Using the Opposition Effect in Remotely Sensed Data to Assist in the Retrieval of Bulk Density

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Using the Opposition Effect in Remotely Sensed Data to Assist in the Retrieval of Bulk Density

by

Brittany L. Ambeau

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in the Chester F. Carlson Center for Imaging Science College of Science Rochester Institute of Technology

August 8, 2017

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Submitted to the
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Abstract

Bulk density is an important geophysical property that impacts the mobility of military vehicles and personnel. Accurate retrieval of bulk density from remotely sensed data is, therefore, needed to estimate the mobility on “off-road” terrain. For a particulate surface, the functional form of the opposition effect can provide valuable information about composition and structure. In this research, we examine the relationship between bulk density and angular width of the opposition effect for a controlled set of laboratory experiments. Given a sample with a known bulk density, we collect reflectance measurements on a spherical grid for various illumination and view geometries — increasing the amount of reflectance measurements collected at small phase angles near the opposition direction. Bulk densities are varied using a custom-made pluviation device, samples are measured using the Goniometer of the Rochester Institute of Technology-Two (GRIT-T), and observations are fit to the Hapke model using a grid-search method. The method that is selected allows for the direct estimation of five parameters: the single-scattering albedo, the amplitude of the opposition effect, the angular width of the opposition effect, and the two parameters that describe the single-particle phase function. As a test of the Hapke model, the retrieved bulk densities are compared to the known bulk densities. Results show that with an increase in the availability of multi-angular reflectance measurements, the prospects for retrieving the spatial distribution of bulk density from satellite and airborne sensors are imminent.
Acknowledgements

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To my loving parents
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Chapter 1

Introduction

Military operations are highly dependent on accurate knowledge of the terrain. Today, in modern warfare, there are many situations wherein armed forces are expected to travel “off-road”. When these situations occur, decision makers and strategic planners rely on estimates of the geophysical properties of the terrain to evaluate its capacity to support military vehicles and personnel. Agricultural outputs are also highly dependent on accurate knowledge of the terrain. This is because soil compaction reduces crop yields. Subsoiling is a practice that breaks up the terrain to allow for increased water movement, aeration, and access to nutrients and minerals \[4\]. But, subsoiling is also a practice that is time consuming and costly. Therefore, at the start of each growing season, farmers rely on estimates of the geophysical properties of the terrain to identify the areas where soil compaction exists, and where subsoiling is needed.

In both of these applications, estimates of the geophysical properties include, but are not limited to, the bulk density, the particle size distribution, and the moisture content. Measurement of these geophysical properties can be slow and tedious, especially when the area to be evaluated is large. Measurement can also be denied, especially when the area to be evaluated is inaccessible. If we consider the time and risk associated with \textit{in situ} measurements, then the need for remote measurements becomes obvious.

1.1 Overview

Over the past 40 years, a large number of satellite and airborne sensors have been launched to measure the solar irradiance reflected by the Earth’s surface. From these remote measurements, it is well-known that the reflectance of particulate surfaces, e.g. sand and other sediments, is anisotropic. Therefore, the reflectance at one illumination and viewing geometry is different from the reflectance at another illumination and viewing geometry. In Figure \[1.1\], we observe this angular
dependence for a sand surface from the Algodones Sand Dunes System in California. When the Sun’s azimuth is opposite the viewing direction, the surface appears to be darker, but when the Sun’s azimuth is behind the viewing direction, the surface appears to be brighter.

Likewise, from these remote measurements, it is well-known that the reflectance of particulate surfaces is influenced not only by the optical properties of the individual particles, but also by the orientation and arrangement of these individual particles within the surfaces. The reflectance at one spatial location is, therefore, different from the reflectance at another spatial location. In Figure 1.1, we observe this structural dependence as well. If we examine one image at a time, then at spatial locations where the individual particles are less dense, the surface appears to be darker, but at spatial locations where the individual particles are more dense, the surface appears to be brighter \[5, 6\]. Mathematically, these angular and structural dependencies are described by the Bidirectional Reflectance Distribution Function (BRDF). And, in order to use this mathematical description for retrieval by remote measurements, a BRDF model with parameters that have physical meaning is required.

1.2 Motivation

Currently, to estimate the BRDF from a satellite sensor, multi-angular reflectance measurements are fit to a semi-empirical model (e.g. the Ross-Li model \[7\]). This semi-empirical model, while capable of representing the overall shape, is incapable of providing the physical interpretation. In a preliminary study discussed in Appendix A, we estimate the BRDF of the Algodones Sand Dunes...
1.2. MOTIVATION

System using the current standard outlined by Strahler et. al. The results of this study show that for the red, green, and blue bands of the Landsat-8 Operational Land Imager (OLI) satellite sensor, the estimates are within 5.94%, 3.02%, and 4.49% of the actual measurements. The results also show that the largest errors occur at the illumination and viewing geometries where the Sun is located behind the sensor. At these geometries, the actual measurements exhibit an increase in the reflectance that the estimates do not, as shown in Figure 1.2. This increase is known as the opposition effect.

Figure 1.2: A result from the preliminary study discussed in Appendix A. The data from the red band of the Landsat-8 OLI satellite sensor are indicated with red markers, and the data from the semi-empirical model are indicated with black markers. If we conduct a visual comparison of the data, then we notice that, apart from days 130 - 170, the estimates fit the overall shape of actual measurements. From days 130 - 170, however, we notice an increase in the reflectance in the actual measurements that is not exhibited in the estimates.

The opposition effect, which was first discovered by astronomers, is a sudden and significant increase in the reflectance of particulate surfaces at small phase angles. Here, the phase angle is defined as the angle between the source, the surface, and the sensor. The image in Figure 1.3 is an example of the opposition effect. According to radiative transfer theory, the opposition effect is caused by two phenomena. The first phenomenon is known as the Shadow Hiding Opposition Effect (SHOE) [8, 9]. This occurs when shadows are hidden by the individual particles that cast them.
Thus, at small phase angles, there is an increase in the reflectance because the sensor measures more sunlit surfaces than shadowed surfaces. The SHOE is most pronounced at phase angles that are less than 20-degrees, and is related to bulk density and particle size distribution. The second phenomenon is known as the Coherent Backscatter Opposition Effect (CBOE) [8, 10]. This occurs when the photons that travel in equal and opposite directions interfere constructively. Thus, at very small phase angles, there is an increase in the reflectance by at least a factor of two. Unlike the SHOE, the CBOE is most pronounced at phase angles that are less than 2-degrees, and is related to the orientation and arrangement of the individual particles.

Figure 1.3: An image of an astronaut’s shadow cast on a lunar surface. As the observer, we can see that the astronaut’s shadow is surrounded by a bright glow [1]. This bright glow is known as the opposition effect.

Given that the opposition effect is related to the geophysical properties of particulate surfaces, an accurate description of this increase in the reflectance is required to estimate the BRDF, and to assist in the retrieval. The Hapke model [8], a physical model, accurately describes the opposition effect. Research with this model has focused on the influence of bulk density and particle size distribution on the functional form of the opposition effect. For particulate surfaces consisting of homogeneous and equant particles, the relationship between bulk density and angular width is well understood [8]. However, the same cannot be said for particulate surfaces consisting of composite and irregular particles; and, the latter is more typical of the Earth’s surface. A solid understanding of the relationship between bulk density and angular width for more typical materials is, therefore, essential to understanding how these particulate surfaces reflect light, and how their geophysical properties can be retrieved from the reflected light.
1.3 Objectives

The purpose of this research is to address an open question that is related to using the opposition effect in remotely sensed data to assist in the retrieval of bulk density. The approach taken focuses on measuring the BRDF of a composite, particulate surface at various bulk densities in a laboratory setting, and modeling the measured BRDF using a physical model to retrieve the bulk density. The objectives of this research are, therefore, to:

- Design a set of laboratory experiments to measure the BRDF of a composite, particulate surface at various bulk densities.
- Investigate the relationship between the BRDF and the bulk density of the surface.
- Model the relationship between the BRDF and the bulk density of the surface.

1.4 Dissertation Outline

The purpose of this dissertation is to describe the theory, the background, and the approach to measuring and modeling the BRDF of a particulate surface to retrieve its bulk density. The dissertation is, therefore, outlined as follows:

- Chapter 1: Introduction
- Chapter 2: Theory
- Chapter 3: Background
- Chapter 4: Methodology
- Chapter 5: Results
- Chapter 6: Conclusion
- Appendix A: Preliminary Study
- Appendix B: Air Pluviation Device
- Appendix C: Algodones Dunes Field Experiment

1.5 Related Publications

Portions of this research, as well as preliminary studies and related research, are published in:


Chapter 2

Theory

The theory chapter is organized as follows. First, the theoretical basis necessary for understanding the Bidirectional Reflectance Distribution Function (BRDF) is presented. Next, the BRDF measurement techniques are reviewed. Then, the BRDF models are summarized, and their strengths and weaknesses are discussed.

2.1 Definition of BRDF

Reflection is the process whereby a surface returns a fraction of incident radiation. A reflection can be specular, diffuse, or a combination of both. Specular reflection occurs when a smooth surface causes reflected light rays to travel in a single direction. Here, the angle of reflection is equal to the angle of incidence. A mirror is an example of a surface that exhibits specular reflection. Diffuse reflection occurs when a rough surface causes reflected light rays to travel in different directions. A piece of sand paper is an example of a surface that exhibits diffuse reflection. At a macroscopic scale, a piece of sand paper looks like a smooth surface, but at a microscopic scale the individual sand particles on the surface make it rough.

The most general definition for reflectance is the ratio of the radiant power reflected from a surface to the radiant power incident onto a surface, or

$$\rho = \frac{\Phi_r}{\Phi_i}. \quad (2.1)$$

However, it should be recognized that the reflectance is not an intrinsic property of a surface. Instead, for any surface, the reflectance depends on the illumination and viewing geometry. Consider a surface element $dA_i$ that is illuminated from the direction $(\theta_i, \phi_i)$, and viewed by a sensor in the
CHAPTER 2. THEORY

direction \((\theta_r, \phi_r)\). As shown in Figure 2.1, the incident light subtends an infinitesimal solid angle \(d\omega_i\) at any point on the surface, and the sensor subtends an infinitesimal solid angle \(d\omega_r\) from any point on the surface.

Irradiance is defined as the radiant power per unit area. Thus, the directional irradiance onto a surface is

\[
dE_i(\theta_i, \phi_i) = \frac{d\Phi_i(\theta_i, \phi_i)}{dA} \quad [Wm^{-2}].
\]

(2.2)

Reflected radiance is defined as the radiant power reflected from a surface per unit foreshortened area per unit solid angle, and it is dependent on the direction of the illumination and the direction of the sensor. Thus, the directional radiance is

\[
dL_r(\theta_i, \phi_i, \theta_r, \phi_r) = \frac{d^2\Phi_r(\theta_i, \phi_i, \theta_r, \phi_r)}{dA\cos\theta_r d\omega_r} \quad [Wm^{-2}sr^{-1}].
\]

(2.3)

The relationship between the irradiance of a surface and the reflected radiance of a surface is determined by its reflectance properties. The bidirectional reflectance distribution function (BRDF)
is defined as the ratio of the directional radiance reflected from a surface to the directional irradiance \[1\]. Thus,

\[
f_r(\theta_i, \phi_i, \theta_r, \phi_r) = \frac{dL_r(\theta_i, \phi_i, \theta_r, \phi_r)}{dE_i(\theta_i, \phi_i)} \left[ sr^{-1} \right].
\] (2.4)

For a Lambertian surface, the radiance is assumed to be independent of the direction of the sensor, and therefore, the outgoing intensity of light is independent of view angle. Thus, the BRDF is \( f_r = \frac{\rho}{\pi} \left[ sr^{-1} \right] \).

### 2.2 Measurement of BRDF

Given that the BRDF is defined with infinitesimal quantities, it cannot be directly measured \[11\] \[2\]. Instead, a measurement of the BRDF involves finite sizes of illuminated areas and finite sizes of detector apertures, and therefore, is an approximation of the differential form. A measurement of the BRDF also involves a measurement of the radiance reflected from a nearly lossless reference panel. By and large, this approximation is referred to as the reflectance factor. Here, the word reflectance can be preceded by two adjectives, the first describes the degree of collimation of the source, and the second describes that of the sensor. According to Nicodemus, there are three possible adjectives: directional, conical, and hemispherical. If the two adjectives are identical, then the prefix bi is used. Thus, bidirectional reflectance distribution function is the same as directional-directional reflectance distribution function. Nicodemus et al. classified nine different measurement geometries for a reflection measurement. These measurement geometries are summarized in Figure 2.2, and we will discuss three of them.

#### 2.2.1 Bidirectional Reflectance Factor (BRF)

For practical reasons the Bidirectional Reflectance Factor (BRF) is used to describe the anisotropic reflectance of a surface. The BRF can be estimated by the ratio of the radiance \( L_r \) reflected from the surface in a specific direction to the radiance \( L_{ref} \) reflected from a lossless reference panel with Lambertian reflectance behavior, both measured under an identical illumination geometry \[11\]. Since white reference panels like Spectralon panels do not show ideal Lambertian reflectance behavior, the radiance \( L_{ref} \) has to be corrected by a panel calibration coefficient \( R_{ref} \). Thus,

\[
BRF(\theta_i, \phi_i, \theta_r, \phi_r) = \frac{L_r(\theta_i, \phi_i, \theta_r, \phi_r)}{L_{ref}(\theta_i, \phi_i, \theta_r, \phi_r)} \cdot R_{ref}(\theta_i, \phi_i, \theta_r, \phi_r).
\] (2.5)
According to Schaepman-Strub et al., a measurement of BRF is interrelated to the BRDF by a factor of $\pi$. That is, the BRF divided by $\pi$ reproduces the BRDF of a surface [2].

### 2.2.2 Hemispherical Conical Reflectance Factor (HCRF)

For BRF measurements under field conditions, Equation 2.5 is not applicable. Since the illumination is hemispherical under natural illumination conditions, the best estimation for the BRF would be the measurement of the Hemispherical Directional Reflectance Factor (HDRF). Exact measurements of the HDRF would require a sensor optic with an infinitesimally small instantaneous field of view (IFOV) which is impossible to obtain. Thus, the best estimation of the anisotropic reflectance in the field is the measurement of the hemispherical conical reflectance factor (HCRF).

### 2.2.3 Biconical Reflectance Factor (BCRF)

Similarly, for BRF measurements in a laboratory setting, Equation 2.5 is not applicable. Since the illumination is conical in a laboratory setting, the best estimation for the BRF would be the measurement of the Conical Directional Reflectance Factor (CDRF). Exact CDRF measurements would require a sensor optic with an infinitesimally small IFOV, which is impossible to obtain. Thus, the best estimation of the anisotropic reflectance in the laboratory is the measurement of the Biconical Reflectance Factor (BCRF).
2.2.4 Goniometer

Since a direct BRDF measurement of a surface is not possible, the BRDF characteristics are approximated by measuring the BRF of the surface at various illumination-viewing geometries. Various ground-based instruments, termed goniometers, have been developed in recent years to measure HCRF in a field setting and BCRF in a laboratory setting [12, 13, 14, 15, 16]. Field goniometers have the advantage of measuring the target reflectance under natural illumination conditions, whereas laboratory goniometers have the advantage of measuring the target reflectance under controlled environmental conditions. But, in either case, the main components of goniometers consist of a platform and a spectroradiometer. The platform is used to position the sensor. Thus, the angular accuracy of the platform is essential for quality data.

2.3 Models of BRDF

A large number of BRDF models have been developed to reproduce the anisotropic reflectance of particulate surfaces. In the literature, these BRDF models are classified into three categories: empirical models, semi-empirical models, and physical models. Empirical models describe the shape of the BRDF using simple mathematical functions that do not have any physical meaning [17, 18, 19, 20]. Semi-empirical models describe the shape of the BRDF using a weighted sum of kernels [21, 22, 23]. The kernels are derived from approximations of physical models, and therefore, have some physical meaning. But, the weight given to each of the kernels is determined empirically. Lastly, physical models describe the shape of the BRDF using first principles [8, 24, 25, 26]. These models are based on radiative transfer theory or ray tracing methods, and describe the actual interactions between electromagnetic radiation and surface structure. In this section, we review some of the BRDF models that are proposed in the literature. For details of their derivations, the original references should be consulted. In the BRDF models, $\rho$ is the reflectance, $\theta_i$ is the illumination zenith angle, $\phi_i$ is the illumination azimuth angle, $\theta_r$ is the view zenith angle, and $\phi_r$ is the view azimuth angle.

2.3.1 Empirical Models

2.3.1.1 Minnaert Model

The Minnaert model is one of the earliest models proposed in the literature. This model describes the anisotropic reflectance of the Moon, and has a mathematical form given by [17]:
where \( k \) is the free parameter for limb darkening. If \( k \leq 0.5 \), then the model describes the anisotropic reflectance of a dark surface. If \( k > 0.5 \), then the model describes the anisotropic reflectance of a brighter surface. And, if \( k = 1 \), then the model describes the isotropic reflectance of a Lambertian surface. As the illumination zenith angle decreases, and as the view zenith angle decreases, the model predicts that the reflectance should also increase. However, the reflectance of lunar surfaces varies not only with illumination zenith angle and view zenith angle, but also with relative azimuth angle. Unfortunately, this simple mathematical function does not account for variations in relative azimuth angle, and therefore, cannot adequately describe the anisotropic reflectance of structured surfaces.

### 2.3.1.2 Lommel-Seeliger Model

The Lommel-Seeliger model also describes the anisotropic reflectance of the Moon, and has a mathematical form given by [18]:

\[
fr(\theta_i, \theta_r) = \frac{2\rho}{\pi \cos \theta_i + \cos \theta_r}^{-1}.
\]  

(2.7)

In contrast to the Minnaert model, as the illumination zenith angle increases, and as the view zenith angle increases, the model predicts that the reflectance should increase. Again, similar to the Minnaert model, this simple mathematical function does not account for variations in relative azimuth angle, and therefore, cannot adequately describe the anisotropic reflectance of structured surfaces.

### 2.3.1.3 Walthall Model

The Walthall model describes the anisotropic reflectance of vegetative canopies and bare soils, and has a mathematical form given by [19]:

\[
f_r(\theta_i, \phi_i, \theta_r, \phi_r) = \frac{\rho}{0.13} \left[ c_1 \theta_r^2 + c_2 \theta_r \cos \phi + c_3 \right],
\]

(2.8)

where
This three-term mathematical function is not as simple as the Minnaert model and the Lommel-Seeliger model, and it accounts for variations in relative azimuth angle \( \phi = |\phi_i - \phi_r| \). The first term of the mathematical function \((c_1 \cdot \theta_r^2)\) models the upward bowl shape observed in data. The second term \((c_2 \cdot \theta_r \cdot \cos \phi)\) provides the linear dependence on the view zenith angle, and therefore, models some of the anisotropy observed in data. And, the third term \((c_3)\) models the brightness observed in data. The free parameters \((c_1, c_2, \text{ and } c_3)\) are derived from multiple linear regressions of the mathematical function to extensive field experiment data acquired by Walthall et al. Standard errors in the range of 0.3% to 3.3% demonstrate that the mathematical function is in good agreement with the bare soil reflectance data acquired. Good agreement is also found when the mathematical function is fit to bare soil reflectance data acquired by Ranson et al., with standard errors in the range of 1.6% to 5.3% \[27\]. While the simple mathematical function formulated by Wathall et al. does not account for geophysical properties that characterize individual types of bare soil, it is capable of describing the anisotropic reflectance of multiple types of bare soil.

### 2.3.1.4 Staylor-Suttles Model

The Staylor-Suttles model describes the anisotropic reflectance of desert surfaces, and has a mathematical form given by \[20\]:

\[
f_r(\theta_i, \phi_i, \theta_r, \phi_r) = \frac{1}{\cos \theta_i \cos \theta_r} \left[ c_1 + c_2 \left( \frac{\cos \theta_i \cos \theta_r}{\cos \theta_i + \cos \theta_r} \right)^N \right] \cdots \times \frac{1 + c_3 \cos^2 g}{1 + c_3 \left[ \cos^2 \theta_i \cos^2 \theta_r + (\sin^2 \theta_i \sin^2 \theta_r)/2 \right]},
\]

where \(c_1, c_2, c_3, \text{ and } N\) are the free parameters. The free parameters are derived from multiple linear regressions of the mathematical function to satellite measurements from the Nimbus-7 Earth Radiation Budget (ERB) scanner. In this study, the ERB scanner measured broadband shortwave
and longwave radiation for three desert sites: the Sahara-Arabian Desert, the Gibson Desert, and the Saudi Desert. The reflected shortwave is based on an approximate solution to the radiative transfer equation, and the emitted longwave is based on a power-law of cosines. Standard errors for the reflected shortwave were in the range of 5% to 8%.

2.3.2 Semi-empirical Models

2.3.2.1 Rahman-Pinty-Verstraete Model

The Rahman-Pinty-Verstraete (RPV) model is based on a combination of the Minnaert model and the Lommel-Seeliger model. However, unlike models that describe the anisotropic reflectance of the Moon, the RPV model describes that of vegetative canopies and bare soils, and has a mathematical form given by [21]:

\[
f_r(\theta_i, \phi_i, \theta_r, \phi_r) = c_1 \left( \frac{\cos \theta_i \cos \theta_r}{\cos \theta_i + \cos \theta_r} \right)^{k-1} F(g) [1 + R(G)],
\]

(2.13)

where

\[
F(g) = \frac{1 - c_2^2}{\left[1 + c_2^2 - 2c_2 \cos(\pi - g)\right]^{3/2}},
\]

(2.14)

\[
1 + R(G) = 1 + \frac{1 - c_1}{1 + G},
\]

(2.15)

\[
G = (\tan^2 \theta_i + \tan^2 \theta_r - 2 \tan \theta_i \tan \theta_r \cos \phi)^{1/2}.
\]

(2.16)

Here, \(c_1\), \(c_2\), and \(k\) are the free parameters; \(F(g)\) is the Henyey-Greenstein phase function [28]; and \(1 + R(G)\) is used to approximate the opposition effect. The free parameter \(c_1\) models the intensity of the reflectance. The free parameter \(c_2\) models the relative amounts of forward scattering and backward scattering. And, the free parameter \(k\) models the anisotropy of the surface.
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### 2.3.2.2 Roujean Model

The Roujean model describes the anisotropic reflectance of vegetative canopies and bare soils using an isotropic scattering kernel, a volumetric scattering kernel, and a geometric scattering kernel. The mathematical form for this model is, therefore, kernel-based, and is given by [22]:

\[
f_r(\theta_i, \phi_i, \theta_r, \phi_r) = c_{iso} + c_{vol} K_{vol}(\theta_i, \phi_i, \theta_r, \phi_r) + c_{geo} K_{geo}(\theta_i, \phi_i, \theta_r, \phi_r),
\]

(2.17)

where

\[
K_{vol}(\theta_i, \phi_i, \theta_r, \phi_r) = \frac{(\pi/2 - g) \cos g + \sin g}{\cos \theta_i + \cos \theta_r} - \frac{\pi}{4},
\]

(2.18)

\[
K_{geo}(\theta_i, \phi_i, \theta_r, \phi_r) = \frac{1}{2\pi} [(\pi - \phi) \cos \phi + \sin \phi] \tan \theta_i \tan \theta_r - \frac{1}{\pi} (\tan \theta_i + \tan \theta_r + G).
\]

(2.19)

Here, \(c_{iso}\), \(c_{vol}\), and \(c_{geo}\) are the kernel weights, and \(K_{vol}\) and \(K_{geo}\) are the kernels. The volumetric scattering kernel \(K_{vol}\) accounts for the radiation emerging from small facets that are assumed to be randomly located on the surface. And, the geometric scattering kernel \(K_{geo}\) accounts for the shadowing effects that are assumed to be caused by protrusions on the surface. In the formulation of the geometric scattering kernel, the distance between the protrusions are assumed to be large. Therefore, mutual shadowing of the protrusions is ignored.

### 2.3.2.3 Ross-Li Model

Similar to the Roujean model, the Ross-Li model describes the anisotropic reflectance of vegetative canopies and bare soils using an isotropic scattering kernel, a volumetric scattering kernel, and a geometric scattering kernel, and therefore, has a mathematical form given by [23]:

\[
f_r(\theta_i, \phi_i, \theta_r, \phi_r) = c_{iso} + c_{vol} K_{vol}(\theta_i, \phi_i, \theta_r, \phi_r) + c_{geo} K_{geo}(\theta_i, \phi_i, \theta_r, \phi_r).
\]

(2.20)

For this model, however, two kernels can be selected to describe the volumetric scattering, and two kernels can be selected to describe the geometric scattering. The two kernels that can be selected to describe the volumetric scattering are based on the work of Ross [29]. These kernels, Ross-Thick
(\(K_{\text{thick}}\)) and Ross-Thin (\(K_{\text{thin}}\)), describe the volumetric scattering in terms of large values and small values of the leaf area index, and are given by:

\[
K_{\text{vol}} = K_{\text{thick}} = \left(\frac{\pi}{2} - g\right) \cos g + \sin g \cos \theta_i + \cos \theta_r - \frac{\pi}{4},
\]

\[
K_{\text{vol}} = K_{\text{thin}} = \left(\frac{\pi}{2} - g\right) \cos g + \sin g \cos \theta_i \cos \theta_r - \frac{\pi}{2}.
\]

In the formulation of the Ross kernels, the density of leaves is assumed to be uniform. The two kernels that can be selected to describe the geometric scattering are based on the work of Li and Strahler [30]. These kernels, Li-Sparse (\(K_{\text{sparse}}\)) and Li-Dense (\(K_{\text{dense}}\)), describe the geometric scattering in terms of sunlit and shadowed portions of the vegetative crowns and bare surfaces. The Li-Sparse geometric scattering kernel describes sparse canopies where the emerging shadow is the dominant component, whereas the Li-Dense geometric scattering kernel describes dense canopies that include mutual shading. These geometric scattering kernels are given by:

\[
K_{\text{geo}} = K_{\text{sparse}} = O(\theta_i, \theta_r, \phi) - \sec \theta'_i - \sec \theta'_r + \frac{1}{2} (1 + \cos g') \sec \theta'_r,
\]

\[
K_{\text{geo}} = K_{\text{dense}} = \frac{(1 + \cos g') \sec \theta'_r}{\sec \theta'_r + \sec \theta'_i - O(\theta'_i, \theta'_r)} - 2,
\]

where

\[
O = \frac{1}{\pi} (t - \sin t \cos t) (\sec \theta'_i + \sec \theta'_r),
\]

\[
\cos t = \frac{h}{b} \sqrt{D^2 + (\tan \theta'_i \tan \theta'_r \sin \phi)^2},
\]

\[
D = \sqrt{\tan^2 \theta'_i + \tan^2 \theta'_r - 2 \tan \theta'_i \tan \theta'_r \cos \phi},
\]
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\[
\cos g' = \cos \theta'_i \cos \theta'_r + \sin \theta'_i \sin \theta'_r \cos \phi,
\]
\hfill (2.28)

\[
\theta' = \tan^{-1} \left( \frac{b}{r} \tan \theta \right).
\]
\hfill (2.29)

Here, \( O \) describes the area of overlap in the shadows of the vegetative canopies; \( b/r \) describes the crown shape of the vegetative canopies; and \( h/b \) describes the relative height of the vegetative canopies, where \( h \) is the height, \( b \) is the width, and \( r \) is the minor axis length of an ellipse describing the crown shape. For the BRDF model used by the Moderate Resolution Imaging Spectroradiometer (MODIS) sensor, the Ross-Thick kernel and the Li-Sparse kernel are selected with \( b/r = 1 \) and \( h/b = 2 \) [7].

2.3.3 Physical Models

2.3.3.1 Hapke Model

The Hapke model describes the anisotropic reflectance of particulate media, and has a mathematical form given by [8]:

\[
f_r(\theta_i, \phi_i, \theta_r, \phi_r) = K \frac{\omega}{4\pi} \frac{1}{\mu_i + \mu_r} \left\{ p(g) \left[ 1 + B_{S0} B_{S} (g, K) \right] + \left[ H \left( \frac{\mu_i}{K} \right) H \left( \frac{\mu_r}{K} \right) - 1 \right] \right\} \ldots
\]
\times \left[ 1 + B_{C0} B_{C} (g, K) \right],
\]
\hfill (2.30)

where

\[
K = \frac{-\ln(1 - EL)}{EL},
\]
\hfill (2.31)

\[
B_{S}(g, K) \simeq \frac{1}{1 + \frac{1}{h_S} \tan \left( \frac{g}{2} \right)},
\]
\hfill (2.32)

\[
h_S = \frac{KEa_E}{2},
\]
\hfill (2.33)
\[ H \left( \frac{\mu_i}{K} \right) \approx \frac{1}{1 - \omega \frac{\mu}{K}} \left[ r_0 + \frac{1 - 2r_0}{2} \ln \left( \frac{1 + \frac{\mu}{K}}{1 - \frac{\mu}{K}} \right) \right], \tag{2.34} \]

\[ B_C(g, K) \approx \frac{1}{1 + \left[ 1.3 + K \right]} \left[ \left( \frac{1}{h_C} \tan \left( \frac{\theta}{2} \right) \right) + \left( \frac{1}{h_C} \tan \left( \frac{\omega}{2} \right) \right)^2 \right], \tag{2.35} \]

\[ h_C = \frac{\lambda}{4\pi \Lambda_T}. \tag{2.36} \]

Here, \( K \) is the porosity coefficient, \( E \) is the extinction coefficient, \( L \) is the thickness of the layer, \( \omega \) is the single scattering albedo, \( \mu_i \) and \( \mu_r \) are the cosines, respectively, of the illumination zenith angle and view zenith angle, \( p(g) \) is the single-particle phase function, and \( g \) is the phase angle. The Shadow Hiding Opposition Effect (SHOE) is approximated by [1 + \( B_{S0}B_S(g, K) \)], where \( B_{S0} \) represents the amplitude and \( B_S(g, K) \) represents the functional form. In the functional form, \( h_S \) is the angular width of the SHOE, where \( E \) is the extinction coefficient and \( \alpha_E \) is the extinction cross section. The isotropic multiple scattering component is approximated by \( [H \left( \frac{\mu_i}{K} \right) H \left( \frac{\mu_r}{K} \right) - 1] \), where \( H \left( \frac{\mu}{K} \right) \) is the Ambartsumian-Chandrasekhar \( H \)-function and \( r_0 = \frac{1 - \sqrt{1 - \omega}}{1 + \sqrt{1 + \omega}} \) is the diffusive reflectance. The Coherent Backscatter Opposition Effect (CBOE) is approximated by [1 + \( B_{C0}B_C(g, K, \lambda) \)], where \( B_{C0} \) represents the amplitude and \( B_C(g, K, \lambda) \) represents the functional form. In the functional form, \( h_C \) is the angular width of the CBOE, where \( \Lambda_T \) is the transport mean free path.

### 2.3.3.2 Lumme-Bowell Model

The Lumme-Bowell model describes the anisotropic reflectance of planetary surfaces, and has a mathematical form given by [24, 25]:

\[
f_r(\theta_i, \phi_i, \theta_r, \phi_r) = f_{r_1}(\theta_i, \phi_i, \theta_r, \phi_r) + f_{r_m}(\theta_i, \phi_i, \theta_r, \phi_r)
= \omega \frac{1}{4\pi \mu_i + \mu_r} p(g) \frac{1}{2} F_1(1, 1 + 2x, x) + \frac{\omega^*}{4\pi} H(\mu_i, \omega^*)H(\mu_r, \omega^*) - 1, \tag{2.37}
\]

where
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\[ p(g) = 0.95e^{-0.4g} + 16.11e^{-4.0(\pi-g)}, \]  \hfill (2.38)

\[ 1F_1(a, b, z) = 1 + \frac{a}{b} z + \frac{a(a + 1)}{b(b + 1)} \frac{z^2}{2!} + \ldots \]
\[ = \sum_{k=0}^{\infty} \frac{(a)_k z^k}{(b)_k k!}, \]  \hfill (2.39)

\[ x = \frac{\cos \Lambda + \cos(\Lambda - g)}{2.4 \sin g} \ln \left( \frac{1}{1 - \phi} \right). \]  \hfill (2.40)

Here, \( f_r(\theta_i, \phi_i, \theta_r, \phi_r) \) is the contribution due to single scattering, and \( f_{rm}(\theta_i, \phi_i, \theta_r, \phi_r) \) is the contribution due to multiple scattering. For the single scattering contribution, \( \omega \) is the single scattering albedo, \( p(g) \) is the volume-average particle phase function, \( g \) is the phase angle, \( 1F_1(1, 1 + 2x, x) \) is the description of the SHOE, \( \Lambda \) is the luminance longitude, and \( \phi \) is the filling factor. This model assumes that all particulate media have the same volume-average particle phase function. Therefore, \( p(g) \) is determined empirically from laboratory measurements. For the multiple scattering contribution, \( \omega^* \) is the reduced single scattering albedo and \( H(\mu, \omega^*) \) is the Ambartsumian-Chandrasekhar \( H \)-function. Here, the reduced single scattering albedo is the ratio of isotropic scattering efficiency to total extinction efficiency.

2.3.3.3 Shkuratov Model

The Shkuratov model also describes the anisotropic reflectance of planetary surfaces, and has a mathematical function given by [26]:

\[ f_r(\theta_i, \phi_i, \theta_r, \phi_r) = \frac{A_n}{\pi} f(\Lambda, \mathcal{L}, g) \]
\[ = \frac{A_n}{\pi} f_1(g) f_2(g) f_3(\Lambda, \mathcal{L}, g), \]  \hfill (2.41)

where

\[ f_1(g) = e^{K g}, \]  \hfill (2.42)
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\[ f_2(g) = \frac{1}{2 + e^{-d/\Lambda_E}} \left\{ 2 + \frac{e^{-d/\Lambda_E}}{\sqrt{1 + \left[(4\pi\Lambda_E/\lambda) \sin(g/2)\right]^2}} \right\}, \]  
(2.43)

\[ f_3(g) = \frac{\cos \left[ \frac{\pi}{\pi-g} (\Lambda - \frac{g}{2}) \right]}{\cos \Lambda} (\cos \Lambda)^{g/(g - g)}. \]  
(2.44)

Here, \( A_n \) is the normal albedo, \( f(\Lambda, \mathcal{L}, g) = f_1(g)f_2(g)f_3(\Lambda, \mathcal{L}, g) \) is the photometric function, \( \Lambda \) is the luminance longitude, \( \mathcal{L} \) is the luminance latitude, and \( g \) is the phase angle. The first term in the photometric function (\( f_1(g) \)) describes the SHOE, where \( K \) is the free parameter that decreases as the normal albedo increases. The second term (\( f_2(g) \)) describes the CBOE, where \( \Lambda_E \) is the extinction mean free path, and \( d \) is the separation distance that contributes to coherent backscatter. And, the third term (\( f_3(\Lambda, \mathcal{L}, g) \)) describes the angular distribution of the increased reflectance at larger phase angles.

2.4 Concluding Remarks

The main objective of the theory chapter was to review a wide range of BRDF models. For this reason, we reviewed a handful of empirical models, semi-empirical models, and physical models. Empirical models are useful for describing the anisotropic reflectance of particulate surfaces, but the parameters are not explicitly related to the geophysical properties of the surface. That is, the mathematical form cannot be inverted to estimate the geophysical properties directly on the basis of reflectance measurements, nor can the mathematical form be used to predict the BRDF on the basis of geotechnical measurements. Semi-empirical models retain some of the physical interpretation through approximations made from physical models; yet offer the advantage of being versatile and rapidly inverted. At the present, however, there is only a limited understanding of the physical significance of the parameters derived from these models. Physical models are more complex than empirical or semi-empirical models. They contain more parameters, and deal more rigorously with the underlying physics. The overriding factor, however, is the necessity to reduce the number of parameters for a robust inversion. Computationally speaking, the greater the number of parameters the longer it will take to process, and the greater the number of reflectance measurements required. In the end, a physical approach is probably the most accurate at modeling the reflectance at the microscopic scale, but it also requires the most computational load.
Chapter 3

Background

The background chapter is organized as follows. First, the related work is discussed. Next, the equipment that is used to measure and control the geophysical properties of particulate surfaces is presented. Then, the goniometers used to measure the BCRF are presented. And, lastly, the laboratory set-up is presented.

3.1 Relevant Work

Investigations to validate the fidelity and physical interpretability of physically motivated BRDF models involve laboratory studies. The focus of many laboratory studies has been to test and validate the Hapke model [31, 32, 33, 34, 35, 36, 37, 38, 39, 40, 41]. Before we discuss our methodology for the retrieval of bulk density, we provide an overview of the relevant work. This overview includes a set of experiments that either evaluates or retrieves the bulk density of natural particulate surfaces.

Demattê et al. (2010) evaluated the bulk density of two particulate surfaces using reflectance measurements collected in a laboratory setting [42]. The two particulate surfaces evaluated were Typic Quartzpisament (TQ) and Rhodic Paleudalf (RP), i.e. two Brazilian soils used in agriculture for pasture, sugar cane, citrus, and eucalyptus. In their experiment, Demattê et al. obtained eight replicates of natural, undisturbed samples at 0-20 cm and 60-80 cm depths in a 100 cm³ cylinder for each soil profile. A subset of the cylinders were oven-dried at 45°C for 24 hours. Then, these cylinders were taken to a spectral laboratory and the reflectance was measured at nadir using an infra-red intelligent spectroradiometer (IRIS) with a spectral range of 450-2500 nm, and a spectral sampling of 2 nm at 450-1000 nm and 4 nm at 1001-2500 nm. The white reference standard used to collect the reflectance measurements was a Spectrafect panel. The sensor measured an area of 2 cm² at the center of the sample. The illumination source was a 650 W halogen lamp and a
parabolic reflector with a non-collimated beam. The lamp was placed at 61 cm from the sample at an illumination zenith angle of 15-degrees. To maintain constant illumination, the electric energy powering the illumination source was controlled by a 1% power source. Following the reflectance measurements, the cylinders were taken to a physics laboratory and inserted into pressurizing equipment to simulate soil compaction effects. A load of 1000 kPA was applied gradually over five minutes to each sample following the procedure described by O’Sullivan (1992). Then, the cylinders went back to the spectral laboratory and the reflectance was measured for comparison. The results of this experiment showed that the reflectance measurements could detect high bulk density from low bulk density. This was because the compacted soils had greater reflectance intensity than non-compacted soils. However, the results also showed that this was true mainly in the Infrared and Near Infrared wavelengths. Furthermore, the discrimination in the TQ soils was less evident and occurred in few spectral bands. This was because of the natural soil structure of the TQ soils. Sandy soils (i.e. TQ soils) presented reduced bulk density when compared to clay soils (i.e. RP soils).

Bachmann et al. (2014) evaluated the bulk density of three particulate surfaces using reflectance measurements collected in a laboratory setting [5]. The three particulate surfaces evaluated were beach sands collected from Hog Island, Virginia (VA), Kailua Bay, Hawaii (HI), and Tinian Island, Commonwealth of the Northern Mariana Islands (CNMI). The beach sand from Hog Island, Virginia was composed of quartz and magnetite, the one from Kailua Bay, Hawaii was composed of olivine, and the one from Tinian Island, CNMI was composed of limestone and calcite. In the field, samples were hand excavated and saved in a container. Then, in the laboratory, samples were oven-dried and air-pluviated to prepare a maximum and near-minimum bulk density. The reflectance of these prepared samples were measured in the principal plane using an Analytical Spectral Devices (ASD) spectroradiometer with a spectral range of 350-2500 nm and an 8-degree field-of-view foreoptic. The illumination source was a 70 W quartz-tungsten-halogen lamp with an integrated reflector. The lamp was placed at a distance that provided uniform illumination across the sample at an illumination zenith angle of 20-degrees. Reflectance measurements were collected at a range of step sizes from -13-30 degrees in zenith, i.e. at every 1-degree for phase angles less than 10-degrees, and at every 5-degrees for phase angles greater than 10-degrees. The results of this experiment showed that, for the beach sand from Hog Island, VA, the low bulk density sample produced higher reflectances than the high bulk density sample. This result conflicted with the expected, general trend. Bachmann et al. expected that as the bulk density of the particulate surface increased, the overall reflectance would increase. Instead, the researchers observed the opposite, and they attributed this result to the inherent, composite nature of the sand. The researchers conjectured that the darker, and on average, smaller mineral fractions of the sand tended to fill the pore space
more completely when the bulk density was increased. Therefore, the down-welling irradiance was more readily absorbed, the multiple scattering was diminished, and the overall reflectance was lower. For the beach sand collected from Kailua Bay, HI, as the bulk density of the particulate surface was increased, the overall reflectance increased, but only at shorter wavelengths. At longer wavelengths in the SWIR, the low bulk density sample produced higher reflectances at phase angles greater than 30-degrees, while the high bulk density sample produced higher reflectances at phase angles less than 30-degrees. The researchers, again, attributed this result to the inherent nature of the sand. This sand, unlike the one from Hog Island, VA, had translucent mineral fractions with small dark spots. Therefore, as the bulk density was increased, the pore space was lessening, but not because of smaller mineral fractions. At shorter wavelengths, the reflectance measurements followed the general trend, but at longer wavelengths, the reflectance measurements were affected by the spectral contrast of the translucent mineral fraction and its small dark spots. Lastly, for the beach sand collected from Tinian Island, CNMI, as the bulk density of the particulate surface was increased, the overall reflectance did not dramatically change. This sand, unlike the previous two sands, did not have darker mineral fractions. Instead, the mineral fractions were light-colored and semi-translucent to opaque. While the opaque mineral fractions may have suppressed some of the multiple scattering, the change in the overall reflectance was negligible between the low and high bulk density samples. The fact that the general trend did not breakdown for sand with only light mineral fractions suggested that the researchers’ conjectures were reasonable. Thus, for a particulate surface with dark, and on average, small mineral fractions, as the bulk density increases, the overall reflectance decreases because the dark, and on average, small mineral fractions fill the pore space and suppress the multiple scattering.

Peck et al. (2015) evaluated the bulk density of a particulate surface using reflectance measurements collected in a laboratory setting [6]. In this experiment, the particulate surface evaluated was a beach sand collected from Chimney Bluffs, NY. Similar to the sand from Hog Island, VA that Bachmann et al. (2014) evaluated, this sand was composed of optically contrasting mineral fractions, e.g. mica, chlorite, vermiculite, kaolinite, and quartz. In the field, samples were hand excavated and saved in a container. Then, in the laboratory, samples were oven-dried and air-pluviated to prepare four different densities. The reflectance of these prepared samples was measured with the Goniometer of the Rochester Institute of Technology (GRIT) that will be discussed in Section 3.3.1. The GRIT used an ASD FieldSpec 4 Hi-Res High Resolution spectroradiometer with a spectral range of 350-2500 nm, and a spectral sampling of 1.4 nm at 450-1000 nm and 1.1 nm at 1001-2500 nm. The white reference standard used to collect the reflectance measurements was a Spectralon panel. The sensor measured an area of 3.9 cm² at the center of the sample at nadir. The illumination source was a 70 W quartz-tungsten-halogen lamp with an integrated reflector.
The lamp was placed at 2 m from the sample at illumination zenith angles of 5-degrees, 20-degrees, 35-degrees, 50-degrees, 65-degrees, and 80-degrees. Reflectance measurements were collected every 10-degrees in azimuth from 0-360 degrees, and every 10-degrees in zenith from 0-60 degrees. Four results were shown in this experiment. The first result showed that as the bulk density increased, the overall diffuseness of the BCRF decreased. Peck et al. conjectured that this resulted because there was an increase in the amount of single scattering events, and a decrease in the amount of multiple scattering events. The second result showed that as the bulk density increased, the forward scattering increased. The third result showed that at more oblique illumination zenith angles, the forward and backward scattered lobes were more defined, whereas at near-nadir illumination zenith angles, only the forward scattered lobe was defined. Therefore, the researchers conjectured that the BRDF would be less diffuse for high bulk densities, but more diffuse for near-nadir illumination zenith angles. The fourth and the last result showed that for more oblique illumination zenith angles, as the bulk density increased, the overall reflectance increased. But, for near-nadir illumination zenith angles, as the bulk density increased, the overall reflectance decreased. Similar to the conjecture that Bachmann et al. (2014) made, the researchers attributed this result to the inherent, composite nature of the sand.

Bachmann et al. (2015) also evaluated the beach sand from Chimney Bluffs, NY [43]. For this experiment, the researchers used the same laboratory setup and sample preparation discussed in Peck et al. (2015), but they collected an additional set of reflectance measurements. Reflectance measurements were collected using a constant phase angle paradigm shown in Figure 3.1. The primary purpose for constraining the reflectance measurements in this manner was to reduce the complexity of the Hapke model. For instance, with these “constant phase angle” measurements, the single scattering component of the Hapke model was constant. This allowed for a direct comparison between the multiple scattering component and the scaled version of the BCRF data. From this direct comparison, Bachmann et al. (2015) expected that a regression of the multiple scattering component on the scaled version of the BCRF would yield a linear fit. Instead, the researchers were unable to retrieve values for the fill factor and the single scattering albedo that were realistic across all of the wavelengths. And, as a result, the regression yielded a quadratic fit. Bachmann et al. (2015) conjectured that a more robust version of the multiple scattering component was needed. Consequently, the researchers replaced the isotropic approximation inherent to the multiple scattering component with that of directionality. With this replacement, a regression of the modified multiple scattering component on the scaled version of the BCRF yielded a linear fit. This improved fit suggested that the researchers’ conjectures were reasonable. Thus, a multiple scattering component with directionality was a better description of the BCRF data.
3.2 Field Equipment and Laboratory Equipment

In this research, we are concerned with retrieving bulk density from remotely sensed data. To achieve this, however, we must start small and narrow the scope of the problem. That is, we must retrieve bulk density from remotely sensed data that are transparent and controlled. Remotely sensed data that are measured in both a field setting and a laboratory setting provide this transparency and control. In a field setting, certain equipment is used to measure the in-place bulk density, moisture content, and particle size distribution — all of which are geophysical properties that influence the BRDF of particulate surfaces. By measuring these geophysical properties in a field setting, the ability to replicate the natural state of particulate surfaces in a laboratory setting is increased.

3.2.1 Sand Cone Apparatus

To determine the in-place bulk density, we use the sand cone apparatus and base plate that are shown in Figure 3.2, we use a conditioned sand with known bulk density, and we follow the test procedure outlined in ASTM D1556/D1556M-15 “Standard Test Method for Density and Unit Weight of Soil in Place by Sand-Cone Method” [44]. First, the sand cone apparatus is filled with the conditioned sand, and the total mass is determined. Next, the base plate is seated on the
particulate surface to be tested, and a test hole is hand-excavated. And, all of the test material from the test hole is saved in a container. Then, the sand cone apparatus is inverted, and the funnel is seated into the flanged hole of the base plate. Next, the valve of the sand cone apparatus is opened, and the conditioned sand is allowed to fill the test hole, the base plate, and the funnel. Then, the valve of the sand cone apparatus is closed, and the mass of the sand cone apparatus with the remaining conditioned sand is determined. At this point, the in-place bulk density is determined. To determine the in-place bulk density the mass of the removed test material is divided by the volume of the test hole. And, the volume of the test hole is:

\[ v = \frac{m_1 - m_2}{\rho_{cs}} \, [cm^3], \]  

(3.1)

where \( m_1 \) is the mass of the conditioned sand used to fill the test hole, the base plate, and the funnel, \( m_2 \) is the mass of the conditioned sand used to fill the base plate and the funnel, and \( \rho_{cs} \) is the known bulk density of the conditioned sand. Thus, the in-place bulk density is:

\[ \rho = \frac{m}{v} \, [g/cm^3], \]  

(3.2)

where \( m \) is the mass of the removed test material.
3.2 FIELD EQUIPMENT AND LABORATORY EQUIPMENT

3.2.2 Drying Oven

Moisture content is a geophysical property that influences the BRDF of particulate surfaces. In this research, we are not concerned with studying the effects of moisture content, and therefore, an accurate assessment and removal of the moisture content is required. To assess and remove the moisture content, we follow the test procedure outlined in ASTM D2216-10 “Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass” [45]. First, the test material is weighed. Then, the test material is dried to a constant weight in the Humboldt H-30145E Lab Bench Oven that is shown in Figure 3.3. And afterwards, the test material is weighed a second and final time. The moisture content of the test material is:

\[
w = \left( \frac{m_{cmm} - m_{cdm}}{m_{cdm} - m_c} \right) \times 100\% ,
\]

(3.3)

where \(m_{cmm}\) is the mass of the container and moist test material, \(m_{cdm}\) is the mass of the container and dry oven test material, and \(m_c\) is the mass of the container. By accurately assessing and removing the moisture content, we retain information for future laboratory experiments, and we ease the complexity of modeling and retrieving bulk density from the BRDF.

Figure 3.3: The drying oven used to determine the moisture content of a test material [3].
3.2.3 Sieve Shaker

Most of the Earth’s surface consists of particles with various shapes and sizes. The particle size distribution, i.e. the relative amount of material distributed over a range of sizes, influences the BRDF of particulate surfaces. There are a number of different methods for determining the particle size distribution. However, the choice of a particular method depends on the degree of fineness of the test material. The oldest and most widely accepted method is determination by sieve analysis.

Figure 3.4: The sieve shaker used to determine the particle size distribution of a test material [3].

Sieve analysis is used to divide the test material into size fractions, and then to determine the weight of these size fractions. To perform sieve analysis, we follow the test procedure outlined in ASTM D6913-04, “Standard Test Methods for Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis” [46]. First, each of the test sieves is weighed. Then, the test sieves are stacked on top of each other in ascending degrees of coarseness. Next, the test material is weighed and placed on the top (coarsest) test sieve. The stack of test sieves is completed with a bottom pan at the base, and a cover at the top. Following completion, the stack of test sieves is placed on the Humboldt H-4325 Economy Sieve Shaker that is shown in Figure 3.4, and is subjected to a standardized period of agitated movement. This movement causes the test material to distribute between the test sieves. Following the standardized period, each test sieve is removed from the stack and reweighed. That way, the amount of test material on each of the test sieves can be determined. The amount of test material in the bottom pan is determined in a similar manner. Once the analysis is completed, the test material is reconciled, and the results are organized.
3.2.4 Air Pluviation Device

Again, for this work, we are concerned with retrieving bulk density from remotely sensed data that are transparent and controlled. Therefore, preparation of samples with repeatable and uniform densities is required. There are a number of different methods for sample preparation. The most widely accepted method, however, is preparation by air pluviation [47, 48, 49, 50, 51, 52, 53, 54].

Figure 3.5: The air pluviation device used to control the bulk density of a test material in a laboratory setting.

Air pluviation is used to rain the test material into a mold at a controlled deposition rate. To perform air pluviation, we constructed a device that was developed by Miura and Toki [55] and described by Lo Presti et al. [56]. The design of the device consists of a hopper, an opening system, and a stack of test sieves. The hopper is used to store the test material. The opening system is used to release the test material from the hopper by gravity. The stack of test sieves is used to deposit the test material in a uniform manner, and at different rates. The air pluviation device constructed in our laboratory is shown in Figure 3.5 and discussed further in Appendix C. To use
this device, we follow the test procedure outlined next. First, the mesh size for each of the test sieves is determined. Then, the test sieves are stacked on top of each other in ascending degrees of coarseness and placed on the test sieve platform. Next, the distance between the bottom of the hopper and the uppermost test sieve is determined, and the distance between the lowermost test sieve and the top of the mold is determined. Then, the test material is placed in the hopper, the air duct is pulled over the entire device, the button for the opening system is pressed, and the test material is rained into the mold. Once the test material has settled, the air duct is raised and the test sample is leveled with a straight edge. The bulk density of the test sample is:

\[ d = \frac{m_{mdm} - m_m}{v_m} \text{[g/cm}^3\text{]}, \]  

where \( m_{mdm} \) is the mass of the mold and dry test material, \( m_m \) is the mass of the mold, and \( v_m \) is the volume of the mold.

To vary the bulk density of the test sample using this device, we adjust two parameters: the drop height and the deposition rate. The drop height is defined as the distance between the lowermost test sieve and the top of the mold. Therefore, to increase the bulk density, we must decrease the drop height. The rate of deposition is defined as the amount of test material raining into the mold per unit area per unit time, and is controlled by varying the mesh size of the sieves. Therefore, to increase the bulk density, we must decrease the deposition rate. Samples prepared with the air pluviation device and sand collected from the Algodones Dunes Sand System had bulk densities ranging from 1.59 g/cm\(^3\) to 1.82 g/cm\(^3\), and were repeatable to within 1%. For reference, this type of soil tends to have bulk densities ranging from 1.40 g/cm\(^3\) to 1.80 g/cm\(^3\) [57] .

3.3 Goniometers

In this research, we use a goniometer to collect the data. The goniometers that are presented were designed and built in the Chester F. Carlson Center for Imaging Science at RIT, and are used in both a field setting and a laboratory setting.

3.3.1 Goniometer of the Rochester Institute of Technology (GRIT)

The Goniometer of the Rochester Institute of Technology (GRIT) is a first-generation goniometric system that was designed and built in April 2014 [43]. The GRIT, shown in Figure 3.6, collects reflected radiance on a spherical grid in both a field setting and a laboratory setting. The design consists of an azimuth ring, a zenith arc, and a sensor carriage. To collect reflected radiance,
the system moves the sensor carriage to pre-defined positions along the zenith arc, and then, the system rotates the zenith arc to a pre-defined and subsequent position along the azimuth ring. Thus, with each rotation of the zenith arc, the GRIT collects reflected radiance on a spherical grid for one azimuth position from 0-360 degrees, and for several zenith positions from 0-65 degrees. In this work, the GRIT collected reflected radiance every 10-degrees in azimuth from 0-360 degrees, and every 10-degrees in zenith from 0-60 degrees, and this spherical grid is completed in about three-and-a-half hours.

Figure 3.6: The Goniometer of the Rochester Institute of Technology (GRIT).

To rotate the zenith arc along the azimuth ring, and to move the sensor carriage along the zenith arc, the GRIT uses two stepper motors. To determine the true azimuth position and the true zenith position of these motions, the GRIT uses two IMUs. One IMU, a VectorNav 100 IMU, is positioned on the sensor carriage and provides information on the attitude (i.e., the yaw, the pitch, and the roll) at every zenith position on the spherical grid. The other IMU, a VectorNav 300 with Dual Antenna GPS, is positioned on the azimuth ring and provides information on the differential heading at every azimuth position on the spherical grid. The reflected radiance measurements are collected using an ASD FieldSpec 4 Hi-Res High Resolution spectroradiometer with a spectral range of 350-2500 nm, and a spectral sampling of 1.4 nm at 350-1000 nm and 1.1 nm at 1001-2500 nm. The routines for the motions, the cues for the IMU data, and the reflected radiance measurements are commanded and stored using the integrated GRIT software.
3.3.2 GRIT-Two (GRIT-T)

The GRIT-Two (GRIT-T) is a second-generation goniometric system that was designed and built in the Chester F. Carlson Center for Imaging Science at RIT [58, 59]. Similar to the first-generation, the GRIT-T collects reflected radiance on a spherical grid in both a field setting and a laboratory setting. However, in a field setting, the GRIT-T collects simultaneous incoming and reflected radiance. The GRIT-T, shown in Figure 3.7, consists of three main components: the frame, the carriage, and the command and data handling. The frame includes the ring, the mounting plate for the sensors, and the mounting points for the self-leveling actuators. The ring is designed in a C-shape (i.e., 220-degrees) to reduce self-shading. The mounting plate is designed to hold two ASD FieldSpec 4 Hi-Res High Resolution Spectroradiometers. And, the mounting points are designed to attach three actuators that provide reliable, accurate, and stable leveling. The carriage includes the carriage plate, the pointing arm, and the pointing head. The carriage plate is designed to move the sensor from 0-180 degrees with respect to the ring. The pointing arm is designed to move the sensor from 0-70 degrees with respect to the positive and negative zenith directions. And, the pointing head is designed to aim the sensor at the same point on the ground for every position on the spherical grid, even on uneven terrain. Thus, the pointing arm performs the large zenith movements, and the pointing head performs the small counter-rotated zenith offsets that ensure accurate tracking of the same location on the surface. An alignment test performed by Harms et al. indicates that the maximum error recorded in any direction from the origin is 10.5 mm [59].

The command and data handling includes the two spectroradiometers, the main computer, and the integrated GRIT-T software. To collect reflected radiance, the user sets the scan pattern in the graphical user interface provided by the integrated GRIT-T software, and then observes as the system is commanded to measure the distance to the target, move the sensor to the pre-defined positions on the spherical grid, and save the data from the spectroradiometers. A laser distance unit located on the pointing head measures the at-nadir distance between the sensor and the target at the beginning of each scan. That way, the software can determine the coordinated motions of the pointing arm and the pointing head to ensure accurate tracking of the same spot on the target, even on uneven terrain.

In the laboratory, only one of the spectroradiometers is attached to the mounting plate. This spectroradiometer, i.e. the downward looking spectrometer, is usually operated with a 5-degree field-of-view foreoptic, and is connected to the sensor using a 2-meter fiber optic. Furthermore, in the experiments reported here, the GRIT-T collected reflected radiance every 10-degrees in azimuth from 0-360 degrees, and every 10-degrees in zenith from 0-70 degrees, and this spherical grid was completed in about two-and-a-half hours.
3.4 Laboratory Set-Up

Laboratory experiments provide the ability to measure the reflectance of a surface under controlled environmental conditions. These conditions are independent of variations due to atmosphere, time of day, or time of year, and are desirable when the intrinsic properties of the surface are to be investigated. The GRIT Laboratory at RIT is set up to prepare samples, and to measure the reflectance of samples. Therefore, half of the laboratory is dedicated to sample preparation, and half of the laboratory is dedicated to reflectance measurements. The half of the laboratory that is dedicated to sample preparation has a drying oven, a sieve shaker, and an air pluviation device. And, the half of the laboratory that is dedicated to reflectance measurements has a light source, a goniometer (i.e., the GRIT or the GRIT-T), and an optical table. This half of the laboratory is lined with a black material that absorbs the scattered radiation.

3.4.1 Light Source

A 120 W halogen flood light is used as an artificial light source in the GRIT Laboratory. In the laboratory, the lamp is attached to a large, computer-controlled, rotating support that replicates outdoor solar conditions. The radius of the support is approximately 2 m. At this distance, the light...
rays incident onto the sample are approximately parallel, and therefore, the light source illuminates the sample in a uniform manner. The light source configuration is shown in Figure 3.8.

Figure 3.8: The light source configuration that is used in the GRIT Laboratory.

### 3.4.2 Optical Table

A vibration controlled optical table is also used in the GRIT Laboratory. The surface of the table is designed to be very rigid with minimum deflection. And, as a result, the alignment of the light source and the physical structure of the samples remain intact. The surface of the optical table is stainless steel, and therefore, is also lined with a black material that absorbs the scattered radiation.

### 3.5 Concluding Remarks

The main objective of the background chapter was to discuss the relevant work, and to present the equipment, the goniometers, and the laboratory set-up that are required to retrieve bulk density from remotely sensed data. For this reason, we presented the protocols of the field and laboratory equipment that are used to measure and to control, the bulk density, the moisture content, and the particle size distribution of particulate surfaces. Furthermore, we presented two goniometers — the GRIT and the GRIT-T — that are used to measure the BRDF of particulate surfaces. And, we presented the laboratory set-up that is used in the GRIT Laboratory.
Chapter 4

Methodology

The methodology chapter is organized as follows. First, the research strategy is discussed. Next, the test material is discussed. Then, the set of laboratory experiments is discussed. And, the data processing is discussed.

4.1 Research Strategy

One of the main goals of modeling the BRDF of particulate surfaces is to retrieve information on the geophysical properties. From the models discussed in Chapter 2, the Hapke model is the most widely accepted. This is because the Hapke model is based on first principles of radiative transfer theory, correlates the geophysical properties to the reflected light, and has proven accuracy in laboratory measurements. Therefore, in this research, we decide to use the Hapke model to assist in the retrieval of bulk density. As shown in Chapter 2, the mathematical form of the Hapke model is given by:

\[
f_r(\theta_i, \phi_i, \theta_r, \phi_r) = \frac{K \omega}{4\pi} \frac{1}{\mu_i + \mu_r} \left\{ p(g) \left[ 1 + B_{S0} B_S (g, K) \right] + \left[ H \left( \frac{\mu_i}{K} \right) H \left( \frac{\mu_r}{K} \right) - 1 \right] \right\} \ldots \tag{4.1}
\]

where \( K \frac{\omega}{4\pi} \frac{1}{\mu_i + \mu_r} \times p(g) \) describes the single scattering, \( K \frac{\omega}{4\pi} \frac{1}{\mu_i + \mu_r} \times \left[ H \left( \frac{\mu_i}{K} \right) H \left( \frac{\mu_r}{K} \right) - 1 \right] \) describes the multiple scattering, \( \left[ 1 + B_{S0} B_S (g, K) \right] \) describes the SHOE, and \( \left[ 1 + B_{C0} B_C (g, K) \right] \) describes the CBOE. In this research, we also decide to use the GRIT-T to measure the BRDF of particulate surfaces. But, since the minimum phase angle measured by the GRIT-T is larger than the angular region of influence of the CBOE (\( g > 3 \)), the CBOE is ignored. Therefore, the
CHAPTER 4. METHODOLOGY

The mathematical form of the Hapke model is modified and given by:

\[
f_r(\theta_i, \phi_i, \theta_r, \phi_r) = K \frac{\omega}{4\pi} \frac{1}{\mu_i + \mu_r} \left\{ p(g) \left[ 1 + B_{S0} B_S(g, K) \right] + \left[ H \left( \frac{\mu_i}{K} \right) H \left( \frac{\mu_r}{K} \right) - 1 \right] \right\}. \tag{4.2}
\]

In addition to the model and the goniometer, we also decide to use a handful of assumptions. First, we assume that particles are equant, or approximately spherical in shape [8]. Therefore, \( K \approx -\ln(1 - 1.209 \phi^2/3) \), \( \phi \) is an index that characterizes the packing condition of the particulate surface. This index is known as the fill factor, and is proportional to the bulk density of the particulate surface. Second, we assume that the single-particle phase function is double-lobed. Therefore,

\[
p(g) = \frac{1 + c}{2} \frac{1 - b^2}{(1 - 2b\cos(\pi - g) + b^2)^{3/2}} + \frac{1 - c}{2} \frac{1 - b^2}{(1 + 2b\cos(\pi - g) + b^2)^{3/2}}, \tag{4.4}
\]

where the first term describes the backward lobe, the second term describes the forward lobe, and the free parameters \( b \) and \( c \) describe the width and the amplitude of the lobes. This double-lobed Henyey-Greenstein phase function can be formulated using two parameters or three parameters. But, for simplicity, we use two parameters. Third, we assume that the particle size distribution is uni-modal with the form \( n(r) \propto re^{r/\bar{r}} \), where \( r \) represents the particle radius and \( \bar{r} \) represents the average radius of the particles [8]. Therefore,

\[
h_S = \left( \frac{3}{8} \right)^{2/3} K \phi. \tag{4.5}
\]

According to the Hapke model, one approximation to the Ambartsumian-Chandrasekhar \( H \)-function has a relative error of less than 4%. For our application, a relative error of less than 4% is inadequate. Therefore, we assume

\[
H \left( \frac{\mu}{K} \right) \simeq \frac{1}{1 - \omega \frac{\mu}{K}} \left[ r_0 + \frac{1 - 2r_0 \frac{\mu}{K}}{2} \ln \left( \frac{1 + \frac{\mu}{K}}{\frac{\mu}{K}} \right) \right]. \tag{4.6}
\]
where $r_0 = \frac{1 - \sqrt{1 - \omega}}{1 + \sqrt{1 + \omega}}$ is the diffusive reflectance, and the relative error is less than 1%. With these assumptions, $\phi$, $\omega$, $b$, $c$, and $B_{S0}$ are the unknown parameters.

In principle, if we design a set of laboratory experiments to measure the BRDF of a test material with a measurement scheme with a sufficient amount of data, then the BRDF can be inverted to find the five unknown parameters. The word “sufficient” is used to represent a much larger number of positions on the spherical grid above a test material than the total number of unknown parameters. In this context, the problem of finding the parameters is overdetermined. The general theory of finding parameters in an overdetermined problem is called regression analysis. And, the most common method of finding parameters is to compare the calculated reflectance with the measured reflectance while varying these parameters until the best agreement is obtained. The usual criterion for finding the best agreement is to minimize the Root Mean Square (RMS) residual between the calculated reflectance and measured reflectance.

Moreover, if we design a set of laboratory experiments with an identical measurement scheme for multiple illumination zenith angles and wavelengths, then the method of finding parameters can be constrained. This constraint is shown in Table 4.1. As shown in the table, if there are changes in illumination zenith angle and wavelength, then the fill factor does not change. This makes sense because the fill factor is a geophysical property of a test material. Furthermore, as shown in the table, if there are changes in illumination zenith angle, then the single scattering albedo does not change. The same, however, cannot be said if there are changes in wavelength. But again, this makes sense because the single scattering albedo is an intrinsic optical property of a test material. Dissimilar to the fill factor and single scattering albedo, the remaining three parameters (i.e. $b$, $c$, and $B_{S0}$) can vary as free parameters. The organizational flow of these concepts is shown in Figure 4.1. And, the first two steps within this figure are later discussed in Section 4.4.1.

<table>
<thead>
<tr>
<th>$\phi$</th>
<th>$\omega$</th>
<th>$b$</th>
<th>$c$</th>
<th>$B_{S0}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\theta_i$</td>
<td>$\times$</td>
<td>$\times$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\lambda$</td>
<td>$\times$</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.1: The unknown parameters of the Hapke model that remain the same ($\times$) with changes in illumination angle and/or wavelength, and those that vary ( ) with changes.

Lastly, if we design a set of laboratory experiments with a measurement scheme that increases the amount of reflectance measurements at small phase angles near the opposition effect, then the angular width of the opposition effect can be delineated to find the fill factor, and to assist in the retrieval of bulk density. According to Equation 4.5, the angular width of the SHOE is a function of the porosity coefficient and the fill factor. Because the porosity coefficient increases with an increase in the fill factor, the width parameter is also expected to increase with an increase in the
fill factor. Thus, particulate surfaces with a larger fill factor (and higher bulk density) are expected to have wider opposition effects than those with a smaller fill factor (and lower bulk density).

Flow Chart of Methodology

Figure 4.1: The flow chart of the methodology. The individual steps are represented with filled colored boxes, and the assumptions for the individual steps are represented with empty colored boxes.
4.2 Test Material

In this research, we used a sand surface from the Algodones Sand Dunes System as the test material. This surface was chosen because it is a composite, particulate surface, it is a pseudo-invariant, and it has been measured in the field. According to a study conducted by the U.S. Department of Interior Geological Survey (USGS), the Algodones Sand Dunes System contains quartz, feldspar, rock fragments, and heavy minerals (e.g. magnetite, epidote, zircon, biotite, garnet, tourmaline, and hornblende). The quartz is 70 - 80% of the composition, the feldspar is 10 - 15%, the rock fragments are 5 - 15%, and the heavy minerals are less than one percent [60]. Independent from the aforementioned study, a research group from RIT conducted a field experiment in the Algodones Sand Dunes System as shown in Appendix A [16, 61]. And, it was during this field experiment that the test material was collected. In the field, the constituents of the test material were labeled as Site Code: 0903-T-02 and Site Code: 0922-T-03. A microscope picture of the test material is shown Figure 4.2. The moisture content for the test material is measured using the method described in Section 3.1.2, and was estimated to be 0.34%. Likewise, the particle size distribution for the test material was measured using the method described in Section 3.1.3, and is shown in Figure 4.3 and Figure 4.4.

Figure 4.2: A microscope picture of the test material collected from the Algodones Sand Dunes System. This is captured with a Celestron Deluxe Handheld Digital Microscope.
CHAPTER 4. METHODOLOGY

Figure 4.3: A histogram plot of the particle size distribution of the test material.

Figure 4.4: A cumulative distribution plot of the particle size distribution of the test material.
4.3 Laboratory Experiments

In this research, we measured the BRDF of the test material at five different bulk densities. These bulk densities were estimated to be 1.59 g/cm$^3$, 1.66 g/cm$^3$, 1.72 g/cm$^3$, 1.79 g/cm$^3$, and 1.82 g/cm$^3$, and are shown in Figure 4.5. To prepare the samples with these bulk densities, the test material is dried and coarsely sieved to remove moisture and constituents other than sediment. Then, the test material is rained using the methods of Section 3.1.4 into an Avian Black-S aluminum sample holder (20.32 cm diameter, 13.24 cm height), and leveled with a straight edge. To vary the bulk density, we adjust the drop height and the deposition rate with the air pluviation device shown in Figure 3.5. For the sample with the bulk density estimated to be 1.59 g/cm$^3$, we used a high drop height and a fast deposition rate. For the sample with the bulk density estimated to be 1.66 g/cm$^3$, we used a low drop height, and a fast deposition rate. For the sample with the bulk density estimated to be 1.72 g/cm$^3$, we used a medium drop height, and a moderate deposition rate. For the sample with the bulk density estimated to be 1.79 g/cm$^3$, we used a high drop height, and a slow deposition rate. And, for the sample with the bulk density estimated to be 1.82 g/cm$^3$, we used a low drop height, and a slow deposition rate.

![Figure 4.5: Five overhead photographs of the prepared samples. [Disclaimer: No conclusions should be drawn from the figure. It is merely a visual aid.](image-url)]
4.3.1 BCRF Measurements

As previously mentioned, in this research, we used the GRIT-T to measure the BCRF of the test material. The measurement scheme that was used is shown in Figure 4.6. This custom-designed scan pattern collects reflected light at angular positions every 15-degrees in azimuth from 0-360 degrees, and at every 15-degrees in zenith from 0-60 degrees. To obtain greater angular accuracy, additional collections that are focused on the angular region surrounding the opposition direction were collected every 5-degrees in azimuth and every 5-degrees in zenith. This measurement scheme uses a scan pattern with 169 positions on the spherical grid above the test material. In a laboratory setting, we have the ability to measure the reflected light from a surface under controlled environmental conditions, so the scan patterns can be as dense, and therefore, as long as desired.

Figure 4.6: The custom-designed scan pattern for the GRIT-T in a laboratory setting. The scan pattern has a higher measurement density around the backscattered region of the solar principal plane, and as a result, the scan pattern has 169 view angle positions.

During BCRF measurements, one of the two ASD FieldSpec 4 Hi-Res spectroradiometers on-board the GRIT-T collects hyperspectral sample radiance. This spectroradiometer is fitted with a 5-degree field of view fore optic. At the same time, the second spectroradiometer collects hyperspectral sample irradiance onto the test material. This spectroradiometer is fitted with a cosine collector, and is meant to monitor the temporal stability of the artificial light source. The artificial
4.3. LABORATORY EXPERIMENTS

Light source is placed at illumination zenith angles of 20-degrees and 40-degrees with respect to nadir. At a minimum, hyperspectral white reference radiance from a Spectralon panel is collected at the beginning and end of each sample measurement. Here, the Spectralon reference panel is measured at the nadir view angle position. Nevertheless, the preliminary results of the BCRF measurements displayed unnatural irregularities, e.g. abrupt decreases in reflectance. Investigation into the cause of these irregularities revealed variability in the temporal stability of the artificial light source, and ultimately, a current and voltage distortion in the GRIT Laboratory. Consequently, hyperspectral white reference radiance is collected at every position on the spherical grid above the test material. First, an individual view angle of the sample is collected, and then that same individual view angle for the white reference is collected — without moving the GRIT-T. This interleave is continued for every point in the scan pattern, and visually explained in Figure 4.7. The Spectralon panel is placed in virtually the same position and orientation with fiducials referenced to positions on the table. The purpose of this mechanism is to minimize the time, and therefore, the variations in the light source between the sample measurements and the white reference measurements.

![Figure 4.7: The scan mechanism used to collect BCRF measurements.](image)

4.3.2 Particle Density Measurements

The key to testing the accuracy of the research strategy is the ability to obtain an actual estimate of the fill factor for each of the prepared samples. Mathematically, the fill factor is defined as,

\[
\text{Fill Factor} = 1 - \text{Porosity} \quad \text{(4.7)}
\]

\[
= \frac{\text{Bulk Density}}{\text{Particle Density}} \quad \text{(4.8)}
\]
Here, the bulk density is the mass of the particles per unit volume of the test material (i.e., per unit volume of the particles and the pore space), and the particle density is the mass of the particles per unit volume of the particles. In order to obtain an actual estimate of the fill factor, we must measure the bulk densities and the particle density of the test material. In Section 4.3, the bulk densities of the test material are estimated as 1.59 \( g/cm^3 \), 1.62 \( g/cm^3 \), 1.66 \( g/cm^3 \), 1.79 \( g/cm^3 \), and 1.82 \( g/cm^3 \). The particle density, however, has yet to be estimated. To estimate the particle density, we obtain a precision weighing scale, a subset of the test material, a funnel, a graduated cylinder, a container, and a gallon of purified water, as shown in Figure 4.8, and we adhere to the following procedure that is outlined by Thien and Graveel [62]:

1. Weigh 50 \( g \) of dry test material.
2. Using a funnel, transfer the dry test material to a 100 \( mL \) graduated cylinder.
3. Tap the graduated cylinder in a repeatable manner to settle the dry test material.
4. Record the volume of the dry test material, and calculate the bulk density.
5. Transfer the dry test material to a different container.
6. Add approximately 60 \( mL \) of water to the graduated cylinder.
7. Record the volume of the water, and assume that the density is 1 \( g/cm^3 \).
8. Transfer the dry test material from Step 5 back into the graduated cylinder.
9. Stir the mixture in the graduated cylinder to remove any air.
10. Record the volume of the test material particles.
11. Calculate the particle density by dividing the weight of the dry test material by the volume of the test material particles.

From this procedure, the particle density of the test material is estimated as 2.63 \( g/cm^3 \), and the fill factors are estimated to be 0.60, 0.63, 0.65, 0.68, and 0.69, respectively. For sand and other sediments, the particle density is typical taken to be 2.65 \( g/cm^3 \). This is because quartz has a particle density of 2.65 \( g/cm^3 \), and quartz is often the dominant mineral. In Figure 4.9, the relationship between density and fill factor for the test material is shown in a scatter plot.
4.3. LABORATORY EXPERIMENTS

Figure 4.8: The supplies and equipment needed to measure the particle density of the test material.

Figure 4.9: A scatter plot of the relationship between density and fill factor for the test material.
4.4 Data Analysis

4.4.1 Data Processing

First, the spectrometer data is pre-processed. The first step in the data pre-processing is to convert raw digital number to radiance. This conversion requires the ViewSpec Pro software application that is provided by ASD Inc., and the calibration files for the specific spectroradiometer and field-of-view fore optic that are used, and that are also provided by ASD Inc. The second step in the data pre-processing is to apply parabolic corrections. Due to inherent variations in the sensitivity of the VNIR array and the SWIR2 detector, a pair of partial parabolas are inserted at the splice points between the VNIR array and the SWIR1 detector, and between the SWIR1 detector and the SWIR2 detector. The third step in the data pre-processing is to convert radiance (with parabolic corrections) to ASCII. That way, the data is stored in a standard format. Similar to the first step, the conversions in the second step, and in the third step, require the ViewSpec Pro software application that is provided by ASD Inc. And, at this point, the data is pre-processed.

Next, the pre-processed data is converted to BCRF data. In order to covert to BCRF data, Equation 2.5 is modified. Due to the current and voltage fluctuations in the GRIT Laboratory, the Spectralon panel measurements were performed at every pre-defined position on the spherical grid. Therefore, the first factor in Equation 2.5 becomes $L_r(\theta_i, \phi_i, \theta_r, \phi_r; \lambda) / L_{ref_1}(\theta_i, \phi_i, \theta_r, \phi_r; \lambda)$. And, due to this measurement scheme, the correction for the non-Lambertian reflectance behavior of the Spectralon panel is accounted for in two parts. First, the correction is partly accounted for by use of the Labsphere Inc. calibration file. This calibration file (i.e., $R_{Labsphere}(\lambda)$) describes the wavelength dependent absorption of the Spectralon panel, and is derived from one measurement taken at an illumination zenith angle of 8-degrees, and a view zenith angle of 0-degrees. Second, the correction is partly accounted for by use of a BRF measurement of the Spectralon panel. This BRF measurement (i.e., $L_{ref_2}(\theta_i, \phi_i, \theta_r, \phi_r; \lambda) / L_{ref_2}(\theta_i, \phi_i, \theta_r, \phi_r; \lambda)$) describes the view angle dependence of the Spectralon panel, and is derived from two sets of measurements taken at the two illumination zenith angles of 20-degrees and 40-degrees, and the view zenith angles defined by the custom-designed scan pattern shown in Figure 4.6. Therefore, the second factor in Equation 2.5 becomes $L_{ref_2}(\theta_i, \phi_i, \theta_r, \phi_r; \lambda) / L_{ref_2}(\theta_i, \phi_i, \theta_r = 0, \phi_r; \lambda) \cdot R_{Labsphere}(\lambda)$, and Equation 2.5, as a whole, is modified to:

$$BCRF(\theta_i, \phi_i, \theta_r, \phi_r; \lambda) = \frac{L_r(\theta_i, \phi_i, \theta_r, \phi_r; \lambda)}{L_{ref_1}(\theta_i, \phi_i, \theta_r, \phi_r; \lambda)} \cdot \frac{L_{ref_2}(\theta_i, \phi_i, \theta_r, \phi_r; \lambda)}{L_{ref_2}(\theta_i, \phi_i, \theta_r = 0, \phi_r; \lambda)} \cdot R_{Labsphere}(\lambda). \quad (4.9)$$

[Note: To collect a BRF measurement of the Spectralon panel, we purchased a voltage regulator and/or a power conditioner for the GRIT Laboratory which eliminated some of the current and
4.5. CONCLUDING REMARKS

voltage fluctuations that were encountered in the preliminary results of the BCRF measurements.

4.4.2 Data Visualization

The BCRF data is stored in a generic database with the information about the illumination zenith angle, illumination azimuth angle, sensor zenith angle, and sensor azimuth angle. However, in order to provide a better interpretation and comparison of the spectro-directional data, we use 2D and 3D plots. That is, we align a visualization model, coded in Python and MATLAB, respectively, to the measurement scheme. In Figure 4.10, we show the polar coordinate systems that are used to present the BCRF data.

Figure 4.10: The polar coordinate system used for presenting BCRF data in 2D plots (left), and the polar coordinate system used for presenting BCRF data in 3D plots (right).

4.5 Concluding Remarks

The main objective of the methodology chapter was to present the research strategy. Two of the limitations of this strategy, however, are in the assumptions. For example, in Equation 4.3, we assume that the particles are equant, or spherical in shape, but in the microscope picture of the test material (i.e., Figure 4.2), we can clearly see that some of the particles are elongated. Therefore, this assumption is not completely valid. Furthermore, in Equation 4.5, we assume that the particle size distribution is uni-modal with the form \( n(r) \propto r e^{-r/\bar{r}} \), but in Figure 4.11, we can also clearly see that the particle size distribution is not a perfect match to this distribution. In Figure 4.12, we demonstrate how the use of a Gaussian distribution can provide a better match.
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Figure 4.11: A plot of the assumed particle size distribution versus the actual particle size distribution of the test material.

Figure 4.12: A plot of an idealized particle size distribution versus the actual particle size distribution of the test material.
Chapter 5

Results

The results chapter is organized as follows. First, the processed data from the laboratory experiments are presented. Then, the best agreements obtained from our research strategy are presented.

5.1 Laboratory Experiments

Bulk density is an important geophysical property that influences the BRDF of particulate surfaces. The influence of bulk density on the BCRF is, therefore, extensively studied in the laboratory [8, 6, 43, 61]. In general, as the bulk density of a particulate surface is increased, the overall reflectance is also expected to increase until a threshold for the bulk density is reached, and then, the overall reflectance is expected to decrease. At this threshold, the individual particles begin to act like a single larger particle, and the overall reflectance decreases [8].

In this research, we present the BCRF data for the test material at two different illumination zenith angles, and at three different wavelengths amongst the 2,151 wavelengths collected by the spectrometer. Figures 5.1, 5.2, and 5.3 show the BCRF data of the test material in 2D plots for an illumination zenith angle of 20-degrees, and for a red, green, and blue wavelength from the spectrometer that correspond to the spectral bands of the Landsat-8 OLI satellite sensor. And, Figures 5.4, 5.5, and 5.6 show the BCRF data in 2D plots of the test material for an illumination zenith angle of 40-degrees, and for the same aforementioned wavelengths that correspond to those of the Landsat-8 OLI satellite sensor. These wavelengths are used for reasons that will become apparent in Section 6.2. As shown in these figures, the general trend seems to hold, and is very apparent in the backscatter and forward scatter directions. That is, as bulk density is increased from $1.59 \text{ g/cm}^3$ to $1.79 \text{ g/cm}^3$, the overall reflectance increases. And, as bulk density is increased from $1.79 \text{ g/cm}^3$ to $1.82 \text{ g/cm}^3$, the overall reflectance decreases. This decrease in the overall reflectance implies that a threshold for the bulk density of the test material is reached. Furthermore, as shown
in Figures 5.1, 5.2, and 5.3, the illumination zenith angle of 20-degrees produces BCRF data that are more diffuse. This is due to the fact that the impact of multiple scatter is larger at illumination zenith angles that are closer to nadir. And, as shown in Figures 5.4, 5.5, and 5.6, the illumination zenith angle of 40-degrees produces measurements of BCRF that are less diffuse in the backscatter direction, and that contain more defined lobes. But, the illumination zenith angle of 40-degrees also produces measurements of BCRF that are also more diffuse in the forward scatter direction, and in the direction perpendicular to the principal plane.

Band 4 – Red (654 nm), Illumination Zenith = 20°

\[
\begin{align*}
\rho &= 1.59 \text{ g/cm}^3 \\
\rho &= 1.66 \text{ g/cm}^3 \\
\rho &= 1.72 \text{ g/cm}^3 \\
\rho &= 1.79 \text{ g/cm}^3 \\
\rho &= 1.82 \text{ g/cm}^3
\end{align*}
\]

Figure 5.1: The BCRF data in 2D plots for the five densities at a red wavelength, and at an illumination zenith angle of 20-degrees.
Figure 5.2: The BCRF data in 2D plots for the five densities at a green wavelength, and at an illumination zenith angle of 20°.

\[ \rho = 1.59 \text{ g/cm}^3 \quad \rho = 1.66 \text{ g/cm}^3 \]

\[ \rho = 1.72 \text{ g/cm}^3 \quad \rho = 1.79 \text{ g/cm}^3 \quad \rho = 1.82 \text{ g/cm}^3 \]

Figure 5.2: The BCRF data in 2D plots for the five densities at a green wavelength, and at an illumination zenith angle of 20-degrees.
CHAPTER 5. RESULTS

Band 2 – Blue (483 nm), Illumination Zenith = 20°

Figure 5.3: The BCRF data in 2D plots for the five densities at a blue wavelength, and at an illumination zenith angle of 20-degrees.
5.1 LABORATORY EXPERIMENTS

Band 4 – Red (654 nm), Illumination Zenith = 40°

Figure 5.4: The BCRF data in 2D plots for the five densities at a red wavelength, and at an illumination zenith angle of 40-degrees.

ρ = 1.59 g/cm³

ρ = 1.66 g/cm³

ρ = 1.72 g/cm³

ρ = 1.79 g/cm³

ρ = 1.82 g/cm³

Figure 5.4: The BCRF data in 2D plots for the five densities at a red wavelength, and at an illumination zenith angle of 40-degrees.
CHAPTER 5. RESULTS

Band 3 – Green (561 nm), Illumination Zenith = 40°

ρ = 1.59 g/cm³  ρ = 1.66 g/cm³

ρ = 1.72 g/cm³  ρ = 1.79 g/cm³  ρ = 1.82 g/cm³

Figure 5.5: The BCRF data in 2D plots for the five densities at a green wavelength, and at an illumination zenith angle of 40-degrees.
5.1. LABORATORY EXPERIMENTS

Figure 5.6: The BCRF data in 2D plots for the five densities at a blue wavelength, and at an illumination zenith angle of 40°.

<table>
<thead>
<tr>
<th>Density</th>
<th>Plot 1</th>
<th>Plot 2</th>
</tr>
</thead>
<tbody>
<tr>
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<td><img src="image1.png" alt="Plot" /></td>
<td><img src="image2.png" alt="Plot" /></td>
</tr>
<tr>
<td>1.66 g/cm³</td>
<td><img src="image3.png" alt="Plot" /></td>
<td><img src="image4.png" alt="Plot" /></td>
</tr>
<tr>
<td>1.72 g/cm³</td>
<td><img src="image5.png" alt="Plot" /></td>
<td><img src="image6.png" alt="Plot" /></td>
</tr>
<tr>
<td>1.79 g/cm³</td>
<td><img src="image7.png" alt="Plot" /></td>
<td><img src="image8.png" alt="Plot" /></td>
</tr>
<tr>
<td>1.82 g/cm³</td>
<td><img src="image9.png" alt="Plot" /></td>
<td><img src="image10.png" alt="Plot" /></td>
</tr>
</tbody>
</table>

Figure 5.6: The BCRF data in 2D plots for the five densities at a blue wavelength, and at an illumination zenith angle of 40-degrees.
5.2 Finding Parameters

Consider a set of BCRF data that are collected in the principal plane. An example of this type of dataset is shown in Figure 5.7 for an illumination zenith angle of 20-degrees, and for a blue wavelength from the spectrometer that corresponds to the Landsat-8 OLI satellite sensor. Similar to the BCRF data in the 2D plots, the general trend seems to hold for the BCRF data in this plot of the principal plane. That is, as bulk density is increased, the overall reflectance increases until a threshold for the bulk density is reached, and then, the overall reflectance decreases. The same can be said for a second example that is shown in Figure 5.8. In this figure, we have an illumination zenith angle of 40-degrees, and the same aforementioned wavelength that corresponds to the Landsat-8 OLI satellite sensor. As shown in both of these figures, there is an increase in the reflectance at small phase angles. Therefore, both of these figures exhibit the opposition effect.

![Graph of Band 2 - Blue (483 nm), Illumination Zenith = 20°](image)

Figure 5.7: The BCRF data in a principal plane plot for the five densities at a blue wavelength, and at an illumination zenith angle of 20-degrees.

To find the five unknown parameters, i.e. $\phi$, $\omega$, $b$, $c$, and $B_{S0}$, we vary these parameters and minimize the RMS residual between the calculated reflectance and measured reflectance. For the fill factor, $\phi$, we vary the values between 0.59 and 0.70 at 0.01 increments. To decide on these values, we assume that,
5.2. FINDING PARAMETERS

Figure 5.8: The BCRF data in a principal plane plot for the five densities at a blue wavelength, and at an illumination zenith angle of 40-degrees.

\[
\frac{\text{min}\{\text{Bulk Density}\}}{\text{Particle Density}} \leq \phi \leq \frac{\text{max}\{\text{Bulk Density}\}}{\text{Particle Density}} \\
1.59 \, \text{g/cm}^3 \leq \phi \leq 1.82 \, \text{g/cm}^3 \\
0.6 \leq \phi \leq 0.69.
\]

And, to add some flexibility, we further assume that,

\[
0.59 \leq \phi \leq 0.70.
\]

For the single scattering albedo, \( \omega \), the values are varied between 0 and 1 at 0.01 increments. For the free parameters, \( b \) and \( c \), that describe the width and amplitude of the backward and forward lobes, respectively, the values are varied between -1 and 1 at 0.01 increments, and between -0.91 and 2.38 at 0.01 increments in accordance with the hockey stick relationship [9]. And lastly, for the amplitude of the SHOE, \( B_{SO} \), the values are varied between 0 and 1 at 0.01 increments. To minimize the RMS residual between the calculated reflectance and measured reflectance, we use a grid-search
CHAPTER 5. RESULTS

method. To refine the grid-search method, however, we assume that each fill factor is unique and
agrees with the general trend. That is, we verify that as $\phi$ increases, the overall reflectance also
increases. Furthermore, we assume that each parameter agrees with Table 4.1. Tables 5.1, 5.2,
and 5.3 show the best agreement obtained from the research strategy for an illumination angle of
20-degrees, and for the red, green, and blue wavelengths from the spectrometer that correspond
to the Landsat-8 OLI satellite sensor. And, Tables 5.4, 5.5, and 5.6 show the best agreement for
an illumination angle of 40-degrees, and for the aforementioned wavelengths from the spectrometer
that correspond to the Landsat-8 OLI satellite sensor. The RMS residual for each best agreement
is also documented. In Figure 5.9, we compare the retrieved fill factor from the best agreement to
the actual fill factors from Section 4.3.2. The average percent difference is approximately 6%. And,
in Figure 5.10 and Figure 5.11, we show the measured BCRF data, and the best agreement for
each of the five densities, in 3D plots for an illumination zenith angle of 20-degrees and 40-degrees,
respectively, and for a blue wavelength from the spectrometer that corresponds to the Landsat-8
OLI satellite sensor. In these 3D plots, the data is cosine-weighted.

<table>
<thead>
<tr>
<th>Band 4 - Red (654 nm), Illumination Zenith = 20°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk Density</td>
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<tr>
<td>---------------</td>
</tr>
<tr>
<td>1.59</td>
</tr>
<tr>
<td>1.66</td>
</tr>
<tr>
<td>1.72</td>
</tr>
<tr>
<td>1.79</td>
</tr>
<tr>
<td>1.82</td>
</tr>
</tbody>
</table>

Table 5.1: The retrieved parameters for a red wavelength and an illumination zenith angle of
20-degrees.

<table>
<thead>
<tr>
<th>Band 3 - Green (561 nm), Illumination Zenith = 20°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk Density</td>
</tr>
<tr>
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</tr>
<tr>
<td>1.59</td>
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<tr>
<td>1.66</td>
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<tr>
<td>1.72</td>
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<tr>
<td>1.79</td>
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<tr>
<td>1.82</td>
</tr>
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</table>

Table 5.2: The retrieved parameters for a green wavelength and an illumination zenith angle of
20-degrees.
## 5.2. Finding Parameters

<table>
<thead>
<tr>
<th>Band 2 - Blue (483 nm), Illumination Zenith = 20°</th>
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</thead>
<tbody>
<tr>
<td>Bulk Density</td>
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<tr>
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</tr>
<tr>
<td>1.66</td>
</tr>
<tr>
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<tr>
<td>1.79</td>
</tr>
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<td>1.82</td>
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Table 5.3: The retrieved parameters for a blue wavelength and an illumination zenith angle of 20-degrees.

<table>
<thead>
<tr>
<th>Band 4 - Red (654 nm), Illumination Zenith = 40°</th>
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<tbody>
<tr>
<td>Bulk Density</td>
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<tr>
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<tr>
<td>1.66</td>
</tr>
<tr>
<td>1.72</td>
</tr>
<tr>
<td>1.79</td>
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<tr>
<td>1.82</td>
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</table>

Table 5.4: The retrieved parameters for a red wavelength and an illumination zenith angle of 40-degrees.

<table>
<thead>
<tr>
<th>Band 3 - Green (561 nm), Illumination Zenith = 40°</th>
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</thead>
<tbody>
<tr>
<td>Bulk Density</td>
</tr>
<tr>
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</tr>
<tr>
<td>1.66</td>
</tr>
<tr>
<td>1.72</td>
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<tr>
<td>1.79</td>
</tr>
<tr>
<td>1.82</td>
</tr>
</tbody>
</table>

Table 5.5: The retrieved parameters for a green wavelength and an illumination zenith angle of 40-degrees.

<table>
<thead>
<tr>
<th>Band 2 - Blue (483 nm), Illumination Zenith = 40°</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bulk Density</td>
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<tr>
<td>1.59</td>
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<tr>
<td>1.66</td>
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<tr>
<td>1.72</td>
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<tr>
<td>1.79</td>
</tr>
<tr>
<td>1.82</td>
</tr>
</tbody>
</table>

Table 5.6: The retrieved parameters for a blue wavelength and an illumination zenith angle of 40-degrees.
CHAPTER 5. RESULTS

![Graph showing retrieved fill factors vs. density](image)

Figure 5.9: A plot of the retrieved fill factors (solid) and the actual fill factors (hollow).

Band 2 – Blue (483 nm), Illumination Zenith = 20°

![3D plots with different densities](image)

\[ \rho = 1.59 \text{ g/cm}^3 \quad \rho = 1.66 \text{ g/cm}^3 \]

\[ \rho = 1.72 \text{ g/cm}^3 \quad \rho = 1.79 \text{ g/cm}^3 \quad \rho = 1.82 \text{ g/cm}^3 \]

Figure 5.10: The measured BCRF data (black dots) and the calculated BCRF data (colored mesh) for the five densities at a blue wavelength, and at an illumination zenith angle of 20-degrees.
5.2. FINDING PARAMETERS

Band 2 – Blue (483 nm), Illumination Zenith = 40°

In Figures 5.10 and 5.11, we see that the modeled data fits the measured data quite well. However, the reader may notice that the 20-degree case appears to fit better than the 40-degree case. In actuality, the 40-degree case provides a better fit, as shown in the tables. The mechanism used to plot the reflectance functions is known to partially skew the data - making it difficult to judge error on illustration alone. Furthermore, the reader may notice that, from the tables, the 40-degree case fits better than the 20-degree case. In previous experiments, we have shown that a less nadir case tends to follow the Hapke model more so than a more nadir case [6]. This is due to the composite nature of the sand, and the fact that as the illumination zenith angle moves to a more nadir position, the multiple scattering increases.
5.3 Measuring Angular Widths

While we are able to retrieve the fill factor, and therefore, the bulk density for the test material from the BCRF data to within 6% of the actual fill factor, we still need to explore the potential to retrieve the fill factor from the angular width of the opposition effect. As discussed in our research strategy, particulate surfaces with a larger fill factor (and higher bulk density) are expected to have wider opposition effect than those with a smaller (and lower bulk density). If we normalize the reflectance in Figure 5.7 and Figure 5.8 then we can explore how the angular width changes with bulk density. These normalized plots are shown in Figure 5.12 and Figure 5.13. In these figures, as bulk density is increased from 1.59 g/cm$^3$ to 1.72 g/cm$^3$, the angular width increases. But, as bulk density is increased from 1.72 g/cm$^3$ to 1.79 g/cm$^3$, and then, from 1.79 g/cm$^3$ to 1.82 g/cm$^3$, the angular width decreases, and then increases, respectively. Therefore, the trend does not seem to hold. But, it is important to realize that, for this set of BCRF data that are collected in the principal plane, there are only nine positions from $-20 \leq g \leq 20$, and only three positions from $-5 \leq g \leq 5$. If we further increase this measurement density around the backscattered region of the solar principal plane, then we might see that the trend does hold.

![Normalized Principal Plane Plot](image)

Figure 5.12: A normalized principal plane plot for the five densities at a blue wavelength, and at an illumination zenith angle of 20-degrees.
5.4 Concluding Remarks

The main objectives of the results chapter were to present the processed data from the laboratory experiments, and to present the best agreement obtained from our research strategy. As we increase the bulk density, we expected the overall reflectance to increase until a threshold, and then we expected the overall reflectance to decrease. As shown in Figures 5.7 and 5.8, this general trend held. However, the change in the overall reflectance across the bulk densities was less than 10%. Due to this small change in the overall reflectance, we conclude that it may be difficult for many remote sensing platforms to accurately retrieve bulk density from the opposition effect. For those interested in creating a platform that can retrieve the bulk density, it is important to realize that a 15% change in the bulk density amounted to approximately a 7% change in the overall reflectance. Therefore, it is critical that the platform’s overall radiometric error be kept to a minimum.

In this research, to find the bulk density, we measured the radiance of the same point on the target at many different view angles. The reader may wonder if the bulk density can be retrieved from one hyperspectral image of the target. While it may be possible, it is important to realize that it depends on the radiometric accuracy of the remote sensing platform, the ground sample distance of the platform, and the spatial uniformity of the target. And, while assumptions can be made to
allow this to be feasible, a second image can provide an increase in the accuracy of the retrieval. This is because when we add a second image, we increase the amount of view angles available of representative pixels. Furthermore, datasets with more than one image can provide a decrease in the impact of the spatial uniformity assumption.
Chapter 6

Conclusion

This research has explored the use of the opposition effect in remotely sensed data to assist in the retrieval of bulk density. The approach taken has focused on measuring the BRDF of a sand surface collected from the Algodones Sand Dunes Systems at various bulk densities in a laboratory setting, and modeling the measured BRDF using the Hapke model to retrieve bulk density. The conclusion chapter is organized as follows. First, we summarize the key contributions of this research, and then we provide some suggestions for future investigation related to this work.

6.1 Contributions

6.1.1 Air Pluviation Device

In Chapter 4, we demonstrated the importance of sample preparation with repeatable and uniform densities. There were a number of different methods considered. But, in the end, we decided to use the most widely accepted method — sample preparation by air pluviation. In order to use this method, an air pluviation device needed to be custom-designed and constructed. The design of the air pluviation device was inspired by the one constructed by Miura and Toki [55]. And, for use by other institutions, the parts list and assembly photographs for the air pluviation device are presented in Appendix A. The samples that were prepared with the air pluviation device and a sand surface collected from the Algodones Dunes Sand System had bulk densities ranging from 1.59 g/cm$^3$ to 1.82 g/cm$^3$, and were representative of those found in nature.

6.1.2 Set of BCRF Measurements

In Chapter 5, we designed a set of laboratory experiments to measure the BCRF of a sand surface from the Algodones Sand Dunes System at various bulk densities, illumination zenith angles, and
wavelengths. To collect these measurements, we used the GRIT-T and a custom-designed scan pattern that had a higher measurement density at small phase angles near the opposition effect. The bulk densities were estimated to be 1.59 g/cm$^3$, 1.66 g/cm$^3$, 1.72 g/cm$^3$, 1.79 g/cm$^3$, and 1.82 g/cm$^3$.

The artificial light source was placed at illumination zenith angles of 20-degrees and 40-degrees with respect to nadir. And, the spectroradiometer onboard the GRIT-T had a spectral range of 350-2500 nm, and a spectral sampling bandwidth of 1.4 nm from 350-1000 nm and 1.1 nm from 1001-2500 nm. Due to the spectral resolution of the spectroradiometer, we were able to measure at 2151 contiguous wavelengths. Following the data processing, this set of BCRF measurements was one of the cleanest datasets that we have seen to date.

### 6.1.3 Constrained Method for Finding Parameters of the Hapke Model

Also, in Chapter 4, we described a constrained method for finding the parameters of the Hapke model. We measured the samples with an identical scan pattern for the two aforementioned illumination zenith angles, and used three representative wavelengths from the 2151 contiguous wavelengths collected by the spectrometer. Then, we were able to constrain two parameters - the fill factor and the scattering albedo. If there were changes in illumination zenith angle and wavelength, then the fill factor did not change. This made sense because the fill factor was a geophysical property of the sample. Furthermore, if there were changes in illumination zenith angle, then the single scattering albedo did not change. The same, however, could not be said if there were changes in wavelength. This constrained method allowed for the retrieval of bulk density to within 6% of the actual bulk density.

### 6.1.4 Validation of the DIRSIG Model

In Appendix A, we conducted a study to assess our ability to simulate satellite sensor data with the DIRSIG model. For the Landsat-8 satellite sensor, the results showed error from approximately 3-6% for the red, green, and blue bands. And, the worst match between the data from real images and the data from simulated images was in the opposition direction. This was because the Ross-Li BRDF model used in DIRSIG did not account for the opposition effect. In the end, we concluded that we could adequately simulate satellite sensor data for the Landsat-8 OLI satellite sensor.

### 6.1.5 Vicarious Calibration Field Experiment

In Appendix C, we described the geotechnical data from a field experiment at the Algodones Sand Dunes System. We described the GPS data, the in-place bulk densities, the moisture contents, and the particle size distributions for the locations where we obtained sediment samples. In September
2016, the data from this field experiment appeared in a SPIE Proceedings titled Volume 9972, Earth Observing Systems XXI, Algodones Field Campaign.

6.2 Future Work

6.2.1 Improvement of the Research Strategy

In Chapter 4, we assume that the particle size distribution of the test material is uni-modal with the form \( n(r) \propto r^{e/r} \). As previously discussed, this is not necessarily the best assumption. A Gaussian distribution, is therefore, proposed to model the particle size distribution of the test material, as it provides a better match. In order to assume that the particle size distribution is uni-modal with a Gaussian form, the angular width of the SHOE must be evaluated following a derivation similar to that found in Hapke [63]. An alternative strategy would be to assume that the angular width of the SHOE has the form as \( h_s = \epsilon K \phi \), where \( \epsilon \) is a free parameter. Here, the \( \epsilon \) resolves the issue of finding an accurate description of the particle size distribution, and therefore an accurate description of the angular width of the SHOE, but adds a sixth parameter to the list of unknown parameters that must be optimized in the Hapke model.

6.2.2 Improvement of the DIRSIG Model

The Digital Imaging and Remote Sensing Image Generation (DIRSIG) model uses open source geometry repositories and first principle radiometric solvers to generate simulated scenes [64]. In the DIRSIG 4 model, the MODIS BRDF product, in conjunction with the Ross-Li model [7], has been used to model anisotropic reflectance. However, as shown in the preliminary study discussed in Appendix A, this combination of model assumptions does not adequately model the opposition effect. This is further shown in Figure 6.1. First, we use the coefficients from the MODIS BRDF product to produce a BRDF using the Ross-Li model. Next, we use the retrieved parameters from Chapter 5 to produce a BRDF using the Hapke model. Then, in comparison, we show that the Ross-Li model does not adequately model the opposition effect. Given that the opposition effect is related to the bulk density, an accurate description of this increase in the reflectance is required to assist in the retrieval of bulk density. A physical model, such as the Hapke model is, therefore, proposed to model the anisotropic reflectance. Unfortunately, a requirement of the DIRSIG 4 model is to use one of the “pre-implemented” models, and the Hapke model is not present in this version. But, as of April 2017, the DIRSIG 5 model was released, and is data-driven. Therefore, any model can be “implemented”. In future investigations, the preliminary study should be repeated for the Hapke model.
CHAPTER 6. CONCLUSION

Figure 6.1: A side-by-side comparison of the Ross-Li BRDF model ($c_{iso} = 0.167$, $c_{vol} = 0.058$, and $c_{geo} = 0$) and the Hapke model ($\phi = 0.59$, $\omega = 0.36$, $b = 0.00$, $c = 2.38$ and $B_{S0} = 0.97$) for an illumination zenith angle of 40-degrees, and for the blue band from the spectrometer that corresponds to the Landsat-8 OLI satellite sensor.
Appendix A

Preliminary Study

In the preliminary study appendix, we assess our ability to simulate satellite sensor data with the Digital Imaging and Remote Sensing Image Generation (DIRSIG) tool [64]. To start, we create a synthetic landscape of a scene by facetizing the terrain, assigning the material spectra, and assigning the BRDF properties. Next, we run simulations of that synthetic landscape for a satellite sensor and its associated viewing geometries. Then, we compare the radiance observed in real images to the radiance observed in simulated images from DIRSIG. For this preliminary study, we create a synthetic landscape of the Algodones Sand Dunes System, and we simulate satellite sensor data of the Landsat-8 OLI satellite sensor for one entire year. A detailed description of the methodology is discussed, and a complete assessment of the results is presented.

A.1 Methodology

A.1.1 Create a Synthetic Landscape of a Scene

To create a synthetic landscape of a scene in DIRSIG, we used the Scene Construction Tool described by Gerace et al. [65]. First, we obtained the four sources of data needed to describe the landscape, i.e. elevation data, high-resolution data, spectral data, and BRDF data. The elevation data was used to facetize the geometric properties of the terrain. The high-resolution data was used to classify, and to provide texture to, the materials. The spectral data was used to describe the spectra of those materials. And, the BRDF data was used to introduce the BRDF properties to that terrain. Once we had all of these sources of data, we used the Environment for Visualizing Images (ENVI) software application to layer stack them. This output from ENVI contained only the extent where all of the sources of data overlapped, and it was provided to the Scene Construction Tool as input.
To create a synthetic landscape of the Algodones Sand Dunes System, we facetized the terrain by using a 2-meter digital elevation model generated by NASA Goddard’s LiDAR, Hyperspectral, and Thermal (G-LiHT) imager [66]. The elevation data collected by G-LiHT were obtained from a field experiment in March 2015 at the Algodones Sand Dunes System [16, 61, 67, 68, 69]. This field experiment is discussed in Appendix C. We classified, and provided texture to, the materials by using 1-meter National Agriculture Imagery Program (NAIP) data obtained from EarthExplorer ([http://earthexplorer.usgs.gov](http://earthexplorer.usgs.gov)). To classify the materials, we performed a mosaic and a k-means clustering on the NAIP data. To provide texture, we selected one of the NAIP bands that best represented the texture of the Algodones Sand Dunes System. We described the material spectra by using hyperspectral measurements of sand collected from the Algodones Sand Dunes System [16, 61]. The spectral data were obtained from the GRIT Laboratory using an Analytical Spectral Devices (ASD) FieldSpec 4 Hi-Res spectroradiometer, and are included in a spectral data image file. To account for spatial-spectral variations in the material, we applied noise to the image file. Lastly, we introduced BRDF properties of the terrain by using MODIS BRDF data in conjunction with the Ross-Li capability in DIRSIG. Similar to the NAIP data, the MODIS BRDF data were obtained from EarthExplorer. Figure A.1 shows the sources of data that were provided to the Scene Construction Tool as input.

A.1.2 Create Simulated Images

To create simulated images in DIRSIG, we provided the model with the geographic location of the synthetic landscape, an estimate of the atmospheric conditions, the imaging platforms, the platform orientations, and the reference dates and times. For the Algodones Sand Dunes System, we defined the geographic location as the center point of the landscape, i.e. 32° 52’ 58.44” N and 115° 1’ 8.4” W. The atmospheric conditions were estimated using a mid-latitude summer profile, a desert aerosol, and a default visibility of 23-kilometers. The imaging platform simulated the spectral response functions of the red, green, and blue bands of the Landsat-8 OLI satellite sensor. Therefore, the imaging platform had a spatial resolution of 30-meters. The platform orientations, and the reference dates and times, corresponded to the real geometries of the Landsat-8 OLI satellite sensor. For the simulations, we obtained cloud-free images for the entire year of 2014. The images that we obtained are shown in Table A.1. Once the simulations were defined, we ran DIRSIG and spectrally resampled the outputs with the relative spectral response function of the Landsat-8 OLI satellite sensor. Then, we averaged the middle 50×50 pixels in each of the simulated images, and we compared the result to the corresponding area in each of the real images.
A.2 Results

In the following figures, the data from the real images are indicated with colored markers, i.e. red, green, and blue markers, and the data from the simulated images are indicated with black markers. Figures A.2, A.3, and A.4 show the results for the red, green, and blue bands of the Landsat-8 OLI satellite sensor. Here, we note that the Algodones Sand Dunes System was located in an area that includes two adjacent scenes from the Landsat-8 OLI satellite sensor. Thus, for a particular scene, we assumed that the sensor zenith and sensor azimuth remained constant for the entire year in which we obtained data. And, when we defined the simulations, we only needed to define two platform geometries. If we conduct a visual comparison of the data, then we notice that, apart from days 130 - 170, the data from the simulated images follow the overall shape of the data from the real images. From days 130 - 170, we notice an increase in the reflectance in the data from the real images. If this increase in the reflectance occurs at small phase angles, then it is known as the opposition effect. The phase angle is defined as the angle between the source, the surface, and the sensor [8]. Figure A.5 shows the phase angles for the entire year in which we obtained data. From this figure, we notice that from days 130 - 170, the phase angles are near the
minimum phase angle achieved for each scene. Thus, these days represent the opposition direction. The Ross-Li capability in DIRSIG does not account for the opposition effect, so this discrepancy is somewhat expected. If we conduct a mathematical comparison of the data, then we notice that for the red, green, and blue bands, the percentage differences are 5.94%, 3.02%, and 4.49%, respectively.

<table>
<thead>
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<th>List of Cloud-Free Images from Landsat-8 OLI</th>
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<tr>
<td>1. DOY: 003, TOD: 1811</td>
</tr>
<tr>
<td>2. DOY: 010, TOD: 1817</td>
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</tbody>
</table>

Table A.1: A list of cloud-free images obtained from the Landsat-8 OLI satellite sensor for a particular day of year (DOY), and for a particular time of day (TOD).
A.2. RESULTS

Figure A.2: A comparison of Landsat-8 OLI satellite sensor and DIRSIG for the red band.

Figure A.3: A comparison of Landsat-8 OLI satellite sensor and DIRSIG for the green band.
Figure A.4: A comparison of Landsat-8 OLI satellite sensor and DIRSIG for the blue band.

Figure A.5: The phase angles of Landsat-8 OLI satellite sensor.
A.3 Concluding Remarks

For this preliminary study, we assessed our ability to simulate satellite sensor data with the DIRSIG model. First, we described how to create synthetic landscapes of generic scenes, and of the Algodones Sand Dunes System. Next, we described how to create simulated images. Then, we tested our ability by comparing the radiance observed in real images to the radiance observed in simulated images. From the visual comparisons that we conducted for the Landsat-8 satellite sensor, we conclude that the worst match between the data from the real images and the data from the simulated images is in the opposition direction. This is because the Ross-Li BRDF model used in DIRSIG does not account for the opposition effect. The results showed errors from approximately 3 - 6%. In the modeling world, errors on the order of 1% are extremely difficult to achieve, and in many cases errors of up to 10% are considered adequate [70]. If we consider this, and the fact that we did not precisely characterize the atmosphere conditions for each simulation, then we conclude that we can adequately simulate satellite sensor data for the Landsat-8 OLI satellite sensor.
Appendix B

Air Pluviation Device

In the air pluviation device appendix, the parts list and assembly photographs for the air pluviation device constructed in Figure B.1 are presented. Some of the parts are designed in Autodesk Inventor and built using a Form 1+ SLA 3D Printer.

Figure B.1: The air pluviation device.
APPENDIX B. AIR PLUVIATION DEVICE

B.1 Parts List

B.1.1 Electrical Box

1. Regulated Switching Power Adapter (Adafruit: 798)
2. CUI Inc., Power Barrel Connector Jack Panel Mount (DigiKey: CP-033A-ND)
3. Eaton, Fuse Holder Panel Mount (DigiKey: 283-2717-ND)
4. Eaton, Cartridge Fuse (DigiKey: 283-2634-ND)
5. TE Connectivity, Circular Connector Receptacle Housing Panel Mount (DigiKey: A1360-ND)
6. TE Connectivity, Circular Connector Plug Housing Coupling Nut (DigiKey: A1357-ND)
7. TE Connectivity, Sealing Boot (DigiKey: A16046-ND)
8. ON Semiconductor, Standard Diode (DigiKey: 1N4004GOS-ND)
9. Bulgin, Rocker Switch Panel Mount (DigiKey: 1091-1069-ND)
10. Electrical Box (Figure B.2)
11. Electrical Box Lid (Figure B.3)

B.1.2 Physical Structure

1. Single Rail (McMaster-Carr: 47065T103)
2. Fixed Height Mounting Foot (McMaster-Carr: 47065T843)
3. 90 Degree Plate (McMaster-Carr: 47065T271)
4. 90 Degree Bracket (McMaster-Carr: 47065T833)
5. Diagonal Brace (McMaster-Carr: 47065T12)
6. Sleeve Bearing Carriage Side Mount (McMaster-Carr: 60585K33)
7. Hand Brake (McMaster-Carr: 60585K32)
8. Thermaflex, S-TL Flexible Air Duct (Global Industries: B35693)
B.1.3 Hopper with Hinged Door

1. Standard-Wall White PVC Pipe Fitting (McMaster-Carr: 48925K26)
2. Standard-Wall White PVC Pipe Fitting Cap (McMaster-Carr: 4880K142)
3. Miniature Magnetic Lock Mount (Figure B.4)
5. Hinged Door (Figure B.5)
6. Surface-Mount Hinge (McMaster-Carr: 1549A57)
7. Hinge Mount (Figure B.6)
8. Hopper Mount (Figure B.7)

B.1.4 Sieve Platform

1. Oversized Multipurpose 6061 Aluminum (McMaster-Carr: 89155K115)
2. Dimensions for the Sieve Platform (Figure B.8)
3. ASTM Sieves (Humboldt: H-3920CS1.000 and H-3920CS.375)

Figure B.2: The electrical box with panel mount openings for the power jack, the fuse holder, the connector for the miniature magnetic lock, and the rocker switch.
APPENDIX B. AIR PLUVIATION DEVICE

Figure B.3: The lid for the electrical box.

Figure B.4: The mount for the miniature magnetic lock.

Figure B.5: The hinged door for the hopper.
Figure B.6: The mount for the hinge.

Figure B.7: The mount for the hopper.

Figure B.8: The platform for the stack of sieves.
B.2 Assembly Photographs

Figure B.9: The inside of the electrical box.
Figure B.10: The outside of the electrical box.
Figure B.11: The hopper with the miniature magnetic lock and hinged door attached. The hopper is attached to the single rails using the mount for the hopper. The mount is attached on the back of the hopper, and on the sleeve bearing carriage side mounts.
Figure B.12: The stack of sieves on the sieve platform.
Appendix C

Algodones Dunes Field Experiment

In the Algodones Dunes Field Experiment appendix, the data collected during the field experiment are organized. These data include the GPS data, the in-place bulk densities, the moisture contents, and the particle size distributions.

Figure C.1: A photo of the NASA G-LiHT imager flying over the GRIT during the Algodones Dunes Field Experiment.

Figure C.1: A photo of the NASA G-LiHT imager flying over the GRIT during the Algodones Dunes Field Experiment.
C.1 Test Site: Algodones Sand Dunes System

The Algodones Sand Dunes System (32° 52' 58.44" N, 115° 1' 8.4" W) is a large erg that is located in the southeast corner of California. The erg is 64 kilometers long and 10 kilometers wide, and it is positioned on a line that extends from the northwest to the southeast [71]. The west side of the erg has the largest dunes composed of relatively coarse sand, and the east side of the erg has the smaller dunes composed of relatively finer sand. The sand throughout the erg contains quartz, feldspar, rock fragments, and heavy minerals (e.g. magnetite, epidote, zircon, biotite, garnet, tourmaline, and hornblende). The quartz is 70 – 80% of the composition, the feldspar is 10 – 15%, the rock fragments are 5 – 15%, and the heavy minerals are less than one percent [60]. The climate of the erg is arid with an average annual temperature of 75.4°F and an average annual precipitation of 114 mm. A Google Earth image of the Algodones Sand Dunes System is located in Figure C.2.

Figure C.2: A Google Earth image of the Algodones Sand Dunes System.

C.2 Description of the Field Experiment

In March 2015, our research group was involved in a field experiment at the Algodones Sand Dune System [16, 61, 67, 68, 69]. The field experiment was a three-day campaign that involved four other
research groups from South Dakota State University, the University of Arizona, the University of Lethbridge, and the NASA Goddard Space Flight Center. The purpose of the field experiment was to characterize the BRDF of the Algodones Sand Dunes System in order to build accurate models for improved satellite sensor inter-calibration, and to test calibration transfer techniques between airborne instruments, field instruments, and laboratory instruments.

C.3 Data from Sand Sample Collections

During the field experiment, airborne measurements from the NASA G-LiHT imager were coordinated with ground-based measurements of hyperspectral BRDF data, as shown in Figure C.1. The research group from RIT, i.e. our research group, collected hyperspectral BRDF data of the erg’s surface with the GRIT. In addition to the hyperspectral BRDF data that were collected, our research group obtained in-situ densities and sediment samples from locations where hyperspectral BRDF data were measured, and sediment samples from locations that extended beyond the scope of the campaign. The latter set of sediment samples was obtained to further the analysis of the Algodones Sand Dunes System, following the experiment, with laboratory-based measurements. These sediment samples consisted of the top 1-inch layer of the sediment. The GRIT collected measurements of BRDF at six different locations: BC01-01, BC01-02, BC02-01, BC02-02, BC03-01, and BC03-03. These six locations are shown on the left-hand-side of Figure C.3 with a white-colored font. The additional in-situ densities and sediment samples were obtained from ten different locations that were to the northeast and to the southeast of the original locations. These ten locations are shown on the right-hand-side of Figure C.3 with a red-colored font and a blue-colored font, respectively. The latitude and longitude for each location is shown in Table C.1. The in-place bulk density is shown in Table C.2. The moisture content is shown in Table C.3. And, the particle size distribution for sediment collected at each location is shown in Figure C.4.
Figure C.3: A Google Earth image with GPS markers for where the GRIT collected HCRF measurements (white-colored font), and for where our research collected sediment samples that extended beyond the scope of the campaign (red-colored font and blue-colored font).
### GRIT GPS Locations

<table>
<thead>
<tr>
<th>Site Code</th>
<th>Latitude</th>
<th>Longitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>BC01-01</td>
<td>32° 55’ 8.25” N</td>
<td>115° 7’ 2.42” W</td>
</tr>
<tr>
<td>BC01-02</td>
<td>32° 55’ 9.47” N</td>
<td>115° 7’ 0.06” W</td>
</tr>
<tr>
<td>BC02-01</td>
<td>32° 54’ 54.77” N</td>
<td>115° 6’ 33.03” W</td>
</tr>
<tr>
<td>BC02-02</td>
<td>32° 54’ 55.35” N</td>
<td>115° 6’ 33.91” W</td>
</tr>
<tr>
<td>BC03-01</td>
<td>32° 54’ 55.07” N</td>
<td>115° 6’ 34.76” W</td>
</tr>
<tr>
<td>BC03-02</td>
<td>32° 54’ 53.98” N</td>
<td>115° 6’ 34.26” W</td>
</tr>
</tbody>
</table>

### Sediment Sample GPS Locations (Northeast of the GRIT)

<table>
<thead>
<tr>
<th>Site Code</th>
<th>Latitude</th>
<th>Longitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>1040-M-01-T</td>
<td>32° 56’ 18.00” N</td>
<td>115° 5’ 12.00” W</td>
</tr>
<tr>
<td>1101-M-01-M</td>
<td>32° 56’ 17.00” N</td>
<td>115° 5’ 10.00” W</td>
</tr>
<tr>
<td>1112-M-01-B</td>
<td>32° 56’ 16.00” N</td>
<td>115° 5’ 10.00” W</td>
</tr>
<tr>
<td>1202-M-02</td>
<td>32° 56’ 33.00” N</td>
<td>115° 3’ 25.00” W</td>
</tr>
<tr>
<td>1306-M-03</td>
<td>32° 58’ 45.00” N</td>
<td>115° 7’ 47.00” W</td>
</tr>
</tbody>
</table>

### Sediment Sample GPS Locations (Southeast of the GRIT)

<table>
<thead>
<tr>
<th>Site Code</th>
<th>Latitude</th>
<th>Longitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>0842-T-1</td>
<td>32° 52’ 16.00” N</td>
<td>115° 4’ 25.00” W</td>
</tr>
<tr>
<td>0903-T-2</td>
<td>32° 52’ 21.00” N</td>
<td>115° 4’ 21.00” W</td>
</tr>
<tr>
<td>0922-T-3</td>
<td>32° 52’ 34.00” N</td>
<td>115° 4’ 9.00” W</td>
</tr>
<tr>
<td>0935-T-4</td>
<td>32° 52’ 34.00” N</td>
<td>115° 4’ 9.05” W</td>
</tr>
<tr>
<td>0947-T-5</td>
<td>32° 52’ 34.00” N</td>
<td>115° 4’ 9.10” W</td>
</tr>
</tbody>
</table>

Table C.1: The latitude and longitude for each location that the research group from RIT collected sediment samples during the Algodones Dunes Field Experiment.
### In-Place Bulk Density

<table>
<thead>
<tr>
<th>Site Code</th>
<th>Wet Density [g/cm³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>BC01-01</td>
<td>1.96</td>
</tr>
<tr>
<td>BC01-02</td>
<td>2.25</td>
</tr>
<tr>
<td>BC02-01</td>
<td>2.18</td>
</tr>
<tr>
<td>BC02-02</td>
<td>2.81</td>
</tr>
<tr>
<td>BC03-01</td>
<td>2.02</td>
</tr>
<tr>
<td>BC03-02</td>
<td>2.19</td>
</tr>
</tbody>
</table>

Table C.2: The in-place bulk density for each location that the GRIT collected HCRF measurements during the Algodones Dunes Field Experiment.

### Moisture Content

<table>
<thead>
<tr>
<th>Site Code</th>
<th>Moisture Content [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>BC01-01</td>
<td>0.30</td>
</tr>
<tr>
<td>BC01-02</td>
<td>0.12</td>
</tr>
<tr>
<td>BC02-01</td>
<td>0.06</td>
</tr>
<tr>
<td>BC02-02</td>
<td>0.91</td>
</tr>
<tr>
<td>BC03-01</td>
<td>0.32</td>
</tr>
<tr>
<td>BC03-02</td>
<td>0.22</td>
</tr>
<tr>
<td>1040-M-01-T</td>
<td>0.71</td>
</tr>
<tr>
<td>1101-M-01-M</td>
<td>0.54</td>
</tr>
<tr>
<td>1112-M-01-B</td>
<td>0.83</td>
</tr>
<tr>
<td>1202-M-02-B</td>
<td>3.11</td>
</tr>
<tr>
<td>1306-M-03-B</td>
<td>0.24</td>
</tr>
<tr>
<td>0842-T-01</td>
<td>0.17</td>
</tr>
<tr>
<td>0903-T-02</td>
<td>0.18</td>
</tr>
<tr>
<td>0922-T-03</td>
<td>0.16</td>
</tr>
<tr>
<td>0935-T-04</td>
<td>0.12</td>
</tr>
<tr>
<td>0947-T-05</td>
<td>0.05</td>
</tr>
</tbody>
</table>

Table C.3: The moisture content for each location that the research group from RIT collected sediment samples during the Algodones Dunes Field Experiment.
Figure C.4: The particle size distributions for sediment collected at each location that the GRIT collected HCRF measurements.
Figure C.5: The particle size distributions for sediment collected at each location that extended beyond the scope of the campaign.
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