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Radiometry, SIMG-370
Laboratory No. 7
Rev. 5-07

Measurement of Reflectance and non-Lambertian Behavior of Materials

INTRODUCTION

The goal of this experiment is to measure the reflectance and non-Lambertion behavior of materials using a calibrated digital camera as a 2D radiometer. That is, we wish to relate the irradiance onto a surface to the radiance leaving the same surface. Discussions and labs thus far have assumed that the surface in question behaved ideally in that the angular energy leaving the surface was the same in all directions. That is, we made the assumption that our surface was *Lambertion.*

In this lab we will explore the validity of this assumption for various materials. In order to relate irradiance onto a surface to the radiance towards the detector, we need to consider the reflectance properties of the material. The reflectance properties are a function of incoming and outgoing angle, wavelength, polarization, and position. For this lab we will only consider a restricted subset of these reflectance parameters, namely incoming and outgoing (illumination and detection) angles. This leaves us with a function, ρ called the Bidirectional Reflectance Distribution Function (BRDF) which can be express as

$$\rho(\theta_i,\phi_i,\theta_r,\phi_r) = \frac{L(\theta_r,\phi_r)}{E(\theta_i,\phi_i)} \quad [sr^{-1}] \tag{1}$$

where *E* is the irradiance onto the surface (as a function of incident illumination zenith, θ_i and azimuth, ϕ_i), and *L* is the measured radiance from the surface (as a function of measured zenith, θ_r and azimuth, ϕ_r angles). The relationship between these parameters can be seen graphically in Figure 1.

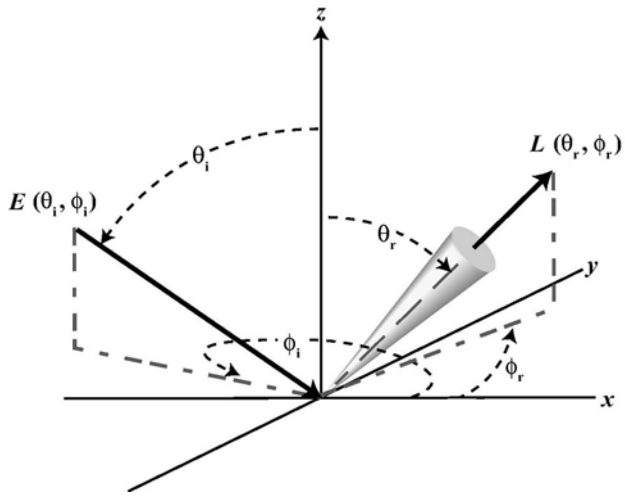

Figure 1 Illustration of BRDF measurement geometry.

For an ideal surface (*i.e.*, Lambertion with a reflectivity of one) we can derive a relationship between the incident irradiance and measured radiance. This relationship was found to be

$$E = L\pi \left[Wm^{-2} \right] \tag{2}$$

where E is sometimes denoted as the exitance, M. The definition of the BRDF, as stated in Eq. (1), is simply the ratio of the irradiance to radiance. For a Lambertion surface with a reflectivity of one we have

$$\rho_{BRDF} = \frac{L}{E} = \frac{1}{\pi} \approx 0.32 \left[sr^{-1} \right] \tag{3}$$

which says the BRDF value should be constant as a function of angle over the hemisphere above the surface. This is illustrated in Figure 2 where we have both a polar and scatter plot of the expected behavior of a Lambertion surface, with a reflectivity of one, as a function of view angle. The BRDF should not be confused with the unitless "reflectance" which ranges from zero to one. In fact, for certain materials and angles, the BRDF can actually take on values larger than one.

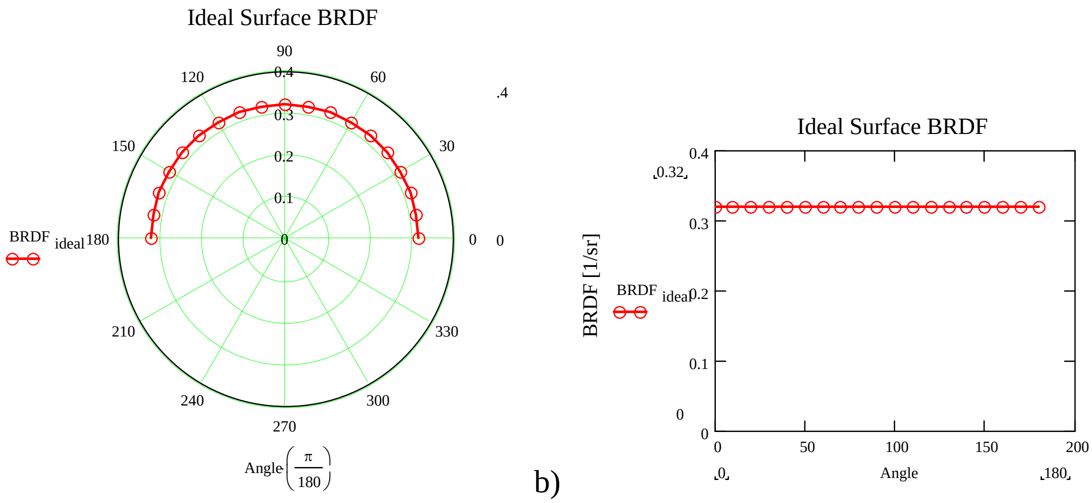

Figure 2 Illustration of expected BRDF value, as a function of angle, for an idealized Lambertion surface with a reflectivity of one. a) Plot in polar and b) Cartesian coordinates for two azimuth angles, $\phi_r = 0$ and $\phi_r = 180$ with the zenith angle ranging from $\theta_r = 0$ to 90 for each azimuth.

MATERIALS

- CCD Camera
- Materials to measure (papers, plastics, etc.)
- Ruler
- Protractor or anything with angle markings on it
- Light source (fiber optic source)

PROCEDURE

In order to rigorously characterize the BRDF, just in terms of angles, would take an enormous amount of effort and set-up beyond the scope of this laboratory. For each illumination angle (θ_i, ϕ_i) we would have to measure the radiance at every angle (θ_r, ϕ_r) in the hemisphere above the sample. For this lab we will simply fix the illumination angle at $\theta_i = 30$ and $\phi_i = 180$ degrees. This can be seen graphically in Figure 3. Measurements, or images, will then be acquired at various zenith angles, θ_r as a function of two azimuth angles ($\phi_r = 0$ and $\phi_r = 180$), as seen in Figure 3.

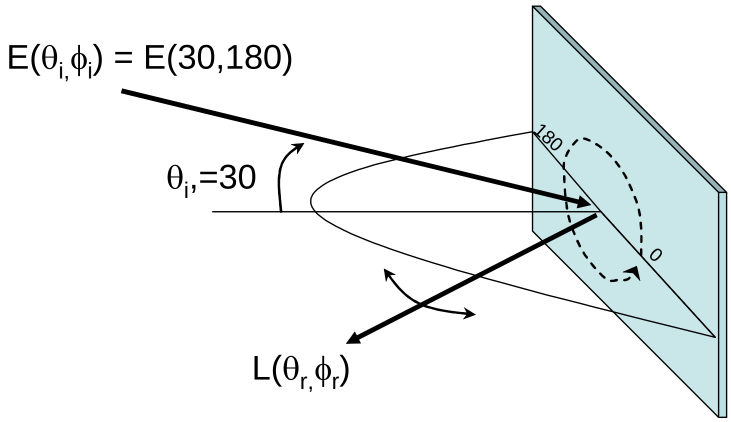

Figure 3 Example setup for measuring the BRDF of a sample.

We now see that we have simplified Eq. (1) significantly by keeping some of the illumination and measurement angles constant. This now reduces our expression for BRDF to the following two forms

$$\rho(30,180,\theta_r,0) = \frac{L(\theta_r,0)}{E(30,180)} \quad [sr^{-1}] \tag{4}$$

$$\rho(30,180,\theta_r,180) = \frac{L(\theta_r,180)}{E(30,180)} \quad [sr^{-1}] \tag{5}$$

where we can see that θ_r varies for two different azimuth cases ($\phi_r = 0$ and $\phi_r = 180$).

ACTUAL SET-UP

Measuring BRDF can be a tricky process. However, you lab instructor has devised a simple experimental setup that should ease your pain yet still be instructional, informative, and practical. An example setup can be seen in Figure 4. This setup allows us to examine a slice of the BRDF function for a particular illumination angle, as previously discussed. In the figure, we have illuminated a material at $\theta_i = 30$, $\phi_i = 180$ degrees, relative to the material normal. To get this angle, and subsequent measurement angles, markings (*i.e.*, stickers, etc.) were placed on a table top in 30 degree increments (using a protractor) at a distance of 30 cm from the material to be measured. You can use any type of "marker" you wish as long as you can differentiate zenith angles on the order of 15 degrees (the importance of which is described below).

After your area is marked-off, point the source directly at the center of the target, which is further illustrated in Figure 3 and Figure 4. This source should be around r = 1 meter from your target. What ever the distance (which produces a good signal), be sure to record it. You will need this to calculate the irradiance later. We will assume our output source has an intensity of approximately I = 10 W/sr.

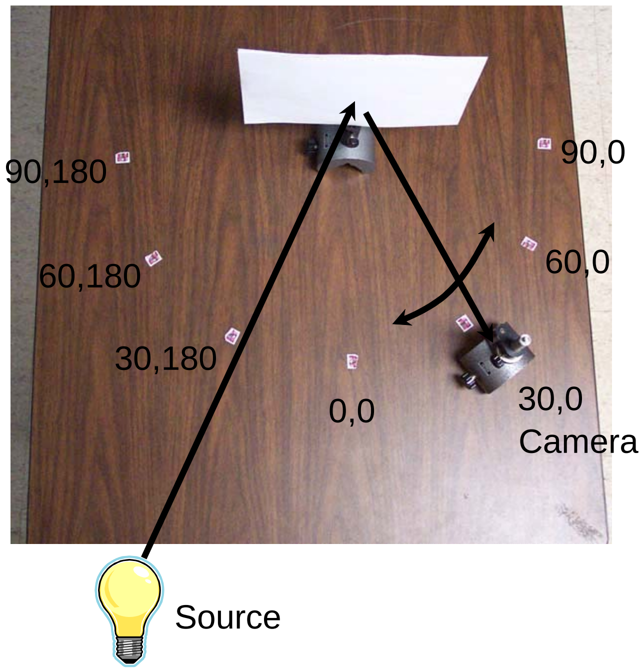

Figure 4 Example setup for measuring BRDF of a sample, for one illumination angle.

SAMPLE DATA

With the source in place, radiance measurements should be made across the hemisphere in 15 degree increments. An example measurement (*i.e.*, image) taken at L(75,180) can be seen in Figure 5. Another image taken at L(30,0) can be seen in Figure 6. In all, for a single material type, you should have a total of *11 images* taken at the same exposure (i.e., same F/# and shutter speed). A summary of measurement orientations is provided in Table 1.

Note: In one of the acquisition positions, L(30,180), your camera will be in the way of the source, thus partially blocking the sample. Take the picture anyway as part of your collection of images. You may still be able to extract some useful information from this location. Otherwise you will have a missing data point in your plots from this location.

Figure 5 Sample image of a "semi-gloss" surface taken at L(75,180).

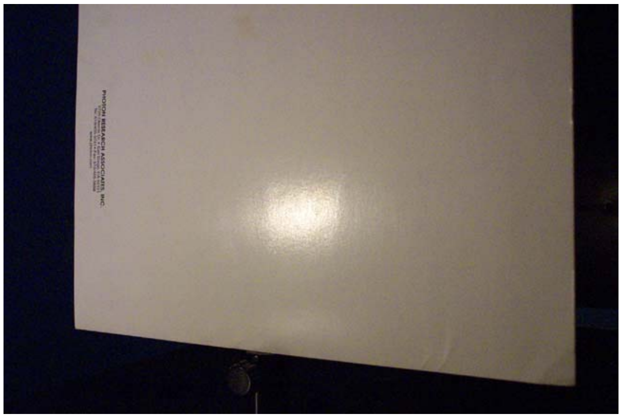

Figure 6 Sample image of a "semi-gloss" surface at L(30,0). Notice the specular spot is directly in the middle of the target, as expected. This is due to the incident illumination angle being E(30,180).

Table 1 Orientation of collected imagery for a material illuminated at E(30,180).

ϕ_r = 0 degrees	Center	ϕ_r = 180 degrees
L(15,0)	L(0,0)	L(15,180)
L(30,0)		L(30,180)
L(45,0)		L(45,180)
L(60,0)		L(60,180)
L(75,0)		L(75,180)
L(90,0)-no image		L(90,180)-no image

MATERIALS TO MEASURE

Once you have your setup put together, you should be able to measure the BRDF of a few materials. One of the materials should be an 8.5 x 11 inch piece of copy paper. We assumed this was Lambertion in previous labs. Now is your chance to see how Lambertion it really is. In the examples illustrated above (Figure 5 and Figure 6), I found an old plastic folder sitting on my shelf that I would say had a 'semi-gloss' finish. Some suggested materials can be seen in Table 2. Feel free to add your own.

Table 2 Some material suggestions for measurement of BRDF.

Diffuse or Matte	Semi-Gloss	Glossy
Copy Paper	Dull Plastics	Photo Paper
Sandpaper	Metals	Shinny Plastics
Cardboard	Brushed Aluminum	Metals
		Ceramic Tile

ANALYSIS

Once you have collected your imagery, you need to determine the actual BRDF and plot it as a function of angle.

1. Take pictures of your samples at the various angles.
2. Transfer your images to your PC/Mac/etc.
3. Extract the mean digital count from each of your images. You can use Adobe® Photoshop® or ImageJ (http://rsb.info.nih.gov/ij).
    a. Be sure to average over the same region in each image. A "mark" at the bottom of your sample may help you identify the same image-to-image region. If you have a 'hot spot' or specular lobe (as seen in Figure 7) you'll want to make sure you capture it at acquisition location L(30,0).
    b. I found using a sampling size of 400 x 400 pixels worked for my imagery. I used this size for all materials imaged. Your size may be different.

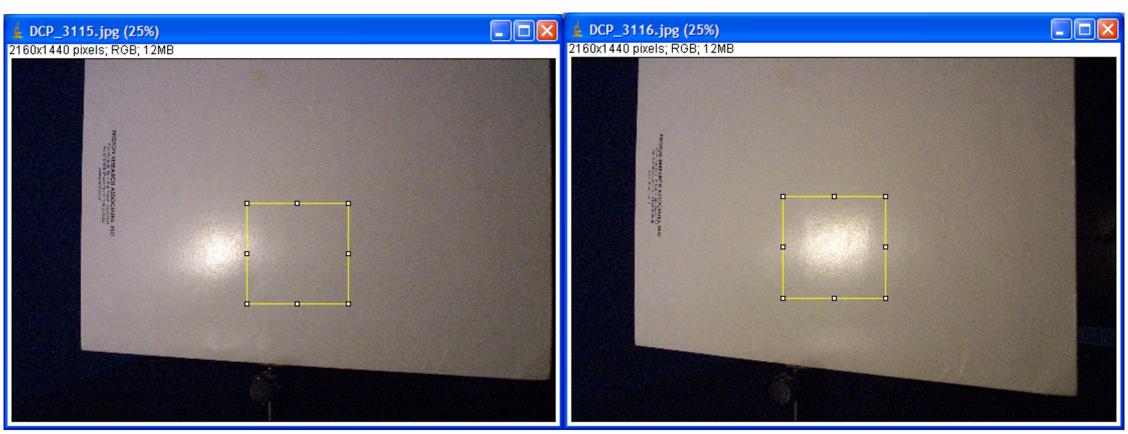

Figure 7 Image of semigloss folder at angles a) L(15, 0) and b) L(30, 0). Notice how the specular lobe moves across the field of view.

4. Calculate the irradiance, *E* onto the sample using the source intensity and distance information provide above.
5. Calculate the radiance using the following LUT which maps digital count (DC) to radiance:
    a. L = 0.066 DC - 2.96
6. Compute your BRDF values as a function of angle (*i.e.,* BRDF = L/E)
7. Create a Cartesian (*i.e.,* scatter) plot of your BRDF values.
    a. It is easier if you simply treat your angles as going from 0 to 180 degrees. Use Figure 2(b) as a reference. In this case, angle 120 would be the same as angle L(30,0), assuming you started (*i.e.,* zero degrees) from the left side of Figure 4.
    b. Try to indicate on your plot what angle is representative of a specular lobe, if it exists.
    c. Try to indicate on your plot where a constant Lambertion BRDF would fall in relation to your plot
    d. Scale your plot with a lower bound of ‘0’.
8. Create a polar plot of your BRDF values. Use Figure 2(a) as a reference.
    a. Scale your plot with a lower bound of ‘0’
9. Repeat above steps for subsequent materials.

<u>REPORT</u>

1. Explanation of your set up (*i.e.,* how you acquired your images)
2. Table of raw DC values for each material
3. Calculation of irradiance for your set up
4. Sample calculation of radiance for your set up (*i.e.,* one example calculation)
5. Table of calculated BRDF values for each material
6. Cartesian and polar plots for each material
    a. What is the *expected* trend of your results?
    b. Comment on what your data looks like
    c. How does this compare to a true Lambertion surface.
7. What assumptions have you made in performing this experiment?
8. What are the sources of error in this experiment?
9. How might you compensate for these sources of error?

COURSE: **Undergraduate Radiometry 1051.370.01** Qtr/Year: SPG/2007

Due Date: 5-11-07

Name: ____________________

Lab Partners: ____________________

Lab # and Name: Measuring BRDF of Materials

CONTENTS	**Total Possible**	**TOTAL**
Introduction and/or Abstract	4.0	____
Explanation of set up	5.0	____
Table of raw DC values for each material	2.0	____
Calculation of irradiance & sample calculation of radiance	2.0	____
Table of calculated BRDF values for each material	2.0	____
Cartesian plots for each material	5.0	____
Polar plots for each material	5.0	____
DISCUSSION		
Expected trend of results	10.0	____
Comments on what your data looks like	10.0	____
How do your measured materials compare to a Lambertion surface	10.0	____
What assumptions have been made in doing experiment	10.0	____
Stated sources of error	10.0	____
Possible ways to mitigate sources of error	10.0	____
GENERAL FORMAT		
Format (includes extraneous data, syntax, layout, spelling, etc.)	5.0	____
Clarity / understanding of material	10.0	____
LATE	-10.0	____
Extensively LATE (more than 2 weeks)	-20.0	____
Total:	100	____