MADLaSR: multi-angle detector of Lambertian and specular reflectivity

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ABSTRACT

The goal of this project was to build a device capable of measuring both the specular reflectivity of black materials, as well as the Lambertian reflectivity of white materials over their full range of incident and observed angles, respectively. The MADLaSR (Multi-Angle Detection of Lambertian and Specular Reflectivity) is a device designed for specular reflectivity testing in the range of $10^o < \theta < 160^o$ and for Lambertian reflectivity testing in the range of $10^o < \theta < 85^o$. The data collected from this device may be used to influence the design of optical systems, aerospace structures, or other devices in which maximum light control is a necessary consideration. This paper will discuss the design and functionality of the MADLaSR.

Keywords: MADLaSR, specular reflectivity, Lambertian reflectivity, optics, instrumentation

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1. INTRODUCTION

Regulation of light is an essential consideration in the design and construction of optical systems. The effects of stray or uneven lighting as caused by unexpected reflections may result in errors. Various materials, coatings, and finishings that are used inside such systems have differing properties, and thus, may lead to these unintended outcomes. We have constructed a device that tests both a material's specular reflectivity over a range of angles $10^o < \theta < 160^o$, as well as a material's Lambertian reflectivity over a range of angles $10^o < \theta < 85^o$. Ideally, a black material will consistently produce minimal reflectivity over the full range of angles of incidence, while a white Lambertian material will consistently produce the same apparent brightness over its full range of angles of observation. Previously, research has been conducted to test for total reflectivity over a range of wavelengths and specular reflectivity over limited angles[1]. This project aims to build upon those endeavors by expanding the investigation of the angle's influence.

2. MADLASR DESIGN

The MADLaSR device consists of two distinct assemblies: first, a system of rotating arms to control the light source and detector, and secondly, a mount for test samples.

The system of rotating arms, shown in figure 1, is composed of a central pivot rod with two independent t-slotted aluminum bars branching off. These bars are each mounted above perpendicular Thorlabs 300mm travel stages. Dowel pins were fitted into both the travel stages and the grooves of the t-slot bars. This allows the rotation of the t-slotted bars to be governed by the movement of the travel stages. The dowel pins were positioned on the travel stages such that they would remain symmetrical with respect to the pivot point and central axis during the full range of travel. In order to minimize forces on the travel stages, supports were added to the far end of the arm to prevent bending moments. These supports were then covered with strips of Teflon to minimize frictional forces.

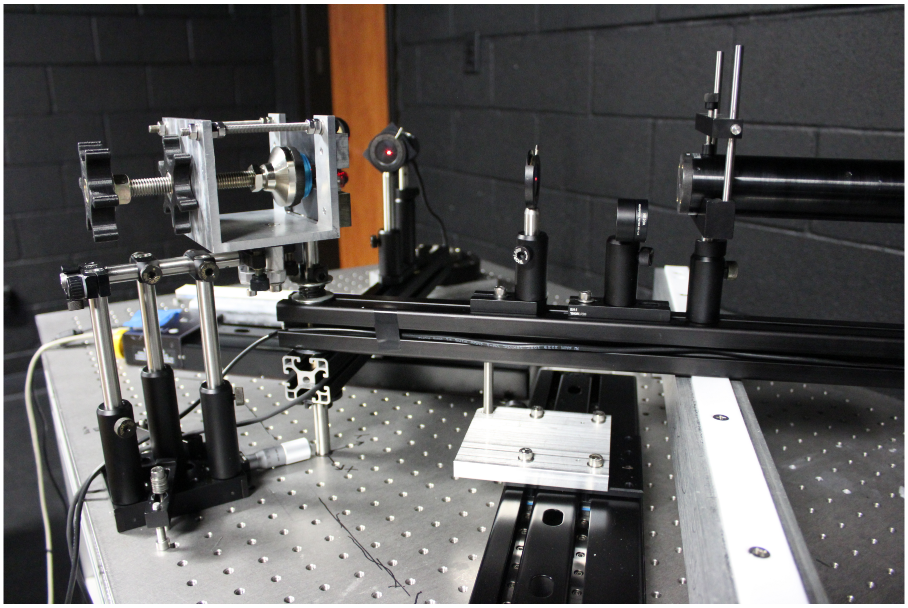


Figure 1. A side view of the MADLaSR is pictured. The travel stages guide the rotation of the t-slot bars about the central pivot. The light source and detector can be seen on each rotating t-slot bar. The test sample mount is seen positioned vertically in plane with this central pivot. Components are as labeled in Figure 3.

The sample mount is a machined square tube with a window in the front face in which the material is exposed and held in place by a swivel-leveling mount. This mount is supported by both a tilt stage and a translation stage in order to accommodate fine adjustments. Fine adjustments are imperative to ensure perfect consistency in the reflective plane between tests.

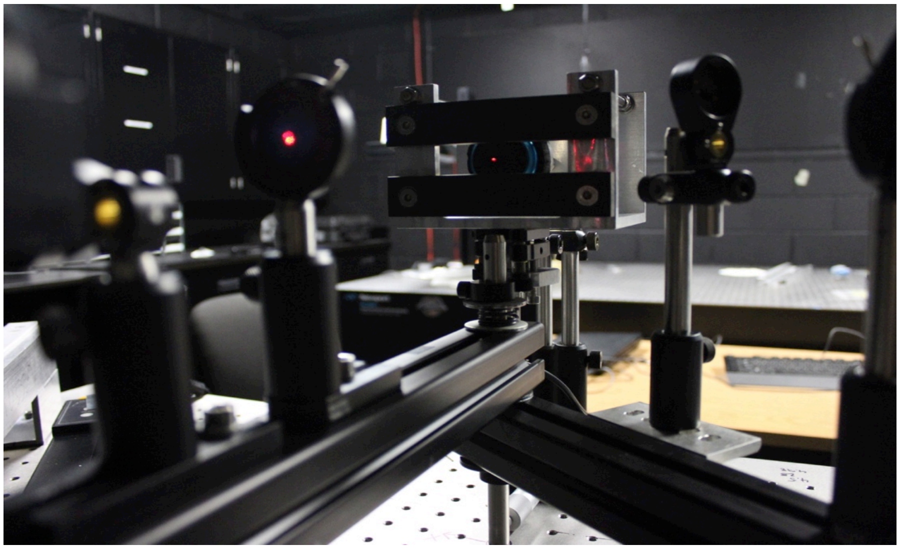


Figure 2. A front view of the MADLaSR is pictured. A material sample is secured in the mount and is reflecting the red laser from our light source.

We are using a helium-neon laser as our light source and a Gentec Photo-Detector (PH100-SiUV; S/N: 181951) as our light detector. Each is mounted on a separate rotating arm. We also include multiple apertures on each arm to mitigate stray reflections that may affect our results.

Due to physical limitations, the minimum angle that the MADLaSR can be positioned at is 10^o. While it is physically capable of reaching a maximum spread of 180^o, our results become potentially inaccurate past 160^o. Thus, we choose to constrain our range of motion between $10^o < \theta < 160^o$ for specular testing and $10^o < \theta < 85^o$ for Lambertian testing.

3. USING THE MADLASR FOR TESTING

3.1 Specular reflectivity testing

When testing for specular reflectivity, the laser and the sensor must be positioned symmetrically with respect to the central axis as defined by the pivot rod. These tests require both travel stages to move to equal positions to ensure that the arms are at equal angles. A dark room environment is required for these tests. An example of this setup in the Munnerlyn Astronomical Instrumentation Laboratory at Texas A&M University is shown in Figure 3.

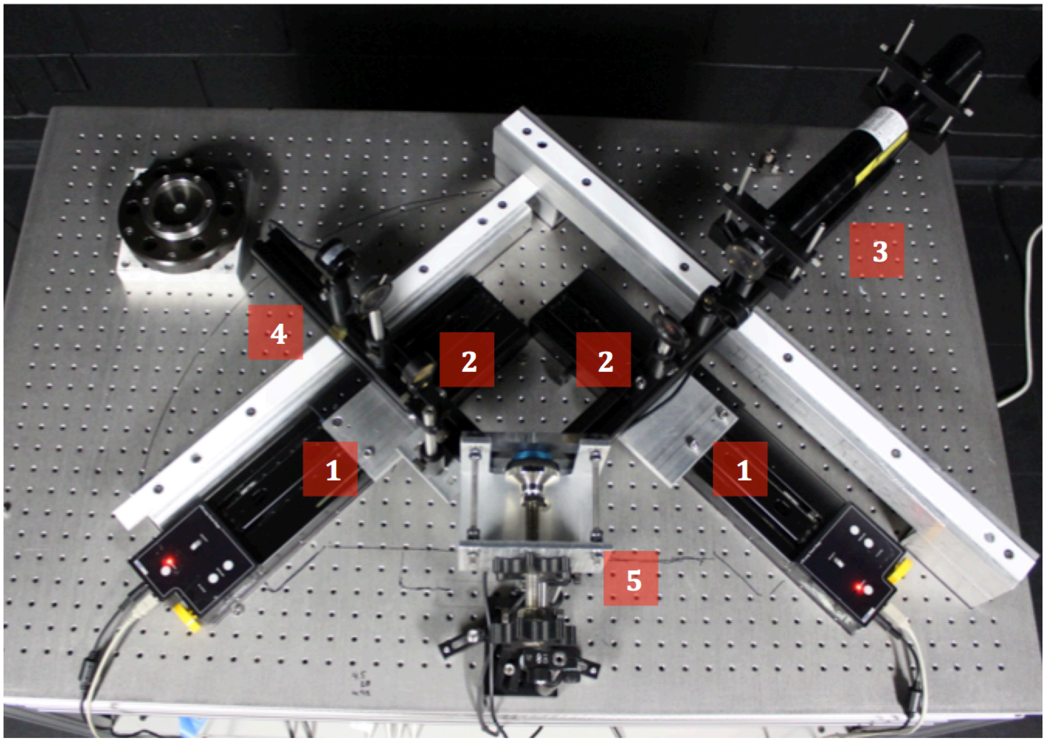
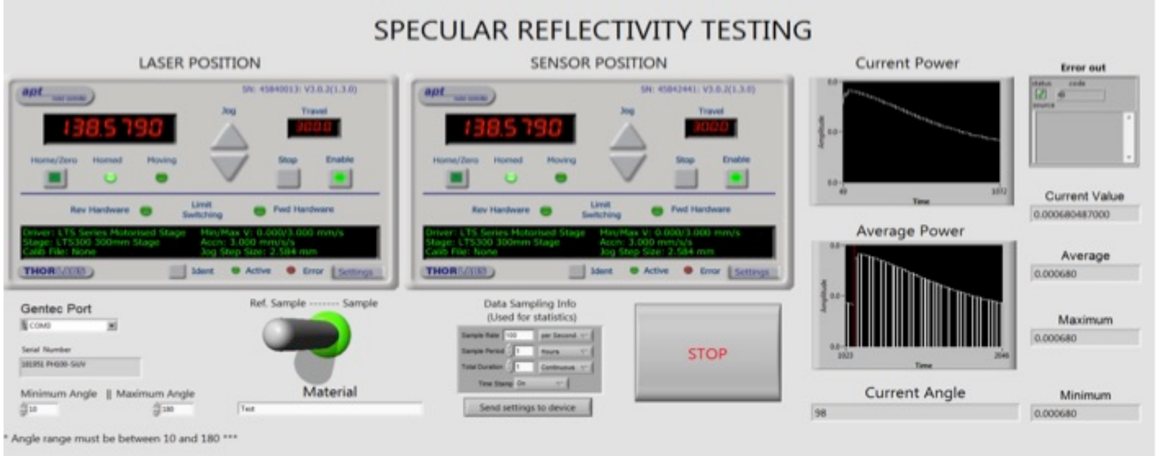


Figure 3. A top view of the MADLaSR is pictured. The setup for specular reflectivity testing is shown with the two arms in symmetric positions with respect to the central axis as defined by the pivot rod. The travel stages (1), rotating arms (2), light source (3), light detector (4), and sample mount positioned above the pivot rod (5) are labeled.

A LabVIEW program controls MADLaSR and allows for the full customization of settings, such as the range of angles to test and adjustments to the sampling rate of data points. As shown in Figure 4, we have constructed an intuitive user interface to control these variables, in addition to the display of real time readouts of the collected data. Along with the readout of results in real time, this program writes all the data to an excel file which the user can access once the test has reached completion.



138.5790

Driver: LTS Series Motorised Stage
Stage: LTS300 300mm Stage
Calib File: None
Min/Max V: 0.000/3.000 mm/s
Accn: 3.000 mm/s/s
Jog Step Size: 2.584 mm

Gentec Port: COM3

Serial Number: 181951 PH100-SiUV

Minimum Angle || Maximum Angle: 10 180

* Angle range must be between 10 and 180 ***

Material: Test

Sample Rate: 100 per Second

Sample Period: 1 hours

Total Duration: 1 Continuous

Time Stamp: On

Current Angle: 98

Current Value: 0.000680487000

Average: 0.000680

Maximum: 0.000680

Minimum: 0.000680

Figure 4. Our LabVIEW user interface allows for full customization of settings while running tests. A real time display of data is shown on the right.

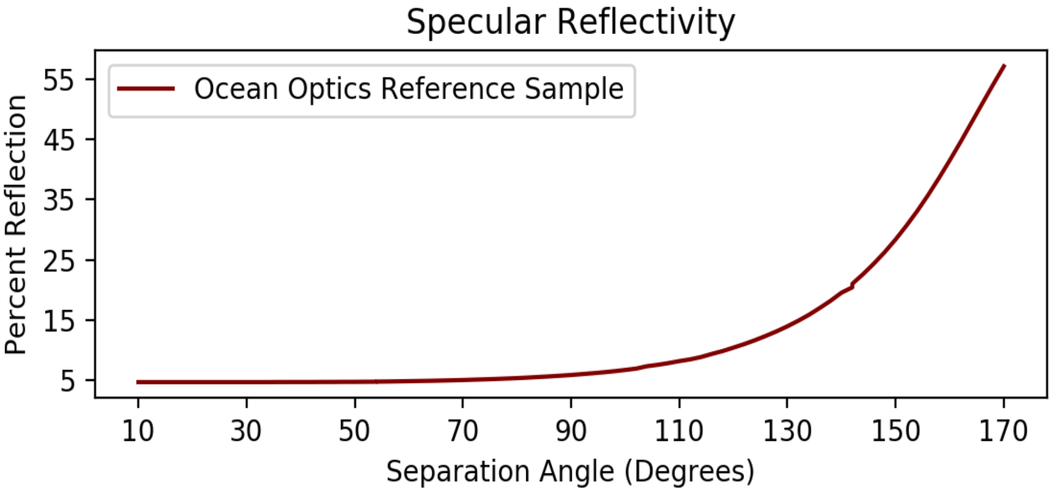


Figure 5. A plot of the data collected from a specular reflectivity test of the Ocean Optics Low Specular Reflectance Standard at a wavelength of 630 nm. We have chosen to use this standard material as a fiducial marker for all subsequent specular reflectivity tests.

3.2 Lambertian reflectivity testing

When testing for Lambertian reflectivity, the laser must be positioned perpendicular to the surface of the material and remain stationary while the sensor is moved to different angles. This setup, as shown in Figure 6, is designed to test for constant apparent surface brightness regardless of the angle of observation. Similar to that of the specular reflectivity testing, this program's user interface allows for full customization of settings in an attempt to be adaptable for all potential uses in future projects. This interface is comparable to that of Figure 4. As aforementioned, a dark room environment is required as well for Lambertian tests.

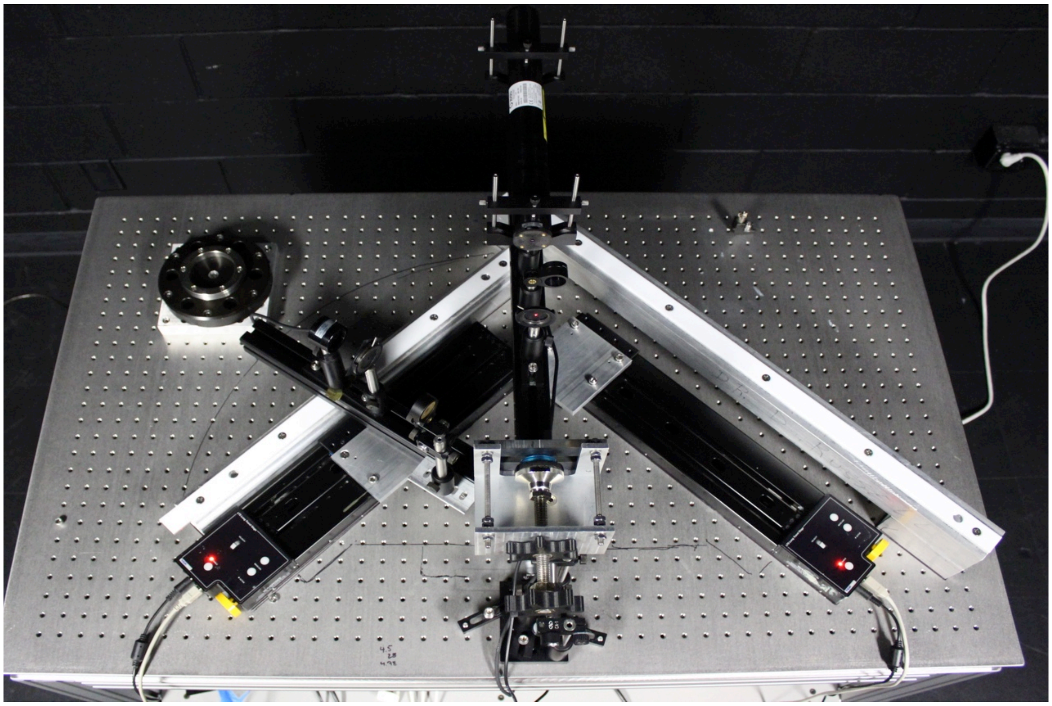


Figure 6. A top view of the MADLaSR is pictured. The setup for Lambertian reflectivity testing is shown with the laser arm positioned perpendicular to the reflective plane of the material sample, while the detector arm is free to move through all angles.

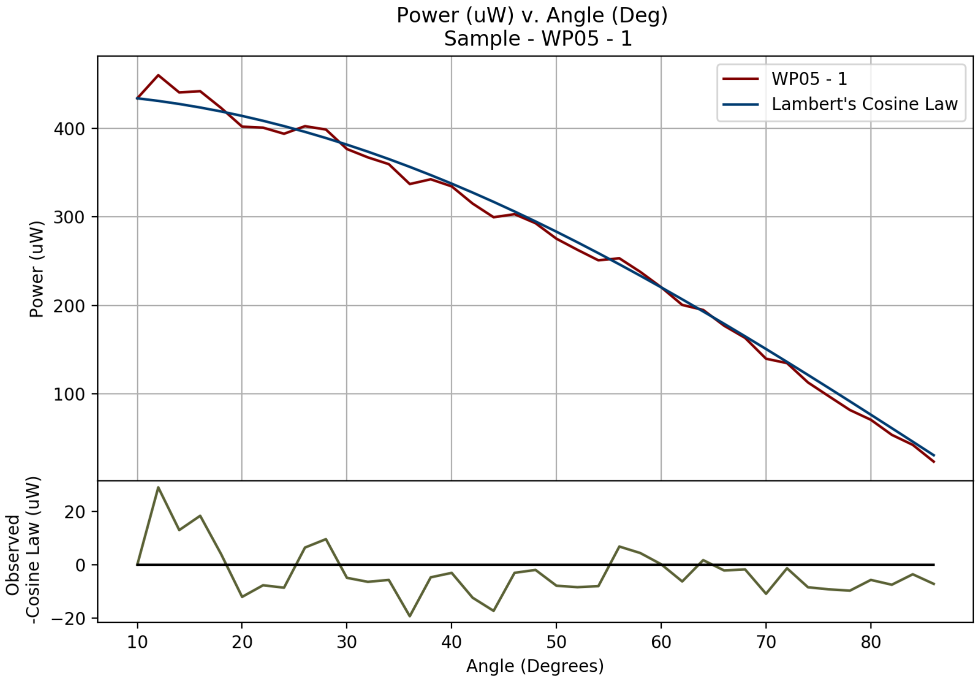


Figure 7. A plot of data collected from a Lambertian reflectivity test of a nylon-spandex fabric at a wavelength of 630 nm. The observed power is plotted with the projected power via Lambert’s Cosine Law: $I = I_o * \cos(\theta)$. The residual plot is shown below.

4. DATA COLLECTION AND ANALYSIS

The data collected consists of two key factors: the angle between the laser and detector, and the corresponding power output. An essential component of the data analysis is the conversion from the travel stage's position into the angle. This conversion is made by the following equations, which are based upon the geometry as shown in Figure 8.

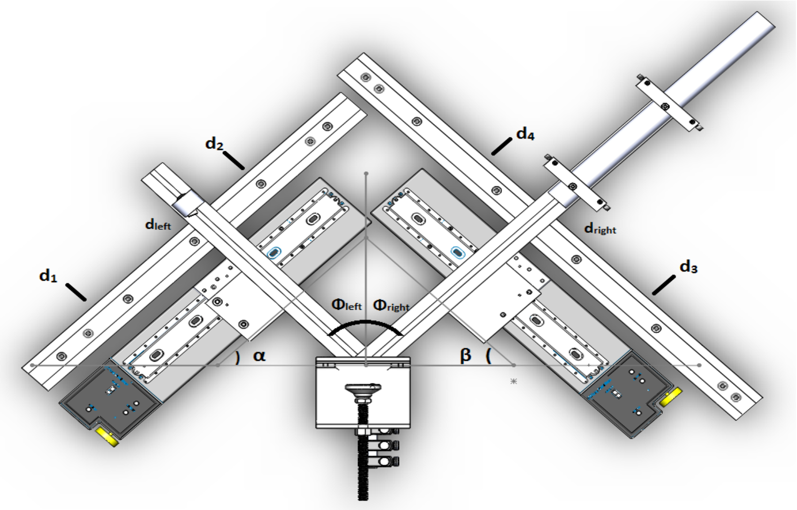


Figure 8. Solidworks Model of MADLaSR with reference points included for the derivation of equations.

Positioning the travel stages at d_1 and d_3 results in the angle of separation between the laser and detector, θ, to be 180^o, while positioning the travel stages at d_2 and d_4 results in a θ of 0^o. From the model shown in Figure 8, we have established that:

$$\theta = \phi_{left} + \phi_{right} \tag{1}$$

And thus through a combination of trigonometric relations, one can see that:

$$\theta = \operatorname{atan}\left(\frac{1}{\tan(\alpha)}\left(\frac{d_2 - d_1}{d_{left} - d_1} - 1\right)\right) + \operatorname{atan}\left(\frac{1}{\tan(\beta)}\left(\frac{d_4 - d_3}{d_{right} - d_3} - 1\right)\right) \tag{2}$$

By calibrating the system to ensure symmetry relative to the centerline, equation (2) can simplify to:

$$\tan\left(\frac{1}{2}\theta\right) = \left(\frac{d_{max} - d_{min}}{d - d_{min}}\right) - 1 \tag{3}$$

The initial values that we are using for the calibration of our device are d_{min}=1.735mm and d_{max}=296mm, which makes our final numerical equation:

$$\tan\left(\frac{1}{2}\theta\right) = \left(\frac{294.265}{d - 1.735}\right) - 1 \tag{4}$$

Through this equation, we are able to convert the position values of the travel stages into the corresponding angles between the two rotating arms. It is important to note that this equation is specifically for specular reflectance testing. For Lambertian testing, a similar derivation results in a nearly identical equation to that of (4) without the scalar for θ.

For both the specular and Lambertian setups, once the travel stages move to their positions, they pause while the sensor collects data. The photodiode collects 10 data points and records the average thereof at each angle interval. While the arms are moving to new positions, the average is reset and the photodiode prepares for the next sampling period.

5. CONCLUSIONS AND FUTURE WORK

We have described the construction and use of the MADLaSR system, which was designed to measure specular and Lambertian reflectivity over a range of incident and observed angles, respectively. This device is used in the ongoing assessment of materials for use in optical instrumentation. This collection of data will expand upon our previous studies of a material's total reflectivity over a range of wavelengths and specular reflectivity over limited angles[1]. Future testing could also be done to investigate the correlation between properties of reflectivity with temperature variance, elapsed time, and exposure to the elements. The affect of wavelengths could also be retested over varying angles of incidence.

REFERENCES

[1] Marshall et al., "Characterization of the Reflectivity of Black Materials," 2014, SPIE, 9147, 167

ACKNOWLEDGEMENTS

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