Something to Reflect Upon:
Diffuse Reflectance Materials & Coatings

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Key Words

DIFFUSE, DIFFUSE REFLECTANCE, SCATTER, SPECULAR, MIRROR, LAMBERTIAN, REFLECTOR, HAZE, BRDF, BTDF, GLOSS, MATTE, COSINE RULE, LIGHT METROLOGY, REMOTE SENSING, LIDAR, ADAS

Introduction

Here's something to reflect upon. Imagine a material which reflects light equally in all directions. It appears equally bright to an observer, regardless of the angle from which they view it. What I am describing is known to optical physicists as a Lambertian reflector. A material that exhibits Lambertian reflectance is one which is a perfectly matte, or diffusely reflecting. In physics, we say that the material obeys Lambert's Cosine Law, named after Johann Lambert, who described the concept of a perfect diffuse reflector in his 1760 book "Photometria".

In this paper, I will detail the important characteristics of diffusely reflecting materials, describe some commercially available Lambertian materials and highlight some of the more interesting applications in science and industry, in particular in relation to the testing of LIDAR systems and the ADAS (autonomous driver assistance systems) sensors that are increasingly being deployed in vehicles.

Specular Reflectance

Let's first consider a surface that is the opposite of a diffusely reflecting material. A mirror is a specular reflector, from which a ray of light incident at an angle ϑ_i to the surface normal is reflected at the exact opposite angle ϑ_r (Figure 1). As commonly expressed for a mirror (or a mirror-like surface), the angle of incidence equals the angle of reflectance. Implicit in this definition is that the intensity of light reflected is equal to that incident on to the specular surface, reduced only by the reflectance factor of the material at that wavelength and at that angle of illumination.

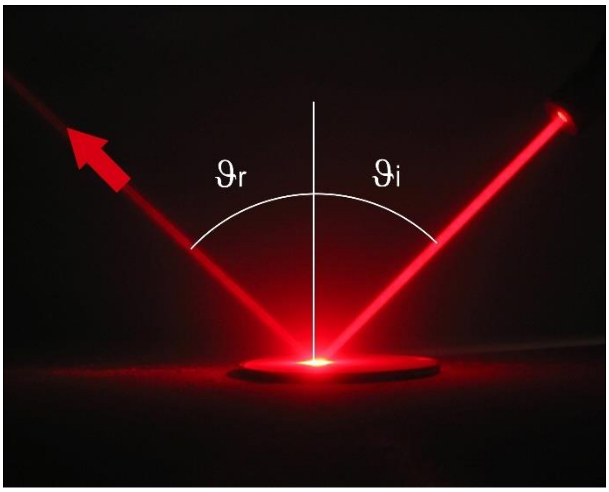

Figure 1: A Mirror Exhibits Specular Reflectance ($\vartheta_i = \vartheta_r$)

Diffuse Reflectance

Very few materials are perfect mirrors (or specular reflectors), with the exception of high quality laser optics. In practice, most materials display both part-specular and part diffuse reflectance (or in lay terms, they are part glossy and part matte).

So what is diffuse reflectance? The 18th century Swiss polymath Johann Heinrich Lambert (1728-1777), described the concept of a perfect diffuse reflector in his 1760 book "Photometria". The adjective "Lambertian" has become synonymous with materials that are matte or diffuse. A diffusely reflecting material behaves very differently to a perfect mirror. Instead of all of the light reflecting in the specular direction, the light reflects in all directions. For a theoretically perfect Lambertian (or diffuse) reflector, the intensity of light reflected obeys Lambert's Cosine Law (see Figure 2).

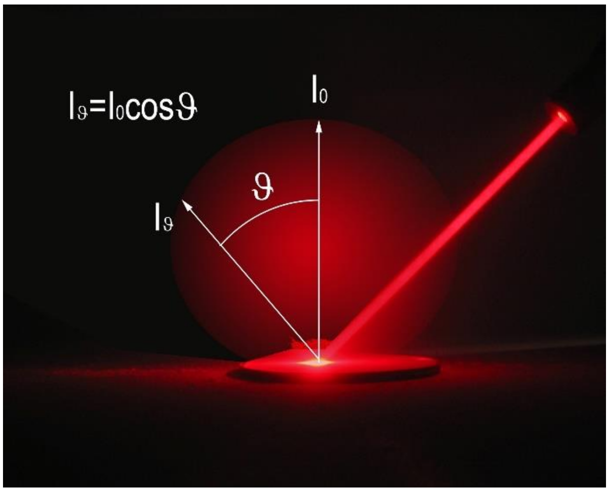

Figure 2: Lambert's Cosine Law for a Perfect Diffuse Reflector

Lambert's law states that the intensity of light reflected from a perfect diffuse reflector at an angle ϑ subtended to the surface normal I_ϑ is equal to intensity reflected in the direction of the surface normal I_0 multiplied by the cosine of the angle subtended. This is expressed as follows (Equation 1):

$$I_\theta = I_0 \cos\theta$$

Thus at normal incidence, the intensity is at a maximum, while at 90° (in the plane of the surface), the intensity has dropped to zero. It is worth noting that "intensity" has an important radiometric definition, distinct from its use in the vernacular (see Figure 3). It is the quantity of radiant or luminous flux ("optical power") reflected (or transmitted or emitted) in a particular direction per steradian, the unit of solid angle. In radiometric terms, radiant intensity in a defined direction is expressed as follows (Equation 2):

$$I = \frac{\Phi}{\Omega}$$

Where I is the radiant intensity (Watts per steradian) in a specified direction, Φ is the total radiant flux reflected from the surface (in Watts) and Ω the solid angle subtended (in steradians). The definition of intensity assumes that the light is emitted (reflected or transmitted) from a theoretical point source of light.

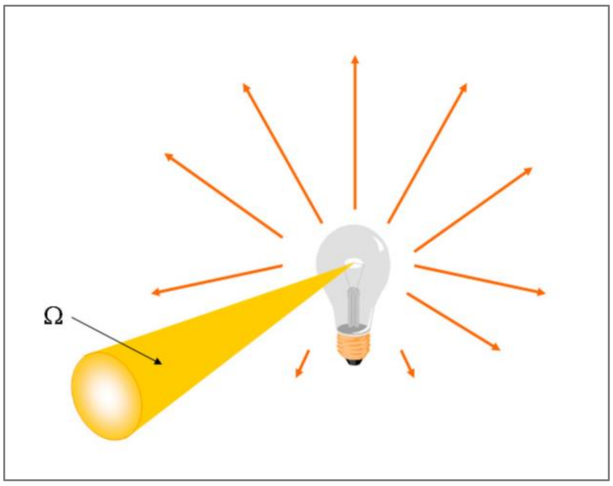

Figure 3: Intensity is the Flux per Unit Solid Angle (Steradian) Reflected (Emitted/Transmitted) from a Point Source of Light

Intensity Versus Radiance

Lambert's law describes how the light reflected from a perfect diffuse reflector varies as a function of the cosine of the angle subtended to the surface normal. However, this cosine relationship appears to contradict the observation that a Lambertian surface reflects with constant brightness (radiance or luminance) as the angle of view varies.

This apparent dichotomy is resolved when you consider that the human vision system observes light reflected as the intensity <u>per unit area</u>, which is termed radiance (or luminance). The radiance is the radiant flux reflected per unit solid angle per unit area, expressed as follows (Equation 3):

$$L = \frac{\Phi}{\Omega A}$$

Where L is the radiance (Watts per steradian per sq. meter), Φ is the radiant flux (Watts), Ω the solid angle (steradians) and A is the area viewed (sq. meters). As shown previously (Equation 2), flux per unit solid angle is intensity, so radiance can therefore be expressed as intensity per unit area (Equation 4):

$$L = I/A$$

We know that intensity varies with the cosine of the angle subtended to the surface normal (see Equation 1). So the radiance observed at angle theta (L_θ) is equal to the product of the intensity at normal incidence (I_0) and the cosine of theta, divided by the projected area at angle theta (A_θ) as shown below (Equation 5):

$$L_\theta = I_0 \cos\theta / A_\theta$$

The observed surface at normal incidence is a circle of area A. When viewed from a higher angle theta, the circle transforms into an ellipse, and the area increases in proportion to the cosine of theta (Equation 6):

$$A_\theta = A_0 \cos\theta$$

So we can now express the radiance at angle theta as shown below (Equation 7):

$$L_\theta = I_0 \cos\theta / A_0 \cos\theta$$

The $\cos\theta$ factor appears in both the nominator and denominator, so abrogates. So we can finally show that the radiance of the light reflected from a Lambertian surface is constant with angle (Equation 8):

$$L_\theta = I_0 / A_0$$

To put it in lay terms, the brightness of a Lambertian (or perfect diffuse reflector) remains constant as you view it from different angles. This is because, the change in intensity with angle (the cosine relationship) is countered by an equal but opposite change in the projected surface area that you view (also a cosine relationship). Thus the Lambertian surface will possess the same brightness (luminance or radiance) regardless of the angle that you view it from.

Near-Specular Reflectance: Haze

The proportion of light scattered at angles close to the specular direction is termed "haze". Haze is what you observe from a dusty or frosted window pane. Haze is a phenomenon which adversely affects our perception of the quality of a glossy surface.

Quantifying The Degree of Scatter

The science of quantifying scattered light (either upon reflection or transmission) is referred to as "scatterometry" (see Figure 4). A scatter measurement will reveal to what extent a material conforms to the theoretical ideal of a perfect specular or perfect diffuse surface. Scatter measurements are reported as the Bi-Directional Reflective Distribution Function (BRDF) or Bi-Directional Transmissive Distribution Function (BTDF). These scatter functions express the ratio of incident irradiance to reflected (or transmitted) radiance, for each angle of illumination, and for each angle of reflectance (or transmittance). The BRDF for a Lambertian material is $1/\pi$ at all angles.

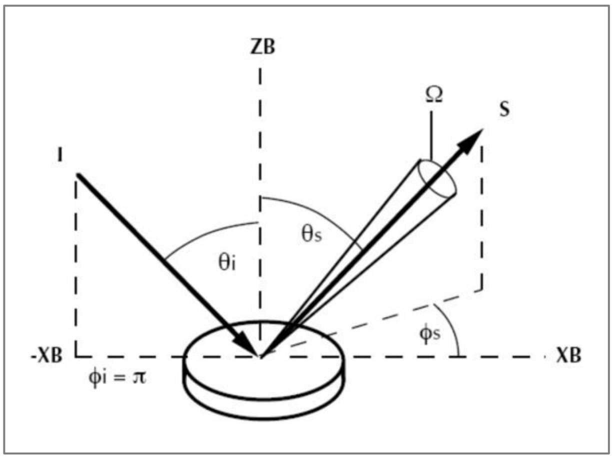

Figure 4: Principle of BRDF Scatterometry

Diffusely Reflecting Materials

So far, so theoretical. What of commercially available diffusely reflecting optical-grade materials? Two companies lead in this field worldwide. One is US firm Labsphere Inc (www.labsphere.com) and the other is SphereOptics GmbH (www.sphereoptics.de), a German company. Both companies developed materials that possess near-perfect Lambertian reflectance. Labsphere's Spectralon® and SphereOptics' Zenith Polymer® are forms of solid, sintered PTFE and possess the following attributes:

- Near-perfect Lambertian reflectance over an almost 2π steradian field.
- >99% total hemispherical reflectance in the 400-1500nm range.
- >95% total hemispherical reflectance in the 250-2500nm range.
- Available as undoped (white) as well as doped (grey-scale) reflectance material.
- Non-wavelength selective, non-fluorescent.

Whereas Spectralon and Zenith-Polymer are bulk scatterers and are deployed as solid, 3D reflectors, other coatings exist that can be applied by spray painting or electro-coating. For the UV-VIS-NIR band, Labsphere produces a spray coating called Spectraflect® which is based on barium sulphate. This coating offers a slightly lower level of optical performance than PTFE albeit at lower cost. For applications requiring a more durable yet cost effective solution, Labsphere developed a coating called Permaflect®. For applications that require Lambertian transmittance, thin sections of Zenith Polymer are offered as diffuser sheets. For applications in the mid to far-infrared band, Labsphere offers an electroplated gold coating called InfraGold that offers ~94% diffuse reflectance from 800nm to 20µm.

Who Uses These Materials?

The commercial products mentioned previously are specialist optical materials and their application is mostly limited to demanding optical applications in science and industry, rather than mass-market consumer applications, for which lower cost, lower performance solutions exist.

In light metrology, integrating spheres are used to measure the flux and irradiance of light sources, and the inside of an integrating sphere requires a high reflectance, Lambertian coating (see Figure 5). Spheres coated with Spectralon/Zenith (PTFE) or Spectraflect ($BaSO_4$) are commonly used in the radiometry and photometry of light sources (lamps, LEDs, lasers etc).

Figure 5: Labsphere Integrating Sphere Radiometer

An internally illuminated integrating sphere provides a source of uniform radiance or irradiance (see Figure 6). These Lambertian light sources are used to test and calibrate image sensors and camera equipment. The uniform light source corrects for aberrations inherent with lens systems, imparts an absolute radiometric calibration onto the camera, can be used to determine the quantum efficiency of a sensor array, performs pixel gain normalisation of a sensor and corrects for photometric non-linearities. Large integrating spheres are used to calibrate spectral radiometers used on board satellites in earth observation science and remote sensing.

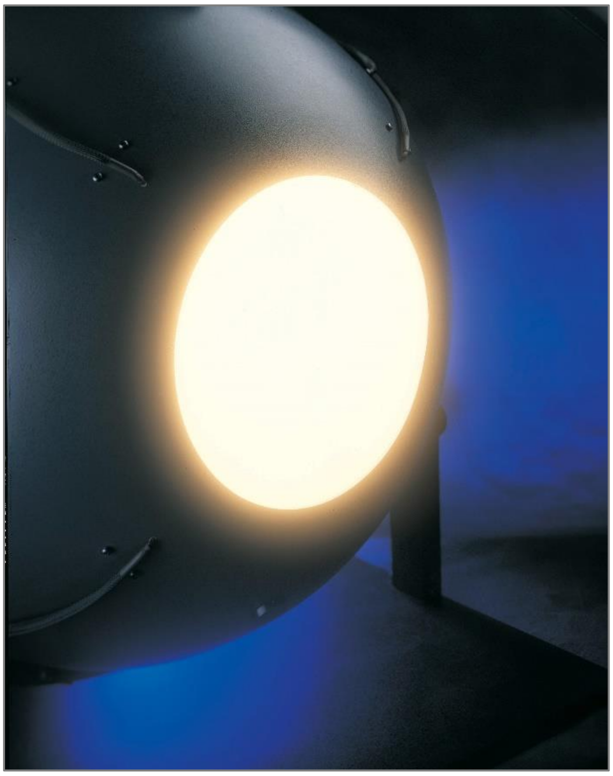

Figure 6: Labsphere Integrating Sphere Uniform Light Source

Integrating spheres are also used to measure the reflectance and transmittance of materials. Indeed, for diffusely reflecting or transmitting materials, an integrating sphere-equipped spectrophotometer is a necessity (Figure 7).

Figure 7: Labsphere Reflectance Measurement Integrating Sphere

To calibrate your integrating sphere-equipped spectrophotometer (or indeed any reflectance measuring instrument), Spectralon/Zenith tiles are sold as calibrated standards of total hemispherical spectral reflectance (Figure 8).

Figure 8: Spectralon Calibrated Diffuse Reflectance Standards

In the remote sensing and environmental sectors, large panels of Spectralon/Zenith, or targets painted with Permaflect are routinely employed for "ground truthing" of satellite and aerial remote sensing radiometers, as well as multi- and hyperspectral imagers (Figure 9).

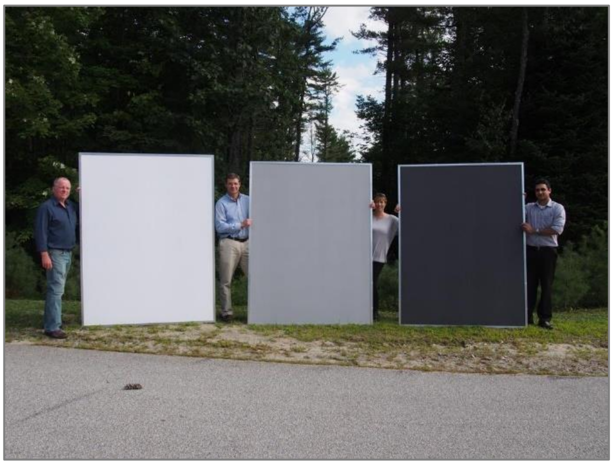

Figure 9: Labsphere Permaflect Large Area Diffuse Reflectance Targets

LIDAR & ADAS System Testing

More recently, the use of diffusely reflecting materials has been exploited in the development of LIDAR and time-of-flight (TOF) proximity systems used in consumer electronic products and in the ADAS (Advanced Driver Assistance Systems) sensors used in autonomous vehicles (Figure 10). Diffuse reflectance is essential in such applications to provide a consistent level of reflectance (and return signal) regardless of the direction of view.

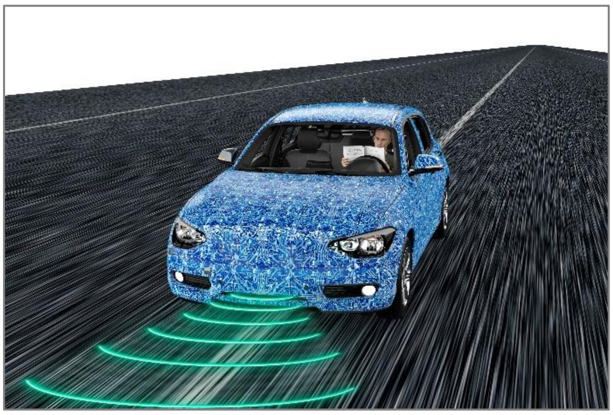

Figure 10: Diffuse Reflectance Targets are Used in the Development and Deployment of LIDAR and ADAS Systems

For satellite ground-truthing experiments and for field trials of LIDAR and ADAS systems, the reflectance targets used need to be of a relatively large area. To that end, both Labsphere and SphereOptics targets are produced in standard sizes from a few cm up to 1m by 1.5m (1.2m by 2.4m for Permaflect) avoiding any seams (or gaps) between panels which could lead to erroneous measurement data were you to assemble your own large area target panel from smaller tiles. Larger targets are needed in LIDAR and ADAS applications to reflect a representative number of points across the target surface over long-range test distances of several hundred meters.

Permaflect spray coating can be applied to large areas or 3D shapes, allowing it to simulate real world objects. Few real-world objects are flat like a target panel, so Permaflect coated objects allow for repeatable, near-Lambertian reflectance levels that can be applied, for example, to a mannequin to simulate a pedestrian (Figure 11).

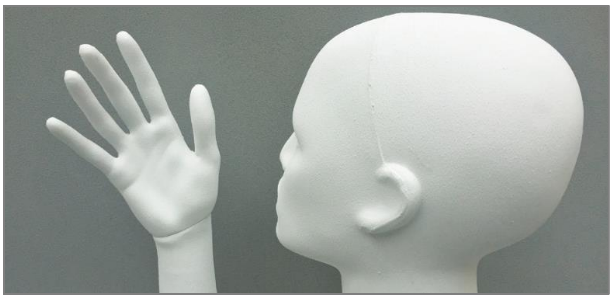

Figure 11: Permaflect Coating Applied to 3D LIDAR Test Objects

Summary

Optical-grade diffuse reflectance materials reduce or eliminate alignment sensitivity in critical light metrology and optical material measurements. A Lambertian reflectance material obeys Lambert's cosine rule yet also provides a constant brightness (radiance or luminance) regardless of the angle from which they are viewed. This property is exploited in large diffuse reflectance targets that are helping to improve the performance and accelerate the development of LIDAR systems and ADAS sensors used in autonomous vehicles.

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Further Reading

Pro-Lite is the parent company of SphereOptics GmbH and also serves as the distributor for Labsphere Inc, and supplies integrating spheres, light metrology instrumentation, uniform light sources, and calibrated diffuse reflectance standards and targets on behalf of both companies.

Pro-Lite Light Metrology Solutions

Pro-Lite Optical Materials

Pro-Lite also supplies instruments for measuring reflectance and BRDF/scatter from Avantes (spectrometer systems), Surface Optics Corp (reflectometers) and from The Scatter Works (scatterometers).

Pro-Lite Spectrometers

Pro-Lite Scatterometers

Surface Optics Reflectometers

In addition, Pro-Lite also provides independent measurement services for scatter (BRDF/BTDF), as well as spectral reflectance and transmittance (250-2500nm and 800nm-15µm), the latter being accredited to ISO 17025.

Pro-Lite Measurement Services