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Surface Characterization Using Scattering Measurement Instrument

Full Paper

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Abstract

The main goal is to test and compare measurement instruments to determine scattering characteristic of diffuse and specular samples through BRDF measurement. The scattering characteristics depend on the respective surface condition. The Bidirectional Scattering Distribution Function (BSDF) gives a relation between scattered radiance and incident radiance depending on all incident directions. That is why it was called bidirectional. Radiance is defined as a flux of radiation emitted per unit solid angle in each direction by a unit area of source. Two instruments were used to get the BRDF measurement of 5 samples are gonio spectrometer REFLET-180 and scatterometer MiniDiff. The BSDF measurement results of both equipment are compared in term of repeatability of the scatter profile.

Keywords: - Scattering characteristic, the bidirectional scattering distribution function (BSDF)

1. Introduction

Stray light is defined as unwanted light that reaches the focal plane of an optical system. The order of stray light path is given by the number of stray light mechanism such as ghost reflection, diffraction from a grating or scatter that occurs in the path. The magnitude of stray light on the focal plane typically decreases exponentially with the path order.

A light path is a unique sequence of events experience by a beam of light, ending at the image plane. Most optical system has only one intended light path. However stray light mechanism such as reflections from refractive optics (also called Fresnel or ghost reflection) or scattering from surface roughness result in a multitude of unintended light path that do not follow the intended one. Stray light mechanism decreases the path transmittance of the intended optical path and increases the path transmittance of unintended path. It is not possible to eliminate all this path, it is only possible to reduce the magnitude, such as the use of anti-reflection coatings.

One of the scattering light mechanism is a scattering from optical surface roughness and coatings. Optical surfaces are the surfaces of the lenses and mirrors that form the image in an optical system. Though these surfaces are typically very smooth, none are perfectly smooth, and their residual roughness will be scattered light. Optical surfaces cannot be made perfectly smooth and therefore will scattered light due to their surface roughness. The magnitude and angular distribution of the surface BSDF is a function of the profile of the surface at the microscopic level. It is difficult to predict the BSDF of a surface based on its scratch and digs number, because the standard used to define these numbers does not provide enough information for BSDF to be computed. Therefore, the best way to determine the BSDF of a given scratch or dig is to measure it.

The light scattering also comes from particulate contaminants. All surfaces have some number of particulate contaminants that increases their BSDF above the level predicted by their surface roughness. The scatterings from particles can be accurately predicted by a model based on Mie scattering theory. Another reason of scattering is from black surface treatments. The BRDF of black surface treatments is usually determined from direct measurement and then fit it to a model.

It is important that BRDF measurement be made at multiple values of incident angles. To get a good fit, a minimum of three widely spaced values of incidence angles are recommended such as 5°, 20°, 40° and 60°. Measuring the BRDF at or near those values at which it is illuminated may also increase the accuracy of the stray light prediction.

2. Literature Review

When light travel and encounters new medium with different refraction index, $\hat{n}$, it will either be transmitted, absorbed or reflected. The light transmitted, absorbed or reflected must be consistent with the conservation of energy:

$$Er + Et + Ea = 1 \tag{1}$$

Where *Er* is the light reflected from the surface of the object, *Et* is the light transmitted through the object, and *Ea* is the light absorbed by the object. Each is a function of a wavelength. Therefore, reflected waves are simply those that are neither transmitted nor absorbed.

The law of reflection states that the incident ray, the reflected ray and the normal to the surface of the mirror all lie in the same plane. The angle of reflection r is equal to the angle of incidence i. Both angles are measured with respect to the normal of the mirror.

For smooth objects such as mirrors, light incident on the surface and is reflected in a single direction following the law of reflection. This reflected light is known as specular reflectance. However, for rough surfaces, the law of reflections remains valid. But rays that are incident at slightly different points on the surface are reflected in completely different directions.

This is due to the reason that normal to a rough surface varies in direction very strongly from point to point on the surface. The type of reflection reflected from rough surface is called diffuse reflections and is what enables us to see non-shiny object.

Thus, we can conclude that the reflections may be specular or diffuse depending on the nature of the surface. For Lambertian surface, a surface with perfectly matte properties, the light incident would result in diffuse reflections with light being reflected from the surface equally in all directions. Therefore, there are two types of reflection, specular and diffuse reflection. However, most objects will display combination of coherent component of specular reflection and diffuse or incoherent scattering component.

There is a way to characterize this uneven scatter and that is called the Bidirectional Scatter Distribution Function (BSDF). BSDF covered both transmission distribution (BTDF) and reflected distribution (BRDF). In term of BRDF, a material may be described as specular or diffuse. A mirror is an example of specular material and a projector screen is diffuse material, thus the viewing angle does not matter, and brightness is equal regardless of the viewing orientation. A perfect diffusing surface is called a Lambertian sample. In the Lambertian sample, the luminance is constant in all direction. Consequently, the BRDF/BTDF of such sample is constant for all direction. On the other hand, for a perfect specular surface or mirror-like sample, light is backscattered in a single direction, called the specular direction *S*.

BRDF is defined by four angles describing the direction of the incident and scattered beams using spherical coordinates. The incidence angle is kept constant and the angle of detector is varied to measure the scattered intensity at different angles.

BRDF quantifies the radiance scattered into all direction from a surface illuminated by a source from any direction above the hemisphere of the surface. In Fest (2013), BRDF is given by:

The bidirectional scattering distribution function (BSDF) is the radiance of a scattering surface, normalized by the irradiance incident of the surface:

$$\mathrm{BSDF}\ (\theta i,\phi i,\theta s,\phi s) = (\partial L(\theta i,\phi i,\theta s,\phi s))/(\partial E(\theta i,\phi i)) \tag{2}$$

Where θi, φi, are the elevation and azimuth angles of the incident ray

θs, φs are the elevation and azimuth angles of the scattered ray

dL is differential radiance of the scattering surface

dE are differential incident irradiance

Solid angle is an important concept in BSDF. Solid angle refers to small surface area on the hemisphere. According to Weisstein (2018), solid angle, **Ω** subtended by a surface S, is defined as the surface area **Ω** of a unit sphere covered by surface projection onto the sphere. Solid angle can be written as:

$$\Omega = \int\int_S \frac{\dot{n}.da}{r^2} \tag{3}$$

Where *n* is the unit vector from origin, *da* is the differential area of surface patch and *r* is the distance from the origin to the patch. Fig.1 below showed the solid angle on a hemisphere.

3. Methodology

Reflet and MiniDiff are 2 instruments used for measuring Bi-directional Scattering Distribution function (BSDF) of sample 1, 2 and 3 in visible light range. The results are visualized, observed and compare in term of repeatability of scattered intensity Plot in 2D Chart and also the BRDF graph produced.

Below are the samples used in measuring of the BRDF and BTDF in Reflet180 and TracePro. Sample 1 and 2 are both translucent, but homogenous and non-homogenous samples respectively.

Fig. 1. Sample 1

Fig. 2. Sample 2

Fig. 3. Sample 3

MiniDiff measure luminous energy distribution which characterize surface of examined sample region in terms of roughness, defects and types of coatings used in the surface. MiniDiff also measures BSDF which represent the way surface scattered incoming light in 3D space.

The setup of a MiniDiff include a light source and a CCD Camera to image the hemisphere scattered intensity. A light source used is a red illumination with wavelength of 630 nm. 4 collimated LEDs are being set up at 0°, 20°, 40° and 60° angle of incident. For transmissivity measurement, 1 collimated LED at 0° incident angle will be used. The hemispherical scattered intensity is imaged at once on a camera.

Instrument is calibrated before the measurement using a calibration plate (black and white) supplied with the instrument. Black calibration was done to cancel the stray light and white/lambertian calibration was done to calibrate the response of camera. The calibration step typically takes less than 30 seconds meanwhile the measurement itself will take about 10 seconds.

The result is scattered intensity and BRDF that can be saved in text formats and exported to optional software formats. Using the MiniDiff, it is possible to measure Reflector, paints, diffusing camera, sockets and optical mounts.

The image data of MiniDiff are consisted of 3 filtered columns of Red, Green and Blue (RGB). Spectrophotometry uses many sensors to separate a beam of reflected or transmitted light into its component's wavelength. It measures the spectral reflectance of an object at each wavelength on the visible spectrum continuum. In MiniDiff, the peak BRDF visualization will be in red, follow by yellow and light blue, lastly deep blue.

The Reflet180 is a gonio spectrophotometer for measuring back and forward scattering of diffusing samples. The optical design of this device is consisted of two symmetric rotating optical system which are the illumination system and detection system that observed the same point of the sample.

The illumination module comprised of an optical system with 2 diaphragms and a motorized 1-axis goniometer which move in the rotation angle of θi°. The detection module is comprised of an interchangeable optical bloc for detection and a motorized 2-axis goniometer which move in rotation angles of θ_d° and ϕ_d°. θ_i° is the illumination zenith angle, θ_d° is zenith detection angle and ϕ_d° is azimuth detection angle. The light incident angle was adjusted by the rotation of θ_i°. The sample position is fix in the sample holder and its upper face is perfectly horizontal.

The detector will move and scan in zenith (θ_d°) and azimuth (ϕ_d°) angles of the range of -90° ≤ θd° ≤ +90 and -105° ≤ ϕ_d° ≤ +105. This will create a scanning area of a hemisphere as shown in Fig. 1 of the coordinate system of the goniophotometer. The illumination module is motorized over 90° angle enabling measurement at 0°, 20°, 40° and 60° angle of incident.

4. Analysis and Findings

BRDF is the mathematical model to characterize the relationship between reflected right in relation to incident light when light hit the surface. We will use the BRDF data to compare the surface characterization between Sample 1 and Sample 2. BRDF is usually defined as found in Stover (1995):

$$\mathrm{BRDF} = \frac{\text{differential radiance}}{\text{differential irradiance}} \approx \frac{dP_s/d\Omega}{P_i \cos\theta_s} \approx \frac{P_s/\Omega}{P_i \cos\theta_s} \tag{3}$$

The BRDF data was obtained from Reflet180 and Minidiff. There are four incident lights that are angled at 0°, 20°, 40° and 60° at the sample surface. The light will be reflected and scattered when the incident light hit the surface and detected by the detector. The detection resolution is 1°. The output of the measurement is the BRDF data in format of matrices 360×181 in 2D which is the image or heatmap of where the scattered light is reflected and scattered and detected by the detector.

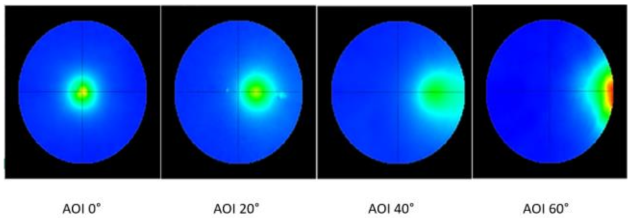

Fig. 4. Scattering profile of Sample 1 as measured in MiniDiff

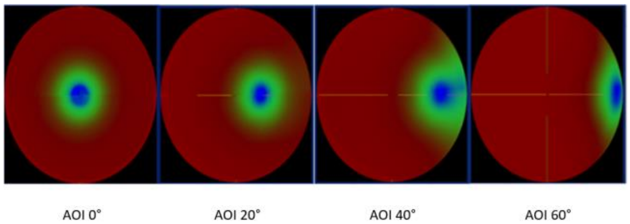

Fig. 5. Scattering profile of Sample 1 as measured in Reflet180

Sample 1 is consisting of glass material. The BRDF measurement was done on the rougher side of the sample. In the BSDF 2D chart Plot of scattered intensity result obtained from both MiniDiff and Reflet at different angle of theta lighting, we could see that an almost identical result in regard to shape and placement of scattered intensity. At 0°-degree angle, the scattered intensity peaked in the middle of the sample for both of the instrument. This showed that results of scattered intensity are comparable between the 2 instruments. The result is almost identical in terms of the peak location and intensity level.

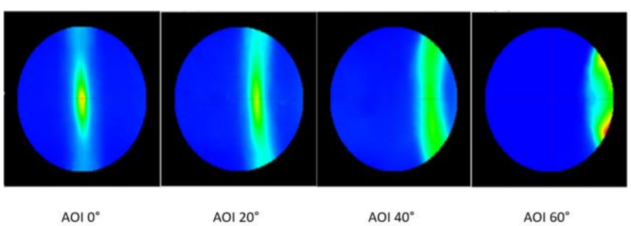

Fig. 6. Scattering profile of Sample 2 as measured in MiniDiff

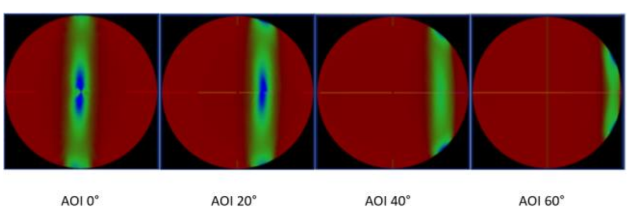

Fig. 7. Scattering profile of Sample 2 as measured in Reflet180

We can see from this result that the shape and peak of the 2D plot of scattered intensity from both instruments to be almost identical. Both scattered peak at blue and red colour respectively. However, the slight difference we could see from this is the tilt of the luminous intensity from the MiniDiff result instead of the straight scattered intensity from 2D Plot Chart from the Reflet result. The shape of the result obtained from Reflet showed the scattered intensity in a narrow and straight line across the centre of the sample with blue colour centre and green colour surrounded it. But the shape of the luminous intensity on 2D plot of the MiniDiff result showed a skew, or a little tilt to left. In theta angle lighting of 20°, 40° and 60°, the same tilt of the luminous intensity shown in 2D Plot of the result from MiniDiff can still be observed. The result from Reflet also showed peaked at both end of the scattered intensity visualization.

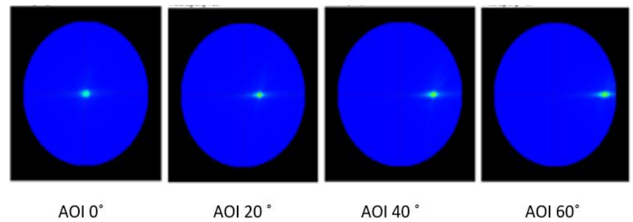

Fig. 8. Scattering profile of Sample 3 as measured in MiniDiff

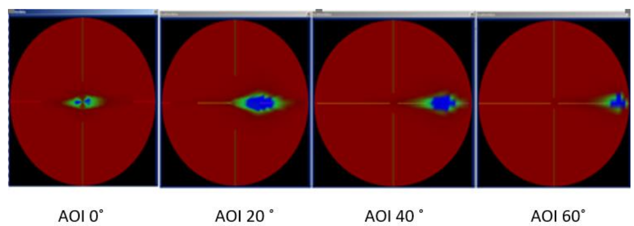

Fig. 9. Scattering profile of Sample 3 as measured in Reflet180

Unlike Sample 1 and Sample 2, Sample 3 is a plate of copper. From the MiniDiff the sample was almost specular in its reflectance. As we could see from the 2D Plot Chart of the intensity, there is a small circle in the middle. The result obtained from Reflet180 showed small, not complete circle in the middle and the shape are retained the same. We could see more detail in the result obtained from Reflet180 meanwhile in result obtained in MiniDiff there is just a small circle of luminous intensity in the middle.

Once again, the result obtained from Reflet180 showed higher scatter intensity in visualization. Meanwhile the result obtained from MiniDiff is rather small and less intensity in scattered visualization.

4. Conclusion and Recommendations

One of the reason of the tilt of Sample 2 could be due to the fact that shape of the MiniDiff lense which is curved resulting in slight shift or tilt. This tilt was not detected in sample 1. Sample 1 consist of glass material and homogenous meanwhile Sample 2 are heterogeneous consist of opaque layer and translucent layer. This could contribute to the differences in the result obtained from both instrument for sample 2 in comparison with sample 1. A different finishing on the sample surface may also contribute to a slight difference in the result between the 2 instruments.

The accuracy of the experimental data in MiniDiff are influence by the fluctuation of the light source, spatial uniformity of the CCD camera and also of the calibration operations. The signature of instruments also has play a role in determining the accuracy of the data.

In conclusion of the result of the same sample measured with Reflet vs measured with MiniDiff, the more detailed and pronounced result can be obtained by Reflet. It is more conclusive and detailed due to peak at both end of the luminous intensity that we do not get to see from the result seen in MiniDiff. The shape of scattered intensity shown in 2D Plot result obtained from MiniDiff is also tilted in comparison with Reflet due to the nature of the curved lense in MiniDiff equipment. Thus if you are looking for more detailed measurement and have more time to do it, Reflet could be a more meaningful tool to use.

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