THE BIDIRECTIONAL REFLECTANCE DISTRIBUTION FUNCTION AND ALBEDO ANALYSIS FOR VARIOUS LAND-COVER TYPES IN THE MIDWESTERN UNITED STATES FOR THE TEMPO SATELLITE

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CHAPTER 1. INTRODUCTION

The multipurpose satellite, Tropospheric Emissions Monitoring of Pollution (TEMPO) will be launched between 2017-2020 to measure the components of air quality including concentrations of ozone, sulfur dioxide, nitrogen dioxide, formaldehyde, and varying aerosols (Zoogman et al. 2017). With an hourly temporal resolution, the TEMPO satellite will provide an opportunity to monitor air quality over North America (NASA 2015). TEMPO observed spectral signatures of atmospheric chemistry are affected by radiant energy reflected from Earth surface so the retrieval of atmospheric gases require a detailed understanding of surface bidirectional reflection distribution function (BRDF) or spectral albedo. Spectral features relate to three basic components: atmospheric absorption and transmittance, surface reflectivity, and emitted radiance component from land surface objects (e.g., fluorescence radiance from vegetation) (Joiner et al. 2013). By separating these spectral features, the total reflectance can be calculated, as seen in equation 1 below.

\[
\rho_{tot}(\lambda) = \rho_s(\lambda) + T(\lambda)\bar{T}(\lambda) + \left(\frac{\pi F_s(\lambda)T(\lambda)}{E(\lambda)\cos(\theta_0)}\right)
\]  

where \(\rho_s(\lambda)\) is the surface reflectance, \(T\) is the total irradiance transmittance, \(\bar{T}\) is the spherical transmittance from the surface back to the TOA, \(\theta_0\) is the solar zenith angle, \(E(\lambda)\) is the observed extraterrestrial solar irradiance, and \(F_s\) is the radiance emission from fluorescence at the surface (Joiner et al. 2013).

The analysis of BRDF, albedo, and land-cover and land-use (LCLU) change is a major research topic in Earth remote sensing due to its influence on climate and importance for retrieval of trace gas measurements from planned geostationary satellites, i.e., TEMPO. Land-cover and land-use influences climate directly through properties such as reflectance/albedo and
the amount of water discharged from soils to the atmosphere (Jones et al. 2015). The bidirectional reflectance distribution function (BRDF) demonstrates the angular distribution of radiance reflected by an illuminated surface (Nicodemus et al. 1977a), which is used to characterize directional reflectance signatures of different types of land-cover. If we know the BRDF and the downwelling solar irradiance, we can calculate the spectral albedo of a target.

The Geostationary Trace gas and Aerosol Sensor Optimization (Geo-TASO) flight instrument was originally created to test the air quality measurements for the Geostationary Coastal and Air Pollution events (Geo-CAPE), but has since become a “precursor test-bed” for the TEMPO satellite (Larkin 2013). The Geo-TASO flight instrument was flown onboard the NASA HU-25C Falcon aircraft to collect data over the St. Louis Metropolitan area on August 13, 2014.

The objective of this research is to develop a spectral database of various LCLU and ground targets found in Midwestern United States using in-situ and airborne Geo-TASO derived spectral albedo and BRDF at TEMPO spectral profiles, which are necessary for the accurate retrieval of tropospheric trace gases and aerosols. The final product of this research is a high resolution spectral database and detailed BRDF characterization of various land-cover types that can be used for further analysis of emissions and air quality using TEMPO.

1.1 Terminology

The following presented definitions are listed to help understand reflectance quantities based off the terminology present in Gatebe and King (2016), Zoogman, et al. (2016), Liang et
1.1.1 Radiance and Reflectance

Radiance is the radiant flux, or energy, emitted, reflected, or transmitted in a specific direction towards a remote sensor, such as a satellite or airplane, and is expressed in the SI units [W m$^{-2}$ sr$^{-1}$ nm$^{-1}$]. Before the radiance can reach the remote sensor, it interacts with a variety of gases, water vapor and particulates in the atmosphere (Liang et al. 2012). Irradiance is defined as the incoming solar flux or downwelling solar irradiance; the irradiance is the energy received by an object per unit of area at all directions (Nicodemus et al. 1977b). The target radiance is the reflected radiance off an object. The reflectance of an object is taken from the ratio of target radiance to the irradiance. The reflectance is solely inclusive to values between 0 and 1 and can be seen along the electromagnetic spectrum as spectral signatures.

1.1.2 The Bidirectional Reflectance Distribution Function (BRDF)

According to the United States National Institute of Standards and Technology (NIST), the BRDF is the single parameter used for describing the reflectance properties of an object (Nicodemus et al. 1977b). The BRDF is the estimated radiance from one particular direction to another particular direction. The mathematical equation for the BRDF can be expressed as $f_r$ in Equation 2 below.

$$f_r(\theta_i, \phi_i; \theta_r, \phi_r) = \frac{dL_r(\theta_i, \phi_i; \theta_r, \phi_r; E_i)}{dE_i(\theta_i, \phi_i)}$$ (2)
where \( dL_r(\theta_i, \varphi_i, \theta_r, \varphi_r; E_i) \) is the reflected radiance in an outgoing direction, \((\theta_r, \varphi_r)\), and \( dE_i(\theta_i, \varphi_i) \) is the target’s incident irradiance in the incoming direction \((\theta_i, \varphi_i)\). \((\theta_i, \theta_r)\) represents the change in the viewing azimuth angle in relation to the sun direction. \((\varphi_i, \varphi_r)\) represent the azimuth angle and can be measured through the incident beam of light (Gatebe and King 2016).

Since the BRDF can never be directly measured because the angles of radiance do not have a measurable amount of radiant flux, simulations must be done to calculate the BRDF of an object. When the parameters of an object change, such as sun direction and satellite location, the BRDF will also change.

### 1.1.3 Reflectance factor

The reflectance factor is the closest measurable physical quantity to the BRDF and is calculated by taking the ratio of the reflected light to the amount of light reflected from a diffuse white surface (Gatebe and King 2016). The amount of light reflected from the diffuse white surface is the best possible reflectance at a specific point of time. The reflectance factor differs from the BRDF for the fact that reflectance factor does not account for the angular dependence of reflected or emitted radiance, which can be larger than one. In order to calculate the BRDF of an object, the reflectance factor is divided by \( \pi \) assuming the surface is Lambertian (Schaepman-Strub et al. 2006). A Lambertian surface is a surface where reflected radiant flux is constant at any angle throughout the surface (Jensen 2009).
1.1.4 Albedo

The albedo of an object is defined as a ratio of upwelling to downwelling solar irradiance at the surface of an object and describes how much energy is reflected and/or absorbed by an object (Ghulam et al. 2007). Albedo can be derived from field collected measurements using a linear weighting combination of both white sky albedo and black sky albedo (Liu et al. 2010). A white sky albedo is present when the diffuse factor is isotropic and there is an absence of a parallel light rays. The black sky albedo is a function of the solar zenith angle and is the albedo in the lack of a diffuse component. Both white sky albedo and black sky albedo are spectral albedos. Spectral albedo is expressed in relation to the wavelength and the geometry of the downwelling solar irradiance. The albedo of a specific spectral band can be calculated by combining the spectral albedo over a specific wavelength range and weighting it by the downwelling solar irradiance for that wavelength range (Liang, Li and Wang 2012). Broadband albedo is the general term for shortwave albedo, visible albedo, and near-infrared albedo. These specific albedo regions are wavelength dependent. The most common broadband albedo is shortwave albedo since solar radiation is mostly distributed in the shortwave region. Shortwave albedo is the albedo over the shortwave bands between 250 nm and 500 nm (Liang et al. 2012).

1.1.5 Ross-Li BRDF Model

The Ross-Li BRDF model uses three parameters and a kernel statistical model to calculate the BRDF of objects. The first parameter is an isotropic parameter ($f_{iso}$), which describes the nadir bidirectional reflectance, the second is a volumetric scattering parameter ($f_{vol}$), and the third is a geometric optics parameter ($f_{geo}$) (Wang et al. 2004). Similarly, the three kernel
coefficients used are the isotropic kernel, geometric kernel, and volumetric scattering kernel. The geometric kernel is a scattering component looks at the geometrical structure of opaque reflectors and shadows by assuming the subpixel surface contains identical protrusions. The protrusions are modeled by a vertical wall of height, width, and length. The volumetric scattering kernel estimates the volume scattering component (Roujean, Leroy and Deschamps 1992). The parameters and kernels coefficients work together to make the Ross-Li BRDF model shown in Equation 3 below.

$$BRDF(\theta_i, \theta_v, \phi, \lambda) = f_{iso}(\lambda) + f_{geo}(\lambda)k_{geo}(\theta_i, \theta_v, \phi) + f_{vol}(\lambda)k_{vol}(\theta_i, \theta_v, \phi)$$ (3)

where $BRDF(\theta_i, \theta_v, \phi, \lambda)$ is the BRDF, $k_{geo}(\theta_i, \theta_v, \phi)$ is the geo-optical scattering kernel, $k_{vol}(\theta_i, \theta_v, \phi)$ is the volumetric scattering kernel, $\phi$ is the solar relative azimuth angle, $\theta_i$ is the incident solar zenith angle, $\theta_v$ is the reflected solar zenith angle, and $f_{iso}(\lambda), f_{geo}(\lambda), f_{vol}(\lambda)$ are the kernel coefficients for the isotropic, geometric, and volumetric scattering (Liu et al. 2010).
CHAPTER 2. LITERATURE REVIEW

Very early on, albedo of various land cover types were studied in order to study the earth’s energy exchange with the sun, atmosphere, and its surface and the effects various plants have on the earth’s albedo (Gates and Tantrapron 1952). Bray et al. (1996) studied crop health with the use of albedo and chlorophyll-a and chlorophyll-b content by researching lowland and upland surface albedo in Central Minnesota (Bray, Sanger and Archer 1966). With slight differences between the albedo of the lowland mesic savannah and the upland forest, it was clear that light saturation influences chlorophyll content. The canopy reflectance of prairie grass, sorghum, wheat, soybeans, and forest communities were studied by Drake (1976) to show the reflectance of vegetation declines in the red region (656 - 705 nm) and increases in the near-infrared region (776 – 826 nm) of the electromagnetic spectrum. By using multiple vegetation types for this study, they proved what normal vegetation spectra looks like with a low in the red region and an increase in the near-infrared region. All reflectance was measured with a handheld radiometer and crop biomass measurements were taken in half a square meter sections (Drake 1976). At this point, sufficient research about albedo, reflectance, and reflectance quantities was available that the National Bureau of Standards released a nomenclature for reflectance to streamline all research with definitions and equations (Nicodemus et al. 1977b).

A number of studies have focused on different ways to calculate spectral albedo at any wavelength, the errors associated with these calculations, and the fact that spectral albedo is dependent on different solar angles (Wiscombe and Warren 1980). Broadband albedo is calculated from broadband sensors; however, atmospheric correction and angular models to convert directional reflectance to spectral albedo need to be applied to the sensor’s data for accurate broadband albedo (Liang 2001).
Radiative transfer simulations are used in order to simulate top of atmosphere (TOA) parameters from field collected spectra. The second simulation of the satellite signal in the solar spectrum (6S) is a radiative transfer simulation code which calculates atmospheric effects used for calculation of the lookup tables for MODIS (Moderate Resolution Imaging Spectroradiometer) (Vermote et al. 1997). BRDF can also be calculated through the 6S radiative transfer simulation. The 6S package accounts for anisotropic and Lambertian surfaces, elevation changes, and atmospheric absorption. These calculations are done by using successive orders of scattering (Vermote et al. 1997; Kotchenova et al. 2006). The Atmospheric CORrection (ATCOR) software uses the Ross-Li BRDF model in order to calculate the bihemispherical reflectance of a specific target (reference here, please!!!). ATCOR applies a BRDF effect correction during the atmospheric compensation in order to transform the hemispherical reflectances to angular dependent spectral albedos from the observer. ATCOR provides derived products from atmospheric correction including bottom of atmosphere (BOA) albedo, aerosol optical thickness, and a water vapor (Schlapfer and Richter 2014; Makarau et al. 2016). A common radiative transfer simulation model is MODTRAN. MODTRAN’s original purpose was to extract land surface temperatures from images; however, modifications were made to allow MODTRAN to also help with calculations for irradiance. MODTRAN is capable of calculating BRDF as well as atmospheric effects. MODTRAN provides a number of BRDF models including Walthall, Ross-Li, Rouhean, and Rahman models. (Lucht, Schaaf and Strahler 2000). Two of the ways MODTRAN differs from the 6S radiative transfer model in spectral resolution and the wavelengths simulated. While MODTRAN can simulate throughout the electromagnetic spectrum, 6S only simulates the visible portion of the electromagnetic spectrum (Kotchenova et al. 2006). The spectral resolution of MODTRAN simulated files can be up to 0.2nm. Liang,
Strahler, and Walthall used MODTRAN to evaluate isotropic reflectance as a function of solar zenith angle by comparing reflectance values from different viewing directions. Ross et al. (2012) compared field collected and simulations with satellite data found no deviations between the simulated and satellite derived BRDF observations (Liang, Strahler and Walthall 1999; Ross et al. 2012).

Kernel models can be used to calculate the BRDF of an object. Li and Strahler have developed kernel BRDF functions that can be used to characterize surface BRDF by using weighted variables scattering geometry. Both angular and spectral based kernel coefficients can be used in the BRDF models (Li and Strahler 1992). Kernel coefficients can be useful when the BRDF is calculated for images with a large number of spectral bands. Kernel coefficients do not increasing the number of unknown variables in the BRDF equation. Since albedo is dependent on the bidirectional reflectance distribution function (BRDF), kernel coefficients can be used to calculate broadband albedo (Liu et al. 2010). Roujean et al. (1992) studied kernel coefficients as a function of the bidirectional reflectance model in order to correct for remotely sensed multitemporal data. They used estimates for geometric scattering and volumetric scattering in order to model BRDF. Their kernel based coefficients agreed reasonably well with their observed data (Roujean et al. 1992).

Atmospheric correction in relation to BRDF calculations has been studied with snow and a cloud absorption radiometer (CAR) (Lyapustin et al. 2010). The CAR works jointly with the Ames Airborne Tracking Sunphotometer and the ground-based Aerosol Robotic Network sunphotometer to derive the BRDF of snow at a 1 degree angular resolution, resulting in an accurate surface albedo when compared to the ground measurements (Lyapustin et al. 2010). By
using weighted function, such as kernel coefficients, the spectral albedo can be calculated to the top of atmosphere (Wright et al. 2014).

The TEMPO mission is a very new concept in the scope of satellites. Since the TEMPO satellite has not launched yet, only preliminary research has been completed. Few research articles have been published explaining the TEMPO mission as well as the specifics on the satellite itself. With hourly measurements over North America and a relatively high spatial resolution, the TEMPO satellite will be able to derive aerosol properties to improve aerosol estimates at the surface (Chance et al. 2013). Pairing TEMPO together with the Asian (GEMS) and European (Sentinel-4) satellite constellation partners, allow for the first tropospheric trace gas measurements to be made from a geostationary satellite. This trio of satellites builds on the low earth orbit instruments by adding a higher spatial and temporal resolutions. The TEMPO satellite addresses some important problems with signal-to-noise, thermal management, and image navigation and registration (Gatebe and King 2016; Zoogman 2017). Land surface reflectance data is used to explain variability between land surface data and satellite data. This analysis of field collected reflectance measurements over different LCLU types is used to calculate the variability in surface reflectance with a high spatial resolution (Zoogman et al. 2016). Hou et al. (2017) expanded the study on land surface data to use the Geo-TASO instrument and TEMPO satellite to study the ability to retrieve aerosols from hyperspectral radiances collected. They performed a principal component analysis of their findings to conclude that information of aerosols depend on the surface type and observation geometries and with 50 common aerosol measurement bands, about 90% of total aerosol information can be observed (Hou et al. 2017).
Although research has already been done regarding the TEMPO satellite, unknowns remain. All the previous TEMPO studies have used the ASTER spectral library for several types of analysis. The ASTER spectral library is comprised of United States Geological Survey (USGS), Jet Propulsion Laboratory (JPL), and the John Hopkins University’s (JHU) spectral databases (Baldridge et al. 2009). These spectral databases have been used numerous times worldwide; however, they are mostly measured in the lab and do not match the TEMPO spectral resolution. Since this database is measured in the laboratory environment, it does not reflect sun and viewing angle geometries. This research creates a TEMPO specific database with field measurements to include both sun and viewing angle geometries and then uses this database for further analysis. Since the TEMPO satellite is a geostationary satellite, research on the solar zenith and solar azimuth angles are key. By researching how changes in solar zenith and solar azimuth angles change the BRF of an object, we can know what angles are key to collecting the BRDF of various land cover types. The key questions addressed by this research include. 1) do changing solar zenith and solar azimuth angles affect the BRDF of various LCLU targets? and 2) can we use the BRDF of a specific target to differentiate between healthy and non-healthy plants?
CHAPTER 3. DATA AND METHODOLOGY

When the TEMPO geostationary satellite is launched, it will be focused on collecting data over North America. The Midwestern United States is a centralized location where many different targets can be collected, such as snow, ice, water, and agricultural crops. Various spectral targets were surveyed in the St. Louis Metropolitan Area within the Geo-TASO flight footprint in 2014. Additional data were collected in 2015. Snow and ice spectra were collected in Boulder, CO on April 2, 2016.

Figure 1 shows the field data locations in the Midwestern United States. 461 upwelling and downwelling irradiiances over 110 sites in Midwestern U.S. were collected covering typical land-cover types; spectral reflectance factor data was collected over 299 locations (which include albedo sample locations) and 110 lab spectral measurements was made on rock samples. Figure 2 shows the location map of the sites for data collection in the St. Louis Metropolitan Area. The field collected data locations are represented by points along with the Geo-TASO flight footprint for reference. Measurement locations in Colorado and Indiana were not included in the Figure 2, where a dozen of measurements of rock, built environment, ice/snow were collected. All field collected data points can be seen in Table 1. Table 1 sorts the field collected data by land use types and includes the number of each land use type collected, the specific target names, the year each spectra was collected, the location, and the field collection dates.
Figure 1. Locations of field collected data within the Midwest United States.

Figure 2. Field collected data within the Geo-TASO footprint around the St. Louis Metropolitan area.
The Spectral Evolution PSR-350 Series Spectroradiometer was used for the field collection of spectral albedo. The spectral range of the PSR-350 is 350 nm – 2500 nm and has a spectral resolution of 1-3 nm in the 350 nm - 1000 nm range, 10 nm in the 1000 nm - 1900 nm range, and 7nm in the 1900 nm - 2500 nm range. This system collects high resolution spectral data in an UV, visible, and near infrared range using an optional calibrated lens fiber optic cable. The fiber optic cable brings the energy into the spectroradiometer. The cosine receptor was mounted on an aluminum arm and held level at 1m above the target. Measurement of both the downwelling and upwelling irradiance were taken in order to calculate the albedo (see Figure 3). Field collections were taken at a 1-3 nm spectral resolution at the visible and near-infrared wavelengths.

Figure 3. PSR-3500 Spectroradiometer equipped with 1.2 m fiber optic and right angle cosine diffuser was used to measure downwelling and upwelling solar irradiance at 1 m above the target.

The spectral albedo (called reflectance factor hereafter), often calculated as a ratio of reflected light over white reference panel readings, was measured by dividing the solar upwelling irradiance to downwelling irradiance obtained from the right angle cosine reflector (Equation 4).

\[
\text{spectral albedo} = \frac{\text{Upwelling radiant flux}}{\text{Downwelling radiant flux}}
\]  

(4)

Three pairs of measurements taken from each target make up the target’s average spectral albedo. Each target’s average spectral albedo was used for comparative analysis. Table 2 shows
the target name, a picture of the field collected target, and the spectral library of each target. The spectral library holds all field collected measurements for each specific target.

Table 1. Field Collected Spectra by LCLU type

<table>
<thead>
<tr>
<th>Land use Type</th>
<th>Number of Spectra Collected</th>
<th>Target Names</th>
<th>Year Collected</th>
<th>Test Sites</th>
<th>Field Collection Dates</th>
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<tbody>
<tr>
<td>Perennial Snow or Ice</td>
<td>17</td>
<td>Snow, Ice</td>
<td>2016</td>
<td>Colorado</td>
<td>4-2-2016</td>
</tr>
</tbody>
</table>
Table 1 Continued.

<table>
<thead>
<tr>
<th>Land use Type</th>
<th>Number of Spectra Collected</th>
<th>Target Names</th>
<th>Year Collected</th>
<th>Test Sites</th>
<th>Field Collection Dates</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rock Land</td>
<td>110</td>
<td>K1 Sandstone, K10 Ultramafic, K14 Carbonatite, K24 Ultramafic</td>
<td>2013</td>
<td>St. Genevieve County, Missouri</td>
<td>8-23-2013, 11-21-2013</td>
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</table>

Table 2. Field Collected Spectra

<table>
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<tr>
<th>Target Name</th>
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Table 2 Continued.

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<tr>
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<td>Spectral Library</td>
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<td>Spectral Library</td>
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<td>Tomato</td>
<td><img src="image3.png" alt="Tomato Photo" /></td>
<td><img src="image4.png" alt="Tomato Library" /></td>
</tr>
<tr>
<td>Target Name</td>
<td>Field Photo</td>
<td>Spectral Library</td>
</tr>
<tr>
<td>-----------------------</td>
<td>-------------</td>
<td>--------------------------------</td>
</tr>
<tr>
<td>Soybean</td>
<td><img src="image" alt="Soybean" /></td>
<td><img src="image" alt="Soybean Library" /></td>
</tr>
<tr>
<td>Impervious Surfaces</td>
<td><img src="image" alt="Impervious Surfaces" /></td>
<td><img src="image" alt="Urban Land Library" /></td>
</tr>
</tbody>
</table>
Table 2 Continued.

<table>
<thead>
<tr>
<th>Target Name</th>
<th>Field Photo</th>
<th>Spectral Library</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td><img src="image1.jpg" alt="Water Photo" /></td>
<td><img src="image2.png" alt="Water Library" /></td>
</tr>
<tr>
<td>Zucchini</td>
<td><img src="image3.jpg" alt="Zucchini Photo" /></td>
<td><img src="image4.png" alt="Zucchini Library" /></td>
</tr>
</tbody>
</table>

Several core test sites were established in the States of Missouri and Illinois to understand spectral albedo/reflectance factor properties of plants exposed to different degrees of water and/or ozone stress. The ozone stressed test sites, located in Maryland Heights, Missouri, Southwestern Illinois College (SWIC), and the St. Louis Science Center, were planted in 2014 with O₃-sensitive and O₃-tolerant soybeans in collaboration with Monsanto and the USDA. The study area in Mt. Vernon, Missouri was established to extend the study to water stressed
grapevines. Table 3 shows the study area locations including the site name, plant type, stressor, several types of sensors and data collected over each test site, and the year the test sites were actively used.

Table 3. Test sites and added plant stressors

<table>
<thead>
<tr>
<th>Site Name</th>
<th>Plant</th>
<th>Stressor</th>
<th>Sensors and Data</th>
<th>Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>St. Louis Science Center</td>
<td>Soybean</td>
<td>Ozone</td>
<td>PSR-3500 Spectroradiometer and a hyperspectral camera mounted on a tripod and faced downward above the soybean canopy</td>
<td>2014, 2015</td>
</tr>
<tr>
<td>Southwestern Illinois College</td>
<td>Soybean</td>
<td>Ozone</td>
<td>PSR-3500 Spectroradiometer and a hyperspectral camera mounted on a tripod and faced downward above the soybean canopy</td>
<td>2014, 2015</td>
</tr>
<tr>
<td>Mount Vernon, MO</td>
<td>Grapevine</td>
<td>Water</td>
<td>PSR-3500 Spectroradiometer, a hyperspectral camera mounted on a tripod and faced downward above the grapevine canopy, and a UAV equipped with multispectral, hyperspectral, and thermal cameras</td>
<td>2014, 2015</td>
</tr>
<tr>
<td>Maryland Heights, MO</td>
<td>Soybean</td>
<td>Ozone</td>
<td>PSR-3500 Spectroradiometer and a hyperspectral camera mounted on a tripod and faced downward above the soybean canopy</td>
<td>2014</td>
</tr>
</tbody>
</table>

3.1 Geo-TASO data

The Geo-TASO flight instrument was flown onboard the NASA HU-25C Falcon aircraft to collect data over the St. Louis Metropolitan Area test site at 0.6 nm spectral resolution with a 0.2 nm sampling interval. The flight was flown on August 13th, 2014. Flight parameters, including aircraft altitude, earth sun distance, solar elevation, solar zenith angle, solar azimuth
angle, viewing azimuth angle, viewing zenith angle, date, and time were taken from the flight images to properly simulate raw collected field data.

3.2 LCLU Data

3.2.1 USDA Cropland data layer

The USDA Cropland data layer is classified by the National Agriculture Statistics Services site. The cropland data layer is a 30-meter ground spatial resolution crop-specific land cover data set produced using satellite imagery, USDA farm service agency common land unit data, and the 2011 national land cover dataset provided from USGS. Data from both 2014 and 2015 were downloaded to compare field collected data to the land-cover and land-use data from each year. The overall accuracy for the Illinois data in 2014 is 96.6% and 96.0% for the 2015 data. The accuracy for the Missouri data in 2014 is 90.6% and 86.7% for 2015. Figure 4 shows the 2014 USDA cropland data layer product for the test sites. The Geo-TASO flight footprint and the field collected spectral albedo points are overlaid for reference.
3.2.2 High resolution Geoeye and WorldView-2/3 data for land cover mapping

High resolution imagery is very important in land cover mapping. The accuracy of the land cover assessment depends on the spatial resolution of the imagery. With high spatial resolution images, the classification is more likely to resemble the field collected data. With a low spatial resolution, the small differences between spectral targets would be missed in the imagery. Because of the high resolution Geoeye, WorldView-2/3 satellite data, Digital Globe imagery was downloaded to improve the Cropland data layer accuracy of LCLU comparison between field collected data and the satellite data. Figure 5 shows the Digital Globe imagery in comparison to the Geo-TASO flight path and field collected data. Imagery was downloaded only for locations with field collected data.
The Geoeye satellite was launched in 2008 and provides data at a 0.46 meter panchromatic spatial resolution and a 1.84 meter multispectral spatial resolution. The temporal resolution is about 3 days with a 3 meter accuracy on each re-visit (DigitalGlobe 2017). The WorldView-2 satellite was launched in 2009 as the first high resolution multispectral satellite with 8 bands. The WorldView-2 satellite provides a 46 cm panchromatic spectral resolution and a 1.85 meter multispectral resolution.

As the industry’s first multi-payload and high resolution satellite, the WorldView-3 provides simultaneous high resolution super-spectral imagery. The 31 cm panchromatic spectral...
reosltuion, 1.24 meter multispectral resolution, 3.7 meter short-wave infrared spectral resoltuion, and the 30 meter CAVIS spectral resoltuion paired together with a temporal resoltuion of less than 1 day is hard to beat when looking at other satellites (DigitalGlobe 2017).

3.3 Spectral albedo calculation procedures

Field Collections were taken at a 1-3 nm spectral resolution at the visible and near-infrared wavelengths. Three pairs of upwelling and downwelling irradiance measurements, taken from each target, were averaged to calculate the average spectral albedo. Each target’s average spectral albedo were then used for comparative analysis.

3.4 BRDF simulations

3.4.1 MODTRAN Simulations

The data processing workflow from raw spectra to final Geo-TASO satellite based spectra can be seen in Figure 6. First, the data was interpolated using a cubic spline interpolation method and a hermite cubic interpolation method to have an even 0.2 nm in between each reflectance measurement (Meijering 2002). Two types of interpolation were used to assess the accuracy of the interpolation methods. The cubic spline interpolation allows for the curve to pass through two specified points with specified derivatives. The hermite cubic interpolation method uses the derivatives along with the function values to interpolate the data. The data were then be compared to the raw data to choose the most accurate interpolation method.
The raw collected spectra from the various locations were simulated through MODTRAN5 (Moderate Spectral Resolution Atmospheric Transmittance Algorithm and Computer Model) in order to resample the data to the Geo-TASO spectral resolution. MODTRAN5 is a narrow band atmospheric radiative transfer package that has been used for over 40 years for simulating data.
with resolutions as low as 0.2 cm\(^{-1}\). MODTRAN5 models the atmosphere as stratified horizontally similar layers and molecular and particulate basic profiles, which may be defined by using defined vertical profiles or built-in models (MODTRAN 2016).

To compare field collected reflectance measurements with the Geo-TASO reflectance values, the data must be simulated to at sensor reflectance. The spectra can then be simulated through MODTRAN5 with Geo-TASO satellite parameters from 2014, 2015, and 2016. Geo-TASO parameters include 23.265° view zenith angle and a solar zenith angles at 37.9170° as in the Geo-TASO flight information on August 13\(^{th}\), 2014.

### 3.4.2 Simulated Spectral Albedo at TEMPO Resolution

The spectral albedo of each target is calculated from the outputs of the MODTRAN5 radiative transfer simulations. The solar irradiance transmitted to the observer, direct ground reflected radiance, and frequency was extracted from the MODTRAN5 simulated files. The bidirectional reflectance factor can then be calculated using the Equation 5.

\[
BRF = \frac{\pi (L_{e,\Omega})(d)}{(E_e)}
\]

(5)

Where \(L_{e,\Omega}\) is the ground reflected radiance, including the reflectance of three downward flux components including the direct solar, the diffuse solar, and the diffuse thermal, \(d\) is the earth sun distance at a date and time, and \(E_e\) is the solar irradiance transmitted to the observer, as a calculated product of the top of atmosphere spectral solar irradiance and the sun to observer spectral transmittance. The frequency can then be converted into wavelengths using the Equation 6.

\[
\lambda = \frac{10,000,000}{\nu}
\]

(6)
where $\lambda$ is the wavelength and $\nu$ is the frequency.

3.4.3 BRDF Analysis

BRDF analysis is completed by converting the BRDF to the bidirectional reflectance factor (BRF). The BRF is a non-dimensional number that is equivalent to the BRDF when multiplied by $\pi$. The BRF is analyzed as a function of the viewing zenith angle and the sun direction. Two different techniques were used to calculate the BRDF and then compared.

3.4.3.1 Lambertian Assumptions

Assuming the ground target is uniform Lambertian surface, field collected spectral data were simulated through MODTRAN5 at various sun and view zenith angles and solar azimuth angles to create polar plots describing BRF patterns. The sensor view zenith angles were set to a range from $0^\circ$ – $80^\circ$, simulating the sensor movement from 0 degrees (right on top of the target) to 80 degrees, almost horizontal near surface. The solar azimuth angles were set to a range from $0^\circ$ – $360^\circ$ which simulates the sun position around the target in a complete circle. The sensor zenith angle can be seen through the radius of the circle and the relative azimuth angle, difference between sun and view azimuth angles, is represented with the polar angle or circumference of the circle.

3.4.3.2 Ross-Li BRDF Model

The Ross-Li BRDF model was also used to calculate the BRDF of a specific target, accounting for target reflectance anisotropy. Two Ross-Li BRDF models were used for each
target spectra. For the first model, kernel coefficients were calculated using three field collected spectral albedo points at different times of day. For the second model, MODTRAN was used to simulate three different solar zenith angles from one field collected spectra. For both Ross-Li BRDF models, Equation 7 shows the Ross-Li volumetric kernel coefficient and Equation 8 shows the geometric kernel coefficient (Schaepman-Strub et al. 2006).

\[
k_{vol} = \frac{(\frac{\pi}{2} - \varepsilon) \cos(\varepsilon) + \sin(\varepsilon)}{\cos(\theta_s) + \cos(\theta_v)} - \frac{\pi}{4}
\]  

(7)

where

\[
\cos(\varepsilon) = \cos(\theta_v) \cos(\theta_s) + \sin(\theta_v) \sin(\theta_s) \cos(\phi)
\]

\[
k_{geo} = O(\theta_s \theta_v \phi) - \sec(\theta_s) - \sec(\theta_v) + \frac{1}{2}(1 + \cos(\varepsilon)) \sec(\theta_s) \sec(\theta_v)
\]

(8)

where.

\[
O = \frac{1}{\pi} (t - \sin(t) \cos(t)) (\sec(\theta_s) + \sec(\theta_v))
\]

\[
\cos(t) = \sqrt{D^2 + \left(\frac{\tan(\theta_s) \tan(\theta_v) \sin(\phi)}{\sec(\theta_s) + \sec(\theta_v)}\right)^2} \times \frac{h}{b}
\]

\[
D = \sqrt{\tan^2 \theta_s + \tan^2 \theta_v - 2 \tan \theta_s \tan \theta_v \cos(\phi)}
\]

Reflectance data from three different solar zenith angles, or three separate times of the day, were used to derive the kernel coefficients. These kernel numbers were derived using the substitution of equations.

3.5 Albedo retrieval from Geo-TASO flight data

Geo-TASO flight images were georeferenced to place the images in their correct geographical location. Since the Geo-TASO flight instrument collects Photon radiance \(L_{q\lambda}\), the
at-sensor photon radiance must be converted to at-sensor reflectance to calculate the albedo. First, photon radiance can be converted to spectral radiance ($L_\lambda$) using Equation 9 below.

$$\quad L_\lambda = L_{q\lambda} \times \frac{hc}{\lambda} \quad (9)$$

where $h$ is the Plank’s constant at $6.626 \times 10^{-34}$ J s, $c$ is the speed of light at $2.99 \times 10^8$ m s$^{-1}$, $\lambda$ represents the selected wavelength, and $L_{q\lambda}$ is the extracted photon radiance value from the GeoTASO image. Then, the spectral radiance was converted to at-sensor reflectance using Equation 10 below.

$$\quad p_p = \frac{(\pi L_\lambda)}{ESUN_\lambda \cdot \cos \theta_s} \frac{1}{d^2} \quad (10)$$

where $p_p$ represents the at-sensor reflectance, $L_\lambda$ is the at-sensor spectral radiance, $d$ is the earth-sun distance in astronomical units, $ESUN_\lambda$ is the band specific solar irradiance, and $\theta_s$ is the solar zenith angle.
CHAPTER 4. RESULTS

4.1 Spectral Libraries

Spectral libraries were created for each land-cover type and one spectral signature was created to represent the target class. Figure 7 shows one spectral signature from all field collected targets for comparison of spectral signatures.

![All Field Collected Spectral Targets](image)

Figure 7. A field collected spectral albedo signature for each target.

Figure 8 shows the field collected spectral albedo for barren land. The spectral signature of barren land starts low in the visual portion of the spectrum and increases constantly throughout the near-infrared. The field collected spectral albedo for barren land ranged from 0.085 to 0.27.
Figure 8. A field collected spectral albedo for barren land.

Figure 9 is the field collected spectral albedo signature for corn. Corn follows an vegetation spectral signature. The spectral albedo starts off low in the blue region, increases through the green region. In the green region, the corn reaches a high spectral albedo peak for green reflectance around 550 nm and starts to decline into the red region. The lowest point in the red region is around 675 nm. Then, the corn spectral albedo increases into the near-infrared and reached a 0.3 spectral albedo.
Figure 9 is the field collected spectral albedo signature for corn. Grapevine also follows vegetation spectral signature. Just like corn, the spectral albedo starts off low in the blue region, increases through the green region, drops through the red region, and increases through the near-infrared region. Grapevine reaches a high of 0.4 in the near-infrared.
Figure 10 is the field collected spectral albedo signature for grapevine. Just like grapevine and corn, the grass spectral albedo also follows an vegetation spectral signature. As with all green vegetation spectral signatures, the spectral albedo starts off low in the blue region, increases through the green region, drops through the red region, and increases through the near-infrared region. The grass region has a high near-infrared spectral albedo of 0.3.
Figure 11. A field collected spectral albedo signature for grassland.

Figure 12 shows the spectral signature for field collected ice. Ice spectral signature follows a water signature with a high in the blue region and continues to decline all the way into the near-infrared region of the spectrum.

Figure 12. A field collected spectral albedo signature for ice.
Figure 13 represents the spectral signature for field collected snow. Snow follows a very similar spectral signature as ice; however, snow has a higher spectral albedo. Just like the ice, the snow spectral signature starts of highest in the blue region and then declines through the near-infrared region. There are a few strong absorption regions found at 440 nm and 470 nm, as seen in the drops of the blue region.

![Figure 13. A field collected spectral albedo signature for snow.](image)

Figure 14 is the field collected soybean. Soybean follows the spectral signature of vegetation. As with all other vegetation spectral signatures, soybean is low in the blue, increases through the green, drops in the red, and increases through the near-infrared region. Soybean reaches a near-infrared spectral albedo maximum of 0.4.
Figure 14. A field collected spectral albedo signature for soybean.

Figure 15 is the field collected spectral albedo for an impervious surface, or pavement in this case. Impervious surfaces follow a barren land or pavement spectral signature. They start low in the blue region and increase through the near-infrared region.

Figure 15. A field collected spectral albedo signature for an impervious surface.
Figure 16 is the field collected spectral albedo for water. Water follows a spectral signature that is high in the blue and decreases through the near-infrared. Ice and Snow also follow this spectral signature. This spectral signature includes a few outliers to vary the water spectra in the blue and green region. If the spectral albedo was recorded with turbid water, this may cause outliers.

4.2 Polar Plot Analysis

4.2.1 Lambertian Assumptions

Since BRF is equivalent to effective BRDF times \( \pi \), we use BRF hereafter for simplicity. Lambertian assumptions are often used to describe reflectance properties of land surface objects assuming that illumination and view geometry has much larger effects on BRDF of an object than its inherent reflective properties, i.e., isotropic or heterogeneous. The BRDF for corn is shown in Figure 17 simulated with Lambertian assumption at a fixed sun zenith angle. The
viewing zenith angle is shown as the radius of the circle. At 0 degrees, the sensor is at nadir and as the sensor zenith angle increases towards 80 degrees, the sensor moves towards the horizon.

The relative azimuth angle is shown in the circumference of the circle with 0 degrees in the north. As the sensor zenith angle increases, the BRF decreases due to the viewing angle of the sensor. Figure 17a represents the BRF at 550 nm, the green region, and reaches a spectral albedo of 0.04; Figure 17b represents the BRF at 675 nm, the red region, whose spectral albedo drops down to 0.035; and Figure 17c shows the BRF at 720 nm, the near-infrared region, with a higher value of 0.08 nm. It is worth noting that the “hotspot” effects, a phenomenon characterized by maximum reflectance at the incident light direction, is not evident from the Figure 17 due to the Lambertian assumption used to simulate the BRF.

Figure 17. Corn BRF using a Lambertian assumption.
4.3 Ross-Li BRDF Model

4.3.1 MODTRAN Simulated data with the Ross-Li BRDF model

Although Lambertian assumptions are commonly accepted when calculating BRF, but it does not provide a precise patterns of BRDF distribution as function of sun, view zenith angle, and solar azimuth angle. To account for target reflectance anisotropy, kernel coefficients were derived by using three spectral albedo values as shown in the Ross-Li equations. Table 4 shows the kernel coefficients for the blue region of the spectrum at 550 nm wavelength. The isotropic, geometric, and volumetric kernels are listed. Similarly, Table 5 shows the kernel coefficients for the red region of the spectrum at 675 nm and Table 6 lists the kernel coefficients for the near-infrared portion of the spectrum at 740 nm wavelength.

Table 4. BRDF kernel coefficients for various land cover types at 550 nm.

<table>
<thead>
<tr>
<th>Target Name</th>
<th>Isotropic Kernel (550 nm)</th>
<th>Geometric Kernel (550 nm)</th>
<th>Volumetric Kernel (550 nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barren Land</td>
<td>0.10251805</td>
<td>0.020178157</td>
<td>0.188450884</td>
</tr>
<tr>
<td>Corn</td>
<td>0.065385844</td>
<td>0.013312991</td>
<td>0.156081381</td>
</tr>
<tr>
<td>Healthy Grapevine</td>
<td>0.152659504</td>
<td>0.054903592</td>
<td>0.170257057</td>
</tr>
<tr>
<td>Water Stressed Grapevine</td>
<td>0.140971054</td>
<td>0.027298131</td>
<td>0.221721453</td>
</tr>
<tr>
<td>Grass</td>
<td>0.067473923</td>
<td>0.013699197</td>
<td>0.157942432</td>
</tr>
<tr>
<td>Healthy Soybean</td>
<td>0.149872</td>
<td>0.02908064</td>
<td>0.22733</td>
</tr>
<tr>
<td>Ozone Damaged Soybean</td>
<td>0.219849416</td>
<td>0.041858009</td>
<td>0.290263</td>
</tr>
<tr>
<td>Impervious Surfaces</td>
<td>0.064779</td>
<td>0.013221864</td>
<td>0.156031</td>
</tr>
<tr>
<td>Water</td>
<td>0.056032</td>
<td>0.012800951</td>
<td>0.154004541</td>
</tr>
</tbody>
</table>
Table 5. BRDF kernel coefficients for various land cover types at 675 nm.

<table>
<thead>
<tr>
<th>Target Name</th>
<th>Isotropic Kernel (675 nm)</th>
<th>Geometric Kernel (675 nm)</th>
<th>Volumetric Kernel (675 nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barren Land</td>
<td>0.088705847</td>
<td>0.017165413</td>
<td>0.139836576</td>
</tr>
<tr>
<td>Corn</td>
<td>0.038000136</td>
<td>0.008232524</td>
<td>0.098085779</td>
</tr>
<tr>
<td>Healthy Grapevine</td>
<td>0.038933344</td>
<td>0.008387637</td>
<td>0.09853654</td>
</tr>
<tr>
<td>Water Stressed Grapevine</td>
<td>0.046176578</td>
<td>0.009679657</td>
<td>0.104849957</td>
</tr>
<tr>
<td>Grass</td>
<td>0.030962558</td>
<td>0.006984067</td>
<td>0.09202742</td>
</tr>
<tr>
<td>Healthy Soybean</td>
<td>0.038937</td>
<td>0.008387637</td>
<td>0.097224</td>
</tr>
<tr>
<td>Ozone Damaged Soybean</td>
<td>0.069579</td>
<td>0.013800243</td>
<td>0.124212</td>
</tr>
<tr>
<td>Impervious Surfaces</td>
<td>0.045902</td>
<td>0.009622812</td>
<td>0.10446</td>
</tr>
<tr>
<td>Water</td>
<td>0.038329</td>
<td>0.009092349</td>
<td>0.102008371</td>
</tr>
</tbody>
</table>

Table 6. BRDF kernel coefficients for various land cover types at 740 nm.

<table>
<thead>
<tr>
<th>Target Name</th>
<th>Isotropic Kernel (740 nm)</th>
<th>Geometric Kernel (740 nm)</th>
<th>Volumetric Kernel (740 nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barren Land</td>
<td>0.088926251</td>
<td>0.016818137</td>
<td>0.124930725</td>
</tr>
<tr>
<td>Corn</td>
<td>0.1075279</td>
<td>0.020058473</td>
<td>0.140224912</td>
</tr>
<tr>
<td>Healthy Grapevine</td>
<td>0.187462662</td>
<td>0.033989908</td>
<td>0.205944452</td>
</tr>
<tr>
<td>Water Stressed Grapevine</td>
<td>0.187632662</td>
<td>0.033989908</td>
<td>0.205944452</td>
</tr>
<tr>
<td>Grass</td>
<td>0.13735491</td>
<td>0.025241699</td>
<td>0.164569744</td>
</tr>
<tr>
<td>Healthy Soybean</td>
<td>0.234213</td>
<td>0.042091124</td>
<td>0.241371</td>
</tr>
<tr>
<td>Ozone Damaged Soybean</td>
<td>0.226525</td>
<td>0.040709967</td>
<td>0.236715</td>
</tr>
<tr>
<td>Impervious Surfaces</td>
<td>0.099198</td>
<td>0.0186052</td>
<td>0.133336</td>
</tr>
<tr>
<td>Water</td>
<td>0.032877</td>
<td>0.007752848</td>
<td>0.082334803</td>
</tr>
</tbody>
</table>

Polar Plots were created using the Ross-Li BRDF model. Polar plots for various land-cover types can be seen in Figure 18. The relative azimuth angle is represented by the circumference of the circle from 0-180 degrees with 0 degrees at north. The sensor zenith is shown in the radius of the circle from 0-80 degrees with 0 degrees being nadir and 80 degrees almost at flat with the surface. Figure 18 shows the BRDF of barren land at 550 nm, 675 nm, and 740 nm. As the wavelength increases, the spectral albedo increases. The solar zenith angle was 29.179°. The highest BRF/spectral albedo location is between 30 and 80 degrees for the sensor.
viewing angle near 180 degrees in the solar azimuth direction. Barren land follows a BRDF signature with a small “hot spot” or a point of highest reflectance around the location of the solar zenith angle. Then, the barren land BRDF decreases as the solar azimuth moves north to 0 degrees. Near 30 – 60 degrees to the north, there is an arch of low reflectance region.

![Barren Land BRDF at 550 nm, 675 nm, and 740 nm](image)

Figure 18. The BRDF of barren land at 550 nm, 675 nm, and 740 nm.

Figure 19 shows the BRDF of corn at 550 nm, 675 nm, and 740 nm. Corn demonstrates a BRDF of a typical healthy vegetation with the solar angle plotted at 28.9170 degrees. Just as with the barren land BRDF plot, the corn BRDF plot also has a hotspot area around the solar zenith angle. Like with the barren land plot, the corn BEDF plot also has an arch like feature of low reflectance around the 30-60 degree area to the north; however, this is not so much of an outlier point, but it slowly increases as it moves to the northwest.
Figure 19. The BRDF of corn at 550 nm, 675 nm, and 740 nm.

Figure 20 shows the BRDF comparison between healthy and water stressed grapevines at 550 nm, 675 nm, and 740 nm, respectively. Figure 20a is the healthy grapevine BRDF polar plot. The healthy grapevine plot follows a vegetation BRDF signature with the solar zenith angle plotted at 47.9946959 degrees. The solar zenith angle is high due to the afternoon field collection time. Figure 20b is the water stressed grapevine BRDF plot. The water stressed grapevine BRDF plot has a different signature than the healthy grapevine. The water stressed grapevine includes an arch-like low reflectance point in the 550 nm plot. This low reflectance point was not seen in the healthy grapevine BRDF plot making the 550 nm region a location to distinguish between water stressed and healthy grapevines.
Figure 20. The BRDF comparison of healthy and water stressed grapevine at 550 nm, 675 nm, and 740 nm. Figure 20a is healthy grapevine and Figure 20b is water stressed grapevine.

Figure 21 is the BRDF plot of grassland at 550 nm, 675 nm, and 740 nm respectively. Grassland follows a similar polar plot signature of agriculture with the arches of low reflectance gradually turning in to higher BRDF points. The arches of low reflectance are shown in the 550 nm plot. The solar zenith angle of 27.7480 degrees can be seen in the hotspot. Just as with the other agriculture plots, as the solar azimuth angle increases towards 180 degrees, the BRDF increases.
Figure 21. The BRDF of grass at 550 nm, 675 nm, and 740 nm.

Figure 22 compares the BRDF polar plot of healthy soybean and ozone damaged soybean at 550 nm, 675 nm, and 740 nm with a solar zenith angle plotted at 29.1470 degrees. Figure 22a shows the healthy soybean BRDF plotted. The near-infrared plot shows a high BRDF value along the 110-180 degree solar azimuth angle with the hot spot located in the solar zenith angle’s position. The ozone damages soybean is shown in Figure 22b. The ozone damaged soybean has a higher reflectance, resulting in larger values in the BRDF plots below. The ozone damaged soybean shows a higher BRDF value in all of the green region. This region can be used to distinguish ozone damaged soybeans from healthy soybeans.
Figure 22. The BRDF comparison of healthy and ozone damaged soybean at 550 nm, 675 nm, and 740 nm. Figure 22a is healthy soybean and Figure 22b is ozone damaged soybean.

Figure 23 is the BRDF for any impervious surface at 550 nm, 675 nm, and 740 nm with a solar zenith angle at 25.9337 degrees. The impervious surface BRDF plot follows a signature similar to barren land. Unlike agriculture, there are no arches of reflectance values at a 0 degree solar azimuth angle. The BRDF increases from the 90 degree to 180 degrees relative azimuth angle.
Figure 23. The BRDF of an impervious surface at 550 nm, 675 nm, and 740 nm.

Figure 24 shows the BRDF for water at 550 nm, 675 nm, and 740 nm. Since the water spectral signature starts high in the blue and decreases constantly through the near-infrared, the BRDF is highest in the 550 nm plot and decreases through the 675 nm plot and the 740 nm plot. In the plot of 550 nm, the water spectra shows a single arch like figure in the northern portion of the plot.

Figure 24. The BRDF of water at 550 nm, 675 nm, and 740 nm.
4.3.2 The effects of solar zenith angle on Surface BRDF

Since the TEMPO satellite is a geostationary satellite with a fixed viewing zenith angle over North America, BRDF polar plots were also created using a fixed viewing zenith angle and a changing solar zenith angle. The changing solar zenith angle reflects diurnal changes of solar irradiances incident upon land surfaces during a day. The viewing angle was set to 23 degrees for the following plots. This was determined based on the viewing zenith angle of airborne Geo-TASO instrument used to collect data in Saint Louis metro area on August 13, 2014. The relative azimuth angle is represented by the circumference of the circle from 0-180 degrees with 0 degrees at north. The solar zenith is shown in the radius of the circle from 0-80 degrees with 0 degrees being nadir and 80 degrees almost at flat with the surface. Figure 25 shows how downwelling solar irradiance changes as the function of cosine of the sun zenith angle $E_\theta = E \times \cos(\theta)$. The cosine law reflects the variance of the amount of downwelling irradiance at different sun angle. As the sun angle changes, the amount of incident light decreases.
Figure 25. Solar irradiance as a function of cosine of the sun zenith angle.

Figure 26 shows the BRDF plot of barren land with a fixed zenith angle. The fixed zenith angle can be seen through the hotspot centered around 30 degrees on the solar zenith angle and 180 degrees on the solar azimuth axis.

Figure 26. The BRDF of barren land with a fixed view angle at 550 nm, 675 nm, and 740 nm as a function of sun zenith angle from 0 to 80 degrees.

Figure 27 is the BRDF polar plot for corn with a fixed viewing angle. The BRDF value is much lower with a fixed viewing zenith angle than with a fixed solar zenith angle. Just as
with the barren land plot, there is a hotspot centered around 30 degrees on the solar zenith angle axis around the sensor view zenith angle. From this plot, the best angle for BRDF retrieval lies between 150-180 degrees in the solar azimuth angle.

Figure 27. The BRDF of corn with a fixed view angle at 550 nm, 675 nm, and 740 nm.

Figure 28 compares the BRDF of healthy and water stressed grapevines with a fixed viewing zenith angle at 550 nm, 675 nm, and 740 nm. Once again, the blue region, at 550 nm, shows the most differentiating results. The hotspot in the healthy grapevine is more circular and centered around 30 degrees at the view zenith angle than the high BRDF portion of the water stressed grapevine plot. The water stressed grapevine plot does not have a circular high BRDF area, but most of the plot is a higher BRDF. When looking at the healthy grapevine, it is apparent that the best relative azimuth angle is around 150-180 degrees. For the water stressed grapevine, the best relative azimuth angle ranges from about 110-180 degrees. These findings provide important implications for detecting and differentiating water and ozone stress.
Figure 28. The BRDF comparison of healthy grapevine and water stressed grapevine with a fixed view angle at 550 nm, 675 nm, and 740 nm. Figure 28a is the healthy grapevine and Figure 28b is the water stressed grapevine.

Figure 29 is the BRDF of grass with a fixed view zenith angle. The grass BRDF with the fixed viewing zenith angle follows directly with the fixed solar zenith angle plot. Both plots show hotspots in the same locations and have similar BRDF values along the solar azimuth axis.

Figure 29. The BRDF of grass with a fixed view zenith angle at 550 nm, 675 nm, and 740 nm.
Figure 30 shows the comparison between healthy and ozone damaged soybeans with a fixed viewing zenith angle. Figure 30a shows the healthy soybeans and Figure 30b shows the ozone damaged soybeans. Just as with the fixed solar angle plots for healthy and ozone damaged soybeans, there is a significant difference in the green, 550 nm, region plot. The hotspot is very apparent in the ozone damaged soybean and it almost non-existent in the healthy soybeans. The same can be seen in a smaller capacity in the red region, 675 nm. The near-infrared region plots are very similar. This implies the significance of green wavelength regions from 531 to 570 nm, that are sensitive to xanthophyll cycle activity, on detection of ozone damage (Gamon et al. 1997).

Figure 30. The BRDF comparison of healthy soybean and ozone damaged soybean with a fixed view angle at 550 nm, 675 nm, and 740 nm. Figure 30a is the healthy soybean and Figure 30b is the ozone damaged soybean.
Figure 3.1 represents the BRDF of an impervious surface with a fixed viewing zenith angle. The impervious surface plot indicates that impervious surface may be less affected by the fixed solar zenith angle in comparison to the fixed viewing zenith angle.

![Impervious Surface BRDF](image)

Figure 3.1. The BRDF of an impervious surface with a fixed zenith angle at 550 nm, 675 nm, and 740 nm.

Figure 3.2 shows the BRDF of water with a fixed zenith angle. The water BRDF plot with the fixed solar zenith angle differs drastically from the fixed viewing zenith angle plot. The viewing zenith angle fixed plot has defined hotspots in the location of the fixed zenith angle in all three plots; this was not visible in the fixed solar zenith angle plot.

![Water BRDF](image)

Figure 3.2. The BRDF of water with a fixed zenith angle at 550 nm, 675 nm, and 740 nm.
CHAPTER 5. CONCLUSION

With the launch of the TEMPO satellite scheduled for the year 2020, the need for a spectral database of various land-cover types is imperative. Since TEMPO provides a high spectral resolution (~0.6 nm) spectral data in the ultraviolet and visible portion of the electromagnetic spectrum, retrieval of atmospheric pollutants can be improved, but only if the BRDF is calculated and removed from the at-sensor reflectance product.

The characterization of BRDF/albedo of various land-cover types in Midwestern United States was completed through a multi-summer field collection of data along with the simulation of BRDF in MODTRAN using the field collected spectra. The 461 upwelling and downwelling field collected solar irradiances and spectral albedos of various land-cover types paired with the field and manned aircraft data collection in Maryland Heights, Missouri allowed for the utilization of Ross-Li Kernel BRDF model and MODTRAN radiative transfer simulations to characterize BRDF/albedo of various land-cover types. Based off plotting the solar zenith and solar azimuth angles with a fixed viewing zenith angle, it is obvious that the changing solar zenith and solar azimuth angles affect the BRDF of a target. Fixing the viewing zenith angle and changing the solar zenith and solar azimuth angles closely resembles how the TEMPO satellite will view targets over North America. The hotspot location where sun and sensor zenith angles overlap, there is a significant difference between healthy and non-healthy vegetation within the green region ranging from 531 nm to 570 nm (e.g., 550 nm). Within this region, we can see differences between healthy and water stressed grapevine and healthy and ozone damaged soybeans, highlighting the potential of TEMPO satellite for monitoring vegetation health and crop productivity.
With TEMPO’s relatively high spatial resolution and hourly temporal resolution covering North America, spectral indices can be calculated using the BRDF/albedo for future crop growth and yield monitoring for regional food security. The BRDF/spectral albedo database developed through this project can be used to remove the radiance component coming from the land surface from at-sensor TEMPO radiances for improved estimation of atmospheric chemistry, once the satellite is launched. The BRDF spectral libraries can also be used for evaluating regional agro-ecosystems when studying regional food security by characterizing unique BRDF patterns of various crops and land-cover types. This research provides an important reference database to the TEMPO mission with high-resolution spectral BRDF/albedo database, which may also promote the use of the TEMPO data for agricultural and ecosystem monitoring.
REFERENCES


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VITA AUCTORIS

Bethany Marshall attended Southern Illinois University Edwardsville (SIUE) to study Geography for her undergraduate studies. From here, she attended Saint Louis University to start the Master of Science in GIScience program in August 2015. She expects to earn her Master of Science in GIScience in May 2017. She will continue her education in the Integrated and Applied Sciences PhD program focusing on Environmental Science and GIS in the fall of 2017.