An Empirical BRDF model for the Queensland rainforests

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Tutor: dr. ir. Wouter Maes

Master’s dissertation submitted in partial fulfillment of the requirements for the degree of

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Abstract

Research on growth, transpiration and carbon storage of tropical forest ecosystems is greatly based on observations from satellites that measure in the visual and near-infrared spectrum. However, the sensor viewing angle and the solar angle are anything but constant. Both angles can influence the observed signal, which is known as the Bidirectional Reflectance Distribution Function or BRDF. Various theoretical and semi-empirical BRDF models were made based on physical principles, often with very different results. A full empirical model is missing, as until recently no method existed to measure the BRDF of a forest ecosystem. Thanks to UAV technology this is now possible.

For this study, an Unmanned Aerial Vehicle (UAV) measuring campaign was conducted over two tropical rainforest sites in Queensland, Australia. The UAV was equipped with a visual and a near-infrared camera. During the flights, the same target area of the forest was scanned under different viewing angles. The flights were repeated several times during the day. In this way the BRDF effects of tropical rainforests could be determined empirically for the first time. With this model we then evaluated the effect of the sun-sensor geometry on frequently used vegetation indices such as the Green Red Vegetation Index (GRVI) and the Green Chromatic Coordinate (GCC). Our results show that the index values changed significantly as the sensor viewing angle was altered, proving the importance of an accurate BRDF correction on all remote sensing studies.
Samenvatting

Het onderzoek naar de groei, transpiratie en koolstofopslagcapaciteit van tropische boscosystemen is voor een groot deel gebaseerd op waarnemingen van satellieten die meten in het visuele en nabij-infrarode spectrum. De kijkhoek waarmee gemeten wordt en de hoek tussen de zon en de sensor is echter allesbehalve constant. Beide hoeken kunnen een impact hebben op het waargenomen signaal, wat bekend staat als de Bidirectional Reflectance Distribution Function of BRDF. Verschillende theoretische en semi-empirische BRDF modellen werden reeds opgesteld gebaseerd op fysische principes, met vaak zeer uiteenlopende resultaten. Een volledig empirisch model ontbreekt omdat er tot voor kort geen enkele methode bestond om de BRDF van boscosystemen te meten. Dit kan nu wel, dankzij het gebruik van UAVs.

Voor dit onderzoek werd een UAV-meetcampagne uitgevoerd boven twee tropisch regenwoud-sites in Queensland, Australië. De UAV werd uitgerust met een visuele en een nabij-infrarood camera. Tijdens de vluchten werd hetzelfde deel van het bos gescand onder verschillende kijkhoeken. De vluchten werden meerdere malen herhaald tijdens de dag. Zo konden voor de eerste keer de BRDF-effecten van tropische regenwouden volledig empirisch worden vastgesteld. Met dit model zijn we vervolgens gaan kijken naar de effecten van de zon-sensor geometrie op veel gebruikte vegetatie indices zoals de Green Red Vegetation Index (GRVI) en de Green Chromatic Coordinate index (GCC). Uit onze resultaten blijkt dat de index waarden een significante verandering ondergaan bij wijziging in de sensor positie. Dit toont duidelijk het belang aan van een goede BRDF correctie voor alle remote sensing studies.
Table of contents

1. Introduction and Literature Study ................................................................. - 1 -
   1.1 Introduction ....................................................................................... - 1 -
   1.2 Literature study ................................................................................ - 3 -
      1.2.1 The BRDF concept ................................................................. - 3 -
      1.2.1.1 Definitions ............................................................................ - 3 -
      1.2.2 BRDF in remote sensing ....................................................... - 6 -
      1.2.2.1 The issue of directional beams ........................................... - 7 -
      1.2.2.2 BRDF reciprocity ............................................................... - 8 -
      1.2.3 Importance and applications of BRDF ..................................... - 9 -
      1.2.3.1 BRDF as a function to correct for the sun-target-sensor-geometry...... - 10 -
      1.2.3.2 Other BRDF applications .................................................. - 14 -
   1.2.4 Modeling BRDF .......................................................................... - 16 -
      1.2.4.1 Model types ......................................................................... - 16 -
      1.2.4.2 Measurement devices ........................................................ - 17 -
      1.2.4.3 BRDF product ..................................................................... - 24 -
2. Materials & Methods ............................................................................... - 27 -
   2.1 Field Campaign .................................................................................. - 27 -
      2.1.1 Measurement sites .................................................................... - 27 -
      2.1.2 Instruments and Setup ............................................................ - 27 -
      2.1.2.1 Equipment for aerial measurements .................................... - 27 -
      2.1.2.2 Ground Equipment .............................................................. - 29 -
      2.1.2.3 Flight Plan ........................................................................... - 30 -
   2.2 Data Processing ................................................................................. - 33 -
      2.2.1 GPS data .................................................................................. - 33 -
      2.2.2 Visual Image processing ......................................................... - 33 -
      2.2.2.1 Overview ............................................................................. - 33 -
      2.2.2.2 Image preparation .............................................................. - 35 -
      2.2.2.3 Image Registration .............................................................. - 35 -
4. Discussion .................................................................................................................. - 95 -
   4.1 Method evaluation .................................................................................................. - 95 -
      4.1.1 Star-shaped flight plan ..................................................................................... - 95 -
      4.1.2 Measurements .................................................................................................. - 95 -
      4.1.3 Data processing ............................................................................................... - 96 -
   4.2 Evaluation of the results ....................................................................................... - 97 -
      4.2.1 Visual camera .................................................................................................. - 97 -
      4.2.2 Near infrared camera ...................................................................................... - 98 -
      4.2.3 Comparison of the measurement sites ............................................................. - 98 -
      4.2.4 Vegetation Indices .......................................................................................... - 99 -
      4.2.5 Future Perspectives ......................................................................................... - 100 -
5. Conclusions ............................................................................................................... - 101 -
   Sources ...................................................................................................................... - 102 -
1. Introduction and Literature Study

1.1 Introduction

In recent years incredible advancements have been made in the field of remote sensing. Multi- and hyperspectrometers are designed with increasing spatial-and wavelength resolutions (Houborg et al., 2015), the calibration and validation of sensors are done with growing precision and major efforts are put into atmospheric corrections (Tian et al., 2016; Hadjimitsis et al., 2010; Mahiny et al., 2007). With these advancements, the number of applications of remote sensing instruments has increased as well. In the field of terrestrial ecology for instance, remote sensing is used for determining ecosystem characteristics such as canopy greenness or vegetation health through vegetation indices like NDVI\(^1\) or EVI\(^2\). With the growing precision in remote sensing techniques, ever more accurate measurements of these indices are expected. However, next to atmospheric and geometric corrections, there is an additional important influencing factor that needs to be corrected for in visual and NIR remote sensing. This is the influence of solar and sensor angles on the measured reflectance. Indeed, remote sensing studies rely on measurement of surface reflectance, which is generally directional and as such is dependent on both the angle of incident light as well as the sensor viewing angle. This means that if no correction is applied for the anisotropic\(^3\) character of the surface, the results of even the most precise sensors are called into doubt.

The influence of sun and sensor geometry on an ecosystem can be characterized by the bidirectional reflectance distribution function or BRDF. Various approaches have been developed to generate BRDF models. Often these are of the first-principles type, where solely rules of physics are used to form the model and no experimental data is needed. This type of model is often preferred as it is a quick and easy method to attain a BRDF. In other cases, semi-empirical models are made that combine physics and a limited set of measured data. Both models are often used and accepted as good approximations of the real BRDF, though only a modest set of measurements is used to validate the accuracy of the predictions. A third and less used model-type is the empirical model, where a large empirical dataset is used to determine the BRDF. In the past, scientists generally refrained from using the pure empirical model due to the difficulty in attaining such a large dataset. However, recent advancements in UAV technology provide the opportunity to quickly measure surface reflectance under various viewing angles and allow the creation of this last model-type. So far, UAV-based

---

\(^1\) Normalized Difference Vegetation Index (NDVI) is index describing vegetation ‘greenness’ based on near-infrared and red light reflectance. \(NDVI = \frac{NIR - red}{NIR + red}\) (Tucker, 1979)

\(^2\) Enhanced Vegetation Index (EVI) is an ‘optimized’ index designed to enhance the vegetation signal using: \(EVI = G\left(\frac{NIR - red}{NIR + C1\cdot red - C2\cdot blue + L}\right)\) (Liu and Huete, 1995)

\(^3\) Exhibiting properties with different values when measured in different directions \(\text{http://www.merriam-webster.com/dictionary/anisotropic}\)
BRDF measurements have been conducted using a so-called goniometer-shape flight plan. With this flight plan, the area viewed is limited and insufficient for heterogeneous, structured surfaces such as forest canopies. It would therefore be interesting to explore alternative flight plans to extend this measurement scheme to the ecosystem level.

BRDF models for two rainforest sites in dry season are constructed based on measurements with a UAV equipped with a near-infrared and visual camera. The typical goniometer-shape flight plan is replaced with a new alternative flight plan, the star-shape. The measurement campaign was held in two separate areas of the Northern Queensland rainforest in Australia. The acquired BRDF models are then used to evaluate the effect of the BRDF on frequently used vegetation indices.
1.2 Literature study

1.2.1 The BRDF concept

1.2.1.1 Definitions

Before the significance of BRDF can be discussed, a clear description of the concept, as it is interpreted in this study, is needed.

To define the bidirectional reflectance it is important to first specify several basic reflectance quantities. These are defined here using the scientifically standardized terminology given by the National Bureau of Standards in 1977 (Nicodemus et al., 1977; Schaepman-strub et al., 2006).

The spectral radiance \( L_\lambda \); [W m\(^{-2}\) sr\(^{-1}\) nm\(^{-1}\)] is the radiant flux \((\Phi \text{ [W]})\) in a beam per unit wavelength \((\lambda \text{ [nm]})\) and per unit area \((A \text{ [m}^2\text{]}\) or \(A \cos \theta \text{ the projected area according to viewing angle } \theta \text{ [rad]}\) and solid angle of that beam \(4 \text{ [sr]}\).

\[
L_\lambda = \frac{d\Phi}{(dA \cos \theta \ d\omega) \ \frac{1}{\lambda}}
\]  
(Eq. 1)

The ratio of the radiant exitance \((M_\lambda = d\Phi/(dA \ d\omega); [W m^{-2} \text{ sr}^{-1} \text{ nm}^{-1}])\) and irradiance \((E_\lambda = d^2\Phi/(dA \ d\omega); [W m^{-2} \text{ sr}^{-1} \text{ nm}^{-1}])\) further results in the reflectance \((\rho_\lambda)\). As the reflectance is a ratio of radiances, it has no unit but has a value between 0 and 1.

\[
\rho_\lambda = \frac{M_\lambda}{E_\lambda} = \frac{d^2\Phi_r}{d^2\Phi_i}
\]  
(Eq. 2)

The reflectance factor \((R_\lambda)\) is then defined as the ratio of the radiant flux reflected by a given surface \((M_\lambda; [W m^{-2} \text{ sr}^{-1} \text{ nm}^{-1}])\) to that of an ideal diffuse (Lambertian) surface \((E_{\lambda, \text{id}}; [W m^{-2} \text{ sr}^{-1} \text{ nm}^{-1}])\), where the radiance does not vary with viewing angle under the same conditions of illumination and observation.

\[
R_\lambda = \frac{M_\lambda}{E_{\lambda, \text{id}}} = \frac{d^2\Phi_r}{d^2\Phi_{\text{rid}}}
\]  
(Eq. 3)

As no surfaces are perfectly Lambertian (100% diffuse, see further), measured reflectance quantities are dependent on both the angle of incident irradiance as well as the viewing angle of the sensor. A function is described that quantifies the geometrical distribution of surface radiance under a certain incident irradiance. This is called the bidirectional reflection distribution function or BRDF. It is defined as the ratio of the radiance scattered by a surface in a specified direction \((L_{\lambda r}; [W m^{-2}\text{sr}^{-1} \text{nm}^{-1}])\) to the unidirectional irradiance reaching

4The solid angle subtended by a surface is defined as the surface area of a covered by the surface's projection onto the sphere [http://mathworld.wolfram.com/SolidAngle.html]
the surface \( (E_{\lambda i}; \text{W}m^{-2}\text{nm}^{-1}) \) for a specific wavelength \( \lambda \) [nm]. The irradiance is a function of the zenith angle \( (\theta_i; \text{[rad]}) \) (angle measured from the Z-axis or the zenith point, imaginary point straight above viewer) and the azimuth angle of the light source \( (\phi_i; \text{[rad]}) \) (horizontal angle compared to a set reference azimuth, usually the magnetic North) (Figure 1). The radiance scattered by the surface varies with incident light and sensor angles, meaning this parameter is a function of the sensor zenith \( (\theta_r; \text{[rad]}) \) and azimuth \( (\phi_r; \text{[rad]}) \) angles as well as of the source angles \( \theta_i \) and \( \phi_i \).

\[
BRDF_{\lambda} = \frac{L_{\lambda r}}{E_{\lambda i}} = \frac{dL_r(\theta_i,\phi_i,\theta_r,\phi_r,\lambda)}{dE_i(\theta_i,\phi_i,\lambda)} \text{[sr}^{-1}\text{]} \quad \text{(Eq. 4a)}
\]

**Figure 1:** Illustration of the zenith and azimuth angles on earth from the point of view of a specific observer standing at the ‘origin’, the intersection of zenith and horizon. The observer turns his head 45° from point N to face point A, this angle is the azimuth value. When the observer tilts his head up 70°, towards point B, this angle is the zenith value - source: [http://www.marysrosaries.com/collaboration/index.php?title=File:Azimuth_003.svg.png](http://www.marysrosaries.com/collaboration/index.php?title=File:Azimuth_003.svg.png)

**Figure 2:** Illustration of the BRDF concept showing the incident light coming from the right and the reflected light leaving the surface in different quantities in various directions - source: [http://www.machrids.wz.cz/blender/index-en.html](http://www.machrids.wz.cz/blender/index-en.html)

The BRDF thus describes the reflectance properties of the observed target. A material is considered perfectly diffuse or Lambertian when the radiance does not vary with viewing orientation or angle of incident light, in which case the BRDF equals 1/\( \pi \). The other extreme
is a perfectly specular surface (mirror surface), where there is minimal scatter outside of the reflectance angle. This situation however only occurs in man-made materials. In nature, no object or surface is perfectly diffuse nor perfectly specular, and so the reflectance changes when the viewing angle is altered (Shell, 2004). These various reflectance models are illustrated in Figure 3.

![Figure 3: BRDF examples illustrating the extremes (specular and diffuse, left) to the more realistic (right) - source: Shell 2004](image)

The surface reflectance of terrestrial ecosystems often changes significantly between various viewing directions, with the lowest reflectance in the forward scattering direction (i.e., with the sun in front of the observer) and highest reflectance in the backscattering direction (i.e., with the sun behind the observer) (NASA, 2016a). This anisotropic scattering of the incident energy can be explained by two effects, namely the surface reflectance and the internal scattering of the studied material. The surface reflectance is a combined effect of the mirror qualities of the surface and its roughness (Kvicala et al., 2013). The former give rise to specular reflectance as mirror-like features, like the waxy cuticula of a leaf, cause directional reflectance in an angle equal to the incidence angle. The roughness on the other hand will give rise to diffuse reflection. It is a measure of the surface texture and is quantified by the amount of surface deviations from the local mean surface height. This roughness causes an interplay between shadow and sunlit facets. In a forest ecosystem, this roughness can be seen both at leaf and at ecosystem level. For example, a flat and relatively homogenous surface such as a desert will have a very low roughness, whereas an uneven-aged forest with various vegetation layers and different plant shapes will have a high roughness value. If a surface is extremely rough, the localized normal vectors of the surface differ greatly between various points on the surface, causing a strong anisotropic reflectance distribution. Another cause of anisotropic reflectance is the internal scattering, where photons get trapped within the material’s hemisphere and bounce between the surface elements (NASA, 2016a; Shell, 2004). In a forest for example, the light often bounces between the tree leaves before escaping the vegetation surface. Figure 4 illustrates these phenomena.
Natural vegetations such as agricultural fields or forests have strongly anisotropic surfaces. Their individual leaves show high anisotropic characteristics due to the cuticula reflectance and a great amount of internal scattering occurs within the layered structure of leaves. But most of all, the complex geometry of plant bodies gives a high roughness value to the ecosystem. Because of this complex geometry, the shadows from leaves and the surrounding vegetation can reduce the radiance reaching or leaving a certain surface. For example, in the forward scattering direction, where the shadow effect is maximal, sensors measure the lowest reflectance values and the vegetation surface appears darker. When the sensor is moved towards the incident light, this shadowing effect decreases and the measured reflectance values increase. This effect becomes very clear when the sensor angle approaches the angle of the incident light and self-shadowing decreases until it is nonexistent. At this point, the BRDF value reaches its maximum, what is called the ‘hotspot phenomenon’. This hotspot is present in the backscattering direction of the illumination source.

1.2.2 BRDF in remote sensing

The BRDF as described above can be used to correct for the anisotropic reflectance of the material. It is mathematically described as:

$$\text{BRDF}_{\lambda} = f_r(\theta_i, \varphi_i, \theta_r, \varphi_r; \lambda) = \frac{dL_r(\theta_r, \varphi_r; \lambda)}{dE_i(\theta_i, \varphi_i; \lambda)} [\text{sr}^{-1}]$$  \hspace{1cm} (Eq. 4b)

where the zenith $\theta$ [rad] and azimuth $\varphi$ [rad] angles together indicate the direction of the light source and the sensor. The subscript $i$ indicates quantities associated with incident radiant flux (emitted from light source), the subscript $r$ indicates quantities associated with reflected radiant flux (measured by sensor), $E$ [W m$^{-2}$ sr$^{-1}$ nm$^{-1}$] is incident irradiance, $L$ [W m$^{-2}$ sr$^{-1}$ nm$^{-1}$] reflected radiance.
From Eq. 4b, it is clear that BRDF is a function of the incident and reflected zenith (θ) and azimuth (φ) angles and the wavelength $\lambda$ [nm]. In this function the zenith angles are determined relative to the local surface normal (where θ=0°). The azimuth is defined relative to the azimuth of the incident light, commonly φ=180° is chosen (Shell, 2004).

### 1.2.2.1 The issue of directional beams

BRDF, as defined in Eq. 4b, is a ratio of infinitesimal quantities and cannot be measured directly. In reality, neither the incident irradiance nor the measured reflectance appear as single directional beams. Indeed, under natural conditions, the incident irradiance is composed of a direct and a diffuse component. The direct component consists of direct sunlight, the diffuse component of the irradiance scattered by atmospheric components such as aerosols, gases, and water particles. Furthermore, unlimited small light sources and sensors do not exist. The Instantaneous Field of View (IFOV), a measure of spatial resolution that defines the angle through which a detector is receiving radiation (often expressed as the ground area that is viewed by a single pixel of the detector at a given moment, does not integrate over infinitesimal differential solid angles. As such the conditions for reflectance measurements do not comply with the requirements for BRDF derivation.

The measurable quantities are better described by a conical or hemispherical geometrical consideration as shown in Figure 5 (Schaepman-strub et al., 2006). The reflectance measurements in remote sensing with aerial sensors and satellites are best described by case 8 in this figure. With the sun as the light source, the size to distance ratio of the light source approaches zero and the incident beam can be considered approximately directional. However, atmospheric conditions give rise to a diffuse component of the irradiance. Under these ambient sky conditions the incident radiance will be of a hemispherical extent. To correct for this diffuse factor an atmospheric correction function must be applied. Furthermore, as the IFOV of sensors used in remote sensing are generally very small, with a full cone angle of approximately 0.1° (Schaepman-strub et al., 2006), the distribution function is equal to that of the directional case as long as the measured irradiance is constant over the entire IFOV. It is thus clear that although direct measurement of BRDF is impossible, a good approximation of this function can be acquired for remote sensing purposes as long as accurate atmospheric corrections are applied.

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5 IFOV [http://www.encyclopedia.com/doc/1O13-instantaneousfieldofview.html]
Another subject of debate in remote sensing BRDF measurements is the validity of the reciprocity principle for BRDF of structured surfaces. The Helmholtz reciprocity principle describes how a ray of light and its reverse ray undergo the same optical path. In BRDF, the incident and refracted light on a surface can be considered reverse rays. If the BRDF is indeed reciprocal, the measured value will be unchanged when the source and detector switch place. When Nicodemus et al. (1977) first described BRDF, it was intended for flat surfaces. Nicodemus et al. (1977) described three necessary conditions which needed to be met. First, the surface must be horizontally homogenous. Second, the area from which the uniform irradiance from a single direction originates must be large enough so the radiance leaving the top of the surface does not vary with horizontal position. Third, BRDF must be defined at one point (Di Girolamo, 2003). When these conditions are met, it is widely accepted that the reciprocal principle is valid for the BRDF. However, the BRDF is also applied to measure the bidirectional properties of structured or rough surfaces, where these conditions are not met and spatial characteristics of illumination and measurement area need to be considered.

The discussion about whether or not reciprocal principle for BRDF is valid for the complex geometry of rough surfaces such as vegetation canopies, is still ongoing. Some researchers say that the abilities of these rough surfaces to focus light, show multiple scattering, and exhibit shadowing effects, will alter the measured value if the light source and detector are switched. Various studies have been conducted with contradicting results (Snyder, 2002a). Li and Wan (1998) for example, conducted measurements of reflective properties of various vegetations from both a tower and an aircraft. They found that the collected data showed significant deviation from reciprocity. However, because the original data source they used

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6 Helmholtz Reciprocity Principle [http://community.worldheritage.org/articles/Helmholtz_reciprocity]
did not discuss reciprocity and they did not perform an error analysis or a comparison of the results with measurement discrepancies, the results of their study are considered insufficient to form a valid argument against the BRDF reciprocity theory (Snyder, 2002a). On the other hand, researchers such as Snyder (2002b) have performed studies that support the reciprocity of BRDF for structured surfaces. By relating BRDF to electromagnetic theorems from physical optics, he showed that for a large class of structured surfaces, BRDF is reciprocal. Yet this study has its limitations as well, as it is based on the physical optics property: obstacle scattering reciprocity. This theory works well for far field geometric measurements, but for near field it only applies between a pair of infinitesimal points. So the conclusions of this study only apply to far field BRDF measurements. Snyder (2002b) attempted to generalize the BRDF definition for the finite field of view case. He argued that by averaging the point BRDF over the finite region, the BRDF obeys reciprocity. But for this definition to fulfill the reciprocity requirement, only the measurement area can be illuminated and no horizontal transfer of light from outside the area may occur. Furthermore, the distribution of media within the measurement area must be periodic outside the measurement area with illumination everywhere at the top boundary (Di Girolamo, 2003). So though Snyders definition of BRDF may obey the reciprocity principle for a certain class of structured surfaces, it is not fully general (Di Girolamo, 2003).

In current BRDF measurement studies, the reciprocity principle is generally assumed to be true for structured surfaces. With this assumption less measurements are needed to build up a model. The reflectance measurements are done under various solar zenith angles and the BRDF is modeled by fixing the solar zenith angle, usually at 30° (Snyder and Wan, 1998). However, if this reciprocity assumption is false, all these existing BRDF models would lose their reliability. It is therefore clear, that the validity of this principle is of great importance to the remote sensing world and more research is needed on this topic. A full empirical model could offer an interesting contribution to the debate. With an elaborate set of measurements taken under various illumination- and sensor angles, a comparison could be made between the model attained with and without sun zenith fixation. If both models correspond well, this would give weight to the reciprocity theory. However, if no such correspondence is found, a strong counter argument could be formed.

1.2.3 Importance and applications of BRDF

BRDF modelling has earned a fair amount of interest due to its many uses. Here we are interested in the valuable contributions the BRDF model can bring to the field of remote sensing. As the non-Lambertian characteristics of earth’s surface are now commonly accepted (Grensdorff, 2011; Von Schönermark, 2004), the BRDF concept has become a real hot-topic in this field of science.
1.2.3.1 BRDF as a function to correct for the sun-target-sensor-geometry

The most important application of BRDF is its application as a correction factor for reflectance data acquired by satellites and airborne remote sensing devices. As natural surfaces are anisotropic (non-Lambertian), the reflectance values measured by a sensor are dependent on the position of both the light source and the sensor. Sometimes sensor positions can be adjusted, like those on UAVs. Mostly however, the viewing angle is set and this is usually the case for satellite measurements. The light source in (outside) remote sensing studies is generally the sun. The sun’s position changes throughout the day and from season to season, meaning measurements at different times can produce varying results. Without correction for these varying angles, the measured reflectance data have little meaning and cannot be compared to data acquired at different days or different seasons, even if the viewing angle did not change. That is where BRDF comes in. The bidirectional reflection distribution function describes the reflection due to the positions of sensor and source. By correcting the measured data with the BRDF, the obtained values are those independent of sun- and viewing position and can be used to draw conclusions about the studied area and make comparisons with other studies (Shell, 2004). This also implies that when an accurate BRDF model is used as a correction factor, more oblique angled sensors can be used. These oblique angles have the benefit that less soil is seen on the images and less shadow interacts with the target surface, giving a better signal-to-noise ratio, and increasing the reliability of the results (Shell, 2004). This is important in sectors as forestry and agriculture, where accurate derivations of biophysical variables like chlorophyll content and biomass are very much desired.

A. Examples of the importance of BRDF correction

i. BRDF effects on Vegetation Indices

An example of the importance of BRDF corrections could be the effect on vegetation indices. Until now, no research has been done on this subject, though the influence could be significant. Vegetation indices are mathematical combinations or transformations of reflectance data in different spectral bands, which give more information about the vegetation than the individual spectral reflectance data can. They can give information about the ‘greenness’ of the vegetation, or the plant status, activity and the density of the vegetation.

The best known example is the Normalized Difference Vegetation Index (NDVI). This is the normalized ratio of the near infra-red and red spectra (Eq. 5):

\[
NDVI = \frac{\rho_{\text{NIR}} - \rho_{\text{Red}}}{\rho_{\text{NIR}} + \rho_{\text{Green}}} \quad \text{(Eq. 5)}
\]

NDVI gives a value between -1 and 1, where the highest values are found in dense, green vegetations (USGS, 2015; Prabakaran et al., 2013; Matsushita et al., 2007). It can be interpreted as a greenness indicator and is related to both greenness (chlorophyll content) of single leaves as to leaf area and density. NDVI is one of the most popular vegetation indices
and is often used to study phenology. However, it is sensitive to saturation, particularly in dense forests. Another alternative is the Enhanced Vegetation Index EVI (Matsushita et al. 2007). This index is based on the NDVI, yet shows an improved sensitivity to dense vegetation. This is the result of a reduction in the atmospheric influence and decoupling of the canopy background signal. EVI is defined as:

\[
EVI = G \frac{\rho_{NIR} - \rho_{Red}}{\rho_{NIR} + (C_1 \rho_{Red} - C_2 \rho_{Blue}) + L}
\]  

(Eq. 6)

Here \( G \) is a gain or scaling factor, \( L \) is a soil adjustment factor, and \( C_1 \) and \( C_2 \) are coefficients used to correct aerosol scattering in the red band by the use of the blue band. In general, \( G=2.5, C_1=6.0, C_2=7.5 \), and \( L=1 \) (Matsushita et al., 2007).

Many other vegetation indices exist and there is an ongoing debate on which vegetation indices respond most accurately to subtle changes in plant phenology (Motohka et al., 2010). Most indices incorporate \( \rho_{NIR} \), but there are a few other indices that only use reflectance of visual spectra (blue, green, red), which can be obtained by consumer-grade phenocams.

The Green Red Vegetation Index (GRVI), developed by Motohka et al. (2010), is one such index:

\[
GRVI = \frac{\rho_{Green} - \rho_{Red}}{\rho_{Red} + \rho_{Green}}
\]  

(Eq. 7)

Motohka et al. (2010) argued that GRVI is more sensitive to leaf colour changes to red or yellow than NDVI. For this index, positive values are found for green vegetations, negative for bare soils and other ground covers. The zero value is used as a threshold value to distinguish between green vegetation and other cover.

Three other common used indices based on reflectance in the visual spectrum are the Excess green index (ExG), the Green Chromatic Coordinate (GCC) (Sonnentag et al., 2011), and the simple Green Red ratio (GRR) (Ritchie et al., 2009 (Eq. 8-10):

\[
Ex_g = 2\rho_{Green} - (\rho_{Red} + \rho_{Blue})
\]  

(Eq. 8)

\[
g_{cc} = \frac{\rho_{Green}}{\rho_{Green} + \rho_{Red} + \rho_{Blue}}
\]  

(Eq. 9)

\[
GRR = \frac{\rho_{Green}}{\rho_{Red}}
\]  

(Eq. 10)

All indices can be interpreted as greenness indices and have been shown to respond closely to differences in ecosystem phenology (leaf area, density and leaf chlorophyll content). They are commonly assessed with phenocams, which are typically fixed on flux towers or on poles over natural canopies. As such, the sensor angle remains unchanged throughout the
measurements (Motohka et al., 2010; Sonnentag et al., 2011). To observe seasonal changes, the measurements are taken at different times of the day, depending on the date. However, the sun position, and thus the illumination source, changes position throughout the seasons and even throughout the day. It is not known, whether these vegetation indices can be applied for seasonal studies without correcting for the changing sun-target-sensor geometry. Sonnentag et al. (2011) argued that the Green Chromatic Coordinate is capable of suppressing the effects of diurnal and seasonal variation and the change in scene illumination to a certain extent. Yet the sensitivity of the index to these variations changed depending on the type of ecosystem where the measurements were done (for example deciduous vs. non-deciduous forests) and in none of the experiments, the variation was fully suppressed.

One goal of this study is to calculate these indices under various viewing and illumination angles and to evaluate the effects of the BRDF. If the changes in vegetation index as a consequence of the sun-target-sensor geometry could be modelled, a correction could be made. With this correction the results from various studies could be compared and possibly prove a valuable contribution towards solving the ‘best index’ debate.

ii. Improving the Landsat archive

Another example is the study done on the effects of BRDF on reflectance estimates made by Landsat 5 sensors (Nagol et al., 2005). The effect of the sun-target-sensor geometry, or the BRDF effect, has not yet been well characterized for Landsat images. In the study by Nagol et al. (2005), the seasonal magnitudinal and latitudinal variation in BRDF on Landsat reflectance measurements and vegetation indices was investigated. The reflectance and BRDF BRDF parameters were extracted from the from Moderate Resolution Imaging Spectroradiometer (MODIS). These parameters can be extracted from MODIS reliably as, onboard the Terra and Aqua satellites, it covers a large area and has a high passing frequency. The data acquired from MODIS for this research was the Nadir BRDF-Adjusted Reflectance (NBAR) product\(^7\). This product gives the directional reflectance data from which the viewing angle effects have been removed. It is the prediction of reflectance for the nadir view at local solar noon. The NBAR is acquired over a 16 day cycle and is computed for each of the seven MODIS spectral bands at local noon. These data were collected for 3 sites at various latitudes and were used to simulate the vegetation reflectance.

The results of this study showed that BRDF does indeed significantly affect Landsat measurements and that the effect varies by latitude. Though Landsat uses consistent overpass times and has a narrow field of view, the assumption of isotropic reflectance when estimating surface reflectance or other surface properties from Landsat data is invalid. BRDF cannot be neglected and applying a correction greatly improves the reliability of the Landsat archive.

\(^7\) MCD43A4 NBAR Product [https://www.umb.edu/spectralmass/terra_aqua_modis/v006/mcd34a4_nbar_product]
iii. Apparent green-up of Amazon forest

A third example that clearly shows the importance of BRDF is in the study of the interannual variability of the Amazon forest. The mechanisms behind this phenology variability are not well understood as several studies have been conducted with ambiguous results. Some studies show decreased photosynthetic activity during the dry season (June-October) due to drought stress (Malhi et al., 1998), while others have found the photosynthetic activity to increase during this season without showing significant signs of stress (Saleska et al., 2003). Huete et al. (2006) found an apparent green-up of the Amazon forest during the dry season, using EVI (Enhanced Vegetation Index) observations from Terra MODIS over the entire Amazon basin. This apparent green-up was attributed to synchronous leaf-turnover during this sunnier dry season as young leaves reflect more near-infra red (NIR) light (Toomey et al., 2009). Furthermore these results suggested that not rainfall but light is the limiting factor for forest productivity. This matches the conclusion made by Saleska et al. (2007), who stated that the increased greenness, seen through satellite measurements, is inconsistent with the expectations from climate models concerning the drought-induced collapse of the Amazon forest. It suggests that the Amazon forest is perhaps more resilient to short-term climate variability than presently assumed (Saleska et al., 2007).

A great controversy exists on this subject though, as some researchers say this observed green-up is merely the result of atmosphere-corrupted data (Samanta et al., 2005) and is insufficient evidence of large-scale greening during dry periods. Morton et al. (2014) challenged the paradigm of light limited net primary production (NPP) in Amazon forest growth during drought conditions, claiming that the Amazon maintains a consistent canopy structure and greenness during the dry season. They stated that the observed increase in EVI and other reflectance-based vegetation indices during the dry season is not necessarily a sign of increased photosynthetic activity but may be the result of seasonal changes in sun-target-sensor geometry, in other words resulting from artefacts of the BRDF-correction. They recognized that the MODIS EVI and LAI used in most green-up studies of this sort are sensitive to NIR reflectance but, as several mechanisms could induce higher NIR reflectance, this data would be insufficient evidence for Amazon green-up. As the studies of Huete et al. (2006) and Saleska et al. (2007) did not explicitly account for changing viewing and illumination conditions, nor normalized to a constant sun-target-sensor geometry for all observations, a correction for these artefacts in optical remote sensing data would be essential to isolate the response of vegetation to seasonal and interannual climate variability. In the study by Morton et al. (2014), the FLIGHT radiative transfer model was used to synthesise a 3D model of the Amazon forest. This model was used to simulate changes in LIDAR and optical remote sensing metrics from seasonal variability in leaf and litter reflectance, LAI, and sun-target-sensor geometry during the dry season. The daily surface reflectance data from Terra and Aqua MODIS sensors (NBAR) were then reprocessed to eliminate artefacts from sun-target-sensor geometry. With this correction, the apparent green-up effect in MODIS EVI
during the dry season was eliminated. Morton et al. (2014) thus concluded that the satellite-observed green-up in the Amazon forest is simply an artefact of sun-sensor geometry variation.

But the debate continued, when in Saleska et al. (2014) responded to the Morton et al. (2014) study in a Nature paper, stating that Morton’s method, of comparing Δ EVI (change in EVI during the dry season) to a preset error estimate of the EVI data, was not enough to assess whether the effects of sun-sensor geometry could fully account for the observed green-up. They argued that, though the corrected Δ EVI is indeed smaller than the uncorrected, a standard statistical test still shows a statistically significant green-up of the Amazon (Saleska et al., 2016). Morton’s reply was simply that Saleska et al. (2014) drew their conclusions from isolated MODIS data (only looking at EVI), thus limiting their insight in the forest mechanisms. Morton et al. (2016) emphasized the need for quantitative error estimates of the MODIS data to ascertain the forest seasonality. And the debate continues as other researchers have found evidence for the dry season green-up effect using data from the Multiangle Imaging Spectroradiometer9 (MISR) (Bi et al., 2015), or tower-based cameras to detect the variation in phenology (Wu et al., 2016).

From this example it is clear, that an accurate BRDF model and good corrections for its effects are indispensible to the remote sensing community, and absolutely necessary to resolve many ongoing debates such as that of the Amazon green-up. Artefacts of the BRDF may have significant effects on optical remote sensing measurements and should not be overlooked. Of course these studies rely on simulated reflectance distributions rather than empirical data, as have many other studies. Drawing up an empirical BRDF model can provide additional evidence for the BRDF effects and refine the BRDF theories. An accurate model is therefore of great importance for the further development in the field of remote sensing.

1.2.3.2 Other BRDF applications

A. Albedo estimation

The surface reflectance properties can be used to estimate the surface albedo for climate models (Shell, 2004). The albedo10 of an object is the fraction of light reflected on the surface. It is a key geophysical parameter that plays an important part in ecosystem’s energy budgets (He et al., 2012). The land surface albedo varies spatially and temporally as vegetation covers differ and seasons change. Also human interference (deforestation, slash and burn agriculture, or construction of roads and buildings) has a big impact on the surface albedo. Defining the land surface albedo is important for all energy budget studies. Especially with current climate change issues, it is very interesting to model the thermal exchange of our planet.

9 The MISR is a sensor aboard the Terra satellite, that views the Earth’s surface with nine cameras simultaneously (Bi et al., 2015)

For the measurement of albedo, two extreme concepts are defined. The first is the so-called black-sky albedo. This concept assumes all energy is coming from direct radiation from the sun, and measures the bi-directional reflection over the viewing hemisphere. The second concept is the white-sky albedo. Here the illumination of the surface is integrated over a hemisphere, complete diffuse illumination is assumed. The real albedo, also called the blue-sky albedo, is caused by a mixture of directional and diffuse radiation. It is calculated by interpolating the black- and white sky measurements, using the fraction of diffuse skylight at the time of measurement. These albedo concepts are visualized in Figure 6.

For these measurements, knowledge of the surface anisotropy is necessary. This is where the BRDF model is needed. To calculate the black-sky directional-hemispherical reflectance, the BRDF is integrated over the exitance hemisphere for a single irradiance direction. For the white-sky (bihemispherical reflectance) case, the BRDF is integrated over all viewing and illumination angles (Strahler et al., 1999). Global land surface albedo data sets are obtained from various satellites. A typical example is MODIS aboard the Terra and Aqua satellites.

**Figure 6**: Illustration of black sky albedo, surface reflection when all illumination comes from direct sun radiation (left) and white sky albedo, surface reflection when illumination is 100% diffuse light (right) - source: European Commission, 2016

B. LAI determination

BRDF can also be used to estimate other surface characteristics, such as to determine the Leaf Area Index (LAI). LAI is defined as the ratio of total one-sided greenleaf area per unit ground area (Mahtab, 2015) and is an important biophysical parameter of the plant canopy. It gives information on the growth and productivity of the vegetation. Next to that the LAI also has an effect on the radiation exchanged between plant and atmosphere. In this way it influences the BRDF model.

Measurement of LAI can be done on the ground but often large scale estimates are wanted, for example for crop growth simulation models. In these cases remote sensing offers a solution. The BRDF model, acquired from remote sensing measurements, is dependent on the LAI of the vegetation and can be inverted, using an optimization procedure, to estimate LAI (Mahtab, 2015).
1.2.4 Modeling BRDF

1.2.4.1 Model types

A. Theoretical models

A first type of model is the theoretical BRDF model, or the first-principle model (Shell, 2014). It relies on first-principle physics of electromagnetic energy and material interactions. More commonly, these theoretical models are known as radiative transfer models, physics-based computational tools to simulate the atmospheric processes (NASA, 2016b). Many of these theoretical models have their origin in optical physics and are manifested in the kirchoff integral of scalar defraction theory, which describes the propagation of light in various configurations using a wave equation (Beckmann, 1963). The inputs for these models are parameters such as the surface roughness and complex index refraction. Theoretical BRDF models have the benefit that they provide quick and easy predictions without any measured data. However, the lack of measurements also makes it difficult to validate the accuracy of the predictions.

An example of a popular theoretical BRDF model is the HE-model (Shell, 2004; HE et al., 1991), a model that has its roots in computer graphics. Another radiative transfer model, used to simulate radiative transfer interactions of light and rough structured canopy surfaces, is the FLIGHT11 model that was used in the study by Morton et al. (2014) mentioned earlier. A last example is the Scope model12, a combined radiative transfer model, where submodels including both leaf and canopy optical models are incorporated.

B. Semi-empirical models

Semi-empirical models use many of the same concepts as theoretical models but also include a modest set of empirical data, such as the measured roughness values, or the reflectance values (BRDF) obtained through monostatic scans around the zenith position. They are prediction models and use measured data to which parameters and constants are fit. The semi-empirical models are the most popular type because they are straightforward and versatile.

There are many semi-empirical models. A well-known example is the Torrence-Sparrow model (Shell, 2004; Torrence and Sparrow, 1967). The model is based on geometrical optics and considers the individual microfacet13 reflections, like many other BRDF models. Each


13 “A tiny facet of the surface of an object being rendered, used in approximating reflections etc.” {http://www.wordsense.eu/microfacet/}
microfacet is treated as a specular surface for which surface normals are distributed according to the Gaussian probability distribution. The diffuse portion of the BRDF is approximated by multiple microfacet reflections. The unknown parameter in this model is the roughness. This value is attained by fitting experimental BRDF data to the model (Shell, 2004).

Another well-known example is the model used in the MODIS BRDF/Albedo algorithm\(^{14}\), namely a semi-empirical kernel-driven model. The kernels are trigonometric functions of sensor- and source zenith angles, and the relative azimuth angle. The BRDF is then modeled as a weighted sum of these kernel functions (Strahler et al., 1996). Typically three components are used for each BRDF model, namely a geometric surface scattering function, a volume scattering function, and a constant. The geometric surface scattering function is represented by the Li-kernel, which allows for a good fit in case of complex shadowed forest canopies (Strahler et al., 1996). This is done by representing the rough surface by a layer with randomly placed spheroidal shapes. The BRDF is then modeled as a function of the relative sunlit, shaded, crown, and background area visible from a certain viewing position. For the volumetric scattering, the Ross-kernel is used, that represents the directional reflectance above a horizontally homogeneous forest canopy (Strahler et al., 1996). Empirical reflectance measurements are then fitted to a set of these semi-empirical models and the best fit is chosen to represent the surface BRDF.

C. Empirical models

Empirical models are those that rely solely on measured BRDF data (Shell, 2004). Through interpolation of the empirical reflectance data, a model is made that is perfectly adapted to the studied area. When measurements are made with reasonable sampling densities, these models show high accuracy. The downside to this model type is that an elaborate dataset is needed, which often requires a significant investment of time and money to collect. Until recently it was also not possible to collect these great datasets for large and rough surfaces such as forest canopies, as no devices could view the necessary large target areas under the different viewing angles. For those reasons empirical BRDF models have been less popular as yet. However, with recent developments in remote sensing, in particular in UAV technology, the possibility for fast and simple BRDF measurements may be here.

1.2.4.2 Measurement devices

As stated before, both semi-empirical and empirical BRDF models require measured data. To make an accurate BRDF model for these model types, a certain target area must be viewed under various sensor and illumination angles. For the semi-empirical models, a modest dataset with a few variations in sensor and illumination angles will suffice. The full empirical models require a more elaborate dataset. In the ideal case the target area is viewed under the full

\(^{14}\) MODIS BRDF/Albedo Product MCD43

[https://www.umb.edu/spectralmass/terra_aqua_modis/modis_brdf_albedo_product_mcd43]
sensor angle range (-180°; 180°) and for all possible azimuth angles (0°-360°). Ideally these measurements are repeated for every possible illumination angle (-180°; 180°).

Although a few commercial devices exist, most measurement systems are customized for the unique application in a certain study. This is also the reason why very few BRDF databases exist, as often inadequate description of the used materials, methods and experimental conditions are given, making it difficult to adapt the system to another user’s interests.

A. Laboratory measurement

For many small or homogeneous materials BRDF can be determined under controlled conditions in a laboratory. A few commercial devices are the SOC200 by the Surface Optics Corporation or the SOC250 designed for its portability and its operation over the VNIR (400-1100nm) and IR (3-12μm) spectrum (Beecroft and Mattison, 1997; Shell, 2004). These laboratory devices are commonly used in quality assessment studies to derive whether a surface meets the required specifications. Customized laboratory measurement methods can also be applied, though only for very limited surface areas, such as single leaves. In these cases an illumination source of small angular extent is generally set at a fixed point and a sensor is used that can measure in several locations to sample under various azimuth and viewing angles. Alternatively, the sensor can be fixed and source and sample are moved around to sample the hemisphere. As most natural materials show heterogeneous characteristics at a larger scale than the average laboratory sample size (think of forest canopy surface), laboratory measurements are not suited and BRDF measurements of these surfaces are best done over larger spatial scales and in their natural environment outdoors.

Figure 7: Image of SOC-200 by Surface Optics Corporation - source:{http://surfaceoptics.com/products/reflectometers-emissometers/soc200/}
In the case of natural materials, the studied surface is often heterogeneous over a spatial extent that is too large for inside laboratory measurements. In these cases, field measurements are conducted, preferably with portable measurement. The advantage of measurements in the field is that with direct measurement of the natural surface and at a greater spatial scale, there is no need to scale up individual material BRDFs that can often interact. Disadvantages are the requirement of good weather conditions (cloud free) and the error of stray light\textsuperscript{15}. This error is further dependent on atmospheric conditions and has a spectral dependence, making the derivation more difficult. Outdoor measurements are generally made over a greater spatial extent. The sample size is considered adequate when the resulting BRDF value is relatively insensitive to changes in the sample area within the FOV of the sensor (Shell, 2004). Outdoor BRDF measurement devices can be divided into three categories, namely the mobile sensors, the immobile sensor and the overhead measurement devices (Shell, 2004).

\textbf{i. Ground-based sensor designs}

The most typical ground-based sensor used for BRDF measurements, is the goniometer. This device can be used to imitate laboratory measurements outside. With the sun as illumination source and the target sample fixed on the ground, the goniometer serves to move the sensor along the hemisphere. Examples of such a system are the Field Goniometer System (FIGOS) or the Sandmeier Field Goniometer (SFG) (Sandmeier, 2000) (Figure 9), whose design is nearly identical. It is made up of a zenith arc resting on an azimuthal circle around the target area. The maximum surface of the target area is limited by the arc measurements. Often it is a circular surface with a radius around 2m, which is still rather limited and allows only for measurements over relatively homogeneous surfaces such as deserts. The goniometer is thus not usable for large surface BRDF studies, such as those over full ecosystems, as here heterogeneity can occur over spatial scales of several dozens of meters. The spectroradiometer

\textsuperscript{15}“Stray Radiant Energy (SRE) or stray light is the measured quantity of light that reaches the detector that is of a wavelength other than that selected.” [http://www.analiticaweb.com.br/newsletter/03/AN51170.pdf]
sensor is computer controlled. Goniometers provide high angular precision and are suitable for highly accurate characterization of field materials. However the system is heavy and takes a long time to assemble, the acquisition time for one hemisphere varies from system to system between several minutes and more than an hour. Measurements with this system are therefore costly and time-consuming in transport and setup. Because of this set-up time, the system also requires good predictions of the weather conditions for suitable measurement periods.
A more recently developed goniometer device is the Manual Transportable Instrument platform (ManTIS) (Figure 10), made at the Alfred Wegener Institute (AWI) (Buchorn et al., 2013). This sector-goniometer holds a hyperspectral sensor system, including two spectro-radiometers for the radiance and irradiance measurements, that can give high quality reflectance measurements of ±6 cm accuracy within the constant observation center. The sensor position can be adjusted up to 30° viewing zenith and 360° azimuth angles. Further advantages are the low-cost and lightweight of the instrument.

**Figure 9**: Field goniometers for BRDF measurements. FIGOS (left), SFG system (middle and right) - source: Shell, 2004

**Figure 10**: ManTIS field spectro-goniometer assembled for a field campaign in the Alaskan Low Arctic showing both GER-1500 spectro-radiometers (front view) - source: Buchorn et al., 2013
In some cases the sensor angle itself is fixed, but changing viewing angles are obtained using various cameras under set viewing angles that move along the axes of the device. This sensor uses a more simple measuring technique, made up of roughly a radiometer on a long pole. The sensor is immobile but the motions around the zenith and azimuth axes, allow measurement at every 5° elevation angle and azimuth angle increment. A good example of this sensor design is the Portable Apparatus for Rapid Aquisition of Bidirectional Observations of Land and Atmosphere (PARABOLA) (Figure 11) (Deering and Leone, 1986). The system consists of two sensor heads mounted on a horizontal pole that rotates continuously along the azimuth circle (0°-360°). Each of these sensor heads, holds four radiometers that synchronously measure from zenith to nadir. Combined with the movement along the vertical axes, the PARABOLA creates a spherical scan around the target area (Helmlinger et al., 2004). This system is used for large homogeneous sample areas. The great advantage of this design is its simplicity and speed, though difficulties are associated with the immobile sensors as well. The sensor for example must be mounted high enough on the mast to ensure that the field of view (FOV) is large enough to average out the inhomogeneities in the landscape. If the texture is not sufficiently averaged, errors will occur in the BRDF data (Shell, 2004).

![Figure 11: Parabola III system showing the sensor and the sensor mounted on broom for field measurements (left and middle) and the PARABOLA field-of-view projection onto the sky hemisphere, and ground projections (right) - source: Shell, 2004 (left and middle), Helmlinger et al., 2004 (right)](image)

ii. Overhead BRDF measurements

Finally BRDF can be obtained from overhead measurements, from satellites, helicopters or UAVs. In various cases where measurements of forest ecosystems or heterogeneous ecosystems are required, the previously defined systems are not able to measure BRDF. This is the case in most ecosystem measurements. Land-based measurement devices such as the goniometer are unfit for this type of measurement due to the height of the vegetation and the lack of homogeneity of the canopy surface. The devices would need unrealistic dimensions to view the canopy surface and a minimum sample area (to approximate homogeneity) beyond the scope of land-based systems. Often these measurement areas are also difficult to reach, think of rainforest canopies. In these cases overhead measurements offer a solution. They can vary from sensors or cameras on satellites or aircrafts. Recently, the use of Unmanned Aerial
Vehicles (UAVs) has also been explored for overhead BRDF assessment. This type of measurement gives rise to an additional factor of uncertainty as the signal needs to cover a great distance to reach the detector during which it can be influenced by atmosphere characteristics. A good atmospheric correction is therefore of great importance.

*Satellite BRDF*

The most often used satellite instrument for semi-empirical BRDF derivation is NASA’s MODIS (Moderate Resolution Imaging Spectroradiometer) aboard the Terra and Aqua satellites. MODIS thanks its popularity for BRDF derivation mainly to its use of a large spectral range, its wide field of view and its frequent coverage of the entire earth’s surface. The Terra orbit is timed to pass over the equator from north to south every morning, while Aqua is programmed to pass the equator from south to north in the afternoon. In this way Terra and Aqua MODIS are viewing the entire earth’s surface every 1 to 2 days. The MODIS BRDF algorithm makes use of these multi-date and multi-spatial passes and uses a kernel-based semi-empirical model to obtain a Nadir BRDF-Adjusted surface Reflectance (NBAR) product (Schaaf et al., 2002). NBAR products are acquired over a 1km grid every 16 days. Though MODIS is a popular choice due to the free availability of data and frequent measurement of large areas, this system also has its downsides. Weather conditions have a great effect on the quality of the BRDF measurement. Because images with cloud cover are filtered out and because of the flying pattern of the satellites, measurement periods cannot be adjusted. The most important drawbacks of this system however lie with the used sensor and illumination angles. The MODIS sensor works with a cross-track scanning along a ±55°scanning pattern (Figure 12). This means that only a small fraction of the possible viewing angles are considered for each area, instead of the ideal ±180°. The sensor azimuth also remains unchanged, each area is viewed under only two different sensor azimuth angles, namely that of the Terra satellite and that of the Aqua one. The satellites Terra and Aqua each pass over an area during the same time every day, meaning BRDF is measured under only two different illumination angles instead of the full zenith range (±180°). So though MODIS may deliver good global BRDF derivations, these must be viewed with caution.
As stated before, the use of Unmanned Aerial Vehicles (UAVs) for determining surface BRDF is a recent development. UAVs are considered to be the middle way approach between ground measurements and manned aircrafts. A great advantage of UAV-use is the flexibility of the measurements. The exact measurement time can easily be adjusted according to the weather conditions so that optimal weather gaps can be selected. Measurements can also be done during different periods of the day and year, allowing data collection under various illumination angles. The sensor viewing angle can easily be adjusted and the same area can be viewed under various sensor azimuth angles.

With a GPS and electronic compass, the UAV is capable of autonomously carrying out complex flights that are needed for good BRDF data. This was studied by Hakala et al. (2010), who programmed a multicopter UAV to fly along predefined paths over the target with high accuracy, taking observations in pre-defined locations from selected directions. What is more, the programming of this system is fairly simple and can be conducted by just two people (Hakala et al., 2010).

A UAV can be equipped with several sensors depending on the specific demands of the user, although the maximum weight of the sensors than can be carried is limited. An example of a complex camera systems is the multi camera system especially designed for micro UAVs with a minimum of 1kg that are now being developed. They allow for oblique looking and converging images along the flight path (Grenzdorffer, 2011). The system is composed of five industrial digital frame cameras with fixed lenses, this configuration is also known as the ‘Maltese Cross’. One camera provides the nadir view and four others provide fixed oblique views in different directions (Figure 13). Another possibility to allow for various sensor angles is through use of an active gimbal (Burkart et al., 2015). The gimbal allows the viewing angle of the sensor to be adjusted during the flights so measurements of the target can be done from several directions (Burkart et al., 2015).
Until now, the UAV-based BRDF studies have used a hemispherical flight pattern, also called a goniometer-shaped flight plan (Figure 14), effectively ‘up-scaling’ of a field goniometer. With this flight pattern images are acquired at a (sometimes limited) set of sensor angles. An example is the flight pattern used by Grenzdorffer et al. (2011) where steps of 30° were made in the azimuth direction and steps of 15° in zenith direction between the various measuring points. BRDF data can be obtained with similar results to ground based field goniometers, over a short period of time, at low cost and with greater flexibility in time management and weather dependency (Hakala et al., 2010). This method is accurate for homogeneous landscapes, but not ideal for very rough surfaces, as the sampled area is limited. For example, if the distance to the vegetation is 100m (this is about the maximal distance feasible with a UAV), and the sensor viewing angle is set to 5°, the targeted area has a radius of only 8.7 m. This is not sufficient for a forest, where crown widths can easily reach up to 20 m. To extend this measurement scheme to structured surfaces the sensor would need to measure at a greater height, which is unachievable with UAV-based studies. In this study an alternative flight pattern is therefore sought, that can offer a solution to the heterogeneity dilemma.

1.2.4.3 BRDF product

The final BRDF product attained from all these modeling types and devices is typically illustrated in a polar plot (Figure 15). It is generally a nadir-corrected reflectance estimate,
meaning the data are estimated for a sensor zenith angle of 0°. The solar zenith angle is set at the local solar noon angle, or at a fixed zenith angle which is typically 30° (Snyder and Wan, 1998). The fixing of the solar zenith at a certain angle can be done when the reciprocity principle is assumed to be true for the surface in question. The azimuth plane is chosen perpendicular to the nadir (0° zenith) axis. The azimuth is defined relative to the azimuth of the incident light, commonly φi=180° is chosen for this incidence angle. The azimuth angles follow the direction opposite of the sun’s movement. With 0° the point exactly opposite the incident light, the angle increases from west to east (Figure 16).

![Figure 15](image1.png)

**Figure 15:** Example BRDF product for wheat reflectance at 480nm shown as a polar plot. Each ‘slice’ represents a different sensor azimuth angles, while each ring represents the sensor viewing angle (with the central ring representing nadir view). The position of the sun during the measurement is shown with the sun-shaped symbol – source: Burkhart et al., 2015

![Figure 16](image2.png)

**Figure 16:** illustration azimuth angles relative to the angle of the incident light
2. Materials & Methods

2.1 Field Campaign

2.1.1 Measurement sites

For this research a field campaign was conducted at two sites in the tropical rainforest of Queensland, Australia. Both wet tropical rainforest sites with a seasonal climate.

The first measurements were done at the Daintree Rainforest Observatory (DRO)\textsuperscript{16}, the eResearch centre in the Daintree rainforest, operated by James Cook University (JCU). The Daintree Rainforest is the largest lowland rainforest area in Australia, with a ground elevation of approximately 65m. With a yearly rainfall of 5143mm, an annual temperature hovering around 24.4°C, and nutrient rich soils, the forest type here can be described as a complex mesophyll vine forest (CMVF), a vegetation with large leaf size and great structural diversity (Webb, 1959). The canopy height varies between 20 and 35m. Measurements at this site were conducted between August 18 and August 22 of 2015, during the dry season.

The second site was the Robson Creek flux station\textsuperscript{17} also managed by JCU, and located on the Atherton Tablelands in the wet tropical rainforests of Australia. This site belongs to the Wet Tropics World Heritage Area\textsuperscript{18}. Situated at Robson Creek, 24km northeast of Atherton on the western slopes of the Lamb Range in Danbulla National Park, this site has an average ground elevation of 700m. The land is moderately inclined with a low relief. Rainfall in this area is more limited than around Cape Tribulation, though with 2236mm yearly, it is still considered a wet tropical rainforest. The yearly temperature average here is 19.4°C. The forest type found in this region is a more simple notophyll vine forest (SNVF), vegetation with limited leaf size and great structural and florictis variation (Webb, 1959), with a canopy height between 26 and 40m. Measurements for the UAV campaign took place here between August 25 and August 28 of 2015.

2.1.2 Instruments and Setup

2.1.2.1 Equipment for aerial measurements

For the measurements a rotary-wing unmanned aerial vehicle (UAV), the Vulcan hexacopter (Vulcan UAV, Gloucestershire, UK), was used with an A2 flight control system (DJI,\textsuperscript{16} FNQ Rainforest Supersite-Daintree node, Terrestrial Ecosystem Research Network (TERN) [http://www.supersites.net.au/supersites/fnqr/daintree]\textsuperscript{17} FNQ Rainforest Supersite-Robson Creek node, Terrestrial Ecosystem Research Network (TERN) [http://www.supersites.net.au/supersites/fnqr/robson]\textsuperscript{18} World Heritage Area – about us [http://www.wettropics.gov.au/about-us]
Shenzhen, China). The hexacopter can carry a weight of up to 10kg, meaning several lightweight sensors can be mounted onto the device. The Vulcan hexacopter is capable of flying fully autonomous along a pre-programmed, waypoint-set flight pattern. The flight time is limited by the battery life to approximately 20 minutes. To sustain the signal between remote control and drone, the vehicle must also stay within a range of 2km. For the Queensland campaign, the UAV take-off was managed manually. Once it was stable in the air, it was switched to the autonomous flight mode, though the UAV remained in sight during the entire flight. When the flight plan was completed, the UAV was switched back to manual pilot for the landing.

The UAV is equipped with a GPS, a barometer (to measure flight altitude precisely), magnetometer and compass to perform its flight. Unfortunately though, the data of these sensors are not logged, and cannot be used for data processing. Another small GPS (Passport GPS Speed Meter, Dynamite RC) was therefore installed on the UAV and logged the latitude, longitude and altitude every 0.5 s.

An active gimbal, the AV2000 gimbal, was also installed onto the drone, controlling the pitch and roll (2-D stabilisation) of the sensors mounted onto the device. It allowed the viewing angle of the sensor to be adjusted during the flights so measurements of the target could be done from several directions. The heading orientation could not be controlled by the gimbal, it was at all times equal to the heading of the UAV.

For the actual measurements, a visual camera and near-infrared camera were mounted onto the gimbal. The visual camera was a Canon S110 (Canon, Japan), with 12.1 Megapixel Canon CMOS-sensor (1/1.7-type) and a DIGIC 5-processor. This camera has a focal length range of 5.2-26mm. During the measurements, it was set at 5.2mm (24 mm equivalent) which corresponds with a field of view of 74° x 53°. At a height of 90 m, the ground area covered by a single image was thus 105 m by 70 m and the pixel resolution was 2.6 cm. Before each flight, the f-number of the sensor was adjusted based on the first shot and kept constant throughout the flight. In this way it varied between 5.6 and 8 for all flights. The camera was programmed with a CHDK to take a picture every 1.2 seconds. All images were taken in Tv-mode, in which the shutter speed, ISO speed, white balance, and exposure time were set manually before each flight.

The near-infrared camera was a Tetracam’s Agricultural Digital Camera (ADC) Lite (Tetracam, Ca, USA) with a camera lens focal length of 8mm. The camera is equipped with a 3.2 Megapixel CMOS sensor (2048x1536 pixels). It is sensitive to green, red and NIR spectra with bands approximately equal to Landsat’s TM2, TM3 and TM4. At a height of 122m above ground level, this camera attains a 100mx75m Field of View (FOV) with a ground resolution of 48.8mm/pixel. The device was fixed onto the gimbal directly above the visual camera to ensure both sensors viewed the same target area under the same forward pitch and heading. The near-infrared camera was programmed to take an 8-bit picture every 2.6 seconds. Before each flight the focal length and exposure time were set manually.
2.1.2.2 Ground Equipment

The ground measurement equipment was set up in a clearing next to the measured forest. The most open and flat area was chosen so the reference panels received as little scatter from the surrounding vegetation as possible. On the ground, a white 75% reflectance panel (Spectralon Labsphere, New Hampshire, US), with near-Lambertian surface properties was installed. Another spectrometer was installed above this panel to allow continuous measurement of the panel throughout the flight. The spectrometer used for this was an OceanOpticsSTS Vis (OceanOptics) that spans the 350-800nm spectrum with 1024 bands, giving a resolution of 0.47nm. The amount of seconds between every measurement varied per day between 2 and 6 due to differences in settings. This spectrometer was connected with a laptop and controlled with OceanView software (OceanOptics). Before the flight, it was connected for dark current settings.

With these continuous measurements the incoming visual and near-infrared radiation during the flight was monitored, allowing for corrections of the incidental light variability during the flight. Next to the 75% reflectance Spectralon reference panel, a range of reference panels (Grey spectralon panel with 10% reflectance, and white, black and multi-coloured panels with unknown reflectance) were placed on a flat surface at the take-off point of the UAV (Figure 19). The black and white panels were matte painted cardboards, the multicoloured panel consisted of 50 differently coloured subpanels. The reflectance of the 10% Grey Spectralon was given by the manufacturer, the reflectance of all other reference panels was measured in lab conditions at the Remote Sensing laboratory of UTS (University of Technology Sydney). The acquisition of these reflectance values will be explained in more detail.
Before and after each flight the UAV was held above the reference panels with the cameras facing down and all reference panels were imaged.

**Figure 19:** Left: Ground equipment set-up; Right: Reference panels (photos of field campaign in DRO Cape Tribulation)

### 2.1.2.3 Flight Plan

The hexacopter UAV, used for this study, can be set to fly autonomously over a predetermined flight plan. To establish this flight plan, various parameters of the flight and drone positioning can be programmed. The drone can be programmed to fly to, and hover at a specific location of which the longitude, latitude and altitude are given. The length of the hovering period and the heading of the drone during this period can be adjusted. When flying from one point to the next, the flight speed can also be set. The heading of the drone during this period can however not be programmed. The UAV will always face its destination point. The viewing angle of the sensors is another parameter that cannot be pre-programmed, but can be adjusted with a switch on the transmitter. The pitch of the active gimbal, carrying the sensors, can be adjusted during the flight.

**A. Alternative Flight Plan**

As mentioned before (1.2.4.2 – UAV BRDF) the goniometer-shape flight plan, that has been the typical choice for UAV based BRDF measurements so far, cannot measure a large enough, representative area to be used over structured, heterogeneous surfaces such as forest canopies. To overcome this problem, an alternative flight plan, the star-shaped flight pattern, was thought up for this study. A Matlab script was developed to program the flight pattern over the desired target area.

This flight plan consists of a 3-level-star-shaped flight (Figure 20) where 6 angular points are set around the target area for 3 different heights and the gimbal tilt is adjusted for every new star from 45° to 30° and finally 0°. The 6 lines of every star are angled 60° from each other, where the heading of the first line is equal to the solar azimuth. The big difference with this
new flight plan in comparison to the goniometer-type, is that the drone does not stop at every angular point but flies from each point to the next in a line crossing the centre of the star. When the sensors aboard the drone are facing the centre of the star, the vehicle is set to fly slowly at a speed of 2 m/s to allow the cameras to make clear images. During this slow part of the flight, measurements are taken over a linear transect of programmable length (in this study, 60 m was used), which ends at the centre of the star. The UAV was programmed so that the exact same linear area is viewed for each viewing angle, and the distance to the vegetation is the same as well. This way, we can make sure that all variation between the viewing angles is due to viewing angle differences. When flights are repeated at different times of the day, the solar azimuth changes, and so does the orientation of the star. The exact same angles relative to the solar azimuth are flown, which implies that the area that is overflown is not the same as in previous or earlier flights. However, similar as in the goniometer design, the centre of the star is the same area for all flights. Furthermore, a large area of vegetation is sampled for each azimuth/viewing angle combination.

![Figure 20: Reconstruction of flight 1 of August 17 2015 above the Cape tribulation site. The green star-shaped shows the targeted area, the blue line represents the programmed flight plan, the red line represents the realised flight (from GPS data). Images showing the target area and flightplan from a nadir view (A), the target area and the realised flight from nadir view (B), and the overlay of target area, programmed flightplan, and realised flight from an oblique viewing angle (C). The visualisation was done by entering the kml-files of this flight into Google Earth.](image)

**B. Programming the flight**

To program the individual flight plans, a Matlab script was developed that can be adjusted for each flight using the following input arguments:

- Location of target area (centre of star) (latitude, longitude, altitude)
- Location of home point (latitude, longitude): point close to taking off/landing location from which the UAV will depart (first Waypoint) and to which it will return (final waypoint).
- Hour of flight + UTC offset: With these inputs, together with the target location, the solar azimuth was calculated using the Matlab function sun_position (Sultan, 2004).
- Vegetation height: was taken at 25 m for Cape Tribulation and Robson Creek
- Distance between UAV and vegetation: this determines the size of the ‘footprint’ watched and was set at 80 m for all flights
- Length of track path: this was taken as 60m for all flights.
- Viewing angles (in the correct order). For all flights, viewing angles of 45°, 30° and 0° were used.
- Flight speeds during slow part (scanning the lines) and fast part (track in between the scan lines)

The target locations were set where the terrain slope was minimal (near-horizontal canopy surface), and where the UAV could remain visible throughout its flight.

With all this information, the script derived the flight plan for each flight with for each point the waypoint location, heading, altitude, hovering time (if any), flight speed and climbing rate and turn mode. This was exported as a AWM file which was opened in Ground Station 4.0.11 (DJI, Shenzhen, China), the software used for communicating with the UAV. The waypoints were sent to the UAV using the wireless 2.4 GHz Data Link module. After going through all safety checks and calibrations, the UAV was brought in the air by the pilot and finally set to waypoint mode with the Data Link module. With this information, the UAV then autonomously flew along each flight plan.

During the flight campaign, two adjustments to the script were incorporated. With the first adjustment, the UAV started the star-flight from the corner point of the star which was closest to the home position, instead of the azimuth direction, in order to reduce flight time. The second adjustment made sure that before flying a scan line, the UAV turned in the right direction and hovered for a few seconds, thus guaranteeing that the entire scanning line was scanned with near-optimal heading.

**Table 1:** Overview of measurement flights

<table>
<thead>
<tr>
<th>Date</th>
<th>Location</th>
<th>Local time</th>
<th>Solar zenith</th>
</tr>
</thead>
<tbody>
<tr>
<td>August 19 2015</td>
<td>Cape Tribulation</td>
<td>13:19-13:35</td>
<td>33.0°</td>
</tr>
<tr>
<td>August 22 2015</td>
<td>Cape Tribulation</td>
<td>09:49-10:12</td>
<td>44.25°</td>
</tr>
<tr>
<td>August 26 2015</td>
<td>Robson Creek</td>
<td>09:30-09:44</td>
<td>47.7°</td>
</tr>
<tr>
<td>August 26 2015</td>
<td>Robson Creek</td>
<td>11:00-11:15</td>
<td>31.8°</td>
</tr>
<tr>
<td>August 26 2015</td>
<td>Robson Creek</td>
<td>11:45-12:00</td>
<td>28.2°</td>
</tr>
<tr>
<td>August 26 2015</td>
<td>Robson Creek</td>
<td>12:46-13:02</td>
<td>29.4°</td>
</tr>
<tr>
<td>August 26 2015</td>
<td>Robson Creek</td>
<td>13:29-13:45</td>
<td>34.3°</td>
</tr>
<tr>
<td>August 26 2015</td>
<td>Robson Creek</td>
<td>14:45-15:02</td>
<td>48.1°</td>
</tr>
</tbody>
</table>
2.2 Data Processing

2.2.1 GPS data

The small GPS logger (Passport GPS Speed Meter, Dynamite RC) that was installed on the UAV logged the latitude, longitude and altitude every 0.5 s. The data from this GPS were downloaded onto the computer as KML files. A Matlab script was developed to read these files, correct them for errors, and export the data as a KML file (for visualisation in Google Earth) and as a data table of the latitude, longitude and altitude of the drone for each 0.5 s.

2.2.2 Visual Image processing

2.2.2.1 Overview

To gain a clear overview, the processing steps are summarized in following flow chart (Figure 21). Each of the chart colours represent a different step in the image processing and will be explained in detail further on.
Figure 21: Representation of the data processing for the images from the visual camera (Canon S110). With grey image preparation, green image registration, blue image selection, purple vignetting and distortion corrections, yellow reflectance calculation, orange BRDF extraction, and red reciprocity testing. Rectangles represent actions, rhomboids represent export products, ellipsoids represent the start and end products.
2.2.2.2 Image preparation

The visual images were downloaded from the Canon S110 camera. Blurry image were removed and only images during the flight and of the reference panels were maintained. In addition, during several flights, the sky was not clear throughout the entire UAV flight and clouds moved in front of the sun, thereby influencing the incident light. The images taken during these cloudy periods could not be used for BRDF modeling and were removed from the dataset.

2.2.2.3 Image Registration

As the goal of this study is to model the influence of the sensor viewing angle and illumination angle on the surface reflectance, it is crucial to know the sensor positioning at the time of each measurement as accurately as possible. This requires information of the longitude, latitude and altitude of the sensor, as well as the yaw (heading), pitch (viewing angle), and roll (Figure 22) of the device at the time of each measurement.

![Figure 22: Pictorial representation of Yaw, Pitch, and Roll - source: {http://toronto-soaring.ca/wordpress/?page_id=30}](image)

From the GPS loggings, only the coordinates of the drone position at each measurement time can be derived, but not the other data. The viewing angle (pitch) was manually set to 45°, 30°, and 0° using the transmitter switch, but being a manual switch, this setting was not very precise. Furthermore, although the gimbal stabilized the pitch, it still changed during the flights, particularly when strong winds tilted the drone. Similarly, the UAV was programmed to correct the roll and keep it at 0°, but the gimbal correction was not adequate enough and changed during the flights. The heading of the UAV (yaw) was not perfectly nose-in but was influenced by the winds as well, and also changed constantly. The programmed pitch, yaw, and roll were therefore not adequately reliable as estimates for the actual camera positions.

To solve this problem, the images of each flight were loaded into Agisoft software (AgiSoftPhotoscan Professional Edition, v 1.2.3; Agisoft, St. Petersburg, Russia), a software package to align UAV imagery. A Matlab script was developed to match each image with the recorded GPS-position, used as input for the software. The software aligned the images and reconstructed the 3D point clouds of the vegetation (alignment phase). During this process, the program calculates the actual latitude, longitude, altitude, yaw, pitch and roll of the
camera for each image. However, because of the limited accuracy of the GPS logger, particularly for altitude measurements, this point cloud was often ‘tilted’. To correct the 3D point cloud, several ground control points, with well-known latitude, longitude and altitude, were added. The AgiSoft processing chain is therefore a multi-step process.

In a first step, an orthophoto, elevation model and terrain model was generated for each of the measuring sites. These products were generated by running AgiSoft with data of the best flight (no clouds, bright, limited wind) from each site. First, images were aligned (setting the alignment at “high accuracy”), after which ground control points were selected and added (with longitude, latitude, altitude data obtained from Google Earth). After this, a dense point cloud was generated (setting the density at “medium density”), on which a 3D mesh was built, leading to a digital elevation model (3D model of the site including terrain and vegetation). To derive the Digital Terrain Model (DTM), ground points were selected using the Classify Ground Points feature. The identified ground points were manually corrected, removing part of the points, and a new 3D mesh was built on the remaining ground points. Based on this new mesh, a DTM was developed. Both DTM and DEM were exported and an orthophoto (resolution 3.2cm/pixel) was created using the DTM as basic mesh.

These three products (Orthophoto, DEM and DTM) could then be opened in QGIS (publisher) or ArcGIS (ESRI, California, US), where they were georeferenced using satellite-based imagery from the ArcGIS library as ground truth. The orthophoto was used to identify recognizable Ground Control Points\(^{19}\) (GCPs) for the aligned images of all flights. With these GCPs, the point cloud could be further georeferenced, correcting for the tilt in the point cloud and improving the precision of the estimated camera positions. The longitude and latitude data of these GCPs could be extracted from the orthophoto directly. Retrieving the altitude data proved a little more difficult. The vegetation height at each point could be determined by subtracting the DTM height from the DEM height at the same coordinates. However the generated DEM and DTM models did not offer accurate data of the height above sea-level. Thus, to acquire accurate values of this height, a Google Earth-derived internet product was consulted (Altitude.nu), which uses interpolation of the Google Earth altitude values. The vegetation height was then added to the height above sea-level to attain the altitude data. The longitude, latitude and altitude values for these GCP’s were then entered into the AgiSoft program and the flight was re-aligned using this new information. For each flight 5-15 GCP’s were added until the tilt was resolved and the images were neatly aligned. The estimates of the camera positions (latitude, longitude, altitude, yaw, pitch and roll) obtained after this re-alignment, corresponded well with the flight plan and the expected camera positions, and were considered reliable estimates of the real camera positions. They were exported from AgiSoft for every flight. The process is illustrated in following flow chart.

\(^{19}\) Ground Control Points are defined as points on the surface of the earth of known location used to geo-reference remote sensing data [http://landsat.usgs.gov/ground_control_points.php]
Figure 23: Overview of Image registration process from extracting the GPS logging to exporting the estimated camera positions from AgiSoft. The subprocess on the left is only done once for each site (using the best flight for each site), the other steps are repeated for each flight. The ellipsoids represent the start- and endpoint of the process, rectangles are actions, rhomboids are export products. The grey arrows show the order of the sequence of the steps, the brown arrows represent inputs.

2.2.2.4 Image Selection

Only the images obtained when the UAV was looking at the target area (linear transect) were maintained for the further processing. The images were selected by combining the Longitude, Latitude, Altitude and Heading information for every image to determine its placement in the star-shaped flight plan, and extracting those with the desirable location and heading. With a Matlab script, the selected images were then sorted into files based on their programmed viewing angle and flight line azimuth angle (heading). For the nadir-viewing measurements, all images were kept and collected in one file, independent of the camera heading at the time of measurement, as azimuth has no effect on nadir images. For the measurements under sensor viewing angles of 30 and 45°, the selected images were collected in 6 different files for
each of the flight line headings (0°, 60°, 120°, 180°, 240°, 300° relative to the solar azimuth). This means that in total 13 files were created with selected images.

### 2.2.2.5 Vignetting & Distortion correction

Before the reflectance data could be extracted from the images, corrections needed to be made for the unwanted effects of vignetting and image distortion.

A. Vignetting

The vignetting effect can be seen as the reduction of the image brightness for the pixels near the periphery of the image (Figure 24). To correct for this effect, the seven different camera settings (shutter speed-f-number combination) during each flight were retrieved and for each setting the vignetting effect was measured separately, following the approach of Kelcey and Lucieer (2012).

![Figure 24](image1.jpg)

**Figure 24:** Illustration of the effects of vignetting: Original image (left), image exhibiting the radial shadowing of vignetting (right) - source: Kelcey and Lucieer, 2012

A matte grey panel with known reflectance of 18% (B.I.G. photo equipment, Germany), was placed on a flat roof, where the influence from the surroundings was limited. The camera settings were changed to match those during the measurements and images were taken of the grey panel from various angles. For each of the camera settings, approximately 300 pictures were taken.

The next step was to calculate the mean reflectance value of the central pixel, over all 300 images and for each of the channels (Red, Green, Blue). The ratio of these central values and the RGB reflectance values from each pixel were then calculated for all images. The outliers were removed and the mean ratio was calculated using the Matlab function ‘trimmean’ (excluding 25% of the outlying values). The script yielded three matrices, one for each of the channels, with for each pixel the multiplication factor needed to correct for the vignetting effect (Figure 25). For every image, the RGB reflectance values of each pixel were then multiplied by the corresponding values in these vignetting matrices to remove the vignetting effect (Figure 26).
Figure 25: Vignetting matrix for channel 2 (green channel) for Canon S110 images taken with shutter time 1/1600 and f-number 8. The pixel values between 0.9369 (black) and 1.3722 (white) represent the multiplication factor needed for eliminating the vignetting effect. The lighter circle in the middle of the image is the result of an impurity on the camera lens, as this circle can be seen on all vignetting correction matrices, it is considered a systematic error in each image. With the vignetting correction this impurity is thus resolved.

Figure 26: Picture of flight 1 on August 19 2015 (taken with Canon S110 with shutter time 1/1600 and f-number 8), before (left) and after (right) vignetting correction. If you look closely you can see the top and bottom edges got lighter after the correction.

B. Distortion

The distortion in images can be seen as a deviation from the original shape, generally near the image periphery (Figure 27).
The correction of this distortion effect was done with the program AgiSoft Lens (AgiSoft Lens V0.4.0., Agisoft LLC, 2011, Russia). This is an automatic lens calibration software that calculates the radial distortion coefficients using the Brown-Conrady distortion model (Brown, 1966). Agisoft Lens software uses a pinhole camera model for lens calibration.

With the chessboard command, a built-in calibration pattern was displayed onto the computer screen. Changing the camera settings to the f-number and shutter speed corresponding to those used during the measurement flights (again 7 different combinations), several images were taken of this calibration pattern from various angles. A minimum of 20 images were taken for each camera setting. These images were imported in the Agisoft Lens program and the calibration tool was used to estimate the radial distortion coefficients $K_1$, $K_2$, $K_3$, $P_1$, and $P_2$ (Figure 28A and B). With these coefficients, the local camera coordinates for each image were then transformed using Eq. 11-14 (Agisoft Lens User Manual: Version 0.4.0, 2011), eliminating the distortion effect.

**Figure 27:** Illustration of lens distortion: original (left), barrel lens distortion (middle), pincushion lens distortion (right) - source: Kelcey and Luc-ieer, 2012

**Figure 28A:** Radial distortion for Canon S110 with shutter time 1/1600 and f-number 8 (Agisoft Lens output)
Figure 28B: Tangential distortion for Canon S110 with shutter time 1/1600 and f-number 8 (Agisoft Lens output)

Figure 29: Picture of flight 1 on August 19 2015 (taken with Canon S110 with shutter time 1/1600 and f-number 8), with vignetting and without distortion correction (left), with vignetting and with distortion correction (right)

\[ x = \frac{x}{z} \]  
\[ y = \frac{y}{z} \]  
\[ x' = x(1 + K_1 r^2 + K_2 r^4 + K_3 r^6) + P_2(r^2 + 2x^2) + 2P_1 x y \]  
\[ y' = y(1 + K_1 r^2 + K_2 r^4 + K_3 r^6) + P_1(r^2 + 2y^2) + 2P_2 x y \]
With (X, Y, Z) coordinates in the local camera coordinate system, (x, y) the projected coordinates in the image frame before distortion correction, and (x', y') the projected coordinates in the image frame after distortion correction.

2.2.2.6 Reflectance Calculation

A. Acquiring the reflectance of all reference targets

The reflectance of the 10% Grey Spectralon was given by the manufacturer, the reflectance of all other reference panels was measured in lab conditions at the Remote Sensing laboratory of UTS (University of Technology Sydney). The spectral properties of the black and white Corflute panels were measured with a FieldSpec spectroradiometer (ASD Inc, PANalytical, Eindhoven, The Netherlands), the reflectance of the multicolour panel was measured with a SOC710-VP hyperspectral imager (Surface Optics Corp., CA, USA). Measurements were taken under white light lamps and using a 10° Spectralon 99% Diffuse Reflectance Standard as a white balance, which was placed at the exact same location just prior to measuring/capturing the reference. The reflectance was then calculated for each wavelength as the ratio of the radiance (dark noise-corrected) of reference panels and that of the observed Spectralon 99%. The hyperspectral image was opened in ENVI 4.7 (Exelis Vis, Colorado, US) and was analysed with the Region Of Interest (ROI) tool. To define which wavelengths are assigned to each of the image bands, we looked at the spectral response graph for the Canon S110 and selected the spectrum giving peak response values for each band (Figure 30).

![Figure 30: Graph of spectral response for each of the image bands (R,G,B) of the Canon S110 visual camera. The Red band has peak values between 600 and 680nm, the Green between 495 and 570nm, and the Blue between 450 and 490nm](image)

B. Calculating reflectance of visual images

Once all these corrections were made, the next step was to find the absolute reflection of the target area in each image. The relation between the at-sensor radiance and the reflectance is
generally assumed to be linear. However for the Canon S110, the at-sensor radiance data (RAW data) were not available and the brightness could only be extracted from the digital number (DN) of the JPG images for each image pixel. For many commercial cameras the relationship between the DN and the absolute reflection is not linear but rather curvilinear (Wang and Myint, 2015). This curvilinear function is used to transform electromagnetic radiation to digital signals, in the same way the human eye perceives greyness. This results in better looking pictures, but is less usable for scientific research. To convert these DNs to absolute reflectance, the relation between both needs to be found. This was done here using the measurements over the reference panels.

As mentioned, the reference panels were imaged before and after each flight. The brightness (0-255) of reference panels and subpanels was obtained using Image J (Open source image processing program) for the three spectral bands (Red, Green, Blue). Brightness values were then plotted against the known reflectance values, and an exponential curve fitted through the dataset (Figure 31). This exponential relation was then used to convert all brightness values from the flight images to reflectance values.

![Figure 31: Absolute reflectance in function of the DN for the reference panels for flight 1 on August 26 2015](image)

The settings (i.e. ISO speed, shutter speed, focal length, f-value) of the camera did not change once they were in continuous logging mode. As such, if the incoming light remained constant, the reflectance of all images during the flight could be calculated from the observed brightness values.

Next, a correction was applied for the fact that the irradiance was not constant throughout the flight. The spectrometer OceanOptics STS Vis (OceanOptics, Florida, USA), was continuously measuring the radiance of the Spectralon 75% diffuse reference target during each flight. A Matlab script was developed to assess this radiance at the moment of image capture of each image. The ratio of the Spectralon reference panel reflectance at the imaging time and the Spectralon reference panel reflectance at the time when the reference targets were imaged could then be used as a correction factor. Finally, the corrected reflectance data
was acquired for each image by multiplying the absolute reflectance data, attained from the previous step, with this ratio.

### 2.2.2.7 BRDF extraction

With the correct camera positions at the time of each image, attained through image registration (2.2.2.3), it was now possible to find the target area within each image and extract the corresponding reflectance values. This was done in several steps.

#### A. Finding the target areas

i. Calculating the coordinates of the projected image, including pitch and roll effects

The Instantaneous Field of View (IFOV) is not constant for all pixels within the image. This can be seen in Figure 32, an image taken with the visual camera of a checkered pattern (AgiSoft Lens).

![Figure 32: Image taken with Canon S110 of the checkerboard pattern provided by AgiSoft Lens (used for measuring the distortion), distances remain equal throughout image](image)

With a constant IFOV, pixels near the image periphery would view a larger ground area and distances would be compressed. However, each normal (i.e. not fish-eye) camera lens aims to preserve the distances throughout the image, implying that not the IFOV, but the measured ground area is constant for each pixel. This constant Ground Sampling Distance (GSD), or Ground Projected IFOV (GPIFOV), is thus only dependent on the height of the camera above the imaged object (Pix4D, 2016). For example, at a flight height of 50m above the images surface, the GDP of each pixel is 1.7cm (MenciSoftware, 2015). This can be expressed with Eq. 15. The symbols used in this equation are explained in Figure 33:
\[
\frac{L'}{H} = \text{constant} = \frac{L}{\text{Resolution}} = \frac{\tan\left(\frac{\text{FOV}}{2}\right)H}{\text{Resolution}}
\]  
(Eq. 15)

**Figure 33:** With L the length of the ground area portrayed in half the image, L’ the fragment of this length that is viewed by one pixel, H the height above the imaged object (here flying height – vegetation height), the resolution the amount of pixels over the image length.

The same concept can be used in the plane perpendicular to the page, to calculate the width of the ground area viewed by each pixel.

\[
\frac{W'}{H} = \text{constant} = \frac{\tan\left(\frac{\text{FOV}}{2}\right)H}{\text{Resolution}}
\]  
(Eq. 16)

With W’ the fragment of the area width viewed by one pixel, H the height above the imaged object (here flying height – vegetation height), the resolution the amount of pixels over the image width. In Eq. 15 and in all following equations, the height H was calculated as the difference of the actual flight height and the canopy height.

In a first step, the image coordinates \((X, Y)\) [m] were calculated assuming that the camera had a viewing angle of 0° (nadir viewing), so ignoring pitch and roll (and yaw) for now. The image coordinates give the imaged ground distance [m] relative to the area viewed at the center of the image, in other words the width and length of the imaged ground surface. The Y-axis is set along the vertical axis of the image plane, the X-axis perpendicular to this, along the horizontal axis. As the camera was facing downwards during the measurements, the heading of the Y-axis is equal to the sensor heading (actual azimuth). Because the image coordinate system uses the center of the image as origin, the image center was assigned a coordinate of \((0, 0)\) and all image coordinates were calculated relative to this image center.

The pixel coordinate system \((u, v)\) has its origin in the top left corner of the image. To convert the pixel coordinates to image coordinates, the origin first needed to be moved to the center of the image. This was done by subtracting the pixel numbers \(u\) and \(v\) by these of the center pixel \((u_c, v_c)\).

The image coordinates of a pixel with pixel coordinates \((u \text{ and } v)\) then became:
With \((X,Y)\) image coordinates, \((u,v)\) pixel coordinates, \((c_x,c_y)\) the center pixel coordinates, and \((L', W')\) the length and width of the ground area covered by each pixel (GSD).

The next step was to take the pitch and roll of the camera into account (Figure 34). The effect of the roll on the image coordinates can be conceptually interpreted as a rotation of \(\text{Roll}\) degrees of the image in the X-direction (or around the Y-axis) (Figure 35A). This 3D rotation implies that a Z-coordinate is needed to describe the image coordinates.

\[
X = ((u-u_c) - c_x) L' \tag{Eq. 17}
\]
\[
Y = ((v-v_c) - c_y) W' \tag{Eq. 18}
\]

\[
\text{Figure 34: Illustration showing the Pitch Roll and Yaw axes, Assuming that the camera is mounted such that the x axis of the camera points towards the right wing, the y axis is pointing towards the tail and the lens is pointing down – source: How does Pix4D define Yaw, Pitch, Roll?, 2015}
\]

The new X-coordinate of the image centre incorporating roll is \(X_{\text{Roll}} = H \times \tan(\text{Roll})\), whereas the Y-coordinate is not affected \((Y_{\text{Roll}}=0)\) and the center is still located on the original XY-plane \((Z_{\text{Roll}}=0)\). The projected X-coordinate \((X_{\text{Roll}})\) of the other pixels is the sum of this translation \((H \times \tan(\text{Roll}))\) and the vertical projection of its coordinate \(X \times \cos(\text{Roll})\), or \(X_{\text{Roll}} = \cos(\text{Roll}) \times x + H \times \tan(\text{Roll})\). Its Y coordinate is not affected by the roll \((Y_{\text{Roll}} = Y)\), its Z coordinate becomes \(Z_{\text{Roll}} = X \times \sin(\text{Roll})\).

Similarly, the effect of the pitch on the image can be interpreted as a rotation of \(\text{Pitch}\) degrees in the Y-direction (or around the X-axis) (Figure 35B). The combined effect of pitch and roll on the projected coordinates \((X_{PR}, Y_{PR}, Z_{PR})\) then becomes:

\[
X_{\text{PitchRoll}} = \cos(\text{Roll}) \times X + H \times \tan(\text{Roll}) \tag{Eq. 19}
\]
\[
Y_{\text{PitchRoll}} = \cos(\text{Pitch}) \times Y + H \times \tan(\text{Pitch}) \tag{Eq. 20}
\]
\[
Z = \sin(\text{Roll}) \times X + \sin(\text{Pitch}) \times Y \tag{Eq. 21}
\]
With \( X_{\text{PitchRoll}}, Y_{\text{PitchRoll}}, Z_{\text{PitchR}} \) the coordinates in the realistic coordinate system where pitch and roll are taken into account, \( X \) and \( Y \) the image coordinates, \( \text{Pitch} \) the pitch of the central pixel, \( \text{Roll} \) the roll of the central pixel, \( c \) the center pixel in case of no pitch and roll, and \( C_{\text{PitchRoll}} \) the center pixel when pitch and roll are accounted for.

However, assuming the canopy is a flat plane with \( z=0 \), the coordinates of the canopy area that is actually imaged in image point \((X,Y)\) can be obtained by drawing a fictional line between the sensor position \((X=0, Y=0, Z=H)\) and \((X_{\text{pr}}, Y_{\text{pr}}, Z_{\text{pr}})\), and calculating the intersection of this line with the \( XY \)-plane:

\[
X_{\text{proj}} = \frac{-1 \cdot H \cdot X_{\text{pr}}}{Z_{\text{pr}} - H} \quad \text{(Eq. 22)}
\]

\[
Y_{\text{proj}} = \frac{-1 \cdot H \cdot Y_{\text{pr}}}{Z_{\text{pr}} - H} \quad \text{(Eq. 23)}
\]

**Figure 35A:** Illustration of influence of the Roll in the XZ-plane (the Y-axis is facing into the page). With \( c(0,0) \) the original image center and \( X \) the X-coordinate of a point \( \Delta X \) from the center with \( Z=0 \) (and \( Y=0 \)). Taking the Roll into account, the new image center is \( c_{\text{Roll}} \), the point \( X \) now moved to \( X_{\text{Roll}}, Z_{\text{Roll}}(Y=0) \). The point is then projected onto the XY-plane at \( X_{\text{proj}}(y=0) \).
Figure 35B: Illustration of influence of the Pitch in the YZ-plane (the X-axis is facing into the page). With \( c(0,0) \) the original image center and \( Y \) the Y-coordinate of a point \( \Delta Y \) from the center with \( Z=0 \) (and \( X=0 \)). Taking the Pitch into account, the new image center is \( c_{Pitch} \), the point \( X \) now moved to \( Y_{Pitch} \), \( Z_{Pitch} \) (\( x = 0 \)). The point is then projected onto the XY-plane at \( Y_{Proj} \) (\( x = 0 \)).

The resulting projected coordinates X and Y thus represent the correct distance [m] on the ground surface relative to the centre of the imaged surface.

ii. Obtaining the coordinates of the target pixels

In the previous step the image coordinates were calculated and a correction was made for the pitch and roll of the central pixel. The XY-map attained represents the projection of the image onto the canopy surface plane. The canopy surface is here considered to be a flat surface.

In the next step, the goal was to find the XY-coordinates [m] of the target pixels and the surrounding target area. The target pixel is defined as the pixel for which the yaw, pitch, and roll angles are closest to the targeted yaw, pitch and roll. The target area represents the collection of pixels around this target pixel of which the reflectance data is used to calculate an average. By taking into account the targeted pitch, yaw and roll, the projected coordinates of these target pixels were calculated. The pitch (zenith) angle determines the distance between the origin (\( c(0,0) \)) and the target pixel. The yaw (azimuth) angle determines the angle between the origin and the target pixel. The combination of the targeted zenith and azimuth angles thus define the polar coordinates of the target pixel, which can be converted to XY-coordinates. The resulting XY-coordinates of the target pixels and the surrounding target area, could then be compared to the projected coordinates from the previous step to locate the target pixels on the image and extract the reflectance data.

This was done in two sub-steps. First, only the targeted pitch and roll were taken into account. For each image the first targeted pitch was chosen as the desired target pitch closest to the actual pitch of the central pixel. For example, an image of which the central pixel had an actual pitch of 32°, the first targeted pitch was 30°. Additional target pitches were those with a
5° and 10° difference with the first. In this example these would be target pitches 20°, 25° and 35°. For BRDF measurements no roll is desired, that is why the target roll was always set at zero. With the target roll set at zero, the distance of the targeted pixel could be calculated using following equation:

\[ Y_{dist} = \tan (\text{Pitch}_{\text{target}}) H \]  
(Eq. 24)

\[ \Delta \text{Az} = \text{Az}_{\text{actual}} - \text{Az}_{\text{target}} \]  
(Eq. 25)

\[ X_{\text{target}} = Y_{\text{dist}} \sin (\Delta \text{Az}) \]  
(Eq. 26)

\[ Y_{\text{target}} = Y_{\text{dist}} \cos (\Delta \text{Az}) \]  

Figure 36: With H the height above the imaged object (flight height – vegetation height), Pitch\(_t\) the targeted pitch, c(0,0) the center pixel, \(c_c(0,Y_{\text{dist}})\) the center pixel at targeted pitch, \(Y_{\text{dist}}\) the distance on the Y-axis between the center pixel and pixel with targeted pitch

The obtained coordinates \((0, Y_{\text{dist}})\) thus correspond to the location of the target area [m] before the azimuth is taken into account. The next step was to incorporate this azimuth.

The difference between the actual azimuth direction of the camera and the targeted azimuth was calculated as \(\Delta \text{Az}\). The targeted coordinates could then be found by rotating along this \(\Delta \text{Az}\).
**Figure 37:** illustration of the target pixel coordinates. With ΔAz the angle between the targeted azimuth and the real azimuth of the image, $Y_{\text{dist}}$ the distance on the Y-axis over which the center pixel is moved under targeted pitch, $c(0,0)$ the original image center, $c_{\text{target}}$ the image center under targeted pitch, $X_{\text{target}}$ and $Y_{\text{target}}$ the coordinates of the pixel under targeted pitch and azimuth.

$X_{\text{target}}$ and $Y_{\text{target}}$ are the coordinates of the target pixel. The next step was to create the target area, the mask around this target pixel.

The target area was defined as the area within a pre-defined viewing angle (set to 2.5° for all pixels) of the target pixels. If the azimuth is not taken into account, this target area can be seen as the circle defined by Eq. 27-29:

$$X_{\text{NoAz}} = \tan\left(\frac{\sin(\text{angle}) \cdot \text{LensAngle}}{2}\right) \frac{H}{\cos(\text{Pitch}_{\text{target}})} = \frac{X}{D}$$  

(Eq. 27)

$$Y_{\text{NoAz}} = \tan\left(\text{Pitch}_{\text{target}} + \cos(\text{angle}) \cdot \frac{\text{LensAngle}}{2}\right)H$$  

(Eq. 28)

$$R = \sqrt{X_{\text{NoAz}}^2 + Y_{\text{NoAz}}^2}$$  

(Eq. 29)

In which `angle` ranges from 0 to 360°. With `LensAngle` the viewing angle over which the mask is made (here 5° was chosen), the tangent of half this angle gives the X-value [m] of the periphery of the mask per meter distance between the sensor and the imaged surface. When the surface is viewed under targeted pitch, this distance can also be written as: $D = \frac{H}{\cos(\text{Pitch}_{\text{target}})}$. Multiplication of both factors thus gives $X_{\text{NoAz}}$ (Figure 38). To get the X-coordinates of a full circle around the targeted pixel, the `LensAngle` was multiplied by a sine function, with the parameter `Angle` varying from 0° to 360° in steps of 0.05°. Eq. 27 was thus repeated 7200 times for each of the `Angle` values.

A similar equation was used to find the Y-value. Here the viewing angle was influenced by the pitch of the sensor. By taking the tangent over the sum of target pitch and `LensAngle`, the Y-coordinate of the mask periphery per meter measuring height (Flight height-vegetation height) was attained. Multiplying by the height then gave $Y_{\text{NoAz}}$ (Figure 38). To then get the
Y-coordinates of a full circle, the \textit{LensAngle} was multiplied by a cosine function of \textit{Angle}. Eq. 28 was also repeated to obtain 7200 coordinate points that formed a circle around the target pixel.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure38}
\caption{Illustration of the $X_{\text{NoAz}}, Y_{\text{NoAz}}$ Coordinates of the mask, with the UAV flying at height $H$ above the vegetation canopy, viewing the surface under the targeted pitch $Pitch_t$. \textit{LensAngle} the angle over which the mask is made, $c_{(0,0)}$ the centre pixel, $c_{\text{target}}$ the centre pixel under targeted pitch (with the distance on the Y-axis between $c_{(0,0)}$ and $c_{\text{target}}$ being $Y_{\text{dist}}$).}
\end{figure}

Next, the targeted azimuth was taken into account (Figure 39). For each of the 7200 coordinate pairs, the inverse tangent was calculated to find the actual azimuth for these points. The difference between the actual azimuth and the target azimuth was then added to this angle (Eq. 24), and the $X_{\text{Az}}$ and $Y_{\text{Az}}$ were obtained by rotating the points with radius $R$ (distance between $c(0,0)$ and $c_{\text{target}}(0,0)$) over this $\Delta \text{Az}$ (Eq. 30-32). The parameter $\theta$, represents the new azimuth angle, the sum of the actual azimuth angle and this azimuth difference $\Delta \text{Az}$.

\begin{align*}
\theta &= \tan^{-1}(X_{\text{NoAz}}, Y_{\text{NoAz}}) + \Delta \text{Az} \quad \text{(Eq. 30)} \\
X_{\text{Az}} &= R \cos(\theta) \quad \text{(Eq. 31)} \\
Y_{\text{Az}} &= R \sin(\theta) \quad \text{(Eq. 32)}
\end{align*}
Figure 39: Illustration of the incorporation of the azimuth, with ∆Az the difference in azimuth between the center pixel azimuth (actual azimuth) and the target azimuth, \( c_{(0,0)} \), the central pixel, \( X_{N0Az} \) and \( Y_{N0Az} \) the coordinates of the point of the mask without considering azimuth, and \( X_{Az} \) and \( Y_{Az} \) the coordinates of the mask point when azimuth is accounted for.

To prevent overlap of neighbouring mask areas (with azimuth target difference of 20°), an extra feature is added to this calculation. When the radius of the mask on the X-axis is bigger than half the distance between two points with 20° azimuth difference, the X-coordinate is multiplied by the ratio of this distance and the mask radius. In these cases, the mask gets an ellipsoid shape.

After solving these equations for all 7200 angle values, the result were coordinates [m] of the pixels in a circle around the pixel with target pitch and azimuth. The next step was to find the corresponding \( X_{Proj} \) and \( Y_{Proj} \) coordinates for each of these pixels to identify which pixels fitted the mask. This was done by searching for all \( X_{Proj} \) coordinates between the minimum and maximum of the 7200 \( X_{Az} \) values, then selecting only those of which the \( Y_{Proj} \) coordinates fell between the minimum and maximum of the 7200 \( Y_{Az} \) values. The projected coordinates that satisfied these conditions were maintained. The pixels with these coordinates thus formed the mask.

An example of the obtained masks is given in Table 2. For the nadir-viewing image 55 masks were made for each of the 16 azimuth targets (0° to 360° in steps of 20°) and for pitch targets 0°, 5°, 10°, and 15°. For the images with a programmed pitch of 30°, 12 masks were made, one for each of the azimuth targets (programmed azimuth, programmed azimuth + 20°, programmed azimuth +40°, and programmed azimuth -20°) and pitch targets 20°, 25°, 30°, and 35°. For images where the camera was tilted 45°, again 12 masks were made, the azimuth targets were defined similarly to those for the 30° flights, the pitch targets here were set at 40°, 45°, 50°, and 55°.
<table>
<thead>
<tr>
<th>Sensor angle set at 0° (nadir)</th>
<th>Image with (left) and without (right) masks:</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Original image:</strong></td>
<td>Central mask:</td>
</tr>
<tr>
<td>Pitch central pixel: 2.3441°</td>
<td>Pitch target: 0°</td>
</tr>
<tr>
<td>Yaw central pixel: 146.6944°</td>
<td>Yaw target: 0° relative to sun azimuth (or 11.3014°)</td>
</tr>
<tr>
<td>Roll central pixel: -2.6410°</td>
<td>Roll target: 0°</td>
</tr>
<tr>
<td>Azimuth sun: 11.3014°</td>
<td>Other masks:</td>
</tr>
<tr>
<td>∆Az: 135.3930°</td>
<td>Pitch targets: 5°, 10°, 15°</td>
</tr>
<tr>
<td></td>
<td>Azimuth targets: 20°, 40°, 60°, 80°, 100°, 120°, 140°, 160°, 180°, 200°, 220°, 240°, 260°, 280°, 300°, 320°, 340° relative to sun azimuth</td>
</tr>
<tr>
<td></td>
<td>Roll target: 0°</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sensor angle set at 30°</th>
<th>Image with (left) and without (right) masks:</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Original image:</strong></td>
<td>Central mask:</td>
</tr>
<tr>
<td>Pitch central pixel: -33.3999°</td>
<td>Pitch target: 30°</td>
</tr>
<tr>
<td>Yaw central pixel: 164.0513°</td>
<td>Yaw target: 200° relative to sun azimuth (or 173.9998° )</td>
</tr>
<tr>
<td>Roll central pixel: -3.2291°</td>
<td>Roll target: 0°</td>
</tr>
<tr>
<td>Azimuth sun: 13.9998°</td>
<td>Other masks:</td>
</tr>
<tr>
<td>∆Az: 350.0516°</td>
<td>Pitch targets: 20°, 25°, 35°</td>
</tr>
<tr>
<td></td>
<td>Azimuth targets: 180°, 220° relative to sun azimuth</td>
</tr>
<tr>
<td></td>
<td>Roll target: 0°</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sensor angle set at 45°</th>
<th>Image with (left) and without (right) masks:</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Original image:</strong></td>
<td>Central mask:</td>
</tr>
<tr>
<td>Pitch central pixel: -46.1151°</td>
<td>Pitch target: 45°</td>
</tr>
<tr>
<td>Yaw central pixel: 231.7690°</td>
<td>Yaw target: 160° relative to sun azimuth (or 232.3479° )</td>
</tr>
<tr>
<td>Roll central pixel: 1.7829°</td>
<td>Roll target: 0°</td>
</tr>
<tr>
<td>Azimuth sun: 32.3479°</td>
<td>Other masks:</td>
</tr>
<tr>
<td>∆Az: 359.4211°</td>
<td>Pitch targets: 40°, 50°, 55°</td>
</tr>
<tr>
<td></td>
<td>Azimuth targets: 140°, 180° relative to sun azimuth</td>
</tr>
<tr>
<td></td>
<td>Roll target: 0°</td>
</tr>
</tbody>
</table>


B. Extracting reflectance data

To make an empirical BRDF model, reflectance values were needed from the forest canopy under various sensor angles during different times of day. The drone flew the star-shape pattern under three different viewing angles (45°, 30° and 0°) and six azimuth angles (0°, 60°, 120°, 180°, 240° and 300° relative to the sun azimuth) for each flight. For each of these zenith-azimuth combinations we wanted to find the reflectance data. As within each image, the zenith and azimuth angle vary (size lens angle), more information can be extracted. For this reason it was decided to extend the target combinations to include all zenith angles between 0° and 55° with a 5° increment, and all azimuth angles between 0° and 340° with a 20° increment. Each image thus contained various target areas.

Having extracted the desired image areas through the previous steps, it was then possible to find the reflectance for each of the target areas in the red, green and blue bands. The brightness values were extracted from the masked areas. The mean and median brightness values for each mask were calculated. In most cases, the mean was accepted as the correct value for the mask. However, when the mask contained saturated pixels (brightness value = 255), the median brightness value was calculated and used for further calculations.

Brightness values were then converted into reflectance values using the previously defined logarithmic function (2.2.2.6). These values were then poured into polar plots. For each 5° viewing angle increment and each 20° azimuth angle increment (each mask), the average reflection was inserted into the designated subplot (Figure 40). Each point in the BRDF plot is thus the average of a number of images, usually 5-10. If for a certain pitch-azimuth combination less than 5 images were selected (for example due to clouds or blurry pictures) this reflectance value was considered insufficiently reliable and was omitted from the BRDF plot.

To omit outliers from the BRDF models, a smoothing script was used. For each cell of the polar plot the standard deviation and the average value of the neighbouring cells were calculated. The significance of the deviation between the cell value and this average neighbour value was tested using a t-test with a 20% significance level. When significant deviations were found, the cell value was replaced by the average value of its neighbouring cells.
2.2.2.8 Testing the reciprocity principle

As mentioned earlier, the debate on the validity of the Helmholtz reciprocity principle for structured surfaces is still ongoing. Current BRDF models generally assume this principle to be true. The reflectance measurements are done under various solar zenith angles and the BRDF is modeled by fixing the solar zenith angle at 30°.

In this study, we tested this reciprocity principle by comparing the BRDF model obtained through the previous steps (using the real solar zenith and sensor viewing angle for each measurement), and the reciprocity-assuming BRDF model (with solar zenith angle fixed at 30° and sensor viewing angle adjusted accordingly).

This was done by adjusting the Matlab scripts for extracting the BRDF, described in the previous section. The angle between the solar zenith and the targeted pitch needed to remain constant (definition reciprocity). The script therefore calculated the difference between the solar zenith angle at each image time, and the fixed 30° zenith. This difference was then added to the target pitch. With these new target areas, the masks were created and the reflectances were measured similarly to before.

2.2.2.9 Testing the BRDF effect on Vegetation Indices

Earlier it was mentioned that vegetation indices are often used for evaluating the seasonal phenological changes of vegetations. However, the measurements for these indices are generally done under a fixed sensor angle, with no corrections being made for changes in the sun-target-sensor geometry. In this study we therefore wanted to test what the influence of changing sensor and illumination source angles is on several frequently used greenness indices.

We evaluated the Green Red Vegetation Index (GRVI), the Green Chromatic Coordinate (GCC), The Excess Green (ExG), and the simple Green Red Ratio (GRR) for the measured target area in Robson Creek and Cape Tribulation (Eq. 7-10). Using the reflectance data
obtained in previous steps, the mathematical transformations of the Canon S110 spectra (Red, Green, Blue) were calculated for each of these indices under each of the targeted zenith-azimuth combinations. As vegetation indices are generally calculated with Digital Numbers (DN) rather than absolute reflectance values, we wanted to see whether different results are obtained with these values. The same calculations of the indices were therefore made using the DN values of the BRDF models.

2.2.3 Near-infrared Images

The processing of the near-infrared images is similar to the approach described for the visual imagery. Therefore only the parts where the process differs will be explained in this section.

2.2.3.1 Overview

To gain a clear overview of the data processing for the near-infrared images, the processing steps are summarized in following flow chart (Figure 41).
Figure 41: Representation of the data processing for the images from the near-infrared camera (tetracam ADC Lite). With grey image preparation, green image registration, blue image selection, purple vignetting and distortion corrections, yellow reflectance calculation, orange BRDF extraction, and red reciprocity testing. Rectangles represent actions, rhomboids represent export products, ellipsoids represent the start – and end products.
2.2.3.2 Image preparation

When downloaded from the ADC camera, the near-infrared images were in RAW format. They were therefore first converted to TIFF format using the software PixelWrench2 (Tetracam, California, US). Before further processing, the image quality was manually checked. Pictures that were either not taken during the flight, were blurred, or contained shadows due to clouds, were removed from the dataset.

2.2.3.3 Image registration

The Agisoft software had more difficulty aligning the near-infrared images. This is a well-known issue that is at least partially caused by the rolling shutter of the near-infrared imagery. When images were aligned using the GPS-input data (as for the visual imagery), poor alignment results (low numbers of images aligned) were obtained. However, as the ADC camera and the Canon S110 had been installed together on the drone with their lenses parallel, the camera positions of the visual camera could be used to estimate those of the near-infrared camera. A spline function (Matlab) was used to match the estimated camera positions from the visual image’s Agisoft output to the corresponding near-infrared pictures. A file with estimated latitude, longitude, altitude, yaw, pitch, and roll values per TIFF image was attained. These values approached the real parameter values closer. Using this data as Agisoft input, almost all near-infrared images could be aligned.

GCP’s were added to georeference the 3D Agisoft model and add to the precision of the parameter estimates. As these easily recognisable points had already been found for the images of the visual camera, the coordinates were already known and there was no need to repeat the dense-cloud building, and mesh generation for the near-infrared flights. It was simply a matter of finding the corresponding points on the near-infrared images, and realigning the flight.

The output of parameter estimates from the 3D models still occasionally deviated strongly from the expected camera positions. For this reason, a Matlab script was developed to calculate the camera positions based on the average difference between the expected positions and the Agisoft-output positions. The ‘expected camera positions’, estimated using the positions of the visual camera, were used once more. For each flight, these expected positions were compared to the Agisoft output for the near-infrared images. Images taken when the UAV was taking off or landing or when it was turning were omitted for this check. For the remaining images, the differences between the expected values and estimated values (from Agisoft) for the parameters yaw, pitch and roll were calculated. Omitting the outliers (with the Matlab function trimmean), the average difference for each of these parameters was calculated. By adding this average difference to the expected values for yaw, pitch, and roll, new camera positions were attained for each of the near-infrared images. With these new positions, the target areas viewed in simultaneously taken visual and near-infrared images, corresponded well. An overview of the image registration process is shown in Figure 42.
Figure 42: Overview of Image registration process for the near-infrared images. The ellipsoids represent the start- and endpoint of the process, rectangles are actions, rhomboids are export products. The grey arrows show the order of the sequence of the steps, the brown arrows represent inputs.

### 2.2.3.4 Image selection

A Matlab script was made to match the near-infrared images to the corresponding visual images based on the observed time difference between the visual and near-infrared imagery (3 seconds). The selection of the images covering the target area was done based on the selected visual images, and the corresponding near-infrared images taken at the same moment. This selection was then copied into files based on their programmed viewing angle and flight line azimuth angle, similar to the visual picture case.

### 2.2.3.5 Vignetting and Distortion correction

Before the reflectance data could be extracted from the images, corrections needed to be made once more for the unwanted effects of vignetting and image distortion.
A. Vignetting

Because the ADC camera had a narrower field of view than the visual camera, the targeted area was often located at the very edge of the image. The vignetting effect was therefore of greater importance here.

The vignetting correction was based on the approach for the visual camera. The big difference with the near-infrared camera however, was that the f-value was adjusted manually before each flight. The f-value and shutter time were not saved in the image info, and were thus unknown. It was therefore not possible to imitate the exact camera settings during the flight.

To get an as accurate possible vignetting correction, images were taken with the near-infrared camera (with shutter time set at 0.5s) of an evenly illuminated Teflon panel. These images were then entered into the same Matlab script used for the visual images, and the correction matrices were obtained (Figure 43). These were then used to eliminate the vignetting effect in each image (Figure 44). The images in the third spectral band (Green) were saturated. But because the vignetting was very similar to that of the second band (Red), this red vignetting matrix was a suitable substitute.

![Vignetting matrix for channel 2 (green channel) for ADC Lite Tetracam images taken with shutter time 0.5s. The pixel values between 0.9628 (black) and 1.3048 (white) represent the multiplication factor needed for eliminating the vignetting effect.](image-url)

**Figure 43:** Vignetting matrix for channel 2 (green channel) for ADC Lite Tetracam images taken with shutter time 0.5s. The pixel values between 0.9628 (black) and 1.3048 (white) represent the multiplication factor needed for eliminating the vignetting effect.
Figure 44: Images showing vignetting correction. Image from flight 3 on August 19 2015 before (left) and after (right) applying the vignetting correction. If you look closely you can see the corners of image turned slightly brighter after the correction.

B. Distortion

For distortion correction, images were again taken of the checkerboard pattern in AgiSoft Lens. For the near-infrared camera, only a radial distortion was found (Figure 45). Using the Brown-Conrady model (Brown, 1966), each of the images was corrected for this effect (Figure 46).

Figure 45: AgiSoft Lens output for the radial distortion of the near-infrared camera
Figure 46: Illustrating the effect of the distortion correction for the tetracam ADC camera. For an image of flight 3 on August 19 2015, the image after vignetting correction and before distortion correction (left), the image after vignetting and distortion correction (right).

2.2.3.6 Reflectance calculation

For finding the absolute reflectance, the same approach was used as for the visual images. The relationship between the DN’s and the absolute reflectance was observed to be linear.

The same data for the Spectralon reference panel and the multicoloured panels from the Envi program output were used, yet here the average values for the spectral bands near-infra red, red, and green were extracted. The tetracam ADC lite, has the highest spectral sensitivity for green, red and NIR in the spectral bands equal to Landsat’s TM2, TM3 and TM4. This means that for NIR, the highest reflectance is for wavelengths between 0.76 and 0.9µm, for red this is between 0.63 and 0.69µm, and for green between 0.52 and 0.6µm (USGS, 2016).

The absolute reflectance value for each of the panels was plotted in function of the near-infrared reference brightness measurements, and the linear relation was found. This relation could then be used to convert all brightness values from the flight images to reflectance values.

Figure 47: Absolute reflectance in function of the DN for the reference panels for flight 1 on August 26 2015
2.2.3.7 BRDF extraction

Once reliable camera positions were obtained, and the necessary image corrections were done, the masks could be made to select the area of each image with the desired pitch, yaw, and roll and the corresponding reflectance values could be extracted. This was done using the same method as for the visual case.

A. Finding the target areas

By simply adjusting the camera characteristics (ex. image length, image width), the same Matlab script could be used as before to create the masks around the target areas. An example of the masks for the near-infrared images is given in Table 3.
Table 3: Examples of masked areas for near-infrared images (taken with tetracam ADC Lite) from flight 3 on August 26 2015. The Yaw, pitch, Roll of the central pixel are given for each image as well as the targeted parameters. The central mask is highlighted in the masked image by a red circle. Masks that fell off the image edge were not used for further measurements.

<table>
<thead>
<tr>
<th>Sensor angle set at 0° (nadir)</th>
<th>Image with (left) and without (right) masks:</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Original image:</strong></td>
<td><img src="image1" alt="Image" /> <img src="image2" alt="Image" /></td>
</tr>
<tr>
<td>Pitch central pixel: 1.6313°</td>
<td><img src="image3" alt="Image" /> <img src="image4" alt="Image" /></td>
</tr>
<tr>
<td>Yaw central pixel: 347.0494°</td>
<td></td>
</tr>
<tr>
<td>Roll central pixel: -3.3148°</td>
<td></td>
</tr>
<tr>
<td>Azimuth sun: 30.3381°</td>
<td></td>
</tr>
<tr>
<td>ΔAz: 316.7113°</td>
<td></td>
</tr>
<tr>
<td><strong>Central mask:</strong></td>
<td><img src="image5" alt="Image" /> <img src="image6" alt="Image" /></td>
</tr>
<tr>
<td>Pitch target: 0°</td>
<td><img src="image7" alt="Image" /> <img src="image8" alt="Image" /></td>
</tr>
<tr>
<td>Yaw target: 0° relative to sun azimuth (or 30.3381°)</td>
<td><img src="image9" alt="Image" /> <img src="image10" alt="Image" /></td>
</tr>
<tr>
<td>Roll target: 0°</td>
<td><img src="image11" alt="Image" /> <img src="image12" alt="Image" /></td>
</tr>
<tr>
<td><strong>Other masks:</strong></td>
<td><img src="image13" alt="Image" /> <img src="image14" alt="Image" /></td>
</tr>
<tr>
<td>Pitch targets: 5°, 10°, 15°</td>
<td><img src="image15" alt="Image" /> <img src="image16" alt="Image" /></td>
</tr>
<tr>
<td>Azimuth targets: 20°, 40°, 60°, 80°, 100°, 120°, 140°, 160°, 180°, 200°, 220°, 240°, 260°, 280°, 300°, 320°, 340° relative to sun azimuth</td>
<td><img src="image17" alt="Image" /> <img src="image18" alt="Image" /></td>
</tr>
<tr>
<td>Roll target: 0°</td>
<td><img src="image19" alt="Image" /> <img src="image20" alt="Image" /></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sensor angle set at 30°</th>
<th><img src="image21" alt="Image" /> <img src="image22" alt="Image" /></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Original image:</strong></td>
<td><img src="image23" alt="Image" /> <img src="image24" alt="Image" /></td>
</tr>
<tr>
<td>Pitch central pixel: -23.5246°</td>
<td><img src="image25" alt="Image" /> <img src="image26" alt="Image" /></td>
</tr>
<tr>
<td>Yaw central pixel: 240.4077°</td>
<td></td>
</tr>
<tr>
<td>Roll central pixel: 0.7234°</td>
<td></td>
</tr>
<tr>
<td>Azimuth sun: 34.5030°</td>
<td></td>
</tr>
<tr>
<td>ΔAz: 5.9047°</td>
<td></td>
</tr>
<tr>
<td><strong>Central mask:</strong></td>
<td><img src="image27" alt="Image" /> <img src="image28" alt="Image" /></td>
</tr>
<tr>
<td>Pitch target: 30°</td>
<td><img src="image29" alt="Image" /> <img src="image30" alt="Image" /></td>
</tr>
<tr>
<td>Yaw target: 160° relative to sun azimuth (or 234.5030°)</td>
<td><img src="image31" alt="Image" /> <img src="image32" alt="Image" /></td>
</tr>
<tr>
<td>Roll target: 0°</td>
<td><img src="image33" alt="Image" /> <img src="image34" alt="Image" /></td>
</tr>
<tr>
<td><strong>Other masks:</strong></td>
<td><img src="image35" alt="Image" /> <img src="image36" alt="Image" /></td>
</tr>
<tr>
<td>Pitch targets: 20°, 25°, 35°</td>
<td><img src="image37" alt="Image" /> <img src="image38" alt="Image" /></td>
</tr>
<tr>
<td>Azimuth targets: 140°, 160°, 180° relative to sun azimuth</td>
<td><img src="image39" alt="Image" /> <img src="image40" alt="Image" /></td>
</tr>
<tr>
<td>Roll target: 0°</td>
<td><img src="image41" alt="Image" /> <img src="image42" alt="Image" /></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sensor angle set at 45°</th>
<th><img src="image43" alt="Image" /> <img src="image44" alt="Image" /></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Original image:</strong></td>
<td><img src="image45" alt="Image" /> <img src="image46" alt="Image" /></td>
</tr>
<tr>
<td>Pitch central pixel: -43.8317°</td>
<td><img src="image47" alt="Image" /> <img src="image48" alt="Image" /></td>
</tr>
<tr>
<td>Yaw central pixel: 231.9611°</td>
<td></td>
</tr>
<tr>
<td>Roll central pixel: -0.1792°</td>
<td></td>
</tr>
<tr>
<td>Azimuth sun: 32.2109°</td>
<td></td>
</tr>
<tr>
<td>ΔAz: 359.7502°</td>
<td></td>
</tr>
<tr>
<td><strong>Central mask:</strong></td>
<td><img src="image49" alt="Image" /> <img src="image50" alt="Image" /></td>
</tr>
<tr>
<td>Pitch target: 45°</td>
<td><img src="image51" alt="Image" /> <img src="image52" alt="Image" /></td>
</tr>
<tr>
<td>Yaw target: 232.2109°</td>
<td></td>
</tr>
<tr>
<td>Roll target: 0°</td>
<td></td>
</tr>
<tr>
<td><strong>Other masks:</strong></td>
<td><img src="image53" alt="Image" /> <img src="image54" alt="Image" /></td>
</tr>
<tr>
<td>Pitch targets: 40°, 50°, 55°</td>
<td><img src="image55" alt="Image" /> <img src="image56" alt="Image" /></td>
</tr>
<tr>
<td>Azimuth targets: 140°, 160°, 180°</td>
<td><img src="image57" alt="Image" /> <img src="image58" alt="Image" /></td>
</tr>
<tr>
<td>Roll target: 0°</td>
<td><img src="image59" alt="Image" /> <img src="image60" alt="Image" /></td>
</tr>
</tbody>
</table>
B. Extracting reflectance data

Having extracted the desired image areas, it was then possible to find the reflectance for each of these pixels in the NIR, red and green bands. The brightness values were extracted from the masked areas. Using the reference measurements before and after each flight, the linear relation between the brightness and absolute reflectance was constructed and used to convert the brightness values to absolute reflectance. These values were then poured into polar plots, in a similar way as explained for the visual processing.

As the near-infrared camera took fewer images per second than the visual camera, the amount of images that could be used for reflectance measurements was more limited. The near-infrared camera also had a smaller field of view, meaning fewer masks could be extracted from each image. A minimum amount of images with each mask is needed however to calculate a reliable reflectance estimate. When a certain target area (mask) was calculated for three or more images, the derived reflectance data was considered reliable. If the targeted area was measured in less than three images, the data was omitted. The missing data, ‘holes’ in the polar plots were filled using the data of the neighbouring plot cells (neighbouring zenith-azimuth target reflectance data) with a mean weighted spline function.

2.2.3.8 Reciprocity testing

This step was done similarly to the visual image approach.
3. Results

3.1 Robson Creek

3.1.1 Visual Camera

3.1.1.1 Actual sun position

To construct the BRDF model for the Robson Creek site, the results of six flights at this site were used, each made during a different time of day (varying sun positions). The results of flight 2 are shown in Figure 49A-C, the results of all other flights can be found in Appendix A1. The empty cells are those where no measurements were done due to the presence of clouds or because insufficient images (n<5) were available to generate reliable estimates. The plots show a symmetrical pattern in the reflectance distribution, with the highest reflectance where sensor and light source are aligned (azimuth 180°) and the viewing angle is close to the solar angle (hotspot). Figure 48 shows the amount of images used to calculate the average reflectance values for each plot cell, and the standard deviation within each cell. Here between 5 and 24 images were used for each reflectance measurement and overall low standard deviations (generally <0.4%) were found for each cell. The low standard deviation values near the hotspot area (less than 0.3% reflectance or 5% of the measured value) show the consistency of the measurements here.

Figure 48: polar plots for flight 2 in Robson Creek showing (A) the reflectance in the green band, (B) the number of images available for the calculation of this average reflectance for each cell in the plot (B) and (C) the standard deviation for the reflectance value of each cell.
Figure 49 BRDF plots showing reflectance data [\% incident light] for (A) the red (600-680nm), (B) green (495-570nm) and (C) blue (450-490nm) band of the Canon S110 camera images taken during flight 2 in Robson Creek (August 26 2015, 11:00-11:15).

The other flights at this site produced similar results. The polar plots for the green reflectance are given in Figure 50. From the amount of missing data, it is clear the measurement conditions were not ideal. However as six flights were done over the same target area, nearly all azimuth-zenith combinations were measured at least once. All flights show similar reflectance values, with a maximal hotspot reflectance of around 4\% in the red spectrum, 5\% in the green spectrum, and 2\% in the blue spectrum. The ‘ring’ (sensor pitch) in which this bright spot is seen differs between the flights as the solar zenith changes. Table 4 shows the expected and observed camera pitch under which the hotspot is seen for each flight. The observed hotspots correspond well with their expected position.
Figure 50: polar plots for all flights in Robson Creek showing the reflectance in the green band [% incident light]. Empty cells reflect solar azimuth-viewing angle combinations where insufficient images were available or clouds influenced the measurements.

Table 4: The pitch angle of the camera where the hotspot can be seen. For each measurement flight in Robson Creek, the expected pitch angle (solar zenith at time of measurement) and observed pitch angle for each of the spectral bands is given.

<table>
<thead>
<tr>
<th>Flight</th>
<th>Expected hotspot</th>
<th>Observed hotspot</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Red</td>
</tr>
</tbody>
</table>
| 1. Date: August 26  
Local Time: 09:30-09:44 | 47.7°  | 52.5-57.5°   | 52.5-57.5°   | 52.5-57.5°   |
| 2. Date: August 26  
Local Time: 11:00-11:15 | 31.8°  | 32.5-37.5°   | 32.5-37.5°   | 32.5-37.5°   |
| 3. Date: August 26  
Local Time: 11:45-12:00 | 28.2°  | 27.5-32.5°   | 27.5-32.5°   | 27.5-32.5°   |
| 4. Date: August 26 | 29.4°  | 27.5-32.5°   | 27.5-32.5°   | 27.5-32.5°   |
### 3.1.1.2 Fixed sun position

Under the assumption that the Helmholtz reciprocity principle is valid for BRDF measurements over a rough forest canopy, the data of all flights can be recalculated so that the solar zenith angle is fixed at 30° (solar noon). The results of this tilting of the six flights are shown in appendix B1. For easy comparison with the plots under real sun position, the polar plots for the green reflectance are shown for each flight in Figure 51.

The symmetry is maintained, the reflectance hotspot is simply shifted to the sensor viewing angle of 30° for all flights. This is best visible for flights 1 and 6, as these measurements were done under the best weather conditions. This corresponds with the expectations (Table 5). The
reflectances are very similar and remain relatively unchanged, with hotspot values around 4.5%, 5.5% and 2% in the red, green and blue band respectively.

With the flights corrected for the same illumination condition, they can be used to calculate an average model of the Robson Creek site. This average BRDF model for the Robson Creek measurement site is shown in Figure 52A-C. This model clearly shows the reflectance distribution, with the lowest reflectance values where the sensor is positioned opposite of the light source (0° azimuth). The reflectance values increase as the sensor angle approaches the sun azimuth. A symmetrical distribution pattern can be seen for each of the spectral bands. Figure 52D-F also shows the standard deviation between the reflectance data for each flight and the average model. The highest values are found near the hotspot, here the reflectance values vary the most between the six flights, with maximal standard deviations from the average model of 1%. In Figure 52G, the number of images used for the calculations of each plot cell (each azimuth-zenith combination) is given. This amount generally varied between 20 and 150 images per cell. For the nadir reflectance values, more than 700 images were used in total. For the hotspot cell (Azimuth 180° zenith 30°), 71 images were used.
**Figure 52:** Average Robson Creek model. A-C: Polar plots showing the reflectance values [% of incident light] for each of the Canon S110 spectral bands (Red, Green, Blue) for each measured sensor position (zenith: 0°-55°, azimuth: 0°-340°) and a fixed sun zenith of 30°; D-F: polar plots showing the standard deviation between the reflectance values measured for each flight and the average site reflectance for each cell; G: polar plot showing the total amount of images used to calculate the average reflectance values for each cell.
Table 5: The pitch angle of the camera where the hotspot can be seen. For each measurement flight in Robson Creek, the expected pitch angle (30° as sun zenith was fixed) and observed pitch angle for each of the spectral bands is given.

<table>
<thead>
<tr>
<th>Flight</th>
<th>Expected hotspot</th>
<th>Observed hotspot</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Red</td>
</tr>
<tr>
<td>1.</td>
<td>Date: August 26</td>
<td>30°</td>
</tr>
<tr>
<td></td>
<td>Local Time: 09:30-09:44</td>
<td></td>
</tr>
<tr>
<td>2.</td>
<td>Date: August 26</td>
<td>30°</td>
</tr>
<tr>
<td></td>
<td>Local Time:11:00-11:15</td>
<td></td>
</tr>
<tr>
<td>3.</td>
<td>Date: August 26</td>
<td>30°</td>
</tr>
<tr>
<td></td>
<td>Local Time:11:45-12:00</td>
<td></td>
</tr>
<tr>
<td>4.</td>
<td>Date: August 26</td>
<td>30°</td>
</tr>
<tr>
<td></td>
<td>Local Time:12:46-13:02</td>
<td></td>
</tr>
<tr>
<td>5.</td>
<td>Date: August 26</td>
<td>30°</td>
</tr>
<tr>
<td></td>
<td>Local Time:13:29-13:45</td>
<td></td>
</tr>
<tr>
<td>6.</td>
<td>Date: August 26</td>
<td>30°</td>
</tr>
<tr>
<td></td>
<td>Local Time:14:45-15:02</td>
<td></td>
</tr>
</tbody>
</table>

3.1.1.3 Vegetation Indices

The reflectance data for each of the azimuth-zenith combinations were also used to calculate several frequently used vegetation indices. The Green Red Vegetation Index (GRVI), Green Chromatic Coordinate (GCC), Excess Green (ExG), and Green Red Ratio (GRR) were calculated for each of the six flights in Robson Creek. The polar plots for flight 1, with the solar zenith fixed at 30°, are shown in Table 6, along with the standard deviation for each index. The results of the other flights can be found in Appendix C1.
Table 6: Polar plots showing the vegetation index values for each of the targeted azimuth-zenith combinations for flight 1 in Robson Creek (column 2). The calculated vegetation indices are shown in the first column, along with their equations. The third column shows the standard deviation between the values for each flight and the average sight value for each cell.

<table>
<thead>
<tr>
<th>Equation</th>
<th>BRDF model VI</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$GRVI = \frac{\rho_{\text{green}} - \rho_{\text{red}}}{\rho_{\text{red}} + \rho_{\text{green}}}$</td>
<td><img src="image1.png" alt="Image" /></td>
<td><img src="image2.png" alt="Image" /></td>
</tr>
<tr>
<td>$g_{cc} = \frac{\rho_{\text{green}}}{\rho_{\text{green}} + \rho_{\text{red}} + \rho_{\text{blue}}}$</td>
<td><img src="image3.png" alt="Image" /></td>
<td><img src="image4.png" alt="Image" /></td>
</tr>
<tr>
<td>$Ex_g = 2 \cdot \rho_{\text{green}} - (\rho_{\text{red}} + \rho_{\text{blue}})$</td>
<td><img src="image5.png" alt="Image" /></td>
<td><img src="image6.png" alt="Image" /></td>
</tr>
</tbody>
</table>
From the results in table 6 it immediately becomes clear that the measured vegetation indices are highly dependent on the sun-target sensor geometry. For each of these indices a relatively symmetrical plot is seen with a clear hotspot zone near the illumination source angle. Average polar plots were also constructed for each of the indices for the Robson Creek site. These are shown in table 7.

**Table 7:** Polar plots showing the vegetation index values for each of the targeted azimuth-zenith combinations averaged for the Robson Creek site (using six flights) (column 2). The calculated vegetation indices are shown in the first column, along with their equations. The third column shows the standard deviation for each cell.
The most prominent BRDF effect can be seen for the Excess Green index. The vegetation indices that work with ratio calculations, are slightly less influenced by changing sensor geometries. By using ratios, the relative changes in reflectance are measured. However, as the BRDF model differs for each of the spectral bands, and the green band reflectance shows the greatest variation with altered sensor positions, strong variations are still seen over the polar plots. From the Green Red Ratio GRR plot you can clearly see how the green reflectance changes 10% more with varying viewing angles than the red reflectance. The Green Red Vegetation Index shows a very similar pattern, as it is also based on the ratio between green and red reflectance. The GRVI shows a gradual increase of the index value from 0.045 where the sensor is positioned opposite the illumination source, to more than double that value, namely 0.095, as the sensor angle approaches that of the illumination source.

As vegetation indices are generally calculated using Digital Numbers (DN), the calculations were repeated using the DN’s for each flight (Appendix C2). The average results for the Robson Creek measurement site are presented in table 8.
Table 8: Polar plots showing the vegetation index values based on the DN’s for each of the targeted azimuth-zenith combinations averaged for the Robson Creek site (using six flights) (column 2). The calculated vegetation indices are shown in the first column, along with their equations. The third column shows the standard deviation for each cell.

<table>
<thead>
<tr>
<th>Equation</th>
<th>BRDF model VI</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>[ GRVI = \frac{\rho_{\text{Green}} - \rho_{\text{Red}}}{\rho_{\text{Red}} + \rho_{\text{Green}}} ]</td>
<td><img src="image1.png" alt="Image of GRVI" /></td>
<td><img src="image2.png" alt="Image of Standard Deviation" /></td>
</tr>
<tr>
<td>[ \gamma_{\text{cc}} = \frac{\rho_{\text{Green}}}{\rho_{\text{Green}} + \rho_{\text{Red}} + \rho_{\text{Blue}}} ]</td>
<td><img src="image3.png" alt="Image of Gamma cc" /></td>
<td><img src="image2.png" alt="Image of Standard Deviation" /></td>
</tr>
<tr>
<td>[ E_{\text{xg}} = 2 \times \rho_{\text{Green}} - (\rho_{\text{Red}} + \rho_{\text{Blue}}) ]</td>
<td><img src="image4.png" alt="Image of Exg" /></td>
<td><img src="image2.png" alt="Image of Standard Deviation" /></td>
</tr>
</tbody>
</table>
The polar plot for Excess green shows a similar pattern as before, with a hotspot region near azimuth 180°. However, the other vegetation indices give different results from their reflectance based versions. For GRVI, GCC, and GRR, no clear distribution pattern can be distinguished for each of the flight models (Appendix C2), though slightly higher values seem to occur more frequently near azimuth 0° and nadir viewing conditions. With exception of several outliers, the range of each of these values has decreased compared to their reflectance counterparts.

3.1.2 Near infrared camera

3.1.2.1 Actual sun position

The same calculations were made for the images taken with the near-infrared camera. As an example, the resulting BRDF model for flight 2 in Robson Creek are shown in Figure 53A. The results of the other flights are shown in Appendix D1. Figure 53B shows the amount of images used for the reflectance measurements in this flight, and Figure 53C shows the standard deviation for each plot cell for the NIR reflectance.

![Figure 53: polar plots for flight 2 in Robson Creek showing the reflectance in the NIR band (A), the amount of images used to calculate the this average reflectance for each cell in the plot (B), the standard deviation for the reflectance value of each cell (C). Blank cells are due to clouds or insufficient images.](image)
The other flights at this site produced similar results, both in absolute values and in the general pattern. The polar plots for the green reflectance are given in Figure 54. All flights show similar reflectance values, with a maximal hotspot reflectance of around 45% in the near-infrared spectrum. The ‘ring’ (sensor pitch) in which this bright spot is seen again differs between the flights as the sun position changes. Table 9 shows the expected and observed camera pitch under which the hotspot is seen for each flight. For most flights the observed hotspots correspond well with their expected position. However for flight 4 and 6 the hotspot is seen at a sensor azimuth of 160° instead of the expected 180°.

<table>
<thead>
<tr>
<th>Flight 1</th>
<th>Flight 2</th>
<th>Flight 3</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="Polar plot for Flight 1" /></td>
<td><img src="image2" alt="Polar plot for Flight 2" /></td>
<td><img src="image3" alt="Polar plot for Flight 3" /></td>
</tr>
<tr>
<td>Flight 4</td>
<td>Flight 5</td>
<td>Flight 6</td>
</tr>
<tr>
<td><img src="image4" alt="Polar plot for Flight 4" /></td>
<td><img src="image5" alt="Polar plot for Flight 5" /></td>
<td><img src="image6" alt="Polar plot for Flight 6" /></td>
</tr>
</tbody>
</table>

*Figure 54:* polar plots for all flights in Robson Creek showing the reflectance in the NIR band [% incident light]
Table 9: The pitch angle of the camera where the hotspot can be seen. For each measurement flight in Robson Creek, the expected pitch angle (solar zenith at time of measurement) and observed pitch angle for each of the spectral bands is given.

<table>
<thead>
<tr>
<th>Flight</th>
<th>Expected hotspot</th>
<th>Observed hotspot</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Date: August 26</td>
<td>47.7°</td>
</tr>
<tr>
<td></td>
<td>Local Time: 09:30-09:44</td>
<td></td>
</tr>
<tr>
<td>2.</td>
<td>Date: August 26</td>
<td>31.8°</td>
</tr>
<tr>
<td></td>
<td>Local Time: 11:00-11:15</td>
<td></td>
</tr>
<tr>
<td>3.</td>
<td>Date: August 26</td>
<td>28.2°</td>
</tr>
<tr>
<td></td>
<td>Local Time: 11:45-12:00</td>
<td></td>
</tr>
<tr>
<td>4.</td>
<td>Date: August 26</td>
<td>29.4°</td>
</tr>
<tr>
<td></td>
<td>Local Time: 12:46-13:02</td>
<td></td>
</tr>
<tr>
<td>5.</td>
<td>Date: August 26</td>
<td>34.3°</td>
</tr>
<tr>
<td></td>
<td>Local Time: 13:29-13:45</td>
<td></td>
</tr>
<tr>
<td>6.</td>
<td>Date: August 26</td>
<td>48.1°</td>
</tr>
<tr>
<td></td>
<td>Local Time: 14:45-15:02</td>
<td></td>
</tr>
</tbody>
</table>

3.1.2.2 Fixed sun position

By fixing the sun zenith at 30°, new polar plots were constructed for each of the six flights. The overall distribution remained unchanged, but a shift of the hotspot occurred (Appendix). The results for the green spectral band are shown in Figure 55. The hotspot is expected to be visible a sensor azimuth of 180° and a pitch of 30° (table 10). This is the case for flights 1 and 2. For flights 3 and 4 the hotspot can be seen near this pitch but at a sensor azimuth of 160°. For flights 6 the hotspot is visible at a pitch of 20°, slightly lower than expected.
Figure 55: polar plots for all flights in Robson Creek showing the reflectance in the NIR band [% incident light], with sun zenith fixed at 30°.

Table 10: The pitch angle of the camera where the hotspot can be seen. For each measurement flight in Robson Creek, the expected pitch angle (30° as sun zenith was fixed) and observed pitch angle for each of the spectral bands is given.

<table>
<thead>
<tr>
<th>Flight</th>
<th>Expected hotspot</th>
<th>Observed hotspot</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>NIR</td>
</tr>
<tr>
<td>7.</td>
<td>Date: August 26</td>
<td>30°</td>
</tr>
<tr>
<td></td>
<td>Local Time: 09:30-09:44</td>
<td></td>
</tr>
<tr>
<td>8.</td>
<td>Date: August 26</td>
<td>30°</td>
</tr>
<tr>
<td></td>
<td>Local Time: 11:00-11:15</td>
<td></td>
</tr>
<tr>
<td>9.</td>
<td>Date: August 26</td>
<td>30°</td>
</tr>
<tr>
<td></td>
<td>Local Time: 11:45-12:00</td>
<td></td>
</tr>
</tbody>
</table>
The models of each of these six flights were then used to draw up an average BRDF model for the Robson Creek site. The result can be seen in Figure 56. The total amount of pictures used to calculate the average reflectance for each plot cell varies between 3 and 60 for most azimuth-zenith combinations. For the nadir values more than 700 images were used. The highest reflectance is observed at a sensor azimuth of 180° and a zenith of 45°, which does not correspond with the expected location of a hotspot at the illumination angle (30°). The higher reflectance values in flight 1 influences the overall model a great deal at these higher pitch positions.

![Figure 56](image_url)

**Figure 56:** Average BRDF model for NIR reflectance in Robson Creek. A: polar plots showing reflectance distribution for various sensor positions; B: Standard deviation between the reflectance values of each flight and the average model; C: polar plot showing total amount of images used for reflectance calculations of each plot cell.
3.2 Cape Tribulation

3.2.1 Visual Camera

3.2.1.1 True sun position

Similar to the measurements at Robson Creek, BRDF models were constructed for Cape Tribulation. Due to bad weather conditions, only two flights were used to model the BRDF. Nevertheless, a similar pattern can be seen for this site. This is most clear for flight 1, with a clear hotspot where the sensor was positioned with an azimuth angle of 180° (equal to sun azimuth) and a viewing angle of 30° (Figure 57A, 58). All other data are given in Appendix A2. For easy comparison the BRDF models for the green band are shown for both flights in Figure 59.

Figure 57: A: polar plot showing reflectance distribution for green spectrum for flight 1 in Cape Tribulation; B: amount of images used to calculate average reflectance for each plot cell; C: Standard deviation for green reflectance.

Figure 58: Polar plots showing BRDF model for flight 1 in Cape Tribulation. For spectral bands red (A), green (B), and blue (C).
Hotspot values around 4%, 5% and 2% for respectively the red green and blue band, are observed near the expected sensor pitch (table 11).

**Table 11:** The pitch angle of the camera where the hotspot can be seen. For each measurement flight in Cape Tribulation, the expected pitch angle (solar zenith at time of measurement) and observed pitch angle for each of the spectral bands is given.

<table>
<thead>
<tr>
<th>Flight</th>
<th>Expected hotspot</th>
<th>Observed hotspot</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Red</td>
</tr>
<tr>
<td>1.</td>
<td>Date: August 19</td>
<td>33°</td>
</tr>
<tr>
<td></td>
<td>Local Time: 13:19-13:35</td>
<td></td>
</tr>
<tr>
<td>2.</td>
<td>Date: August 22</td>
<td>44.25°</td>
</tr>
<tr>
<td></td>
<td>Local Time: 09:49-10:12</td>
<td></td>
</tr>
</tbody>
</table>

### 3.2.1.2 Fixed sun position

By fixing the solar angle at 30°, the same shift of the hotspot to sensor pitch of 30° occurred while the distribution pattern was maintained, in agreement with the reciprocity principle (Appendix B2) (table 12). For flight 1 in Cape Tribulation, little change was observed as the sun zenith during this flight was already at 33° (near solar noon). For flight 2, this shift is more obvious (Figure 60).
The average values were then calculated to estimate the site model (Figure 61). This average model showed a very clear hotspot at a viewing angle of 30°, with reflectance values around 4%, 5% and 2.2% in the red, green and blue spectral bands.
Figure 61: A-C: Average BRDF model for Cape tribulation site based on BRDF models of two measurement flights; D-E: Standard deviation for each polar plot cell; G: total amount of images used for reflectance calculation of each cell.
Table 12: The pitch angle of the camera where the hotspot can be seen. For each measurement flight in Cape Tribulation, the expected pitch angle (solar zenith at 30°) and observed pitch angle for each of the spectral bands is given.

<table>
<thead>
<tr>
<th>Flight</th>
<th>Expected hotspot</th>
<th>Observed hotspot</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Red</td>
</tr>
<tr>
<td>1.</td>
<td>Date: August 19</td>
<td>30°</td>
</tr>
<tr>
<td></td>
<td>Local Time: 13:19-13:35</td>
<td></td>
</tr>
<tr>
<td>2.</td>
<td>Date: August 22</td>
<td>30°</td>
</tr>
<tr>
<td></td>
<td>Local Time:09:49-10:12</td>
<td></td>
</tr>
</tbody>
</table>

3.2.1.3 Vegetation Indices

Using the Cape tribulation BRDF models (with fixed solar zenith 30°), several vegetation indices were calculated for each individual site and an average BRDF model for each index was attained (table 13).

Table 13: Polar plots showing the vegetation index values based on the absolute reflectance data for each of the targeted azimuth-zenith combinations averaged for the Cape Tribulation site (using two flights) (column 2). The calculated vegetation indices are shown in the first column, along with their equations. The third column shows the standard deviation for each cell.
\[ g_{cc} = \frac{\rho_{\text{green}}}{\rho_{\text{green}} + \rho_{\text{red}} + \rho_{\text{blue}}} \]

\[ E_{x_g} = 2 \cdot \rho_{\text{green}} - (\rho_{\text{red}} + \rho_{\text{blue}}) \]

\[ \text{GRR} = \frac{\rho_{\text{green}}}{\rho_{\text{red}}} \]
These calculations were then repeated using the DN values (Appendix C4) instead of absolute reflectance values. The resulting polar plots are shown in table 14.

**Table 14**: Polar plots showing the vegetation index values based on the DN’s for each of the targeted azimuth-zenith combinations averaged for the Cape Tribulation site (using two flights) (column 2). The calculated vegetation indices are shown in the first column, along with their equations. The third column shows the standard deviation for each cell.

<table>
<thead>
<tr>
<th>Equation</th>
<th>BRDF model VI</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>[ GRVI = \frac{\rho_{\text{green}} - \rho_{\text{red}}}{\rho_{\text{red}} + \rho_{\text{green}}} ]</td>
<td><img src="image1.png" alt="Polar plot" /></td>
<td><img src="image2.png" alt="Standard deviation" /></td>
</tr>
<tr>
<td>[ \beta_{cc} = \frac{\rho_{\text{green}}}{\rho_{\text{green}} + \rho_{\text{red}} + \rho_{\text{blue}}} ]</td>
<td><img src="image3.png" alt="Polar plot" /></td>
<td><img src="image4.png" alt="Standard deviation" /></td>
</tr>
<tr>
<td>[ Ex_g = 2 \cdot \rho_{\text{green}} - (\rho_{\text{red}} + \rho_{\text{blue}}) ]</td>
<td><img src="image5.png" alt="Polar plot" /></td>
<td><img src="image6.png" alt="Standard deviation" /></td>
</tr>
</tbody>
</table>
Using the reflectance values, clear symmetrical BRDF models are attained with hotspot values near azimuth 180° and zenith 30° for each of the indices. Using the DN values gives a very different result. Though still a clear difference in values between measurements from changing sensor positions, no clear pattern can be distinguished. The ExG index however remains relatively unchanged.

3.2.2 Near infrared camera

3.2.2.1 Actual sun position

Using the measurements with the near-infrared camera, the BRDF model for the NIR band could be drawn up. As an example, the results for flight 1 in Robson creek are shown in Figure 62. All other data are given in Appendix D2. The hotspot is clearly visible for this flight where the sensor position equals the illumination angle and maximal reflectance values of 55% for the NIR band.

A. B. C.

Figure 62: A: polar plot showing reflectance distribution for NIR spectrum for flight 1 in Cape Tribulation; B: amount of images used to calculate average reflectance for each plot cell; C: Standard deviation for green reflectance.

To compare the flights, the results for the green band of both are shown in Figure 63. Though both show similar distribution patterns and maximal values, the hotspot in flight 2 is observed at a sensor azimuth of 160° and not the expected 180° (table 15).
Figure 63: NIR reflectance BRDF plots for each of the measurement flights in Cape Tribulation.

Table 15: The pitch angle of the camera where the hotspot can be seen. For each measurement flight in Cape Tribulation, the expected pitch angle (solar zenith at time of measurement) and observed pitch angle for each of the spectral bands is given.

<table>
<thead>
<tr>
<th>Flight</th>
<th>Expected hotspot</th>
<th>Observed hotspot</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Date: August 19</td>
<td>33°</td>
</tr>
<tr>
<td></td>
<td>Local Time: 13:19-13:35</td>
<td>27.5-32.5°</td>
</tr>
<tr>
<td>2.</td>
<td>Date: August 22</td>
<td>44.25°</td>
</tr>
<tr>
<td></td>
<td>Local Time: 09:49-10:12</td>
<td>42.5-52.5° but azimuth 160°</td>
</tr>
</tbody>
</table>
3.2.2.2 Fixed sun position

By fixing the sun position at 30°, the hotspot is once again shifted. The overall distribution remains the same (Figure 64).

<table>
<thead>
<tr>
<th>Flight 1</th>
<th>Flight 2</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="Flight 1" /></td>
<td><img src="image2.png" alt="Flight 2" /></td>
</tr>
</tbody>
</table>

**Figure 64:** NIR reflectance BRDF plots for each of the measurement flights in Cape Tribulation.

The average BRDF model for Cape Tribulation was then constructed based on the results for both flights (Figure 65). As only two flights were used to calculate the average, the influence of each on the site model is great. For this reason you can see a high reflectance values at an azimuth of 160° as opposed to the expected hotspot near 180°.

<table>
<thead>
<tr>
<th>A.</th>
<th>B.</th>
<th>C.</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image3.png" alt="A" /></td>
<td><img src="image4.png" alt="B" /></td>
<td><img src="image5.png" alt="C" /></td>
</tr>
</tbody>
</table>

**Figure 65:** A: Average BRDF model for Cape tribulation site based on BRDF models of two measurement flights; B: Standard deviation for each polar plot cell; C: total amount of images used for reflectance calculation of each cell.
**Table 16:** The pitch angle of the camera where the hotspot can be seen. For each measurement flight in Cape Tribulation, the expected pitch angle (solar zenith at time of measurement) and observed pitch angle for each of the spectral bands is given.

<table>
<thead>
<tr>
<th>Flight</th>
<th>Expected hotspot</th>
<th>Observed hotspot</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Date: August 19</td>
<td>30°</td>
</tr>
<tr>
<td>Local Time: 13:19-13:35</td>
<td></td>
<td>22.5-27.5°</td>
</tr>
<tr>
<td>2.</td>
<td>Date: August 22</td>
<td>30°</td>
</tr>
<tr>
<td>Local Time:09:49-10:12</td>
<td></td>
<td>32.5-37.5° but azimuth 160°</td>
</tr>
</tbody>
</table>

3.3 Comparison of the measured sites

To compare the BRDF models for each of the measurement sites, the difference was calculated between the reflectance values for each azimuth-zenith combination for each of the spectral bands. The significance of this difference was then tested using a t-test. The result can be seen in table 17. For each spectral band, the smallest differences are observed near the hotspot. As the sensor moves away from the illumination source, the difference in reflectance values between both sites increases. The results of the t-test show that the difference is indeed significant for most sensor positions. Solely near the hotspot, the difference is insignificant.

**Table 17:** Comparison of Cape Tribulation and Robson Creek average BRDF models based on measurements with the visual camera (Canon S110). The First row shows the absolute difference in reflectance values for each cell of the polar plot. The second row shows the significance of the difference calculated using a T-test with a significance level of 1%. Yellow areas show where the difference is significant, purple areas represent insignificant difference between Robson and cape Tribulation reflectance values.
The same comparison was done for the near-infrared results. A very similar pattern was observed. The difference is solely insignificant near the hotspot and near nadir viewing conditions.

**Table 18:** Comparison of Cape Tribulation and Robson Creek average BRDF models based on measurements with the near-infrared camera (Tetracam ADC Lite). The left figure shows the absolute difference in reflectance values for each cell of the polar plot. The right figure shows the significance of the difference calculated using a T-test with a significance level 1%. Yellow areas show where the difference is significant, purple areas represent insignificant difference between Robson and cape Tribulation reflectance values.
4. Discussion

4.1 Method evaluation

4.1.1 Star-shaped flight plan

The star-shaped flight plan allowed us to take measurements over a target area with a 60m radius. The reflectance data measured from various angles above this area showed a gradual transition from low values where the sensor was positioned opposite the illumination source, to maximal values where sensor and source were aligned. The absence of significant outliers in these BRDF models shows that the sampled area size was adequate for reflectance distribution measurements over the forest canopy. The angle between subsequent flight lines, 60° for this flight plan, also seems sufficiently small. No abrupt changes in reflectance values were observed between data extracted from neighbouring flight lines.

The standard deviation for each target area (each cell within the polar plot) was generally limited. For the green reflectance measured with the visual camera, for example, standard deviations between 0.05 and 0.3% [% of incident light] were found, corresponding to deviations of 1-30% of the average value. However, ‘hotspots’ in standard deviation values occurred several times near the nadir and 5°-10° sensor viewing positions. This can be seen for the green reflectance in the first Cape Tribulation flight, where a standard deviation of almost 1% could be found where the sensor pitch was 5°. Similarly, BRDF obtained with the near-infrared camera showed overall standard deviations between 1 and 3% (2.5-30% of average value) but maximal standard deviations of 7% for several cells where the sensor pitch is 5°.

This means that overall, the amount of images used for constructing the BRDF model is sufficient. Yet for very small sensor pitch angles (5-10°) more precise measurement or a greater sample size could be used for more reliable estimates.

4.1.2 Measurements

For the measurements, affordable and lightweight cameras were used, allowing for easy and fast set-up and measurements. The near-infrared camera used here (Tetracam ADC Lite) did not store information such as the f-number and the shutter speed for each image, needed for precise vignetting and distortion corrections. In addition, the red band was undersaturated for most images, whereas the green band gave unrealistically high reflectance values. For future measurements it would therefore be advisable to consider a near-infrared camera of better quality and with more flexible settings.

Another improvement for future measurements would be to install a precision GPS on the sensors. As the UAV was not able to withstand influences from strong winds and gimbal stabilisation did not work optimally, small deviations from the flight path were inevitable.
With a precision GPS on the sensors, these deviations could be tracked more accurately, simplifying the data processing.

To convert the Digital Number (DN) values to absolute reflectance, a set of reference panels were used. The panels with varying levels of grey (from light to dark-grey) proved most useful for finding the relation between the DN and reflectance values with a high fit ($R^2 > 0.95$).

Incoming radiation measurements were carried out throughout all flights to allow correction for changing illumination during the flight. This correction proved very useful, as incoming radiation varied with a factor of about 20% throughout several flights. Still, this correction did not account for all illumination and weather variations throughout the flights. Hotspot values between the flights differed with almost 1% in the green spectrum of the visual images. This is most likely the result of differences in weather conditions between and throughout the flights. The incoming radiation was measured on the Spectralon reference panel, placed in a clearing close to the measurement area. Still, it is preferable to measure incoming radiation on the UAV, where incoming light can still be slightly different than that in the clearing. For example, in the late afternoon the sun was low and little light could reach the clearing behind the forest, whereas the target area was still in full sunlight. Also small local clouds around either the targeted area or the Spectralon reference panel could influence the calibration with the Spectralon reference panel. If the UAV can be equipped with an incoming radiation sensor, these issues will be avoided.

However, a greater issue was the fact that the diffuse radiation was not measured. We used a SunPhotometer II (MicroTops) to measure diffuse radiation, but unfortunately, the estimates of aerosol concentration were unreliable (giving negative values) for all measurements. These data could therefore not be used and no distinction was made between the spectral and diffuse reflectance measured over the target area.

### 4.1.3 Data processing

The greatest challenge for the data processing was retrieving the camera position of each image. Estimations of the positions were done by linking each image to the logged GPS coordinated, after which the cameras were aligned using the AgiSoft software. For the images from the visual camera, the software generally worked quite well, resulting in reliable alignments with small errors. For the near infrared images, the alignment was more problematic. This is a well-known issue related to the rolling shutter and relatively limited viewing angle.

The input of the altitude was based on GPS (not altimeter) data and these were not very reliable. As a consequence, the resulting point clouds were often ‘tilted’ compared to the actual ground/canopy, and this would cause an error on the camera pitch and roll estimates. This was corrected by adding Ground Control Points (GCP). Finding reliable estimates of the altitude of these GCPs proved difficult, particularly for GCPs over dense forest. As a consequence, the addition of some points improved the camera alignment (removed the
tilting) whereas the addition of other points, for no apparent reason, resulted in large errors. The unpredictable nature of the program lengthened the alignment process considerably. One way to check the precision of the AgiSoft output in future research could be tested by comparing the coordinates of the same points in different images, and checking the differences between the calculated reflectance of these points. The process of finding the exact camera positions could also be simplified greatly by installing a very precise device for measuring the pitch, yaw and roll on the gimbal. These systems are currently installed on hyperspectral cameras for use on UAV’s.

The GCP coordinates were found using latitude and longitude data from orthophotos, and altitude data using the GoogleEarth based source, Altitude.nu. For better accuracy of the GCP coordinates, future measurements could work with predefined GCP coordinates from one (reliable) source, measured with an high precision RTK-GPS system, which unfortunately wasn’t available in this study.

Using the Matlab scripts, the targeted areas within each image were identified. The scripts proved successful in finding the target area for most flights. This was for instance illustrated by the fact that in consecutive images, the selected areas nicely followed the projected scanned line. For several of the near-infrared images however, the AgiSoft camera position estimations were not accurate enough and the azimuth of the image positions was observed to have a systematic bias. Consequently, hotspots areas could clearly be observed between two neighbouring masked areas. The obtained BRDF models for these flights were thus rotated over a certain azimuth angle (see for example flight 2 in Cape Tribulation, where they were rotated by about 20°, see Tables 14 and 15). A possible solution could be to find the hotspot in each image by comparing the reflectance values of all pixels and locating the area where a group of pixels shows a significantly higher reflectance than their neighbouring pixels. The azimuth angle at which this hotspot is observed could then be equated to 180° and the masks could be rotated accordingly.

Another possible improvement to the method is to incorporate the 3D model of the sample area into the script. The current method assumes the canopy surface to be a flat surface. By accounting for the surface roughness, the search for the target areas could be done with more precision.

4.2 Evaluation of the results

4.2.1 Visual camera

The resulting BRDF models for the green, red and blue band of the visual camera show a similar symmetric pattern with the lowest reflectance values observed when the sensor is positioned opposite the illumination source (R: 1.5%, G:1.5%, B:1%) and a gradual increase in reflectance values as the sensor approaches the illumination angle (Robson Creek, Figure 49), where a clear hotspot reflectance is observed (R: 4.5%, G: 5.5%, B: 2%). The pattern consistency between the various measurement flights (Figure 50) and the low standard
deviation values (Figure 48C), give a high reliability to the BRDF models. Slight differences in reflectance values between subsequent measurement flights can be attributed to small variations in illumination or weather conditions between the measured area and the location where incoming radiation was measured, and to the lack of corrections to differences in diffuse radiation.

The BRDF models correspond well with the expectations from theoretical knowledge, which predict that the great amount of internal scattering within the layered structure of leaves and the roughness of the forest canopy will give rise to anisotropic reflectance (NASA, 2016a; Shell, 2004). In the forward scattering direction, the shadowing effect is maximal, causing the sensor to measure a lower reflectance. As the sensor moves towards the illumination source, the self-shadowing decreases until the measured reflectance values reach their maximum in the backscattering direction (Shell, 2004).

By fixing the sun zenith at 30° - i.e. recalculating the sensor viewing angle - the hotspot was shifted to the 30° viewing angle. After this correction, the different flights at each location had very similar BRDF models (Figures 51 and 52). This implies that the Helmholtz reciprocity principle is indeed valid here even without separating the spectral and diffuse reflectance of the canopy surface. The measured reflectance values are a sum of both. As roughness of the surface increases, so does the diffuse portion of the measured reflectance (Kvicala et al., 2013). This means that the ratio of spectral and diffuse reflectance may change as the viewing direction is adjusted. To distinguish which part of the measured reflectance comes from the spectral portion and which is the result of internal scattering and shadowing effects, and thus of the anisotropic surface characteristics, knowledge of this ratio is needed. This could be done using polarization measurements, as the spectral reflected light is polarized whereas the diffuse reflectance is not (Bousquet et al., 2005).

### 4.2.2 Near infrared camera

For the measurements of the near-infrared, similar conclusions can be drawn as those of the visual images (Figures 53 and 54). The BRDF models based on the near-infrared measurements show a near-infrared reflectance around 20% in the darkest areas, to 50% at the hotspot (Figure 56). This corresponds well with expected reflectance. Indeed the NIR band of the ADC camera corresponds to Landsat’s TM4 band, meaning similar average reflectance values are expected.

### 4.2.3 Comparison of the measurement sites

The models attained for both the Robson Creek and the Cape Tribulation measurement site, showed similar patterns and hotspot values. Yet, whereas the values of blue, green, red and near-infrared reflectance were not significantly different close to the hotspot area, they were lower in Cape Tribulation for other azimuth-viewing angle combinations (Tables 17 and 18). This implies that the average albedo is different for both sites, as the Robson site is overall ‘brighter’ than Cape Tribulation. This can be attributed to the differences in the vegetation
characteristics. Both sites differ in vegetation composition, total rainfall, and rainfall in the dry season. This would mean that similar ecosystems can have significantly different BRDF models and thus that for accurate corrections the specific BRDF model of each ecosystem type is needed. Of course it must be kept in mind that only two flights were used to create the BRDF model for the Cape Tribulation site. Due to bad weather conditions it was not possible to do more measurements. With more repetitions, this difference could be established with greater reliability.

4.2.4 Vegetation Indices

Until now, no corrections are applied for the effect of changing sun-target-sensor geometry on phenocam vegetation indices. Measurements for these index calculations are generally done using phenocams mounted on towers or platforms which remain in a fixed position (Goldman, 2016). The calculations are also usually based on DN values rather than absolute reflectance values (Klosterman et al. 2014).

The BRDF models of both measurement sites reveal a large effect of the sun-target-sensor geometry on all calculated vegetation index measurements, when calculated with absolute reflectance values and with the DN values.

For the reflectance based calculations, our results showed significant changes in the measured index values depending on the angle of the sensor relative to the sun (Tables 7 and 8) and low standard deviation values. These results also show that the debate about which vegetation index is most sensitive to seasonal changes in phenology (Sonnentag et al., 2011; Motohka et al., 2010) is overlooking an important factor. Without a correction for the changing sun positions, sensor type and the differences in sensor set-up (viewing angle), comparisons of different indices have little meaning. For example, the claim made by Sonnentag et al. (2011) that the Green Chromatic Coordinate should be the index of choice for the timing of key phenological events as it is effective in suppressing changes in scene illumination, is not confirmed by the BRDF model. The reflectance results show that the GCC is indeed less sensitive to changing sensor positions than the ExG index, where ExG has a very clear hotspot and a maximal difference in index value between sensor positions of almost 400%. For the GCC the hotspot is slightly more spread out, as this index calculates ratios rather than absolute values. However, the GCC values of the same target area still ranges from 0.38 to 0.45 by simply changing the sensor angle. This range is about the same as the difference in the vegetation response of budbreak, according to Sonnentag et al (2011), which covers the transition from completely brown to completely foliated vegetation under one fixed viewing angle. This means that without a correction for the sun-target-sensor geometry, faulty conclusions might be made relating to phenological processes. The same conclusions could be made for the other calculated vegetation indices. The GRVI showed a doubling of its value due to changes of the viewing angle. Calculating the GRR clearly showed the difference in BRDF on the separate spectral bands, with green being more sensitive to the sensor position than red, the ratio also changed significantly. These results clearly show the importance of incorporating a BRDF correction in the vegetation index calculations.
From the DN based results it immediately becomes clear that they do not match their reflectance based versions. Only for ExG, a similar distribution can be found, with a clear hotspot near azimuth 180° and a similar range. The other indices, that all use ratios of spectral bands, however, do maintain relatively large value ranges within their BRDF plots, yet do not show a clear distribution pattern (Appendix C2). This can be explained by the exponential relation that was found between the DN and reflectance values for the Canon S110 camera. If this relation were to be linear, it can be expected that the BRDF-influence of the DN-values would resemble those of the reflectance-based BRDF models more closely. As it is here, the reflectance-DN ratio increases as the measured radiation increases (higher DN). Each spectral band also shows a slightly different exponential curve. For example a difference in DN value of 0.5 between the red and the green band, would correspond to a difference of 0.5% reflectance at lower DN values (near azimuth 0°), yet would correspond to a difference of 1.5% reflectance at higher DN values (near hotpot). So though little changes may occur in the DN ratios of the various spectral bands, the corresponding reflectance ratios will show the real variation, and thus the clear BRDF pattern. Because the range of the values is similar to the reflectance based BRDF models, a correction for the sensor angle is necessary to make reliable conclusions. However, the lack of a clear pattern makes this correction difficult. This shows the importance of finding the relation between DN and reflectance values for the camera used. As often consumer-grade digital cameras are used for these index measurements and the calculations are done solely based on DN values, ignorance of this relation could lead to faulty conclusions. Comparison between measurements of different cameras may be jeopardized as some cameras might respond linearly whereas others will respond exponentially to linear increases in radiation.

4.2.5 Future Perspectives

Nowadays, BRDF models are theoretical or at best semi-empirical type, so a lot can be learnt by comparing these models to those constructed from empirical data. For future studies it would be interesting to use this UAV-based empirical method on various ecosystems and compare the results with current models. For instance, the MODIS BRDF corrections are very frequently used, yet the accuracy of the model is rarely called into doubt. These corrections are used for a great amount of remote sensing studies over a large range of ecosystems through the MODIS NBAR product, with very different surface characteristics. By comparing the MODIS-generated BRDF-model with an empirical model, the accuracy of the first can be evaluated and, if needed, adjusted. A large set of empirically modelled ecosystems will undoubtedly improve the current understanding of the BRDF effect and allow for better theoretical and semi-empirical BRDF estimations as well.

More accurate BRDF corrections will improve the reliability of remote sensing research. Several on-going debates could be at least partially resolved if simply a good correction for the varying sensor or sun angle is applied. The best example is the on-going debate about the apparent green-up in the Amazon (e.g. Morton et al., 2014 vs Saleska et al., 2016). To find out whether light or water is the most limiting factor for forest productivity, the influence of the seasonal changes and sensor angles must be eliminated. By applying an accurate
correction for the change in sun-target-sensor geometry, the BRDF effects could easily be distinguished from the actual vegetation reflectance and the possible higher reflectance due to leaf-turnover in the dry season. Another example is the on-going search for the best vegetation index to follow up phenological changes throughout the seasons (Motohka et al., 2010). As the purpose is to measure throughout the year, and throughout various sun positions and the phenological changes are distinguished based on small differences in these indicator values, effects of the BRDF could allow for faulty conclusions. Each of the indices measured in this study showed a change in value with varying sensor angles that is comparable to the range between completely brown and green vegetation from one fixed camera position. Comparison of these indices is meaningless without correction for the differences in measurement conditions. Once a correction is applied for the effects of BRDF, the various indices can be properly evaluated and the changes in phenology will be distinguishable from seasonal variation in illumination.

5. Conclusions

The flexibility of UAVs allow for fast measurements of surface reflectance from various angles. Because UAVs can fly relatively high (>80m) above the imaged surface, a large target area can be sampled. UAVs can therefore be used to construct full empirical BRDF models for various ecosystems, ranging from homogeneous to heterogeneous, rough surfaces. The method described in this study produces consistent and realistic BRDF models, which correspond to the general expectations from the theoretical knowledge concerning vegetation reflectance, such as the hotspot reflectance values for each spectral band. But these results also offer more information than a general theoretical idea. The reflectance distribution calculation based on empirical data results in a unique BRDF model for each observed ecosystem, where the specific surface roughness of the observed area is taken into account.

These empirical BRDF models offer many interesting future perspectives, from the evaluation and improvement of the theoretical and semi-empirical models that are currently in use, to the solution of on-going debates in remote sensing, such as that concerning the apparent Amazon green-up. With accurate BRDF models, accurate corrections can be made for its effects. This will significantly increase the quality of remote sensing data. Studies involving phenocam-based vegetation indices will also benefit greatly from these corrections and produce more reliable data.

These are only a few examples of where an accurate BRDF model can make a great difference. With ever increasing applications of remote sensing measurements, the reliability of the reflectance results is of great importance. Accurate models need large datasets over many different ecosystem types. And that is exactly where UAV-based modelling can offer a fast, easy and reliable solution.
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