FLAT-PANEL ISSUE

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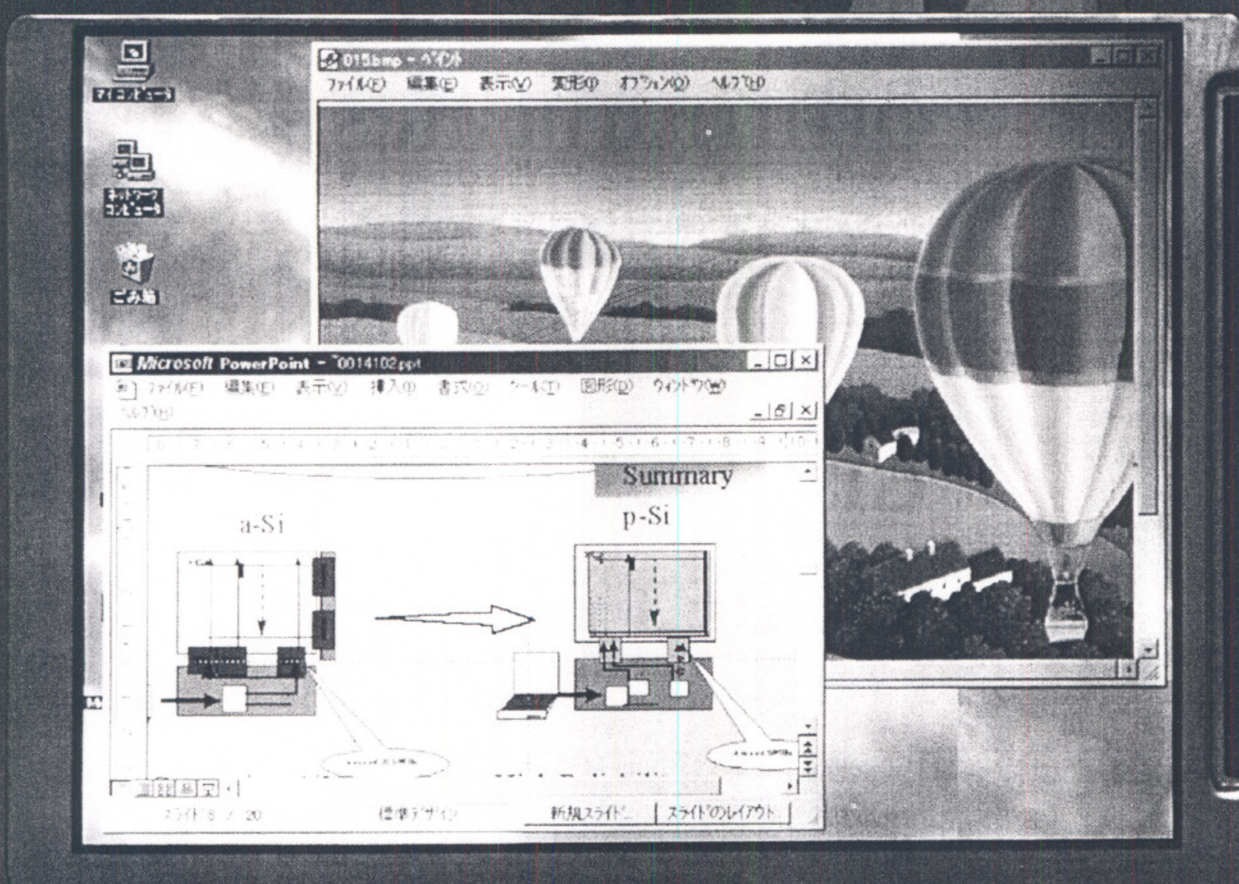

Reflective Color LCDs: Ready for Low-Power Portable Systems

- The "Iron Law" 25 Years Later
- Reflective Color LCDs
- Display Reflections
- Worries at Computex Taipei

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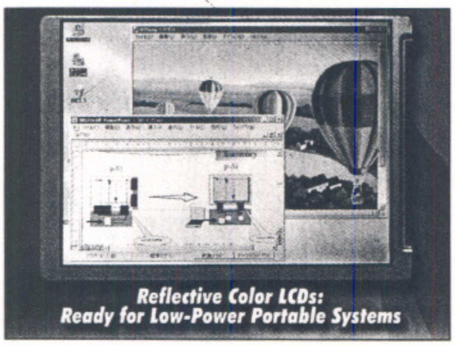
COVER: Reflective color LCDs using several different technologies are now good enough to begin filling a growing demand in a variety of applications that require low power consumption, ranging from cellular phones to notebook computers. This is Toshiba's 8.4-in. AMLCD, which uses polysilicon TFTs and integrated drivers.



Credit: Toshiba America

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Next Month in *Information Display*

Manufacturing Issue
- Repair and Rework of FPDs
- Electrostatic Discharge
- Flat-Panel Television
- Continuous-Grain Silicon
- Manufacturing Cost Structures

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The Three Components of Reflection

The ambient light that reflects off a display screen can affect image quality more than the light intentionally produced by the display – but which type of reflection is the most important? This is the second in a series of articles from NIST.

by Edward F. Kelley, George R. Jones, and Thomas A. Germer

"BEAUTIFUL DARKS IN BRIGHT LIGHT." That's another way of saying that reflections from the display surface are under control. Perhaps we will see advertisements making this statement in the future (Fig. 1). But the actual meaning of such claims is vague unless the reflection properties are clearly indicated.

If we were to state only the familiar diffuse and specular reflection properties, would the specifications be adequate? Not really: we might still not know how the display will look to the eye. There are actually three components of reflection with which we must contend in order to properly describe display reflection as it is perceived by the eye.

This is not a criticism of existing reflection-measurement methods and recommended practices. Defining how an electronic display actually appears to the eye may require a more complete description than is needed for fabric or paint.

When considering reflection properties, specular (mirror-like) reflection and diffuse reflection (as seen with surfaces like common copy paper and walls painted with flat, or matte, paint) are often thought of. With specular reflection, the observed luminance in the virtual image is proportional to the luminance of the source. The luminance of reflected images in a mirror doesn't depend upon their distance from the mirror, just as the luminance of objects does not vary with distance when we observe the objects directly.

With the so-called diffuse reflection, many people think in terms of Lambertian reflection - the luminance of the surface is independent of the direction from which the surface is observed and depends only upon the illuminance of that surface. (A nearly perfect Lambertian surface is not common and is difficult to produce in practice.)

The problem here is that the display industry sometimes think that the terms "diffuse" and "Lambertian" mean the same thing, and that is generally *not* the case for displays. According to the American Society for Test-

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Fig. 1: This fictional advertisement, which specifies three kinds of reflectance, could not honestly be used to describe any display that exists today.

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ing and Materials (ASTM), a diffuser is a surface that takes light energy away from the specular direction and distributes it in many other directions.[1] The term is not constrained to refer only to a Lambertian surface. So, it makes sense to use the term "Lambertian" for reflectance properties associated with a perfectly diffuse reflection.[2]

Four different screens showing the same-sized text with a black-and-white metal target on the front surface, to assure they are rendered equivalently in the reproduction, are shown in Fig. 2. The screens are illuminated by a 60-W light bulb in a small aluminum shade, and the bulb has a small opaque black square on its surface.

Figures 2(a) and 2(b) show cathode-ray tubes (CRTs), and Figs. 2(c) and 2(d) show flat-panel displays (FPDs). Figure 2(a) is an older CRT monitor that appears to have a medium-gray screen when turned off; the CRT in Fig. 2(b) appears dark gray when turned off. When the FPD screens are turned off, the surface of the FPD in Fig. 2(d) will appear darker than that in Fig. 2(c). Unfortunately, the limitations of the camera used and the printing of the images on paper severely restrict the range of contrast that is rendered here for all the displays, especially for the CRT in Fig. 2(b) and the FPD in Fig. 2(d).

How should these reflection properties be described so that we can understand how usable a display would be in a particular envi-

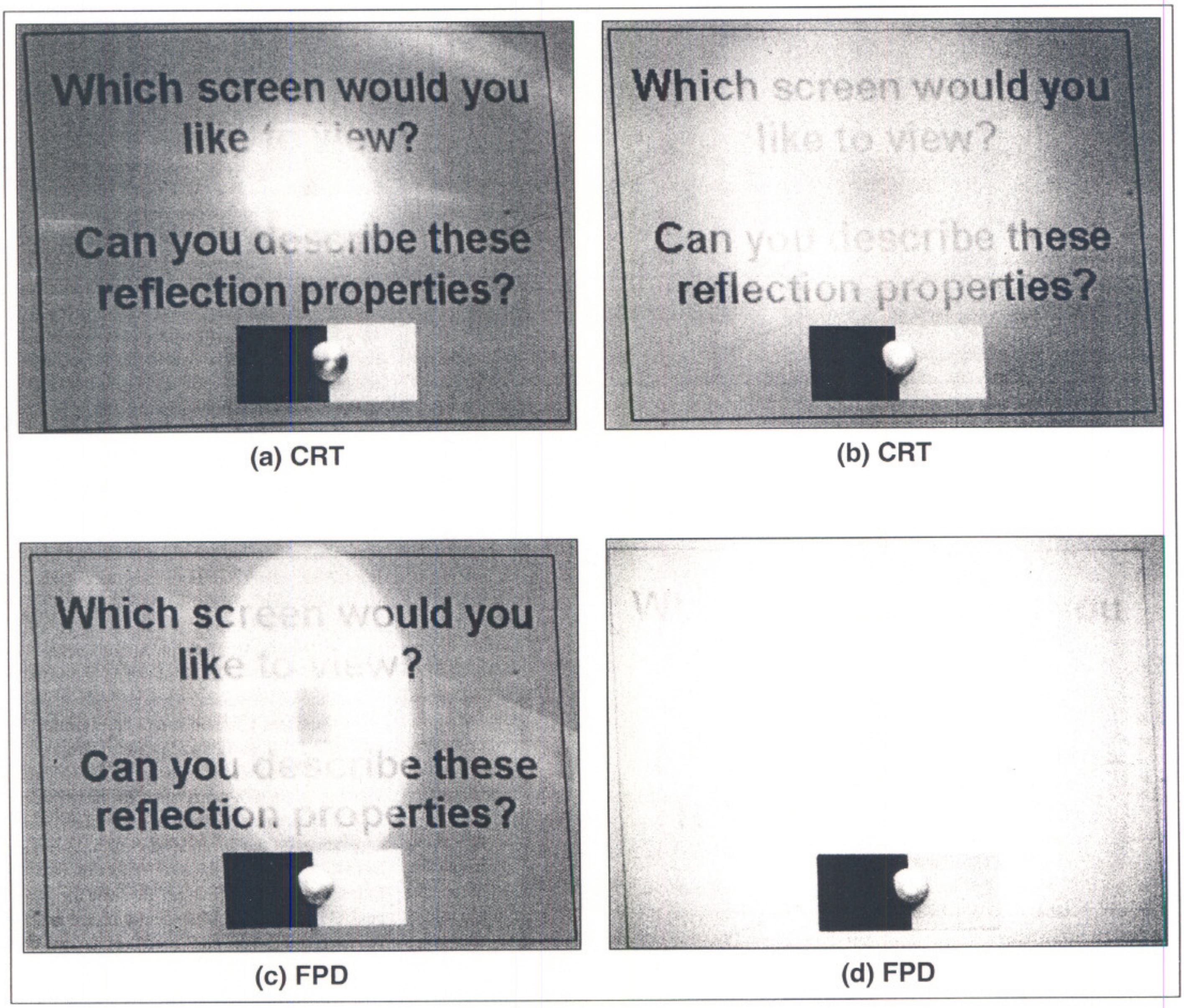
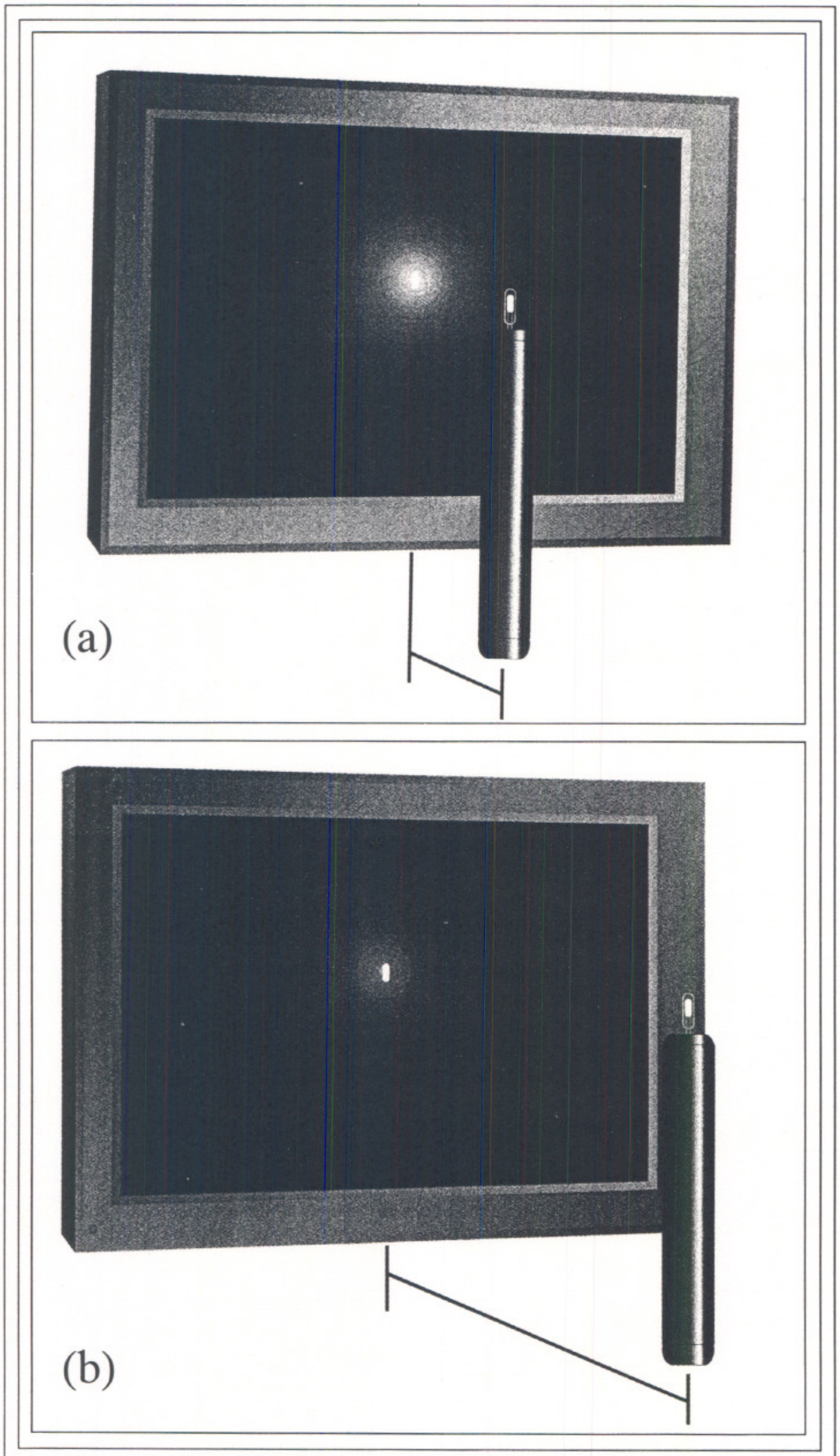


Fig. 2: These four displays exhibit very different reflection characteristics, each one representing a different combination of specular, Lambertian, and haze reflectance.



ronment and how it would appear to the eye? Would specifying the specular and Lambertian (or diffuse) components convey enough information to describe the reflected image? Probably not; something more is needed.

The best way to observe the reflection properties of a display surface is to look at the reflection of a point source of light. (With some flashlights, the head can be removed to expose the small high-intensity bare bulb. This will serve well as a point source of light.) In general, and with most CRT screens, three manifestations of the reflection of the point source can be observed (Figs. 3 and 4).

If there is a specular component, as is the case with most CRT computer monitors, a distinct virtual image of the point source will be observed. The brightness of the virtual-image point source will remain constant as the point is moved away from the screen. A general background gray that persists far away from the virtual image of the point source may also be observed. Again, this is especially true with CRTs, in which that gray background is the surface containing the phosphors. It is very much like a Lambertian surface in that its luminance remains relatively independent of the observation direction and is proportional to the illuminance upon its surface - it will get darker as the point source is moved away from the screen. If the screen has a front-surface semi-diffusing treatment, a fuzzy ball of light that surrounds the specular image can be observed. This is referred to as the haze component of reflection for want of a better term.[3] For CRTs, where there is a thick faceplate, a small fuzzy ball of haze without a specular image centered within it can be seen. This haze ball comes from the phosphor surface behind the front surface and would be located to the side of the specular image.

As the flashlight bulb is moved, it can be positioned so that the haze peaks are aligned. If a flat screen is used, decreasing the specular viewing angle will better align the haze peaks.

The luminance of the haze reflection depends upon the distance of the point source from the screen, but the haze reflection itself follows the specular image. Because the haze peak is aligned with the specular image and the luminances add, and since the haze peak

Fig. 3: *The reflection of a point source changes depending upon its distance from the display.*

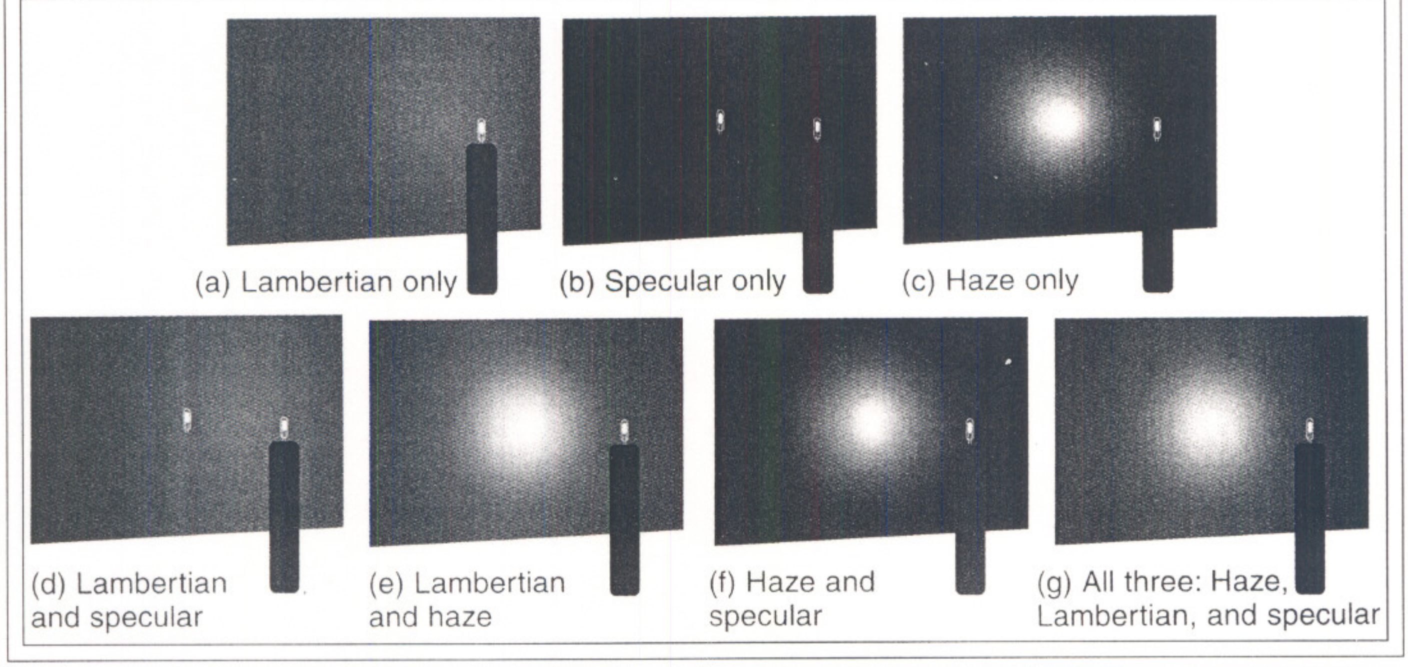


Fig. 4: Displays can have various mixtures of the three different reflection components. Often, one or two of the components can be made trivial.

decreases as the source is moved away while the specular luminance remains constant, a viewer can get the impression that the specular image is decreasing in luminance as the source image moves away, which is not the case.

So three types of reflection associated with displays can be seen: the general background-gray Lambertian component, the specular component having a distinct image of the source, and the haze component – the fuzzy ball of light that follows the specular image. The haze component is like the Lambertian component in that it is proportional to the illuminance, but the haze component is also like the specular component in that it is peaked in the specular direction. The haze is the reflection property that exists between the two extremes represented by specular (with a distinct image) and Lambertian.

Another way to see the three distinct reflection components is to direct a laser beam at the surface and allow the reflected light to illuminate a large white card – all in a very dark room (Fig. 5). The general, usually very soft, illumination of the whole card is the Lambertian component. The sharp point of light is the specular component, and the fuzzy ball of light around the specular point is the haze component.

Measuring What We See

Observing the three reflection components is one thing; measuring them accurately is another matter. If all we had to deal with were the specular and Lambertian components, reflection characterization would be simple. However, the existence of haze requires us to employ more sophisticated methods, such as the bidirectional reflectance distribution function (BRDF).

The BRDF is the directional dependence of the ratio of the reflected luminance to the incident illuminance. Since the observation direction and the illumination direction can be different, the BRDF is a four-dimensional function of the incident and reflection angle. If we were to add wavelength dependence and polarization dependence, the BRDF would become a six-dimensional function.

When we look at the reflected luminance distribution of a point source or observe the reflected distribution of a laser beam on a white card, we are viewing a geometrical distortion of the BRDF. It is obviously possible to look through a small-aperture viewing tube fixed in space (to make sure we only look at the same point on the screen) and move a point light source around (Fig. 6). Suppose we constrain our apparatus so that the tube and source are in the horizontal plane.

If the eye could measure the luminance and all three components of reflection that were present, we could measure the in-plane BRDF and get results similar to those shown in the plot of Fig. 6. As the point source approaches the specular direction, the luminance dramatically increases as we move up the haze peak – note the log scale – until the bright specular image of the bulb comes into view. To turn this conceptual apparatus into an instrument, we would need to replace the eye with a detector, calibrate the apparatus, and apply a cosine correction to the point-source illuminance as it is moved away from the specular direction.

But using a point source is not the best way to measure the BRDF. If we can account for (or avoid) the effects of veiling glare in a camera system, a photograph of the reflection of a point source might be a useful way to supply a measurement of the shape of the BRDF. The best methods, however, use lenses and practical light sources.[4] If these goniophotometric methods are not followed carefully, however, the result of the haze measurement may be ambiguous because the result can depend upon the distances of the source and detector from the screen, apertures of the source and detector, and the foci of the detector and source.

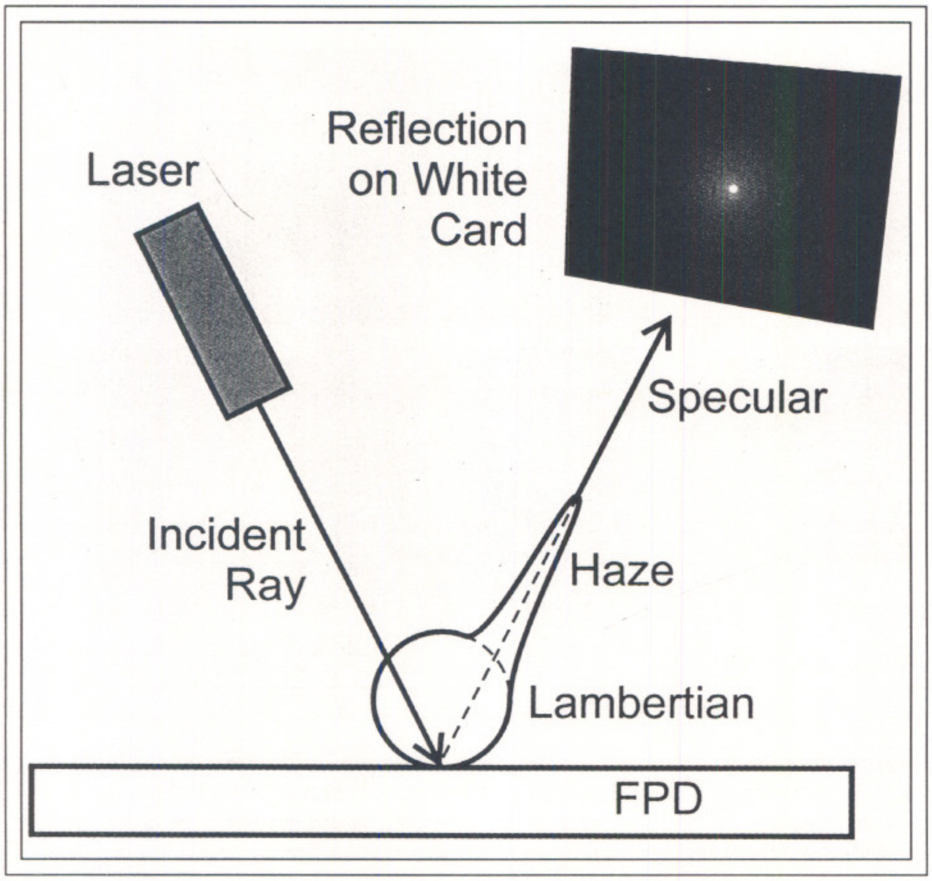


Fig. 5: The different reflection properties can also be manifested by the reflection of a laser beam onto a white card in a very dark room.

Those who measure BRDFs often fix the light source and move the detector. There is little difference in the BRDFs obtained by moving the source or moving the detector as applied to displays, provided that the specular angle - the angle from the normal - of the fixed part of the apparatus is small. When measuring the BRDF in a plane, the light source will obscure the detector (or the detector will obscure the light source) for some range of angles, and no data will be obtained. An idealized apparatus would be obtained if the detector and source were so infinitesimally small that they would not interfere with one another, and a BRDF could thus be obtained based on the normal direction and not some off-normal specular configuration.

For displays, the BRDF is almost always symmetric in any single plane aligned with the normal of the screen, but the haze need not be rotationally symmetric about the specular direction. If there is a pixel matrix beneath the front surface, the haze may have spikes in several planes (most often either the horizontal or vertical planes, or both, and sometimes in planes at 45% from the horizontal plane).

One advantage of displays is that the haze profile doesn't change dramatically as it is viewed from different angles. This can be seen by moving the flashlight point source around (keeping the head fixed at the normal of the display) so that the haze reflection is viewed in all parts of the screen. Thus, a center-screen measurement of the BRDF is a sufficient specification of reflection in most cases.

The beauty of the BRDF is that, once obtained, it permits the calculation of how a display will appear in its environment, based upon the distribution of light sources in the room. In fact, that is the goal of this research: to provide a method of characterizing the BRDF parametrically in order to permit an adequate characterization of the three components of reflection so that the performance of a screen can be calculated for any given environment. Research is currently under way to provide simple methods to parameterize the BRDF using simple instrumentation that does not require complicated goniophotometric data collection.[5]

Ultimately, we might expect to see four or five parameters required to specify reflection: the Lambertian component, the specular component, the peak of the haze component, some width measure of the haze component, and perhaps a shape parameter associated with the haze component. Probably the first three parameters will tell the main story, as in the fictitious advertisement at the beginning of this article, but three parameters are insufficient to permit a calculation of the reflected luminance in a given ambience.

If we were to go back to Fig. 2 and try to describe the reflection properties, this is what we would say. In Fig. 2(a), the CRT has a moderate Lambertian component, with a strong specular component and a front-surface treatment that produces some haze. In Fig. 2(b), the CRT has a much lower - but still not trivial - Lambertian component, very little haze, and a reduced but significant specular component. The reduction in the specular component from Fig. 2(a) to Fig. 2(b) is accomplished by a multi-layer anti-reflection coating applied to the front surface. The FPD in Fig. 2(c) does not display well in the photo, but it has only a haze component. The specular and Lambertian components are at least four orders of magnitude lower than the haze peak. The only non-trivial component in the FPD in Fig. 2(d) is also the haze component, but the peak of this haze component is reduced by the application of a multi-layer anti-reflection coating.

All of the preceding tells us that the metrology of display reflection is not a simple matter. We have discovered something disturbing but extremely useful: it is no longer adequate to limit our thinking to two types of reflection, diffuse and specular. Rather, there are three distinct components of reflection perceived by the eye when using electronic displays. Further research should clarify and simplify the complications associated with display reflection metrology.

References

[1]*ASTM Standards on Color and Appearance Measurement,* American Society for Testing

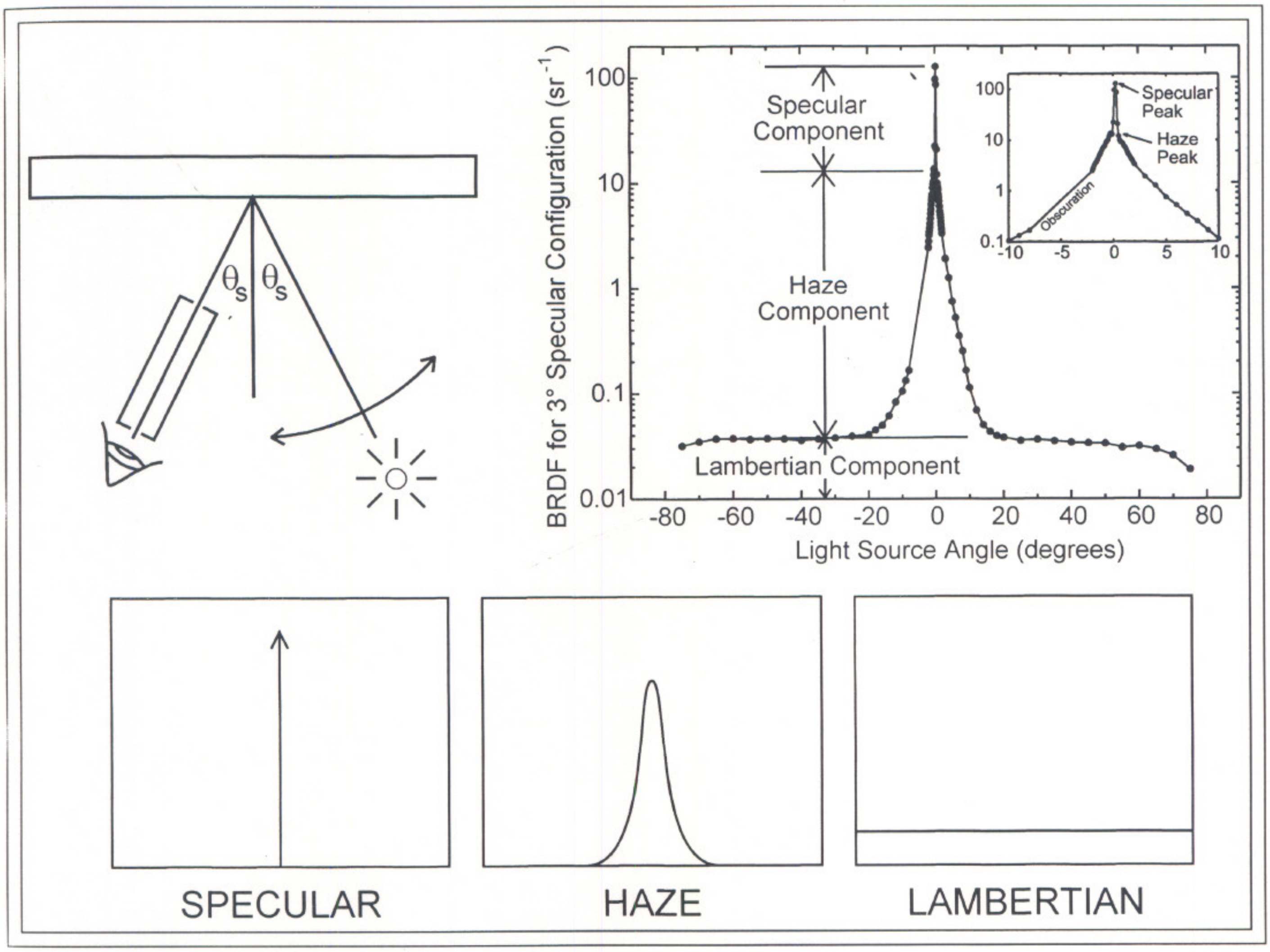


Fig. 6: This simple apparatus can be used to observe the reflection characteristics from a point source of light. Just as the three different components are distinctly visible to the eye, they are readily apparent in a bidirectional reflectance distribution function (BRDF).

and Materials, "Standard Terminology of Appearance," E284 95a, pp. 235-252.

[2]Michael Becker has recommended the use of the term "Lambertian" in this three-component model to avoid any confusion that may arise with using the term "diffuse." See Michael Becker, "Evaluation and Characterization of Display Reflectance," *Displays* **19**/1, 35-54 (June 30, 1998).

[3]ASTM, *op. cit.,* "Standard Test Method for Visual Evaluation of Gloss Differences Between Surfaces of Similar Appearance," D4449-90 (reapproved 1995), pp. 178-182.

[4]ASTM, *op. cit.,* "Standard Practice for Goniophotometry of Objects and Materials," E167-91, pp. 206-209.

[5]E. F. Kelley, G. R. Jones, and T. A. Germer, "Display Reflectance Model Based on the BRDF Displays," *Displays* **19**/1, 27-34 (June 30, 1998). Also see the VESA (Video Electronics Standards Association) *Flat Panel Display Measurements Standard* (FPDM), sections 308 and A217 for more details on the complications of display reflection metrology (www.vesa.org). ■