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The Three Components of Reflection

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

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 like this in the future. However, such a description is vague unless the reflection properties are clearly indicated. If we were to only state the familiar diffuse and specular reflection properties, would the specifications be adequate? Not really, you may still not know how the display will look to your eye. This article will show that there are 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. The appearance of an electronic display to the eye may require a more complete description than the appearance of fabric or paint. What we offer here is an extension to existing reflection specifications.

When considering reflection properties, people often think of specular reflection (mirror like) and diffuse reflection (as with surfaces like common copy paper or walls painted with flat or matte paint). With specular reflection—as with a mirror—the observed luminance in the virtual image is proportional to the luminance of the source. This is obvious—the luminances of the reflected images in a mirror don't depend upon their distance from the mirror just as when we observe the objects directly. With the so-called diffuse reflection, many people think in terms of Lambertian reflection where the luminance of the surface is independent of the direction from which the surface is observed and only depends upon the illuminance of that surface—a perfect Lambertian surface has not yet been realized in practice. The problem here is, in the display industry, the terms "diffuse" and "Lambertian" have been sometimes thought of as meaning the same thing, and that is generally not the case for displays. According to the ASTM, a diffuser is a surface that takes light energy away from the specular direction and distributes it is 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 perfect diffuse reflection. [2]

In Fig. 2. we show four different screens showing the same size text (linear size on the screen) with a black-white-metal target on the front surface to assure they are rendered equivalently in the reproduction. They are illuminated by a 60 W light bulb in a small aluminum shade, where the bulb has a small opaque-black square on its surface. Figures 2a and 2b are CRTs (cathode ray tubes); Figs. 2c and 2d are FPDs (flat panel displays). Figure 2a is an older CRT monitor that appears to have a medium gray screen when turned off. In comparison with 2a, the CRT in 2b appears dark gray when turned off. With the FPD screens, when they are turned off, the surface of the FPD in 2d will appear darker than 2c. 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 in all the displays, but especially the CRT in 2b and the FPD in 2d. How do we describe these reflection properties so that a person could understand how useable the display would be in an environment and how it would appear to the eye? Would it be sufficient to specify the specular and Lambertian (or diffuse) components to convey enough information to describe the reflected image? You might think it would not be sufficient, and you would be correct. Something more is needed.

The best way to observe the reflection properties of a display surface with your eye is to look at the reflection of a point source of light. (Several flashlights permit the removal of the head exposing the small high-intensity bare bulb that will serve well as a point source of light.) In general, and with most CRT screens, you can observe three manifestations of the reflection of the point source—see Figs. 3 and 4. If there is a specular component, as is the case with most CRT computer monitors, you will observe a distinct virtual image of the point source. The brightness of the virtual image point source will remain constant as you move the point away from the screen. You may also observe a general background gray that persists far away from the virtual image of the point source—again, this is especially true with CRTs where 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 you move the point source away from the screen. However, notice the fuzzy ball of light that surrounds the specular image. We will call this the haze component of reflection for want of another term (see ASTM D4449 [1]). For CRTs, where there is a thick faceplate, you may see a small fuzzy ball of haze without a specular image coming from the phosphor surface behind the front surface and to the side of the specular image. As you move the bulb around, you will be able to position it so that the haze peaks will be aligned. If you are looking at a flat screen, decreasing the specular viewing angle will better align the haze peaks. If there is any diffusing treatment of the front surface of the CRT tube, then you will see additional haze reflection around the distinct specular image. Note that the luminance of the haze reflection depends upon the distance that the point source is from the screen, but follows the specular image. Since the haze peak is aligned with the specular image and the luminances add, as the source is moved away the haze peak decreases while the specular luminance remains constant. This can give the impression that the specular image is decreasing in luminance, which is not the case.

Thus, we can see three types of reflection associated with displays: 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 of 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 done in a very dark room—see 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.

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, because of the existence of haze we must employ methods that are more sophisticated. This brings us to a discussion of the bidirectional reflectance distribution function (BRDF). Simply put, the BRDF is the directional dependence of the ratio of the reflected luminance to the incident illuminance. Since both 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. In Fig. 6 we 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. Suppose we constrain our apparatus so that the tube and source are in the horizontal plane. If our eye could measure the luminance and all three components of reflection were present, we would measure the in-plane BRDF such as shown in the graph in Fig. 6. As the point source approaches the specular direction, the luminance dramatically increase as we move up the haze peak (note the log scale) until the bright specular image of the bulb comes into view. Of course, this simple apparatus would need to have the eye replaced by a detector, the apparatus would have to be calibrated, and a cosine correction would have to be applied to the point source illuminance as it is moved away from the specular direction.

Using a point source is not the best way to perform the measurement of 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 useful to supply a measurement of the shape of the BRDF. However, for the best methods using lenses and practical light sources see ASTM E167-91. [4] If such goniophotometric methods are not carefully followed, the result of the measurement of haze may be ambiguous since it 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. People 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, at some range of angles either the light source obscures the detector or visa versa, and no data can be obtained. An idealized apparatus would be obtained if the detector and source were infinitesimally small so they would not interfere with one another, then a BRDF could 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 even both planes, sometimes in planes at 45 degrees from the horizontal plane). One advantage of displays is that the haze profile doesn't change dramatically as you view it 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 under way to provide simple methods to parameterize the BRDF using uncomplicated instrumentation (not requiring complicated goniophotometric data collection methods). [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, such as in our fake advertisement at the start, but only 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 now try to describe the reflection properties, here is what we would say: In 2a, the CRT has a moderate Lambertian component with a strong specular component and a front surface treatment producing some haze. In 2b, the CRT has a much lower Lambertian component (but it is not trivial), has very little haze, and a reduced—but significant—specular component. The reduction in the specular component from 2a to 2b is accomplished by a multi-layer anti-reflection coating on the front surface. The FPD in 2c 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 FPD in 2d also has only a non-trivial haze component, but the peak of the haze component is reduced with the application of a multi-layer anti-reflection coating.

From all of the above we find that the metrology of display reflection is not a simple matter. No longer is it 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.

[1] *ASTM Standards on Color and Appearance Measurement*, American Society for Testing and Material, "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*, to be published.

[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*, to be published. Also see the VESA (Video Electronics Standard Association) *Flat Panel Display Measurements Standard* (FPDM), sections 308 and A217 for more details on the complications of display reflection metrology (www.vesa.org).

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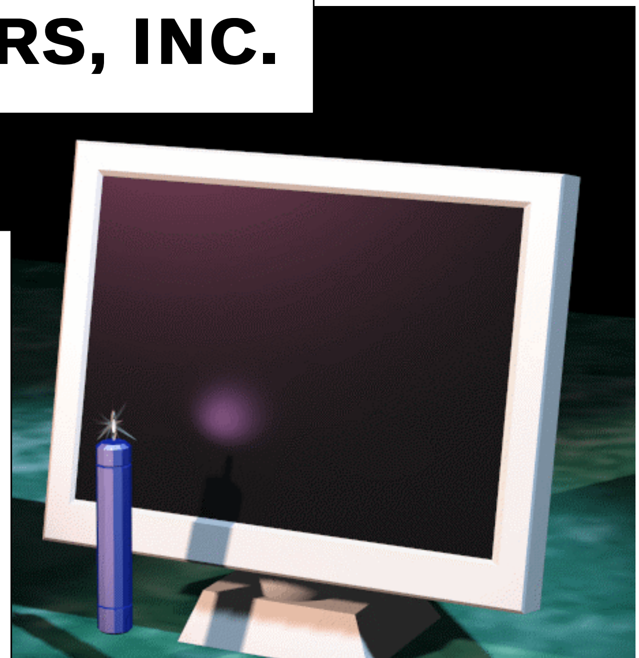

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- Ambient contrast 150:1 using an illuminance of 500 lx.
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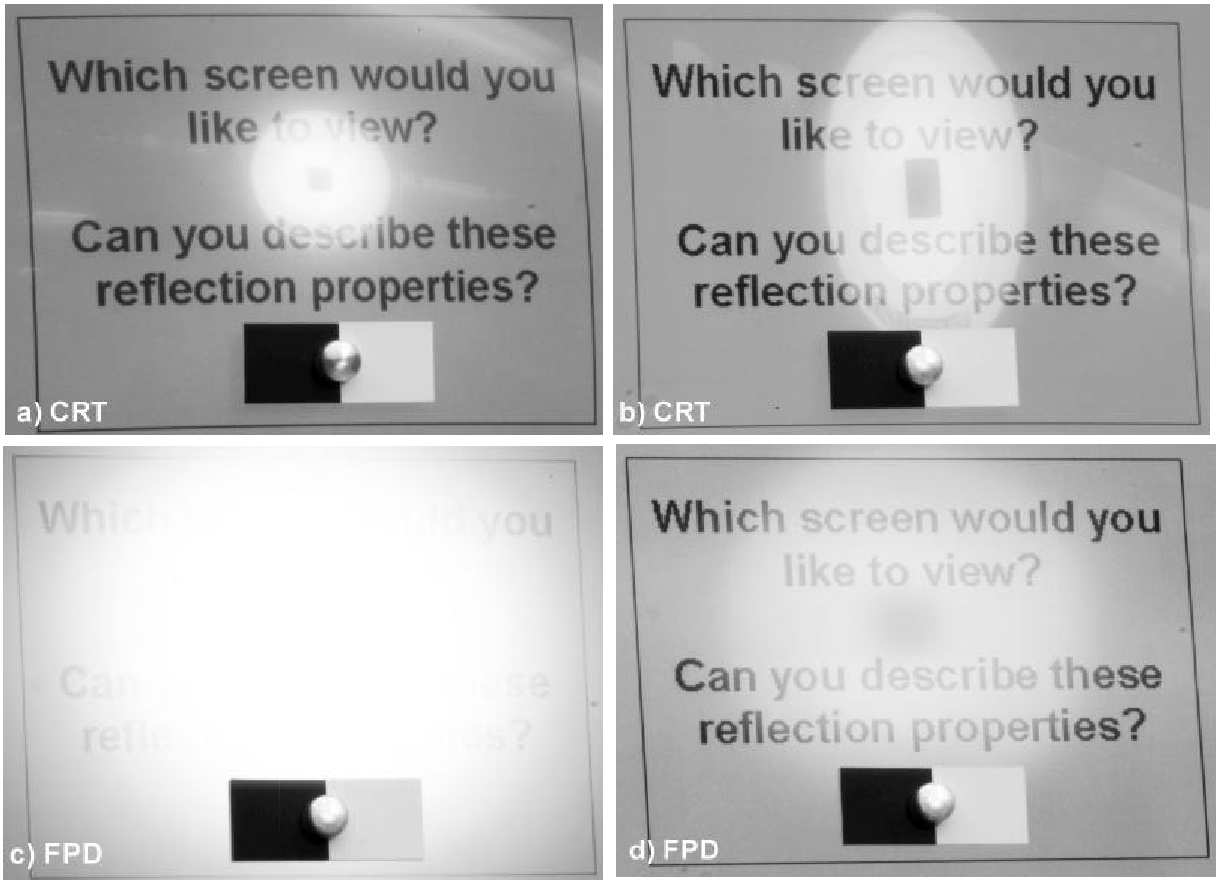

Fig. 2. *Examples of different reflection characteristics.*

Specular reflection:

$$L = r_s L_s ,$$

where r_s is the specular reflectance (a unitless number less than one), L is the observed luminance, and L_s is the source luminance.

Lambertian reflection (often called diffuse reflection):

$$L = r_p E / \pi ,$$

where, to avoid possible confusion, we will call r_p the Lambertian reflectance (unitless, less than one), and E is the illuminance. (We use “p” as a subscript to refer to a perfect diffuser. We cannot use “L” for Lambertian since “L” is used for luminance, and “d” for diffuse is not as clearly defined as some would like.)

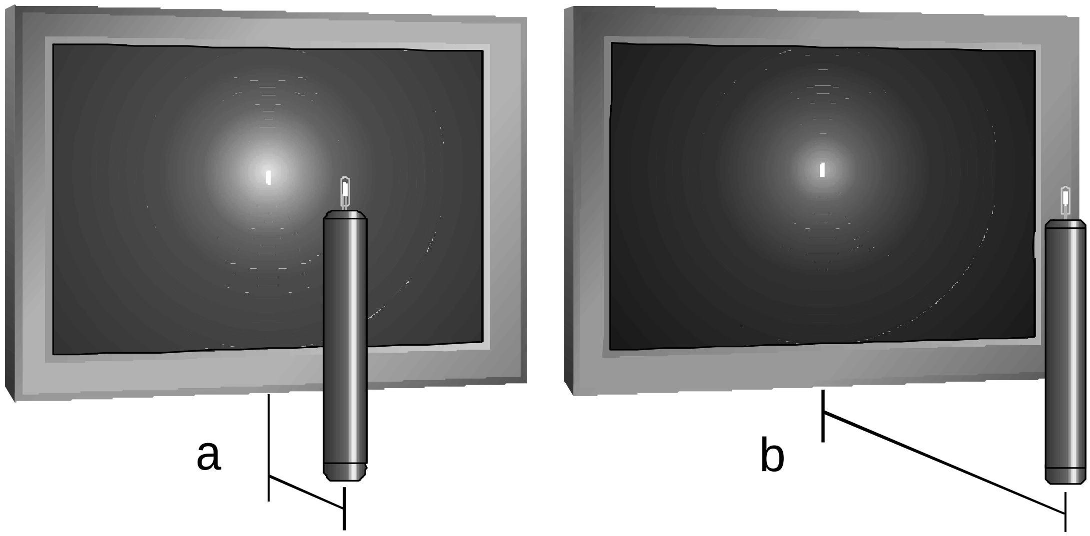

Fig. 3. *Reflection of point source changes depending upon the distance of the point source from the display.*

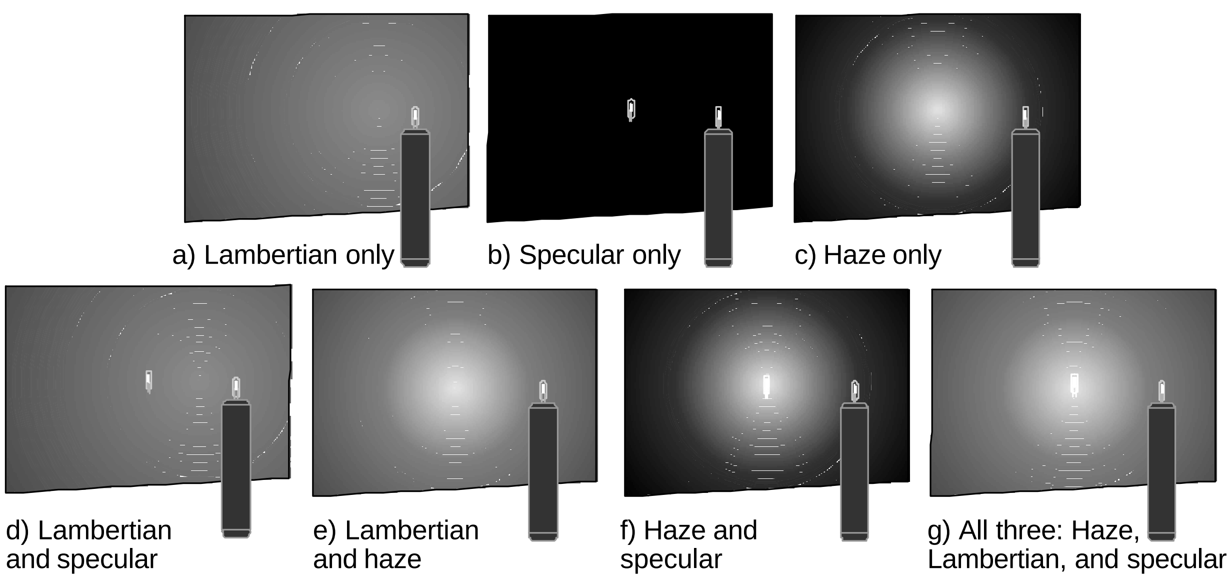

Fig. 4*. Displays can have various mixtures of the three different reflection components. Often one or two of the components can be made to be trivial.*

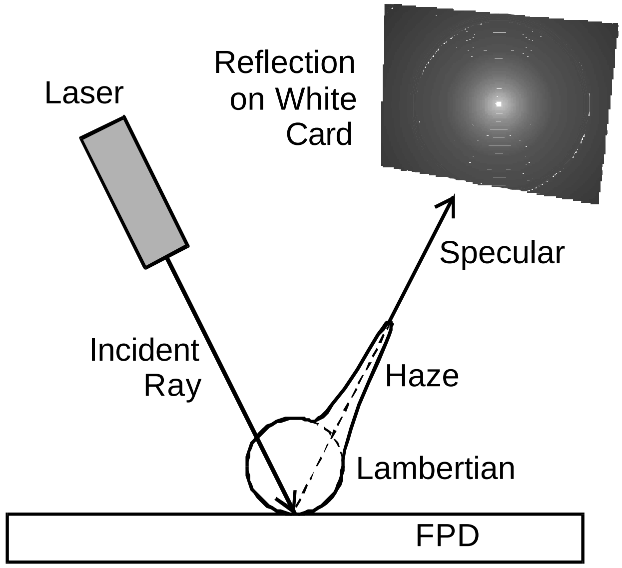

Fig. 5. The distinct reflection properties can also be manifested by the reflection of a laser beam onto a white card in a very dark room. The radial distribution of the reflected luminous intensity is indicated.

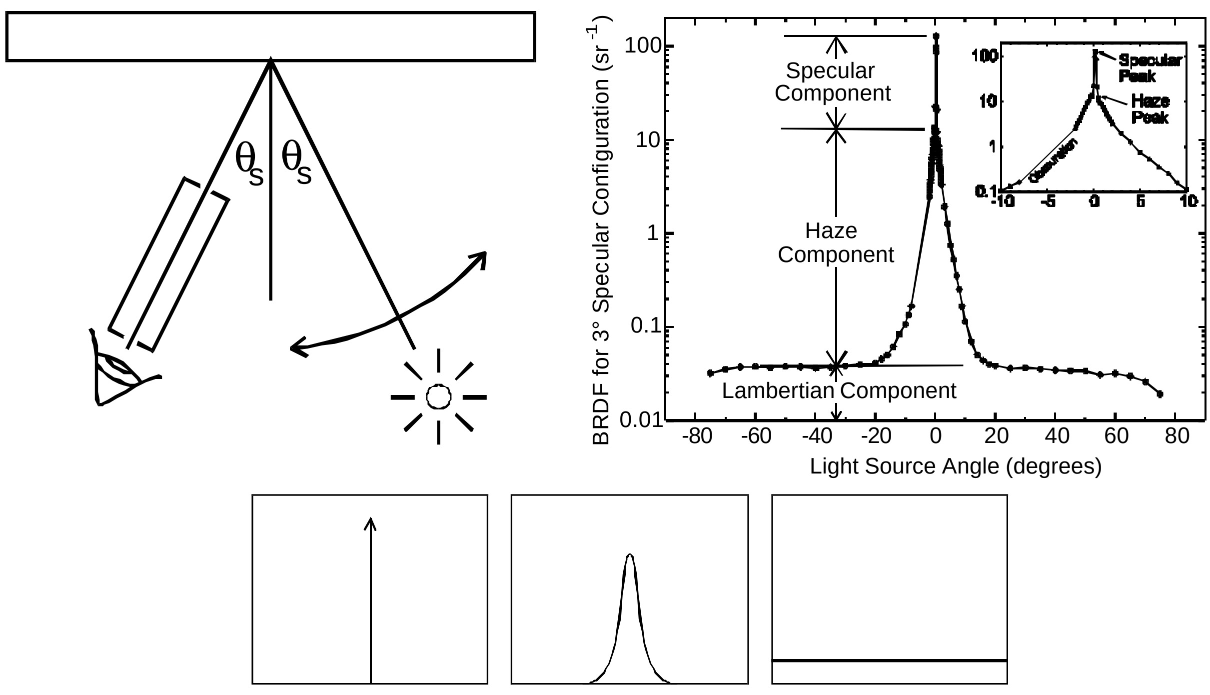

Fig. 6. *Simple apparatus for carefully observing the reflection characteristics from a point source of light. Just as the three components are distinctly visible to the eye, they are readily apparent in the BRDF. If we separate the three components, it is easy to see how the two extremes of the haze are the specular (when the haze sharpens to a delta function) and Lambertian (when the haze flattens out). For electronic display purposes, these three components appear distinct to the eye.*