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2.1—Invited: Diffuse Reflectance and Ambient Contrast Measurements Using a Sampling Sphere

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Abstract: *Display performance under ambient conditions is as important for display characterization as are darkroom measurements. We review ambient-contrast measurements and the design and use of sampling spheres rather than large integrating spheres for making diffuse-reflectance measurements.*

Keywords: ambient contrast; diffuse reflectance; display measurements; integrating sphere; sampling integrating volume; sampling sphere

1. Introduction

People are very aware of how important it is to characterize electronic displays in an ambient environment that replicates their observing conditions. We hear "ambient contrast" and "bright-room contrast" quite a bit at conferences, exhibitions, and in publications. Darkroom measurements of displays are important and necessary, to be sure. They provide a baseline but they do not provide all the information to fully characterize a display for use in an illuminated surround. Many different apparatus configurations are under consideration for making reflection measurements and have been for some time, as is evident in numerous standards for electronic displays. This paper promotes the measurement of diffuse reflectance as a fundamental characterization property of displays.

2. Diffuse Reflectance and Ambient Contrast

Diffuse reflectance ρ is a precisely defined term. It refers to a measurement of the ratio of the luminous flux diffusely reflected from a surface to the luminous flux hitting the surface. [1] Because of reciprocity, diffuse reflectance ρ and luminance factor β can be related; that is, $\rho_{\theta/d} = \beta_{d/\theta}$. [2] Thus, we can apply a uniform diffuse illumination (uniform over 2π sr) to a surface and measure the reflected luminance L_R from some angle θ from the normal of that surface to obtain the diffuse reflectance:

$$\rho = \rho_{\theta/\mathrm{d}} = \beta_{\mathrm{d}/\theta} = \frac{\pi L_\mathrm{R}}{E}, \quad (1)$$

where E is the uniform diffuse illuminance. The contrast measured under uniform diffuse illumination has been called ambient contrast C_A. [3]

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Diffuse illumination is not uncommon as some have suggested. We experience bright ambient surrounds when using a handheld device on a bright overcast day, on a beach, on snow, or when viewing a television in a bright living room with light walls, furniture, and carpet. In fact, in almost any viewing environment, short of a good darkroom, there is always a background luminance level in the surround that is equivalent to a uniform diffuse illumination.

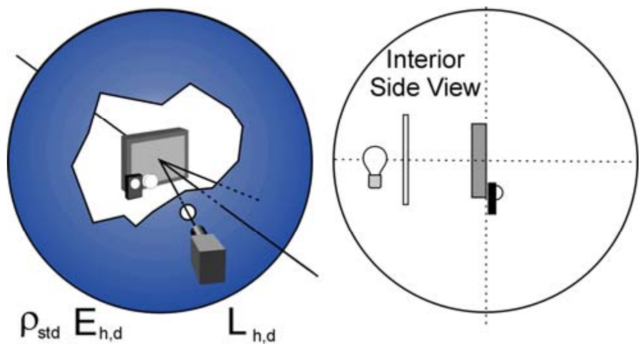

Fig. 1. Integrating sphere enclosing the display with illuminance meter and white diffuse standard. A baffled lamp is located behind the display. The measurement is made 10° from the display normal.

Figure 1 shows a display placed inside an integrating sphere. The display is rotated so that the luminance meter measures the screen 10° from the normal. If the display emits light, then the darkroom luminance of the display must be subtracted from the luminance measured under reflection to obtain the net reflected luminance. For our two cases of white (W) and black (K) screens the diffuse reflectances are:

$$\rho_\mathrm{W} = \frac{\pi(L_\mathrm{h} - G_\mathrm{W})}{E_\mathrm{h}}, \quad (2)$$

$$\rho_\mathrm{K} = \frac{\pi(L_\mathrm{d} - G_\mathrm{K})}{E_\mathrm{d}}. \quad (3)$$

Here, L_h (L_d) is the measured luminance of the white (black) screen under illumination (subscripts "h" is for "high" and "d" is for "dark"), G_W (G_K) is the darkroom luminance measured at the same location on the screen and from the same angle (10°) as used in measuring L_h (L_d), and E_h (E_d) is the illuminance falling on the screen providing uniform diffuse illumination. Note that the illuminances are measured at the same time and under the same conditions that the reflected luminances are measured; that is, the display, illuminance meter, and/or white reflectance standard are not moved during the measurements. Only the full-screen color (white or black) is changed during the measurements. Also note that with emissive displays, because of the subtraction in the numerator, it is very important that the interior illumination from the integrating-sphere lamp be bright enough so that the measured luminance under illumination is significantly brighter than the darkroom luminance. If this is not the case, then a large uncertainty in the diffuse reflectance values can result because of the small difference in the numerator.

If a white reflectance standard with diffuse reflectance ρ_{std} is employed to make the illuminance measurement, then the illuminance is

$$E = \frac{\pi L_{std}}{\rho_{std}} . \tag{4}$$

The advantage of using a white standard is that the same photopic response in the luminance meter can be used to measure the standard as is used to measure the luminance of the screen. If an illuminance meter is used to measure the illuminance, then if the spectrum of the illumination changes, its response may not be exactly the same as the luminance meter. Because an emissive display when showing a white screen will add to the illuminance by back reflections within the sphere, the spectrum of the illumination changes. How much it changes depends upon the relative amounts of the flux from the screen compared to the flux from the integrating-sphere lamp.

The ambient contrast can be calculated for any given illuminance E_0; that is, we scale the laboratory results to the required illuminance levels. For skylight we might use 10 klx, 6 klx, or 5 klx, depending upon the application. For an office we might use 500 lx or 250 lx. For a darkened living room we might use 10 lx down to 1 lx. We add the calculated luminance from the uniform diffuse illumination to the darkroom luminances L_W and L_K obtained from the design viewing direction (often the normal of the screen) to obtain the screen luminances K_W and K_K under uniform diffuse ambient illuminance level E_0:

$$K_{W,K} = L_{W,K} + \frac{\rho_{W,K}}{\pi} E_0 . \tag{5}$$

The ambient contrast is the luminance ratio

$$C_A = \frac{K_W}{K_K} = \frac{L_W + \frac{\rho_W}{\pi} E_0}{L_K + \frac{\rho_K}{\pi} E_0} \tag{6}$$

for any given desired illuminance E_0.

3. Sampling Sphere Considerations

Several methods can be used to make a diffuse reflectance measurement. Placing the display in an integrating sphere is probably the best way to measure its diffuse reflectance. However, for large displays it may be impractical to obtain an integrating sphere large enough to enclose the display. This gives rise to the use of a sampling sphere. Sometimes a sphere is not used but some other suitable volume or enclosure will suffice. In general, open boxes or open hemispheres can have difficulties in supplying adequate uniformity of illumination to be used with all display types. We will, therefore, limit our discussion to the design considerations for a sphere as the preferred measurement tool.

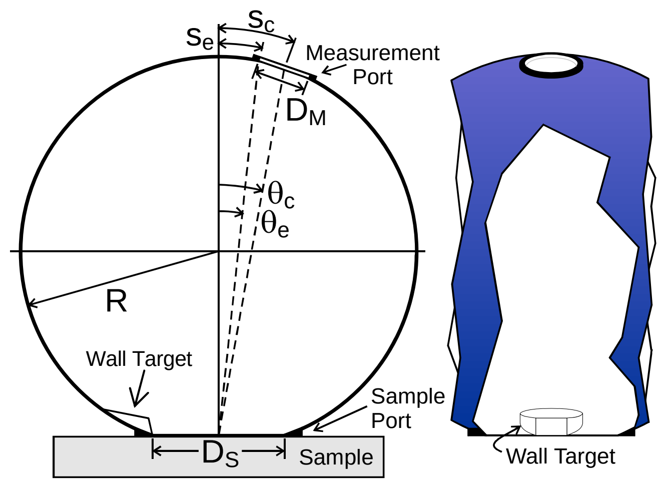

Fig. 2. Sampling sphere. Luminance measurements are made through the measurement port.

Figure 2 shows a sampling sphere in contact with the sample or display for which the diffuse reflectance is to be measured. The wall target shown is a white surface that is tilted away from the sample port so that any light from the sample (or emissive display) will not directly fall upon the wall target. If the interior brightness dominates any illumination from an emissive screen, then a simple wall measurement may suffice.

The size D_M of the measurement port is determined by the size of the lens of the luminance meter and should be a little larger than the lens diameter by 30 % or more. It is essential that any of the rays of light that contribute to the measurement of either the sample or the wall target are not intercepted by the measurement port; so good alignment is necessary. See Fig. 3.

Given the size D_M of the measurement port it is necessary to determine the radius R of the needed sphere. The angles in Fig. 2 are selected to be $\theta_c = 10°$ to the center of the measurement port and $\theta_e = 6°$ to the interior edge of the measurement port. Assuring that the interior edge of the measurement port is 6° away from the normal of the sample port reduces the affect that the measurement port hole has on the results. If the port is closer to the normal than 6° then we run the risk of introducing significant errors in making the diffuse reflectance measurement particularly whenever the display exhibits a nontrivial haze component of reflection. Assuming a zero diameter sample port allows us to make a simple approximation to the radius R. Letting the difference in angles define half the width of the measurement port at a distance of $2R$ obtains an approximate value

$$R \cong \frac{D_M}{4(\theta_c - \theta_e)} = 3.6\, D_M. \quad (7)$$

Here, the angles are measured in radians, and the right side is evaluated for $\theta_c = 10°$ and $\theta_e = 6°$. Rounding this value of R up to a convenient size provides a sufficiently large sphere to accommodate the desired measurement port size. Details for calculating the arc length s_c to locate the port on the sphere will be left for an archival version of this paper (or an exercise for the reader).

Figure 4 shows how the wall target is calibrated using a separate white reflectance standard. With the white standard surface in the plane of the sample port, the luminance L_{std} of the standard is measured and then the luminance L_{cal} of the wall target is measured without moving the white standard. The calibration constant is

$$k = \frac{L_{std}}{L_{cal}}. \quad (8)$$

During the measurement of a sample, the wall target luminance L_{wall} is measured to provide the illuminance at the sample port,

$$E = \frac{\pi k L_{wall}}{\rho_{std}}. \quad (9)$$

This illuminance is measured with the sample (display) at the sample port. Nothing changes in measuring the luminance of the sample and the luminance of the wall except the position of the luminance meter.

Other methods can be used to provide a calibration of the sampling sphere. A photopic photodiode might be employed to monitor the wall luminance away from the sample port. Such a monitor can either be baffled from the direct rays of either the lamp or the display or it can be recessed from the sphere surface to avoid such rays. One difficulty with using such a monitor is that it is very unlikely that its photopic response is identical to the photopic response of the luminance meter. When a photopic photodiode is used as a monitor, it can be calibrated with the white standard or using an illuminance meter properly placed at the sample port. Here again, however, is the problem of the photopic responses not being identical to that of the luminance meter. The wall target luminance measurement avoids many of these problems particularly when non-gray display colors are encountered.

When the sampling sphere is used to measure samples darker than the interior wall, it is important that the luminance meter be moved back away from the measurement port so that no rays from the bright sections of the interior wall hit the lens of the luminance meter—see Fig. 5. Otherwise it is possible to corrupt the measurements of darker objects with veiling glare arising from the bright wall. It is also particularly important to focus the lens on the sample and not on the measurement port.

Whenever the front surface of the display is near the pixel surface, as is the case with many liquid-crystal displays (LCDs), the diameter of the sample port is usually not an issue. For such cases we would make the sample port larger than twice the size of the measurement field of the luminance meter, and certainly larger than the measurement port. However, when measuring displays where there is a front glass that separates the pixel surface from very close to the front of the display, such as current plasma display panels (PDPs) and cathode-ray-tube (CRT) displays, then more attention must be paid to the size of the sample port.

Figure 6 shows the details of the sample port for a PDP where the front glass is offset from the pixel surface by a distance h. The angle θ_g is given by

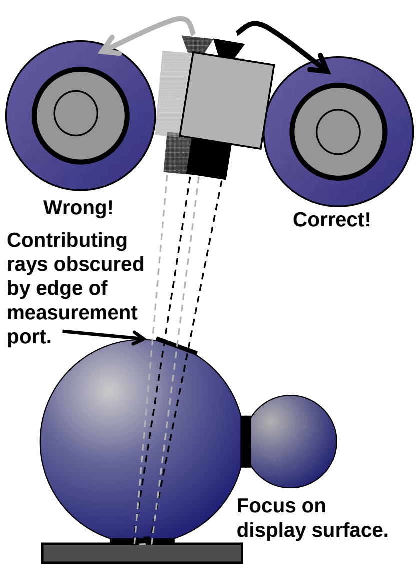

Fig. 3. Proper alignment of luminance meter with the measurement port is critical.

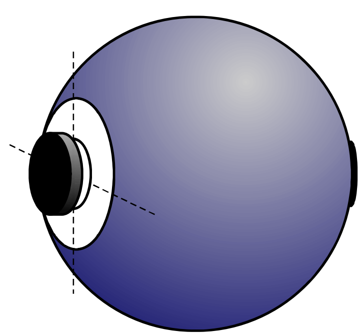

Fig. 4. White standard placed in the plane of the sample port for calibration of the wall target.

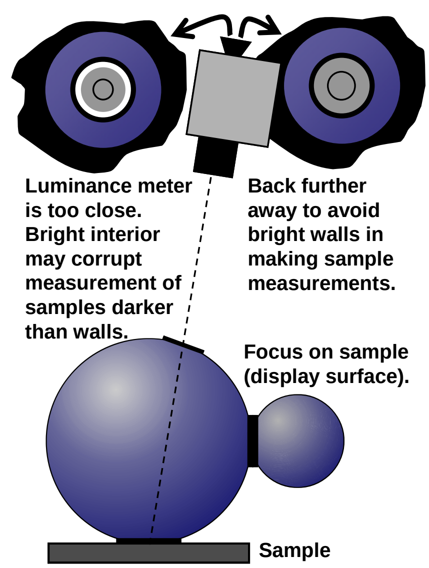

Fig. 5. Position of luminance meter sufficiently far away from measurement port to avoid veiling-glare corruption of darker samples.

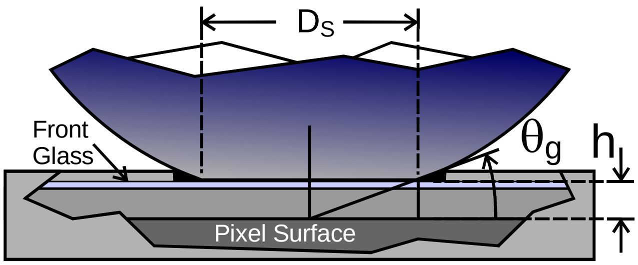

Fig. 6. Example of a sample port on the cover glass of a PDP where the pixel surface is offset from the front surface by a distance h.

$$\theta_g = \tan^{-1}\left(\frac{2h}{D_s}\right). \qquad (10)$$

How large must the sample port be to provide an accurate measurement of the diffuse reflectance? By examining a bidirectional reflectance distribution function (BRDF) model for a Lambertian-like display, we can establish some limits. A BRDF for a display without a perfect Lambertian component can be represented as

$$L = \zeta L_s + L_s \int H(\theta_i, \phi_i)\cos(\theta_i)\mathrm{d}\Omega_i\ , \qquad (11)$$

where ζ is the specular reflectance, L_s is the luminance of the interior wall of the integrating sphere, $d\Omega_i$ is the element of solid angle, $H(\theta_i, \phi_i)$ is the haze component of reflection that retains the quasi-Lambertian appearance, and (θ_i, ϕ_i) are the coordinates of the surface element of the wall. Many current PDPs and CRTs exhibit a quasi-Lambertian look of a background matte dark gray with a specular component added. A simplified BRDF for such a display would have a sharp peak at the specular configuration angle that represents the specular component. At larger angles it would be relatively constant on a log scale (the Lambertian nature).

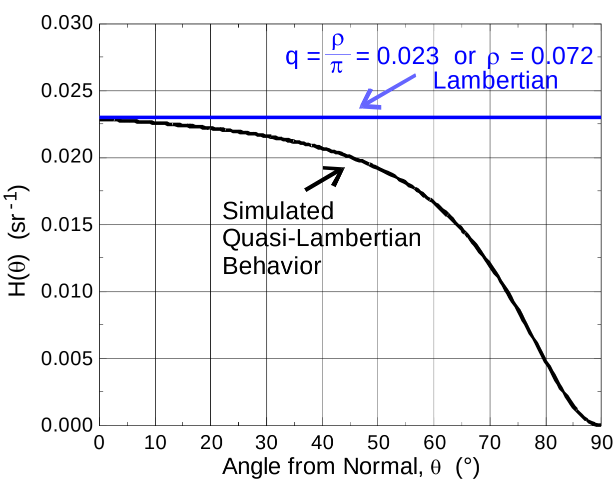

Fig. 7. Simulated analytical model of a BRDF, H(θ), for a quasi-Lambertian display with a front glass where the specular component is represented as an arrow at $\theta = 0$.

However, any glass or plastic front surface would cause the quasi-Lambertian flatness to decrease because reflections off surfaces increase as grazing angles decrease. Figure 7 illustrates the quasi-Lambertian shape of a simplified BRDF. Normally, BRDFs are shown on a log scale whereby the droop shown in Fig. 7 (a linear scale) would not be as evident until after approximately 60°.

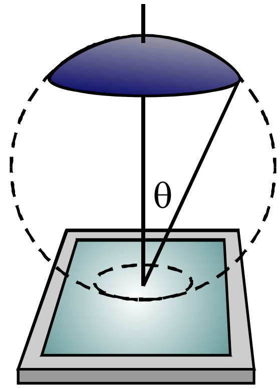

Fig. 8. Imaginary spherical section increasing in size over display.

Suppose we have an imaginary integrating sphere that we can extend as a spherical cap from a point above the display to having a sampling port against the display surface as shown in Fig. 8. Assume that its walls are self luminous with luminance L_s. We observe the luminance from the normal direction (with an imaginary luminance meter). We look at the luminance of the screen as a function of θ where we will include the specular reflectance of $\zeta = 0.02$, which is very small. Assuming the haze is symmetric about the normal, we can rewrite Eq. (11) as

$$L(\theta) = L_s\left[\zeta + 2\pi\int_0^\theta H(\theta_i)\cos(\theta_i)\sin(\theta_i)\mathrm{d}\theta_i\right]. \qquad (12)$$

The worst case for sensitivity to light coming from large angles from the normal is a Lambertian reflector. Figure 7 shows a dark value selected for quasi-Lambertian screens of a diffuse reflectance of $\rho = 7.2$ % — a very dark gray (matte-black paint is approximately 5 %). [4] The Lambertian assumption gives $H(\theta) = q = \rho/\pi$, a constant (q is the luminance coefficient), and the integration gives the luminance $L_L(\theta)$ for the Lambertian model as

$$L_L(\theta) = L_s\left[\zeta + \rho\sin^2(\theta)\right]\ . \qquad (13)$$

The quasi-Lambertian model in Fig. 7 is given by

$$H(\theta) = h\left[1 - \left(1 + \left(\frac{\pi/2 - \theta}{\pi/9}\right)^2\right)^{-1}\right], \qquad (14)$$

where $h = 0.024$ to match the Lambertian level at $\theta = 0$, and θ is in radians. The integration in Eq. (12) is done numerically to obtain the quasi-Lambertian model luminance $L_Q(\theta)$. Because we are trying to determine the errors that are caused by not being able to extend θ to fully 90°, the quantity of interest is the deviation from the 90° value:

$$\frac{\delta L}{L_{\max}} = \frac{L(90°) - L(\theta)}{L(90°)}, \qquad (15)$$

and the resulting graph for both models is shown in Fig. 9. This graph shows how big an error we encounter as the sampling port pulls away from being in touch with the pixel

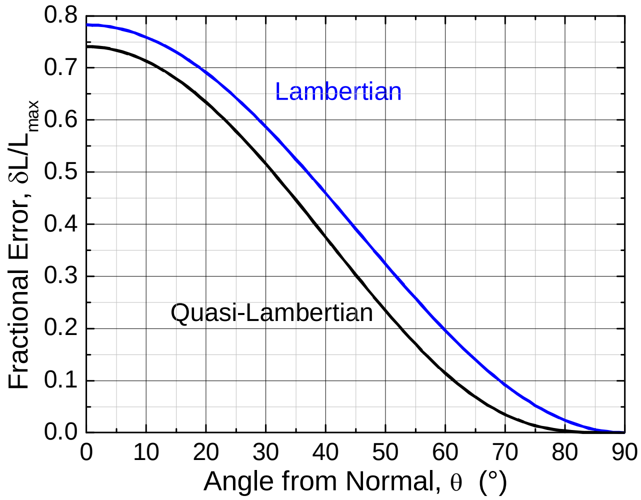

Fig. 9. Fractional error in luminance measurement for sampling port not being next to the pixel surface.

surface based upon these models. Here, $\theta_g = \pi/2 - \theta$. The errors for various angles are shown in Table 1.

Figure 9 and Table 1 show how large in diameter D_S the sampling port must be compared to the pixel-surface offset h in order to obtain a certain accuracy in our measurement results. Suppose we use a sampling port diameter $D_S = 16h$, then we can anticipate an error of approximately 1 % for a Lambertian material (with a small specular component) and an ignorable error of 0.08 % if the material exhibits the quasi-Lambertian behavior in our model (with a small specular component added).

Table 1. Error in luminance measurement for sampling port displaced from the pixel surface—from Fig. 9.

θ (°)	θ_g (°)	$D_S/h = 2/\tan\theta_g$ [Eq. (10)]	Error for Lambertian Model	Error for Quasi-Lambertian Model
85	5	22.8	0.59 %	0.02 %
83	7	16.3	1.2 %	0.08 %
80	10	11.3	2.4 %	0.32 %
75	15	7.46	5.2 %	1.3 %
70	20	5.49	9.2 %	3.5 %
65	25	4.29	14.0 %	6.8 %
60	30	3.46	19.6 %	11.4 %

Putting this all together, suppose we have a luminance-meter lens diameter of 30 mm, and we select our measurement-port diameter to be $D_M = 40$ mm. Our sampling-sphere radius estimate, Eq. (7), gives $R \cong 143$ mm. Rounding this radius up to 150 mm provides us with a sphere of diameter $D = 300$ mm. If we anticipate a pixel-surface offset of $h = 10$ mm and select $D_S = 10\,h = 100$ mm, then, from Table 1, our measurements of even the worst case of a perfectly Lambertian surface (with a small specular component) should be within 3 % of the correct value and within 0.5 % if the surface is like our quasi-Lambertian model. In practice, however, we might anticipate slightly larger errors because of apparatus configuration imperfections. For example, depending upon the robustness of the display surface, we try to avoid bringing the sampling port in contact with the display surface for fear of scratching or mechanically distorting the display surface; a gap of approximately 1 mm might be anticipated. A thin soft padding material or fabric might also cover the part of the sampling port that could possibly touch the screen to protect the screen from scratches. Thus, 2 mm or more can be added to h in practice.

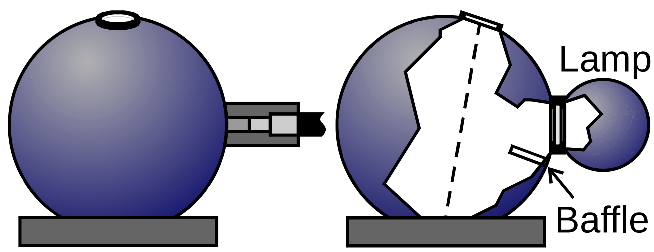

Fig. 10. Sampling sphere illumination possibilities using a fiber-optic illuminator (cutaway at left) or a satellite sphere with diffuser (right).

As a final note, Fig. 10 shows two of many possibilities for arranging illumination for the sampling sphere. The left drawing shows a fiber-optic illuminator that is recessed so that the bright end of the fiber optic does not directly shine on the sample-port area. The fiber-optic illuminator is placed at right angles to the plane of the measurement port and center of the sphere. The right drawing shows a satellite sphere with diffuser and baffle. The baffle prevents direct rays from the bright diffuser from directly hitting the sample-port area. Depending upon how nonuniform the interior light distribution is, more baffling of bright areas may be needed.

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