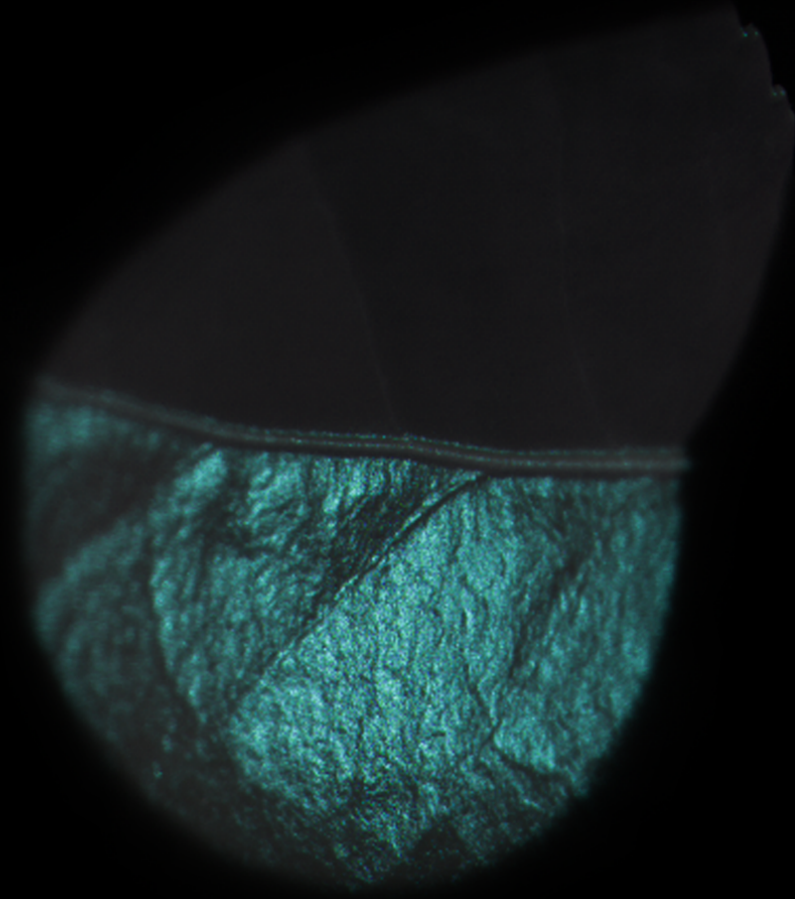


Exploring optical polarimetry for monitoring agriculture and biodiversity

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Exploring optical polarimetry for monitoring agriculture and biodiversity

Thesis Report

by

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Abstract

The field of vegetation remote sensing has historically been dominated by radiative transfer models (*RTM*'s) employing spectral reflectance as a means of characterising the interaction between vegetation and incident radiation. In recent years, polarimetry has received increasing attention as a complementary source of information in remote sensing, driven in part by advances in polarimetric instrumentation and the increasing availability of measurements capable of resolving the polarisation state of reflected radiation. The polarisation state of light contains information on the optical and structural properties of vegetation that is not captured by conventional radiometric measurements. This study explores whether polarimetric observations of leaves contain relationships between illumination geometry, viewing geometry and leaf degree and angle of linear polarisation (*DoLP*, *AoLP*), with the broader aim of assessing if polarimetry could enhance vegetation remote sensing by revealing information on physical and environmental vegetation characteristics. Two radiative transfer models, *PROPOLAR* and *DART*, are assessed in their ability to reproduce vegetation polarisation. The modelling component further aims to assess whether current *RTM* approaches can provide a sufficiently accurate physical description of vegetation polarisation to support the future development of a retrieval method between polarimetric observations and vegetation physical and environmental traits. The results show that both *DART* and *PROPOLAR*, in their current implementations, are unable to adequately reproduce the laboratory measurements, with discrepancies potentially arising from their respective implementations of leaf microfacet properties. The laboratory measurements nevertheless show the existence of systematic relationships between observation geometry, leaf architecture, and the resulting *DoLP* and *AoLP*, indicating that polarimetry may be further developed to retrieve information about vegetation structure.

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Nomenclature

List of Acronyms

<i>SZA</i>	Sun Zenith Angle
<i>VAA</i>	Viewing Azimuth Angle
<i>VZA</i>	Viewing Zenith Angle
3MI	Multi-viewing Multi-channel Multi-polarisation Imager
ADEOS-1/2	Advanced Earth Observing Satellite
BPRF	Bi-directional Polarisation Distribution Function
BRDF/BRF	Bi-directional (Reflectance) Distribution Function
CBD	Convention on Biological Diversity
CMOS	Complementary Metal–Oxide–Semiconductor
DART	Discrete Anisotropic Radiative Transfer
DoLP	Degree of Linear Polarisation
DoP	Degree of Polarisation
GBF	Global Biodiversity Framework
HARP-2	Hyper-Angular Rainbow Polarimeter 2
LAD	Leaf Angle Distribution
LIA	Leaf Area Index
LIA	Leaf Inclination Angle
NASA	National Aeronautics and Space Administration
PACE	Plankton, Aerosol, Cloud, ocean Ecosystem
PARASOL	Polarisation and Anisotropy of Reflectances for Atmospheric Science coupled with Observations from a Lidar
POLDER	POL arization and DIR ectionality of the Earth's REF lectances
RTE	Radiative Transfer Equation
RTM	Radiative Transfer Model
SRON	Stichting Ruimte Onderzoek Nederland/Space Research Organisation Netherlands

List of Symbols

α	Angle of ellipse semi-major axis (<i>rad</i>)
ϵ	Phase difference (<i>rad</i>)
λ	Wavelength (<i>m</i>)
ψ	Arbitrary wave function
σ	Surface roughness
θ	Tilt angle of electric field $\vec{E}$ (<i>rad</i>)
$\vec{S}$	Stokes vector
$\vec{E}$	Electric field vector (<i>V/m</i>)
$\vec{k}$	Angular wave vector (<i>rad/m</i>)
$\vec{r}$	Wave propagation direction
C_m	Structural dry mass per area ($kg \cdot m^{-2}$)
C_w	Equivalent water thickness (<i>m</i>)
C_{a+b}	Total chlorophyll content ($kg \cdot m^{-2}$)
C_{ant}	Anthocyanins ($kg \cdot m^{-2}$)
C_{car}	Carotenoids ($kg \cdot m^{-2}$)
k	Angular wave number (<i>rad/m</i>)
N	Leaf Structure Parameter
n	Refractive index
R	Total reflectance
$S_0 = I$	Stokes S_0 component
$S_1 = Q$	Stokes S_1 component
$S_2 = U$	Stokes S_2 component
$S_3 = V$	Stokes S_3 component
v	Velocity of wave propagation (<i>m/s</i>)
x	Distance travelled by wave (<i>m</i>)
Z_e	Statistical score or Z-score
e	Euler's number

Introduction

1.1. Background

The last century has seen a dramatic decline in worldwide biodiversity: forests only span 68% of their preindustrial extent, and it is estimated ecological communities have lost 20% of their original biodiversity on average. Human activity is having a clear, measurable and accelerating effect on ecosystems and their extent and integrity, the distribution of wild species and their abundance and distinctiveness[1, 2]. The Convention on Biological Diversity (CBD) aims to promote sustainable development and conservation of biodiversity through national policies. In December 2022, governments have released the final text of the Kunming-Montreal Global Biodiversity Framework (GBF) with a set of ambitious long-term goals — to be achieved in 2050 — and specific targets — for 2030 — that require immediate action[1]. Within this convention's monitoring framework, certain components and indicators of biodiversity have been identified to help track progress towards achieving these targets. It is believed that satellite remote sensing could play a major role in determining these biodiversity indicators.

Years of research have shown that the interaction between light and plants can provide valuable insights, both at the leaf and canopy level. The literature shows that light reflected off of plants has two elements: a diffuse or Lambertian element — light reflecting off a surface in every direction, a consequence of the interaction of the light with the volume and interior of the leaves; and a specular or Fresnel element, a direct reflection off the surface of the leaf.[3–8]. Like most translucent materials, the light entering the leaves is scattered in all directions, and multiple scattering results in the diffuse reflectance that results from the interaction. It is a well-established fact that relevant information about plant canopies can be gathered by measuring by measuring this diffuse element [9–12].

The polarisation of leaves has been measured extensively in lab settings; however, while polarimetry has been and is being extensively used for aerosol measurement, at present it has not been integrated within satellite remote sensing frameworks for characterising essential canopy characteristics of vegetation.

1.2. Research questions

A broad objective of pushing spectro-polarimetry was set at the beginning of this thesis, further refinement of the exact goals only occurred after a thorough literature study. This resulted in a four unique research questions:

1. **RQ-1:** Can leaf polarisation be accurately modelled?
2. **RQ-2:** Can canopy polarisation be accurately modelled?
 - How does leaf polarisation aggregate at the canopy level?
 - Is there a clear link between canopy geometry and measured polarisation?
3. **RQ-3:** How well do canopy models reflect measured remote sensing data?
4. **RQ-4:** Could existing models be used to measure vegetation functional traits?

- Can leaf properties (chlorophyll, equivalent leaf water thickness, dry matter content, etc) be retrieved through remote sensing?
- Can canopy characteristics (Leaf Area Index, Leaf Inclination Angle, etc) be retrieved through remote sensing?
- What are the optimal measurement conditions for retrievals?

1.3. Structure

This report opens with Chapter 2, which presents an exploration of the existing body of literature on vegetation remote sensing and polarisation, including a brief overview of the most relevant aspects of polarisation as seen through the lens of the electromagnetic theory of light. A formulation of a methodology to address the different research questions is presented in Chapter 3. It is immediately followed up with Chapter 4, where the results of both a series of simulations and a set of experiments are presented. A discussion on the results and their implications is presented in Chapter 5. Conclusions on these chapters are presented in Chapter 6, and the thesis closes off with a series of recommendations for further research in Chapter 7.

The appendix is added at the end, and contains a series of topics and results that were not entirely relevant to the research process but which are in some way tangentially related, and may prove of interest to the reader.

Background and state of the art

This chapter contains the products of an extensive review of the existing literature. It aims to provide an overview of the study of polarisation of vegetation signals, providing both the historical context and a broader view of developments in the field which have been used or could potentially be used in its study.

The chapter opens with a conceptual and formal introduction to polarisation in Section 2.1. The mechanisms introduced in this section are then applied in the context of vegetation signals in Section 2.2. This is followed up by a review of the methods experimentally employed in remote sensing of vegetation in Section 2.3, with a more in-depth discussion of the relevant radiative transfer models in Section 2.4. Finally, a number of formerly and currently operating space-borne polarimeters are introduced in Section 2.5.

2.1. Polarisation

The polarisation of light is a phenomenon first recorded in the 17th century by Danish scientist Rasmus Bartholin, who observed double refraction within a piece of calcite — also known as Iceland Spar. A complete explanation of the phenomenon would have to wait until the 19th century, however. It would be Augustin-Jean Fresnel who would frame the phenomenon through the lens of the wave theory of light.

Despite Fresnel's contribution, polarisation would come to be understood in its entirety with the advent of the electromagnetic theory of light. This theory models light — and all other electromagnetic waves — as an electric field $\vec{E}$ and a magnetic field $\vec{B}$, perpendicular to each other and coupled together, such that they infinitely propagate each other through space in an orthogonal direction, as shown in Figure 2.2.

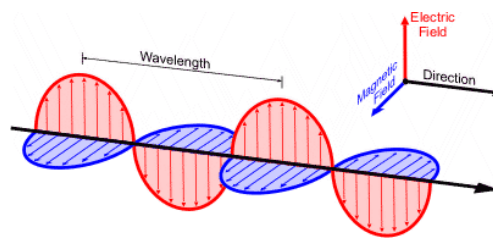


Figure 2.2: A classic depiction of an electromagnetic wave[14].

2.1.1. Mathematical description and formalism

Polarisation can be modelled by treating light as a transverse electromagnetic wave. A planar wave — a hypothetical wave that remains constant in its direction of propagation, and whose wavefront is entirely perpendicular to said direction — can be expressed as:

$$\vec{E}_i = \vec{E}_{0i} e^{[i(\vec{k}_i \cdot \vec{r} - \omega_i t)]} \quad (2.1)$$

or more simply, in a non-complex form:

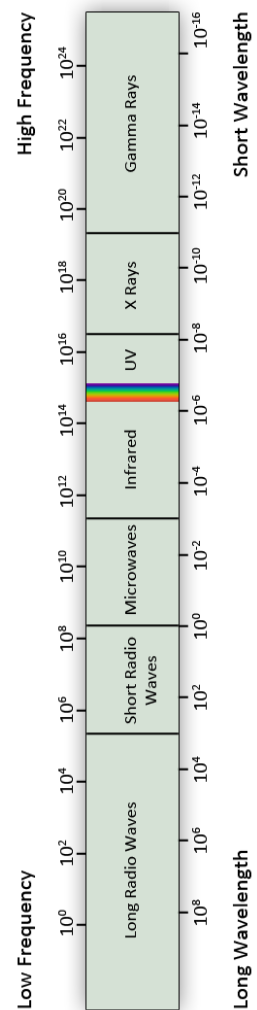


Figure 2.1: The electromagnetic spectrum. Visible light is only a small subset of the broader spectrum[13].

$$\vec{E}_i = \vec{E}_{0i} \cos(\vec{k}_i \cdot \vec{r} - \omega_i t) \quad (2.2)$$

Equation 2.2 is a useful expression in describing planar waves, but waves observed in nature are seldom planar. However, it can be shown that any wave can be modelled as a superposition of all waves in the same region of space. If one takes the differential form of the wave equation:

$$\frac{\partial^2 \psi}{\partial x^2} = \frac{1}{v^2} \frac{\partial^2 \psi}{\partial t^2} \quad (2.3)$$

Where v is the velocity of propagation, x the distance travelled from the origin, and ψ a wave function, one can show that for any set of waves ψ_1, ψ_2 :

$$\frac{\partial^2 \psi_1}{\partial x^2} + \frac{\partial^2 \psi_2}{\partial x^2} = \frac{1}{v^2} \frac{\partial^2 \psi_1}{\partial t^2} + \frac{1}{v^2} \frac{\partial^2 \psi_2}{\partial t^2} \quad (2.4)$$

yielding:

$$\frac{\partial^2}{\partial x^2}(\psi_1 + \psi_2) = \frac{1}{v^2} \frac{\partial^2}{\partial t^2}(\psi_1 + \psi_2) \quad (2.5)$$

Where Equation 2.5 shows that $(\psi_1 + \psi_2)$ is a solution of the wave equation 2.3. In mathematical terms, it expresses that the resulting wave at any point in which waves overlap is the sum of the individual waves at said location. Knowing this, any given wave can be expressed as the sum of two orthogonal planar waves, for example:

$$\vec{E}_x(z, t) = \hat{i} E_{0x} \cos(kz - \omega t) \quad (2.6)$$

$$\vec{E}_y(z, t) = \hat{j} E_{0y} \cos(kz - \omega t + \varepsilon) \quad (2.7)$$

Where both waves are travelling in the z -direction, and ε represents a phase difference between them, such that one of the waves "lags" behind the other. The terms $\hat{i}$ and $\hat{j}$ express their orientation, where the i and j directions are orthogonal.

2.1.1.1. Linear polarisation

Any planar wave can be said to be *linearly polarised*: the orientation of its electric field is constant in time. From Equations 2.6 and 2.7 one can show that, if the phase difference or "lag" is 0, or a multiple of $\pm 2\pi$, then:

$$\vec{E} = (\hat{i} E_{0x} + \hat{j} E_{0y}) \cos(kz - \omega t) \quad (2.8)$$

Which shows that the resultant wave has a fixed amplitude, equal to $\hat{i} E_{0x} + \hat{j} E_{0y}$, and is thus linearly polarised. Figure 2.3 visually represents the phenomenon.

An observer placed at a plane orthogonal to the direction of travel of the wave would find that the electric field $\vec{E}$ oscillates along a straight line — hence "linear" polarisation — with a given tilt angle, which one may refer to as θ . Using basic trigonometry, one can determine said angle θ from the ratio of the amplitudes of the original orthogonal waves:

$$\tan \theta = \frac{E_{0y}}{E_{0x}} \quad (2.9)$$

The wave shown in Figure 2.3 is the result of both fields having the same amplitude, i.e. $E_{0y} = E_{0x}$, such that $\tan \theta = 1, \Rightarrow \theta = 45^\circ$.

Naturally, this mathematical expression can be applied in reverse as well, decomposing any existing wave into two orthogonal components for ease of representation, or for the purpose

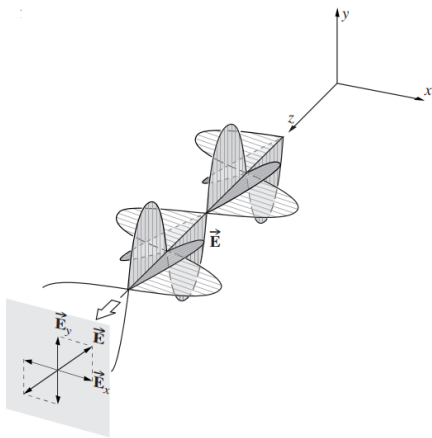


Figure 2.3: Linear polarisation visualised: the incoming wave will always oscillate along a straight line on a plane orthogonal to the direction of travel $\hat{z}$ [15].

of coordinate transformation.

2.1.1.2. Elliptical polarisation

The case for linear polarisation assumed that the phase difference ε is either 0 or a multiple of $\pm 2\pi$. If this were not the case, the resultant electric field $\vec{E}$ will rotate over time.

An additional assumption was that amplitude remains constant over time, yet this need not always be the case either. When both of these assumptions are eliminated, the remainder is an endpoint of $\vec{E}$ which will trace out an ellipse on an orthogonal plane, as shown in Figure 2.3. One can thus state that linear polarisation is a very specific case of *elliptical polarisation*. This form of polarisation can be represented mathematically by manipulating Equations 2.6 and 2.7 to remove any dependence on either position (z) or time (t). For the sake of brevity, the entirety of the process is omitted. One result of the manipulation is shown in Equation 2.10, where α represents the angle of the semi-major axis of the ellipse with the (E_x, E_y) coordinate system.

$$\tan 2\alpha = \frac{2E_{0x}E_{0y} \cos \varepsilon}{E_{0x}^2 - E_{0y}^2} \quad (2.10)$$

2.1.1.3. Circular Polarisation

If one attempts to make the principal axes of the ellipse described in Equation 2.10 match the axes of the coordinate system — *i.e.*, $\alpha = 0$ — the resultant expression takes the form:

$$\frac{E_y^2}{E_{0y}^2} + \frac{E_x^2}{E_{0x}^2} = 1 \quad (2.11)$$

Additionally, one can set $E_y = E_x = E_0$, then

$$E_y^2 + E_x^2 = E_0^2 \quad (2.12)$$

Which follows the mathematical structure $a^2 + b^2 = r^2$, which describes a circle. Hence, as long as the amplitudes of the orthogonal waves remain equal, the resultant wave can be said to be *circularly polarised*.

Circular polarisation is therefore another special case of *elliptical polarisation*. It can be shown that for circular polarisation and elliptical polarisation more broadly, the path swept out by $\vec{E}$ can rotate both clockwise or anti-clockwise, depending on the phase difference ε . In the case of the wave rotating clockwise, it is said to be *right-circularly polarised*, and vice-versa, if rotating anti-clockwise, it is *left-circularly polarised*.

2.1.1.4. Stokes Formalism

Thus far it has been shown that polarisation states can be mathematically represented by using orthogonal, superimposed electrical fields. However, for the purposes of optical analysis and design, it proves convenient to adopt a more versatile mode of representation. This is achieved through the use of *Stokes calculus*. In its essence, Stokes calculus represents the polarisation state of a wave through the use of a *Stokes vector* $\vec{S}$, composed of four elements. Depending on the source, these four elements are denoted as:

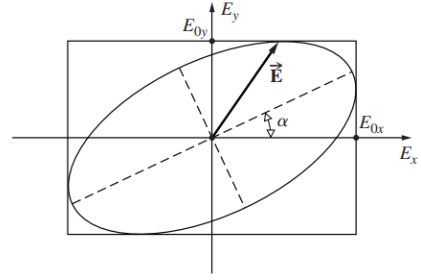


Figure 2.4: An ellipse as swept out by $\vec{E}$. For the purpose of visualisation, one should picture this figure on the plane shown in Figure 2.3[15].

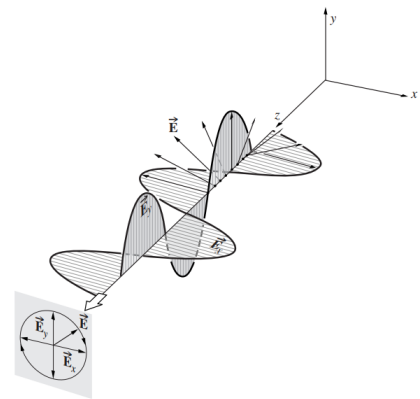


Figure 2.5: A right-circularly polarised wave. One will notice that in this image, $\vec{E}_x$ appears to lead by a half-wave, resulting in a circular plot that appears to rotate clockwise[15].

$$\vec{\mathbf{S}} = \begin{bmatrix} S_0 \\ S_1 \\ S_2 \\ S_3 \end{bmatrix} = \begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix} \quad (2.13)$$

Where S_0 or I describes the total intensity of the light, S_1 or Q measures the difference between the intensity in the horizontal and vertical direction — such that $Q > 0$ reflects a more horizontal polarisation state, and $Q < 0$ a more vertical one —, S_2 or U measures the difference between the intensity at a polarisation of 45° and -45° — such that, once again, $U > 0$ inclines the state further towards the first and third quadrants, and $U < 0$ does so towards the second and fourth quadrants —, and S_3 or V reflects the tendency of the polarisation state towards right-handed rotation ($V > 0$) or left-handed rotation ($V < 0$). The parameters are thus equal to:

$$\vec{\mathbf{S}} = \begin{bmatrix} I \\ Q \\ U \\ V \end{bmatrix} = \begin{bmatrix} E_{0x}^2 + E_{0y}^2 \\ E_{0x}^2 - E_{0y}^2 \\ 2E_{0x}E_{0y} \cos \Delta\varepsilon \\ 2E_{0x}E_{0y} \sin \Delta\varepsilon \end{bmatrix} \quad (2.14)$$

Where $\Delta\varepsilon$ is the difference between the phases of the horizontal and vertical electric fields, $\vec{\mathbf{E}}_x$ and $\vec{\mathbf{E}}_y$. One will notice that, in this notation, the following relation holds:

$$I^2 = Q^2 + U^2 + V^2 \quad (2.15)$$

Having established the relationship between the total intensity of light and the polarised parameters Q, U, V , it is useful to introduce the concept of *degree of polarisation* DoP , which represents the fraction of polarised light in a signal:

$$DoP = \frac{\sqrt{Q^2 + U^2 + V^2}}{I} \quad (2.16)$$

Given that linear states of polarisation both occur more commonly and easier to measure, another quantity often employed is the *Degree of linear polarisation* $DoLP$:

$$DoLP = \frac{\sqrt{Q^2 + U^2}}{I} \quad (2.17)$$

Both DoP and $DoLP$ are dimensionless parameters. A few examples of different polarisation states of signals and their respective Stokes vectors are shown in Table 2.1.

Polarisation state	Horizontally polarised	Vertically polarised	45° polarised	-45° polarised	Right-circularly polarised	Left-circularly polarised
Stokes Vector $\vec{\mathbf{S}}$	$I \begin{bmatrix} 1 \\ 1 \\ 0 \\ 0 \end{bmatrix}$	$I \begin{bmatrix} 1 \\ -1 \\ 0 \\ 0 \end{bmatrix}$	$I \begin{bmatrix} 1 \\ 0 \\ 1 \\ 0 \end{bmatrix}$	$I \begin{bmatrix} 1 \\ 0 \\ -1 \\ 0 \end{bmatrix}$	$I \begin{bmatrix} 1 \\ 0 \\ 0 \\ 1 \end{bmatrix}$	$I \begin{bmatrix} 1 \\ 0 \\ 0 \\ -1 \end{bmatrix}$

Table 2.1: Stokes vectors for different polarisation states.

Stokes vectors are a convenient way of describing the polarisation state of light, but their functionality extends to the manipulation of said states as well. Any changes of the polarisation state of light — through interaction with a polarising filter, for example — can be modelled by operating on the Stokes vector $\vec{\mathbf{S}}$ with a *Mueller Matrix*, represented by $\mathbf{A}$: A 4×4 matrix that describes the transformation of light passing through an optical element. An incident Stokes vector $\vec{\mathbf{S}}_i$ and the transmitted vector $\vec{\mathbf{S}}_t$ are thus related by:

$$\vec{\mathbf{S}}_t = \mathbf{A} \vec{\mathbf{S}}_i \quad (2.18)$$

If a wave passes through a series of optical elements $\mathbf{A}_1, \mathbf{A}_2, \dots, \mathbf{A}_n$ (in this order), then the emerging wave $\vec{\mathbf{S}}_t$ will be:

$$\vec{\mathbf{S}}_t = \mathbf{A}_n \dots \mathbf{A}_2 \mathbf{A}_1 \vec{\mathbf{S}}_i \quad (2.19)$$

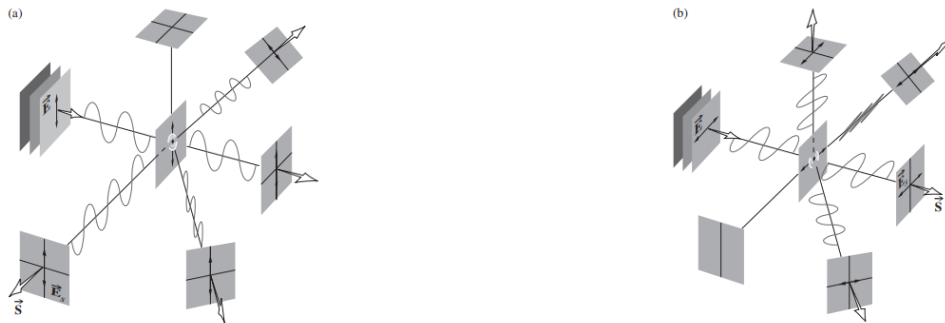
It is important to note that, as is the norm with matrices, the matrices in question are not commutable — *i.e.*, the order in which they are employed cannot be changed.

2.1.2. Polarisation in nature

2.1.2.1. Scattering

The blue colour displayed by the daylight sky is almost universally understood to be the direct consequence of sunlight "*bouncing*" against air molecules in the atmosphere. This phenomenon is what is commonly referred to as *scattering*. Despite its name, it is important to observe that scattering is composed of two fundamentally distinct processes: so-called *Rayleigh* scattering, and *Mie* scattering.

The former of the two — the one responsible for the colour of the sky — is a phenomenon that occurs when light encounters a particle that is much smaller than its own wavelength. The incoming light's own electric field interacts with the electrons and nucleus of the atom in question, creating a certain temporary oscillation, also called a *dipole*. According to electromagnetic theory, any accelerating charge will emit electromagnetic waves: it is these emitted waves that are referred to as Rayleigh scattering. One can think of each individual atom as a small antenna: the incoming waves provide it of energy, which it radiates outwards in the form of new waves. This effect is heavily dependent on the incoming wavelength — proportional to $1/\lambda^4$, where λ is the wavelength. As a direct consequence, light with a smaller wavelength — purples and blues in the visible spectrum — gets scattered much more strongly than larger wavelengths. The blue colour of the sky is a reflection — for lack of a better term — of this phenomenon: sunlight propagates through the atmosphere, is scattered in every direction, and is perceived by us as being much more blue than anything else.



(a) Scattering of a vertically-oriented electric field[15].

(b) Scattering of a horizontally-oriented electric field[15].

Figure 2.6: Dipole scattering of orthogonal components of a wave. One can observe that the dipole oscillates in the same direction as the waves in each scenario.

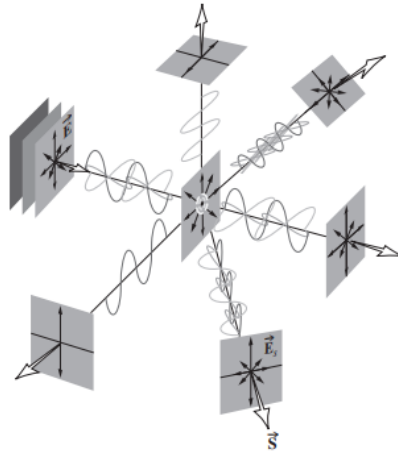


Figure 2.7: Scattering of unpolarised light[15]

A direct consequence of the mechanics involved in this phenomenon is the polarisation of incoming light. Assuming the incoming light is planar — and therefore linearly polarised in a given direction—, it will induce the atom's oscillation within the same plane, and at an axis orthogonal to the direction of propagation. Consequently, the scattered light will be emitted in every direction but the axis of oscillation itself, as is shown in Figures 2.6a and 2.6b. In nature, however, light is seldom entirely planar or linearly polarised in a given direction. So-called unpolarised light will be scattered in every direction, but will show very clear linear polarisation at angles orthogonal to the direction of propagation, as shown in Figure 2.7. This can be observed in the sky: a polarising filter pointed at the sky 90° from where the Sun is shining will only let through light polarised in a given direction.

The other phenomenon, *Mie scattering*, occurs when light encounters a particle of similar dimensions to its own wavelength. These particles are composed of multiple atoms, such that the interaction described for Rayleigh scattering does occur, but different atoms within the particle will scatter in different phases, and these interfere with each other in outgoing directions. This interference makes the resulting emissions depend highly the geometry of the particle and its composition and refractive index. This indicates that at specific geometries, some light orientations are favoured over others, resulting in the polarisation of incoming light. While Mie scattering occurs much more strongly in the direction of travel of the wave, the maximum polarisation is often found at 90° from it.

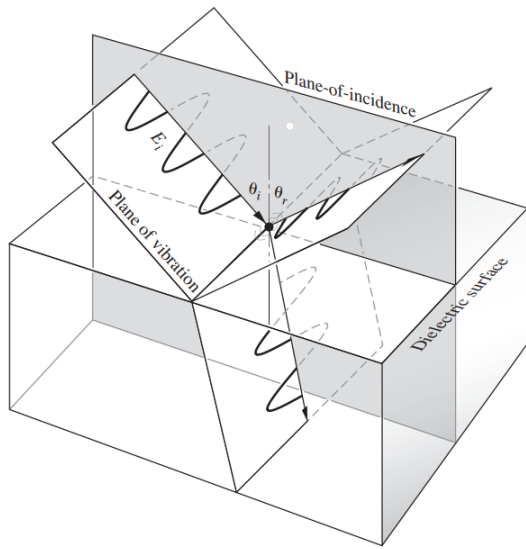
2.1.2.2. Reflection

A very common form of polarisation — and the more interesting one in this document — is that which is caused by reflection. This happens when light interacts with a *dielectric medium*: a material which does not naturally conduct electricity, but which allows light to pass through. This term describes the phenomena of glare on window panes or on the surface of water, or the sheen on glass surfaces or indeed well-nourished leaves.

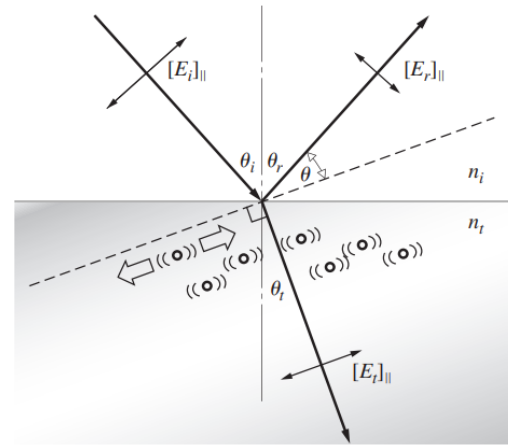
Figure 2.8a shows a planar wave interacting with the interface between two media. Here the wave is shown as orthogonal to the plane-of-incidence. Upon encountering the interface, a part of that wave is transmitted into the material. The transmitted wave then drives the bound electrons in the material, which act as a dipole and re-radiate outwards, creating a reflected wave that is also perpendicular to the plane-of-incidence. Conversely, if the incoming wave is oriented along the plane-of-incidence — as is shown in Figure 2.8b — then the dipoles oscillate along the plane-of-incidence as well, and the reflected wave is formed on the same plane, at an angle θ from the oscillation direction of the dipoles.



Figure 2.9: A body of water observed at Brewster's Angle. The photo on the left shows a significant amount of glare. The photo on the right is taken with a polarisation filter oriented normal to the plane-of-incidence, such that all reflected light — the glare — is filtered out, leaving only the light transmitted back through the water[16].



(a) A planar wave incident on a dielectric surface[15].



(b) Dipole orientation axis θ with respect to the reflected wave[15].

A special case occurs when the angle θ is set equal to 0, which occurs when the angles $\theta_r + \theta_t = 90^\circ$. When that happens, any component within the plane-of-incidence will be entirely transmitted — in other words, only the component normal to the plane of incidence will reflect, resulting in a polarised wave. The angle of incidence at which this phenomenon takes place is usually denoted by θ_p , and is referred to as *Brewster's Angle*. It follows from Snell's law that:

$$\tan \theta_p = n_t / n_i \quad (2.20)$$

An expression commonly referred to as *Brewster's Law*.

Polarisation by reflection is often modelled by means of Equations 2.21 to 2.24, known as the *Fresnel Equations*. Here the symbols r and t denote the ratios of the amplitudes in reflection and transmission — *i.e* the fraction of the total incident light that is reflected or transmitted. θ_i and θ_t denote the angles of incidence and transmission, n_i and n_t denote the refraction indices of the incident medium and the transmission medium, and $\perp$ and $\parallel$ denote whether the incident electric field $\vec{E}$ is perpendicular or parallel to the plane-of-incidence, respectively.

$$r_{\perp} \equiv \left(\frac{E_{0r}}{E_{0i}} \right)_{\perp} = \frac{n_i \cos \theta_i - n_t \cos \theta_t}{n_i \cos \theta_i + n_t \cos \theta_t} \quad (2.21)$$

$$t_{\perp} \equiv \left(\frac{E_{0t}}{E_{0i}} \right)_{\perp} = \frac{2n_i \cos \theta_i}{n_i \cos \theta_i + n_t \cos \theta_t} \quad (2.22)$$

$$r_{\parallel} = \frac{n_t \cos \theta_i - n_i \cos \theta_t}{n_i \cos \theta_t + n_t \cos \theta_i} \quad (2.23)$$

$$t_{\parallel} = \frac{2n_i \cos \theta_i}{n_i \cos \theta_t + n_t \cos \theta_i} \quad (2.24)$$

Given that the total irradiance ratio of light on a surface is proportional to the square of these ratios, one can write:

$$R_{\perp} = r_{\perp}^2 = (E_{0r}/E_{0i})_{\perp}^2 \quad (2.25) \quad R_{\parallel} = r_{\parallel}^2 = (E_{0r}/E_{0i})_{\parallel}^2 \quad (2.26)$$

These values are known as the *reflectances*, and are a measure of the power of the signal as opposed to the amplitude. Squaring the corresponding Fresnel equations yields:

$$R_{\perp} = \frac{\sin^2(\theta_i - \theta_t)}{\sin^2(\theta_i + \theta_t)} \quad (2.27)$$

$$R_{\parallel} = \frac{\tan^2(\theta_i - \theta_t)}{\tan^2(\theta_i + \theta_t)} \quad (2.28)$$

Assuming any incoming light is unpolarised, one can represent it with two orthogonal electric fields, as was demonstrated before. Assuming these two orthogonal fields have the same amplitude, it follows that they will carry the same amount of energy. In other words, the incident irradiance I_i will be composed of two components, such that $I_{i\parallel} = I_{i\perp} = I_i/2$. Consequently, it will be the case that if $I_{r\parallel} = R_{\parallel}I_{i\parallel}$ (and similarly, $I_{r\perp} = R_{\perp}I_{i\perp}$), then:

$$I_{r\parallel} = R_{\parallel} \frac{I_i}{2} \quad (2.29)$$

$$I_{r\perp} = R_{\perp} \frac{I_i}{2} \quad (2.30)$$

Then the total reflectance in natural light R is I_r/I_i , which can now be computed as:

$$R = \frac{I_{r\parallel} + I_{r\perp}}{I_i} = \frac{1}{2}(R_{\parallel} + R_{\perp}) \quad (2.31)$$

One can use the relationships in Equation 2.1.2.2 and the definition in Equation 2.14 to fully describe the specularly reflected ray in terms of Stokes parameters.

2.2. Polarisation of vegetation

Polarised signals from vegetation are a well-established phenomenon. Years of research have shown that the interaction between light and plants can provide valuable insights, both at the leaf and canopy level. The literature shows that light reflected off of plants has two elements: a diffuse or Lambertian element — light reflecting off a surface in every direction, a consequence of the interaction of the light with the volume and interior of the leaves; and a specular or Fresnel element, a direct reflection off the surface of the leaf.[3–8]. As is the case with most translucent materials, the light entering the leaves is scattered in all directions, and multiple scattering results in the diffuse reflectance that results from the interaction. It is a well-established fact that relevant information about plant canopies can be gathered by measuring the spectral response of this diffuse element [9–12]. By contrast, the polarisation of leaves has been measured extensively in lab settings; however, while polarimetry has been and is being extensively used for aerosol measurement, at present it has not been integrated within satellite remote sensing frameworks for characterising essential canopy characteristics of vegetation. The physical mechanisms that cause it can be broken up into three different components: specular reflection, surface scattering, and molecular chirality.

The specular component is caused by a cuticle wax layer on the surface of leaves: the interaction at the boundary between air and this wax layer ensures that a great portion of the light never enters the leaf [17, 18]. Some studies add onto this that there is a smaller element of surface scattering present [8, 19]. As a consequence of these two mechanisms, linearly polarised signals appear at certain illumination-observation geometries[20]. Most of the aforementioned sources either measure this polarisation directly, or use it as a mechanism for separating the specular and diffuse elements. This specular, polarised element has also been shown to be practically independent from wavelength [21, 22]. Additionally, it may be linked to leaf and canopy parameters relevant in remote sensing, namely the Leaf Inclination Angle (LIA) [23, 24].

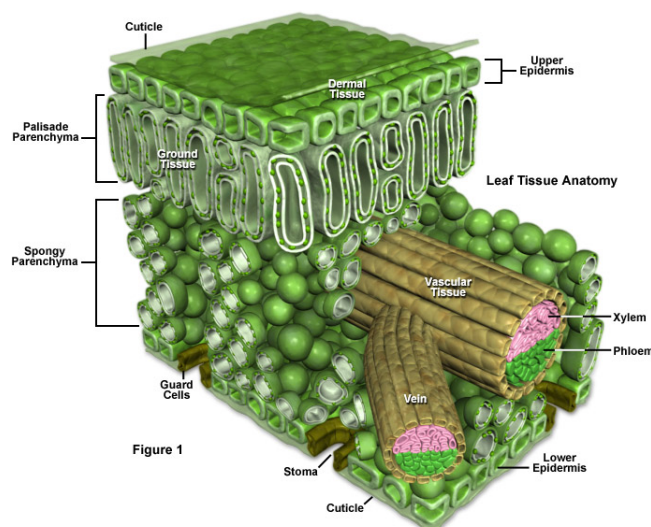


Figure 2.10: *The internal structure of a leaf[25]. Clearly displayed is the thin cuticle both on the top and bottom of the leaf, where specular reflection occurs.*

Circular polarisation from plant life has been measured in some instances [26–29]. This circular polarisation is induced by chiral molecules in the structure of plants, and is widely considered to be an agnostic sign of life — and often consequently employed in astrobiology. However, these circularly polarised signals from plants are tenuous compared to the incoming linear polarisation, and do not appear to indicate much about the characteristics of the plants themselves.

2.3. Remote sensing of vegetation

Researchers in the field of remote sensing are currently developing various models and techniques to characterise the Earth and the systems in its environment. To secure a better understanding of some of these systems and assist managers and policymakers in decision-making, a variety of biophysical vegetation parameters can be estimated through remote sensing techniques. While a discussion on the hardware and instruments employed in taking these measurements is discussed in Section 2.5, special attention must be paid to the methods used to retrieve said parameters from spectral measurements. Broadly speaking, this information is retrieved through inversion algorithms, which are traditionally grouped into the two categories of statistical and physical algorithms [30, 31].

Statistical algorithms employ tools such as regression equations, deriving an empirical relationship between remote sensing observations and conditions on the ground. Physical methods attempt to model the physical relationships between the biophysical parameters and the signals measured, often through the use of radiative transfer models. Both of these approaches are, by their very nature, *ill-posed*, as the number of parameters tends to be much greater than the number of independent observations, and these observations are subject to noise, bias and uncertainty [31].

2.3.1. Statistical methods

Statistical methods have historically been used extensively in optical remote sensing. As mentioned previously, this is often accomplished through regression and similar techniques, though the approach employed can differ. Broadly speaking, these could be divided into two distinct types: *parametric* and *non-parametric* regression. [32]

Parametric models assume a specific form of relationship between physical variables and the observations resulting from them. This is often accomplished by selecting a limited number of spectral bands of specific interest, often due to the impact that a given parameter has on them. These specific bands could be connected to leaf or canopy properties, for example. By far the oldest of these approaches are *vegetation indices* or *VIs*: these were defined such that specific spectral properties would be enhanced, whilst other bands that might add uncertainty or disturbances were minimised. These came about at a time when multispectral measurements were rare and computational power expensive, and *VIs* offered a simple solution. However, as technology has improved, new methods have been developed that better exploit the availability of spectral data. A family of these approaches has received the appellation of *shape indices*, which extract "shape"-related information from continuous spectral signals, that they then correlate with specific parameters. Examples include, but are not limited to:

- *Red-edge positioning* (REP), which observes the sudden increase in reflection in near-infrared wavelengths, the first derivative of which is known to be sensitive to chlorophyll content and, to a lesser degree, Leaf Area Index (*LAI*).
- *Derivative-based indices*, similar to red-edge positioning but considering other spectral regions.
- *Integration-based indices*, which integrate spectral regions. This approach exploits spectral regions related to water absorption to estimate water content.
- *Continuum removal*, which aims to flatten the entire reflectance spectrum, allowing for comparison with a common baseline.

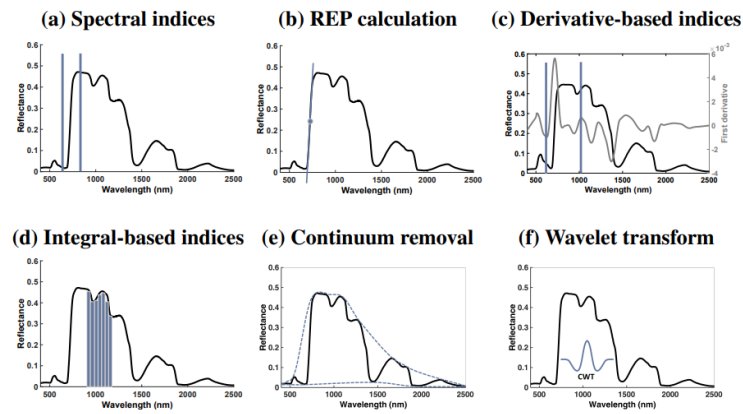


Figure 2.11: Illustration of common parametric regression methods[32].

Non-parametric methods, by contrast, exploit the data itself by applying some form of optimisation of weights or coefficients, which are adjusted to minimise the errors in the estimated values retrieved. An intrinsic advantage of this method is that it allows for the use of the entire spectral range, though like all training-based methods, it carries the risk of overfitting. These models can be as simple as multivariate linear regression, or employ machine learning techniques such as Support Vector regression or neural networks.

2.3.2. Physical methods

As described previously, physical methods aim to establish relationships between cause and effect in their attempt to simulate radiation reflection signals. The resulting *Radiative Transfer models* vary greatly in complexity and functionality. Given the broad extent and relevance of the topic, a fuller discussion of individual models is reserved for Section 2.4. More broadly, these models can be categorised into two different categories: those which can be economically inverted, and those that cannot. For the purpose of brevity these are often referred to as "invertible" and "non-invertible", respectively. It is often the case that the more complex a model is, the more computationally expensive it becomes to successfully invert it. Models with relatively few inputs are usually fast in their computations, and are thus often easily inverted by numerical means. More detailed models that render more complex scenes tend to be non-invertible, and are thus better employed in lieu of physical experiments or labs, and for the generation of realistic data with which to simulate environments or validate other, less complex models. Common approaches to RTM inversion include numerical optimisation, look-up table inversion, and hybrid look-up table and machine learning inversion.

Numerical optimisation inversion minimises a cost function related to the difference between measured and estimated values. These tend to be computationally expensive, but the advent of more modern hardware has brought about an increase in computational power, thereby making inversion by numerical optimisation relatively viable.

Look-up table (LUT) inversion refers to the generation of great volumes of spectral scenarios, which reduces the problem of inversion to one of matching the measurement to the most similar or likely pre-conceived scenario. These methods employ different cost functions to evaluate the similarity of the measured and predicted measurements across the spectrum. Naturally the generation of the look-up table itself is computationally expensive — and more so the more complex a model gets —, but it need only be carried out once, and it predates the inversion process itself, such that the inversion of a specific measurement is done in relatively short order.

Hybrid LUT-Machine learning approaches are those in which pre-generated LUTs are employed in the process of training a machine learning model. In doing so, they combine the physical significance of RTMs with the computational efficiency of more statistical methods. [32]

2.4. Radiative transfer

In broad terms, a *radiative transfer model* (RTM) describes a mathematical process which aims to describe the transfer of energy through electromagnetic waves, and the effect of processes such as absorption, scattering and emission. In mathematical terms, the entire interaction of light travelling through a medium is given in Equation 2.32, commonly known as the *Radiative Transfer Equation* (RTE).

$$\frac{dI_v(\mathbf{r}, \hat{\mathbf{s}})}{ds} = -\kappa_v I_v - j_{v,scat,out} + j_{v,emit} + j_{v,scat,in} \quad (2.32)$$

where:

v	Radiation frequency
I_v	Specific intensity at frequency v
s	Distance along a ray path s
$\hat{\mathbf{s}}$	Direction of propagation vector
$\mathbf{r}$	Position vector
κ_v	Absorption coefficient
j_v	Emission coefficient

This expression, in essence, states that the change in radiation will be the result of the losses in the form of scattering and absorption, together with gains from scattering and emission. While there are many different types of RTMs for a plurality of purposes, this expression is fundamental to all of them.

Radiative transfer models exist that attempt to simulate the interaction of radiation with vegetation — most notably, they seek to simulate the transmission and reflection of vegetation for remote sensing purposes. It is these models that are of greatest interest for the purpose of this research, and they fall into two broad categories: leaf models, and canopy models.

2.4.1. Leaf models

Leaf radiative transfer models have existed for decades, and their goal is to simulate the optical properties of various forms of vegetation based off of some physical and chemical properties of said plants.

Perhaps the most prolific of these models is *PROSPECT*. *PROSPECT* can accurately simulate the spectral signal of plants within a wavelength range of 400[nm] to 2500[nm]. [33]. It does so by treating vegetation as a translucent plate, composed of N parallel layers stacked on top of each other, separated by $N - 1$ spaces. It then models the spread of light through the layers as a light cone, employing several parameters that were fixed experimentally, such that signals can be simulated with three inputs: the *Leaf structure parameter* N , which corresponds to the effective number of mesophyll layers (and is thus a measure of the complexity of the leaf's internal structure); the total pigment content C_{a+b} , known also as the total chlorophyll content¹; and the *equivalent water thickness* C_w , a measure of the leaf's water content. *PROSPECT* has spawned many variants over the years[34], incorporating parameters such as the dry matter content C_m , which represents structural dry mass per unit area; Carotenoids C_{car} , which control absorption in the blue-green regions of the spectrum²; and anthocyanins C_{ant} , with a similar effect to carotenoids.

Most interesting among *PROSPECT*'s spawn are *PROSPECULAR*[38] and *PROPOLAR*[37], both models developed in the same institute. These models attempt to build on *PROSPECT* by adding the effects of specular reflection — a variable that is not considered in the original version. Specular reflection being an anisotropic phenomenon, incorporating it required converting the model from a 1D model — plane-parallel and homogeneous, with a single signal recorded at nadir — to a 3D

¹The use of the word pigment is not coincidental. It is chlorophyll that is broadly responsible for the green hues often observed in plants.

²It is the breakdown of chlorophyll with the advent of senescence — a leaf getting "older" and having its nutrients recycled by the plant in question — that makes carotenoids more predominant[35, 36]. The subsequent absorption of green-blue light is what leads to the predominantly yellow and red tones.

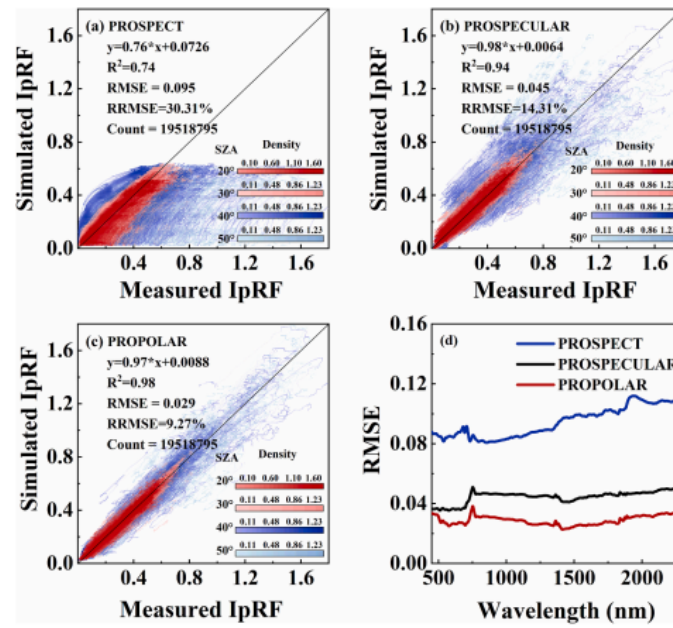


Figure 2.12: Comparison of *PROSPECT*, *PROSPECTULAR* and *PROPOLAR*[37]. The results in this comparison suggest a decrease in root-mean-square error RMSE with increasing complexity and functionality.

environment, in which different results are obtained for different angular regions within a semi-sphere. *PROSPECTULAR* demonstrated more accurate simulations of reflection on leaves[38]; *PROPOLAR* built on this advance to estimate a degree of linear polarisation (DoLP), making it the first model in the *PROSPECT* family to do so, and consequently one of the most interesting for the purpose of this research.

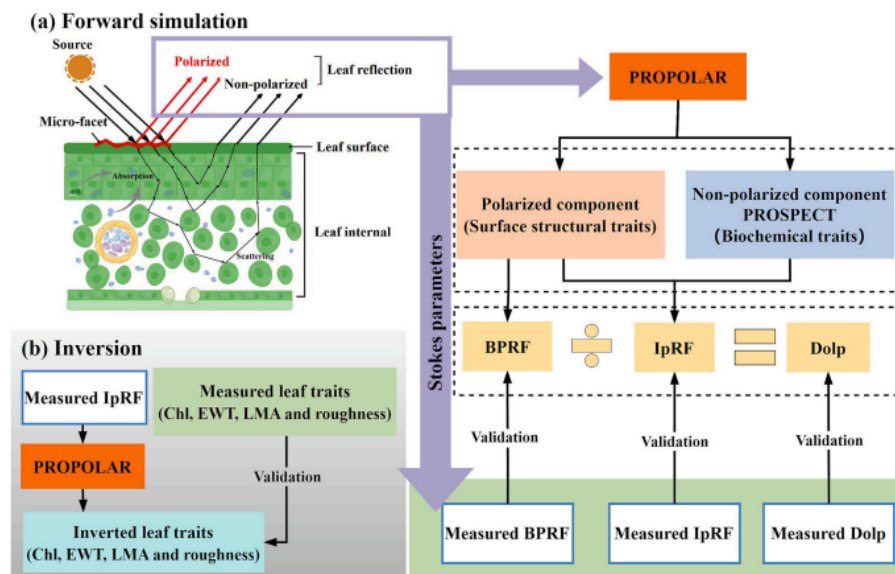


Figure 2.13: Flow chart of *PROPOLAR*[37]. The authors validated each of the different products — the Bi-directional Polarised Reflection Function (BPRF), the measured intensity (IpRF), which is a ratio between the reflected radiances of a leaf against a reference surface, and the Degree of Linear Polarisation DoLP.

One of *PROSPECT*'s most glaring limitations is made manifest when one considers the leaf structure it employs: a series of plates may well mimic most broadleaf plants and trees. Leaves with different shapes — such as needles — cannot be accurately simulated by *PROSPECT*. Models do exist that fill this niche, most notably *LIBERTY*[39]. Where *PROSPECT* employs flat planes, *LIBERTY* employs a series of spheres separated by air gaps. It employs a number of geometric parameters — the sphere diameter, the separation between spheres and the thickness of the needle — coupled

with a number of chemical parameters, similar to *PROSPECT*. Its output is a 1D bulk spectral signal, with a range of 400[nm] to 2500[nm].

2.4.2. Canopy models

Canopy models form the other major group of models related to vegetation remote sensing. Discussions of canopy models often begin with *SAIL*, the oldest of these models. *SAIL*, first published in 1984, treats canopies as a single, horizontal and homogeneous layer, within which leaves are randomly distributed according to a given *leaf angle distribution (LAD)*. It then models two fluxes: a downwards flux of sunlight entering the canopy, and an upward flux of reflected and/or scattered light leaving it. It does so by statistically modelling the probability of interactions occurring within the volume, and does not track individual leaves. Its inputs are: the aforementioned *LAD*, a statistical distribution of random azimuths for the leaves; the *Leaf Area Index LAI*, which quantifies the leaf material per ground area; and three optical properties in the form of the leaf reflectance ρ_l and transmittance τ_l , and the soil reflectance ρ_s . Later, more sophisticated versions include a hotspot parameter, which is used to correct for the reduction in shadowing resulting from the view angle being close to the sun angle. Like the leaf models discussed heretofore, *SAIL* outputs a 1D spectral signal. Unlike said models, it requires one to specify not just a sun zenith angle — which determines the angle at which the sun illuminates the scene —, but also a viewing zenith angle, together with an azimuth angle (relative to the sun zenith angle).

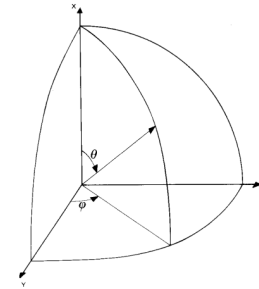


Figure 2.14: Definition of zenith and azimuth angles[40].

The *SAIL* model has been used extensively since its inception, and has spawned a sizeable amount of variants. Most notable among them are *GeoSAIL*[41], which allows for canopy clumping, to better reflect agricultural formations such as crop rows; *4SAIL*[42] and *4SAIL 2*[43], which introduce the use of four streams of light instead of two (by splitting the downward and upward fluxes into direct and diffuse components); and most notably, the *PROSAIL*[44] family, which is a *PROSPECT-SAIL* coupling, able to model vegetation canopy signals based on the chemical and physical characteristics outlined for both of its progenitor models. Most importantly, all of these models are fully invertible.

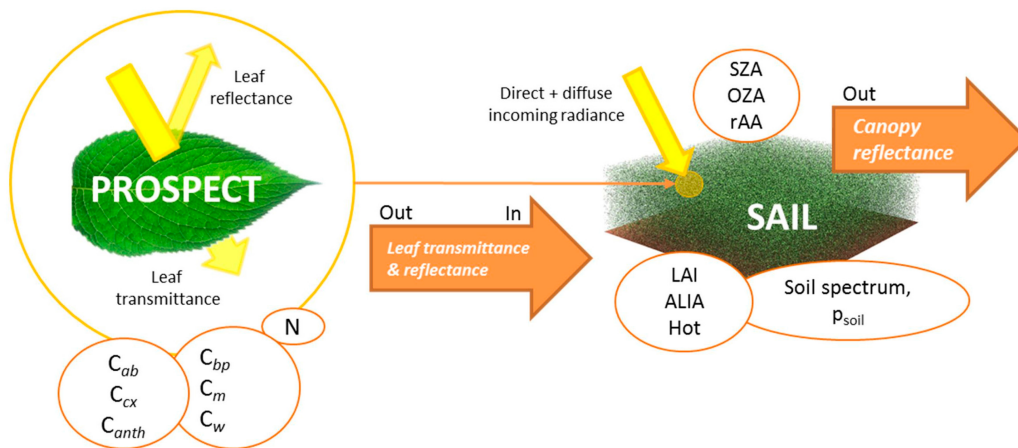


Figure 2.15: A visual representation of the functionalities of *PROSAIL*[45].

Despite the broad functionality and use cases of the *SAIL* and *PROSAIL* model families, none of them are capable of simulating canopy polarisation at the current moment. Other canopy models do exist, however — these are primarily used to isolate potential noise in aerosol measurements, and are empirical or semi-empirical "hybrids" as a consequence [46–52]. While these models have been shown to accurately match real measurements[51], their function implies that most of them make use of empirical parameters that bear little relation to the actual canopy being observed.

The *DART* model[53] — Discrete Anisotropic Radiative Transfer —, whilst not being a canopy model, is a radiative transfer model of relevance in this context. *DART* is a 3D model designed to simulate the interactions of light with realistic Earth scenes, containing complex geometries such as buildings, sloped terrains, vegetation and different atmospheric conditions. It does so by splitting a scene into discrete *voxels*³, each of which has assigned optical properties. It then simulates radiative transfer by tracking discrete rays through the scene. How it does so depends on the mode of use, as *DART* can be set to either *DART-FT* — which solves the radiative transfer equation through use of the Discrete Ordinates method — or *DART-Lux*, which uses Monte Carlo ray-tracing in order to simulate the same scene. *DART-FT* is fully deterministic and devoid of any additional sources of noise, and is therefore highly accurate. It is more often used for energy budget and flux simulations. It is, however, computationally expensive. *DART-Lux* was developed to allow for faster and less memory-expensive simulation of radiative transfer images. However, due to its stochastic nature it introduces a small amount of noise into each image. Being non-deterministic, *DART-Lux* suffers from non-uniqueness, effectively making it impossible to invert. By comparison, *DART-FT* is technically invertible; nevertheless, such a feat has yet to be accomplished.

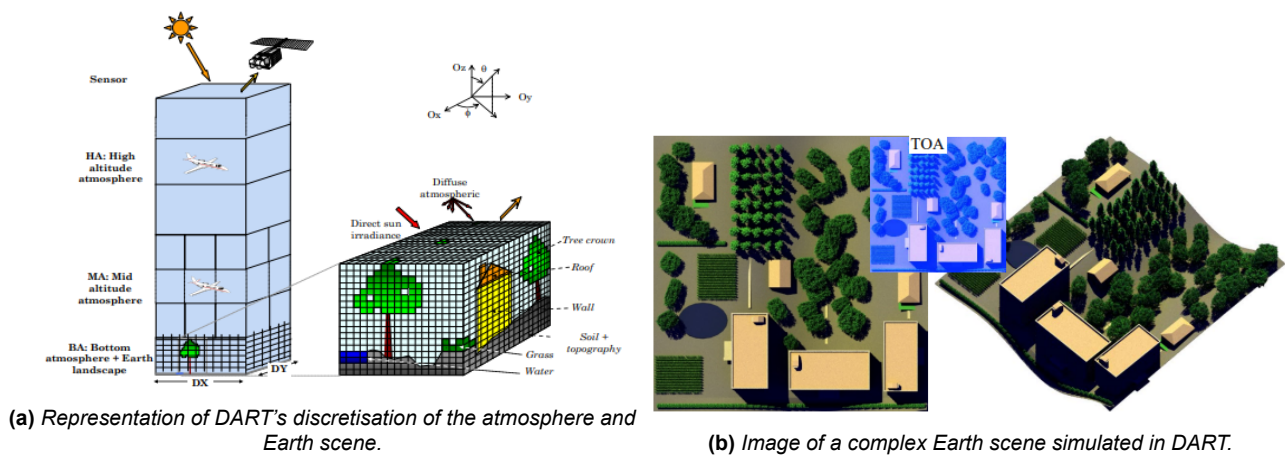


Figure 2.16: *DART*'s complexity illustrated. [54, 55]

DART is of special interest due to its feature of simulating vegetation — incorporating different versions of *PROSPECT* in its optical properties definitions — and its ability to simulate specular reflection and, more importantly, full-Stokes polarisation[56, 57].

Table 2.2 summarises the contents of this section in a way that allows for rapid comparison between them and their functionalities.

Model	Scale	Concept	Inputs	Output	Invertible	Polarisation	Additional notes
PROSPECT	Leaf (flat)	Flat plate model, upward/downward flux tracking.	Leaf structural and chemical parameters (depends on version).	Leaf reflectance and transmittance spectra.	Yes	No	Fast. Standard leaf model. No explicit leaf anatomy.
LIBERTY	Leaf(needle)	Spherical components model.	Leaf structural and chemical parameters.	Leaf reflectance and transmittance spectra.	Yes	No	More suited to conifers. More complex than PROSPECT, less commonly used.
PROSPECTULAR	Leaf	Flat plate model, PROSPECT + Fresnel-based reflection at the leaf interface.	PROSPECT inputs, refractive index and surface roughness.	Bi-directional Reflection Distribution Function, leaf spectra.	Yes	No	Captures specular reflection. Less standardised inversion due to additional parameters.
PROPOLAR	Leaf	Iteration on PROSPECTULAR, models light polarisation at leaf interface.	PROSPECT inputs, refractive index, surface optical properties.	BRDF, Polarised BRDF (BPRF), DoLP, leaf spectra.	Yes	Yes	Slightly more computationally demanding than standard PROSPECT, relatively new and untested, limited validation.
SAIL	Canopy	Homogeneous turbid volume, employs statistical distribution of leaf angles.	Leaf Area Index, Leaf Angle Distribution, Illumination/Viewing geometry, Leaf/Soil reflectance, leaf transmittance	Top of canopy reflectance spectra.	Yes	No	Fast, invertible, widely used. Scalar only.
PROSAIL	Canopy		PROSPECT inputs, SAIL inputs	Top of canopy reflectance spectra.	Yes	No	Fast. Standard forward canopy model. Scalar only, no leaf anatomy or heterogeneous canopies.
DART	Canopy/Earth scene	3D voxel model, models emission, transmission and reflection. Models polarisation. Highly complex.	3D geometry, atmospheric parameters, surface optical properties (can be defined through PROSPECT).	Hyperspectral images, BRDF, Stokes Parameter images, top of atmosphere radiance.	No	Yes	Most complex model. Much more computationally expensive as a consequence.

Table 2.2: Summary of the Radiative Transfer Models properties discussed.

³A voxel can be visualised as the 3D equivalent of a pixel, see Figure 2.16a.

2.5. Space-borne spectropolarimeters

A polarimeter is a scientific instrument that can analyse certain properties of the polarisation of light, such as the degree of polarisation or angle of polarisation. There are many different polarimeter architectures, each employing their own principles to obtain measurements. Broadly, all of these designs belong to one of two different branches of development: either *division-of-time* or *division-of-space* polarimeters:

- *Division-of-time*: These polarimeters measure polarisation by varying system parameters over time, be it through means of hardware or software. Doing so modifies the input light in ways which allow one to determine its Stokes parameters. An example configuration of this method involves directing collimated light into a rotating quarter-wave plate - altering the incoming light's polarisation over time - and then filtering it through a fixed polariser, reducing the input to a time-varying intensity. Performing Fourier Analysis on this intensity reveals the components of the input light - directly related to its Stokes parameters. While they have the obvious advantage of providing a compact and straightforward means of measuring polarisation, the necessity of mechanically rotating the quarter-wave plate significantly affects the measurement speed and the device's stability. The added mechanical complexity makes it more prone to failure.
- *Division-of-space*: These polarimeters employ a division of the incoming beam of light, separating it into components which can be measured individually — after having been filtered, allowing for the determination of each Stokes parameter — or a well-established combination of them — independently. A typical configuration of this sort will employ optical elements that partially specularly reflect light in sequence. While these tend to be more mechanically stable than the division-of-time methods, these usually require the deployment of a larger volume of optical elements, making them more expensive and bulky (a significant concern for space applications). They also carry the risk of optical misalignments.

While spectrometers have been employed on space platforms for decades, the story of space-borne spectropolarimetry begins with CNES' *POLDER* instrument. *POLDER* was flown on three different platforms (*ADEOS-1*, *ADEOS-2* and *PARASOL*). *POLDER*'s hardware consisted of a CCD detector array — 242×274 detectors —, with a field of view of around $2400 [km]$, and when in orbit had a ground sampling resolution of roughly $6 [km]$. It employed 14 different measurement angles, such that as it moved across its orbital track it was able to view the same scene from different perspectives[58], and therefore able to sample a part of the *Bidirectional Reflectance Distribution Function* (BRDF) of the scene[59].

Its most innovative aspect was arguably its use of a rotating wheel carrying spectral and polarised filters[58], allowing it to take measurements of several narrow spectral bands ($443, 490, 565, 670, 763, 765, 865, 910 [nm]$)[60], and multiple polarisation angles. *POLDER* was used primarily in the context of aerosol and cloud characterisation, and a vast array of data products it spawned are publicly available[61].

Nevertheless, remote sensing of polarisation has advances significantly since the days of *POLDER*. The current state-of-the-art as far as spaceborn spectropolarimetry is represented are three instruments: *3MI*, *SpexOne*, and *HARP-2*.

The first of these, *3MI*, employs a rotating wheel equipped with different polarisation filters, allowing it to measure different linear polarisation states. Each state is measured three times in one full rotation of the wheel, which takes approximately 5.5 seconds. It boasts a polarimetric accuracy of roughly 0.5%. It covers 12 different spectral bands, ranging from the visible to the short-wave infrared ($410-2310 [nm]$, with a resolution of $10-50 [nm]$ depending on the band) and has a spatial resolution of roughly $4 [km]$ and a field-of-view of

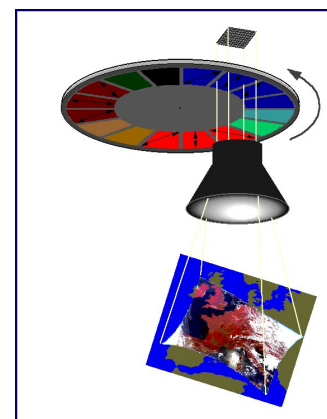


Figure 2.17: *POLDER* rotating filter wheel. The lines shown on some of the filters denote different polarisation directions. However, the image is merely representative[60].

2200[*km*]. It was launched aboard the MetOp-SG satellite in 2025[62, 63].

HARP-2 is a division-of-space pushbroom spectropolarimeter. While it measures only four spectral bands, it splits all incoming light into 120 different spatial regions, each of them corresponding to a different angle of incident light. The light is separated into three different detectors through the use of a custom-built Phillips prism. Each of these detectors is equipped with a polariser, in the 0°, 90° and 45° directions. Consequently, it is capable of measuring linear polarisation. It possesses a spatial resolution of around 5 km and a polarisation accuracy of under 1%, capable of reaching >0.5% in most cases. It has a ground track of 400-700[*km*]. It measures the spectrum from 400-900[*nm*] at a resolution of 50-100[*nm*]. Its first space-borne iteration was launched from the International Space Station on board a CubeSat in 2020.[64, 65].

Finally, *SpexOne* is SRON's latest instrument. It uses an ambitious method of modulating polarisation onto the spectrum of incoming light in order to make it measurable without splitting the beam or dividing it across time. This allows it to measure the full breadth of the visible spectrum and both the degree and angle of linear polarisation of incoming light. It does so with an absolute accuracy of less than 0.01% and accomplishes this while retaining a compact design. It is hyperspectral and measures from 385-770nm at a resolution of 2-5 nm. It has a spatial resolution of about 5[*km*] (with a sampling distance of 2.7[*km*]) and a swath of 100[*km*] across the five angles it measures. It was launched aboard NASA's *PACE* mission in 2024.[66, 67].

Each of these instruments has its own associated dataset in which all different products produced are collected. While these datasets exist and are publicly available — or soon will be —, they have not been used for remote sensing of vegetation due to the relative immaturity of the technology involved, as there exist no reliable methods of retrieving vegetation characteristics from such observations.

When undertaking a research project of any significant breadth, it is imperative to pursue a structured and well-defined approach. This chapter presents the definition of said research approach by underlining the gaps in the scientific state-of-the-art as concerns the remote sensing of vegetation, especially relating to polarisation. It is based off of the literature study conducted prior to the definition of the research approach, which can be found in Chapter 2.

3.1. The missing links in the state-of-the-art

As far as concerns physical principles, it is shown in Section 2.1 that the polarisation of light is generally well-understood, and can be readily modelled as a phenomenon of electromagnetic nature. Existing structures, with the Stokes formalism perhaps being chief among them, prove perfectly capable of describing the polarisation of light and predicting the results of its interactions. The mechanism by which vegetation polarises incoming light is therefore easily inferred: there exists in the vegetation itself some form of dielectric medium through which light must propagate or reflect, and then be sent in the direction of an observer.

It is shown in Section 2.2 that said dielectric medium is found in the form of the cuticle on the surface of most leaves. This cuticle is a thin, wax-like layer that exists mainly for the purpose of water retention. Specular reflection off of this cuticle is the main cause of linear polarisation of vegetation signals. Said signal is highly sensitive to the observation geometry — both the leaf's angle with respect to incoming light and the viewing angle heavily affect the polarisation, such that the *DoLP* ranges from 0.1 to 0.6/0.7 depending on geometry. A more minor element of circular polarisation is present due to the interaction of light with chiral molecules inside the leaf¹. Different works have remarked on the presence of this polarisation, both at the leaf level and at the canopy level — abundant literature exists on experiments performed in laboratory settings.

Existing space-borne polarimeters have been able to record polarisation whilst flying over highly vegetated areas. The primary function of these instruments is that of measuring aerosols suspended in the atmosphere — a task which requires observations at multiple angles. This function typically renders any signal originating from below the atmosphere — as vegetation signals would be — as a background signal that needs to be removed. This is commonly done by means of empirical models built for this purpose. This fact reveals that there exists a signal that originates from vegetation, which can be seen from space, and which is significant enough to pose challenges to measurements of other variables.

It can therefore be said that while electromagnetism and the Stokes formalism may be fully complete within the realm of theory, but there exists a clear gap between the interactions happening at the bottom of the atmosphere — at the leaf and canopy levels — and what is perceived from a space-based platform. Similarly, the effects of integrating polarisation from the leaf level into a canopy are not entirely well-understood.

The literature on forward-modelling of leaf polarisation could be described as being of humble extent, being limited to one radiative transfer model: *PROPOLAR*. However, due to how recent it is, there is no additional literature validating it or employing it. The situation at the canopy level is even more stark, with there being no dedicated canopy model that manages to simulate polarisation. More elaborate radiative transfer models do exist which can simulate polarisation, but they are neither dedicated to canopy polarisation nor computationally cheap. *DART* is the best candidate for the

¹The degree of circular polarisation *DoCP* is in the order of 10^{-3} .

purpose of attempting to forward-simulate canopy polarisation, and having been validated extensively, may offer the best means of validating other existing models.

On the topic of polarised signals from vegetation there is, therefore, a clear lack of integration between measurements and models at a leaf level, canopy level and space level. The literature is broad enough to suggest a fertile ground for the development of a more complete understanding of this phenomenon. This improved understanding would present an opportunity to better monitor vegetation on Earth, both by potentially enabling for the monitoring of variables thus far not considered in remote sensing — such as canopy architecture and leaf angle —, and by reducing ambiguities when combined with spectral data, which may enable more accurate classification and parameter estimation.

3.2. Research questions and approach

Having established this gap in the knowledge, a few vital research questions were originally formulated:

1. **RQ-1:** Can leaf polarisation be accurately modelled?
2. **RQ-2:** Can canopy polarisation be accurately modelled?
 - How does leaf polarisation aggregate at the canopy level?
 - Is there a clear link between canopy geometry and measured polarisation?
3. **RQ-3:** How well do canopy models reflect measured remote sensing data?
4. **RQ-4:** Could existing models be used to measure vegetation functional traits?
 - Can leaf properties (chlorophyll, equivalent leaf water thickness, dry matter content, etc) be retrieved through remote sensing?
 - Can canopy characteristics (Leaf Area Index, Leaf Inclination Angle, etc) be retrieved through remote sensing?
 - What are the optimal measurement conditions for retrievals?

These questions were formulated before the start of the research phase. As a consequence of an evolving understanding over the course of this phase, and a developing realisation of the loftiness of these goals, the scope was reduced to **RQ-1** and **RQ-2**, focusing primarily on **RQ-1** in hopes of eventually developing a better understanding of how leaf polarisation might aggregate at the canopy level. No work was performed on **RQ-3** and **RQ-4** as a consequence, though the relevance of these questions remains, and these are questions that should be investigated in the pursuit of a more complete understanding of the topic.

In order to determine whether vegetation polarisation can be modelled either at the leaf or canopy level, it is necessary to evaluate the existing models. The motivation behind this evaluation is explained by the immaturity of the existing models. Only two models currently exist that claim to directly simulate any sort of vegetation polarisation. The *PROPOLAR* model is the first of these, and having been created for the specific purpose of simulating leaf signals — simulating the diffuse spectral element, an unpolarised specular element and a degree of linear polarisation *DoLP*. This model represents an ideal candidate to simulate leaf *DoLP* — though not the angle of linear polarisation *AoLP*. However, it has never been validated by any party except the authors themselves. This lack of validation by third parties is explained by its relative newness. Testing whether this model works is therefore paramount to answering the question of whether leaf polarisation can be simulated accurately.

Another model with that features polarisation is *DART*. It is a much more versatile model, and unlike *PROPOLAR* it is not designed specifically to simulate vegetation. However, it is capable of simulating surfaces with detailed optical properties and the signals they emit and reflect, including polarisation in the form of Stokes vectors. Given that *DART* has integrated the use of *PROSPECT* in the definition of optical properties of the surfaces it simulates, it is possible to replicate the structure of *PROPOLAR* in the form of a *DART* simulation. *DART* is therefore:

- A potential means of simulating leaf polarisation, given that a simple 1D geometry such as the one in *PROPOLAR* can be simulated with the same optical properties.
- A benchmark to which *PROPOLAR* can be compared, given that *DART* has been extensively validated.

It is for that reason that one of the methods employed in this research is the comparison between *PROPOLAR* and *DART* with similar configurations: significant differences between them would highlight possible limitations within these models.

The approach outlined in the preceding paragraphs would not definitively answer the question. While it is true that *DART* is the more thoroughly validated of the two models, a discrepancy between them would not necessarily mean that *PROPOLAR* is less accurate — it may in fact be more accurate. The only way to establish any degree of certainty in this matter is to compare the results of these simulations to real measurements. It was therefore determined that a measurement strategy would be employed in addition to the model comparison to more firmly establish the accuracy of these models. It is presented in Section 3.4

3.3. Model intercomparison

A number of simulations were carried out in the course of this research, using both the *DART* and *PROPOLAR* models. This process was done in a number of steps. *PROPOLAR* is fairly simple in its structure and purpose, and is therefore simple to run and work with. The challenge lies in simulating a scene resembling a leaf within *DART*, given that it is not its stated purpose. This was in essence an iterative process, and while the methods employed in the latter simulations are presented here, information on intermediary steps is omitted. An introduction to both models is presented in Appendix A, omitted here in the interest of brevity. Section B.1 contains a simulation of a series of trees which may be of interest at a later point, though it is not connected to the main body of research.

3.3.1. Qualitative *DART* assessment

The ability of *DART* to perform simulations of polarised vegetation emissions was tested by using a simulation with vegetation-related parameters and a simple geometry. The leaf surface was modelled as a flat plane of constrained dimensions, as shown in Figure 3.1. It contains only the flat plane at a 0° angle, and the soil underneath. The scene was allowed to repeat a number of times to minimize the effects of boundaries. The exact dimensions of the geometry as set in the simulation are given in Table 3.1.

The exact environmental parameters are given in Table 3.2: the scene temperature was set at an average value of 300K. Two wavelengths were selected to reveal if there were noticeable differences in terms of polarisation, which should not be present. The remaining parameters pertain to numerical aspects of the simulation, and were chosen as a result of trial-and-error, until changes in them failed to produce significantly different results.

The optical properties of both the leaf and the soil are given in Table 3.3: the leaf diffuse parameters correspond to the inputs of a *PROSPECT* model, as this is being used to characterise this specific optical property. They represent common values for a *Fagus Sylvatica* leaf found in existing literature, and were chosen due to their conventionality. The specular element contains the roughness $\sigma = 0.3$, which was similarly gathered from literature. In radiative transfer modelling of vegetation, said roughness is conventionally measured as the *Root-Mean-Square (RMS)* of the slope of the leaf surface, such that it can easily be measured using a microscope — see Figure 3.2. The incident medium, being air, has a refractive index $n_i = 1$. The leaf's own refractive index $n_t = 1.33$, the value

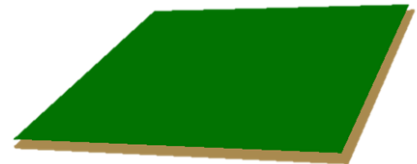


Figure 3.1: A visual representation of the plane in *DART*. Note that this does not show scene repetition. If one imagines this plane to be virtually infinite, the leaf plane is an accurate visualisation of the scene as simulated in *PROPOLAR* as well.

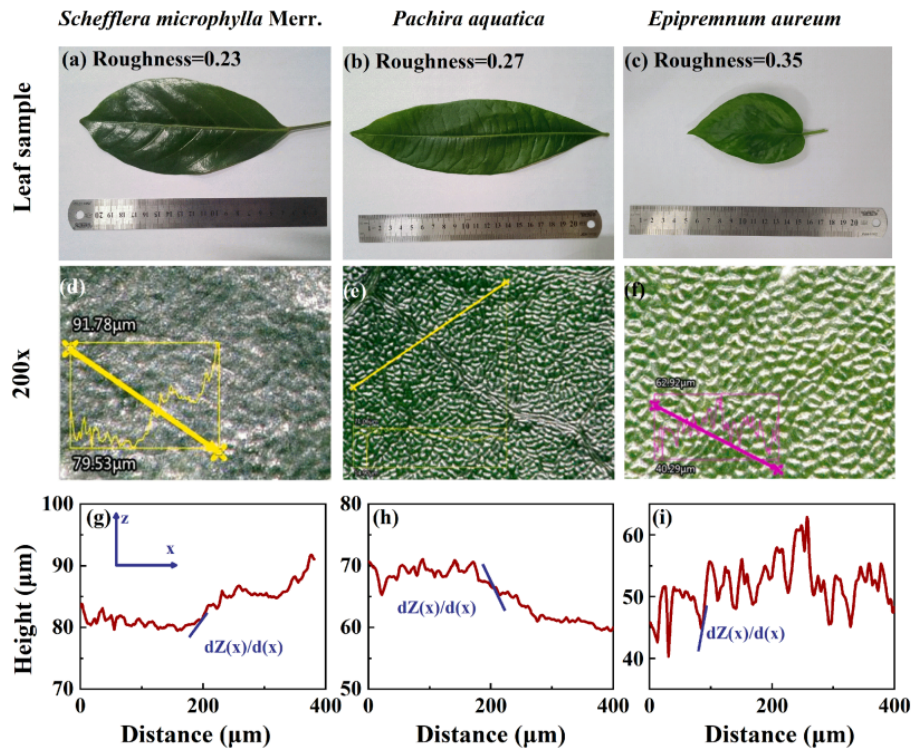


Figure 3.2: Measurements of the roughness of different types of leaves[37]. The *RMS* of the slopes of the given set of measurements can be used as a measurement for roughness.

of water given visible light at room temperature, set as an approximation. The optical properties for the soil were left untouched from *DART*'s own default values.

	Object type	Object dimensions	Object position
Geometry	Square.obj	X = 1 m Y = 1 m Z = 1 m	X = 0.5 m Y = 0.5 m Z = 0.01m

Table 3.1: Geometry of the flat plane.

The total runtime of this simulation was roughly 1'20", though that figure is heavily dependent on the available hardware resources.

	Scene average temperature	Wavelengths	Target pixel size	Target pixel density	Max. Render Time per image	Number of scene repetitions	Relative energy threshold for ray-stopping [-]	Max. number of scattering events per ray	Products	Number of directions
Environment parameters	300 K	$\in [400, 900]$ nm.	0.0005 m	100	400 s	4	$1 \cdot 10^{-6}$	130	BRF maps(1° resolution), Polarisation images	500

Table 3.2: Flat plane simulation parameters.

	Leaf specular	Leaf diffuse	Ground specular	Ground diffuse
Optical properties	$n_i = 1$, $n_t = 1.33$, $\sigma = 0.3$	Structure coefficient = 2, Chlorophyll = $50 \mu\text{g} \cdot \text{cm}^{-2}$, Carotenoid = $80 \mu\text{g} \cdot \text{cm}^{-2}$, Brown Pigment = 0.0, Equivalent water thickness = 0.010 cm, Anthocyanin = $0 \mu\text{g} \cdot \text{cm}^{-2}$, Dry matter content = $0.012 \text{ g} \cdot \text{cm}^{-2}$, Carbon-based dry matter = $0.009 \text{ g} \cdot \text{cm}^{-2}$, Nitrogen-based dry matter protein = $0.001 \text{ g} \cdot \text{cm}^{-2}$,	$n_i = 1$, $n_t = 1.33$, $\sigma = 0.07$	2D Lambertian model: "loam_sandy_brown_fine_clean_smooth"

Table 3.3: Flat plane optical parameters.

3.3.1.1. Roughness analysis

An additional analysis was performed on the effects of roughness — measured as the *RMS* of the surface's slopes — by generating outputs of the same scene, varying the roughness alone. This was done in an effort to better understand how sensitive the results would be to roughness, given that it is one of the main parameters affecting the polarisation of the simulated signals. A number of simulations were carried out, with parameters described in Table 3.4. The roughnesses employed were

$\sigma \in [0.05, 0.10, 0.15, 0.20, 0.25, 0.30, 0.35, 0.40, 0.45, 0.5, 0.6, 0.7]$ [-]. The results of said simulations are shown in Section 4.1.1.1.

An attempt was made to implement roughness differently, by reducing the roughness within the *DART* interface and instead adding roughness to the surface 3D model directly. More details on this attempt can be found in Section B.2.

	Scene average temperature	Wavelengths	Target pixel size	Target pixel density	Max. Render Time per image	Number of scene repetitions	Relative energy threshold for ray-stopping [-]	Max. number of scattering events per ray	Products	Number of directions
Environment parameters	300 K	610 nm, 850 nm.	0.0001 m	120	150 s	8	$1 \cdot 10^{-7}$	120	BRF maps(^{1°} resolution), Polarisation images	200

Table 3.4: Flat plane simulation parameters.

3.3.1.2. Leaf angle analysis

One advantage of *DART* over *PROPOLAR* is that its versatile scene editor allows for the leaf surface to be tilted. It is therefore possible to attempt to use surface inclination to simulate different leaf angles. Being able to simulate leaves at different angles effectively is a necessary step in simulating the polarised signals of entire canopies.

A series of simulations were produced that would show the variation in both the *Bi-directional Reflectance Function* *BRF* and the *Bi-directional Polarised Reflectance Function* *BPRF* with respect to the angle of the leaf surface. While the whole scene is simulated, Figure 3.3 shows the measurements that are ultimately employed: the *BRF* and *BPRF* are thus measured in directions contained in the plane shown. As the simulation results are now restricted to this plane, it is convenient to define a new coordinate system to describe them, as opposed to employing the familiar zenith and azimuth angles. A zenith angle can be employed as is shown in Figure 3.4.

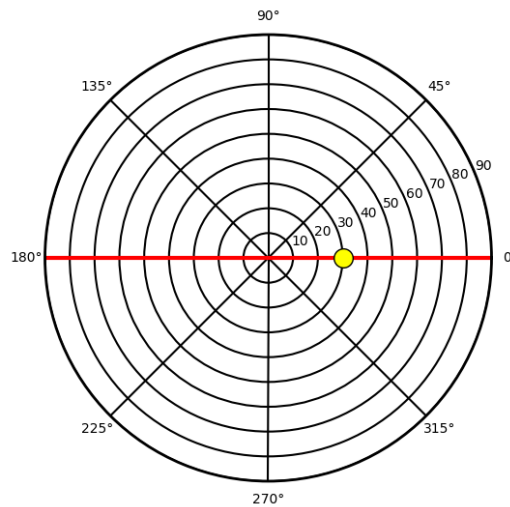


Figure 3.3: Polar plot showing the section of the space taken. The yellow dot indicates the Sun direction; the red line represents the area from which the measurements are taken.

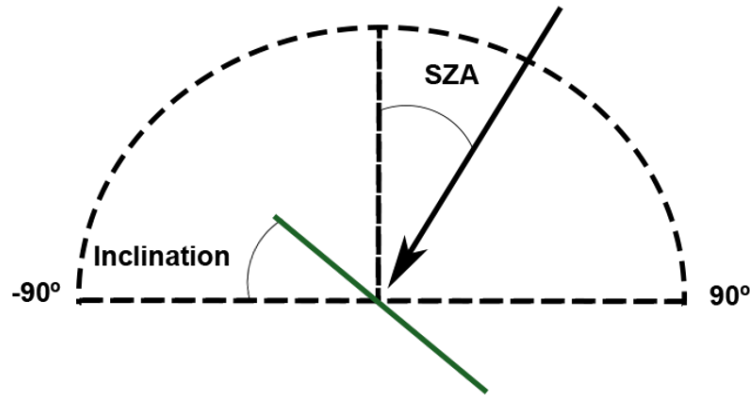


Figure 3.4: Coordinate system used to display the results of leaf angle simulations. *SZA* stands for Sun Zenith Angle.

The parameters employed in the simulation are presented in Table 3.5. Compared to previous simulations, the number of viewing directions is minimised to improve computation time. A sequence of simulations was created, in which the leaf angle was increased within the range $[0, 90]$ with increments of 1° . Additionally, the range of wavelengths employed was expanded, selecting points of interest along the spectral curve shown in Figure 4.2b. Despite the reduction in viewing directions, the entire simulation process requires upwards of 4 hours. The results are presented in Section 4.1.1.2

	Scene average temperature	Wavelengths	Target pixel size	Target pixel density	Max. Render Time per image	Number of scene repetitions	Relative energy threshold for ray-stopping [-]	Max. number of scattering events per ray	Products	Number of directions
Environment parameters	300 K	560 nm, 610 nm, 670 nm, 720 nm, 750 nm, 850 nm, 900 nm.	0.0005 m	100	220 s	4	$1 \cdot 10^{-6}$	130	BRF maps (1° resolution), Polarisation images	100

Table 3.5: Flat plane simulation parameters.

3.3.2. Qualitative PROPOLAR assessment

The *PROPOLAR* model was assessed on its own merits. Given its limited scope compared to *DART*, the implementation of the simulation is straightforward. *PROPOLAR*'s geometry limits it to a plane, with the only geometric inputs being the Sun Zenith Angle *SZA* — which was set to 30° , as in Section 3.3.1. The Sun Azimuth Angle is fixed at 0° . α is a coefficient adjusted to measurements of specific leaves. Lacking any prior measurements, this coefficient was kept at the default value. The roughness parameter σ and refractive index n were set at the same values as in Section 3.3.1, and selected for the same reasons. The wavelengths simulated were the same $610nm$ and $850nm$. The values are summarised in Table 3.6.

Linear coefficient α	Roughness parameter σ	Refractive index n	Zenith Range	Azimuth range
0.9	0.3	1.33	$\in [0, 90] [^\circ], 1^\circ$ increments	$\in [0, 360] [^\circ], 1^\circ$ increments

Table 3.6: *PROPOLAR* polarisation input parameters.

3.3.3. Quantitative Intercomparison between DART and PROPOLAR

Having produced these simulations — the results of which can be found in Chapter 4 —, a comparison between the results of each was performed. Initially this was done by comparing the absolute and relative differences between *DART* and *PROPOLAR*, both in the *Bi-directional Reflectance Function* (*BRF*) and the *Bi-directional Polarised Reflectance Function* (*BPRF*). Some of the resulting plots were clipped to minimise the effect of outliers. This was done by computing the distribution of the differences, and then a Z-score for every difference:

$$Z_e = \frac{x_e - \mu_e}{\sigma_e} \quad (3.1)$$

Where Z_e is the Z-score of a specific difference, x_e is the difference, μ_e is the mean of the differences, and σ_e is the standard deviation of these differences. The results of said comparison are

found in Section 4.1.3

In order to further establish the reasons for any discrepancies between the models' results, simulations were carried out in both models with the aim of determining whether any discrepancies were due to differences in modelling, differences in parameters or implementation errors. This was done by simulating a simpler scene. Both models employ the *PROSPECT* model in some capacity: *PROPOLAR* uses it as its diffuse reflection layer — see Figure 2.13 — and as shown in Section 3.3.1, *DART* determines the diffuse optical properties of the leaf surface using *PROSPECT*. Comparing simulations in which both models emit only diffuse reflection therefore determines whether any major discrepancies are due the scenes not being comparable — *DART*'s being a finite 3D scene made to resemble *PROPOLAR*'s fundamentally homogeneous and infinite scene —, or whether it is due to how polarisation is implemented. To perform a full comparison, the wavelengths at which these simulations were run were changed for both simulations. A range of $\lambda \in [400, 2500]nm$ was chosen, measured at increments of $\Delta\lambda = 1nm$.

The values employed for this comparison are the same as those in Table 3.6 for *PROPOLAR*. The values modified in *DART* are shown in Table 3.7; some parameters were adjusted to reduce the runtime, given the much larger number of independent wavelengths in the simulation.

The *DART* simulation output is composed of two parts: one is a purely *PROSPECT*-based spectral curve, produced by inputting the values in Table 3.3 into the *PROSPECT* model in *DART*'s interface, such that the results are purely the result of the *PROSPECT* implementation, and completely disconnected from the geometry. The other output is the result of using these *PROSPECT* results as the optical properties within the scene, such that geometry does affect the output.

	Scene average temperature	Wavelengths	Target pixel size	Target pixel density	Max. Render Time per image	Number of scene repetitions	Relative energy threshold for ray-stopping [-]	Max. number of scattering events per ray	Products	Number of directions
Environment parameters	300 K	$\in (400nm, 2500nm]$	0.001 m	80	120 s	4	$1 \cdot 10^{-7}$	20	BRF maps(1° resolution), Polarisation images	200

Table 3.7: Flat plane simulation parameters.

3.4. Experimental Assessment

Comparing the results of the *DART* and *PROPOLAR* simulations to real measurements is essential to determine whether they bear any accurate relation to the reality they attempt to simulate — this cannot be achieved by solely comparing models to each other. Furthermore, while examples exist in the literature which have measured vegetation polarisation, it remains a relatively unexplored phenomenon. Previous experiments have measured polarisation, but no comprehensive databases with complete *Bi-directional Polarised Reflectance Functions (BPRFs)* exist. Access to polarisation cameras is not widespread, and any addition to this relatively meagre body of data is a valuable one. It is therefore that this section is devoted to presenting the methodology of a number of experiments that were performed during the span of this research.

3.4.1. Experiment objectives

As stated in Section 3.1, in order to determine whether the radiative transfer models analysed are in any way accurate they must be compared to real measurements. Additionally, characterising the *BPRF* and consequently the *degree of linear polarisation DoLP* of different leaves is a critical step in building towards an understanding of polarisation at the canopy level. Different canopies have different *leaf angle distributions (LAI)*: therefore characterising the effects of leaf angle on the *BPRF* may be key to characterising canopies. Given that these variables are driven by leaf geometry, it is expected that different species and different states of leaf decay should produce different results, and as such it is important to perform measurements on different samples.

To briefly summarise, these experiments aim to:

- Verify whether vegetation polarisation can be measured with the means available.
- Characterise the *BPRF*, *DoLP*, and *AoLP* curves of leaves with respect to viewing angles.
- Highlight the similarities and differences between leaves of different species and states of decay.

- Analyse the relationship between Leaf Inclination Angle LIA and $BPRF/DoLP/AoLP$.

3.4.2. Experimental setup

If any rigorous measurements can be taken, it is essential to have a mechanical setup that controls all variables as tightly as possible to ensure the stability and repeatability of measurements. This section describes the setup employed in these experiments.

Originally, a setup was put together based on preliminary, loose requirements. Said setup was never employed, but is presented in Section D.1. Ultimately, a more robust mechanical setup was utilised in the measurements, and is shown in Figure 3.5. Given that the ultimate goal was to characterise the $BPRF$ of leaves, the setup had to:

- Maintain the leaf in a fixed, stable position.
- Maintain camera stability during measurements.
- Allow for measurements at multiple angles with respect to the leaf.
- Minimise the effect of the environment.
- Maintain a roughly equal distance between the camera and the leaf measured.

This setup consists of a flat surface mounted onto an axle that can be rotated to a specific angle and tightened to remain there. The aforementioned camera is mounted on an extensible arm sitting on a gimbal graded for 15° increments. The camera is equipped with an objective, allowing for the adjustment of the focal point and giving it an operating range of $[10cm, \infty]$ [68]. A collimated light source is aimed horizontally at the assembly, such that it shines on the normal of the plate if it is set to 0° inclination. While the figure shows background illumination, this is only present for the purpose of making the necessary adjustments.

The setup allows the angle of the leaf with respect to the light source to be set. It was set at 30° in all the experiments mentioned. All viewing angles are given with respect to the leaf normal, as shown in Figure 3.6.

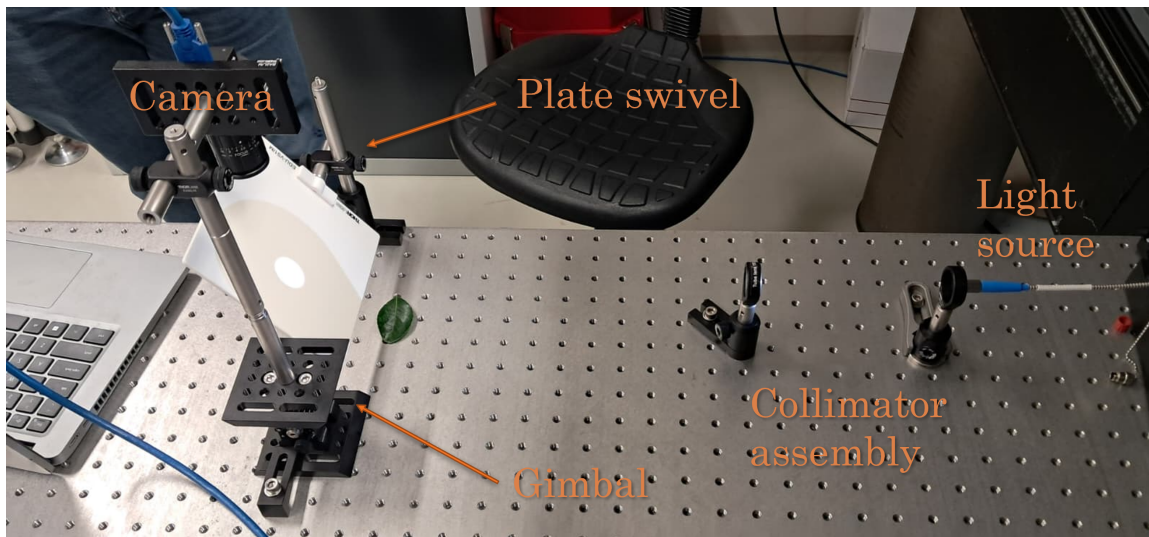


Figure 3.5: Picture of the mechanical setup.

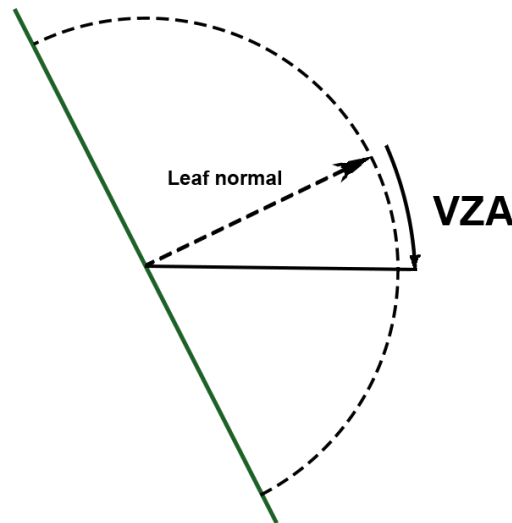


Figure 3.6: Coordinate system employed in describing the viewing zenith angle in the measurements. The zenith angle represents the angle from the normal at which the observing element (whether that be the naked eye or an optical instrument) is placed.

3.4.3. Polarisation camera

The polarisation camera employed in these measurements is Teledyne's BFS-U3-51S5P-C[69]. A list of relevant optical parameters is given in Table 3.8. The spectral response of the camera is given in Figure 3.8. As the camera output is monochromatic, the measurements taken from it represent a weighted average of the measured spectrum.

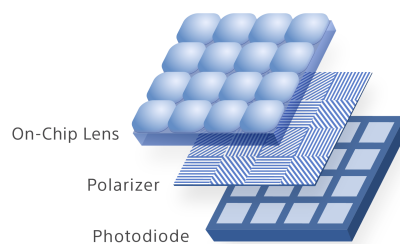


Figure 3.7: Structure of the polarisation sensor in the camera[70]. The photodiode element underneath transforms incoming light into an electrical current, which can then be processed into a digital signal. The polariser array has four different orientations, one on each pixel, such that a 2×2 grid of pixels can resolve the I, Q and U Stokes parameters.

As stated in Table 3.8, the camera employs a *CMOS* sensor for measurement. It can measure polarisation due to a micropolariser array layered on top of the sensor, covering each pixel with a polarising filter oriented along a different direction, as shown in Figure 3.7. Consequently, any measurement of the incoming polarisation needs to be aggregated from readings on four individual pixels in a 2×2 grid. A more detailed description of this process is provided in Section 3.4.3.1. The camera is equipped with its own software suite, which allows for the tuning of parameters such as the exposure time, and which provides a real-time visualisation of the camera's images.

Given that these pixels can be overexposed, an overexposed pixel within the 2×2 grid will lead to a faulty polarisation state measurement. For that reason, during the measurement process it is imperative to adjust the exposure time such that no pixels are visibly overexposed.

Parameter	BFS-U3-51S5P
Resolution	2448 × 2048 pixels
Frame rate	75 FPS
Megapixels	5.0 MP
Chroma	Polarized
Sensor	Sony IMX250MZR, CMOS, 2/3"
Readout method	Global shutter
Pixel size	3.45 μm
Lens mount	C-mount
ADC	10-bit / 12-bit
Minimum frame rate	1 FPS
Gain range	0 to 47 dB
Exposure range	6 μs to 30 s
Dimensions (W × H × D)	29 × 29 × 30 mm
Temperature	Operating: 0° to 50°, Storage: −30° to 60°.

Table 3.8: Optical specifications and dimensions of the BFS-U3-51S5P camera[69].

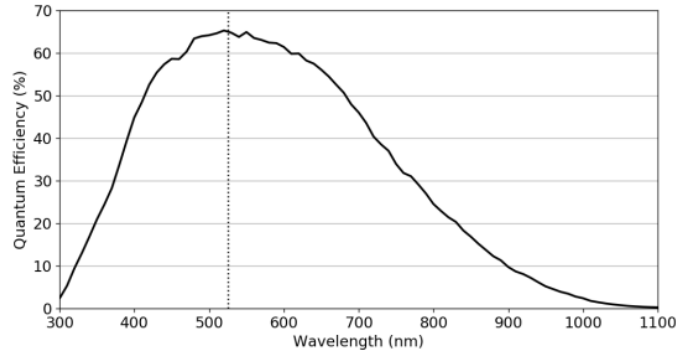


Figure 3.8: Spectral response of the polarisation camera[71].

3.4.3.1. Polarisation state retrieval

The camera described can measure different polarisation orientations on different pixels, but it does not aggregate these states into an image representing the polarisation state of incoming light. Specialised image processing software is required for this purpose. Utilised as part of this research is *PolarVis*[72, 73], an open-source program for calibrating, processing and visualising such measurements.

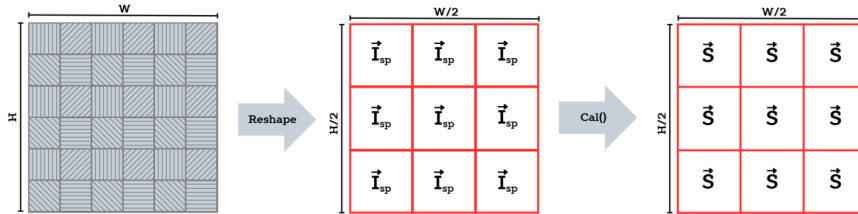


Figure 3.9: Diagram of the image processing in *PolarVis*[72].

Figure 3.9 briefly summarises how the measurements are processed.² A vector of intensities is measured from each of the pixels in a 2x2 region, referred to as a *super-pixel*. Through comparison with a set of input measurements with known Stokes vectors, it is possible to construct a calibration function $\vec{S} = \text{Cal}(\vec{I})$, where $\vec{I}$ is the intensity vector for a given *super-pixel*. This renders the original

²While outside of the scope of this work, the exact details on processing and calibration are thought-provoking, and can be found in their entirety in [72].

input array with dimensions (H,W) into an array with dimensions (H/2,W/2,3), with this additional channel representing a truncated Stokes vector with components I, Q, U ³. From this Stokes vector, *PolarVis* retrieves the intensity I , *degree of linear polarisation* $DoLP$, and *angle of linear polarisation* $AoLP$.

It is worth noting that this software has a few limitations. Given the nature of the instrument it pertains to, it makes a number of assumptions. Firstly, given that the instrument cannot measure circular polarisation, the software treats it as non-existent — hence the truncated Stokes vector without a V -component. The camera is monochromatic, which in turn means the output is a weighted average of the polarisation across all wavelengths. Figure 3.8 shows the spectral response of the camera with respect to wavelength, which is shown to clearly vary. *PolarVis* assumes that polarisation remains roughly steady with respect to wavelength. This is not a concern for this application, given that it has been shown in the literature that vegetation polarisation is roughly wavelength-independent[22]. It is also stated that a single super-pixel is assumed to receive the same light, provided the image remains smooth, though sharper edges and discontinuities can generate artifacts.

It must be noted that, at the time of measurement, no calibration had been performed on the instrument. Consequently, none of the measurements taken are precise enough for hard quantitative conclusions. However, it is shown that the effect of the calibration is relatively small[72]; qualitative assessments based on the measurements produced are thus entirely viable, as long as a degree of healthy scepticism is maintained.

3.4.4. Experimental tests

A series of experiments was performed to assess the measurability of leaf polarisation, its angular dependence, and its variation between leaves and over time.

Given the desired diversity in leaf characteristics and age, a number of different species of leaf were gathered and had measurements performed on them. Some of these leaves were harvested and had measurements performed on them at different times to evaluate the effect of ageing on the measurements. The leaves were chosen based on their surface roughness, waxiness and cuticle thickness — where leaves with a flatter, more mirror-like surface and a thicker cuticle were preferred, given that the polarisation signal is expected to be stronger in those cases: the thicker dielectric layer should polarise the more of the incoming light, and therefore render it easier to measure. In spite of this, leaves were sampled which had a thinner cuticle for the purpose of comparison. Four different species of leaves were used: *Euonymus Japonicus*, *Strelitzia Nicolai*, *Chrysalidocarpus lutescens* and *Prunus Laurocerasus*. Images of the different leaves employed can be found in Appendix C.

Each of these leaf species was selected for these specific characteristics:

- *Euonymus japonicus*: Evergreen (thick cuticle), thick (and thus resilient), relatively smooth and rigid, visibly waxy and glossy. Easy to source.
- *Strelitzia nicolai*: Very large leaves, relatively flat (minimising the difficulty of fully clamping it down onto the setup), very pronounced parallel venation (sharp contrast in structure with other leaves). Some shine (visibly less than the prior).
- *Chrysalidocarpus lutescens*: Thin cuticle, long thin, with a considerable curve in their cross-section.
- *Prunus laurocerasus*: Broad and rigid leaf, visibly waxy and glossy. The centre of the leaf is relatively flat (with a bit of curvature at the edges.)

These leaves can qualitatively be said to have different degrees of glossiness. It is unclear whether *E. japonicus* or *P. laurocerasus* has the shinier appearance. They are both shinier than *S. nicolai*, which is in turn shinier than *C. lutescens*. It is expected that the different glossiness will influence the magnitude of the polarisation observed, such that the more glossy leaves exhibit a greater *degree of linear polarisation* $DoLP$. The comparatively flat structure of all but *E. japonicus* was preferable, after

³The V Stokes component is not included, given the physical limitations imposed on a polariser array. The micropolariser array does not sense any information regarding the relative phases between the two orthogonal elements of the electric field $\vec{E}$, such that circular or elliptical polarisation — which V describes — cannot be measured.

measurements with *E. japonicus* proved more challenging due to its geometry. Broader leaves such as those of *S. nicolai* and *P. laurocerasus* were preferred to minimise the chances of light illuminating the background.

Four experimental sessions were carried out in total, with each session building upon the results and experience gained from the previous one. Session 1 served as an initial test of whether the polarisation signal could be measured at all. For this purpose, only a single leaf of *Euonymus japonicus* was measured. In Session 2, the experimental setup described in Section 3.4.2 was used for the first time, allowing measurements to be performed over a range of observation angles. This session also introduced two additional leaves of the same species, allowing measurements from different leaves to be compared.

Session 3 expanded the measurements to additional species, allowing differences between leaves of different species to be investigated. One of the measurements in this session was performed at a higher angular resolution, where a subset of the angular range was measured at 5° intervals, to provide more detailed information on the angular dependence of the measured polarisation. However, the method used to achieve this increased angular resolution introduced additional uncertainty in the exact observation angle. Session 4 further expanded the dataset by introducing a new species while also revisiting several leaves measured in earlier sessions. These repeated measurements, together with measurements of new leaves of the same species, allowed temporal changes in the measured polarisation associated with leaf ageing to be investigated. Finally, the newly introduced *Prunus laurocerasus* leaf was measured again approximately 45 minutes after its initial measurements to assess the short-term stability and repeatability of the measurements.

A full overview of the leaves utilised and the experiments performed on them can be found in Table 3.9. The exact angles measured in each experiment type are shown in Table 3.10. Given the time constraints imposed on these experiments, and the laborious process of performing a full scan, these were done sparingly. The gradation on the gimbal mentioned in Section 3.4.2 limits the angular positions that can be set accurately to increments of 15° . The labelled "higher resolution" scans were performed by adjusting the gimbal and manually holding it in position, as shown in Figure 3.10. The angles were measured using a protractor. Given the relative instability of the holding method and the inherent inaccuracy of the angular measurements, it is likely that these angles are subject to a small error. Angles at which this error may be present are marked in Table 3.10 with an asterisk (*).

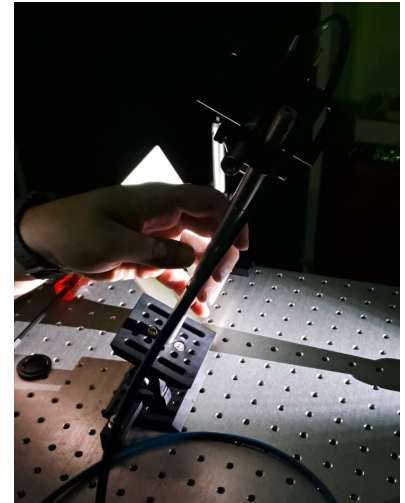


Figure 3.10: The gimbal being held in position manually.

Species	Label	Session	Time since first measurement	Experiment	Position
<i>Euonymus japonicus</i>	EJ-1	1	New	Single image	Top
<i>Euonymus japonicus</i>	EJ-1	2	1 wk	Single image	Top
<i>Euonymus japonicus</i>	EJ-2	2	New	Angular scan	Top
<i>Euonymus japonicus</i>	EJ-3	2	New	Single image	Top
<i>Strelitzia Nicolai</i>	S-1	3	New	Higher-res. angular	Top
<i>Strelitzia Nicolai</i>	S-1	3	New	Angular scan	Bottom
<i>Chrysalidocarpus lutescens</i>	CL-1	3	New	Single image	Top
<i>Euonymus japonicus</i>	EJ-2	4	2 wk	Single image	Top
<i>Euonymus japonicus</i>	EJ-4	4	New	Single image	Top
<i>Strelitzia Nicolai</i>	S-1	4	1 wk	Single image	Top
<i>Strelitzia Nicolai</i>	S-2	4	New	Single image	Top
<i>Chrysalidocarpus lutescens</i>	CL-1	4	1 wk	Single image	Top
<i>Chrysalidocarpus lutescens</i>	CL-2	4	New	Single image	Top
<i>Prunus laurocerasus</i>	PL-1	4	New	Higher-res. angular	Top
<i>Prunus laurocerasus</i>	PL-1	4	New	Angular scan	Bottom
<i>Prunus laurocerasus</i>	PL-1	4	45 min	Angular scan	Top

Table 3.9: Overview of leaf samples and measurements performed during the four experimental sessions. "Position" identifies whether the top or the bottom of the leaf was measured.

Type	Angles
Single image	-60°
Angular scan	$-75^\circ, -60^\circ, -45^\circ, -30^\circ, -15^\circ, 0^\circ$
Higher-res. angular	$-75^\circ, -70^\circ*, -65^\circ*, -60^\circ, -55^\circ*, -50^\circ*, -45^\circ, -30^\circ, -15^\circ, 0^\circ$

Table 3.10: Angular sampling used for each experiment type. Angles with potential errors are marked with an asterisk.

3.4.4.1. Processing of measurements

The measurements taken were processed from *.bmp* files containing the raw intensity measurements of each pixel into *.npy* files containing the intensity, *Degree of linear polarisation DoLP*, and *Angle of linear polarisation AoLP* by using the software described in Section 3.4.3.1. This format allowed for the direct analysis of the polarisation measured without subsequent analysis.

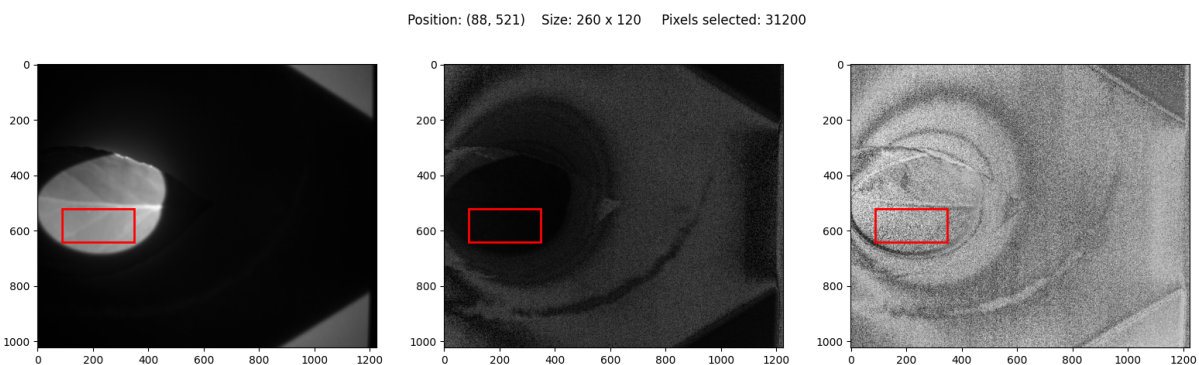


Figure 3.11: A region selection for a specific image. From left to right: Intensity, DoLP, AoLP. All these regions are perfectly overlapping: the same region is selected from all three dimensions.

For quantitative analysis, a region of interest (ROI) was manually selected within each image. The same pixel coordinates were applied to the intensity, *DoLP*, and *AoLP* arrays, ensuring that the quantities were extracted from the same spatial region, as shown in Figure 3.11. A tool was developed that allowed for the manual selection of these areas sequentially for all measurements. It is possible

that some measurements contain a much larger pixel count than others, such that those with a smaller number of pixels — caused primarily by the leaf's geometry — may be more susceptible to statistical noise and inaccuracy.

3.5. Comparison of measurements and simulations

As a final result, a comparison is produced between the radiative transfer models and the measurements produced. Relevant input values for *Prunus laurocerasus* were gathered from literature[74]. The relevant simulation parameters are shown in Table 3.11, Table 3.12 and Table 3.13. Given the unavailability of existing data on the *PROSPECT* inputs for *Euonymus japonicus* and *Strelitzia nicolai*, values were estimated based on informed judgement. These are found in Table 3.16 for *Euonymus japonicus*, and in Table 3.18 for *Strelitzia nicolai*. Both of these species' simulations employ the same simulation configuration, shown in Table 3.15.

In order to produce a *DoLP*/viewing angle curve that can be compared to the monochromatic curves measured, the outputs of the simulation must be made equivalent. In both *PROPOLAR* and *DART*, the scenes are simulated for a spectral range of $\lambda \in [400, 900]nm$. The *DoLP* is then gathered into a single value per angle through a weighed sum:

$$DoLP(VZA) = \frac{\sum_{\lambda=400}^{\lambda=900} DoLP(VZA, \lambda) \cdot I(VZA, \lambda)}{\sum_{\lambda=400}^{\lambda=900} I(VZA, \lambda)} \quad (3.2)$$

Where I is the intensity at a given wavelength λ , and *VZA* stands for *View Zenith Angle*.

3.5.1. Parameters of comparison simulations

The *DART* input geometry in Table 3.11 remains the same for all three simulations.

	Object type	Object dimensions	Object position
Geometry	Square.obj	X = 0.05 m Y = 0.05 m Z = 0.05 m	X = 0.025 m Y = 0.025 m Z = 0.001m

Table 3.11: Geometry of the flat plane for the *DART* simulations.

3.5.1.1. *Prunus laurocerasus*

	Scene average temperature	Wavelengths	Target pixel size	Target pixel density	Max. Render Time per image	Number of scene repetitions	Relative energy threshold for ray-stopping [-]	Max. number of scattering events per ray	Products	Number of directions
Environment parameters	300 K	$\in [400, 900] nm$	0.0005 m	100	400 s	4	$1 \cdot 10^{-6}$	130	BRF maps(⁴ resolution), Polarisation images	500

Table 3.12: *DART* flat plane simulation parameters for *Prunus Laurocerasus*.

	Leaf specular	Leaf diffuse	Ground specular	Ground diffuse
Optical properties	$n_i = 1, n_t = 1.51,$ $\sigma = 0.12$	Structure coefficient = 2, Chlorophyll = $50 \mu g \cdot cm^{-2}$, Carotenoid = $10 \mu g \cdot cm^{-2}$, Brown Pigment = 0.0, Equivalent water thickness = 0.025 cm, Anthocyanin = $0 \mu g \cdot cm^{-2}$, Dry matter content = $0.010 g \cdot cm^{-2}$, Carbon-based dry matter = $0.009 g \cdot cm^{-2}$, Nitrogen-based dry matter protein = $0.001 g \cdot cm^{-2}$,	$n_i = 1, n_t = 1.33,$ $\sigma = 0.07$	2D Lambertian model: "loam_sandy_brown_fine_clean_smooth"

Table 3.13: *DART* flat plane optical simulation parameters for *Prunus laurocerasus*. The values were retrieved from [74].

Linear coefficient α	Roughness parameter σ	Refractive index n	Zenith Range	Azimuth range	Spectral range
0.9	0.12	1.51	$\in [0, 90] [^\circ], 1^\circ$ increments	$\in [0, 360] [^\circ], 1^\circ$ increments	$\in [400, 900]nm$

Table 3.14: *PROPOLAR* polarisation input parameters for *Prunus laurocerasus*. The remaining input parameters are those presented in Table 3.13.

3.5.1.2. *Euonymus japonicus*

	Scene average temperature	Wavelengths	Target pixel size	Target pixel density	Max. Render Time per image	Number of scene repetitions	Relative energy threshold for ray-stopping [-]	Max. number of scattering events per ray	Products	Number of directions
Environment parameters	300 K	$\in [400, 900]$ nm	0.0005 m	100	180 s	4	$1 \cdot 10^{-6}$	130	BRF maps(1° resolution), Polarisation images	250

Table 3.15: DART flat plane simulation parameters for both *Strelitzia Nicolai* and *Euonymus japonicus*.

	Leaf specular	Leaf diffuse	Ground specular	Ground diffuse
Optical properties	$n_i = 1, n_t = 1.51, \sigma = 0.25$	Structure coefficient = 1.5, Chlorophyll = $40 \mu g \cdot cm^{-2}$, Carotenoid = $10 \mu g \cdot cm^{-2}$, Brown Pigment = 0.0, Equivalent water thickness = 0.025 cm, Anthocyanin = $0 \mu g \cdot cm^{-2}$, Dry matter content = $0.010 g \cdot cm^{-2}$, Carbon-based dry matter = $0.009 g \cdot cm^{-2}$, Nitrogen-based dry matter protein = $0.001 g \cdot cm^{-2}$,	$n_i = 1, n_t = 1.33, \sigma = 0.07$	2D Lambertian model: "loam_sandy_brown_fine_clean_smooth"

Table 3.16: Flat plane optical parameters for *Euonymus japonicus*.

Linear coefficient α	Roughness parameter σ	Refractive index n	Zenith Range	Azimuth range	Spectral range
0.9	0.25	1.51	$\in [0, 90] [^\circ], 1^\circ$ increments	$\in [0, 360] [^\circ], 1^\circ$ increments	$\in [400, 900]$ nm

Table 3.17: PROPOLAR polarisation input parameters for *Euonymus japonicus*. The remaining input parameters are those presented in Table 3.16.

3.5.1.3. *Strelitzia nicolai*

	Leaf specular	Leaf diffuse	Ground specular	Ground diffuse
Optical properties	$n_i = 1, n_t = 1.51, \sigma = 0.4$	Structure coefficient = 1.7, Chlorophyll = $40 \mu g \cdot cm^{-2}$, Carotenoid = $10 \mu g \cdot cm^{-2}$, Brown Pigment = 0.0, Equivalent water thickness = 0.025 cm, Anthocyanin = $0 \mu g \cdot cm^{-2}$, Dry matter content = $0.015 g \cdot cm^{-2}$, Carbon-based dry matter = $0.009 g \cdot cm^{-2}$, Nitrogen-based dry matter protein = $0.001 g \cdot cm^{-2}$,	$n_i = 1, n_t = 1.33, \sigma = 0.07$	2D Lambertian model: "loam_sandy_brown_fine_clean_smooth"

Table 3.18: Flat plane optical parameters for *Strelitzia nicolai*.

Linear coefficient α	Roughness parameter σ	Refractive index n	Zenith Range	Azimuth range	Spectral range
0.9	0.4	1.51	$\in [0, 90] [^\circ], 1^\circ$ increments	$\in [0, 360] [^\circ], 1^\circ$ increments	$\in [400, 900]$ nm

Table 3.19: PROPOLAR polarisation input parameters for *Prunus laurocerasus*. The remaining input parameters are those presented in Table 3.18.

The results for the processes described in Chapter 3 are shown here. As described in Chapter 3, the results of both the simulations carried out over the course of this research, and a qualitative assessment of both the measurements taken as part of the experimental portion of this work, and the similarities and differences between these measurements and the simulation results. Section 4.1 contains the results of the simulations previously described, with a brief discussion of each and its general implications. Section 3.4 contains a breakdown of the measured leaf samples and statistical analyses performed on them. Section 4.3 shows the results of a simulation compared to real measurements. A more in-depth discussion of the general implications of each result is presented in Chapter 5.

4.1. Model intercomparison

The results of the simulations described in Chapter 3 are shown here. In a departure from the structure in Chapter 3, all *DART* results are discussed first for the purpose of clarity, with the *PROPOLAR* results and the intercomparison following afterwards.

4.1.1. Qualitative DART assessment

As detailed in Section 3.3.1, an initial qualitative assessment of *DART*'s ability to simulate leaf polarisation was carried out.

The relevant results are presented in the following plots. Figure 4.1a shows the *Bi-directional Reflectance Distribution Function* *BRDF* for $\lambda = 610nm$, and Figure 4.1b shows the same for $\lambda = 850nm$. The most immediately noticeable difference is in the comparative uniformity of the plot on the right. As the values on the colourbar exceed 1, this may indicate a numerical error, as values above 1 are not physically possible — a body cannot reflect more light than it is receiving. Figure 4.2a shows the same results for $\lambda = 850nm$ with an adjusted scale.

The geometry at both wavelengths appears to be similar, with most of the reflected light concentrating towards shallow angles at an azimuth of $\varphi = 180^\circ$. The main disparity is present in the magnitudes, where the highest results at $\lambda = 850nm$ appear to be more than twice those at $\lambda = 610nm$. This disparity can be explained by observing Figure 4.2b, which shows a typical spectral response graph for vegetation. This figure shows that the reflectance is drastically different from one wavelength to the other: $850nm$ is well past the so-called *red edge*, a well-known feature in remote sensing[75]. The difference in magnitude between the two plots is explained by this phenomenon. The grainy quality of the $850nm$ plot compared to the $610nm$ plot is similarly connected to Figure 4.2b, and is explained by numerical noise: the rays in the latter are absorbed much faster (lower reflectance), leading to a reduced number of multiple scattering events. This is not the case for $\lambda = 850nm$, where most of the light is reflected at every interaction. The apparent "ring" observed at the highest zenith angles (towards the edges of the plots) are explained by the Z-direction offset: as shown in Figure 3.1, the plane finds itself $0.01m$ over the ground, and at the most shallow illumination angles the rays are able to penetrate beneath the plane and onto the ground, producing this ring of lower reflectance.

Plots corresponding to the other three elements of the Stokes vector — Q , U , and V — are found in Figure 4.3, Figure 4.4, and Figure 4.5. A discussion of those results is found on the page following these.

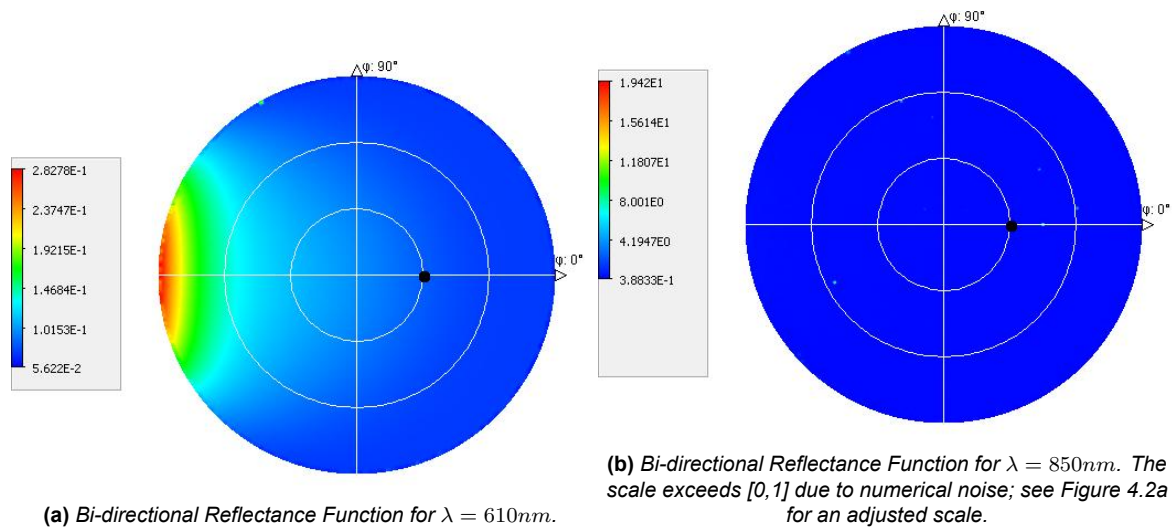


Figure 4.1: BRF for $\lambda = 610, 850nm$, with different ranges. Black dots indicate the Sun direction.

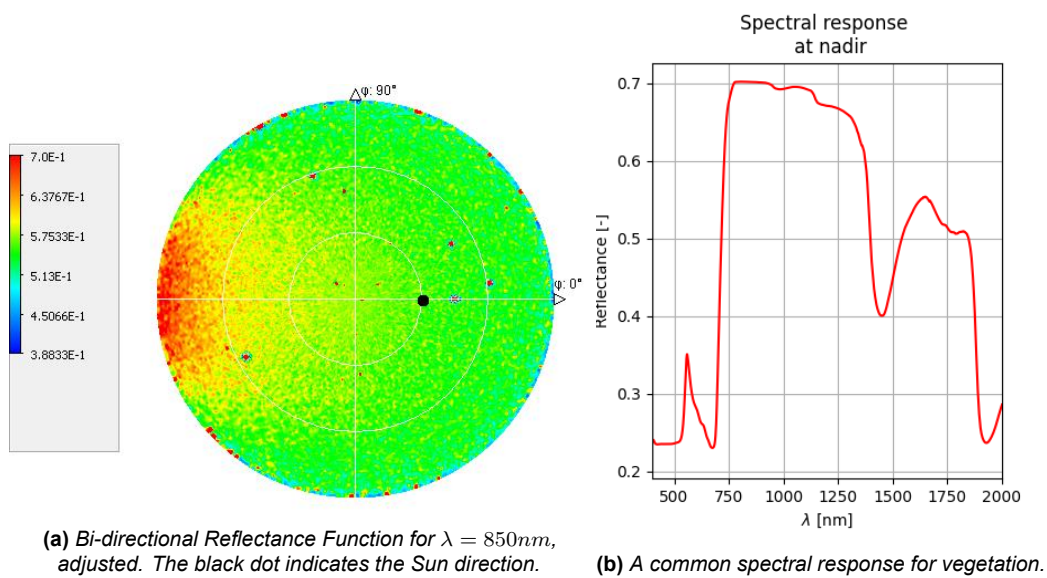


Figure 4.2: Graphical explanation for the apparent graininess of the BRF for $\lambda = 850nm$.

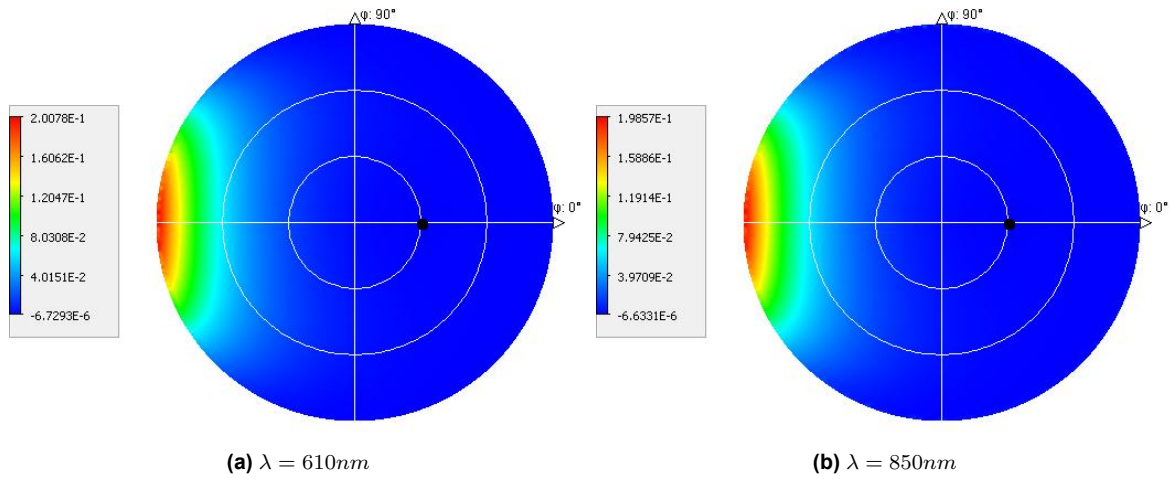


Figure 4.3: *Q-parameter Bi-directional Reflectance Function as simulated on a flat plane. The black dot indicates the Sun direction.*

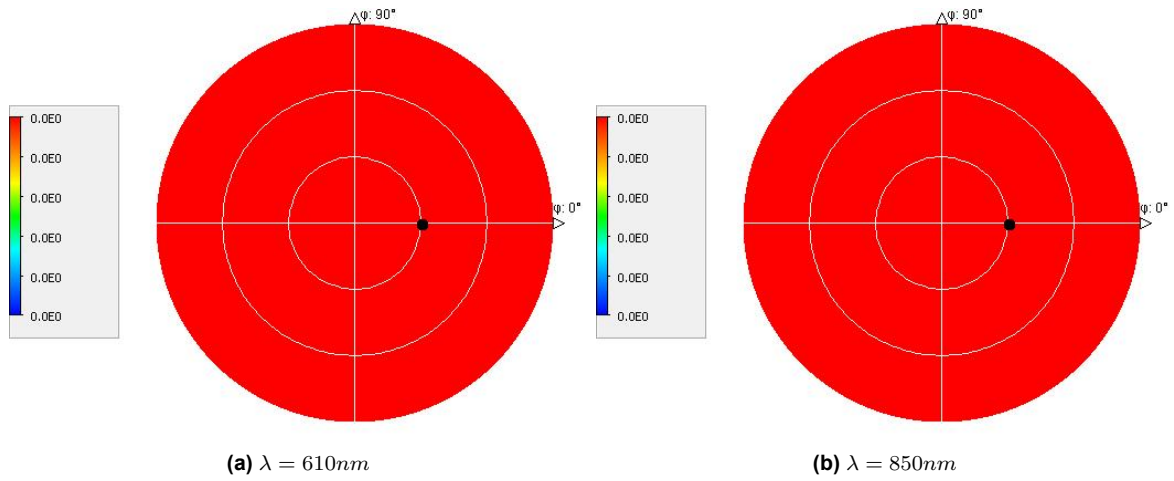


Figure 4.4: *U-parameter Bi-directional Reflectance Function as simulated on a flat plane. The black dot indicates the Sun direction.*

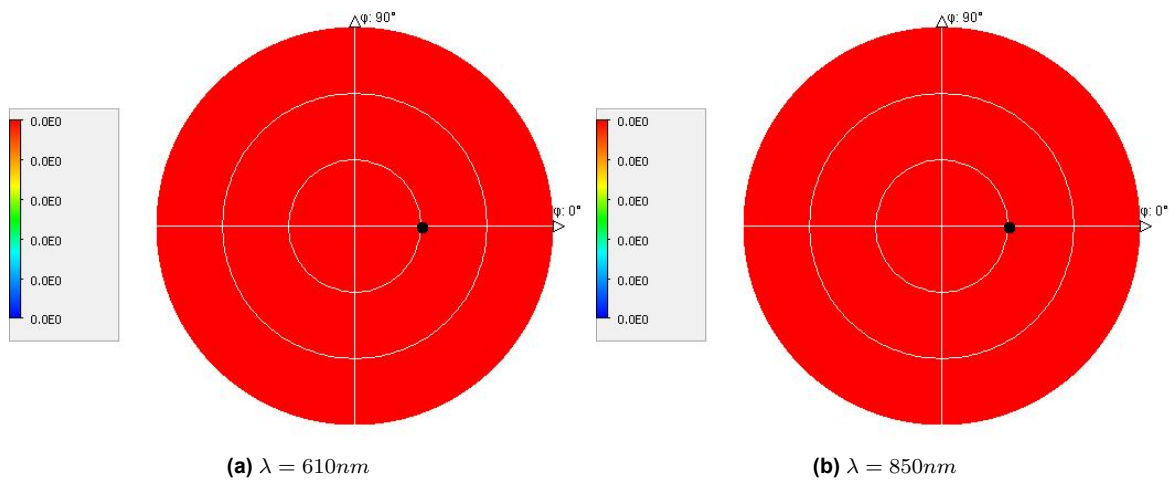


Figure 4.5: *V-parameter Bi-directional Reflectance Function as simulated on a flat plane. The black dot indicates the Sun direction.*

The comparison in Figure 4.3 reveals that both wavelengths show similar features. The reflected light concentrates at a shallow zenith angle — near the edge. Given that specular reflection is the dominant source of polarisation in vegetation, and that in a perfect dielectric surface the reflection should occur at the exact same angle of incidence, this result is unexpected. The magnitudes in both wavelengths is in the same rough order, which the existing literature corroborates as a result to expect[22]. Comparing these results to the *BRF* results shows that while the areas of greatest magnitude occupy the same region, the *BRF* is more spread out than the Stokes *Q*-parameter, which can be attributed to the diffuse base reflecting incoming light in a broader range, but not polarising it.

The results for the *U* and *V* Stokes parameters can then be addressed. It is unsurprising that the *V* parameter is entirely null; as explained in Section 2.2, circular polarisation signals from vegetation do exist, but they are more tenuous and are caused by chirality in the molecules inside the leaf — a feature that *DART* does not simulate. Given this limitation, no more *V* parameter results will be considered in the remainder of this document.

The lack of results in the *U* component suggests that linearly polarised light can only ever be either vertically or horizontally polarised, a conclusion that is opposed by both intuition, and experimental results. It is all the more surprising when considering that the other simulations — as shown in Section B.1 — do exhibit signs of a *U*-component. This is a shortcoming that must be addressed: both the complete absence of a *U* Stokes parameter and the highly shallow angle at which the cone of specular reflection is appearing in the *DART* results suggests there may be an element that is not functioning adequately.

4.1.1.1. Roughness analysis

The results of altering the roughness on the simulations as described in Section 3.3.1.1 are shown in Figure 4.6 and Figure 4.7. These show a clear trend: with increasing roughness comes a greater spread, shallower angle and lower intensity, both in the overall reflectance and the polarised reflectance. Curiously, the simulations with the lowest roughness $\sigma = 0.05$ — a value corresponding to a relatively smooth plane — all appear to be concentrated close to the specular reflection angle — a noted concern on the simulations in the prior simulations. Roughnesses higher than the $\sigma = 0.3$ — a higher-end value in leaf roughness — employed previously all appear to spread the reflection over a large area. This is worthy of note, as it is very common for leaves to have a roughness around that magnitude.

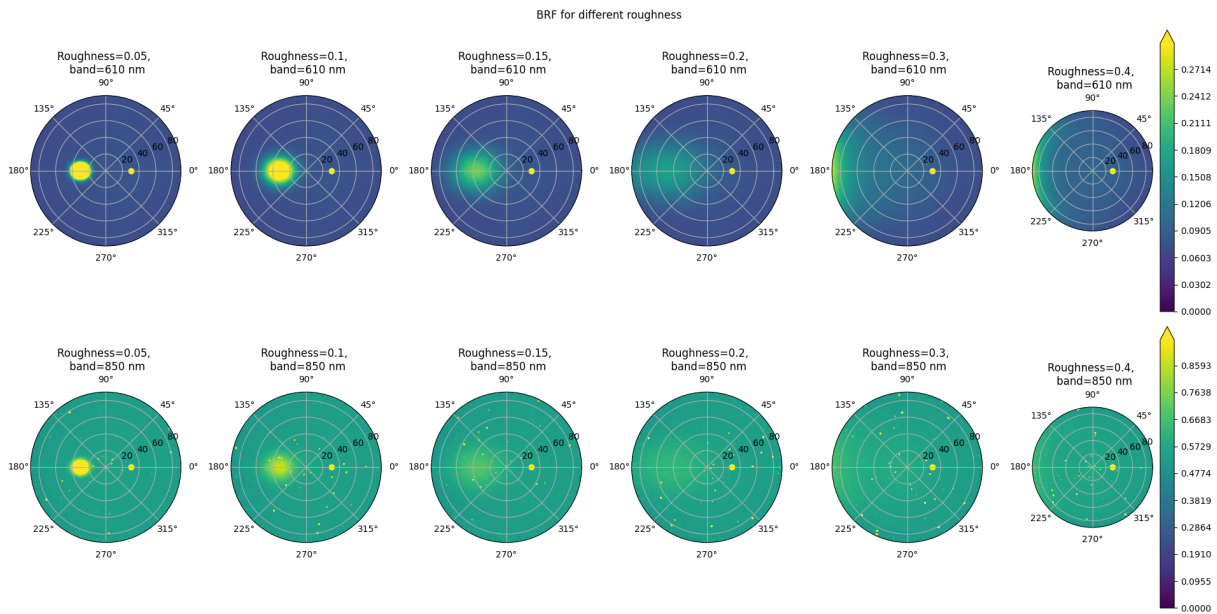


Figure 4.6: DART BRF for $\lambda = 610, 850\text{nm}$ and increasing σ . The light source angles are indicated by the yellow dot.

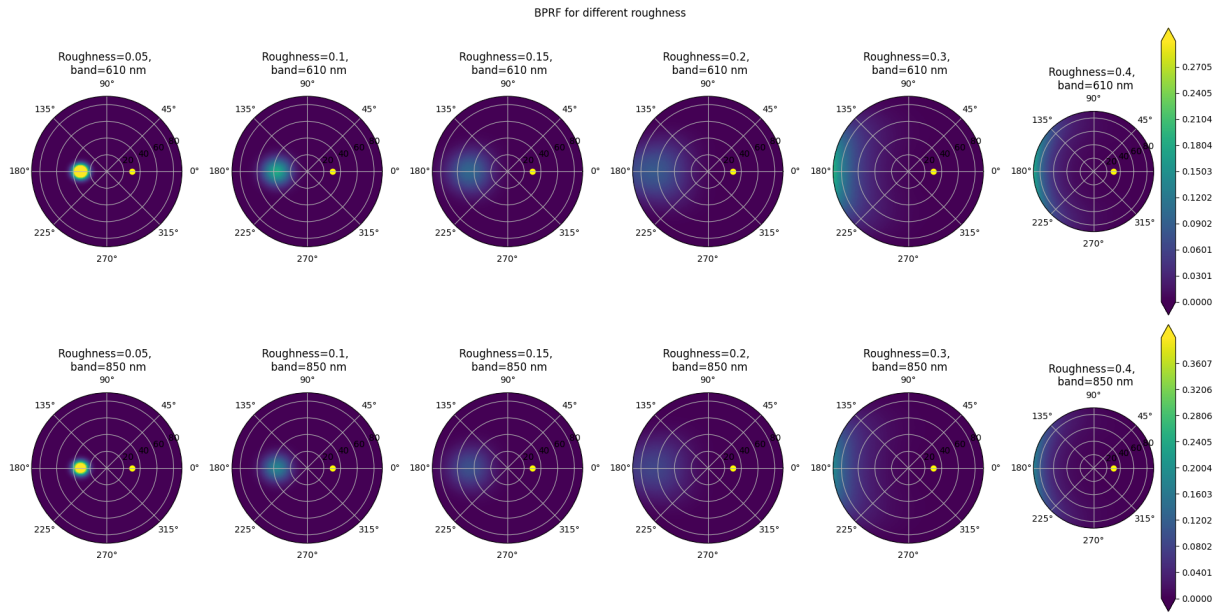


Figure 4.7: DART BPRF for $\lambda = 610, 850\text{nm}$ and increasing σ . The light source angles are indicated by the yellow dot.

4.1.1.2. Leaf Angle Analysis

The more relevant results of these simulations are given in Figure 4.8. These show that there is a clear dependence between the leaf angle and the $DoLP$. As stated in Section 3.3.1.2, a number of different wavelengths were selected, corresponding to points of interest along the spectral curve shown in Figure 4.2b. It is worth noting the different magnitudes of the $DoLP$ with respect to the wavelength λ : the highest signal among the wavelengths simulated appears for $\lambda = 670\text{nm}$; this is not to be interpreted this wavelength having the highest polarisation reflectance, but as a function of the overall reflectance. The polarised reflectance ought to stay relatively constant throughout. The effect can be interpreted in terms of signal to noise: the reflectance at 670nm is, overall, much lower than in the other wavelengths — see Figure 4.2b. This explains the apparent difference in noise throughout the plots. Despite this difference in magnitude, a clear shape appears to emerge in all the plots shown.

Figure 4.9 shows the same results as Figure 4.8b for a select number of leaf angles. If it is accurate, this result suggests that one could identify the leaf angle observed by measuring at a number of viewing angles and attempting to match those measurements to one of these curves.

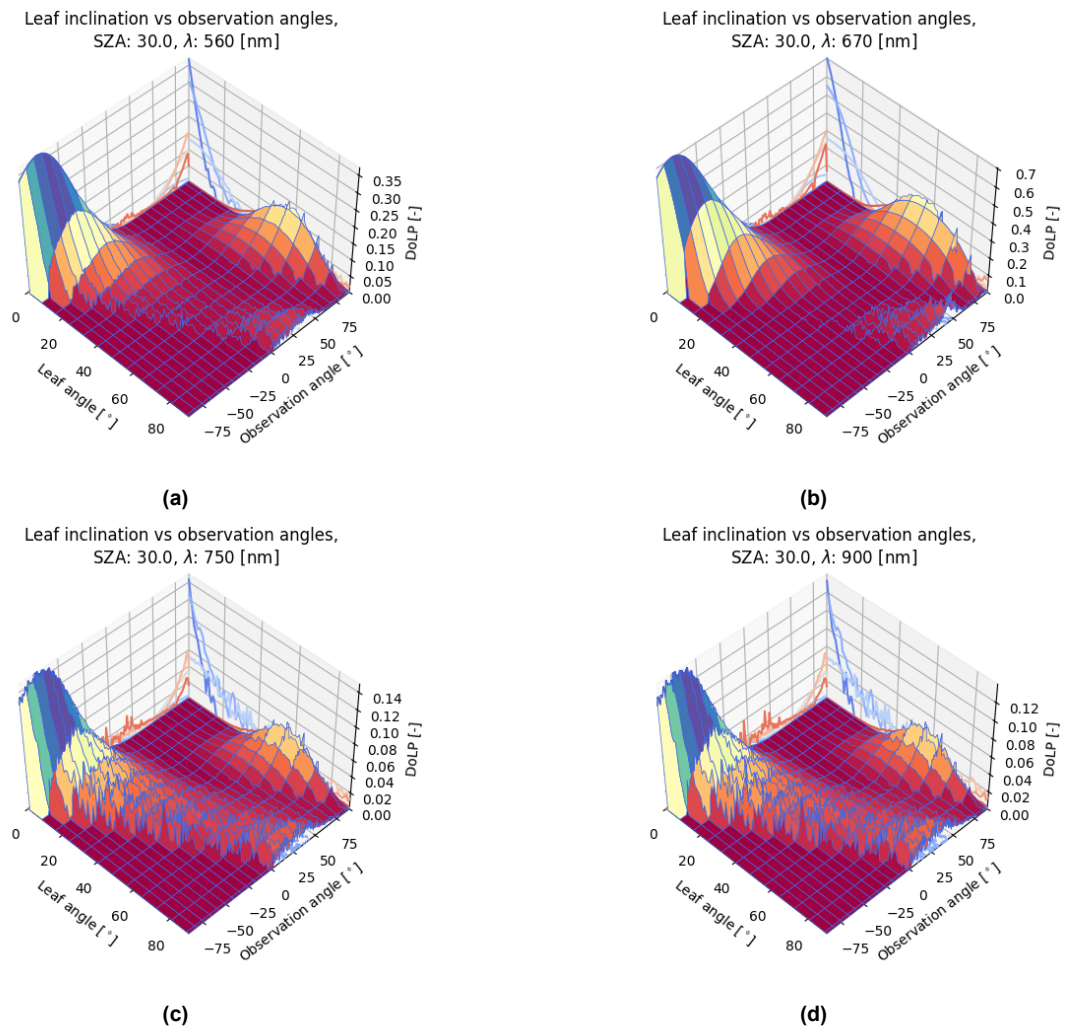


Figure 4.8: Changing $DoLP$ for different leaf angles and observation angles, for four wavelengths over the visible and NIR.

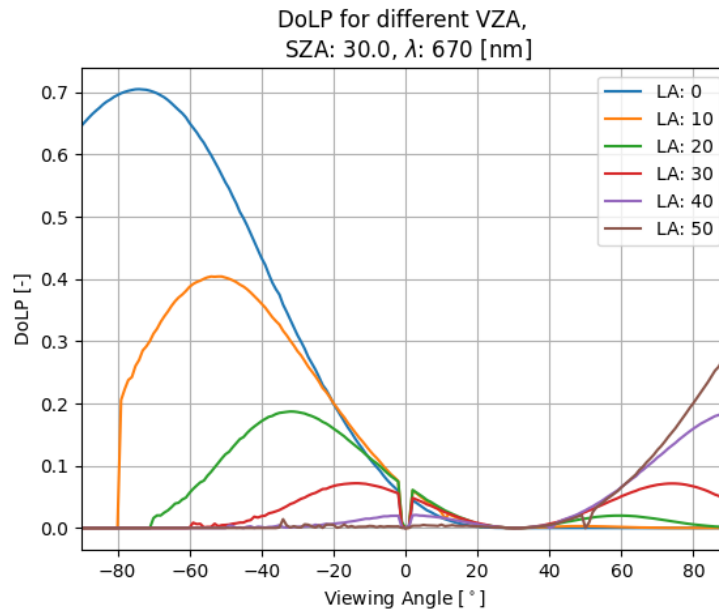


Figure 4.9: Degree of linear polarisation curve with respect to viewing angle, for a number of leaf angles and $\lambda = 670\text{nm}$. Note the precipitous drop towards the leftmost ends of $LA = 10^\circ$: it corresponds to the point at which the viewing angle crosses the edge of the plane, thereby observing the bottom face. This drop is present for other angles, only much less noticeably so. The dip for all leaf angles at a viewing angle of 0° is a quirk of the simulation, and does not represent a physical result.

4.1.2. Qualitative PROPOLAR assessment

The results are found in Figure 4.10 and Figure 4.11. As in Section 4.1.1 these results show the influence of the uneven spectral reflectance with respect to wavelength, as shown in Figure 4.2b: beyond the red edge¹ the reflectance becomes much higher than is found before it. The *DoLP* plots have the magnitudes inverted: it appears that the *DoLP* is much higher at lower wavelengths. This is consistent with the knowledge that polarised reflection is roughly invariant with respect to wavelength[22]. Equation 2.17 shows clearly that, if polarised reflectance remains constant, a doubling in overall reflectance will lead to a halving of *DoLP*, which is in rough terms what is observed here. Curiously, the *DoLP* plots show a much wider lobe than the *BRF* plots — the opposite of what is observed for *DART*. This is unexpected, as one would expect the purely specular element to be more localised than the overall reflectance.

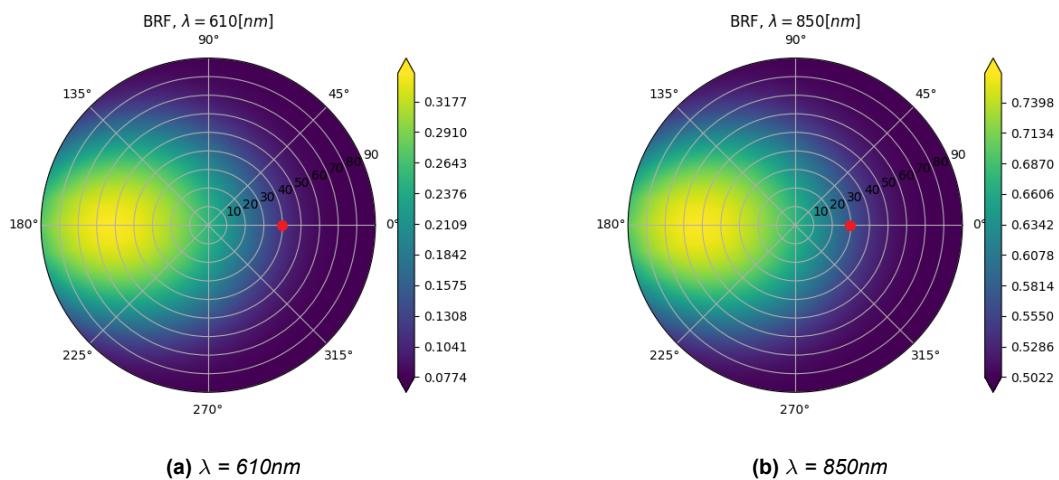


Figure 4.10: Initial PROPOLAR BRF results. The incident sun angles are represented by the red dot.

¹The red edge refers to a well-known feature in remote sensing[75], where beyond a certain wavelength the reflectance of vegetation becomes much more pronounced, see Figure 4.2b.

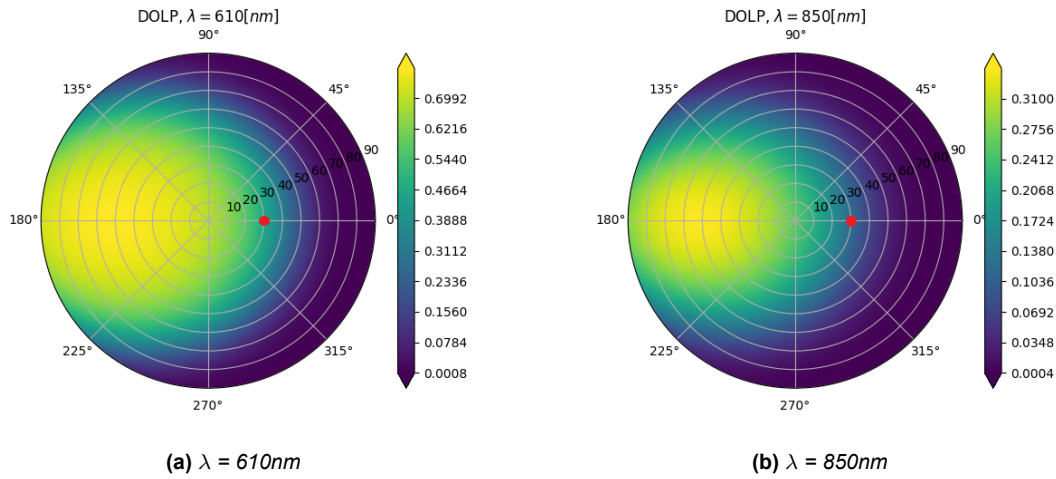


Figure 4.11: Initial PROPOLAR DoLP results. The incident sun angles are represented by the red dot.

4.1.3. Quantitative model intercomparison

Exact plots of the differences between the *DART* and *PROPOLAR* simulations are seen in Figure 4.12, Figure 4.13 and Figure 4.14. The colour scales were limited to the error corresponding to a Z-score of 2, calculated from the distribution of errors. Values exceeding this threshold were therefore displayed using the same colour to reduce the influence of outliers on the visualisation. The *BRF* is shown to be only locally similar, and only to a certain extent. The absolute error can reach magnitudes up to and beyond 0.5^2 , and the relative error shows large disagreements. The *BPRF* plots show significant differences as well: errors of about 90% occur across the domain, and are consistent across wavelengths. The *DoLP* plots show similarly poor agreement between the models (with $\lambda = 670\text{nm}$ reaching an absolute error of 0.75. This magnitude is substantial relative to the physically plausible range of *DoLP*, as a *DoLP* of 0.75 would itself represent a strongly polarised signal.). The *DoLP* at $\lambda = 720\text{nm}$ shows an especially large error, limited to extremely shallow angles. Given that the absolute error is relatively low compared to other results, it is likely that this is a product of dividing a large absolute error over a small localised value: this wavelength corresponds to a region in the red edge, where a small difference between the two models would result in a significant disparity of outcomes.

²All quantities discussed below are dimensionless unless stated otherwise; reflectance and DoLP are therefore reported as ratios rather than percentages.

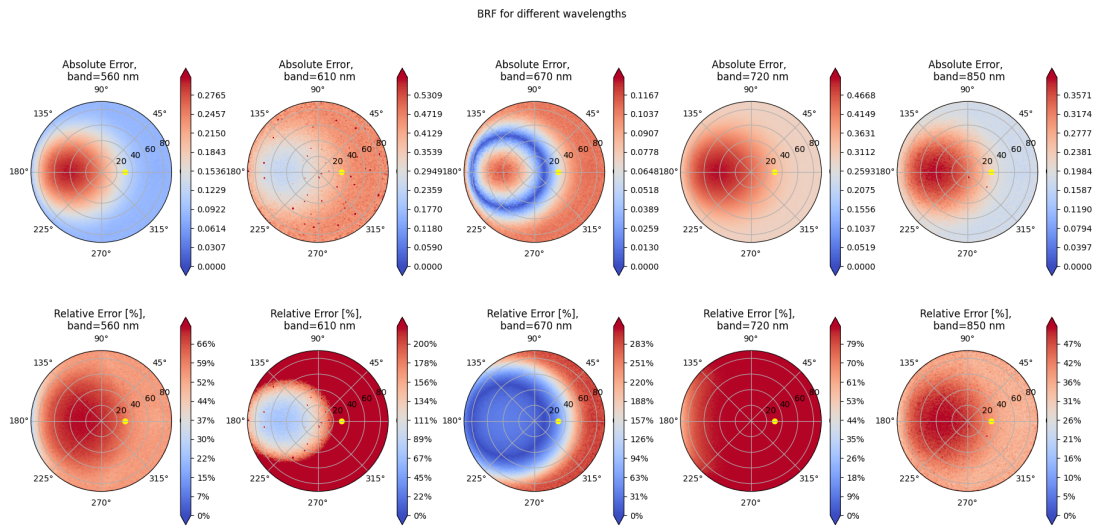


Figure 4.12: Absolute and relative errors between the BRFs of DART and PROPOLAR. The yellow dot represents the incoming sunlight's angle.

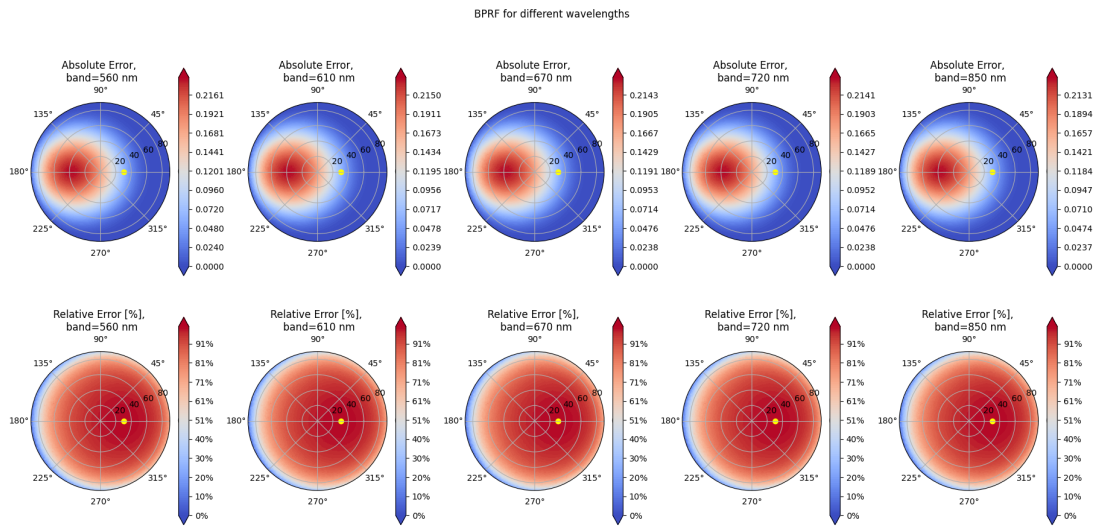


Figure 4.13: Absolute and relative errors between the BPRFs of DART and PROPOLAR.

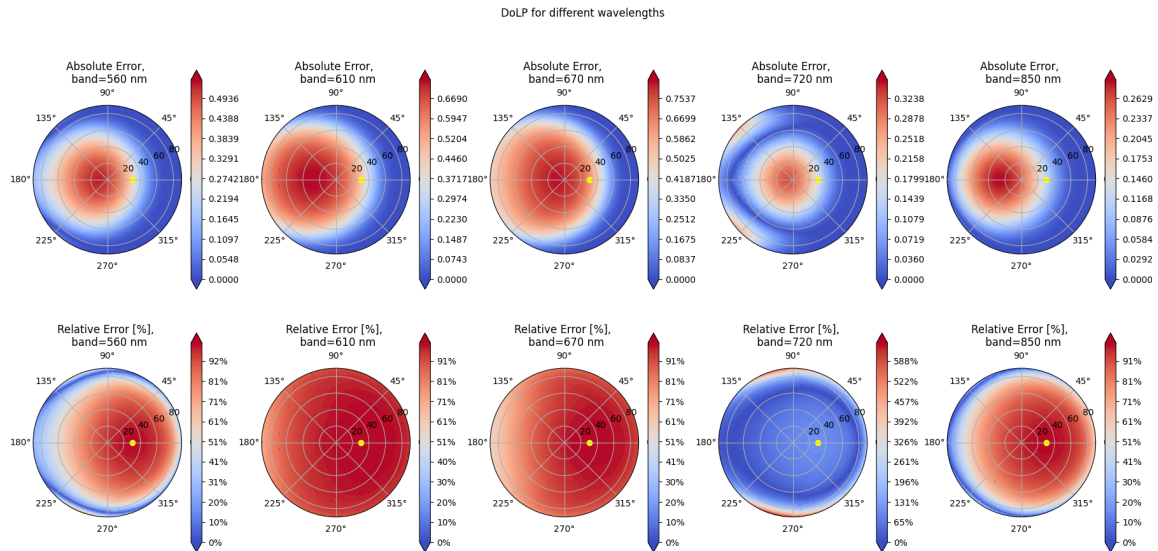


Figure 4.14: Absolute and relative errors between the BRFs of DART and PROPOLAR.

These results suggest that at least one of the models is not functioning adequately. While simulating the same scene, the two models show radically different results. Furthermore, they both challenge expectations in more than one way: *PROPOLAR* appears to spread its reflection over a very broad area, and often produces elevated magnitudes — though expectations such as these are no indication of the truth and no conclusions can be drawn from them. *DART* produces light reflected at an extremely shallow angle, which challenges established theory on specular reflection. Additionally, it seems not to output a U Stokes parameter, which is indicative of a missing element. Whether this is caused by the physical principles employed by the models, by the simulation parameters, or by numerical errors cannot be established from these results alone.

4.1.3.1. PROSPECT implementation comparison

As described in Section 3.3.3, in order to explain these discrepancies both simulations were stripped down to their *PROSPECT* implementations. Both models integrate *PROSPECT* — *PROPOLAR* uses it as its diffuse reflection layer, and *DART* has been set to simulate the optical properties of the leaf surface with it. Establishing whether these two models have similar results when stripped down to only Lambertian reflection may verify whether the scenes they are simulating resemble each other, and thereby indicate whether they are at all comparable.

DART's integrated *PROSPECT* model was used to generate a purely *PROSPECT*-based spectral curve. Another spectral curve was simulated within *DART*'s 3D environment, employing only Lambertian reflection as an optical property. *PROPOLAR* likewise outputs both its own *PROSPECT* implementation — Lambertian only — and the full model results — with a specular element. The full spectral response —including the polarised element — is shown for a few different viewing angles in Figure 4.15. Figure 4.16 shows the comparison: The top left shows an expected difference between *DART*'s *PROSPECT* and *PROPOLAR*. The plot next to it displays the absolute difference when *PROPOLAR* is employed without any form of polarisation. It is expected that this curve should be exactly 0. There is a sharp peak around the blue-green transition: Figure 4.2b shows that there is generally a sharp increase in reflectance in this region; it is therefore likely — though not certain — that this peak corresponds to their respective implementations, and that the difference is not significant. However, it is curious that the same difference does not appear at the red edge as well. There is additionally a small amount of noise, though it all remains under 1% relative error, as shown in the plots below. That the plots on the right show little disparity confirms that the differences observed between the prior full simulations are not due to their *PROSPECT* implementations.

Figure 4.17 shows two additional results: at the top is the product of comparing this *DART* simulation to the *PROSPECT* result. It is natural that there should be a difference, as *PROSPECT* simulates

a homogeneous 1D medium analytically, whereas *DART* simulates an anisotropic, 3D medium numerically. As the *DART* simulation is a flat plane with the same optical input parameters, these plots serve to evaluate the "costs" of the transition to this new model. The top right plot shows that this difference is significantly wavelength-dependent; some specific points correspond exactly to *PROSPECT*, but the difference appears to be mostly contained between 5% and 20%. If *PROSPECT* is assumed to be an accurate representation of a leaf, then this *DART* implementation's reflectance is only accurate to within ± 0.08 — occurring at roughly $\lambda = 1300\text{nm}$; other wavelengths show smaller differences.

The two plots below (in red) correspond to *PROPOLAR* results: comparing the full model to base *PROSPECT* is naturally going to produce divergent results, given that the former adds a specularly reflected element. These plots serve to illustrate how significant this difference can be. Given that *PROPOLAR* is composed of *PROSPECT* in addition to specular reflection — both unpolarised and polarised —, the left plot shows the magnitude of this specular component. Since one would expect the polarised reflection to remain roughly constant across the spectrum[22], the variability shown here is theorised to be the result of the unpolarised specular element. While the relative error is shown to be quite large overall — though much more pronouncedly so in specific wavelength regions —, the absolute error does not appear physically impossible. Though this may appear reasonable, it has yet to be compared to any real measurements as part of this investigation, and therefore no conclusions on its accuracy can be drawn yet.

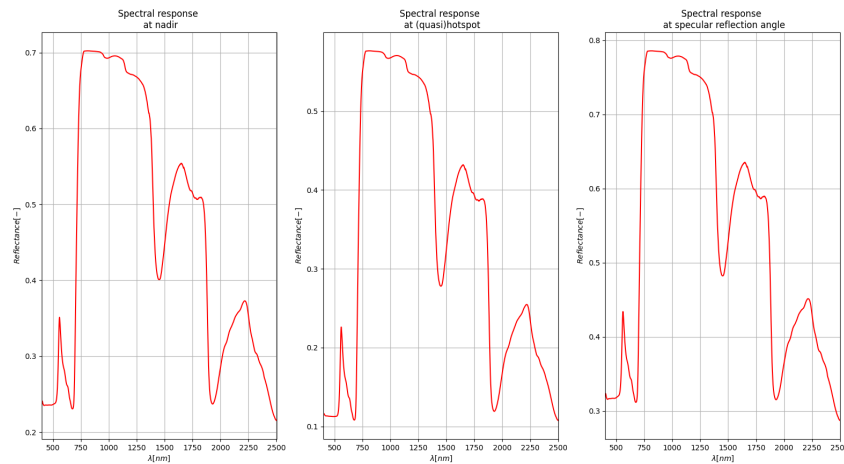


Figure 4.15: Various viewing geometries of *PROPOLAR*'s spectral response. (Quasi)-hotspot denotes that *PROPOLAR* cannot compute the illumination at the hotspot (it produces a singularity), and thus a point close to it was chosen. Note that while the shape remains nearly constant, the reflectance magnitude changes between different viewing geometries.

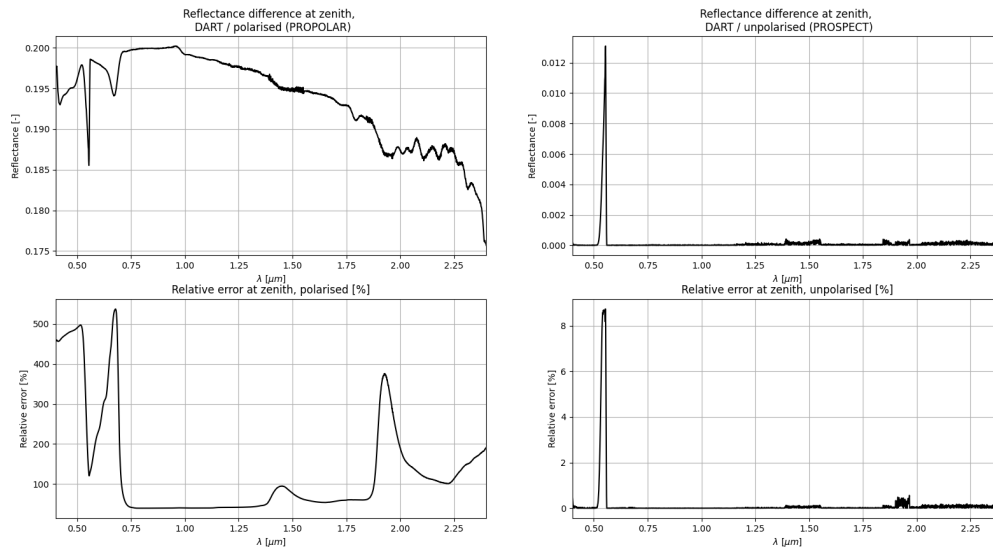


Figure 4.16: *Top left:* Zenith reflectance difference between DART's PROSPECT implementation and an unmodified PROPOLAR. *Top right:* Zenith reflectance difference between DART's PROSPECT implementation and PROPOLAR's. *Bottom left:* Relative difference for the plot above. *Bottom right:* Relative error for the plot above.

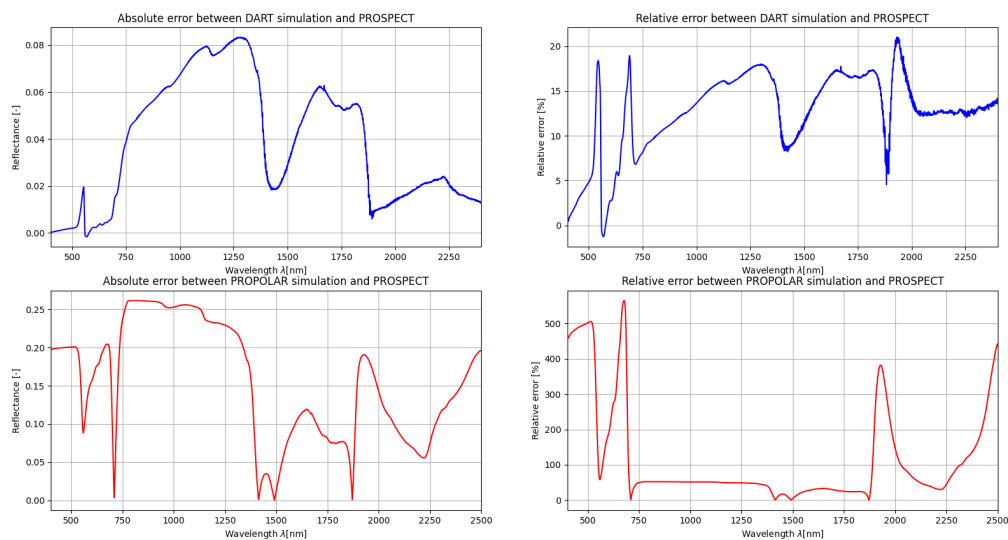


Figure 4.17: *Top:* Difference between the same scene simulated in DART and PROSPECT. *Bottom:* Difference between base PROSPECT and PROPOLAR.

This section has shown quite clearly that there is a significant disagreement between the two models. The standalone analysis of these models does reveal a few conclusions. For the benefit of clarity, the few conclusions drawn from this latter analysis are divided into the corresponding models:

- **DART:** Perhaps the most important proof gathered from this section is that the PROSPECT model in DART works as intended. It is shown that as an approximation, the flat plane scene in DART is not producing results that are physically unlikely, though it is likewise failing to match PROPOLAR's results. As stated, this approximation's reflectance can only be said to be ± 0.08 accurate in some regions — though it is shown to be more accurate in others.
- **PROPOLAR:** That its implementation of PROSPECT is matching is no surprise, as it employs the same scripts. What is notable about PROPOLAR is that its specular reflection shows such

wide differences across the spectrum.

4.2. Experiments

4.2.1. *Euonymus Japonicus* results

As is stated in Section 3.4.1, the first goal is verifying if measurements of vegetation polarisation can be taken with the existing equipment, shown in Section 3.4.2. Session 1 verified this: Figure 4.19 shows the leaf in question measured from multiple angles, measured by means of a protractor. As these pictures were not saved in the appropriate format for processing — the experiment was carried out before having access to the software described in Section 3.4.3.1 — little insight could be gathered beyond what is shown in Figure 4.20: a present albeit tenuous pattern which suggests the presence of polarised signals — see Figure 4.18 for a clearer example.

Further results were produced in subsequent experiments. Figure 4.21 and Figure 4.22 show polarisation images of *EJ-2* and *EJ-3*. They present three distinct dimensions of the images taken, and a composite of the three. Figure 4.23 shows similar measurements for *EJ-1*, now a week old.

In the case of *EJ-2*, it is important to note that the two sides of the leaf were slightly angled, and that only one of these was clamped down — the one showing the greater intensity. This was done for purely practical reasons, as it saved time, although it reveals a curious phenomenon that shall be discussed further into the document.

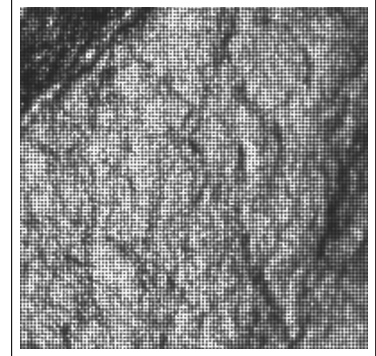
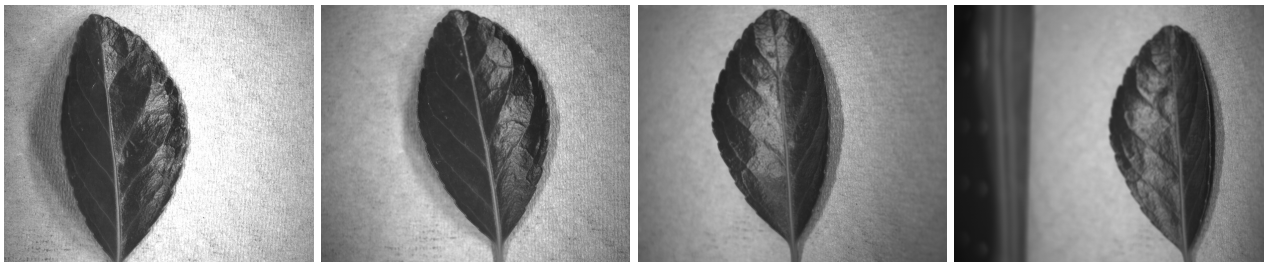


Figure 4.18: Zoomed-in raw image of one of the measurements. The grid-like pattern visible is due to the polariser array: given the different states they are measuring, intensities can rise or fall sharply between adjacent pixels. Seeing this pattern is often a sign that there is a strongly polarised signal.



(a) Leaf illuminated at 0° angle. (b) Leaf illuminated at 20° angle. (c) Leaf illuminated at 50° angle. (d) Leaf illuminated at 70° angle.

Figure 4.19: Polarisation images of *Euonymus Japonicus* for a range of angles.

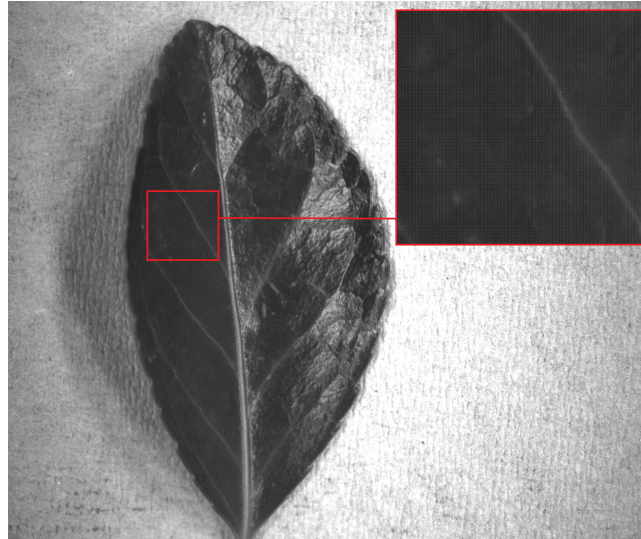


Figure 4.20: A magnified view of the pixel pattern on the leaves.

The intensity image in Figure 4.21 clearly shows the area of the setup lit by the light source, which is filled in its entirety by the leaf. It is clear that the polarisation signal is strongest at the leaf, especially on the flatter (bottom) side. This is a consequence of specular reflection taking place. The $DoLP$'s greatest magnitude is found in this same region, which is consistent with the theoretical understanding of leaf polarisation. The $AoLP$ in that same region is close to 90° throughout, which suggests a dominant Stokes parameter Q . The other side of the leaf, which is slightly angled, appears to show degrees ranging from 110° to 150° , with a significant part clustering around 135° . This is indicative of a Stokes parameter U or V being present — this is theorised to be a U -parameter, for the reasons established in Section 2.2. The composite image shows that though some light is reflected off of the angled side, it appears to be much lower in its intensity than on the flat side, which gives reason to be sceptical of the angle of polarisation measured there, as it may be the cause of the relative noisiness of the measurements in that region. Future experiments should consider this phenomenon and try to repeat measurements on similarly angled leaves, to verify that it is truly present and not a product of noise.

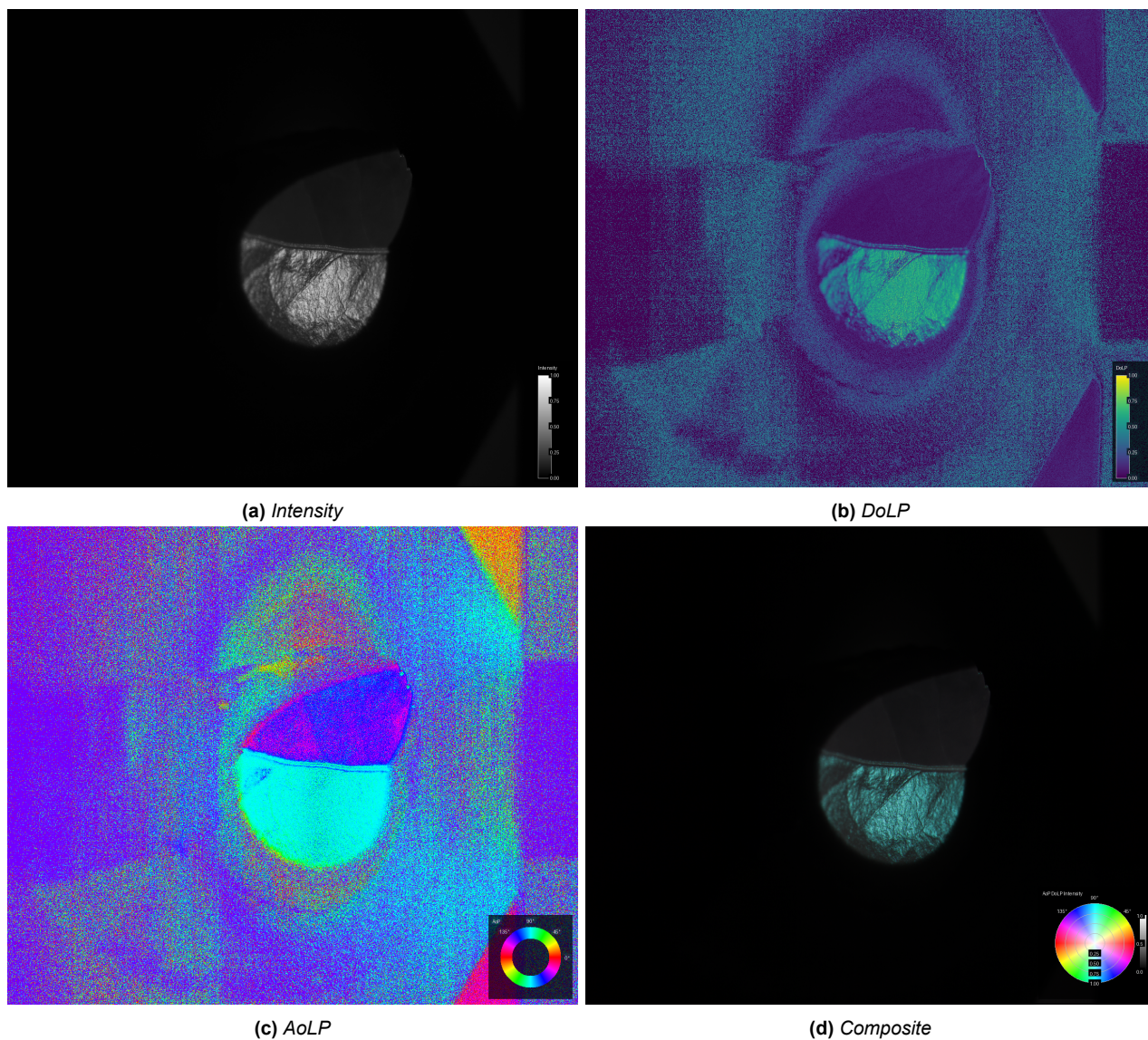


Figure 4.21: Visualisation of the 0° image taken of EJ-2.

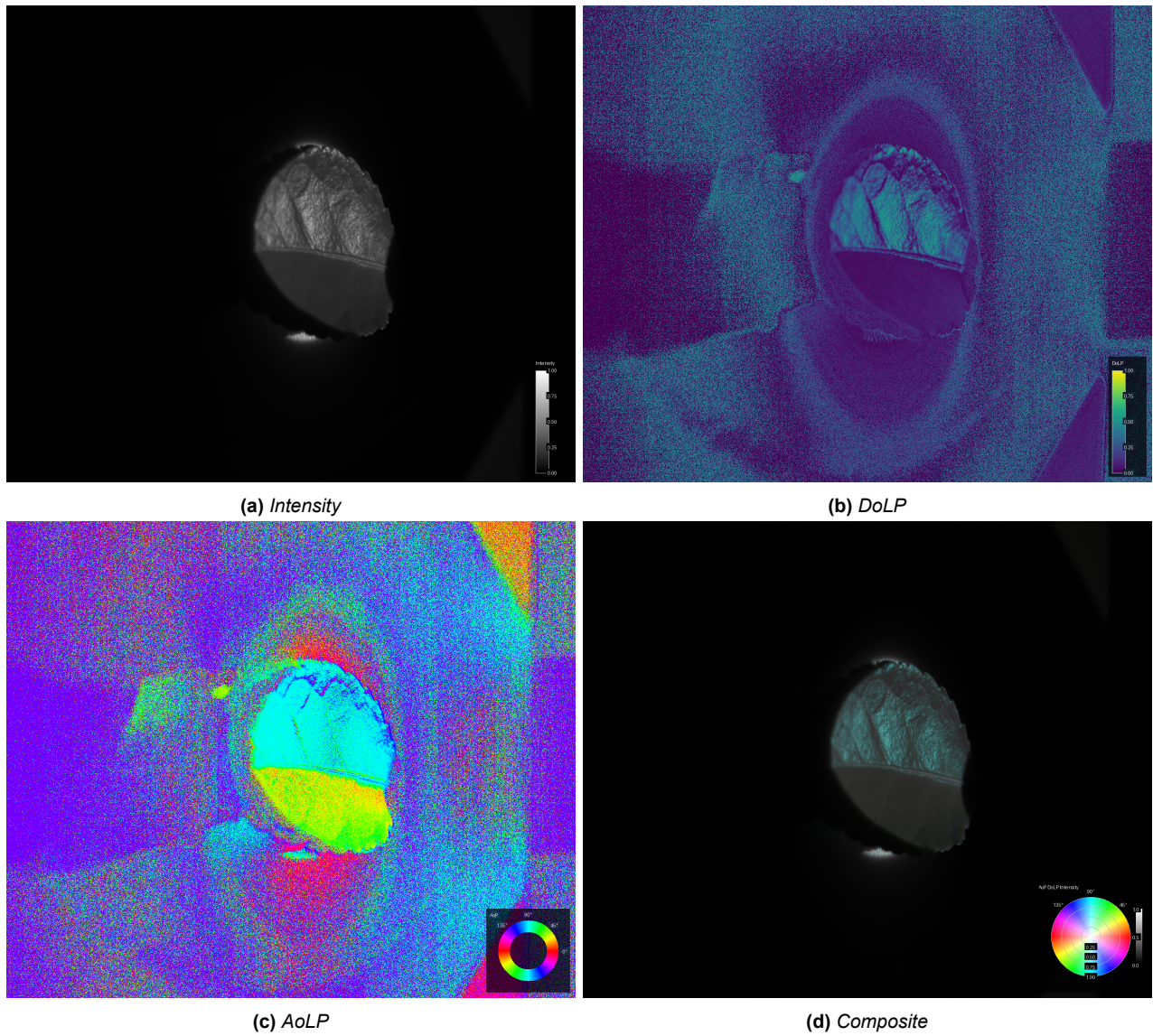


Figure 4.22: Visualisation of the 0° image taken of EJ-3.

EJ-3 in Figure 4.22 is clamped on the side facing the top of the figure, as opposed to Figure 4.21. A familiar image repeats itself: the flat side appears to specularly reflect light more intensely than its counterpart; said flat side appears to have a higher *DoLP*, and its *AoLP* appears to average 90°. Once again the composite image appears to show the preponderance of the flat side over the angled one in terms of absolute intensity, yet once more the angled side appears to differ in its *AoLP*: this time, with measurements hovering between as low as 15° and as high as 55°, yet showing regions of clear 45° linear polarisation. This once more suggests the presence of a *U*-component, though opposed to the one found in *EJ-2*. This may be related to the leaf being clamped on the opposite side.

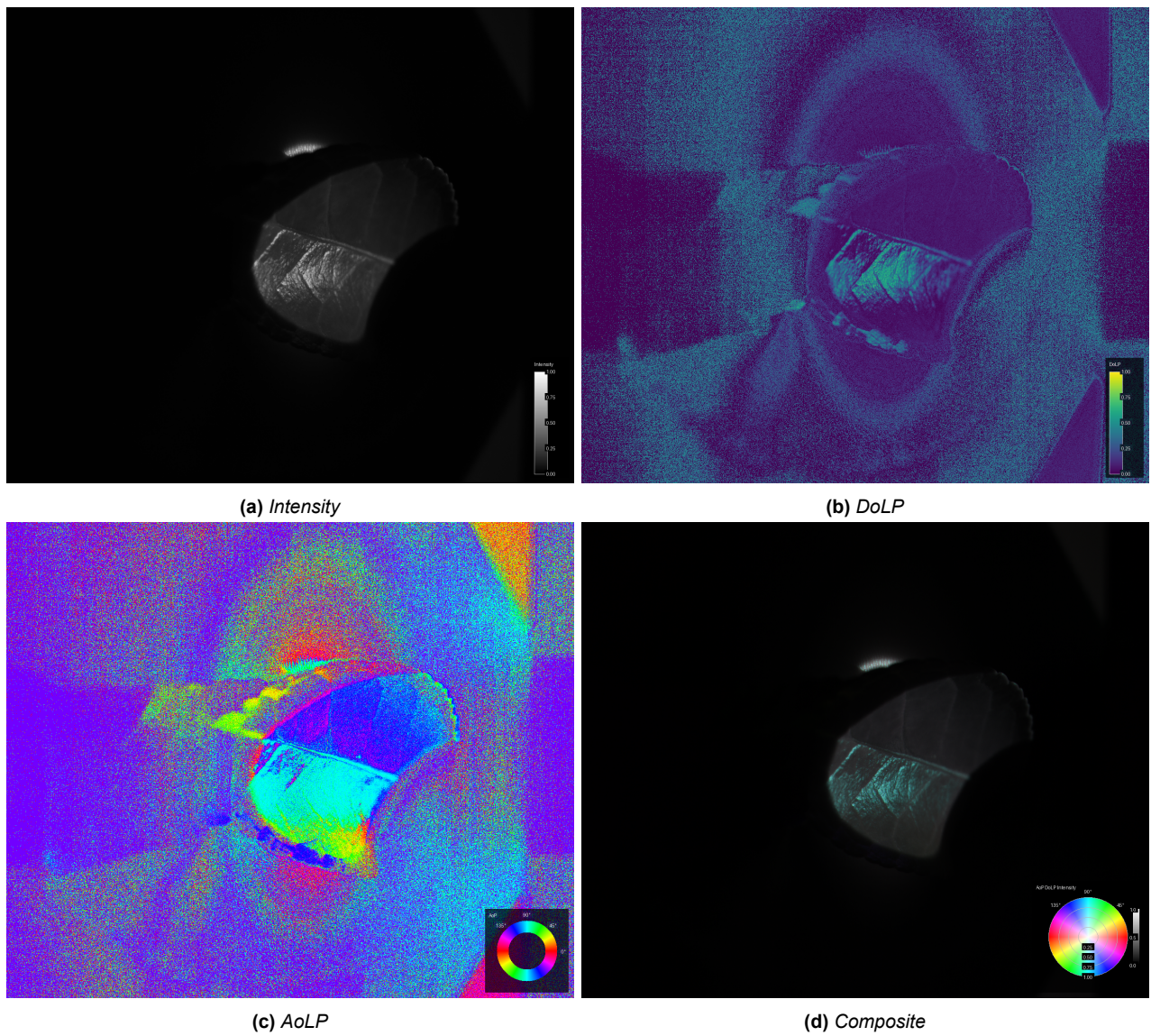


Figure 4.23: Visualisation of the 0° image taken of leaf 3.

EJ-1 in Figure 4.23 was harder to capture, given that its more advanced state of decay made it harder to clamp down effectively. This is evident in the small sliver of illuminated surface underneath seen both in the intensity and the composite images, and in the relatively small area in which there is clear specular reflection. These images should therefore be viewed with scepticism. The *AoLP* seems to show similar trends to Figure 4.21 — both of these being clamped down on the bottom-facing side. Once again the flat side shows a tendency towards 90° , and the opposing side is angled closer to the 135° .

These results show that, at least for these specific samples of *Euonymus Japonicus*, there is clear and measurable polarised reflection under collimated light and in the absence of other comparable light sources. While the ability to measure *DoLP* is promising, the trend identified in *AoLP* measurements came as a veritable surprise, as to the knowledge of the author there is no existing mention of the observed phenomena in the current literature on the topic of vegetation polarisation.

As described in Section 3.4.1, one of the aims was the characterisation of the *DoLP* of leaves with respect to viewing angle. Figure 4.24 was produced using the approach described in Section 3.4.4.1. The leftmost graph shows the evolution of the *DoLP* over the range of measurements. It is notable that the pixels at -75° show a great number of outliers — all of them trending upwards — which may be caused by the relative shallowness of the angle, and the lower pixel count. It is interesting to see the relatively low measurements in the higher angles, especially considering the statistical stability they display. The *AoLP* shows a relatively stable distribution for all bins except the one corresponding to

-30° , where it appears to be shifting suddenly from one *AoLP* to another. While these measurements are too limited to make conclusive statements, they do suggest a trend that warrants higher resolution observation. The main lessons learnt from this experiment are that stabilising the leaf would be beneficial when performing measurements; that *AoLP* measurements of leaves at odd angles might reveal more about the mechanism behind the *AoLP*, and that there appears to be a trend in the *DoLP* which warrants further examination.

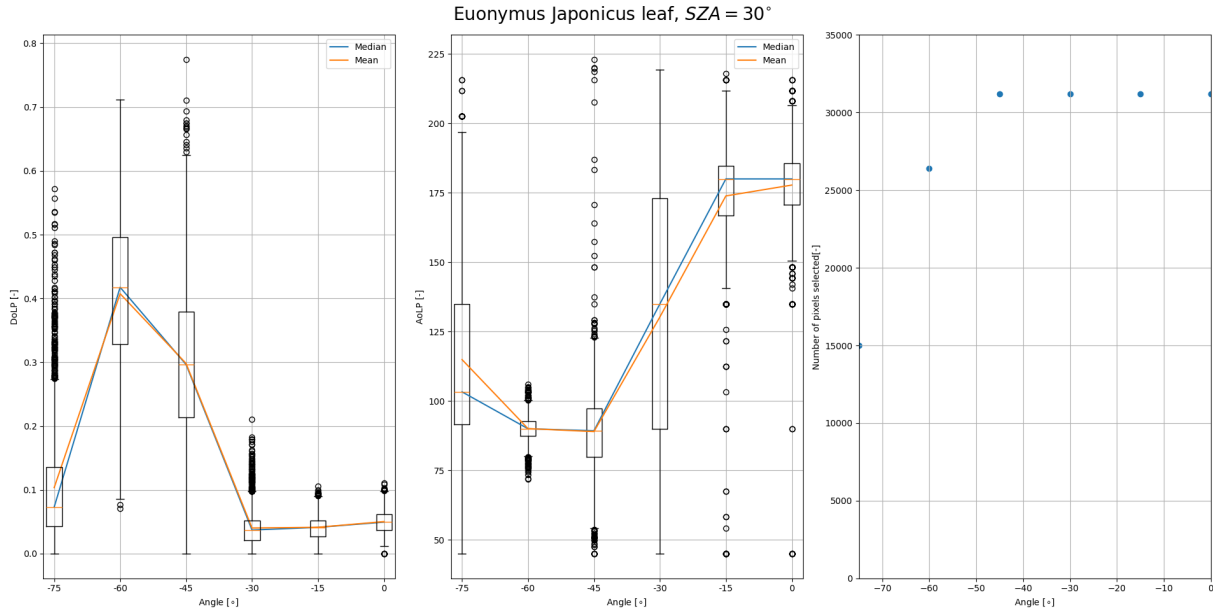


Figure 4.24: *Left:* Measured *DoLP* at different viewing angles. *Centre:* Measured *AoLP* at different viewing angles. *Right:* Number of pixels selected for the statistics. All angles are given relative to the leaf normal. *Right:* Number of individual pixels employed in computing the distribution at any given angle. The boxes represent the interquartile range, with the horizontal line indicating the median. The whiskers extend to the most extreme values within 1.5 times the interquartile range, while points beyond the whiskers indicate outliers.

4.2.2. *Strelitzia nicolai* results

Figure 4.25 shows one of the many pictures taken of S-1. The overall *DoLP* is lower than what was found in Section 4.2.1. This is potentially due to a thinner cuticle on the surface of the leaf, or may be caused in part by a roughness in the surface that is not visible to the naked eye. Compared to the results in Section 4.2.1, the *DoLP* is more evenly distributed over the lit surface of the leaf, and its larger size implies that the entire light beam is constrained to one side of the leaf. The *AoLP* shows a tendency towards values around 90° , with it appearing less noisy than the measurements in Section 4.2.1. No part of the image appears to show angles that are suggestive of a dominant Stokes parameter U , which reinforces the hypothesis formulated in Section 4.2.1 that surfaces angled diagonally may be responsible for that mode of polarisation.

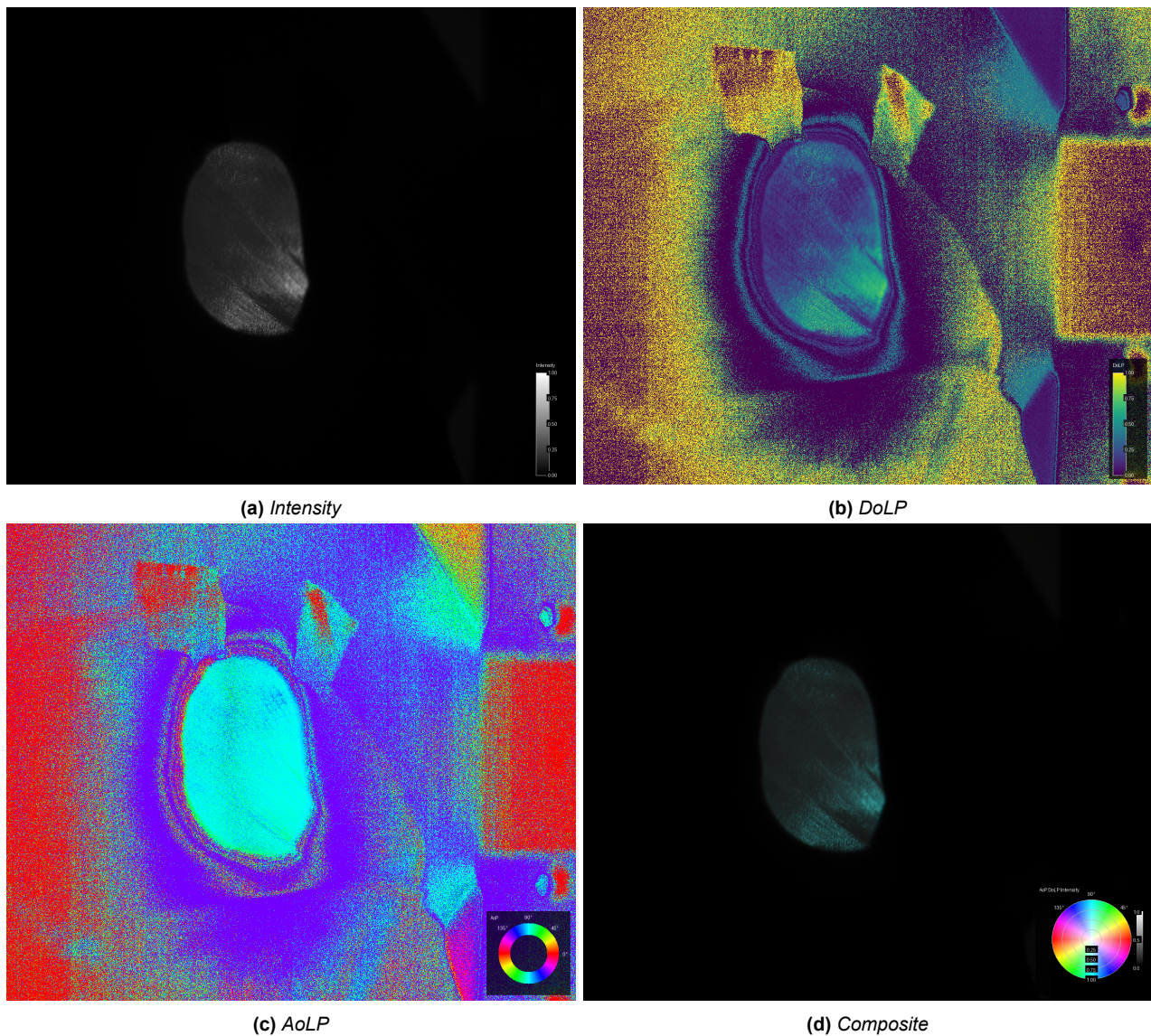


Figure 4.25: Visualisation of the -60° image of the top of the *Strelitzia* leaf.

Figure 4.26 shows a statistical analysis of the images taken. It displays the top of *S-1*. Compared to the previously-seen results, the *DoLP* curve is flatter despite the added angular resolution³. It peaks around -45° , which still does not coincide with the expectations from specular theory — that the reflection should happen at -30° — but is closer than the previous measurements, possibly due to the increased flatness of the leaf. Additionally, the number of outliers — the vast majority of which trend upwards — suggests that this curve may be highly sensitive to small geometry changes. It is notable that there appear to be more outliers at -35° , -40° , -45° , and -50° , which are also the angles at which the greatest amount of pixels are sampled. The *AoLP* once again shows a trend towards 90° at shallower angles, a higher uncertainty around -30° , and a flattening around 170° for angles closer to the normal.

³The reader is reminded to be wary of taking certain angles mentioned in Table 3.10 as exact measurements.

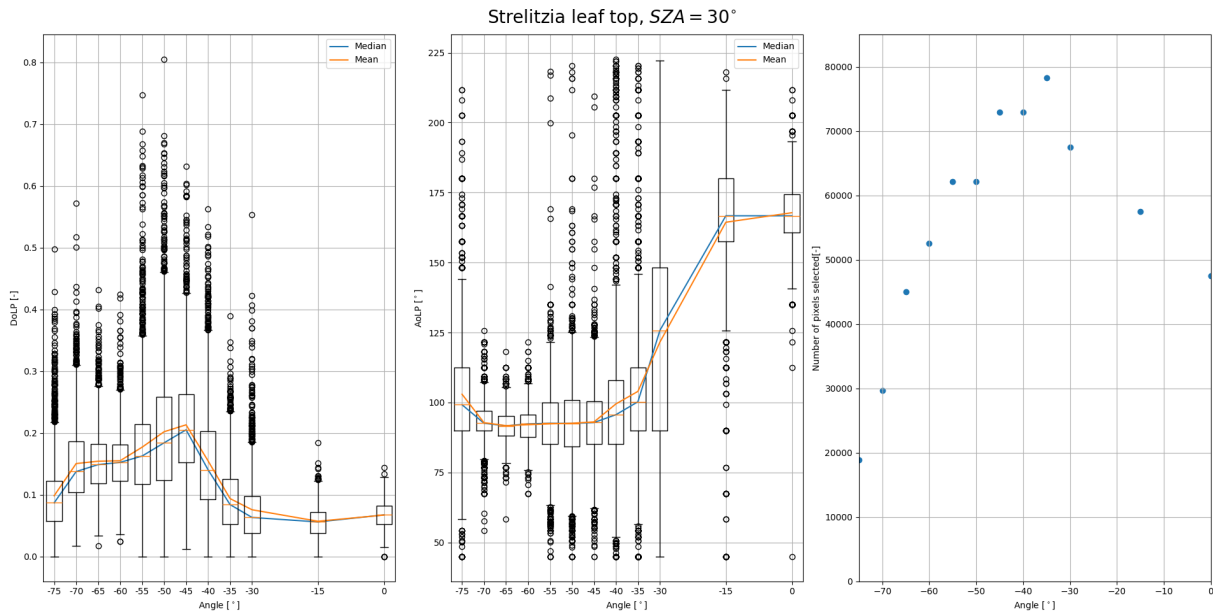


Figure 4.26: Statistical analysis of the top of the *Strelitzia* leaf. **Left:** Measured *DoLP* at different viewing angles. **Centre:** Measured *AoLP* at different viewing angles. **Right:** Number of pixels selected for the statistics. All angles are given relative to the leaf normal. **Right:** Number of individual pixels employed in computing the distribution at any given angle. The boxes represent the interquartile range, with the horizontal line indicating the median. The whiskers extend to the most extreme values within 1.5 times the interquartile range, while points beyond the whiskers indicate outliers.

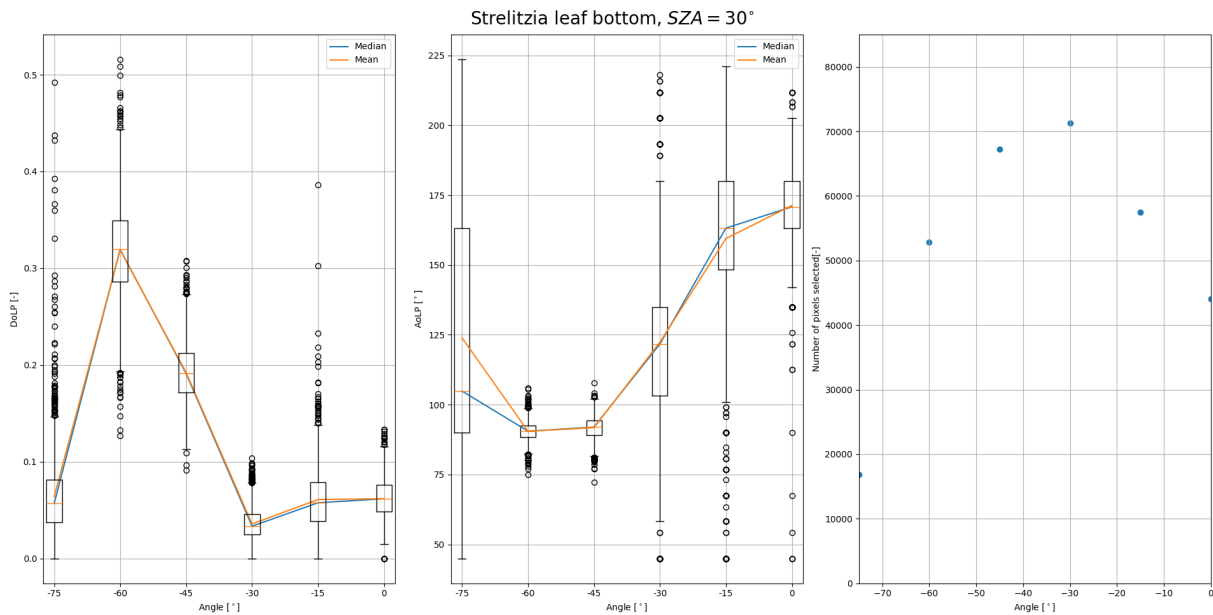


Figure 4.27: Statistical analysis of the bottom of the *Strelitzia* leaf. **Left:** Measured *DoLP* at different viewing angles. **Centre:** Measured *AoLP* at different viewing angles. **Right:** Number of pixels selected for the statistics. All angles are given relative to the leaf normal. **Right:** Number of individual pixels employed in computing the distribution at any given angle. The boxes represent the interquartile range, with the horizontal line indicating the median. The whiskers extend to the most extreme values within 1.5 times the interquartile range, while points beyond the whiskers indicate outliers.

Figure 4.27 shows the same analysis performed on the measurements at the bottom of the leaf. The maximum value for *DoLP* encountered appears to be much larger than on the top. This leaf appears to be quite sensitive to small changes in geometry and pixel areas, which may account for the discrepancy. That this is simply indicative of higher reflectivity on the bottom of the leaf remains entirely possible, however. The *AoLP* values once again show the trend towards 90° at shallow observation angles and towards $150^\circ+$ for angles closer to the normal, with the same uncertainty at -30° , and high uncertainty at the shallowest angle -75° .

Overall, these specific measurements conclusively show that the *AoLP* phenomenon of vertically polarised light is not unique to the *Euonymus Japonicus* leaves, as it seems to reoccur on both the top and bottom of the *Strelitzia* leaf. There do appear to be commonalities in the *DoLP*, but those are qualitatively limited to a general "hump" at shallow observation angles, whose magnitude does not appear to be shared between leaves — a fact that may be attributed to the difference in cuticle thickness. Curiously, both the top and bottom of the *Strelitzia* leaf exhibit similar levels of polarisation.

4.2.3. *Prunus Laurocerasus* results

Selected for its shiny appearance, large size and relatively flat surface, the *Prunus laurocerasus* leaf results are presented here. It was measured twice in quick succession — once on the top, another time on the bottom — and then the top was measured 45 minutes later to establish whether the samples degraded significantly in such a short span of time.

The results shown in Figure 4.28 display some of the same trends seen in every other experiment thus far. While still containing some obvious roughness, the *DoLP* in the image is shown as being relatively consistent over large areas. As in the previous experiments, there appears to be tendency for the *AoLP* to hover around 90° , except in the regions where the leaf shows some roughness and its geometry is slightly angled instead of flat.

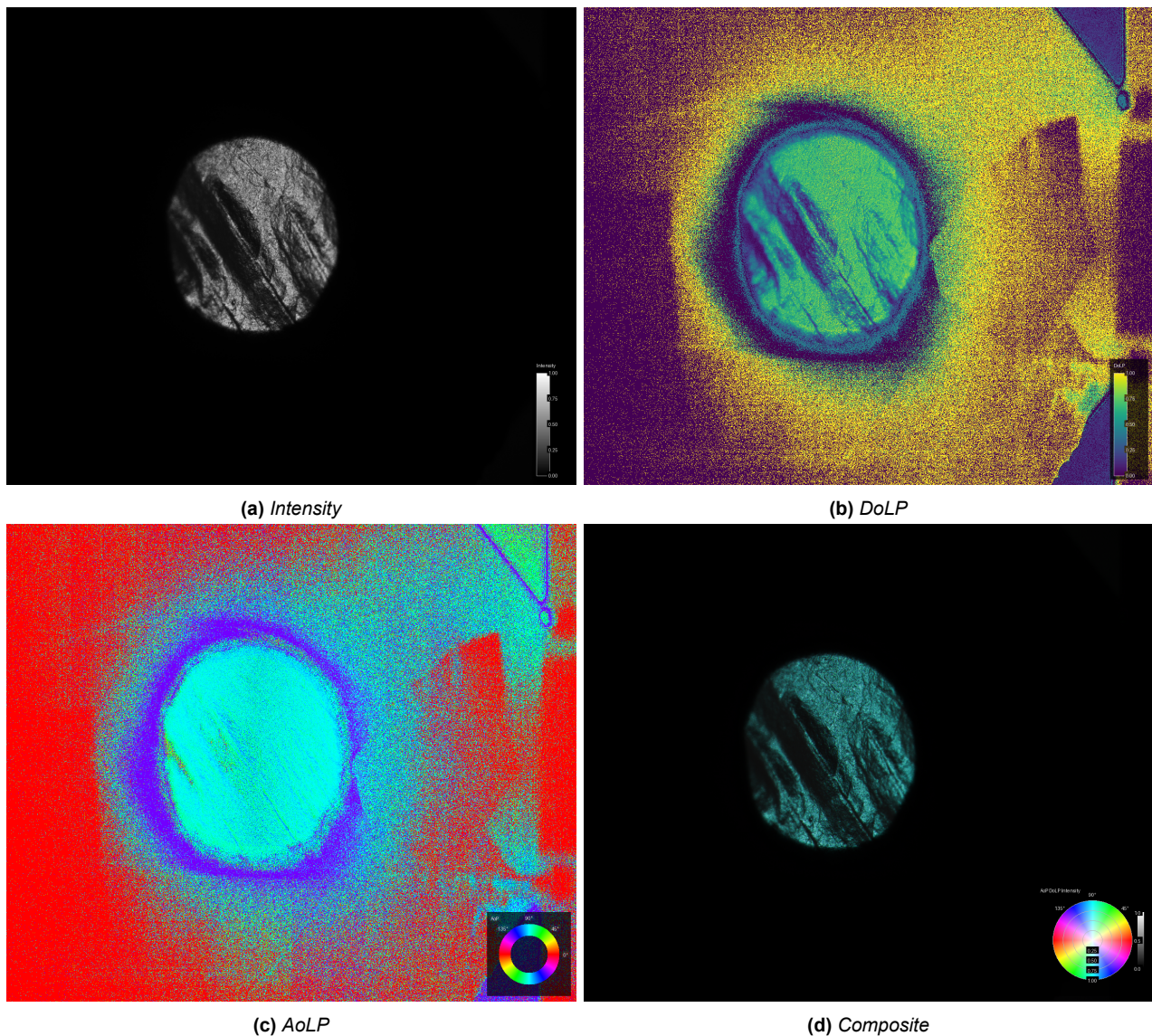


Figure 4.28: Visualisation of the 0° image of the top of the *Prunus Laurocerasus* leaf.

The *DoLP* curve is shown in Figure 4.30 unlike in previous experiments, it does not seem to

find its highest point around -60° ; instead, the median of the pixels is spread out over a range of angles. There is a larger statistical spread over this range: at -70° , for example, both 0.5 and 0.1 fall under one standard deviation. Within three standard deviations, the measurement may be almost completely polarised, completely unpolarised, or any state in-between. The number and spread of the outliers is also a cause for concern. Further measurements will reveal whether this is inherent to the leaf or caused by sensitivity to specific geometry. The *AoLP* curve shows a more stable trend: approximately 90° at shallow angles, a sharp transition, and then values over 170° .

Figure 4.31 shows the results corresponding to the bottom of the leaf. Here a departure from the norms observed thus far is shown: the *DoLP* curve, instead of showing a hump, appears to reveal a downward trend. This departure from the norm prompted further investigation into what may have caused it. Both the number of pixels employed and the number of downward-trending outliers — something which has not been observed very often in other experiments — hint at the cause, and Figure 4.29 provides some further insight: at such a shallow angle, the rough microfeatures of said angle are less visible and thus left out. This combined with the selection area being limited to a sliver in the middle, where reflection concentrates the most, results in the higher median. It is possible that had more angles been measured in the region, this curve would have looked as a "hump" as well. However, as this is the only measurement performed on the bottom of this leaf, and as no measurements have been carried out on other such leaves, it is impossible to say for certain. The *DoLP* itself has lower values than on the top face of the leaf. The *AoLP* shows the same trends as on the top of the leaf, with a slightly greater spread.

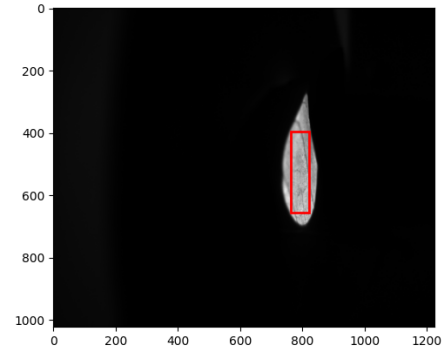


Figure 4.29: Area of pixels selected over the intensity plot of -75° .

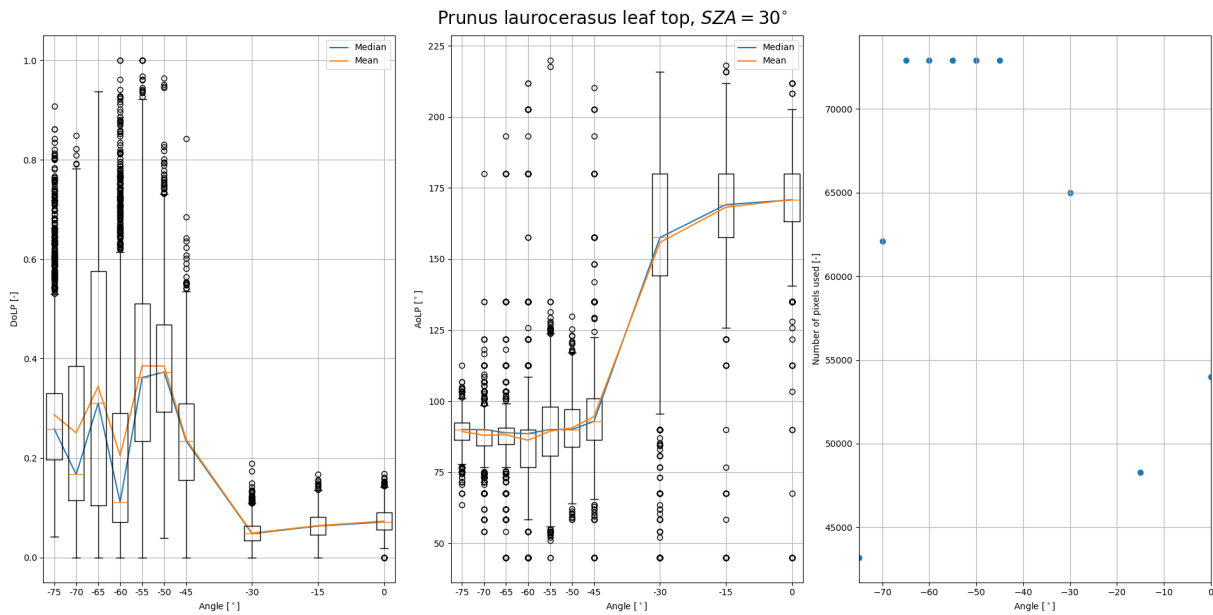


Figure 4.30: Statistical analysis results of the top of the *Prunus Laurocerasus* leaf. **Centre:** Measured *AoLP* at different viewing angles. **Right:** Number of pixels selected for the statistics. All angles are given relative to the leaf normal. **Right:** Number of individual pixels employed in computing the distribution at any given angle (see Section 3.4.4.1). The boxes represent the interquartile range, with the horizontal line indicating the median. The whiskers extend to the most extreme values within 1.5 times the interquartile range, while points beyond the whiskers indicate outliers.

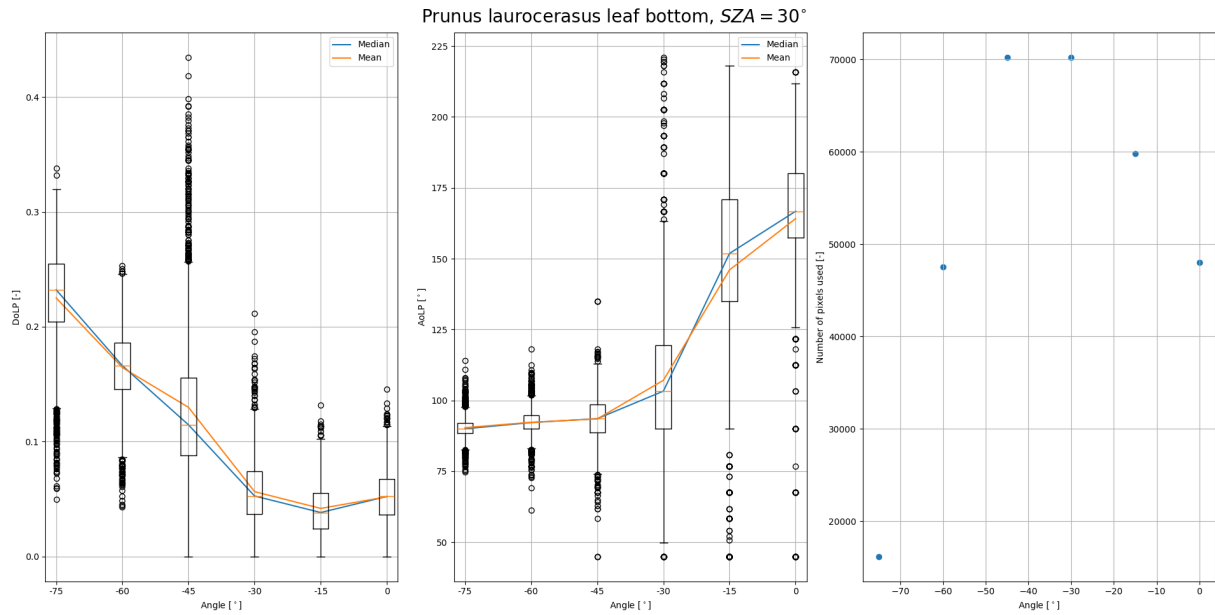


Figure 4.31: Statistical analysis results of the bottom of the *Prunus Laurocerasus* leaf. **Centre:** Measured AoLP at different viewing angles. **Right:** Number of pixels selected for the statistics. All angles are given relative to the leaf normal. **Right:** Number of individual pixels employed in computing the distribution at any given angle (see Section 3.4.4.1). The boxes represent the interquartile range, with the horizontal line indicating the median. The whiskers extend to the most extreme values within 1.5 times the interquartile range, while points beyond the whiskers indicate outliers.

Figure 4.32 shows the measurements taken of the top of the *Prunus Laurocerasus* leaf roughly 45 minutes after the first measurement. Despite the lower resolution, the AoLP's behaviour appears to remain similar. The DoLP "hump" is more noticeable than in the previous measurement. This is only an appearance, as the values reach the same as the ones found in the previous experiment. It may appear more mound-like due to its low angular resolution. There is no clear indication that there are any major differences, and it is not clear whether the differences observed are due to the passage of time or a change in geometry or pixel sampling.

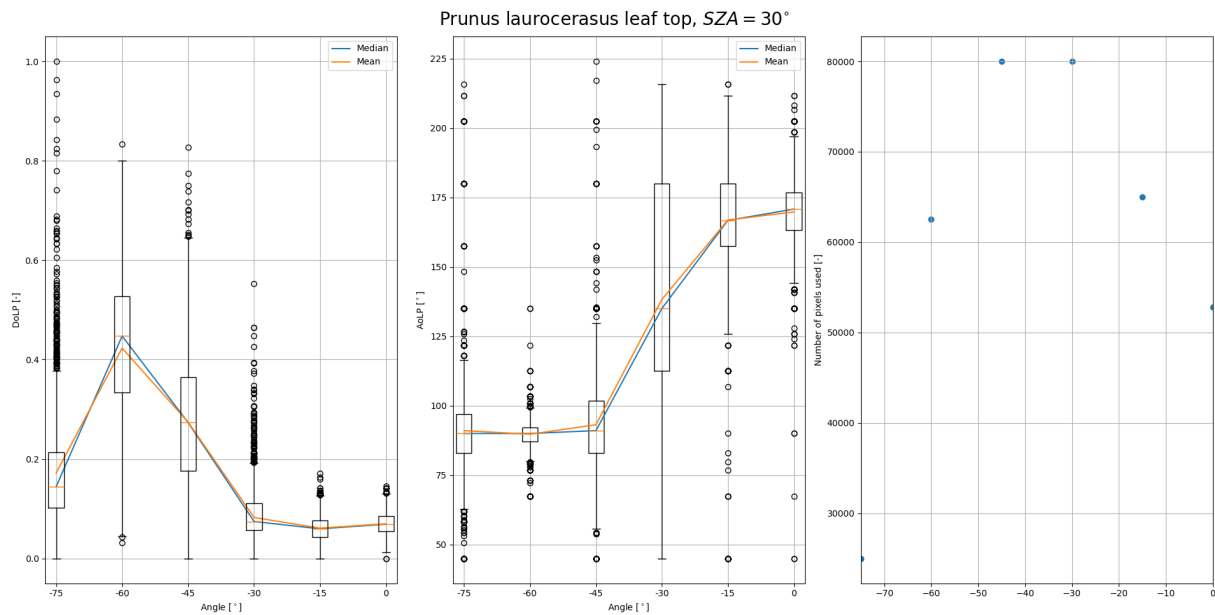


Figure 4.32: Statistical analysis results of the top of the *Prunus Laurocerasus* leaf, taken approximately 45 minutes after the first measurements. **Centre:** Measured AoLP at different viewing angles. **Right:** Number of pixels selected for the statistics. All angles are given relative to the leaf normal. **Right:** Number of individual pixels employed in computing the distribution at any given angle (see Section 3.4.4.1). The boxes represent the interquartile range, with the horizontal line indicating the median. The whiskers extend to the most extreme values within 1.5 times the interquartile range, while points beyond the whiskers indicate outliers.

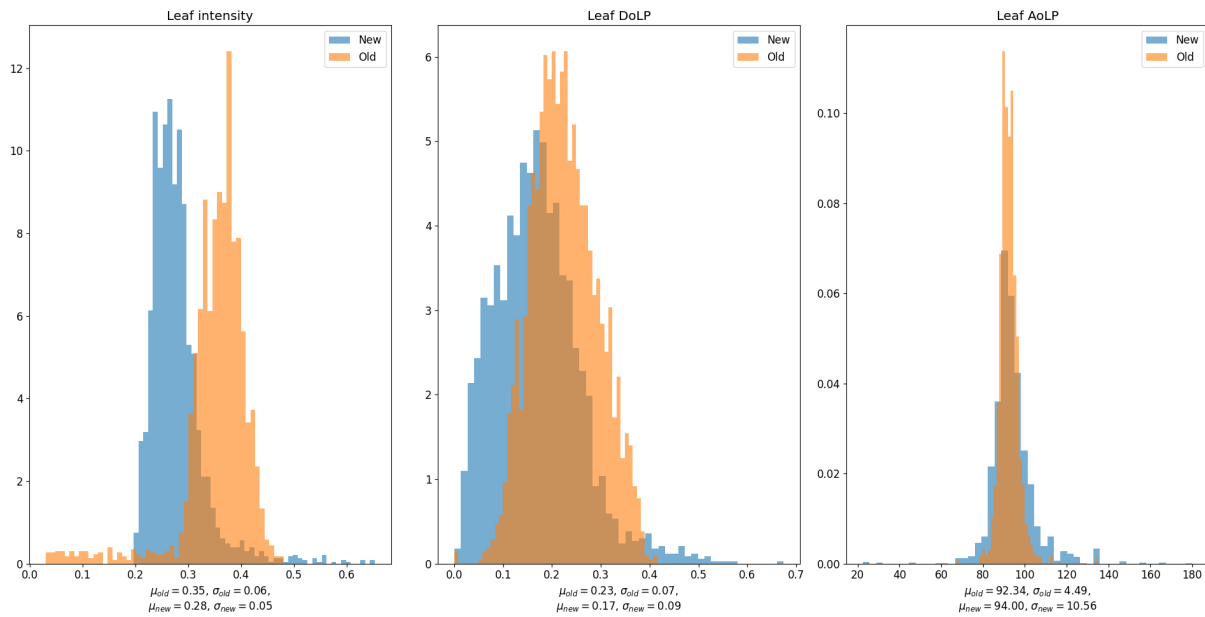


Figure 4.33: Histograms showing the pixel Probability Density Function (PDF) of both the old and new *Euonymus japonicus* leaves. The number of pixels selected from the new leaf is 29400. The number of pixels selected from the old leaf is 52800.

4.2.4. Comparison of aged and fresh leaves:

A comparison is presented between older and newer leaves of the same species. Images of these leaves can be seen in Appendix C. Figure 4.33 shows the statistical distributions of both the pixels of both the old and new leaves. *EJ-2* is the old leaf, and *EJ-4* the new one. The figure shows that the overall reflected intensity is greater for the old leaf than the newly plucked one. The *DoLP* displays a similar trend, albeit less pronounced.

The same procedure was undertaken with *S. nicolai*, where one can see from the pictures that the older leaf has curled up significantly in the intervening week. Figure 4.34 shows that there is a difference in the intensity between the two leaves; in this case the newer one appears to possess the greater intensity of the two. The difference is present in the *DoLP*, where the newer one also displays the greater magnitude, and appears much more narrowly concentrated around its mean of 0.47 than its counterpart, which shows a greater spread. Both leaves have their *AoLP* at almost exactly 90° , although the older leaf shows a greater spread as well.

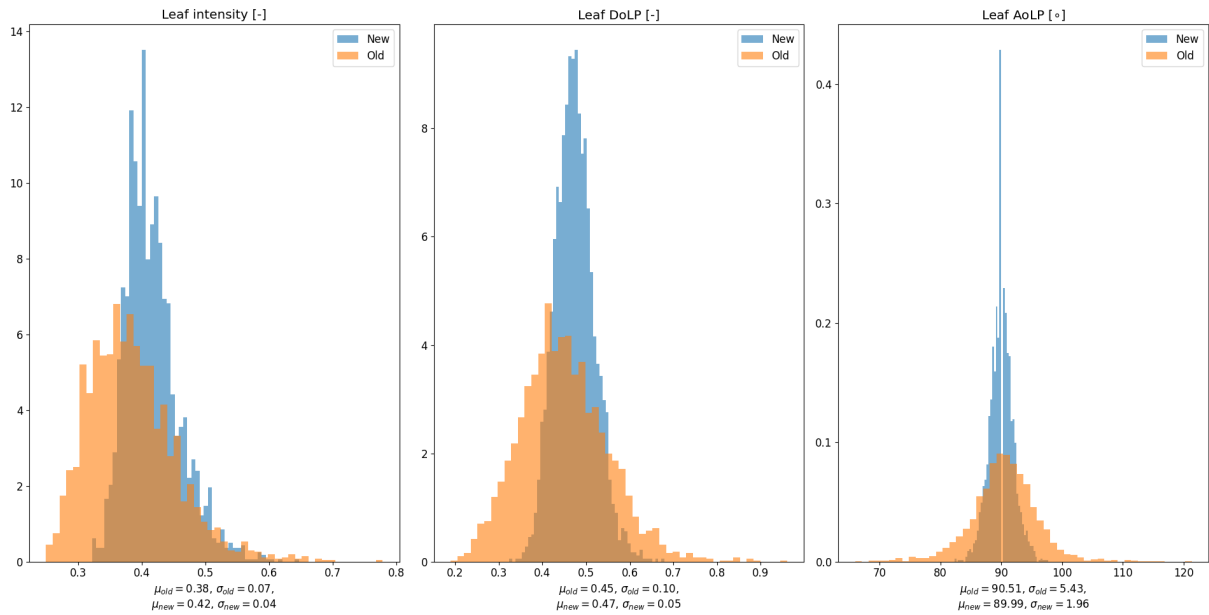


Figure 4.34: Histograms showing the pixel Probability Density Function (PDF) of both the old and new *Strelitzia* leaves. The number of pixels selected from the new leaf is 33600. The number of pixels selected from the old leaf is 42000.

The comparison between different samples of *Chrysalidocarpus Lutescens* proved to be a lot more complicated, as the older leaf had significantly crumpled up and dried out, such that it was not possible to lay it entirely flat — see Appendix C. Additionally, the slenderness of the leaf does not lend itself well to pixel sampling, as the amount of pixels one can sample is limited by the light beam's projection and the breadth of the leaf. The results shown in Figure 4.35 put the more aged plant's intensity and *DoLP* at higher magnitudes than the newer counterpart, although the spread appears roughly equivalent. The *AoLP* is shown as being concentrated around 90° for both leaves, with a roughly equivalent spread.

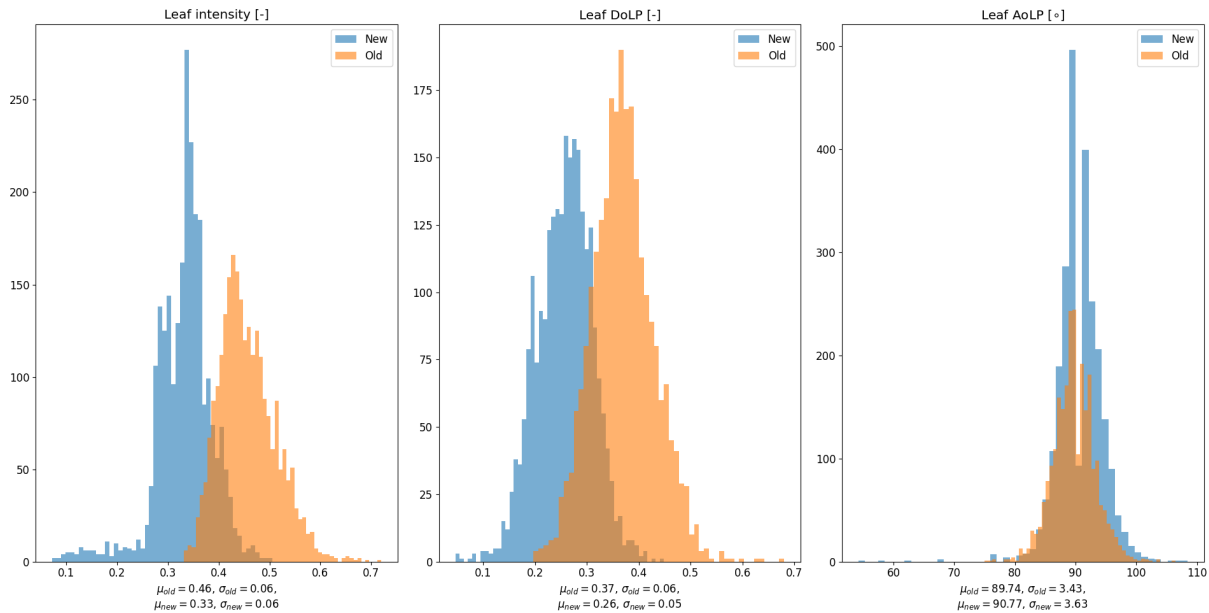


Figure 4.35: Histograms showing the pixel Probability Density Function (PDF) of both the old and new *Chrysalidocarpus lutescens* leaves. The number of pixels selected from the new leaf is 31330. The number of pixels selected from the old leaf is 17655.

4.3. Comparison of measurements and simulations

This section shows the results of comparing simulations specific to *Euonymus japonicus*, *Strelitzia nicolai*⁴ and *Prunus laurocerasus* to the real measurements gathered during the experimental work. The exact methodology is described in Section 3.5. The results are shown in Figure 4.36, Figure 4.37 and Figure 4.38.

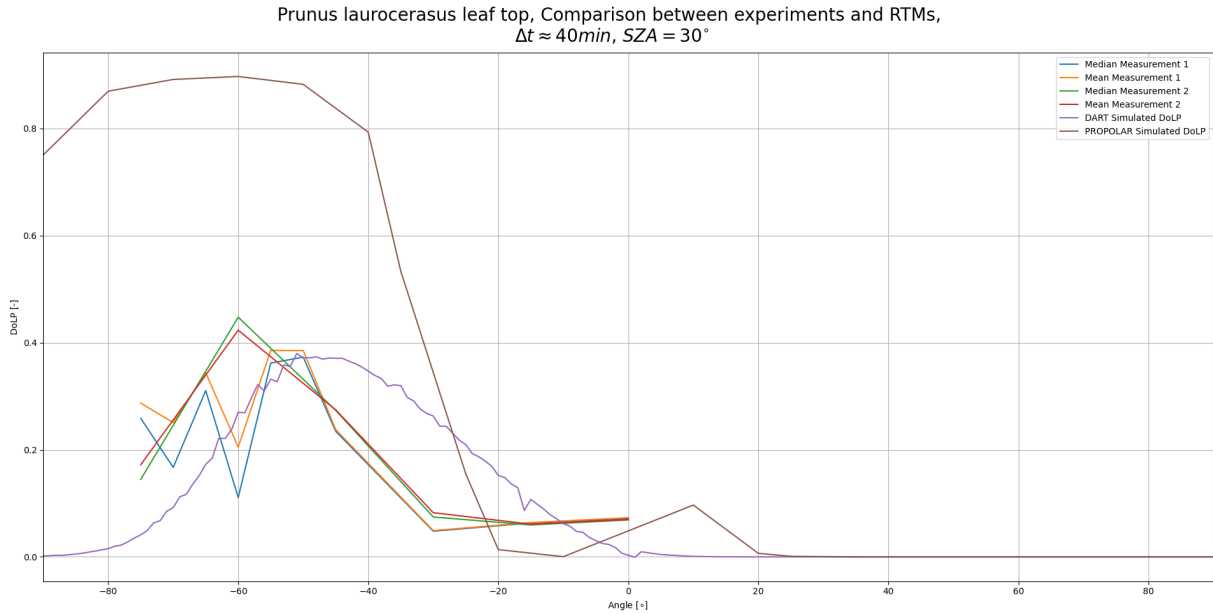


Figure 4.36: Results of two measurements of the top of the *Prunus Laurocerasus* leaf, together with DART and PROPOLAR simulations of the same leaf. The missing stretches in the DART curve are points in which the simulation failed to converge on time.

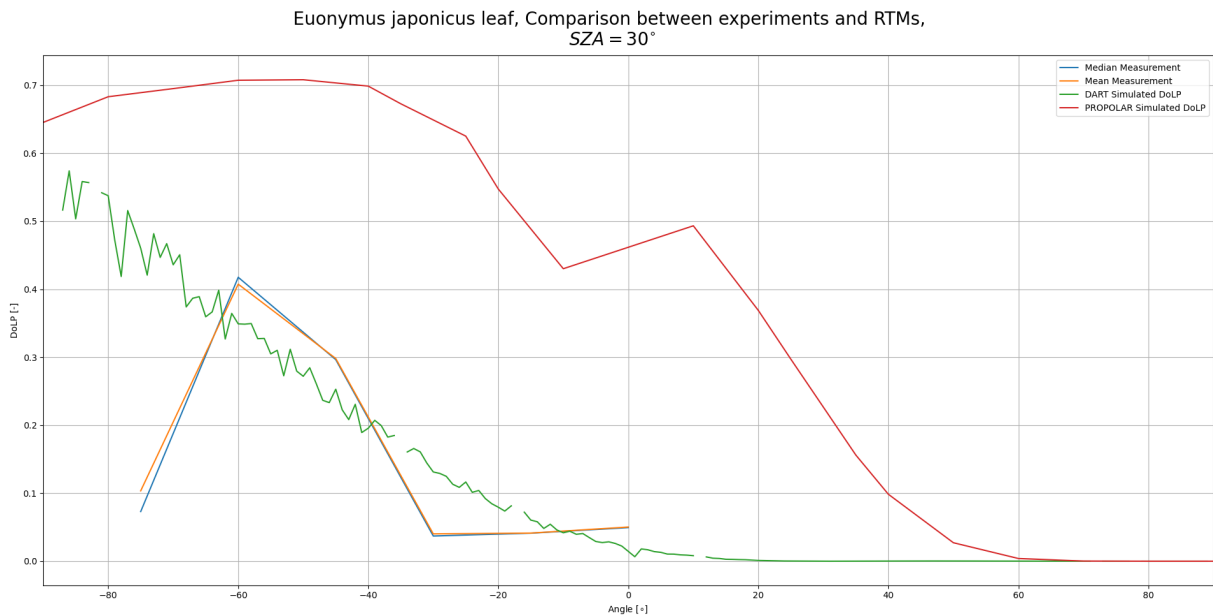


Figure 4.37: Results of measurements of the top of the *Euonymus japonicus* leaf, together with DART and PROPOLAR simulations of the same leaf. The missing stretches in the DART curve are points in which the simulation failed to converge on time.

⁴Note that the simulation parameters for *Euonymus japonicus* and *Strelitzia nicolai* are estimates. For more details see Section 3.5.1.

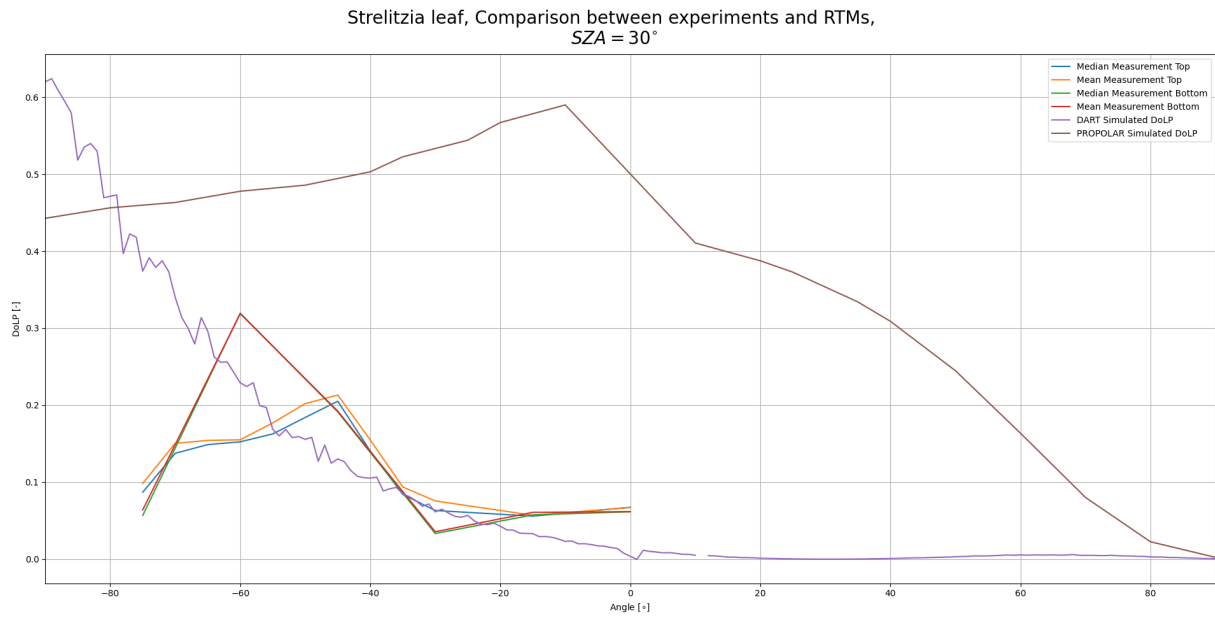


Figure 4.38: Results of two measurements of the top and bottom of the *Strelitzia nicolai* leaf, together with DART and PROPOLAR simulations of the same leaf. The missing stretches in the DART curve are points in which the simulation failed to converge on time.

These plots present a number of interesting points. The most glaring is that *PROPOLAR* fails to approach the magnitude and shape of the measurements gathered. With increasing roughness σ , the *PROPOLAR* curve becomes more spread over the angular domain — this can be attributed to the roughness, as it is the only parameter connected to specular reflection that changes from one plot to the next.

The magnitude in the *DART* results appears to remain more bounded than that of *PROPOLAR*, remaining closer to the measured values: in Figure 4.36 it appears to roughly match the shape of the measurements, only shifted slightly towards less shallow angles. In both Figure 4.37 and Figure 4.38 it displays a similar increasing trend in magnitude as the angle gets shallower, until the peak in the measured magnitude is reached. The similarities end there: *DART* continues to increase, whereas the measured *DoLP* drops precipitously.

Both models fail to match the measurements exactly: *PROPOLAR* shows a significant difference with all of the measurements. *DART* is shown to be closer in all three comparisons, although it too shows a discrepancy with the measurements shown. The increase in roughness — from 0.12 for *P. laurocerasus* to 0.4 for *S. nicolai* is theorised to play a role in the unnatural behaviour at shallow angles — the greater the roughness, the more pronounced it gets.

5.1. On the broader implications for vegetation spectro-polarimetry

This research has shown that individual leaves exhibit structured and potentially characterisable variations in both degree of linear polarisation *DoLP* and angle of linear polarisation *AoLP* as a function of observation geometry. The *DoLP* response exhibits a pronounced angular patterns, resembling the directional behaviour expected from a specular component of reflection. This indicates that the polarised component of leaf reflectance is strongly dependent on the relative geometry between illumination, observation, and the leaf surface. Such directional behaviour may potentially be developed into a mean of characterising leaf orientation. Furthermore, the *AoLP* dimension provides additional information: when observations are performed within the plane of incidence, the angle is approximately 90° for relatively shallow incidence angles, and undergoes a transition to approximately 170° as the angle shifts closer to the normal. This change indicates that *AoLP* is not a constant characteristic of the leaf, and that it varies substantially with observation geometry. Furthermore, measurements outside this plane of incidence further demonstrated changes in *AoLP* as the azimuthal angle varied. This behaviour can be explained by an increasing Stokes *U*-component. As a consequence, the full linear polarisation state (*DoLP* and *AoLP*) may provide information concerning the relationship between illumination direction, viewing direction and the orientation of the leaf surface.

5.2. Implications for vegetation spectro-polarimetry

The outcomes presented above have significant and promising implications in the field of Earth observation, as they provide information on an essential variable that is presently not well considered. Presently, vegetation remote sensing employs the wavelength-dependent intensity of reflected radiation as a means of inferring biochemical and physiological properties of vegetation such as water content or pigment concentration. However, the influence of vegetation structure and geometry [24] are generally overlooked. In particular, the so-called Leaf Inclination Angle *LIA*, for example, influences the distribution of intercepted and reflected radiation within a canopy, and can therefore affect measurements. Given that polarimetric measurements appear to be especially sensitive to observation and structural geometry, they potentially provide complimentary information to further refine vegetation radiative transfer models. This research shows that the highly directional nature of vegetation linear polarisation could be exploited to estimate leaf orientation or leaf inclination distributions. If a reproducible relationship can be glimpsed between the characteristics of the polarimetric response — the shape and intensity of the *DoLP* lobe, or the transition of the *AoLP* curve, for instance — and the orientation of individual leaves, it may then be possible to derive statistical relationships between canopy-level observations and the leaf inclination angle distribution. This would enable the retrieval of the leaf inclination angle distribution, which is a highly relevant parameter in remote sensing of vegetation [24], and which could become a major parameter in the associated radiative transfer models.

When considering thematic fields in which this novel approach monitoring has significance to, agriculture and ecology are deemed the most interesting. The first due to the need for the better monitoring of biodiversity loss, the latter because of the increasing demands and pressures on food security [1]. Specifically, environmental pressures on crop development and/or physiological stress have been known to affect leaf orientation, which in turn could produce measurable changes in the angular polarimetric response [24]. In particular, water stress caused by droughts has been shown to significantly alter a crop's leaf inclination distribution. Improving monitoring capacity would enhance

precision agriculture, potentially yielding both economic and environmental returns.

While the field of agriculture may provide the most clear application — in part due to the relative ease of retrieving valuable information from agricultural environments, dominated by clearly-defined boundaries and monocultures —, characterizing the leaf inclination distribution has equal potential in the field of biodiversity monitoring. Different plant species can possess substantially different leaf morphologies and canopy architectures, even where their spectral signatures overlap[76]. Specifically, because species-driven differences in leaf orientation, surface structure, or polarimetric scattering behaviour are reflected in their angular *DoLP* and *AoLP* responses, polarimetric observations could provide an additional discriminating feature alongside conventional spectral information. At the canopy scale this could translate into the identification of vegetation functional types. Naturally, this would first require demonstrating the maturity of this technology, specifically proving a consistent relationship between observed polarimetric signals within individual species, and a consistent difference between individuals of different species under varying illumination and viewing conditions.

5.3. Reflection on the measurements performed

These potential applications should nevertheless be distinguished from the capabilities demonstrated by the present measurements; the current results illustrate a clear relationship between illumination and viewing geometry and the respective *DoLP* and *AoLP* signatures of vegetation. They do not at present establish a relationship between observed polarimetric variables and physical parameters such as leaf inclination angle. Consequently, before any such applications can be developed, a substantially larger body of measurements needs to be carried out along a range of species, lighting conditions, and environmental conditions. Specific lessons can be learnt that could improve the usefulness of future campaigns from the measurements that were performed within this project. For this purpose, a point-by-point reflection on the objectives discussed in Section 3.4.1 is presented:

5.3.1. Can polarisation be measured with the available means?

This question is firmly answered by the experiments performed. Concessions must be made to the presence of confounding factors such as geometry differences, and differences in leaf species and age; however, these factors do not prove to be a significant challenge when it comes to taking measurements, as all experiments gathered useful data. That none of the measurements provided anomalous or unexpected results is encouraging, and invites further, more accurate experimentation.

5.3.2. How well can the *BPRF*, *DoLP* and *AoLP* be characterised?

The results presented clearly show that, while it was not possible to fully characterise the *DoLP* and *AoLP* curves of the specimens examined, doing so may be very well possible given further experimentation. From these results alone some trends in both *DoLP* and *AoLP* can be glimpsed, which both verify the theoretical understanding of vegetation polarisation and provide useful indications on what future research might wish to focus on.

The *DoLP* curve was measured in most of these experiments, and while the resolution of these is low and the number of measurements modest, it is sufficient for overall trends to manifest. These can be described as the "hump" as shallower observation angles — corresponding to the highest concentration of reflected light — followed by a tenuously polarised signal at angles closer to the normal. While these results are quite positive — there is ample reason to believe they could be refined into a more thorough understanding of vegetation polarisation — a healthy degree of scepticism is required when it comes to their accuracy: the error bars at some specific angles are relatively large, in some cases suggesting that the signal could be either entirely polarised, or entirely unpolarised. Given that these measurements were performed on individual leaves of each species, and in most cases were not repeated, it is possible that these error bars are specific to the measurements in question and not part of an overall trend. A greater volume of measurements, both of the same leaves and of others of the same species, may prove useful in narrowing the error bars and revealing a clearer statistical trend underlying the measurements. Experience and rigour may play a role as well: no measurements of this sort were taken before by those involved, and a refinement of technique

(especially in clamping down the leaves) and the experimental setup (such that a higher resolution is achieved, and perhaps a higher throughput) may aid in suppressing these confounding factors.

The *AoLP* curve characterisation is a major success, and perhaps the most interesting result of this research. Every measurement taken shows relatively narrow error bars — except for the one angle where it transitions from 90° to 170° . There is a clear, repeatable trend that holds across specimens, and little spatial dependence. It is a curious series of experiments, as the literature study turned up no information to suggest that the measurements would appear as they do. It is similarly fortuitous to observe the measurements of the angles on the angled side of *Euonymus japonicus* in Section 4.2.1. The angles being so different from the trend in leaves measured within the plane-of-incidence¹ opens a door to further research, as it may prove interesting to look at vegetation from other angles outside of the plane-of-incidence.

5.3.3. How does polarimetry (*DoLP* and *AoLP*) change between leaf species and age?

The experiments comparing leaves of different ages successfully show the apparent difference in the *DoLP* measured; however, the degree to which these changes occur and whether they increase or decrease polarisation varies from one specimen to another. The existing differences may be connected to the features described in Section 3.4.4. However, it is important to consider that the results observed may be influenced by differences intrinsic to the specific leaves employed, as opposed to the age itself. Had the difference between these leaves been more stark, it may have suggested that age was an important factor — after all, one would not expect stark differences between leaves that are relatively similar aside from their age. One thing that all of these leaves have in common is the *AoLP* being centred at 90° , mirroring the results of every other measured leaf in every other experiment. There is reason to suspect this may be a feature common to most leaves; however, further experiments should be performed to make the sample size more representative before firm conclusions can be drawn on this matter.

5.3.4. What is the effect of the Leaf Inclination Angle *LIA* on polarimetry?

The *DART* simulations in Section 4.1.1.2 make the possibility of measuring the same relationships tantalising. While mechanically the existing setup is perfectly capable of performing these measurements, it was ultimately deemed excessively time-consuming: adding different leaf angles would have meant multiplying the number of individual measurements per leaf by the number of inclination angles, which may have turned hour-long sessions into week-long endeavours. The matter, regrettably, had to be left unexamined. This proved a sound choice, however: the *DoLP* curves that have been measured are not accurate enough to justify changing inclination angles at this stage. The measuring methods must be tuned, the understanding of individual curves refined, before a solid relationship can be drawn between the Leaf Inclination Angle and the measured *DoLP*.

5.3.5. A note regarding experimental conditions

One note of caution should be entertained: these experiments were all performed in laboratory settings: they were exposed to a single light source, which was both unpolarised and collimated². Unpolarised and collimated, light outside of the laboratory is not. Conclusions drawn from the experiments henceforth implicitly contain the stipulation that they may only apply to these conditions. Generalising these conclusions would require performing similar experiments in more complex conditions.

5.4. Interpreting the radiative transfer models

Given the results from the comparison between the measured and observed *DoLP* and *AoLP*, and the intercomparison between the two radiative transfer models (*PROPOLAR* and *DART*), it can be argued that further development is definitively needed before polarimetric signals can be used for agricul-

¹The plane of incidence refers to the plane formed by the incoming light and the normal of the surface on which it reflects.

²Aside from the first measurements taken, which were taken under ambient lighting conditions and had no analysis performed on them beyond a qualitative check for polarised signals

tural and ecological purposes. Specifically, the analysis of the radiative transfer models reveals that, whilst they can be applied to the study of vegetation polarisation and in some cases even produce results that correspond with measurements, they do in their current form contain certain inadequacies that limit their potential. It is not certain whether this is due to their own characteristics or the implementation of the simulations carried out as part of this work. However, based on the results obtained here, the case can be made that there are fundamental flaws in both *DART* and *PROPOLAR*.

5.4.1. On PROPOLAR

The results of the qualitative comparison between *DART* and *PROPOLAR* (presented in Section 4.1.2) reveal specular reflection lobes in the *DoLP* that are and have a greater magnitude than initially expected. Stripping *PROPOLAR* down to merely its *PROSPECT* implementation in Section 4.1.3.1 — by omitting the specular and polarimetric post-processing — showed near perfect agreement with *DART*'s own implementation. This effectively isolates the problem to the implementation of specular reflection, which appears to dominate in the visible band of the spectrum based on the bottom right plot in Figure 4.17. These results do not seem to match real measurements either, as the comparison in Section 4.3 show it highly overestimating the *DoLP*. Given the validation of *PROPOLAR*'s training presented in the 2025 paper[37], it can be argued that the model may be overtuned on the experimental conditions present in the measurements off of which it was based. Regardless of the root cause, it cannot be said to be performing adequately for the purposes of this work. Given the limited number of variables that one can tune in *PROPOLAR*, there is not much that can be said about how to improve the results shown here without altering the model itself. Whether or not these results are accurate is impossible to determine at this stage; however, none of the results — except perhaps the greater angular extent of the specular reflection cone — can be said to be outside of the realm of physical possibility.

5.4.2. On DART

The simulations of the effect of the *leaf inclination angle LIA* in Section 4.1.1.2 show very clear curves which may indicate its usefulness in determining the *Leaf Angle Distribution LAI* of a given specimen through multi-angle polarisation measurements. However, on the basis of the discrepancies between the *DART* simulations and measurements, it appears that this radiative transfer model has modelling issues when simulating vegetation polarisation. While its implementation of the diffuse component appears not to differ greatly from a 1D *PROSPECT* simulation (see Figure 4.17), the specularly reflected light appears to concentrate at very shallow angles, which challenges the theoretical understanding of how specular reflection operates — where a perfect mirror-like surface should reflect light at the exact angle that it comes in. Given that the polarisation in *DART* is uniquely tied to specular reflection, how this reflection is implemented is at the root of the issue.

Section 4.1.1.1 shows a clear trend in the evolution of the angle of reflection with the roughness σ of the surface³ Low roughness values σ show the reflection where the theory suggests they ought to be, implying that the more smooth and mirror-like the surface, the more true it stays to the theory. That in itself is uncontroversial, but both intuition and the comparisons with real measurements (both with the *DoLP/Viewing angle* curves found in Section 4.2 and the comparison in Section 4.3) suggest that *DART* overestimates the effect of roughness on specular reflection, given that the most shallow angles at which maxima occurred in the measurements were all approximately 60° .

It is similarly unexpected that the Stokes component U is shown to be exactly null throughout the domain in all *DART* results presented. While the measurements performed on perfectly flat leaves did show angles consistent with a small U Stokes parameter (*i.e* close to 90°), the *Euonymus Japonicus* leaves that had a diagonally tilted section in the measurements had angles that would imply the presence of a much larger U -component. Additionally, while the U -component may in some cases be expected to be low, it is impossible for it to be exactly 0 throughout the domain in a real scenario.

The origin of these discrepancies is hypothesised to arise from how *DART* uses the microfacet distribution function to simulate roughness[55]:

³Where roughness is defined as the *RMS* of the slopes on the surface, see Section 3.3.1.1.

$$P(\beta, \sigma) = \frac{1}{2\sigma^2 \cos^4(\beta)} e^{\frac{-\tan^2 \beta}{2\sigma^2}} \quad (5.1)$$

Here, Equation 5.1 is applied as a multiplicative factor on the vector, and is nearly identical to the expression employed in Equation A.9⁴, where the only difference is the exponent on the cosine. A full explanation of each term is attached to Equation A.9. This difference has severe impacts, as the exponent gives more weight to the angle β of the normal of the microfacet to the macroscopic normal. The higher this angle is, the lower the denominator will be — and consequently, the greater the scaling on the overall *BPRF*.

More importantly, this insight may explain the reason that the *U* component remains null throughout every simulation. A slight variation is expected given the presence of microfacets. The influence may average out to a small value — the microfacet inclination follows a Gaussian distribution, after all — but should not be exactly 0. However, it would appear that the roughness is not treated as a geometrical feature, only as a multiplier for an existing vector. Therefore, the ray is essentially encountering a geometrically flat plane. If reflection on said plane does not generate a Stokes *U*-component, then it shall not be present.

Given that the Fresnel coefficients act independently on the s- and p-polarised components, the Mueller matrix for specular reflection on the incidence plane will have the form[77]:

$$M = \begin{bmatrix} A & B & 0 & 0 \\ B & A & 0 & 0 \\ 0 & 0 & C & D \\ 0 & 0 & -D & C \end{bmatrix} \quad (5.2)$$

Consequently, for unpolarised light $\vec{S} = [I, 0, 0, 0]$, the result of any specular reflection will have a Stokes vector $M \cdot \vec{S} = [AI, BI, 0, 0]$, i.e there will be no *U*-component after reflection. Naturally, this only applies to a single ray. Multiple rays incident at the same angle — such as might be received from a collimated light source — would reflect within the same plane-of-incidence, and would thus be coherent and not cause any *U*-component to arise. This is the situation that *DART* is simulating. The reality for a microfaceted plane would most likely differ from this rule, however: the introduction of slight tilts implies a modification of the incident plane⁵. Once transformed into a global frame, it is almost certain that the interaction between rays from different microfacets would result in a non-zero *U*-component. It is, however, hard to estimate the magnitude of this component, and it may be possible that the Stokes *Q*-component of any polarised signal dominates. However, this clears away some doubt as to why *DART* does not produce a Stokes *U*-component for these simulations, but does for the first test that was run with complex 3D trees in Section B.1, for example. It suggests that a more complex geometry might provide the means to simulate this signal.

⁴The *DART* user manual provides this equation with different characters. These have been made consistent with Equation A.9 to accentuate the similarity.

⁵The incident plane is defined by the incident light vector and the surface normal at the point of incidence, see Figure 2.8a.

Conclusions

6.1. Closing remarks

The undertaking of this thesis has produced a large range of results on disparate but related topics. On the topic of radiative transfer models, it has shown both the capabilities and limitations of the *DART* model in simulating polarised signals of leaves, comparing them both to *PROSPECT* and *PROPOLAR*, and performing an analysis on what factors may drive the deficiencies and supply the errors. It was shown that a flat plane cannot accurately simulate a leaf, given the limitations imposed on *DART* by the implementation of the statistical distribution of microfacets. It additionally showed that *PROPOLAR* shared the same limitation: the effect of surface roughness on specular reflection and polarisation are poorly simulated by both models. Additionally, these two models cannot simulate the same scene simple leaf scene and produce converging results. It has been shown that a large volume of additional measurements are necessary in order to characterise vegetation polarisation and compare it to these models; until these are taken, it cannot be said with certainty that either of these models is inaccurate. In a series of experiments it was shown that *Euonymus Japonica*, *Strelitzia nicolai* and *Prunus Laurocerasus* have measurable linear polarisation: it showed clear trends appearing the plane-of-incidence, where *DoLP* and *AoLP* were shown to have physical relations to the observation geometry. The *AoLP* specifically was shown to have peculiar behaviour, both when specular reflection was viewed from within the plane-of-incidence and when viewed from outside it. This is a phenomenon that, to the author's knowledge, has never been formally recorded in the literature. Analysis was performed on the differences between leaves of different species and ages, both of which remain inconclusive, but open avenues for further research. Given the novel nature of this field of research, it is unsurprising that more questions remain than were posed at the beginning. This research highlights multiple entry points which could expand the understanding of this topic.

6.2. Reflections on the research questions

Four main research questions were formulated at the start of this thesis. Of these, it has been stated that two of them — How well canopy models reflect measured remote sensing data, and if existing models could be used to measure vegetation functional traits — were not pursued as the true scope of the research became apparent. The other two were approached simultaneously, pursuing two different approaches: a simulation approach, and an experimental approach.

6.2.1. Can leaf polarisation be adequately modelled?

The question of whether leaf polarisation can be adequately modelled is a pre-emptive one. While multiple studies exist on the polarisation of leaves, the existing literature has not reached a consensus on how this polarisation can be characterised at the leaf level. A single model exists that claims to be able to simulate it, and it has never been externally validated. If leaf polarisation is to be modelled, it is fundamental that it be measured adequately first. This research has shown some attempts at characterising leaf polarisation within the plane-of-incidence, with varying degrees of success. Different leaves were shown to have similar trends in their *DoLP* across different viewing angles. The accuracy of these trends is uncertain, but the trends suggest a physical mechanism that could be better understood through a greater volume of measurements. It was shown that the *AoLP* of these leaves showed a much clearer trend, and that all of these leaves produced polarisation at the same

vertical angle.

6.2.2. Can canopy polarisation be accurately modelled?

Canopy polarisation is a well-established phenomenon: space-based remote sensing equipment has measured polarised signals over wooded or vegetated terrain. However, no models exist to describe polarisation at the canopy level, as it is often assumed that multiple scattering occurring within canopies has a depolarising effect. How leaf polarisation aggregates at a canopy level is therefore a question that must be answered in order to understand canopy polarisation. This thesis attempted to build a leaf model within the *DART* model, comparing it to the *PROPOLAR* model. *DART* has been shown to have limitations in accurately simulating leaf scenes, with results that fundamentally disagree with *PROPOLAR*, and which deviate slightly from the *PROSPECT* model on the spectral dimension. Limitations of the leaf scene implementation have been highlighted: a flat or slightly rough plane cannot produce full-Stokes polarisation signals within *DART*, and the model for specular reflection employed does not lend itself well to leaf simulation. Simulations were performed in an attempt to approximate the effect of the Leaf Inclination Angle (LIA), for the purposes of both determining if a canopy's Leaf Inclination Angle distribution could be approximated through remote sensing, and to provide a guide into experiments that could be performed in the future.

Recommendations

This chapter provides a more in-depth look into strategies suggested to continue this avenue of research in the future. One of the main products of this project has been to highlight the multiple directions into which further research into polarimetry in remote sensing of vegetation can be taken into the future.

If the stated use of polarimetry expressed in Section 5.1 is to be taken as the ultimate goal, then there are a number of steps that must be taken for it to be reached. If polarimetry is to be applied to the remote sensing of agriculture and biodiversity monitoring, the relationships between the physical characteristics of vegetation and the measured linear polarisation (both *DoLP* and *AoLP*) needs to be precisely understood. This project has shown that there is a clear relationship between illumination geometry, viewing geometry and the *DoLP* and *AoLP* of vegetation. In order to this to ultimately translate into valuable remote sensing data, a few steps need to be taken. These steps are presented in the following sections, and summarised in Figure 7.1.

7.1. Concerning future experiments

The first of these steps is to establish a more well-defined relationship. The results of this research show that the link is there, but attempts to characterise the *DoLP* and *AoLP* curves failed to show a strictly-defined, invertible relationship. This limitation can be attributed to the limited time available during the experimental phase of this thesis, which severely restricted the data volume that could be measured and analysed. There are many variables to consider, and as such any experimental approach to revealing more concrete relationships between polarimetric signals and vegetation physical characteristics has to sequentially approach all of these, increasing the level of complexity at every stage. While these may not necessarily need to follow the order presented in the following paragraphs, it would not be advisable to start from a latter point than the one here presented.

The first hurdle is to establish a more robust database on the plane of incidence *DoLP* and *AoLP* curves of different species of leaves. The relationship between polarisation and plant physical characteristics must be shown to be roughly constant across leaves of a given species, at least to the degree that the degree of ambiguity is not so significant as to render measurements impossible to invert consistently.

Following this, measurements can be taken at different inclination angles, which may aid in reconstructing curves akin to the relationships shown in Section 4.1.1.2. Results of this sort may ultimately enable the identification of the Leaf Inclination Angle distribution at a canopy level. Hemispherical or semi-hemispherical measurements may want to be considered as well — especially concerning the *AoLP*, given its curious behaviour outside the plane of incidence. These may aid in ultimately highlighting a specific statistical relationship between measured polarisation and canopy architecture.

Additionally, considering leaves of different ages and conditions may provide the necessary insights to correlate polarimetric measurements with vegetation age, development, environmental conditions and physiological stress. Once a sufficient body of knowledge has been acquired, it may prove possible to highlight differences between the polarimetric signals of different species, and their physical and environmental conditions. This would in turn enable the retrieval of vegetation architectures (and their Leaf Inclination Angle distribution) and perhaps even allow for specific phenotyping, enabling no-contact biodiversity monitoring.

If these relationships can be established to a satisfactory degree in the laboratory, it would then naturally follow that this relationship should be tested outside of laboratory conditions, where the

acquired knowledge can be tested against real conditions.

7.2. On radiative transfer models

Even if they were, on the whole, not able to accurately match the measurements carried out over the course of this work, both *DART* and *PROPOLAR* show potential in being employed for the simulation of polarimetric vegetation signals. Given that the volume of measured data was low, the comparisons to the simulations may show exceptionally poor results due to unknown variables. Additional measurement data would enable a more comprehensive evaluation of these models, and would prove extremely valuable in their further refinement and tuning.

As mentioned in Chapter 5, the main shortcoming of these models in simulation vegetation polarisation appears to be the microfacets models they employ, which are remarkably similar. Further refinement of this specific aspect of both models may bring them much closer to real measurements. As such, this is an avenue worth exploring that may not require much initial investment before the returns become clear. Additionally, *DART*'s current implementation of this microfacet model does not appear to simulate vectorial light reflection, such that the Stokes parameters are not simulated adequately. A further rethinking of this specific aspect of *DART* may provide the capability of simulating full-Stokes vegetation polarisation, enabling comparison to *AoLP* measurements, and an improved understanding of the phenomena that stem from it.

Another radiative transfer model exists, which was not experimented with given that it was published close to the conclusion of this research. *ERADIATE*[78] is an open-source, 3D model capable of simulating fully vectorial (and therefore polarised) light. Given the backing behind it, it is possible that this model will be further developed in the future, and a similar analysis to that conducted on *DART* and *PROPOLAR* may reveal whether it is suitable for the purposes of simulating vegetation polarisation. It may prove more accessible and easy to modify, as its implementation is entirely open-source and relies on both Python and C++.

7.3. On remote sensing

While it may be possible to measure vegetation polarisation at relatively small distances, it is as yet unclear whether similar measurements may be carried out from spaceborne platforms. Discussions with peers from *SRON* and existing literature suggest that polarised signals from vegetation are clearly visible from space, but as yet no analysis has been carried out on it. While the two steps mentioned prior would prove valuable by themselves — airborne platforms, for instance, could enable localised retrievals —, a spaceborne platform could provide data on a global scale, which would be of enormous value to biodiversity monitoring. It is important to determine if canopy-scale polarimetric characteristics can be observed from spaceborne platforms. Spaceborne measurements introduce a number of additional factors that are absent or comparatively well controlled in laboratory measurements, including increased spatial and spectral averaging, atmospheric effects, variable illumination and observation geometry, and the aggregation of many leaves and canopy elements within a single measurement footprint. These effects may substantially reduce, modify, or potentially obscure the polarimetric signatures identified at the leaf scale.

This constitutes an important step before the development of dedicated spaceborne spectropolarimetric instruments for vegetation monitoring. If existing observations contain reproducible relationships between polarimetric measurements and vegetation properties, they could provide an initial demonstration of the feasibility of such measurements and help identify the most informative observing geometries and spectral regions. Conversely, if the relevant signals are found to be substantially diminished at existing spatial or spectral resolutions, this would provide useful information for defining the requirements of future instruments. In either case, the analysis of existing spaceborne observations would therefore help establish whether the phenomena identified at the leaf scale have practical relevance for remote sensing and, if so, what observational capabilities would be required to exploit them.

7.4. Work Breakdown Structure

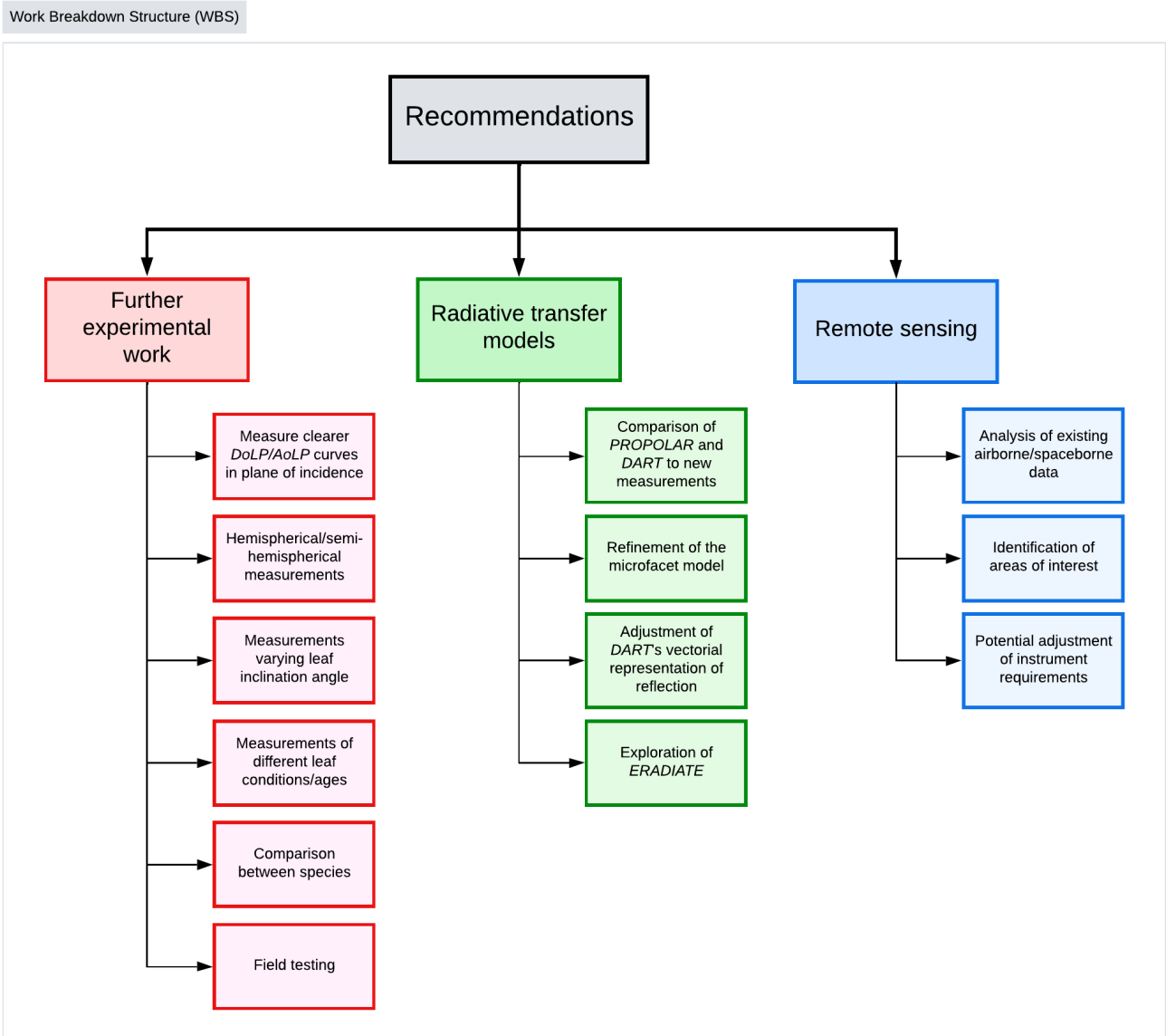


Figure 7.1: Work Breakdown Structure summarising the contents of the recommendations section.

A brief introduction to DART and PROPOLAR

A.1. Introduction to DART

While much has been said about *DART* over the course of this report, little part of it has been devoted to explaining its inner functioning. While a comprehensive survey of all its capabilities and functions would be extremely lengthy — the user manual alone exceeds 300 pages[55], and can at times be somewhat cryptic — an overview of the functions related to these experiments and the mechanisms employed by them in simulating physical processes is provided here, to further the understanding and gratify the curiosity of the reader.

A.1.1. Physical principles

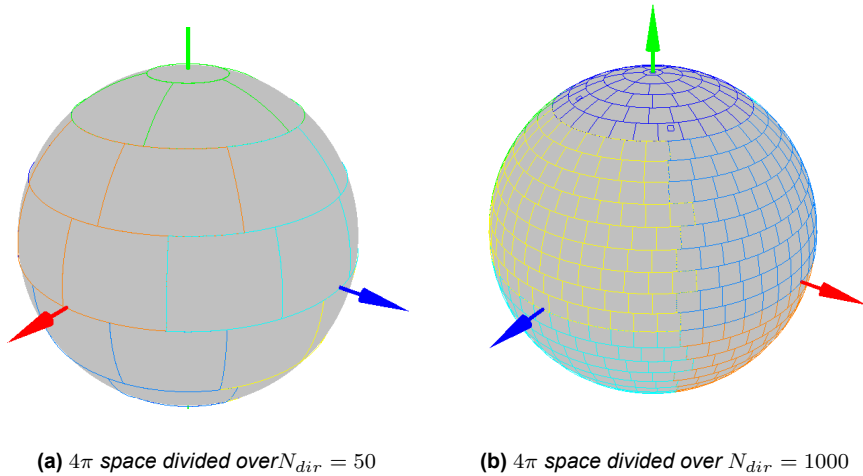


Figure A.1: *DART* discretisation of angular space. The reader is invited to note the difference between the two and consider which may produce more accurate results.

At its core, *DART* is a discrete model¹: it carries out its radiative transfer process for a discrete number of directions across a predefined scene, dividing the angular space Ω into N_{dir} directions. Each of these directions — referred to as ordinates — corresponds to a ray traced through the scene, where its intensity decreases due to interception or absorption, or is increased by thermal emission (if present). Scattering occurs upon encountering an object, generating new rays that scatter in those same N_{dir} directions, and can themselves scatter again upon encountering another object. Once a ray's intensity has decreased below a certain threshold, it is removed from the scene. The radiative transfer equation is then approximated by summing the directions over the whole 4π spherical space, where each direction is appropriately weighed to its solid angle, as shown in Figure A.1. Given the discretisation, it is often the case that a low number of discrete ordinates may result in inaccurate results.

The main advantage of *DART* over other models for the purpose of this research is its vectorial nature. Where other models treat light as a scalar quantity, every ray cast by *DART* is treated as an

¹The "D" in *DART* stands for Discrete.

individual vector, each of which represents an electric field $E(t)$ which then defines the Stokes vector in its own local coordinate system. Figure A.2 shows how the coordinate system for each Stokes vector is defined. Both the input and output vectors are expressed with reference to the absolute reference frame: both $N_{(\Omega_{in}, z)}$ and $N_{(\Omega_{out}, z)}$ are defined as the plane formed by the ray and the global z -coordinate.

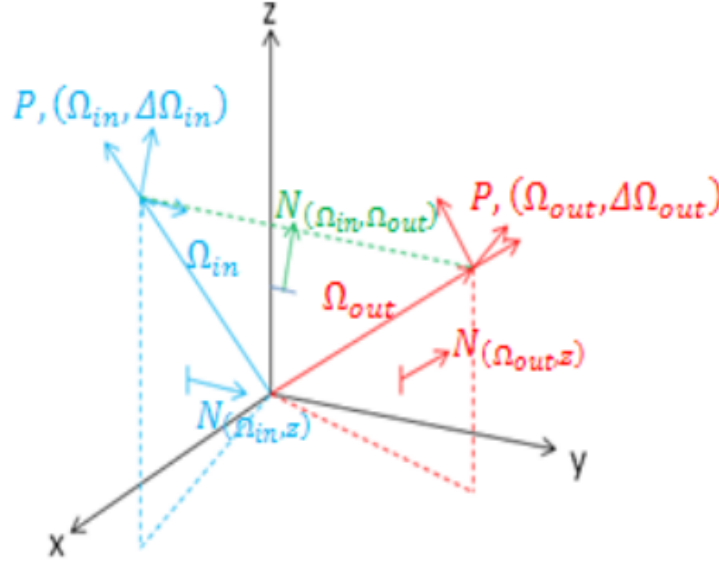


Figure A.2: Coordinate system on which the Stokes vector is defined[54].

A Mueller matrix M is used to represent the interaction of the vector with the media it encounters. Said matrix M is defined in the scattering plane. The input vector $P_{(\Omega_{in}, \Delta\Omega_{in})}$ has to be defined according to the scattering plane as well, and therefore needs to be rotated first:

$$P_{(\Omega_{in}, \Delta\Omega_{in})_{scat}} = R_{P_{(\Omega_{in}, \Delta\Omega_{in})} \rightarrow P_{(\Omega_{in}, \Delta\Omega_{in})_{scat}}} \cdot P_{(\Omega_{in}, \Delta\Omega_{in})} \quad (A.1)$$

This vector is then scattered through the use of the Mueller matrix M :

$$P_{(\Omega_{out}, \Delta\Omega_{out})_{scat}} = M \cdot P_{(\Omega_{in}, \Delta\Omega_{in})_{scat}} \quad (A.2)$$

Which is then rotated into the outgoing ray's coordinate system:

$$P_{(\Omega_{out}, \Delta\Omega_{out})} = R_{P_{(\Omega_{out}, \Delta\Omega_{out})_{scat}} \rightarrow P_{(\Omega_{out}, \Delta\Omega_{out})}} \cdot P_{(\Omega_{out}, \Delta\Omega_{out})_{scat}} \quad (A.3)$$

Such that every ray across the 4π space is defined in accordance in its own local Stokes plane, which is normal to the ray's propagation direction and oriented such that the y -axis is in the plane $(z, \hat{z})$, where $\hat{z}$ is the ray's propagation direction. Multiple different Mueller matrices are employed by *DART*, supporting different types of scattering taking place, such as Fresnel or specular reflection, Rayleigh scattering, Mie scattering or leaf volume scattering.

A problem arises when treating specular reflection within a discretised system such as *DART*: given the nature of a specularly reflected ray — being reflected as a single ray —, and the fact that the rays of light are projected along random directions, the odds that the outgoing ray's orientation exactly matches that of one of the tracked ordinates is exceedingly low. Consequently, most specularly reflected vectors would go unobserved if not for the approach *DART* employs. *DART* treats the reflected ray as a solid angle, where the power reflected by the surface is distributed over an angular region, as shown in Figure A.7b. In doing so, it makes a series of assumptions:

- Both refractive indices n_{in} (incident medium) and n_t (transmitted medium) are assumed to be real for all wavelengths. It is noted that this may not always be the case in reality — in the thermal infrared or when encountering metals the imaginary component may play a role.

- Both the angular widths $\alpha_{face,up-down}$ and $\alpha_{trans,up-down}$ are independent of the incidence angle. The same applies to two multiplicative factors $A_{face,up-down}$ and $A_{trans,up-down}$, which are used as weights for the Fresnel coefficients.

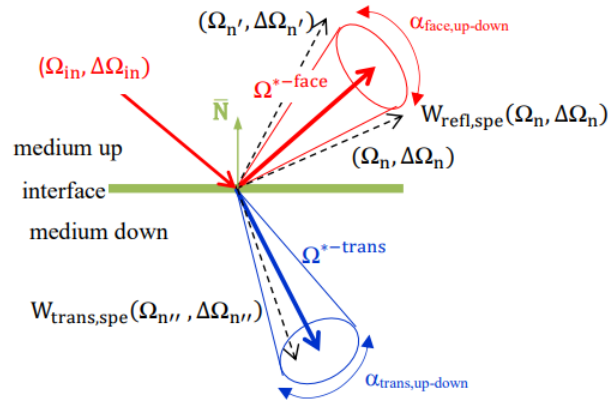


Figure A.3: DART's modelling of specular reflection as a solid angle as opposed to a clear ray[54]

If the incident power is given by W_{in} , then the specular reflected power of a ray is:

$$W_{refl} = r^2(\theta_{in}) W_{in}(\Omega_{in}, \Delta\Omega_{in}) \quad (A.4)$$

Where r^2 is the total reflected fraction of power,

$$r^2 = \frac{r_{\parallel}^2 + r_{\perp}^2}{2} \quad (A.5)$$

Such that this component serves to represent the fraction of power reflected. The power transmitted is therefore:

$$W_{trans} = [1 - r^2(\theta_{in})] W_{in}(\Omega_{in}, \Delta\Omega_{in}) \quad (A.6)$$

As mentioned, it is assumed that the specular radiance is maximal at the exact angle of specular reflection. A one-dimensional distribution function $f(\psi_{\Delta\Omega^*, \Delta\Omega})$ is then employed to scale the radiance value in the angular area. This distribution function is either constant, normal or parabolic. A specularly reflected vector received in a discrete direction n will thus be:

$$P_{(\Omega_n, \Delta\Omega_n)} = A_{face, up-down} r^2(\theta_{in}) \frac{\vec{N} \Omega_n}{\vec{N} \Omega_{face-*}} \frac{f(\Delta\Omega_{face-*}, \Delta\Omega_n^{face-*}) \Delta\Omega_n^{face-*}}{\sum_n f(\Delta\Omega_{face-*}, \Delta\Omega_n^{face-*}) \Delta\Omega_n^{face-*}} \cdot P_{(\Omega_{out}, \Delta\Omega_{out})} \quad (A.7)$$

Where $P_{(\Omega_{out}, \Delta\Omega_{out})}$ is expressed in Equation A.3, and the fraction serves to distribute the power of the ray over discrete directions ($\vec{N}$ represents the unit normal of a facet. The sum in the denominator adds up to the total reflected power over the entire cone).

A.1.2. User interface

DART comes equipped with a complete user interface which allows for the rapid editing of simulations. Figure A.4 displays the simulation editor, with a number of features visible. Under bi-directional parameters, one is free to modify variables such as the size of the target pixels (the dimensions of the area viewed by a single pixel), the number of repetitions of the scene (the scene is repeated around the edges, to avoid artifacts due to the terrain being absent, for instance), the energy threshold to stop tracking a ray, or the number of times a ray can scatter.² and handbook[54]. The simulation in Figure A.4 shows seven different spectral bands being employed: these can be defined individually or as a range, and can be given custom bandwidths.

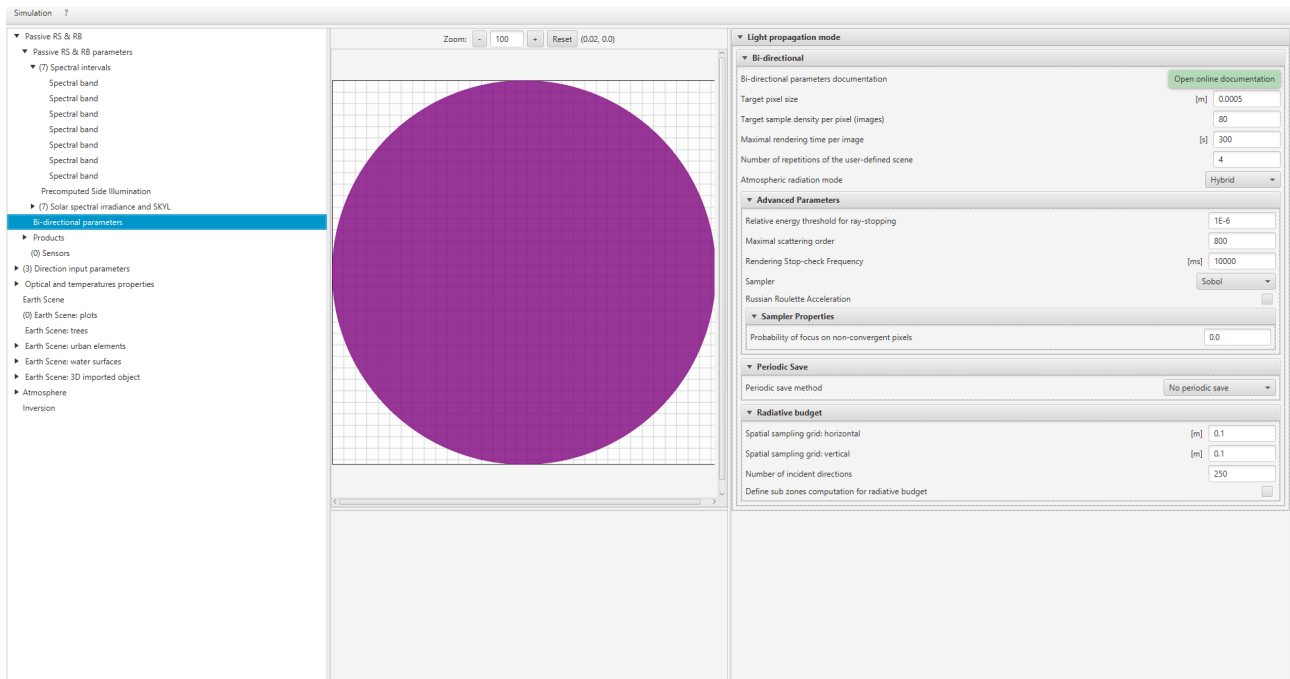
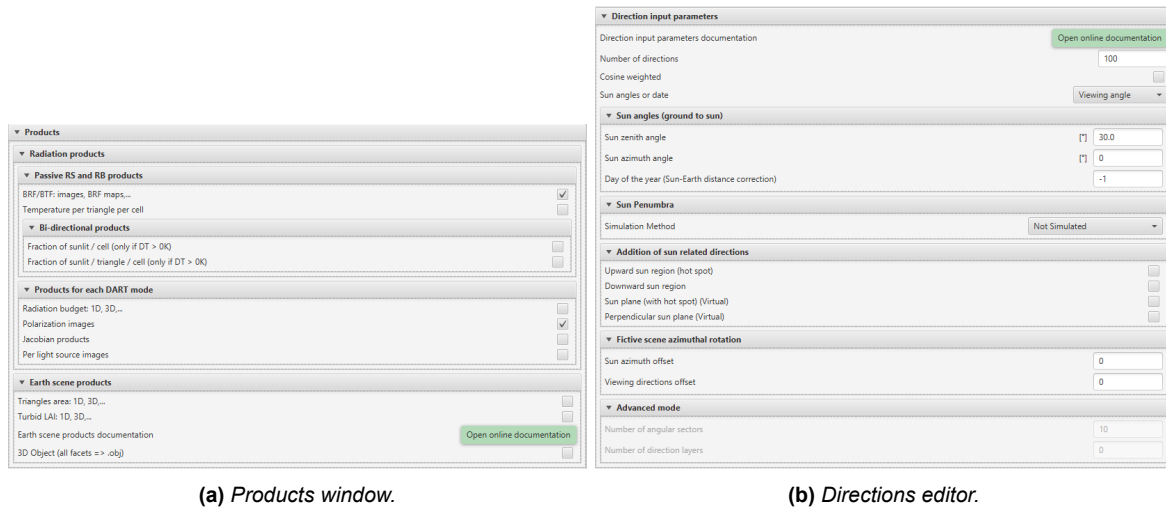


Figure A.4: Overview of *DART*'s interface.

Figure A.5a shows the product selection window, where one can select which products *DART* will output. Some of these are necessarily computed as part of *DART*'s standard operation, but the option is given to limit the size of the output files. Notably, the mode employed in the image shown is Passive Remote Sensing, which calculates a radiative budget for each voxel in the scene; this can be seen in the products including the option to save said radiative budget. The Monte Carlo mode is computationally cheaper, but does not compute the radiative budget.

Figure A.5b shows the directional input parameters window. It is here that one can determine the direction from which sunlight is coming, the number of discrete ordinates employed in the simulation, which regions to sample in greater detail, etc. One can freely specify additional directions corresponding to a set of zenith and azimuth angles, and even save images in these directions.

²A complete explanation of the meaning of each input parameter is beyond the scope of this research. An inquisitive reader may satisfy their curiosity by consulting the *DART* user manual[55]



(a) Products window.

(b) Directions editor.

Figure A.5: Two parameter windows in DART's simulation editor.

Perhaps one of the more useful features of *DART* is its implementation of optical properties. One is free to create different materials or media with different optical properties, then freely apply these to the objects within the scene. The more important categories for the purpose of this research are the Lambertian and Specular modes. Remarkably, it is possible combine different optical properties in a single surface: Figure A.7b shows the definition of a specularly-reflecting surface, where n_i is modelled as that the refractive index of air, and n_t is that of water. A display of the values of both refractive indices across the spectrum is shown by pressing the corresponding display button. Custom properties can be defined by adding them to *DART*'s database.

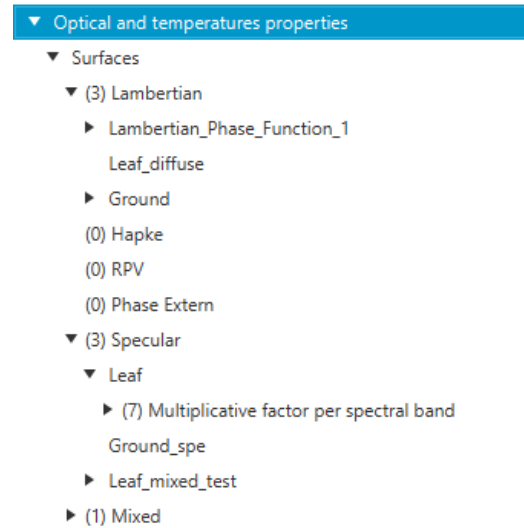
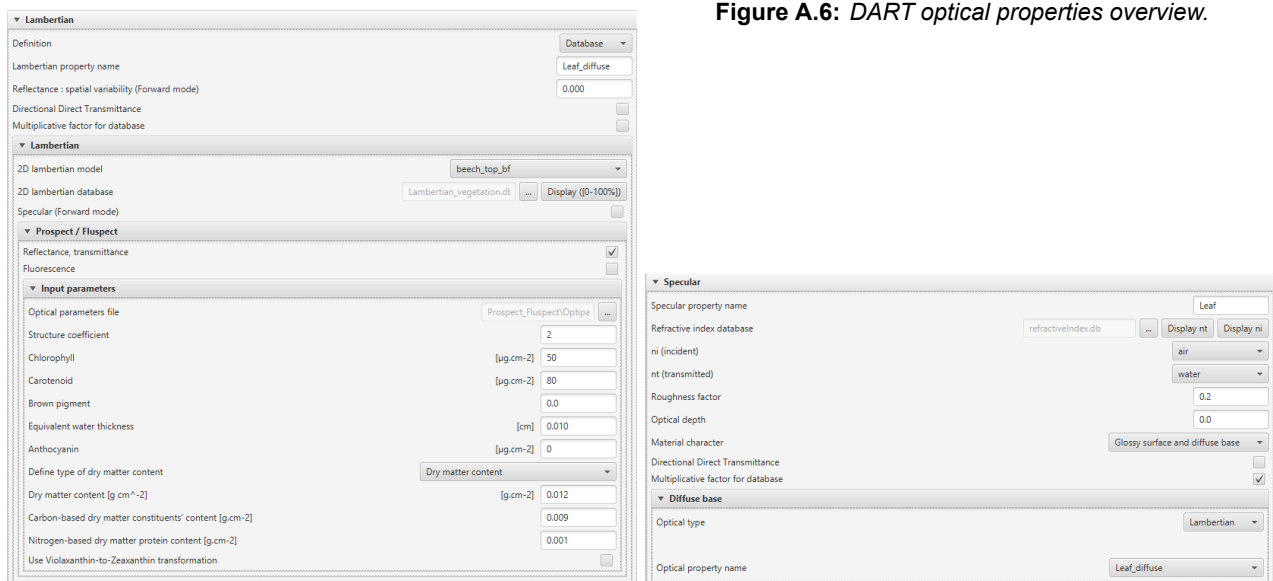


Figure A.6: DART optical properties overview.



(a) Lambertian Surface Optical Properties Definition.

(b) Specular Optical Properties Definition.

Figure A.7: Optical property definition windows.

The specular properties include the option of adding a diffuse base; in this case, "leaf_diffuse" is selected, which is shown in Figure A.7a. The most notable aspect of this window is the integration of *PROSPECT* into the optical properties themselves. *DART* has integrated several different versions of *PROSPECT* for use in simulating optical properties. This is, naturally, exceedingly helpful in this research topic, as it allows for the use of *PROSPECT* within a 3D environment, whilst adding a specular reflection component to the emissions modelled by it.

A.2. Introduction to PROPOLAR

An overview of how *PROPOLAR* functions is provided in this section. Given its relative simplicity compared to *DART*, this section is much briefer. The main difference arises from *PROPOLAR* being an analytical model as opposed to a numerical one: while for practical applications one does not compute a near-continuous distribution — whether that be *BRF* or *BPRF* — the analytical expressions are given.

PROPOLAR employs a fundamental assumption that has been applied to other simulations in this document as well: it divides reflected light into a diffuse, non-polarised Lambertian component, and a specularly reflected and polarised one. The former is assumed to display wavelength dependence, which it models using *PROSPECT-D*[79]: a more recent version of *PROSPECT* (and the one employed in the *DART* simulations as well).

The leaf surface, by comparison, is modelled as a number of microfacets[37]. It mathematically divides a smooth, flat surface into minuscule sections, each of which has a slightly different slope and orientation, and each of which reflects light specularly. The *BPRF* of this surface is modelled as:

$$BPRF(\alpha, n, \sigma, \lambda, \theta_s, \varphi_s, \theta_v, \varphi_v) = \frac{\alpha \pi^2 F_p(n, \gamma)}{4 \cos \beta (\cos \theta_s + \cos \theta_v)} P(\beta, \sigma) \quad (\text{A.8})$$

Where α is a model parameter, n is the leaf surface refractive index, and σ is the leaf's roughness, measured as the Root Mean Square (*RMS*) of measured slopes. Interestingly, the refractive index is modelled as a factor f_{PROPOLAR} that scales a wavelength-dependent "basic" refractive index. It is common for the refractive index to vary slightly with wavelength, but the authors do not specify which values f_{PROPOLAR} takes; it is therefore hard to evaluate if this factor is used to eliminate this wavelength dependence or for some other purpose. The expression $F_p(n, \gamma)$ represents the polarisation component of the Fresnel reflection equations applied to a microfaceted surface, based on the formulations found in references [37, 46, 49]. The term γ represents the scattering angle, θ_i is half the phase angle — complementary to the scattering angle γ — and θ_t is the refraction angle as derived from Snell's Law. The parameter β represents the angle between the leaf and microfacet normals, and $P(\beta, \sigma)$ is the microfacet distribution function, which follows the form:

$$P(\beta, \sigma) = \frac{1}{2\sigma^2\pi \cos^3(\beta)} e^{\frac{-\tan^2 \beta}{2\sigma^2}} \quad (\text{A.9})$$

The physical meaning of Equation A.8 is as follows: $F_p(n, \gamma)$ represents the Fresnel reflection upon the surface of a given microfacet. Expression $P(\beta, \sigma)$ represents the probability density of microfacet orientation, *i.e* it acts as a weight representing how many microfacets happen to be oriented in a specific direction. The rest of the expression weighs the result with the viewing and illumination geometry. *PROPOLAR* then combines this result with the *PROSPECT-D* results (and a small specular, non-polarised component modelled as a weight $F_{\text{correction}}$ on the Lambertian component[37]) to form the results. Having both *BRF* and *BPRF*, it can also output the degree of linear polarisation *DoLP*.

Ancillary simulations

B.1. A tree simulation

One of the first simulations performed in *DART* was carried out for the mere purpose of familiarising with its workings. This simulation is presented here as proof that *DART* is capable of simulating the Stokes parameter U as well as Q , which the results of the main simulations in Chapter 4 do not show.

The simulation is composed of a simple scene: a flat soil layer covered with a sparse tree canopy, as shown in Figure B.1. The trees are all the same 3D model — included by default as part of *DART* — with different orientations so as to produce a more unique effect. The 3D object is composed of both the leaf canopy and trunk, to which independent optical properties can be applied. Figure B.1 shows that the leaves were given a specular property (with parameters identical to those seen in Figure A.7b) and the pre-defined Lambertian properties of a maize plant (for want of an optical property for the cherry tree, the tree in question).

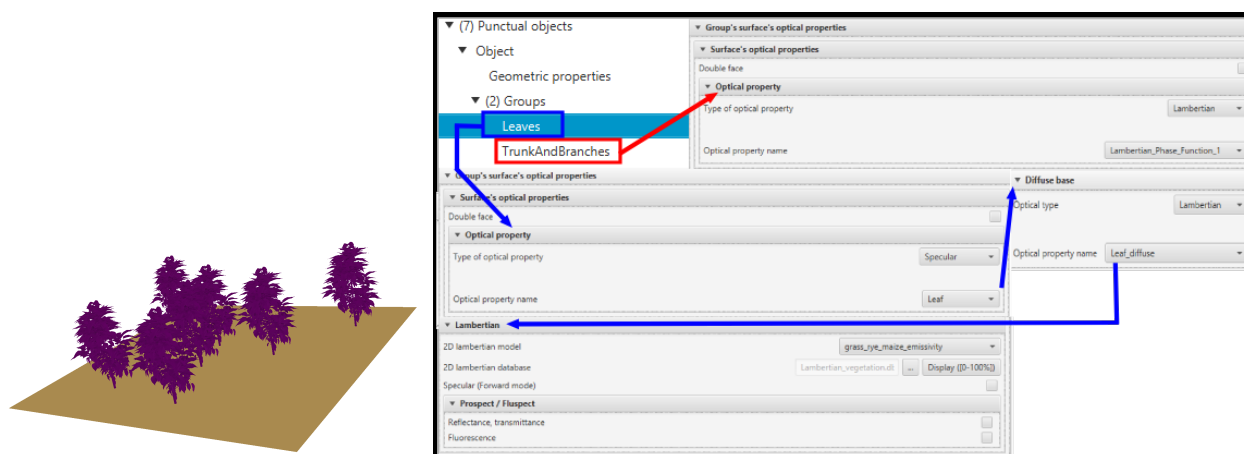


Figure B.1: First simulation scene. On the left, a 3D representation of the scene in question — note that the distinct purple colouring of the trees is merely a function of the editor, and not the result of the simulation. On the right, the optical properties of said trees.

The polarisation results are shown in Figure B.2; in it, one can appreciate that there is a clear element of specular reflection that is polarised, and mostly concentrated around the angle of specular reflection. There is a U -component to the polarisation as well, which appears much more evenly distributed across the domain. Figure B.2c shows an image of the same scene in Figure B.1 seen from an angle. The shape of the tree canopies can be made out, yet the trunks are not visible — an expected result, given that their optical properties are fully Lambertian.

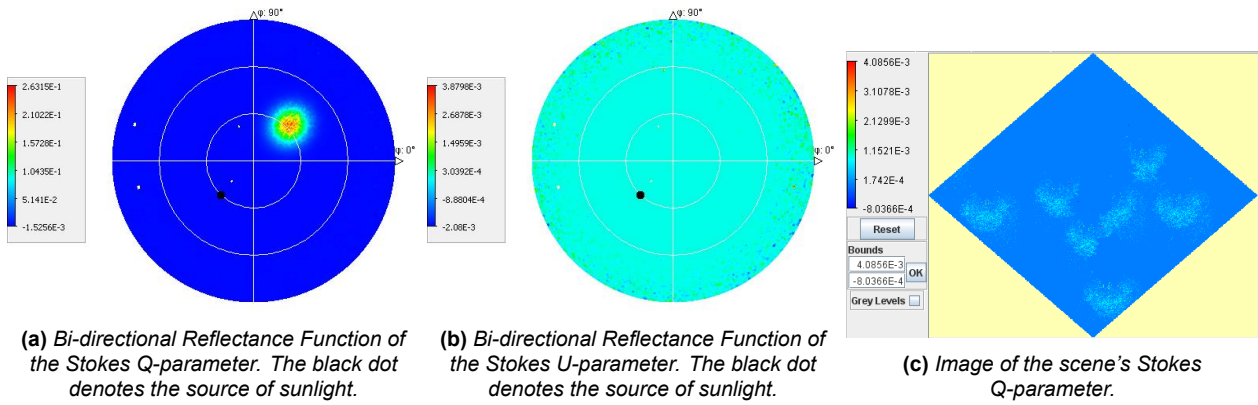


Figure B.2: Results of the initial simulation.

The results of this simulation prove that *DART* can simulate polarisation provided a suitable 3D object.

B.2. Microfacets

An attempt was made to circumvent the problem of *DART*'s roughness distribution by substituting the built-in implementation of roughness — a weight applied onto a broader function — with roughness on the plane geometry itself. A script was devised that generated *.obj* files in accordance with a desired number of microfacets, a desired roughness and a factor with which to scale the height of the vertices. Some qualitative results are shown in Figure B.3 and Figure B.4. Exact figures could have been provided, but no further analysis was carried out on this concept given that the time that was invested in it did not justify the returns. It appears from the plots that, while *DART* can simulate these, the results are unnatural. The results can be made more intricate (showing greater spread over a larger number of points) by increasing the roughness within the optical parameter in *DART* itself, though that implies adding more roughness onto an already rough plane. Decreasing the roughness in the optical properties produces only a more narrow distribution of points where the signal is much weaker. The concept of microfaceted geometries does not integrate well into *DART*'s existing architecture. The one interesting result is that non-zero *U* Stokes parameters, though weak, were present often.

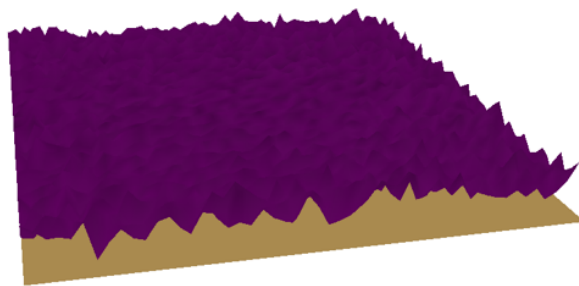


Figure B.3: A visualisation of the *.obj* file, for $N=50$ microfacets and a roughness of 0.3. The vertex height was dramatised for the purpose of visualisation.

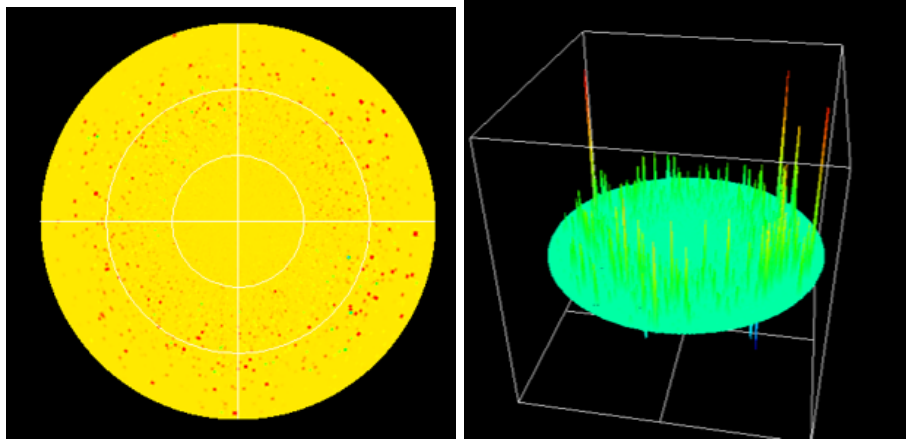


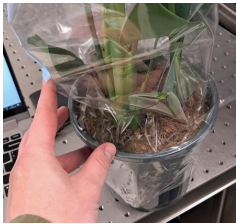
Figure B.4: *Left: A BPRF for $N=50$ microfacets and a roughness of 0.3. Right: A 3D graph of the same results.*

C

Leaf sample pictures

Image	Label	Description
	<i>EJ-1</i>	The picture shown corresponds to measurements in Session 2: it is aged by a week.
	<i>EJ-2</i>	The top image shows the leaf after harvesting. The bottom shows the leaf in Session 4, aged two weeks.

Continued on next page

Image	Label	Description
	<i>EJ-3</i>	Shown after harvesting.
 	<i>S-1</i>	The top picture shows the leaf before harvesting, as part of its plant of origin. The bottom image shows it aged a week.
	<i>S-2</i>	Shown after harvesting.

Continued on next page

Image	Label	Description
	CL-1	Shown aged a week.
	CL-2	Shown after harvesting.
 	PL-1	Shown a few hours after harvesting, after measurement session.

Table C.1: *Leaf samples used in the various experiments.*

D.1. Homemade goniometric setup

Before access was granted to more specialised equipment, a goniometric setup was built out of spare material. Figure D.1 and Figure D.2 show the results: the structure was designed to hold a measurement instrument, which would be mounted onto the platform on the frame and slid across, allowing for (roughly) equidistant measurements of the same object from multiple angles.



Figure D.1: *Improvised goniometric setup.*



Figure D.2: *Improvised goniometric setup.*

D.2. A plastic leaf

During one of the measurement sessions, a further sample was introduced and a single picture of it was taken. This was a plastic leaf of dubious provenance (it had sat on a desk for years). It was thought interesting to take a single measurement to highlight the difference between real vegetation and replicas. Interestingly, it showed that the plastic leaf did exhibit some degree of polarization, noisy in appearance but uniform across the entire measurement. It is hard to appreciate from this picture, but the leaf has a woven structure. It is possible that some textiles may emit similar signals, which could be explored in other research projects.

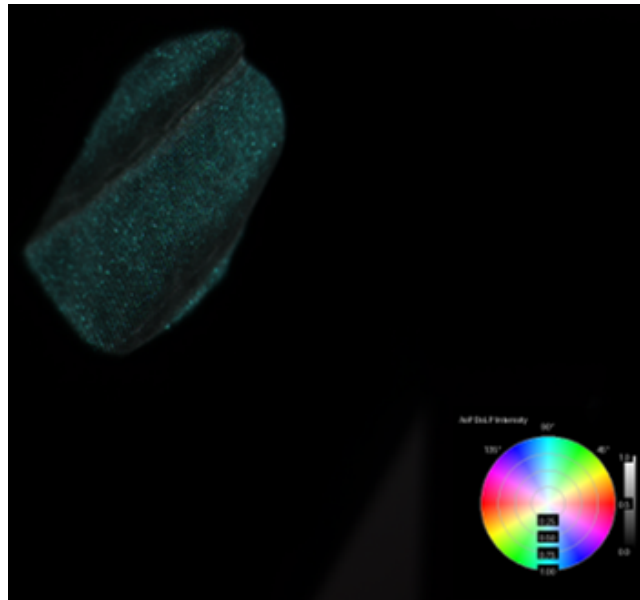


Figure D.3: *Colourmap of the polarisation of a plastic leaf.*

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