source is considered an important quantity; and (4) reflectance ρ measurements as made by placing the display into an integrating sphere

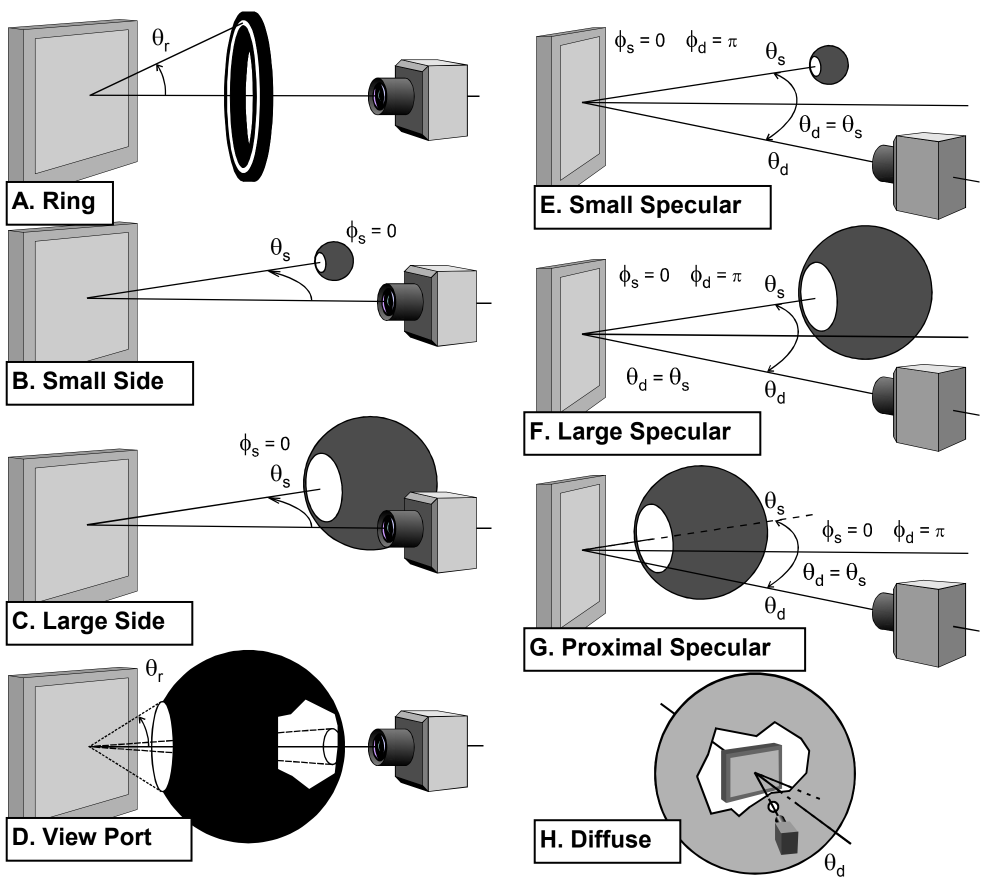

Fig. 1. *Eight reflection measurement apparatus often used to characterize display reflection. The names refer to the placement and/or type of the source illumination.*

source. Actually, in (4) we are making a luminance-factor $\beta_{d/10}$ measurement using a diffuse source from some detector angle $\theta_d = 10°$ away from the normal, but this is the same as the reflectance $\rho_{10/d}$ [1]. The Cartesian coordinate system used here is centered at the ideal position of the screen with the y-axis as up, the z-

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Table 1. Some of the Parameters Specifying Reflection Measurement Apparatus			
DETECTOR PARAMETERS:			
r_d	Distance of the center of the detector front surface (or lens) from the center (often z_d when detector is on the optical axis)	α	Measurement field angle (the angle of the measured region from the viewpoint of the detector)
θ_d	Inclination angle of detector from the z-axis	R_d	Radius of the entrance pupil of the detector
ϕ_d	Rotation angle of the detector about the z-axis starting from the x-axis and going counter clockwise	κ_d	Subtense of the entrance pupil of the detector or angular aperture: $\tan(\kappa_d/2) = R_d / r_d$
F	The luminance meter is either focused on the source (F = S) or the display (F = D).		
SOURCE PARAMETERS:			
r_s	Distance of center of the source exit port from the center of coordinate system (often z_s when the source is on the optical axis)	θ_r	Angle of ring light outer diameter from normal or angle of outer diameter edge of the exit port of a source positioned close to the display as measured from the normal: $\tan\theta_r = R_s / r_s$
θ_s	Rotation angle of the source from the z-axis	R_v	Radius of the view port (if so equipped)
ϕ_s	Rotation angle of the source about the z-axis starting from the x-axis and going counter clockwise	κ_s	Subtense of source from the center: $\tan(\kappa_s/2) = R_s / r_s$, $\kappa_s = 2\theta_r$
R_s	Radius of the source exit port (outer diameter of ring light source)	U	The average uniformity of the source luminance over the full extent of the exit port

axis along the display surface normal, and the x-axis in the horizontal plane to the right along the display surface. The display or sample surface is positioned within 0.5 mm of the ideal position and oriented within 0.1° of the ideal z-axis. Table 1 provides the list of parameters that specify the reflection apparatus.

In general, the uniformity $U \cong 1$ % for the large sources and any source used in a specular configuration. In configuration D a view-port box source is used. In the standard configuration, the view port is centered along the z-axis and serves as the hole through which the luminance measurements are made.

3. Analysis and Results

For the diffuse source configuration H, we employ two entirely different apparatus. One is a 2 m diameter integrating sphere at the center of which is placed the sample with an illuminance meter in the same plane as the sample and placed nearby the sample. For a display that has only a non-trivial haze component (SAEH in Table 3), the reflectance measures $\rho_{d/\theta} = 0.0557$ with a standard deviation of less than 0.3% over the detector angle range from 6° to 20°—a very robust measurement. The second reflectance measurement is performed using a sampling sphere—a closed-cell polystyrene-foam hollow sphere—with a fiber-optic source and a photopic photodiode. The sample is placed upon the exit port. With nothing on the exit port, a photocurrent of J_k is obtained. A white reflectance standard ($\rho_{std} = 0.99$) placed on the exit port gives a photocurrent J_{std}. With the sample in place we get photocurrent J. The reflectance of the sample is $\rho = \rho_{std}(J - J_k)/(J_{std} - J_k) = 0.0554$ with a standard deviation of less than 3 %. The large standard deviation arises because of the relatively soft exit port (plastic foam). A more rigid sphere would provide more precise results. The polystyrene integrating sphere is used to show that even with a fairly crude apparatus the results can be surprisingly good—less than a 1 % difference between using the crude plastic foam sphere and the large integrating sphere. Thus, the reflectance measurement using diffuse illumination is very robust.

For each of the other experiments or apparatus configurations, a small subset of parameters is selected for sensitivity testing and the rest are held fixed. For each experiment there are a set of k parameters p_i, $i = 1, 2, \ldots k$ (normally $k = 3, 4,$ or 5), for which there are standard settings s_i that are changed to varied settings v_i. The varied settings are to simulate alignment and positioning errors from the standard settings. Methods of experimental design are employed whereby full or fractional factorial designs are used with randomized blocks to provide an approximate model of the result y—which can be β, ζ, ρ, or L—in terms of the parameters [4]. The result y is some unknown function of the parameters $y = g(p_1, p_2, \ldots, p_k)$. The value of y at the standard settings s_i is $y_0 = g(s_1, s_2, \ldots, s_k)$ for any experiment (apparatus A, B, …, G). We form the quantity $f = y/y_0$, which provides us a result relative to the standard settings. The sensitivities S_i, expressed in percent, are obtained from the experimental design results in terms of partial derivatives of f:

$$S_i = 100\% \left.\frac{\partial f}{\partial p_i}\right|_{s_i} . \qquad (1)$$

The units of these sensitivities are the inverse units of the parameter p_i. These sensitivities are tabulated for reasonable errors in apparatus set-up such as in per mm of positioning or per degree of misalignment or angular size. In the process of conducting these experiments it is found that the detector distance r_d has no important effect, as should be expected. The detector distance is $r_d = 1$ m or more, and the detector's moderately small angular aperture is $\kappa_d \cong 1°$. This is not to say that the detector acceptance area size cannot be important, it can be [3]. However, no provision is made to deliberately change the detector acceptance area size in these experiments.

In Table 2 we show the standard settings s_i and the varied settings v_i for all configurations expect for configuration H (diffuse source measurements, which is dealt with separately above). Thick-lined boxes highlight the variables that are changed. Table 3 shows the samples measured with a brief description of their reflection components and properties ("L" for Lambertian, "S" for specular, and "H" for haze; boldface indicates the dominant component; smaller font size indicates a lesser contribution). Table 4 shows the sensitivity results. (Relative reproducibility of the sensitivities of repeated experiments proved to be 0.1 %. We report a relative expanded uncertainty with a coverage factor of two of 3 % for these results based upon experience, equipment calibration, and linearity)

Space does not permit a full discussion of these results. The rows labeled "Measured" indicate what is measured in determining the sensitivity: either β (when illuminance is considered important), ζ (when a specular configuration is used), or the luminance L (as for

Table 2a. *Settings for each configuration.*

		A		B-30		B-15		C		D		E-15		E'-15	
		Ring Light Source		Small Side Source at 30°		Small Side Source at 15°		Large Side Source at 30°		View-Port Box Source		Small Specular Source at 15°		Small Specular Source at 15°	
p_i	Unit	s_i	v_i	s_i	v_i	s_i	v_i	s_i	v_i	s_i	v_i	s_i	v_i	s_i	v_i
r_s	mm	76.2	83.8	515.6	464.1	515.6	464.1	474.7	427.3	76.2	83.8	515.6	464.1	515.6	464.1
θ_s	°	0	1	30	32	15	17	30	32	0	1	15	17	15	17
θ_d	°	0	1	0	2	0	2	0	2	0	1	$= \theta_s$	$= \theta_s$	$= \theta_s$	$= \theta_s$
α	°	1.0	0.25	1.0		1.0		1.0		1.0	0.25	0.125	0.25	0.125	0.25
R_v	mm									31.8	44.5				
F		D		D		D		D		D		S		D	
R_s	mm	48.9		4.5		4.5		62.5		76.2		9	8	9	8
κ_s	°	40		1		1		15		90		1		1	

Table 2b. *Settings for each configuration, continued.*

		E'-15		F-15		F-30		F'-30		G-45/45		G-45/30	
		Small Specular Source at 15°		Large Specular Source at 15°		Large Specular Source at 30°		Large Specular Source at 30°		Proximal Specular Source		Proximal Specular Source	
p_i	Unit	s_i	v_i	s_i	v_i	s_i	v_i	s_i	v_i	s_i	v_i	s_i	v_i
r_s	mm	515.6	464.1	474.7	427.3	474.7	427.3	474.7	427.3	80	65	80	70
θ_s	°	15	17	15	17	30	32	30	32	45	47	45	47
θ_d	°	$= \theta_s$	$= \theta_s$	15	17	30	32	30	32	45	47	30	32
α	°	0.125	0.25	1		1		1		1		1	
F		D		D		D		S		D		D	
R_s	mm	9	8	62.5		62.5		62.5		76.2		76.2	
κ_s	°	1		15		15		15		?		?	

contrast measurements—often the luminance sensitivity is identical to that for ζ). The sensitivity indicated for the measurement field angle α arises somewhat from calibration errors of ±0.1 % between measurement field angle settings; so we might excuse between 0.5 % and up to 1 % for calibration errors, but no more than that amount. In general, it should be observed that whenever haze is present ("H" in the "Components" row) the results can show a remarkable sensitivity to small changes in the parameters. In the cases of either a small-specular-source or a small-side-source apparatus a strong sensitivity is observed. It may be that the requisite alignment will not permit these configuration to be employed except in laboratory settings whenever haze is an important factor in display reflection.

Of all the apparatus configurations, the ring light (A), the large specular source (F), and—as mentioned earlier—the diffuse apparatus (H) prove to be the least sensitive to geometrical variations and are therefore the most robust methods. Even in these more robust cases, except for the diffuse illumination (H), a reasonable effort still must be made to carefully set the apparatus geometry—often to within a fraction of a millimeter and a fraction of a degree—in order to achieve a 1 % reproducibility.

Assume that a sample exhibits all three components of reflection: Lambertian, haze, and specular. Reflection from the diffuse illumination apparatus (H) arises from all three reflection components in the most robust manner. Reflection from the ring light (A) arises from the far wings of the haze profile and any quasi-

Table 3. *Reflection Samples*

Name	Components	Description
SAEH	**H**L	Display used in automotive research having only a nontrivial haze component, Lambertian component is small. The display is off.
OCRT	SL	Sample, looks like an old CRT B&W monitor, no haze component, only Lambertian and specular.
FPD	s**H**L	Sample, from FPD manufacturer, used as front glass, strong haze, weak specular, small Lambertian.
CRT	SHL	Sample, resembles a modern color CRT with front-surface diffusion treatment (haze), weak specular, moderate Lambertian.
FPD2	**H**L	Tighter haze than FPD (gloss 70), no specular, strong haze, small Lambertian.

Lambertian behavior. Reflection from the large specular source (F) includes the specular reflection, the haze peak, and an integration over much of the significant part of the haze profile around the peak; reflection from the Lambertian component is reduced from that obtained from either the ring light or the diffuse illumination. Additionally, these three methods (ring, large specular, diffuse) integrate the reflection contributions from all rotation angles around the normal or specular direction—a single direction is not preferred.

Table 4a. *Sensitivities to parameter variation (S_i in per unit).*

Configuration:		A: Ring Light Source, Focus on Display				B: Small Side Source, Focus on Display								
						B-30: Source at 30°		B-15: Source at 15°						
Sample:		SAEH	SAEH	OCRT	FPD	SAEH	SAEH	SAEH	SAEH	OCRT	OCRT	FPD	FPD	CRT
Components:		**H**L	**H**L	SL	s**H**L	**H**L	**H**L	**H**L	**H**L	SL	SL	s**H**L	s**H**L	SHL
Measured:		β	*L*	β	β	β	*L*	β	*L*	β	*L*	β	*L*	β
Result for settings s_i, y_0:		0.0416		0.0381	1.62×10^{-3}	0.0177		0.101		0.0407		2.72×10^{-3}		0.0283
p_i	Unit	S_i	S_i	S_i	S_i	S_i	S_i	S_i	S_i	S_i	S_i	S_i	S_i	S_i
r_s	mm	1.8%	-0.4%	0.1%	0.5%	0.0%	-0.4%	0.0%	-0.5%	0.0%	-0.4%	0.0%	-0.5%	0.0%
θ_s	°	-0.7%	-0.8%	-0.3%	0.1%	-8.0%	-8.8%	-19.7%	-21.5%	-1.2%	-1.3%	-20.1%	-22.0%	-19.8%
θ_d	°	0.6%	0.7%	0.1%	-0.3%	6.9%	7.5%	20.1%	21.9%	-0.6%	-0.6%	20.2%	22.0%	19.7%
α	°	-1.0%	-1.8%	-2.9%	-1.4%									

Table 4b. *Sensitivities to parameter variation (S_i in per unit), continued.*

Configuration:		C: Large Side Source, 30°, Focus: Display		D: View-Port Box, Focus on Display			E: Small Specular Source at 15°							
							Focus on Source					Focus on Display		
Sample:		SAEH	OCRT	SAEH	FPD	OCRT	SAEH	OCRT	CRT	FPD	FPD2	SAEH	FPD	FPD2
Components:		**H**L	SL	**H**L	s**H**L	SL	**H**L	SL	SHL	s**H**L	**H**L	**H**L	s**H**L	**H**L
Measured:		β	β	β	β	β	ζ, *L*	ζ, *L*	ζ, *L*	ζ, *L*	ζ, *L*	ζ, *L*	ζ, *L*	ζ, *L*
Result for settings s_i, y_0:		0.0177	0.0404	0.0835	0.0184	0.0435	5.15×10^{-4}	0.0390	0.0148	2.72×10^{-3}	1.01×10^{-3}	4.70×10^{-4}	2.73×10^{-3}	1.04×10^{-3}
p_i	Unit	S_i	S_i	S_i	S_i	S_i	S_i	S_i	S_i	S_i	S_i	S_i	S_i	S_i
r_s	mm	0.0%	0.0%	1.3%	1.1%	0.0%	-0.3%	0.0%	-0.1%	-0.3%	-0.4%	-0.5%	-0.3%	-0.4%
θ_s	°	-7.8%	-0.2%	-0.4%	0.5%	0.2%	-2.2%	0.1%	-0.1%	0.4%	1.0%	-2.8%	1.3%	0.9%
θ_d	°	7.9%	-0.2%	0.4%	-4.4%	-0.1%	-	-	-	-	-	-	-	-
α	°			-1.6%	-1.0%	-0.2%	-39.1%	5.1%	-7.6%	-1.2%	-23.4%	-18.3%	-23.3%	-36.6%
R_v or R_s	mm			1.3%	10.4%	-0.1%	22.8%	-0.3%	6.9%	16.6%	20.6%	22.3%	15.8%	20.9%

Table 4c. *Sensitivities to parameter variation (S_i in per unit), continued.*

Configuration:		F: Large Specular Source at…, Focus on …						G: Proximal Specular Source, Focus on Display					
		15°, Display	30°, Display				Source	Source at 45°, Detector at 45°				Source at 45°, Detector at 30°	
Sample:		SAEH	SAEH	OCRT	FPD	FPD2	SAEH	SAEH	SAEH	OCRT	OCRT	SAEH	SAEH
Components:		**H**L	**H**L	SL	s**H**L	**H**L	**H**L	**H**L	**H**L	SL	SL	**H**L	**H**L
Measured:		ζ, *L*	ζ, *L*	ζ, *L*	ζ, *L*	ζ, *L*	ζ, *L*	β	ζ, *L*	β	ζ, *L*	β	ζ, *L*
Result for settings s_i, y_0:		0.0317	0.0344	0.0478	0.0434	0.0426	0.0345	0.2075	0.0627	0.247	0.0747	0.178	0.0551
p_i	Unit	S_i	S_i	S_i	S_i	S_i	S_i	S_i	S_i	S_i	S_i	S_i	S_i
r_s	mm	-0.2%	-0.2%	0.0%	0.0%	0.0%	-0.2%	1.2%	0.0%	1.6%	-0.3%	1.8%	-0.1%
θ_s	°	-1.0%	-1.0%	0.1%	-0.2%	-0.5%	-0.7%	1.7%	0.0%	1.4%	-0.4%	1.5%	-0.2%
θ_d	°	1.0%	1.0%	0.5%	0.8%	1.1%	1.6%	1.6%	1.8%	1.8%	1.9%	0.7%	0.8%

4. References

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